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Fish pass Steffstep – a solution for disconnected rivers?

Potential application and efficiency of a new fish pass type

Master thesis in environmental science v.1.1
Department of Environmental Systems Science

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cover picture
***left**: Fish pass Steffstep on August 2015*
***top right**: Brown trout (*Salmo trutta *resident form), Anja Trachsel, 2015*
***bottom right**: Eva Baier is tagging a brown trout, Anja Trachsel, 2015*

Abstract

Fish are migrating organisms, which need free flowing rivers to live in. However, nowadays rivers are highly fragmented due to human intervention. Barriers, weirs and falls are gradually getting removed. Reducing the negative impacts of these man-made obstacles requires significant resources and time. To enable a fish migration in due time, the new modular fish pass type Steffstep was developed. In this master thesis a prototype of such a Steffstep was evaluated with respect to its efficiency and potential application for Switzerland. In order to quantify the fish migration, 672 fishes were marked with PIT-tags (PIT = passive integrated transponder). Additionally, a video camera and a fish trap were installed at the fish pass. The focus on the research lay on the target species brown trout (S*almo trutta* resident form) and minnow (*Phoxinus phoxinus).*

The results show, that the attraction efficiency of the Steffstep prototype for the target species was rather low (brown trout 28 %, minnow 12 %). The passage efficiency of the brown trout was sufficient (65 %), whereas the minnows were not able to pass the facility (0 %). This result matches with other field studies, where minnows also did not use fish pass facilities. For the brown trout a size selection was observed: fish smaller than 211 mm (median) had a lower passage efficiency (47 %) than bigger ones (80 %), though both had almost the same attraction efficiency. Therefore, improvements to the flow velocity within the fish pass for small fishes, as well as optimizations to increase the attraction efficiency for all fishes are strongly recommended. Overall, the low attraction efficiency resulted in a rather low total efficiency in comparison to conventional vertical-slot fish passes or block ramps. However, these facilities focus on other functionalities than Steffstep.

The fish preferably migrated during an increased discharge. No correlation between day time or water temperature and the fish migration was observed. The bigger fish were ascending the fish pass slightly faster than the smaller ones. Some brown trout were using the fish pass more than once (n = 13). The fish were slightly faster at the second and third run than they were at the first run. Additionally, ten of the ascending fish were recorded using the fish pass even downstream.

The potential application of Steffstep is high at rivers with a mean annual discharge of up to 10 m^3/s, where suitable fish habitats are fragmented through an obstacle that will not to be rebuilt within the next few years. The amount of suitable sites is roughly estimated to be in the order of a few thousands in Switzerland. The research illustrated that the efficiency of this prototype for brown trout is almost sufficient. Continuing investigation is recommended for efficiency monitoring of other species as well as for a systematic approach to determine locations, where this fish pass would be useful.

Zusammenfassung

Fische sind aufgrund ihrer Biologie darauf angewiesen, wandern zu können, was heute durch massive Eingriffe des Menschen in die Fliessgewässer weitgehend verhindert wird. Zur Lösung dieses Problems werden Hindernisse wieder zurückgebaut und Flussabschnitte revitalisiert, was üblicherweise viel kostet und lange Planungs- und Bauhorizonte mit sich bringt. Die Biodiversität der Fischpopulationen nimmt stetig ab, wodurch rasche Lösungen nötig sind. Um die Zeit bis zu einer Revitalisierung zu überbrücken, hat die Walter Reist Holding AG (WRH) eine günstige, modular aufgebaute Fischtreppe für künstliche Querbauwerke in kleinen bis mittelgrossen Flüssen entwickelt. Die sogenannte Steffstep kann eingebaut werden bis ein Hindernis endgültig beseitigt wird. Im Rahmen dieser Masterarbeit wurde ein Prototyp einer solchen Fischtreppe auf seine ökologische Funktionstüchtigkeit hin untersucht sowie eine Potentialabschätzung zu ihrem Einsatz in der Schweiz durchgeführt.

Für die ökologische Erfolgskontrolle wurden insgesamt 672 Fische mit PIT-Tags markiert (PIT = passive integrated transponder). Zusätzlich wurde auch eine Reuse sowie eine Kamera zur Zählung und Beobachtung der Fische verwendet. Für die zwei Zielarten Bachforelle (*Salmo trutta* resident form) und Elritze (*Phoxinus phoxinus*) konnte eine Auffindbarkeit der Fischtreppe von 28 % respektive von 12 % nachgewiesen werden. Dies ist weniger als erwartet und sollte unbedingt durch Änderungen der Konstruktion verbessert werden. Die Elritzen stiegen durch die Steffstep nicht auf, was sich weitgehend mit Befunden an herkömmlichen Fischtreppen und Blockrampen deckt. Für Bachforellen konnte hingegen eine Passierbarkeit der Steffstep von durchschnittlich 65 % nachgewiesen werden. Die Steffstep zeigt eine Grössenselektion: Bachforellen unter 21 cm (Median) wiesen eine viel tiefere Passierbarkeit der Fischtreppe auf (47 % anstatt 80 %) bei einer fast gleich grossen Auffindbarkeit wie die grossen Tiere. Dies bedingt, dass innerhalb der Fischtreppe Anpassungen zugunsten der kleinen Fische gemacht werden müssen.
Während der Feldstudie fiel ungewöhnlich wenig Regen, wodurch die Fischwanderung beeinflusst wurde und nur konzentriert an wenigen Tagen stattfand, meistens bei erhöhtem Abfluss. Ein paar Bachforellen (n = 13) nutzen den Fischpass mehrfach, wobei sie beim zweiten Mal im Schnitt schneller waren als beim ersten Aufstieg. Von den 53 aufgestiegenen Bachforellen nutzten 10 Tiere die Fischtreppe auch für den Abstieg.

Für den Einsatz der Steffstep geeignet sind grundsätzlich alle Hindernisse, welche vorhandene Fischhabitate voneinander trennen und in den kommenden Jahren nicht zurückgebaut werden. Der durchschnittliche Jahresabfluss sollte dabei 10 m³/s nicht übersteigen. Es wird davon ausgegangen, dass diese Bedingungen grob geschätzt mindestens an jedem hundertsten Hindernis in der Schweiz vorhanden sind und somit ein Einsatzpotential von mehreren Tausend Hindernissen besteht. Die Resultate ergaben, dass die Steffstep in der aktuellen Version vor allem für Bachforellen geeignet ist. Für die ökologische Funktionstüchtigkeit für weitere Fischarten sowie für eine genauer quantifizierte Potentialabschätzung werden aufbauende Untersuchungen empfohlen. Eine deutsche Zusammenfassung der Resultate sowie Empfehlungen für weitere Schritte sind in einem Bericht zuhanden des Bundesamtes für Umwelt am Ende der Arbeit zu finden.

Acknowledgement

First, I would like to thank Dr. Armin Peter sincerely for his indispensable supervision, for sharing his knowledge, support in the field, unbroken patience with the technique and his professional inputs for this thesis. It was a pleasure to work with you. Furthermore, I want to thank Prof. Bernhard Wehrli for his time and great supervision and his help in writing and structuring this report.

I would like to express special thanks to the Walter Reist Holding AG, which enabled me to realize this master thesis. I want to name specifically four people who have given me solid support also outside working hours: Heinz Möckli, Peter Hausmann, Walter Schmid and Willy Leu. They organized an office container for me with directly at the river and with electricity, they supported me with material (video camera, truck battery, fish trap, …) and any occurring problem was solved in no time. I thank the Federal Office for the Environment (FOEN) for its financial support. I also thank the canton of Zurich, especially the Office of Landscape, Agriculture and Environment (ALN) and the Office of Waste, Water, Energy and Air (AWEL) for the permission to test the fish pass Steffstep in the canton of Zurich, the good cooperation during the implementation and the support in electrofishing. Therefore I want to thank particularly Dr. Andreas Hertig and Werner Honold of the hunting and fishery administration for their personal commitment.

In addition, I thank Bühler AG that gave the permission to test the fish pass at this site. I also want to express my thanks to Mr. and Mrs. Naef-Crivelli, residents near the river, for their support with power connection, tools and everything that was missing in everyday life.

A special thank goes to my friends, which helped me with the electrofishing, marking the fish and checking my text for linguistic mistakes. I would like to mention by name Benjamin Baier, Johanna Rüegg, Muriel Siegwart, Anja Trachsel, Benedikt Ummen and Ralf Weise. I also thank my parents, who have always encouraged me to continue running my project. And finally, I want to express my warm thanks to Cédric Sonderegger for supporting me at all levels during the whole project time.

Prehistory

In 2011, I recognized the problem of the inhibited fish migration in Switzerland and developed the idea of a simple fish pass for non-power station-related obstacles. Thereupon, I created a project team with members of the ALN, AWEL, FOEN and World Wide Fund for Nature Switzerland (WWF) to implement a first prototype. For that, I wrote my bachelor thesis for the ecological examination and organized a master thesis for a construction engineer student to dimension the prototype. In parallel I organized the financing for the implementation and besides that I won the second place at the start-up competition “For a green economy” of the Impact HUB Zurich with this project. In 2014, a cooperation with the WRH AG arose, which also wanted to realize a similar concept of a new fish pass type. In addition to my ecological consulting for this company, which I was doing beside my studies, I examined their fish pass in terms of its efficiency with this master thesis.

All information about the project, scientific writing, reports, presentations as well as further developments can be found on my website: www.fischwanderung.ch

Contents

List of abbreviations

ALN	Office of Landscape, Agriculture and Environment of the canton of Zurich
ARE	Office for Spatial Development of the canton of Zurich
AWEL	Office of Waste, Water, Energy and Air of the canton of Zurich
BAFU	Bundesamt für Umwelt = FOEN
BLV	Bundesamt für Lebensmittelsicherheit und Veterinärwesen
BMLFUW	Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management
BMUB	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Deutschland = Federal Ministry for the Environment, Nature Conversation, Building and Nuclear Safety, Germany
BGF	Federal Act on Fisheries
BUWAL	Bundesamt für Umwelt, Wald und Landschaft, previously FOEN
DWA	German Association for Water, Wastewater and Waste
Eawag	Swiss Federal Institute of Aquatic Science and Technology
FIBER	Schweizerische Fischereiberatungsstelle
FOEN	Federal Office for the Environment
ICAR	International Committee for Animal Recording
ICPR	International Commission for the Protection of the Rhine
MUNLV	Ministry for Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia, Germany
LANAT	Amt für Landwirtschaft und Natur, Kanton Bern
SWV	Schweizerischer Wasserwirtschaftsverband
VAW	Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich
VBGF	Ordinance concerning the Federal Act on Fisheries
WFD	EU Water Framework Directive
WRH	Walter Reist Holding AG
WWF	World Wide Fund For Nature

1 Introduction

1.1 Background

Freshwater systems cover only 0.8 % of the earth's surface (Crook et al., 2015) but they are essential for human existence. For thousands of years humans have settled preferably at rivers (BMUB, 2006; Freund, 2007). Close to the rivers fish have served as an important source of food (Lucas & Baras, 2001), soil near the water has been fertile and the climate has been mild. These are good conditions for agriculture, fruit growing, viticulture and therefore good conditions for settlement (BMUB, 2006). To this day streams are used as transport routes, supply of food and drinking water, for agriculture irrigation, energy production and cooling of industry facilities, like nuclear power plants (Wohl, 2004; BMUB, 2006; Freund et al., 2007). However, the use of fresh water for human activities, like those mentioned above, change rivers fundamentally. Dams prevent migration of organisms and natural transport of bed-load, straightening of rivers changes the hydrological and morphological dynamics and pollution influences the chemical composition of the water. But beside the human needs riverine ecosystems play an important role as habitats for diverse species (Wohl, 2004). The fundamental changes on their environment therefore have a direct impact on their existence. In this master thesis the focus lies on the negative consequences of the so-called longitudinally disconnected rivers for upstream fish migration and a potential solution to mitigate these negative consequences.

1.1.1 Importance of connectivity for riverine ecosystems

Each ecosystem is highly connected in itself via various biological, physical and biochemical pathways. The connections affect energy fluxes, food web dynamics, species communities and biodiversity (Crook et al., 2015). In riverine ecosystems the exchange and interactions of different habitats take place in three ways: longitudinal, lateral and vertical. Longitudinal connectivity means an exchange between the habitats in a river downstream, upstream and to tributaries. Along all these directions migrations, e.g. from fishes or transport of plant seedlings, takes place and therefore a gene flow between their populations exists. The lateral connectivity is between the aquatic and the terrestrial ecosystems. It is especially important for arthropods, amphibians or aquatic insects, because they need different habitats during their life-cycle. And they are again a popular prey of birds, reptiles and fishes, which indirectly also need a lateral connectivity. In addition organisms exist which are dependent on the leaves from trees as food resource (e.g. crayfish). The vertical connectivity describes the interactions between the free water in a river and the hyporheic interstitial. This is necessary for the exfiltration and infiltration of the ground water and is the basis for the development of some organisms in the bottom substrate (e.g. invertebrates, fishes) (Werth et al., 2012). According to Wohl (2004) the functions of a “healthy” river are to provide habitats and nutrients for diverse species. Contrary to the saying “form follows function”, rivers can only fulfill its many functions when it can flow in a natural form, connected to the surrounding environment. The connections in all directions are one of the key factors for a sound riverine ecosystem, for which natural dynamic and habitat complexity have to be present. It has to be considered that the connectivity can vary during the year depending on the natural or man-made changing of flow regimes (Werth et al., 2012; Crook et al., 2015) and that a reconnection of disconnected river sections can only be useful when thereby inhabited habitats get linked (Wohl, 2004; Crook et al., 2015).

Problems with disconnected rivers

According to Riesch et al. (2015) habitat fragmentation represents one of the strongest and most penetrating anthropogenic environmental impacts. Because different ways of connectivity exist in a river, the consequences of disconnections are “numerous, complex and often highly specific to the species and environment of concern” (Crook et al., 2015, p. 61). The environmental tolerance of organisms and their ability to adapt their behavior and physiology in response to environmental change (phenotypical placity) are crucial to predict the consequences of disconnections to them (Crook et al., 2015). Nevertheless, generally accepted impacts on disconnected rivers exist. The transport of plant seeds, nutrients and bed-load, the drift of insect larvae and the active migration of organisms can only take place in longitudinally connected rivers. Otherwise the threat of a local extinction exists (Wohl, 2004; Werth et al., 2012; Crook et al., 2015).

There is a difference between structural and functional connectivity. *Structural* means that theoretically a connectivity is present, but only when this connection is used by organisms it is called *functional* (Werth et al., 2012). If populations are functionally connected, they have and maintain a higher level of genetic variability through genetic exchange, which then again improves their long-term viability (Crook et al., 2015; Gouskov et al., 2015). However, if populations are genetically disconnected, the threat of loss of genetic diversity exists. This can again result in a local extinction of migratory organisms (Werth et al., 2012; Crook et al., 2015; Gouskov et al., 2015; Lasne et al., 2015). Sometimes some organisms are able to adapt easily to fragmented habitats and dominate the river section at the expense of other species. So the composition of the species communities can change and the biodiversity can decrease (Lasne, 2015; Riesch et al., 2015). But it is known that ecosystems are more stable and adaptable to environmental changes (like climate change) or disturbances (like floods) when they are diverse and well connected (Wohl, 2004; Crook et al., 2015). There are other effects of fragmentation. For example, fragmentation can reduce the terrestrial sediment supply to the coast. This can change the sediment budget and morphology of a delta at the river mouths (Gelfenbaum et al., 2015). According to Delestrac (2013), one quarter of the global reserves of sand are trapped behind dams and therefore never reach the ocean.

To summarize, the disconnection of rivers influences the “behavioral, developmental, physiological and environmental factors that act and often interact – simultaneously over a wide range of spatial and temporal scales” (Crook et al., 2015, p. 59).

1.1.2 Fish migration

Fish migrations are essential for many fishes but they are also important for other creatures: for example in some regions the migrating fish are an important food resource for terrestrial animals (Ulmann, 1998) or the fishes are propagation vectors for plants (De Rooy, 2015).

Reasons for fish migration

The availability of resources changes spatially and temporarily within the environment. Animals seek to optimize their fitness, hence they must be well adapted to changing environmental conditions. Movement is one of the main options available to fish to enable an adequate response (Lucas & Baras, 2001). There is no universally accepted definition for migration (Castro-Santos Kemp, 2015), however different approaches to define migration can be found in literature. Lucas & Baras (2001) defined migration as synchronized movements by species beyond their average home ranges at specific stages of their lifecycle. Home range is the area or region in which animals spend their life and find their key resources. Within the home range different habitats can be present (Lucas & Baras, 2001). Northcote described migration more precisely as a directed movement which is done by the majority of a population and occurs periodically (Northcote, 1987). This implies that the animals return to the place from which they have started (McKeown, 1984; Northcote 1978).

Furthermore, Northcote described three functional types of fish habitats and therefore three principle categories of migration between these living areas (Northcote, 1978) (Figure 1). The fish are using the habitats depending on their development status. Often the fish use the different areas to live there alternatingly during the year: s*pawning grounds* mostly in spring, *feeding habitats* mostly in summer and *refuge areas* mostly in winter.

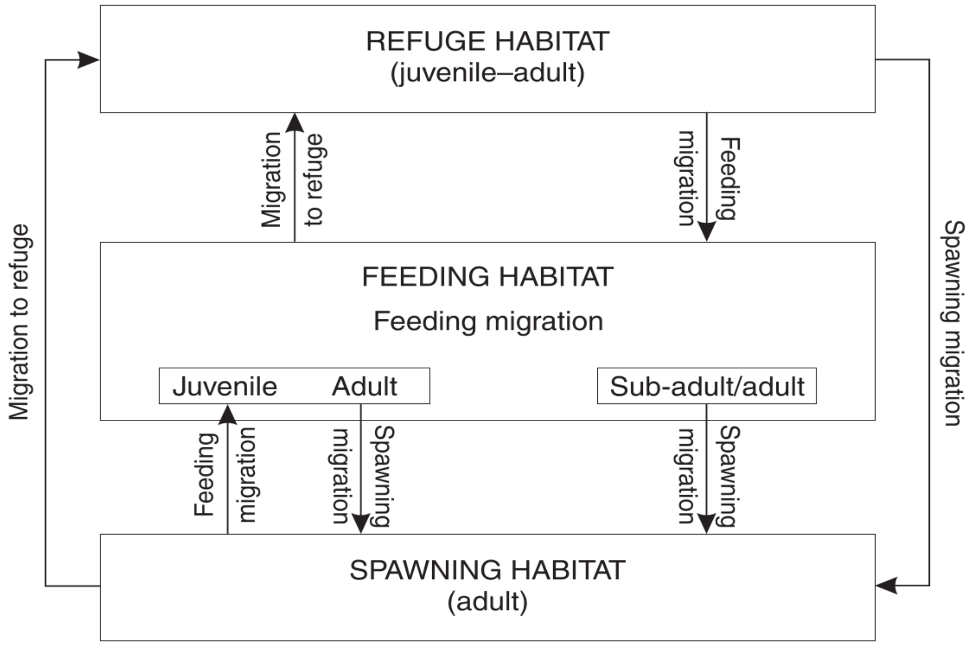


Figure 1: Theory of fish migration from Northcote (1978) (Lucas & Baras, 2001)

In summary, fish migrate to optimize food uptake as well as for reproduction and to escape from unfavorable conditions (Northcote, 1978; 1984). In addition, fish are swimming upstream to compensate drift and downstream transport, e.g. after flood conditions (MUNLV, 2005).

Types of migration

The distance of a migration varies between a few meters and thousands of kilometers (DWA, 2014). According to Lucas & Baras (2001), the migration of fish is independent of its distance but substantially important for survival and reproduction. These authors described three types of migration:

1. Oceanodromy: migrations within the oceans (salt water)
2. Potamodromy: migrations within fresh water
3. Diadromy: migrations between freshwater and marine environments

The diadromous fish are further divided into three subtypes:

a) Anadromy: reproduction in fresh water, feeding and growing in salt water
   e.g. Atlantic salmon (*Salmo salar*) (DWA, 2014)
b) Catadromy: reproduction in salt water, feeding and growing in fresh water
   e.g. European eel (*Anguilla anguilla*) (DWA, 2014)
c) Amphidromy: regularly change between fresh and saltwater

In reality there is no clear categorization of all species to one or another migration type, and moreover also transition forms can be found. For example the Atlantic salmon (*Salmo salar*) is known as an anadromous species but in some cases resident or temporary resident individuals were observed (DWA, 2014; Mertens, 2015). In other cases, there are examples that the migratory behavior of fishes changes with latitude (Lucas & Baras, 2001). It is assumed that migration takes place when the benefits overweight the costs, which is depending on the availability of resources (Castro-Santos & Kemp, 2015).

Migration factors and times

In principle, there are external and internal factors, which trigger a migration (Lucas & Baras, 2001). Amman (2006) summarized these factors from literature: *External factors* are availability of prey, prevention of predation, climate, hydrology, temperature and water quality. Whereas *internal factors* are changes in ontogeny, hunger and homing. Observations showed that migration additionally depends on the variability of the habitat (Amman, 2006). Lucas & Baras (2001) described that fishes in many European rivers show seasonal migration of spring-upstream and autumn-downstream movement. The motivation behind the migration can be different between the age-stages: adults can migrate in spring upstream to spawn, while juvenile with the same migration may compensate drift or search summer feeding areas (Lucas & Baras, 2001). It should be noted that indeed upstream fish migration of diadromous fishes could occur at specified seasons, but the processes are complex and therefore fish migration can take place all over the year. Particularly the migration of anadromous fishes is not linked to an age-stage and can therefore take place the whole year as well (DWA, 2014). Kirchhofer (2015) nicely summarized these facts: to the current state of knowledge, all fish species and all age stages have to be able to migrate at any time of the year.

It is to recognize, that fish migration in pristine rivers takes place upstream and downstream as well as lateral to tributaries (MUNLV, 2005). This master thesis focuses just on upstream fish migration, especially at non-power station-related obstacles.

1.1.3 Upstream fish pass facilities

The following section focuses on the upstream fish migration, however fish passes are also used by invertebrates, crayfish and sometimes vertebrates (e.g. birds, beaver, otters).

Basics

A fish pass is an artificial construction which enables fish and other aquatic animals to pass a vertical obstacle in a river. Such a construction should allow a sufficient gene flow, so that a species can maintain its evolutionary potential and the negative effects of a barrier on population connectivity can be diminished (Gouskov et al., 2015). A fish pass has to be constructed in such a way that the fish can pass it without delay, undue stress or injury (Thorncraft & Harris, 2000). Therefore, the dimensions and hydrological conditions have to be adapted to the behavior and performance capacity of the local fish fauna (DWA, 2014). To build a functional fish pass a large number of guidance documents with thresholds of the dimensions, recommendations for optimal hydrological conditions and guidelines for the fish pass types and their optimal arrangement exist. These guidelines should help to avoid structural problems and unfavorable hydrological conditions before the construction is built (DWA, 2014). Some important aspects of dimensioning fish pass facilities are highlighted in the following.

As shown in chapter 1.1.2 a fish pass should be functional all year round, according to DWA (2010; 2014) at least 300 days per year, to allow migration of all fish species at each age stage. For small, juvenile and benthic fish, as well as for benthic invertebrates, it is necessary to fill the bottom of the fish pass with natural substrate to make it possible for these species to migrate in a more or less natural environment. Therefore a continuous connection from the bottom of the river to the fish pass should be guaranteed.

It is necessary that the fish can easily find the fish pass. This includes the large-scale arrangement of the fish pass in the river and the arrangement of the local entry point (DWA, 2014). The entry should be as near as possible to the obstacle (Bunt, 2001; Ingenieurbüro Floecksmühle, 2004). The better the arrangements are, the more fish will migrate through the construction. The attraction flow is crucial to attract the fish to the entry and the optimal flow velocity of the attraction flow is depending on the fish fauna. If fish can not quickly find the entry, the delay of the fish migration could cause energy loss, affect the health of the fish and prevent reproduction at the optimal time.

The second important parameter for the connectivity is the passage efficiency of the fish pass. The conditions for a successful migration to the upstream water depend on the fish size: for small fish with low swimming capacities the hydrological conditions are crucial, for big fish the correct dimensions of the fish pass are decisive (DWA, 2014).

Ecological monitoring

For the verification of the efficiency, in addition to structural recommendations, it is very important to evaluate the reaction of the fish to the fish pass facility. Even if a fish pass is built according to one of the numerous guidelines, it is possible that no fish migration takes place. Therefore an ecological monitoring should always be included within a project of a new fish pass. And although an effective monitoring is often very expensive, it is necessary to learn more about the migrating fishes in order to optimize the construction of future fish passes (Gough et al., 2012). Naturally a, fish pass remains functional only if maintained (DWA, 2014).

Efficiency and effectiveness are two different terms common in ecological monitoring, however their usage is not consistent in literature. Therefore the terms are used in this master thesis as follows:

1. **Effectiveness**
   The effectiveness of a fish pass is a qualitative description of its performance. It only demonstrates that a certain amount of fishes is able to pass the facility (Gough et al., 2012). The effectiveness can only be determined with respect to a biological objective (Larinier & Marmulla, 2003). This implies that for each target species the amount of fish which should pass has to be determined before the evaluation starts. The effectiveness can be measured directly by capture techniques (e.g. trapping) or indirectly by visual methods (e.g. video monitoring, sonar-techniques) (Gough et al., 2012). Although the most common method to examine the connectivity of a fish pass is to measure its effectiveness, it is not meaningful to only measure the amount of passing fish. The drawback of using effectiveness to evaluate the connectivity is that not all fish which want to pass the fish pass are considered (DWA, 2006).
2. **Efficiency**
   The efficiency of a fish pass is a quantitative description of its performance (Larinier & Marmulla, 2003). It is the proportion of the fish stock downstream, which want to migrate and those which are able to pass the fish pass successfully in an acceptable period of time (Larinier & Marmulla, 2003; Bunt et al., 2012; Gough et al., 2012). What *acceptable* means, has to be determined for each target species (Larinier & Marmulla, 2003). To test the efficiency of a fish pass is more expensive and time-consuming than to test the effectiveness (Gough et al., 2012). Often the methods of tagging or telemetry are used for it (Larinier & Marmulla, 2003). According to Cooke & Hinch (2013) efficiency is a component of an effectiveness of a fish pass, which again should help to achieve management and ecological objectives.

Furthermore the efficiency can be further broken down into *attraction efficiency* and *passage efficiency* (Bunt et al. 1999; Bunt et al., 2012). According to Castro-Santos et al. (2009) the fish pass entry is a two-step process: first the fish have to be guided on a large-scale to the entry (guidance zone attraction efficiency), second the fish have to detect the structure and actually enter the fish pass (entry zone, entrance efficiency). In both zones the fishes can lose time in searching a possible migration way. The amount of delay is linked with fitness costs.

In summary there are three levels in which the efficiency can be examined:

a) attraction efficiency: fishes are able to find the entrance on a large scale in the river
b) entrance efficiency: fishes are able to enter the fish pass
c) passage efficiency: fishes which entered are able to pass the facility

According to Castro-Santos (2015 a) the fish pass is only efficient when more fish reach the entry zone than are rejected, when more fish enter the fish pass than not and finally when more fish successfully swim through the fish pass than swim back and all of them without delay. He recommends to use the radio-telemetry method to determine the attraction efficiency. This method allows to evaluate the behavior of a fish on a large scale, but it is not useful to evaluate if a fish has entered a fish pass. Therefore and for the passage efficiency he recommends to use PIT-tagging (Castro-Santos, 2015 a).
In this master thesis the definitions based on Bunt et al. (1999; 2012) were used to determine the attraction efficiency, the passage efficiency and the total efficiency with PIT-tagging as followed:

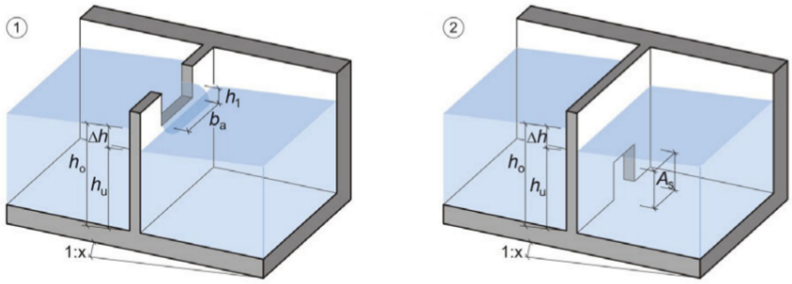
1. **Attraction efficiency [%]**: ratio between the fishes which were detected at the fish pass entrance (downstream) and the number of individuals that were released downstream in the pool near he fish pass entrance.
2. **Passage efficiency [%]**: ratio between the fishes which successfully swam through the fish pass (registered upstream) and the number of individuals that were detected at the fish pass entrance (downstream) .
3. **Total efficiency [%]:** ratio between the amount of fish which successfully swam through the fish pass (registered upstream) and the number of individuals that were released downstream in the pool near the fish pass entrance.

Fish pass types

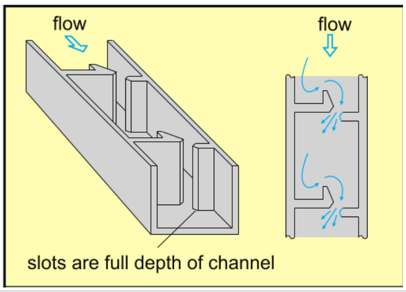
Around the world many types of fish passes exist (Table 1). In literature they were often divided into “nature-like” and “technical” fish ways (Ingenieurbüro Floecksmühle, 2004; MUNLV, 2005; BMLFUW, 2012, Hefti, 2012). DWA (2010; 2014) no longer uses this distinction, because the efficiency of a fish pass would be independent of the building material and the aesthetic point of view. The following table is based on the DWA guidelines.

Table 1: Overview of the main fish pass types*

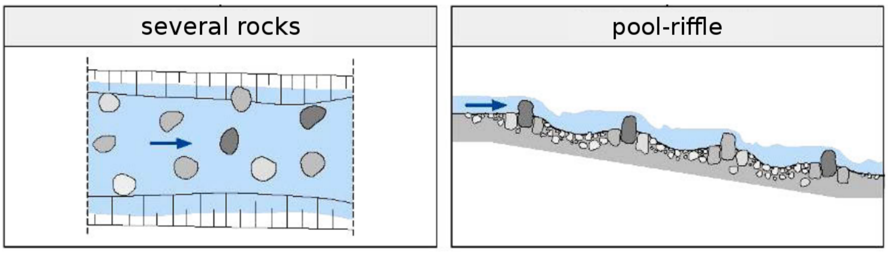
<table>
<tr><th>fish pass type</th><th>description</th></tr>
<tr><td>pool fishway</td><td>- different pools, which are separated by partition walls made of wood or concrete with notches for overfalls (1) and / or loopholes (2)
- pools offer fish possibility to rest, high flow velocity are concentrated in loopholes



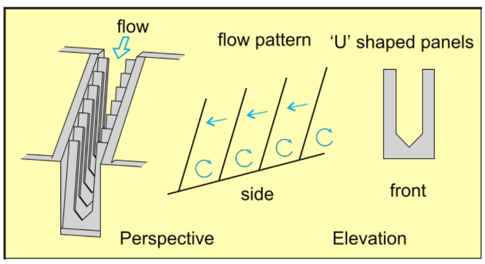
(DWA, 2014)</td></tr>
<tr><td>vertical-slot pass</td><td>- pool fishway with one or two vertical slots in the partition walls



(Thorncraft & Harris, 2000)</td></tr>
<tr><td>pool-riffle fishway / rock ramps</td><td>- combination of pool and channel-like fishway
- pools created by stone bars, with gaps for the fish
- a lot of combinations are possible (several rocks, full-width brinks, …)



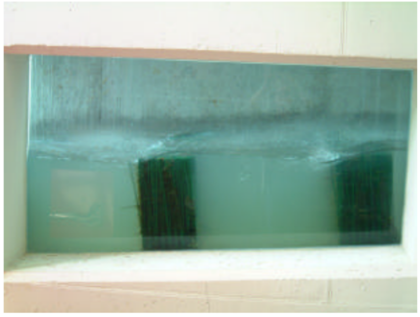
(DWA, 2014, modified)</td></tr>
<tr><td>channel-like fishway</td><td>- channel without further structures or rest areas
- fish have to pass the construction in one go</td></tr>
<tr><td>denil fish pass</td><td>- channel-like fishway with ‘U’-shaped baffles
- steeper channels are possible but construction is not passable for fish with low swimming capacities



(Thorncraft & Harris, 2000)</td></tr>
</table>

bristle fish pass

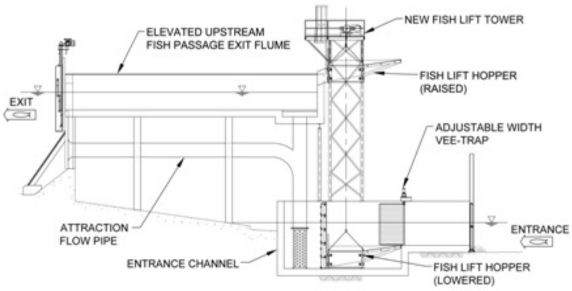
- channel-like fishway with bristles to reduce flow velocity
- high-maintenance required (cleaning) and lifetime around 15 years

(Hintermann, 2003)

fish lift

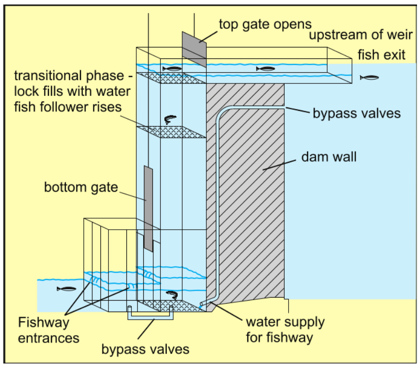
- mechanical lift brings fish in a water filled chamber to the top of the obstacle for release
- active transport of the passive fish



(Kleinschmidt, 2015)

fish lock

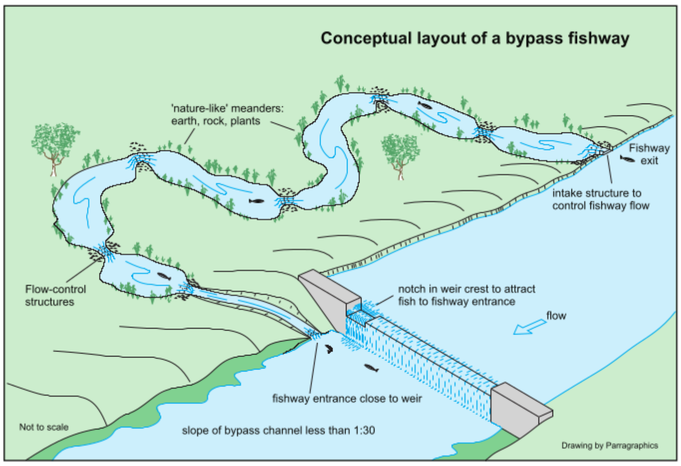
- same operating principle as shipping locks and similar to fish lifts



(Thorncraft & Harris, 2000)

bypass channel

- earthen or rocky channel, mimics the structure of natural streams
- large-scale bypassing of an obstacle
- sometimes used as habitat by the aquatic animals



(Thorncraft & Harris, 2000)

special fish ways

- trap-and-transport
- fishways for eel (*Anguillia sp.*)

* *references texts: Thorncraft & Harris, 2000; Roscoe & Hinch, 2010; Gough et al. 2012; DWA, 2014*

1.1.4 Challenges at non-power station-related obstacles

The presented fish passes are mainly used at hydropower stations. However, there is a huge amount of non-power station-related obstacles worldwide. In Switzerland alone more than 100'000 man-made barriers exist which are higher than 50 cm (see also chapter 1.3.1) (Weissmann et al., 2009). These barriers were built during the last centuries to prevent erosion and floods of the straightened rivers, to measure the discharge, to obtain drinking water or to produce electricity. But hydropower stations, dams, weirs and barrages prevent a free fish migration (Ulmann, 1989; Thorncraft & Harris 2000; Larinier & Marmulla, 2003; Weissmann et al., 2009; BMLFUW, 2012; DWA, 2014). For all aquatic creatures the best solution to enable a free connectivity is a removal of the obstacles (MUNLV, 2005; Gough et al., 2012), provided colonizing organisms can thereby find suitable habitats for their needs (Crook et al., 2015). But the removal is not that easy. To remove an obstacle, the hydrological and morphological development of the stream at a future time has to be researched (MUNLV, 2005). The flood control has to be guaranteed at any time. The removing has to be embedded in a planning of rehabilitation, to facilitate the parallel existence of healthy dynamic streams and the human needs (e.g. settlements, infrastructure, agriculture). Many countries enact laws to rehabilitate the streams and to enable a free fish migration (Larinier & Marmulla, 2003; BGF). However, in all regions it will take generations to enable it. In some cases there is not enough space to build a bypass channel (especially within urban areas), in other situations, there is just not enough money for removing an obstacle or complex ownership structures of the land around a river exist, which prevent a rapid adjustment of the status quo. The usually used fish passes are dimensioned for hydropower stations and are not suitable for non-power station-related obstacles or their costs are disproportionately high. Block ramps can enable a connectivity, when they are correctly dimensioned for the local organisms (Weibel et al., 2012), but they can also be expensive and long planning and implementation times are other drawbacks.

All these facts show, that the reconnection of rivers at non-power station-related obstacles are a huge challenge, at first because reconnection is expensive and second the implementation takes a long time.

1.2 Questions and research approach

The drastic decline in biodiversity as well as the reduction of fish populations in disconnected rivers demands for quick solutions. However, the removing or replacement of non-power station-related obstacles happens with a delay. To bridge this temporal gap, the fish pass with the brand name Steffstep has been developed. The principle of the fish pass Steffstep is described in chapter 1.4. The aim of this master thesis is to examine the fish pass Steffstep with respect to its efficiency on a prototype in the River Töss and to analyze its potential application and limitations in disconnected rivers.

To evaluate the efficiency of this Steffstep prototype two target species were defined: the brown trout (*Salmo trutta* resident form) and the minnow (*Phoxinus phoxinus)*. As it is described above, the efficiency depends on the ability of these species to find and enter the fish pass (attraction efficiency) as well as the ability to pass the fish pass (passage efficiency).

To asses if the Steffstep prototype performs satisfactory, limit values to formulate the following hypothesis had to be defined depending on available data of comparable facilities.

Question 1: What is the attraction efficiency and the passage efficiency of the Steffstep prototype for the target species brown trout?

Hypothesis 1.1: The attraction efficiency for the brown trout is higher than 58 %.

→ If the attraction efficiency for the brown trout is higher than 58 %, the hypothesis is confirmed and the brown trout is able to find and enter the Steffstep prototype.

Bunt et al. (2012) reviewed 19 monitoring studies which examined the efficiency of different fish pass types. They figured out that the attraction efficiency of the examined vertical-slot facilities (n = 29) varied between 0 % - 100 % (mean 63 %, median 80 %). The study evaluated data of 26 species including brown trout. The variation in attraction efficiency is depending on the biological characteristics of the fish. Only for the salmonids the attraction efficiency varied between 12 % - 86 % (mean 54 %, median 58 %) (Bunt et al. 2012). Although only 8 vertical-slot fish passes were examined with the salmonids, this result is taken as a reference value for the Steffstep prototype, because the fish species and fish pass type matches most. So the attraction efficiency of the prototype was considered sufficient if at least 58 % of the brown trout are able to find and enter the fish pass.

Hypothesis 1.2: The passage efficiency for the brown trout is higher than 53 %.
→ If the passage efficiency for the brown trout is higher than 53 %, the hypothesis is confirmed and the brown trout is able to pass the Steffstep prototype.

Noonan et al. (2012) also reviewed 65 papers about efficiency of fish passes. They found a mean upstream passage efficiency of 53 % for salmonids at different pool and slot fish passes (n unknown). Bunt et al. (2012) found comparable data at 8 vertical-slot fish passes for salmonids and therefore this value was taken as a reference value for this master thesis: For the brown trout the passage efficiency of the prototype was considered sufficient if the passage efficiency is at least 53 %.

Question 2: What is the attraction efficiency and the passage efficiency of the Steffstep prototype for the target species minnow?

Hypothesis 2.1: The attraction efficiency for the minnow is 29 %.
→ If the attraction efficiency for the minnow is higher than 29 %, the hypothesis is confirmed and the minnow is able to find and enter the Steffstep prototype.

Hypothesis 2.2: The passage efficiency for the minnow is 0 %.
→ If the passage efficiency for the minnow is 0 %, the hypotheses is confirmed and the minnow is not able to pass the Steffstep prototype.

Minnows are widely known to refuse using fish passes while the reason for this behavior remains unknown (personal communication, Armin Peter, 04.01.16). This behavior can also be observed at block ramps: Weibel & Peter (2012) marked over 1'000 minnows at a block ramp in the River Sissle but none of them passed the facility. Despite these experiences so far the minnow was chosen as one of the target species because they are one of the four species which live in the River Töss and are basically known to migrate. On the basis of the literature it was assumed, that the minnows will not pass the prototype and therefore the passage efficiency will be 0 %. How many minnows will find and enter the facility was difficult to define because no comparable data was found. So a pragmatic approach was taken and it was roughly estimated that half of the value of the attracted brown trout (29 %) will be a suitable attraction efficiency for minnows.

Question 3: What are potential application and limitations of Steffstep?
Based on the experiences of the field study of this master thesis the potential application of Steffstep in Switzerland and its limitations were estimated. Therefore the results of the ecological monitoring and the experiences with the technical design were used.

1.3 Status of upstream fish migration in Switzerland

1.3.1 Status of the rivers

In densely populated Switzerland, rivers have been influenced for hundreds of years. The rivers are used for electricity production and as transportation routes. They were also forced to flow straighter to optimize land usage in agriculture and flood constructions should protect urban facilities against the water (Weissmann et al., 2009). These human interventions have a very high impact on the natural dynamics of streams. The FOEN had investigated the condition of Swiss rivers to estimate the need for action. The results were published in 2009 in Weissmann et al. The following descriptions are based on this publication.

In Switzerland 65'000 km of streams exist, which are classified in five structural categories from *natural* to *artificial* and *piped* (under the ground) (Figure 2). More than half of the streams are natural and a quarter is just little affected. The other three classes together sum up almost another quarter and are in an unnatural status. Particularly these 14'000 km are problematic for fish. The distribution of the categories are not uniformly spread over of the national territory. The ecologically critical categories are mostly in midland urban areas with dense human population.

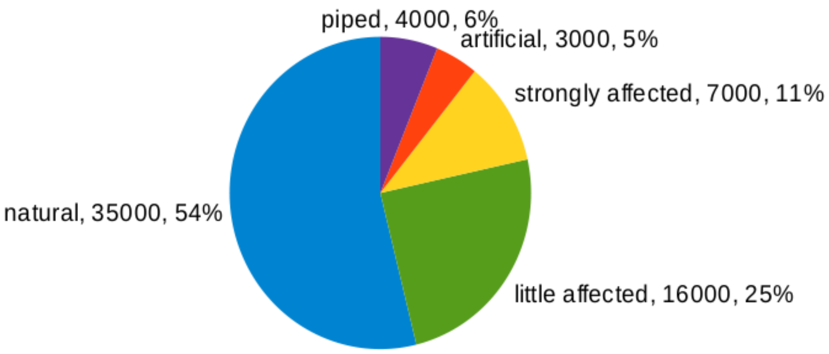


Figure 2: Structural conditions of the Swiss rivers [km] (Weissmann et al., 2009, modified)

In addition to the structural condition of streams, it is very important for fishes to be able to behave naturally and migrate within the rivers. In Switzerland more than 100'000 man-made barriers exist which are higher than 50 cm and therefore prevent a free fish migration. On average there are 1.6 obstacles per river kilometer, in the midland 2.5 obstacles/km. Depending on the fish species even smaller obstacles can be a problem, therefore these species face many more barriers, which implies that they live in smaller, fragmented habitats. The cumulative effect of a number of these barriers can be significant (Thorncraft & Harris, 2000). Based on these results Weissmann et al. (2009) suggested the removing of 50'000 obstacles and rehabilitation of 10'800 kilometers of streams (excluding the huge rivers, settlement areas and steep river sections). According to Göggel (2012) the decision was made to rehabilitate in total 4'000 kilometers of these streams. It is estimated that the rehabilitation will need around 80 years for completion. However, the actual number of removed obstacles is not defined (Göggel, 2012).

Besides the obstacles 413 hydroelectric power stations with a power of 1 MW or more and 919 stations with less than 1 MW exist in Switzerland (SWV, 2015). They also prevent a free fish migration up- and downstream. Article 83 BGF obliged the cantons and the holders of the power plants to take action towards more natural river conditions. At new power stations this includes favorable water conditions for aquatic animals, the possibility of free fish migration, the possibility of natural reproduction and the prevention of injuries or death of fish and crayfish (BGF, Art. 9, Par. 1). These regulations can be prescribed also to consisting power plants if it is economically acceptable (BGF, Art. 9, Par. 2). The refurbishments of the Swiss hydropowert stations must be finished until 2030 (Könitzer et al., 2012).

1.3.2 Fish fauna

In Switzerland the "Ordinance concerning the Federal Act on Fisheries" (VBGF) defines the local fish species. Due to the last review in 2011, 63 species and subspecies exist in Switzerland (VBGF Annex 1). In literature different concepts to define a species can be found. Also the classification of fishes is very difficult, therefore the amount of local species in Switzerland is changing over time (Schweizerische Fischereiberatungsstelle (FIBER, 2012) due to new measurement results. As an important tool for fish management, the ordinance simplifies the newest genotype analyses. Researchers assume that there are more than 100 local fish species in Switzerland (FIBER, 2012).
Another important tool for fish management and the protection of fish is the national red list of fish and cyclostomes. All fish species are classified according to their degree of risk in Annex 1 of the VBGF (Figure 3). Species that are classified as *extinct*, *critically endangered*, *endangered* or *vulnerable* are on the red list (Kirchhofer et al., 2007). Cantons are obliged to especially protect these endangered species, as well as their habitats (BGF, Art. 5, Par. 2).

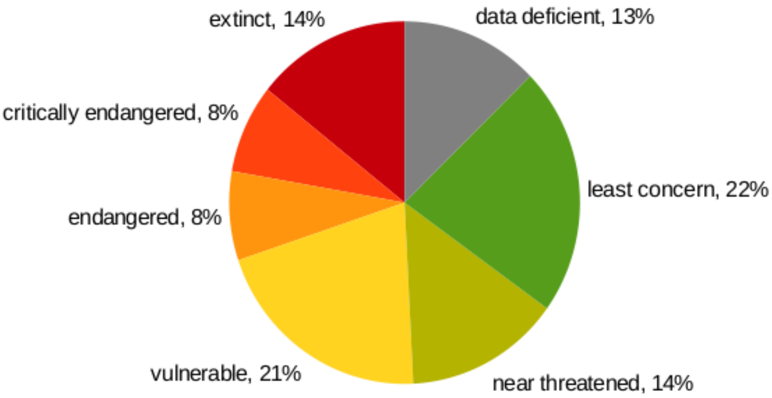


Figure 3: Degree of risk of the Swiss fish fauna (VBGF, modified)

Since 2011, 51 % of the 63 local fish species are on the red list. It should be noted that 13 % of the fish species are not categorized because of insufficient data. The nine extinct species are almost all diadromous species which initially migrated to Switzerland from the sea (VBGF Annex 1). The numerous barriers and power plant stations nowadays prevent their migrations. Even potadromous short migration species, like common nase (*Chondrostoma nasus*) or grayling (*Thymallus thymallus*), struggle with the barriers and are therefore categorized as *critically endangered* or as *vulnerable* (FIBER, 2012). The decrease of the fish species takes place differently on local scale: In the middle of the 19th century 20 species lived in the River Rhine in the canton of Grisons, today only 11 of them are left, whereas a decline from 19 to 5 fish species has been measured in the River Rhone (Fischer et al., 2015). In addition to the red list, Switzerland defines 34 fish species which are nationally prioritized, 18 of them are classified as *very high* or *high*. These "prioritized species" should help to use the available resources for species conservation efficiently (BAFU, 2011).

The critical status of the Swiss fish fauna is not a specific case. Worldwide more than 30 % of the known fish species are already extinct or seriously threatened (Campbell, 2011). According to the living planet index, an index of the biodiversity with various parameters, the situation is particularly alarming in the freshwater ecosystems. In 2010, the populations of freshwater species declined to 76 % compared to 1970 (WWF, 2014). And this development is still ongoing. For example, in the Balkan States exist only 714 water power stations today but more than 2000 are in planning, more than 800 of them in protected areas. The rivers of the Balkan domiciled 28 % of the endangered freshwater fish species of Europe, whereas 69 of them are endemic. Those species get under pressure through the planned expansion of hydro power capacities (Abromeit & Unverzart, 2015).

1.3.3 Fish migration in Swiss rivers

According to Ulmann (1998), in Swiss rivers only diadromous and potamodromous species exist. As it is described above, most diadromous species are already extinct. Only the European eel (*Anguilla anguilla*) is able to reach Switzerland from the sea (Ulmann, 1998), however, it is critically endangered (VBGF Annex 1). The majority of the species are potamodromous and most of them are cyprinids (Ulmann, 1998). These species were not considered for a long time with respect to fish migration, the focus was rather on long-distance migrations of diadromous (Bös et al., 2012) and economically important fishes like salmon (*Salmo salar*, *Oncorhynchus sp.*) (Lucas & Baras, 2001). However, also cyprinids are migrating in spring, early summer upstream to their spawning grounds and in winter downstream to their refuge habitats (Bös et al., 2012). Good examples are chub (*Squalius cephalus*) and common nase (*Chondrostoma nasus*), which are migrating over 100 km to reach their spawning grounds (Peter, 2014). Despite some progress, to date, worldwide a lack of information exists about the migration of numerous freshwater species in river systems (Lucas & Baras, 2001). This is also the case in Switzerland. Here the knowledge of fish migration is also small especially about the downstream migration (Kirchhofer, 2015). Modern techniques (telemetry, tagging, sonar) enable to study the behavior of the fish at barriers and hydropower stations, whereby the spatial and temporal movement patterns become visible (Peter, 2014). But until today they are just sparsely used in Europe (Adam, 2015).

1.3.4 Fish passes in Switzerland

To this day, there is no national database of all fish passes in Switzerland. The cantons keep lists with all power station-related obstacles and the currently existing fish passes at these places. The FOEN plans to collect these individual records from the cantons to create a consistent database (personal communication, Martin Huber-Gysi, FOEN, section habitat waters, 21.09.15).

Currently, there are 287 existing fish passes of different conventional types (examples in Table 2) at power station-related obstacles (Huber-Gysi, 2015). In Switzerland the information about fish passes at non-power station-related obstacles is rare.

Table 2: Examples of typical fish pass types in Switzerland

type	river	operator	construction year	height [m]	costs [kCHF]	source
fish lift	Birs	Ziegler Papier AG	2000	11.4	350	*Hintermann, 2015*
pool-riffle fishway	La Suze	unknown	2003	2	80	*Breitenstein & Kirchhofer, 2010*
bristle fish pass	Schüss	Hydroelectra AG	2005	5	350	*Hydroelectra, 2015*
vertical-slot pass	Limmat	Elektrizitätwerke Zürich	2010	5	1'800	*Gujer AG, 2010*
natural-like bypass channel	Rhein	Energiedienst AG	2012	7	N / A	*Aqua Viva, 2015*
combination 1. vertical slot pass 2. bypass channel with pools 3. near-natural stream	Limmat	Elektrizitätwerke Zürich	2007	18.4	2'500	*Müller, 2015 b*

Only 121 of the 287 existing fish passes are functional. The other 166 fish passes are in bad condition or of unsuitable design. At these sites and at 511 further obstacles a free fish migration should be possible via fish passes by 2030 at the latest (Huber-Gysi, 2015; VBGF Art. 9c, Par. 4). To improve the efficiency of the fish passes a monitoring is required by the new law (VBGF Art. 9c. Par. 3).

1.4 Fish pass Steffstep by WRH AG

1.4.1 Main idea

The enormous amount of barriers in Swiss rivers and the critical condition of the fish fauna requires innovative and quick solutions. To enable a free fish migration in a short time, the company WRH AG of Hinwil developed the fish pass Steffstep. The construction works like a traditional vertical slot fish pass, which is typically featured at power plant stations. Contrary to these Steffstep is a modular and reusable fish pass for non-power station-related obstacles. When the obstacle gets finally gets removed and the whole river is fully rehabilitated, a Steffstep can be removed easily. Most of the material and structure can be used at another obstacle again.

In literature no fish pass similar to Steffstep was found. Only in the USA a private person crafted a model of a fish pass in his garage, which resembles the approach of Steffstep. His idea has not yet been tested in a river (personal communication Bill Weihbrecht, 13.10.15).

1.4.2 Construction, scope of application and challenges

The construction of Steffstep is based on a modular structure, which can be adapted individually for each site, depending on the height of the obstacle and the locally occurring fish species (Figure 4). The substructure of Steffstep is self-supporting and made of steel. Therefore a sufficient stability requires only small adjustments at the obstacle and the riverbed.

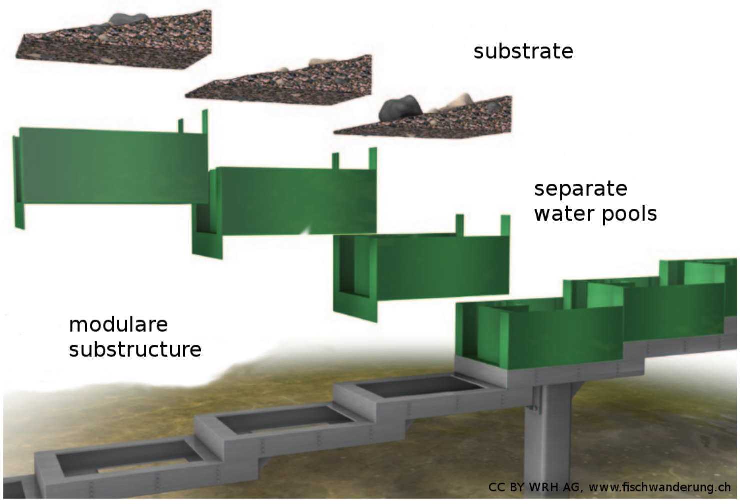


Figure 4: Construction of the fish pass Steffstep (WRH AG, 2014, modified)

Figure 5: Stone imitations in prototype number two

The separate water pools are made of food compatible, strengthened polyester and are filled with substrate of the river. This enables the migration of invertebrates and benthic fish. To hold the substrate at its place, to reduce weight of the construction and nevertheless mimic a natural stone bed, plastic inserts were implemented at each of the pools (Figure 5).

The WRH AG constructed the fish pass according to the "leaflet DWA-M 509, Fish passes and fish passable buildings: design, dimension and quality assurance" of the German Association for Water, Wastewater and Waste (DWA, 2014). This is a widespread and internationally used book with thresholds for the dimensions of the main fish pass types. The existing prototypes had pool dimensions of 150 cm length, 100 cm width and 60 cm height each (pool size 1), but these dimensions are scalable. For example, a further prototype with the target species lake trout *(Salmo trutta* lake trout form) is planned. Therefore, the dimensions of the pools will be 240 cm length, 120 cm width and 70 cm height. The pools are horizontal and divided from each other with a step. This allows the fish pass to be operable with a minimum amount of water (160 l/s for pool size 1). To allow nevertheless a migration of the benthic organisms small ramps connect the pool elements above the steps.

The scope of application of Steffstep covers in theory all kind of obstacles in small to middle-sized rivers (up to an annual average discharge of 10 m^3/s) like barrages, check dams, weirs and similar. Steffstep is mainly designed for use at obstacles which will not be removed within the next 10 - 20 years. The lifetime of the material is estimated around 50 years. It can be reused at another site. The potential application and limitations are discussed in detail in chapter 5.

The challenges of Steffstep are diverse: First, in Switzerland often alternating water conditions occur. On one hand, there can be very low water in the river, e.g. because of water extraction for electricity. On the other hand, after heavy rain or snowmelt, floods rush downstream and take a lot of substrate with them. Therefore, it has to be ensured that there is always enough water in the fish pass and that the structure is resilient enough to resist flood conditions. Second, the optimal dimensions of the fish pass and the right alignment of the entry always requires local examination and adaption. Third, the fish pass should require a low degree of maintenance. Larinier (1998) named the maintenance basically as largely underestimated and recommended frequent visits (minimum each week) for a successful operation of a fish pass.

The costs of Steffstep are depending on the dimensions of the pools, the height of the obstacle (amount of pools) and the environmental conditions (accessibility, quality of the obstacle, present water pipes or electricity lines, depth of the pool and similar). As a rule of thumb the costs can be broken down as follows:

- CHF 4'300 per pool of 150 cm x 100 cm x 60 cm which corresponds to CHF 21'500 per meter (5 pools of this dimension are necessary for an obstacle of 1 m height).
  This includes the self-supporting substructure and the artificial stones.
- CHF 5'500 for the inlet channel.
- CHF 20'000 - 100'000 for the installation and adjusting on-site (depending on environmental conditions), mostly one and a half times the material costs.

A lot of important parameters of this new kind of fish pass are still unknown: the stability and behavior during flood conditions, lifetime of the material, effort for the maintenance, ideal hydrological conditions and behavior of the fish. To investigate which is the best design and the best hydrological conditions the WRH AG built a first prototype in the river Aabach (canton of Zurich) in December 2014. With the experiences of this preproduction model the company built a second prototype in the River Töss, where this master thesis has taken place to acquire additional data and gain more experience.

1.4.3 Steffstep prototype in the River Töss

Kollbrunn is a village in the canton of Zurich in Switzerland (Figure 7). Near the village flows the River Töss. In 1953, an obstacle of 3 m height was built into the river to ensure the bank protection (Figure 6) (AWEL, 1953). Ever since no fish migration could take place. This obstacle was considered an ideal place for installation and evaluation of the Steffstep prototype due to the retaining walls against floods (Figure 8), its good accessibility for the installation of the fish pass and the local fish fauna. The coordinates of the prototype are: N 47.4557, E 8.77261.

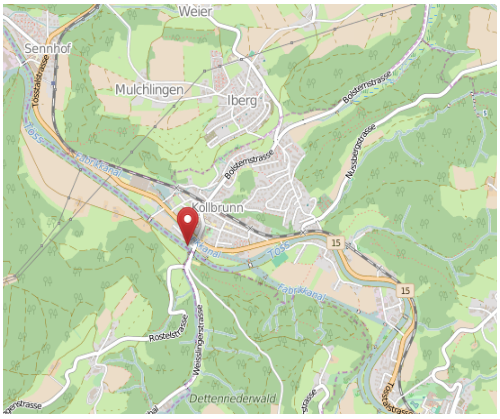


Figure 7: Map of Kollbrunn, the obstacle is marked in red (Open Street Map, 2015)


Figure 6: The obstacle in Kollbrunn in spring 2015

The prototype consists of 13 pool elements of 150 cm length, 100 cm width and 60 cm height each (Figure 8 & Figure 37). The pools are filled with 20 cm of substrate between artificial stones each. The slot of the pools is of 16 cm width and the altitude difference between the pools, the steps, are 20 cm high. The pool elements are maximally dimensioned for brown trout (*Salmo trutta* resident form) of 50 cm length. When the fish pass is fully operational, the pools are filled with ~ 700 l of water each. The weight of one pool with artificial stones, natural substrate and water is around 1200 kg. The load capacity of the substructure is 2.4 t per pool module. The first pool, the entrance for the fish, is 50 cm longer than the other pool elements. The outflow is around 120 l/s and maximally 160 l/s depending on the water level upstream. If the outflow decreases under 120 l/s, the fish pass may not be passable for the fishes. The water velocity within the pools and the flow velocity of the attraction flow were examined during this study and can be found in chapter 3.6.

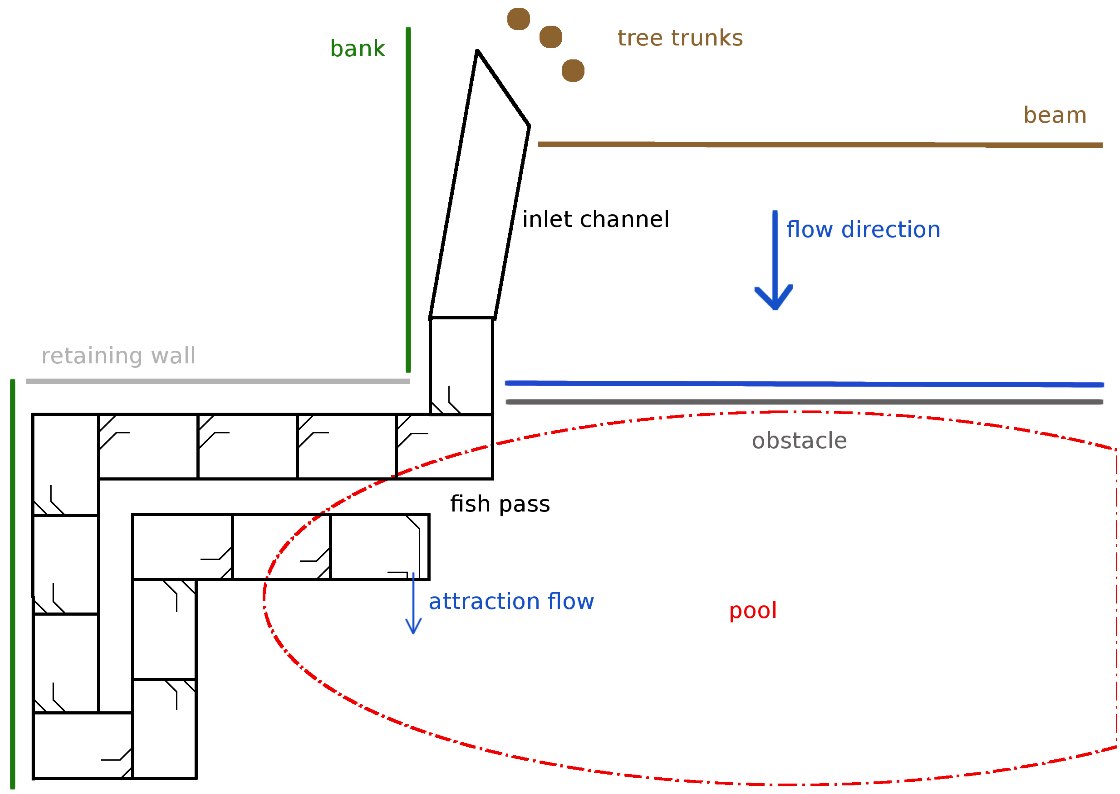


Figure 8: Sketch of the study site from a bird's-eye view

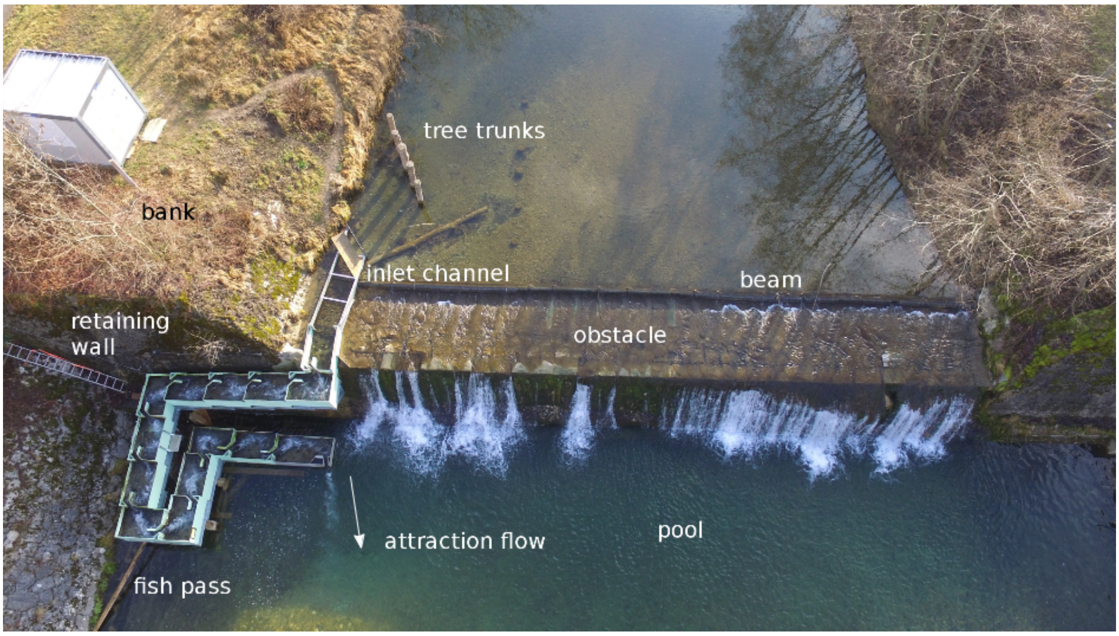


Figure 9: Labelled photo of the Steffstep prototype, January 2016

For the inlet a recess of a few centimeters was taken off the obstacle, so that there is always water in the fish pass – particularly at low water conditions (Figure 10). In addition, beams were led over the whole river, so that the water is directed into the fish pass, again especially at low water conditions. In front of the last pool a channel of 5 m length was built to guide the fish safely out of the prototype away from the fall. In front of the channel, inlet tree trunks are anchored to protect the fish pass against floating debris. On the other side the fish pass ends up at the pool to be as near as possible at the obstacle. The pool beneath the obstacle is 3 m deep and so no bottom connection of the fish pass exists. Two months after the fish pass was installed into the river, the entry and therefore the attraction flow was optimized. The last pool element in flow direction was exchanged, so that the attraction flow now runs in flow direction of the Töss. To obtain a high construction stability, the fish pass rests on wooden piles. To be protected against floods, the construction is built behind the retaining wall on the right river side in flow direction. Therefore only the first and the last pools are affected under flood conditions (Figure 11).

*Figure 10: Low water conditions on 07.11.15 with 0,1 m³/s**

Figure 11: Flood on 26.05.15 with 32 m³/s, the first and last pools are under water*

*The measured values are from the measuring station *520 Töss-Rämismühle (*Apendix A (AWEL, 2015 a)).

The preparations at the obstacle for the installation took 2.5 days. The installation itself was completed within one day. The costs of the prototype are CHF 197'000. They are divided as follows: CHF 82'600 for the material (pools, plastic stones, inlet channel, substructure, assembly) and CHF 114'400 for ancillary costs (planning, concession, measurement, flood protection, transport, installation, adjustments of the inlet channel). The ancillary costs are depending on the terrain conditions and the hydraulic conditions. Here for example, a diver was needed for the installation of the wooden piles in the pool and a water pipe near the surface at the top of the obstacle had to be probed.

1.5 River Töss

1.5.1 Catchment area and connectivity

The River Töss arises through the confluence of Vordere Töss and Hintere Töss at Tössscheidi at 794 m a.s.l. (Tunesi, 1996; Bruderer, 2010). It flows north-west to Winterthur and after around 60 km it ends in the River Rhine at 346 m a.s.l. (Figure 12). The catchment area comprises 430 km² (Eawag & BUWAL, 1995; Tunesi, 1996). The fish pass Steffstep is located at section 24 in Kollbrunn.

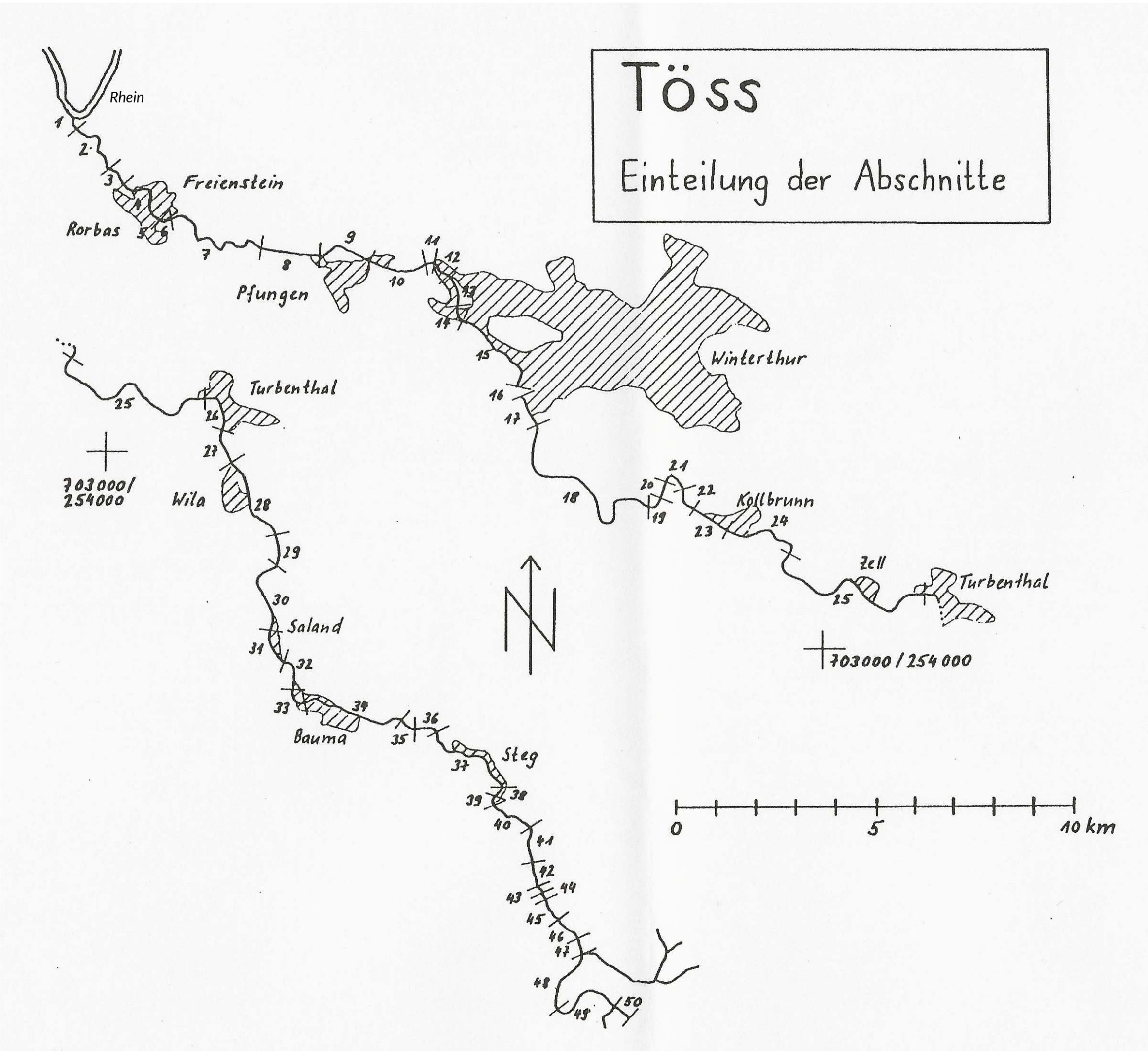


Figure 12: Map of the river Töss with numbered sections (Eawag & BUWAL, 1995, modified)

Like other rivers in Switzerland the Töss was “corrected” at the end of the 19th century. It was forced to flow straighter on a smaller area. Different kinds of obstacles were built to prevent floods and erosion (AWEL,2010 a). In 1995, Eawag and BUWAL examined the ecomorphological constitution of the Töss. The examination shows that the 60 km long river is interrupted by 295 man-made barriers and 273 sole steps. These 568 barriers result in an average of 9.5 artificial interruptions per kilometer, which means that the free flowing stretch is only around 100 m long on average. From that 21 obstacles and 14 sole steps are natural and mostly located in the upper reaches (Eawag & BUWAL, 1995). In a report about the bed-load in the River Töss, the amount of barriers is called around 700 (AWEL, 2010 a). Another source for the ecomorphological constitution of the Töss are the maps, which are published regularly on the website of ARE (*http://maps.zh.ch/)*. According to them, the amount of obstacles declined, but there are still 416 obstacles today, which results in 7.3 barriers per kilometer, which is almost three times as much as the average of the Swiss midland.

In sections 31 to 33 (Figure 12) the groundwater rises to the surface and feeds the river in addition to the springs. But because of insufficient thickness of the molasse in sections 28 to 40 this area falls regularly dry during hot weather conditions since hundreds of years. Downstream of Wila (sections up to number 28), the Töss naturally never falls dry (Tunesi, 1996; Bruderer, 2010). The sections 30 to 32 and 20 to 27 are stretches of residual water of hydroelectric power stations and therefore struggle with unnaturally low water conditions (Eawag & BUWAL, 1995). The residual water stretches are 30 % of the whole River Töss (Peter & Gonser, 1998). Water extraction for drinking water – especially for the city Winterthur (Bruderer, 2010) and for agriculture irrigation exacerbate the problem. The using of the water influences not only the surface discharge but also the groundwater stream (Tunesi, 1996). In addition, the intensive watertight seal of the soil for infrastructure causes that rainwater rapidly flows downstream. Therefore, there is a high peak of additional water in a very short time, instead of a continuous intake of the water from the soil into the river over a long period. In hot and dry summers, like in 2015, parts of the Töss and small tributaries dry out and the fish have to be rescued with electrofishing and put into deeper river sections (verbal message from Werner Honold, fishing supervisor of the Töss, July 2015). Especially for such droughts it is absolutely necessary that the fish can freely migrate into the tributaries, if the River Töss dries out (Tunesi, 1996). But these tributaries mostly join the River Töss with a waterfall. This is a result of the channel regulation which caused a degradation of the Töss channel bed of around 1 - 2 meters (Peter, 1998).

1.5.2 Local fish fauna

Besides the ecomorphology Eawag examined also the fish fauna of the River Töss in 1995. They found out that there is a small fish biomass in the whole river (Eawag & BUWAL, 1995). This is connected with the monotonous habitats in the Töss, which are poor on connectivity to tributaries, diversified bank vegetation, inundation areas, outwashed banks or deadwood (Peter & Gonser, 1998). In sections 8 - 34 the river is highly modified by humans which results in a striking small density of fish. Also the amount of the species decreases from the mouth at the river Rhine up to the springs (Eawag & BUWAL, 1995), indirectly propotional to the increasing number of obstacles. In sections 1 - 3 there are 20 species which are standing in an active exchange with the River Rhine. In section 4 - 6 the first obstacles occur and therefore, only 13 species can be found. At the end of section 6 the dam Freienstein with a height of 6.5 m inhibits fish migration further upstream (Eawag & BUWAL, 1995). Since 2005 two fish passes are installed at the dam, whereby one of them is a vertical slot fish pass and the other one is a pool fish pass with 20 cm steps (ToessStrom, 2015). In 1995 without the fish passes, only ten species can found in the more or less natural section 7 above the weir and in the sections 8 - 11 seven species can be counted. It is assumed that originally all fish species from the lower part of the river lived also in the sections above the dam (Peter & Gonser, 1998). Tunesi (1996) described that in the past without the dam common barbel (*Barbus barbus*) and common nase (*Chondrostoma nasus*) migrated through this river section. No information could be found about the amount of species nowadays with the fish passes. The section 11 ends up with the first natural barrier (Eawag & BUWAL, 1995). Initial fish migrations in the Töss could take place up to this point. Above this barrier there are only four species left and near to the springs only brown trout can be found (Eawag & BUWAL, 1995).
Four species, which are living or partly living in the Töss, are protected under the Berne Convention (1979) all over Europe: First, the common nase (*Chondrostoma nasus*), which is spawning in section two. The adult animals return after spawning in the Rhine. Above the first barrier the common nase has not

been seen. Second, the critically endangered souffia (*Leuciscus souffia*) lives in section 1 - 6. The weir Freienstein at the end of section 6 prevents further migration of this small fish. Third, the endangered schneider (*Alburnoides bipunctatus*), which is present in the lower parts of the Töss. Souffia and schneider reproduce naturally in the first three sections. Finally the grayling (*Thymallus thymallus*) is also sporadically documented in the first four sections (Eawag & BUWAL, 1995) and reproduction of this fish was already observed there (Müller, 2010). All four species are restricted in their natural migration behavior through the enormous amount of artificial obstacles (Eawag & BUWAL, 1995).
The atlantic salmon (*Salmon salar*) is regarded as extinct in Switzerland since 1950s (WWF, 2015). There is much historical evidence that the salmon previously populated the Töss (Dönni, 2008; Dönni, 2015). With the "action plan migratory fish" of the Swiss FOEN and the project "salmon 2020" of the International Commission for the Protection of the Rhine (ICPR) the atlantic salmon should be able to recolonize the whole Rhine up to Basel (WWF, 2015; ICPR, 2015). Thereby, there is a potential for the salmon to live and spawn in the Töss again (Dönni, 2008; Dönni, 2015).
At the Steffstep prototype in section 24 the four species brown trout (*Salmo trutta* resident form), stone loach (*Barbatula barbatula*), minnow (*Phoxinus phoxinus*) and sculpin (*Cottus gobio*) are typically found (Eawag & BUWAL, 1995). These results correspond well to the findings of Straub (2001), that he published in "Neuer Fischatlas des Kanton Zürich". In addition to the four named species he listed a small amount of pike (*Esox lucius*). In 2012 and 2014 the staff of the fishery administration of the canton of Zurich fished in section 23 near the Steffstep site and also caught the four typical species (unpublished data of the fishery of the canton of Zurich).

According to Huet (1949), it is possible to classify streams in "fish regions". In certain biogeographical regions similar environmental conditions and therefore similar fish species can be found (Huet, 1949). The regions are named after one typical species which is representative for the habitat occurring in a determined area of a river. The factors to define a fish region are the slope and the width of the river (Figure 13) (Schager & Peter, 2004). The fish region is essential for the right dimension of a fish pass (BMLFUW, 2012).

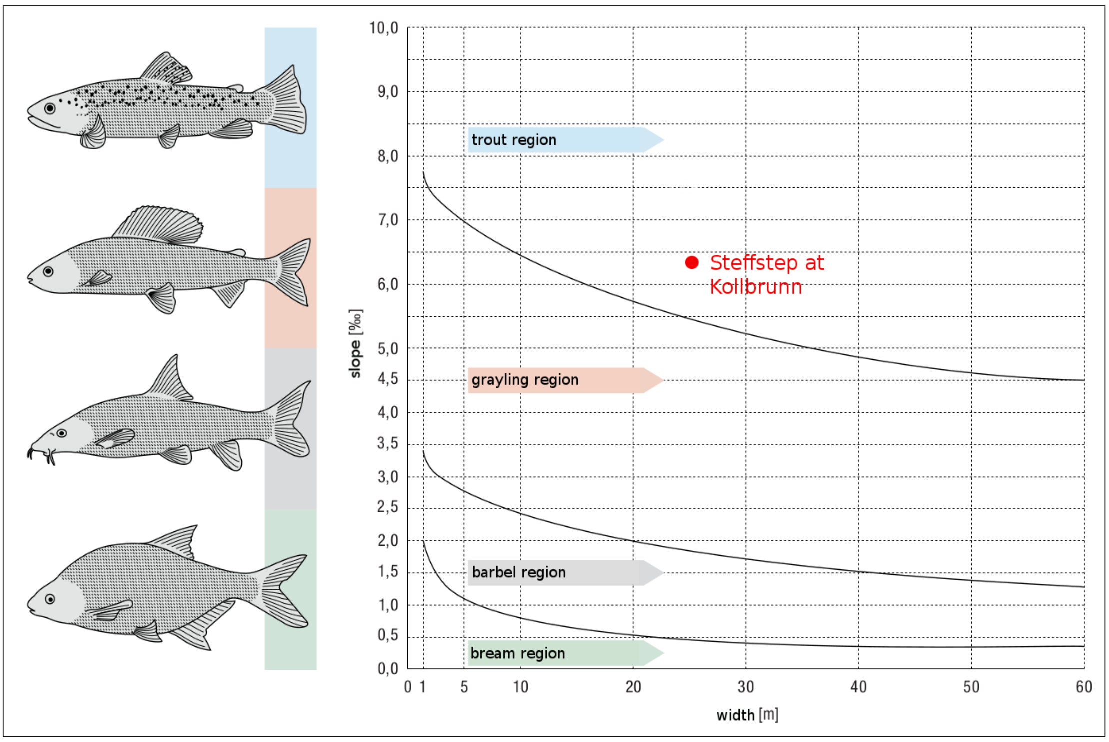


Figure 13: Fish regions (BMLFUW (2012) after Schager & Peter (2004) & Huet (1949), mod.)

The width at the Steffstep site is 25 m at the top of the obstacle (ARE, 2015). The slope is calculated between the discharge measuring stations Töss Rämismühle (524 m a.s.l.) and Töss Neftebach (389 m a.s.l.).

*Slope [‰] = height [m] * 1'000 / length [m] = 135 m * 1'000 / 21'000 m = 6.42*

Therefore the fish pass is located in a trout region (Figure 13).

1.5.3 Target species and migration

Brown trout (*Salmo trutta* resident form)

The brown trout (Figure 14) is the most widespread freshwater fish native in the Palearctic ecozone. It is known for a high morphological diversity and variation in life-history. Over the last 0.5 - 2 million years the brown trout more and more adapted from five major evolutionary lines, which involved geographic isolation in the Pleistocene (Bernatchez, 2001), up to local specialization to individual river systems. Therefore today a high genetic diversity in local populations exists which complicates the classification of the trouts and makes it difficult to define at which point it is called a new species (Hinterhofer et al, 2015). Kottelat & Freyhof (2007) distinguished three forms of the *Salmo trutta*, which are not reproductively isolated: anadromous trout (sea trout), lake trout and resident trout in streams. To divide the three forms it has been established to extend the scientific name with a third part: *S. trutta trutta* (for sea trout), *S. trutta lacustris* (for lake trout) and *S. trutta fario* (for resident trout). Under the International Code of Zoological Nomenclature such names are not correct and should be avoided (Kottelat & Freyhof, 2007). So in this master thesis the additive “resident form” is used instead to be semantically and linguistically correct.

The brown trout and the atlantic salmon (*Salmo salar*) are the two species which are counted among the genus salmo (Figure 15). They are phylogenetically closely related and belong to one of the three sub-families of the salmonidae-family with six others (Baglinière & Maisse, 1991).

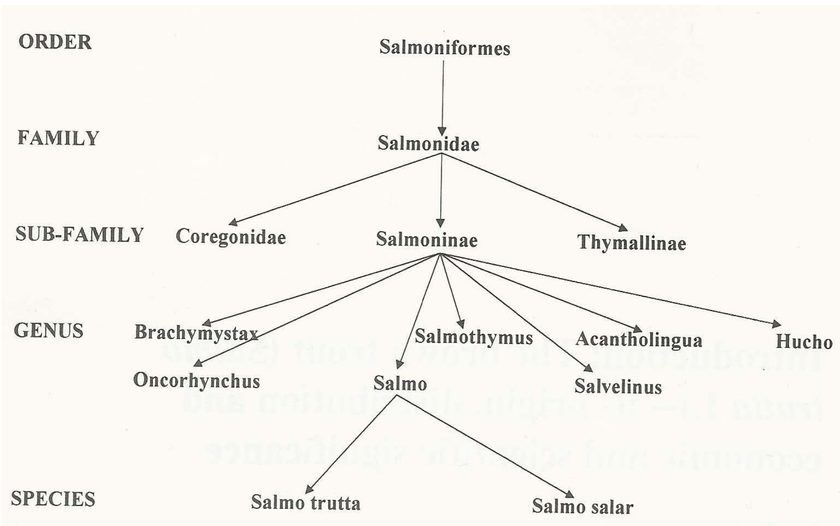


Figure 15: Phylogeny of the Salmo trutta (Baglinière & Maisse, 1991)

Figure 14: Brown trout in the Töss (Anja Trachsel, 2015)

The brown trout are counted among the litho-rheophil species, which means that they prefer the flow (Breitenstein & Kirchhofer, 2010) and need loose, non-clogged gravel to spawn (Baglinière & Maisse, 1991). Depending on the water temperature the adults migrate upstream between November and January to find ideal conditions for spawning. The female lay their eggs in a spawning redds of 15 - 25 cm water depth and the male add their milt. The preferred size of the substrate and the depth of the spawning redd increase with the increasing length of the female. After 420 - 450 degree days the larvae hatch and live another 3 - 4 weeks between the gravel. During this time the larvae need a lot of oxygen in the water (7 - 10 mg/l). At the size of about 3 cm, and after they have lost their yolk sac, they swim up and fill their swim bladder (Peter, 2013). Then the young trout live near the shore. The adult brown trout also prefer resting near the banks (Baglinière & Maisse, 1991). In general, habitats which are rich on structure, e.g. deadwood in the water (Bertiller, 2004), are important to offer cover (Breitenstein & Kirchhofer, 2010). The stronger juvenile trout can already be found within the faster flowing areas. Like the predatory adults, they feed on drifting and benthic invertebrates (Kottelat & Freyhof, 2007), amphibians, snails (LANAT, 2015) and on small fish (Breitenstein & Kirchhofer, 2010), e.g. minnow (*Phoxinus phoxinus*) (Zenner, 2001). The age and size at first maturity is complex and differs between the genders. The majority of males mature for the first time when they are one year old, whereas the majority of females is two years old (Baglinière & Maisse, 1991). The adult brown trout live in deep pools and stay relatively strict in the same area. Camenzind (2008), who investigated the site fidelity and the microhoming of brown trout, also described that adult brown trout prefer to live in deep pools. With increasing fish length their homeranges decrease, whereas young brown trout prefer to be in shallow waters (Camenzind, 2008) and to move around a lot. When the adult brown trout are doing spawning migrations, their homeranges can strongly increase. Baglinière & Maisse (1991) described the territorial behavior as not constant in time but it would vary as a function of time, day or season of the year. The intraspecific competition and the availability of food would therefore play an important role. Brown trout can reach a length of up to 60 cm and have a lifetime of usually 4 - 6 years (Baglinière & Maisse, 1991). They like cold rivers with swift-flowing water (Kottelat & Freyhof, 2007). If the water warms up, the trout stop to eat and stay in deep water. Their lethal temperature is around 24 °C (Baglinière & Maisse, 1991; Breitenstein & Kirchhofer, 2010).

Within their lifecycle the brown trout usually migrate to spawn. Therefore, it is a good target species for this master thesis, because there is motivation of the fish to use the fish pass. The survey deliberately takes place within their spawning season.

Minnow (*Phoxinus phoxinus*)

The minnow (Figure 16) is a small schooling fish (up to 10 cm standard length) which belongs to the family of the cyprinidae (Kottelat & Freyhof, 2007). In contrast to a lot of other cyprinidae the minnows live in the cool trout region (Küttel et al, 2002). Like the brown trout they migrate upstream to spawn on clean gravel (Zenner, 2001; Boschi et al., 2003; Kottelat & Freyhof, 2007). But contrary to the brown trout they are spawning in spring between April and June (Kottelat & Freyhof, 2007) preferably at temperatures between 11 - 22 °C (Küttel et al., 2002). To get to the spawning grounds barriers of 20 cm hight can be insurmountable for this small fish (Boschi et al., 2003). When they reach good spawning conditions, e.g. gravel between 1 cm - 3 cm diameter, they lay their sticky eggs on the gravel. If the substrate is too small or it is clogged with fine-grained sediments, the minnows do not spawn or the development of the larvae are negatively influenced. After the hatching of the larvae they slip up into the protecting gravel. Once the larvae lose their yolk sac (after 7 - 10 days), the young fish crawl out of the gravel into the open water (Bless, 1992). As they are not yet strong, they drift downstream and troop together in slow-flow areas. Even when they are adult, they do prefer structures like dead wood to hide (Boschi et al., 2003). The need to hide increases with decreasing water temperatures and decreasing water level. In the hiding places it can lead to intraspecific competition at costs of the younger minnows (Bless, 1992). Minnows are a popular prey of brown trout (Zenner, 2001). The prey of the minnows are insects, larvae of insects and small crustaceans (Boschi et al., 2003). During winter the minnows withdraw in

deep pools with low flow velocity or in coarse substrate. In rare cases they can reach a lifetime up to 11 years, but usually up to 5 years (Kottelat & Freyhof, 2007).
The minnow was defined as a target species because it is a typical fish in the River Töss and migrates during its life-cycle. A fish pass should be accepted by preferably all natural occurring species. Brown trout and minnows are different in size, swim capacity and behavior. A statement regarding the efficiency of the fish pass should be possible with these two target species.


Figure 16: Minnows in the River Töss (Anja Trachsel, 2015)

According to Lucas & Baras (2001), **bullhead** (*Cottus gobio*) and **stone loach** (*Barbatula barbatula*), which are also present in the river section of the fish pass, use the same habitats for refuge ("winter-habitat"), feeding ("summer-habitat") and as spawning place. Therefore, they "consequently do not need to migrate significant distances" (Lucas & Baras, 2001, p. 10). But Knaepkens et al. (2005) showed that there are differences between resident bullheads and some individuals of the population which migrate between 20 - 270 m over a 7-month period. A similar behavior could be expected of stone loach. Nevertheless those benthic fish were not defined as target species, because the fish pass has no connection to the bottom of the river, where these species typically live.

2 Methods

2.1 Discharge and precipitation

Unless otherwise specified, all data of the discharge and precipitation is from the AWEL measuring station 520 Töss-Rämismühle (Appendix A).

2.2 Electrofishing

Electrofishing is a valuable and commonly used tool to manage and asses fish populations (Emery, 1984). Although this method is broadly used, the interactions between an electric field and the fishes which are inside are not conclusively known (Snyder, 2004). Fact is that the fish are reacting to an electrical field depending on their distances to the electrodes, which create the electrical field. If the fish is around 6 m away from the anode, it will typically flee. If the fish is closer, the automatic taxis, also called "forced swimming" leads the fish through muscle contractions directly to the anode. If the animal is very close, it gets narcotized. The fishes which are near the anode can then be caught. The reaction of the fish is depending on various factors, for example on: fish species, length of the fish, water conductivity, water temperature, electrical output, electrode size and flow velocity (Peter & Erb, 1996; Peter, 2013; Snyder, 2003). Discussions occur frequently about the negative effects of electrofishing, like stress, spinal injuries, hemorrhages or even mortality (Dalbey & McMahon, 1996; Snyder, 2004). Nevertheless this method is considered to be one of the less harmful ones if applied by experienced users (Peter & Erb, 1996; Snyder, 2004; Miranda & Kidwell, 2010). An example for a more harmful method is using gill nets to catch fish. Gill nets are commonly used to sample lakes, but often the fish that are caught with the nets are killed (Rubin, 2015), if the nets were emptied in long time intervals. A lot of publications describe that using direct current instead of alternating current can reduce the harmful effects of electrofishing on fish (Peter & Erb, 1996; Snyder, 2003; Snyder, 2004; Miranda & Kidwell, 2010). Alternating current for electrofishing is therefore prohibited in Switzerland (VBGF, Art. 11, Par. 3).

In this study the fish, which were tagged, were initially captured with backpack electrofishing equipment by the fishery authorities from the canton of Zurich. The used voltage was 300 V, the current 4 A and one anode and one cathode were used.

2.3 PIT-tagging

Since the 1980s *Passive Integrative Transponder* (PIT) tags have been used for research of individual animal characteristics and behavior such as growth rates, movement patterns, identification of zoo animals and similar (Gibbson & Andrews, 2004). The animals are marked with the tags, which are read by an external electromagnetic field. The tags need no battery and can therefore be used in long-term studies (Hodge et al., 2015), theoretically during the whole life of an animal. Sometimes the tags get lost, but this is mostly the result of improper implantation (Gibbson & Andrews, 2004) or during spawning season when the female lay their eggs. In general, the loss of PIT-tags could lead to an underestimation of the efficiency of a fish pass (Cooke & Hinch, 2013). The chips are implanted under the animal's skin, usually into the abdominal cavity or into muscles (Gibbson & Andrews, 2004). The tags have only a short detection range (centimeter range), which is why they are suitable for continuous monitoring and fixed places at limited structures like fish passes (Júnior et al., 2012). With radio frequency identification (RFID) antennae the signals of the tags are registered when a marked animal passes it (Holmes et al., 2013). In the canton of Zurich PIT-tagging is classified as an animal experiment and a permission of the veterinary services is necessary for the application. Furthermore national legislations concerning the handling of wildlife animals have to be considered (BLV & BUWAL, 1996).

In this master thesis two self-made pass-through RFID-antennae were used to record the signal of marked fish. The antennae covered the whole cross section of the fish pass (100 cm x 80 cm). Antenna 1 was located at the end of the first pool element of the Steffstep prototype (the pools are counted from below up to the top of the obstacle). If a fish was registered here, it has successfully entered the fish pass. The second antenna was located at the beginning of the last pool at the top of the obstacle. Each fish, which passed the second antenna, had successfully overcome the fish pass (Figure 17). Each antenna was connected with a tuning box. With these boxes the resonance frequency of the antennae was adjusted to 134,2 kHz, corresponding to the resonance frequency of the PIT-tags. The tuning boxes were linked with a multi antenna reader (produced by Oregon RFID), which stored the data of the passing fish (date, time, individual PIT-tag identity number) on a memory card. Two batteries with 12 V and around 150 Ah supplied by turns the power of constantly 12 V for the whole installation. These batteries were used to get a noise-free electricity for the sensitive amplification electronics. Until 28.11.15 the installation was operated with 19 V via transformed electricity from the socket. Therefore the range of the detection increased up to 1 m for the big tags and 0,5 m for the small tags (personal communication Armin Peter, 04.01.16).

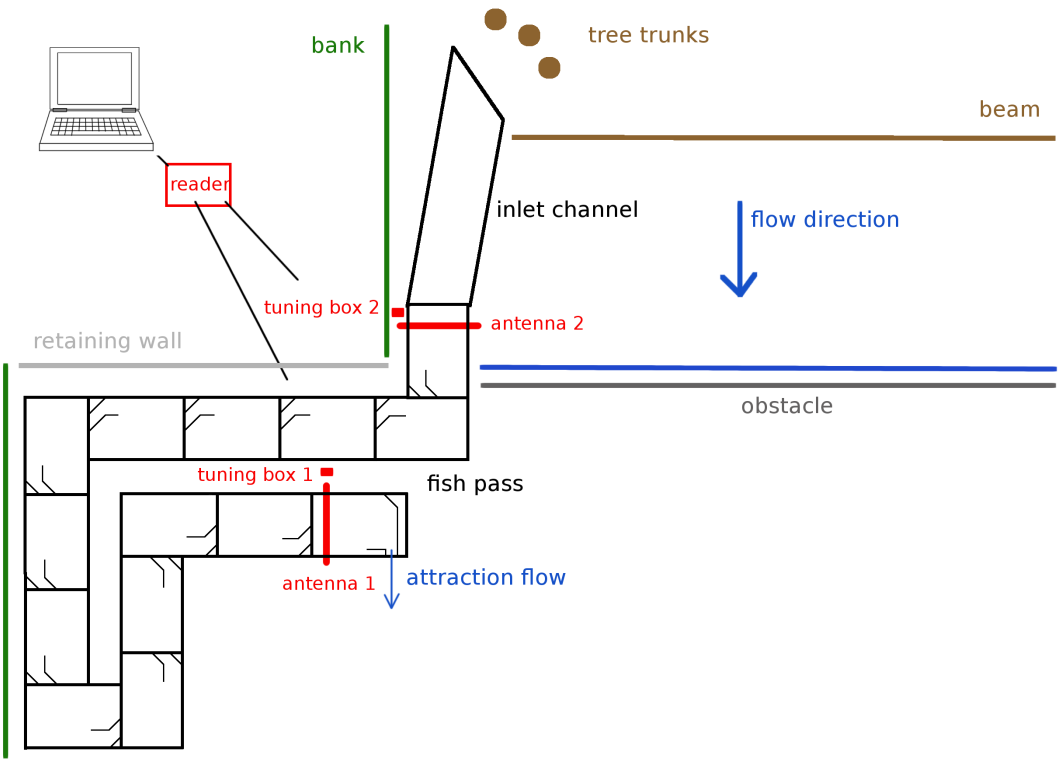


Figure 17: Sketch of the fish pass from a bird's-eye view with location of the PIT-antennae and further equipment

To mark the fish with tags, they were anesthetized in a small tank of 30 liter using solution of 1 ml clove oil and 20 ml alcohol (dissolvent). After the species were identified, their total body length was measured, their weight determined and the tags were placed with a scalpel in the body cavity of each fish. The individual PIT-tag number of each fish was recorded. Two kinds of read-only PIT-tags (Texas Instruments) were used: for smaller fish (up to 100 mm) tags of 12.0 mm x 2.12 mm diameter (HDX ISO 11784/11785 compliant ICAR-registered) with a weight of 0.1 g; for the taller fish (greater than 100 mm)

tags of 23.0 mm x 3.65 mm diameter (with a 64 bit unique ID. ISO 11784/11785 compatible) with a weight of 0.6 g were taken. After the surgery, all fish were kept in well oxygenated water for recovering from the intervention for one hour before they were released into the river.
With the gained data the different efficiencies to evaluate the connectivity of the Steffstep prototype are calculated as followed:

- $attraction\,efficiency\,[\%] = \frac{individuals\,registered\,at\,antenna\,1}{individuals\,released\,in\,the\,pool}$

- $passage\,efficiency\,[\%] = \frac{individuals\,registered\,at\,antenna\,2}{individuals\,registered\,at\,antenna\,1}$

- $total\,efficiency\,[\%] = \frac{individuals\,registered\,at\,antenna\,2}{individuals\,released\,in\,the\,pool}$

2.4 Fish trap

A fish trap is a device that allows easy access to fish but leaving is virtually impossible for the fish due to its construction. This allows testing how many tagged or untagged fish successfully pass through a fish pass. For this purpose, a cage or net trap is installed at the inlet of a fish pass. The grid meshes should be as small as possible to catch also small fishes. But the smaller the grid meshes, the more often the fish trap has to be cleaned. Sharp edges and rough surfaces are to be avoided so that the fish cannot be hurt. In addition, the frequency of control has to be adapted to the amount of migrating fish to avoid stress and injuries of the animals. Therefore, the construction has to be emptied at least once a day (DWA, 2014). However, with a fish trap only the effectiveness of a fish pass can be measured (DWA, 2006; Gough et al., 2012; DWA, 2014). In Switzerland a permission of the fisheries management of the canton is required for the application of a fish trap.

In this master thesis, a temporary fish trap was installed at the inlet channel. In this way, it was possible to catcht all fish which swam successfully through the fish pass - regardless of whether they were marked with tags or not. The fish trap consists of two parts (Figure 19): a closed grid (grid meshes = 2 cm x 2 cm) at the upstream and a nearly closed grid with a hole (14 cm diameter) at the beginning of the last pool element of the fish pass (Figure 18). The fish swim through the hole into the inlet channel and do not find their way out anymore due to the concave shape of the trap. The inlet channel was open at the top, but the fish could hide under a wooden board to prevent predation from birds. At least once a day the construction was controlled. The species of caught fish were determined and their lengths measured with a ruler, before they were released into the water above the obstacle. The fish trap was only used when the water was clear and coverage of floating debris (algae, leafs, twigs, etc.) was low.

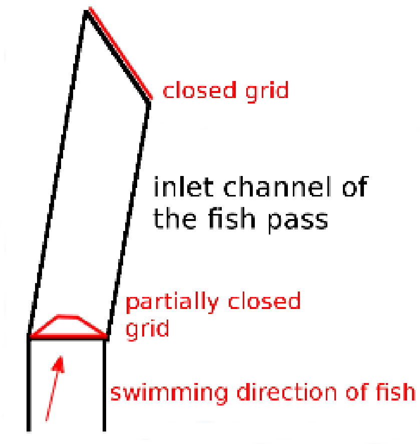


Figure 18: Sketch of the fish trap arrangement from a bird's-eye view

Figure 19: The two parts of the fish trap

2.5 Video recordings

Similar to a fish trap the effectiveness of a fish pass can be measured with video recordings at the inlet (DWA, 2006; Gough et al., 2012; DWA, 2014). In most cases therefore an observation window is used, which gives an insight from the water surface to the bottom of the fish pass. With a video camera all fish, which successfully swim through the fish pass and pass the observation window at the inlet, can be recorded. The recordings can only be evaluated and the species be determined when the water is clear and enough light is present. Through artificial lighting the fish can be deterred, especially night migrating species. In addition, the illumination effects the growth of algae, which can pollute the observation window. Software is available to evaluate the video recordings efficiently (e.g. Aimetis Symphony, INTERACT). If similar species occur or schools of young fish pass the video camera, the personal analysis is much more precise, but very time consuming. Additional the identifying of individual fish to exclude double counting is difficult (Cooke & Hinch, 2013). Nevertheless video recordings are a good addition to other monitoring methods (DWA, 2014), as it allows to observe the behavior of the fish in the fish pass without affecting or handling the animals (Cooke & Hinch, 2013).

In this study an underwater video camera was temporarily installed at the entry of the fish pass, inside the first pool element (Figure 20, position A). The aim was to observe the behavior of the fish, when they enter the fish pass. Until middle of October the camera was installed outside the fish pass (second camera position B), to examine the behavior of the fish outside the entrance. Two “Water Wolf UWC1” cameras with four hours operating time each were used alternatingly during daylight for the recordings.

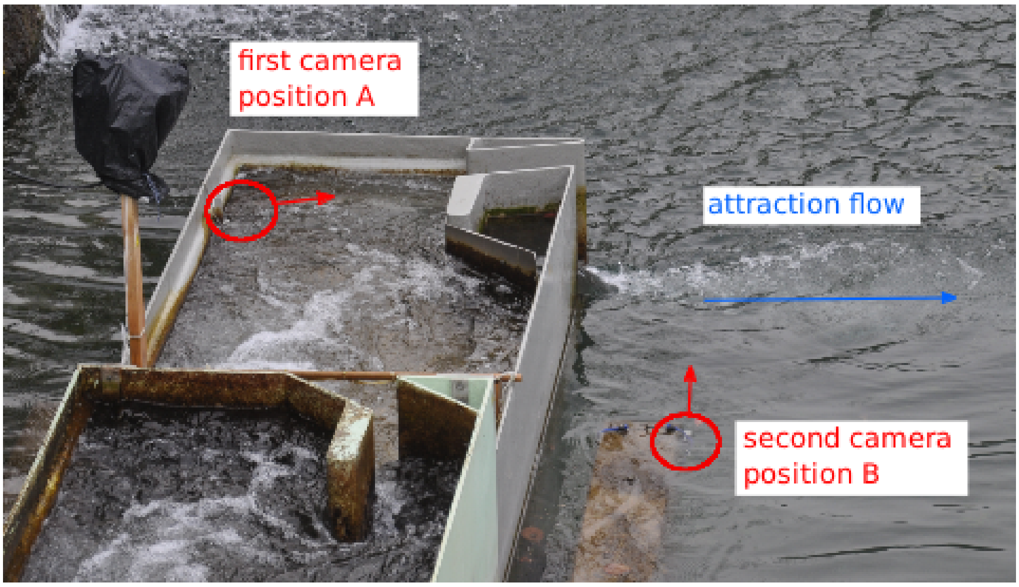


Figure 20: Picture of the fish pass with marked camera positions

2.6 Flow velocity and attraction flow

As it is mentioned before in chapter 1.1.3 the attraction flow and the flow velocity are crucial for the fish to find and to pass a fish pass and therefore have to be adapted on the local fish fauna. The values are determined by the design and the dimensions of the facility, as well as by the discharge.

In this master thesis the flow velocity within the pool elements and the attraction flow was measured with an impeller flow meter (MiniWater®20, made by Schiltknecht). The measurements were taken at two positions in the pools: at the middle of the long site of the pools on the opposite side of the slots (measuring point 1) and directly in the slots (measuring point 2) (Figure 21). Measurements were performed at approximately 50 % depth of water (middle of the water column). The MiniWater®20 measures flow velocities with 2 Hz an average over 10 samples, leading to an accuracy of 2 % full scale according to the manufacturer (Schiltknecht, 2014). In addition the depth of the water column was measured at the measuring point 1 with a pocket rule from the bottom of the pool without substrate up to the water surface.

The attraction flow was measured directly outside of the first slot and 80 cm in front of the slot in around 20 cm depth. Additionally the flow velocity of the water, which flows over the obstacle, was measured 80 cm away from the first pool element in 20 cm depth. This water compete the attraction flow, which should guide the fishes into the fish pass.

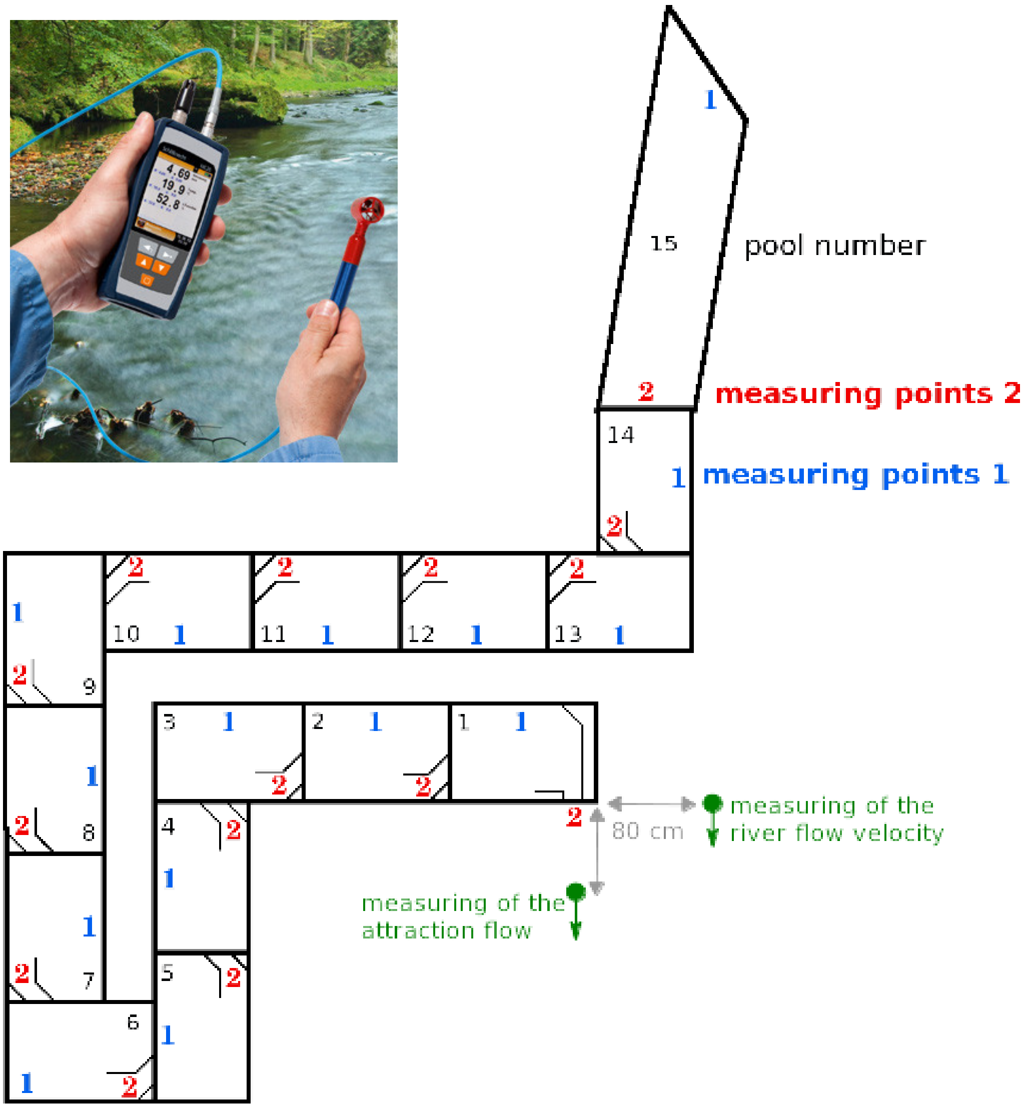


Figure 21: Measurement device Impeller MiniWater®20 (Schiltknecht, 2014) and low velocity and attraction flow measuring points from a bird's-eye view

3 Results

The field study took place from 01.07.15 to 04.01.16. The PIT-study ran only from 11.09.15 to 04.01.16. Overall the fish pass and the monitoring facilities (batteries of the PIT-antennae, fish trap, video camera) were controlled on 107 days, occasionally twice a day during summer.

3.1 Environmental conditions

Precipitation and discharge

The summer and autumn 2015 have been exceptionally dry compared to other years which resulted in a very low discharge during the period of the field study (Figure 22).

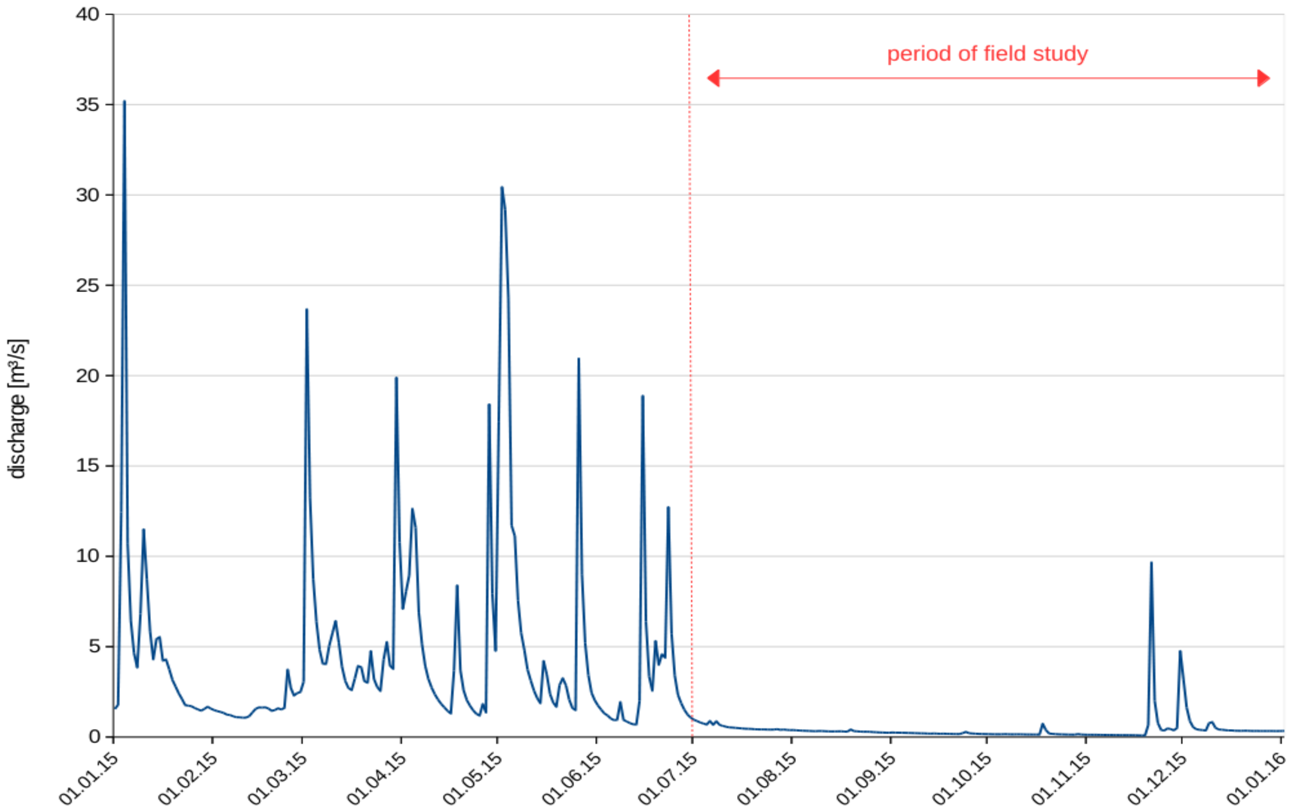


Figure 22: Discharge of the River Töss at the measuring station Töss-Rämismühle 2015

Although the River Töss is known to dry out occasionally in summer (Bruderer, 2010), the comparison with the mean discharge of the last 26 years shows the year 2015 as remarkable dry at the field site (Figure 23). As seen in the following figure, the discharge at the beginning of 2015 was higher than the mean discharge of the last years but since June it was far below average. The precipitation, in green, shows a similar picture. In 2015, the average precipitation per month was higher in the first half of the year than in the last 34 years but in the second half of the year it was significantly lower. Normally, the highest precipitation occur between May and September, often in form of thundershowers (Tunesi, 1996).

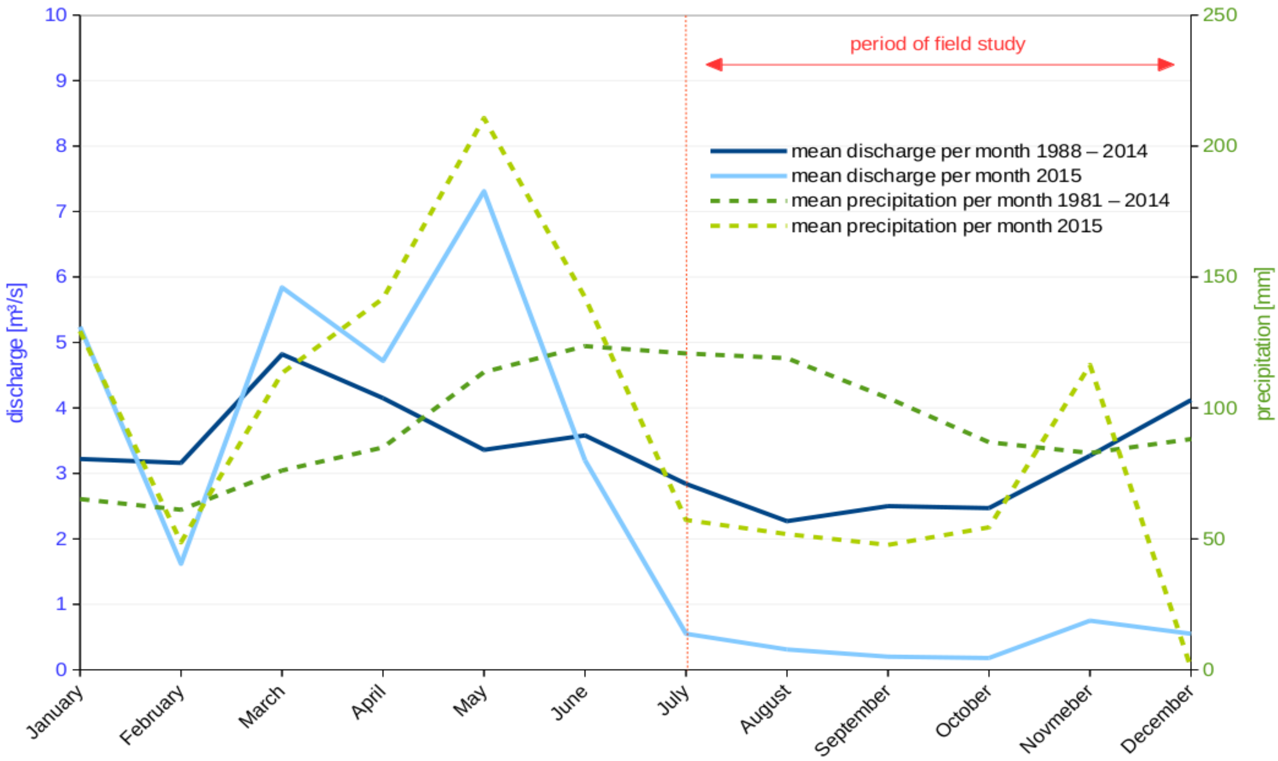


Figure 23: Mean discharge and precipitation per month at measuring station Töss-Rämismühle

The River Töss is almost exclusively fed by precipitation and snow melting (Tunesi, 1996). Therefore, its discharge is strongly depending on weather conditions. This can also be seen in Figure 23, where the discharge 2015 (light-blue line) correlates with the precipitation (light-green line). Two exceptions exist: in March the discharge does not correlate with the precipitation because of the snow melting which additionally fed the discharge. And in November the precipitation fell in form of snow and therefore the discharge only rose slightly. In addition, the soil in November was so dry that most of the melting snow first drenched the soil before it flew into the river causing a peak of the discharge at the end of November (Figure 22).

Water temperature

Between the 16.08.15 and the 16.12.15, a temperature logger recorded the water temperature of the River Töss at the inlet channel of the fish pass every 15 minutes. Overall, the temperature decreased from August to December (Figure 24), with an increase throughout the day and a decrease throughout the night. According to expectations, the amplitude in summer was higher than in autumn and winter. The highest daily amplitude was 4.4 °C and occurred on 28.08.15, whereas the lowest daily amplitude was only 0.4 °C and occurred on 11.10.15. The highest water temperature was measured on 30.08.15 and was 19.9 °C and this is the highest value ever measured in August since 1984 (AWEL, 2014 b). At the beginning of the field study, before the measurements started, the water was probably even warmer because of the hot weather at that time. The lowest water temperature was 3.1 °C and was recorded on 15.12.15. On 21.11.15 a temperature drop occurred.
The monthly mean water temperature in 2015 was 0.1 - 1.8 °C above the monthly average of the past 31 years (Appendix B) (AWEL, 2014 b).

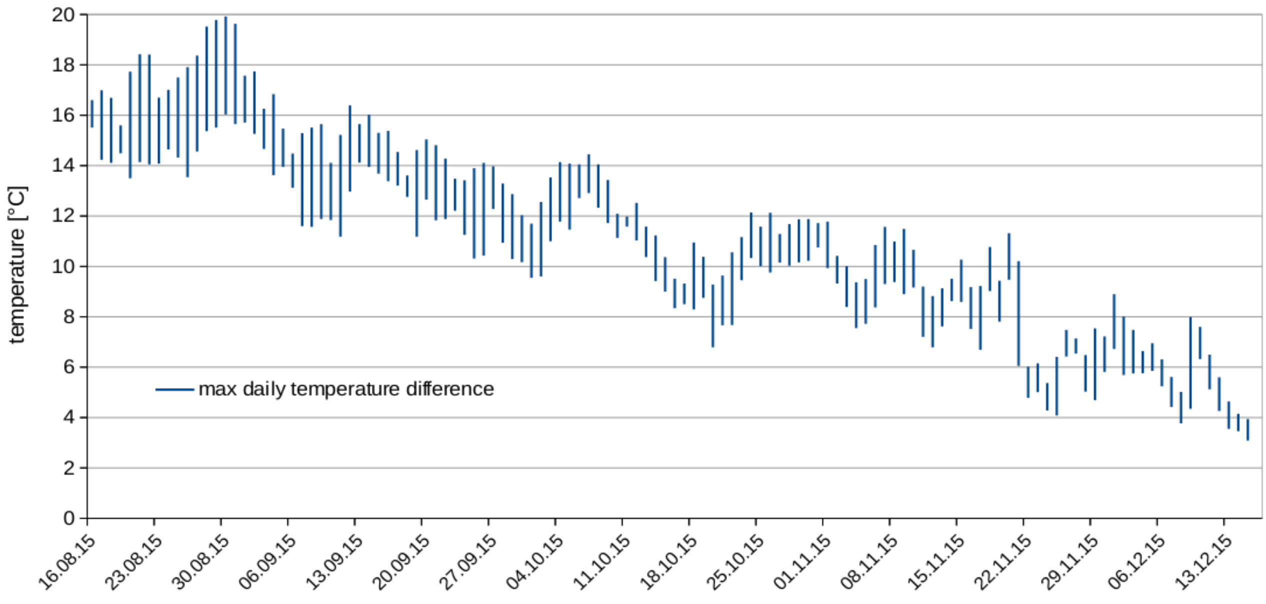


Figure 24: Maximum and minimum of the daily water temperature of the River Töss over time

In the River Töss no data about water chemistry was gained during the field study and it is also not publicly available.

Anthropogenic disturbances

During the field study no vandalism or other kinds of damages at the prototype or related material could be detected. This is, among other reasons, a result of the educational work. An information sign at each river bank informed the visitors about the fish pass and the ongoing study. In addition the neighbors, passers-by, bikers, bathers and dog-owners were actively addressed during the investigation at the field days. Especially during the hot summer, with a lot of people in and near the river, these personal conversations were very important to protect the infrastructure. For some time, swimmers had fun jumping off the obstacle into the pool and climbing up to the top of the obstacle through the fish pass again. Thanks to explanations about the negative effects on the fish and the technical equipment installed in the fish pass and finally the warning signs at the fish pass, the swimmers refrained from walking inside the facility.

3.2 Electrofishing

The electrofishing, marking of the fish and the release took place on two days. The fish were caught and released at different places. The tagged fish were classified into their catchment areas (letters) and release sites (ascending order of numbers with increasing distance to the obstacle with the fish pass) (Figure 25):

- **u** = caught upstream, above the obstacle with the fish pass
- **d** = caught downstream, 300 m below the obstacle with the fish pass
- **1** = released in the pool
- **2** = released ~ 100 m downstream, no barrier up to the fish pass
- **3** = released ~ 280 m downstream, two wooden barriers around 30 cm up to the fish pass
- **4** = released ~ 300 m downstream, three wooden barriers around 30 cm up to the fish pass

Figure 25: Visualization of the fish classification (swisstopo (JD100042/JA100120), 2015, mod.)

The first fishing day was 28.08.15 and all 277 fishes were caught upstream and released downstream of the fish pass (fish classification u2). The second day was 11.09.15 and the 395 fishes were caught and released at different places (fish classification u1, d3 and d4) (Figure 25). In the following the gained data is presented according to the different fish classifications. The fishing was performed randomly (e.g. the distance of the fishing route was not measured), focusing on brown trout and fish with a total length of above 6 cm, because they were expected to be more likely to use the fish pass. Nevertheless other fish species were caught and marked as well to gain additional data.

The target species brown trout was caught by far the most and the majority of the brown trout were caught upstream and released downstream (Table 3). The fish with the classification u2_u1 and u2_d4 were caught on both fishing days. For example the fish u2_u1 were caught at the first day upstream and were released 100 m downstream of the fish pass (u2). Then at the second fishery day, they were again caught upstream (so they had already used the fish pass) and were released in the pool (u1). The fish with the classification d3 and d4 were caught and released at the same places.

Table 3: Classification and amount of marked fish

		amount of fish			
		brown trout	minnow	stone loach	bullhead
fish classification	u1	155	17	0	0
	u2	210	34	22	9
	d3	79	4	0	0
	d4	136	6	0	0
	u2_u1	*3*			
	u2_d4	*1*			
	total	580	61	22	9

As only the sampling size for brown trout were sufficiently big, brown trout data is analyzed in more detail than the other species.

Relationship between total length and weight of the brown trout

The total length and the weight of the caught fish were measured and as it is expected the weight increased with an increased length of the fish. This relationships shows a increasing curvel with a saturation at larger fish sizes (Figure 26). It could be seen that the ascended fish were all taller than 160 cm with one exception.

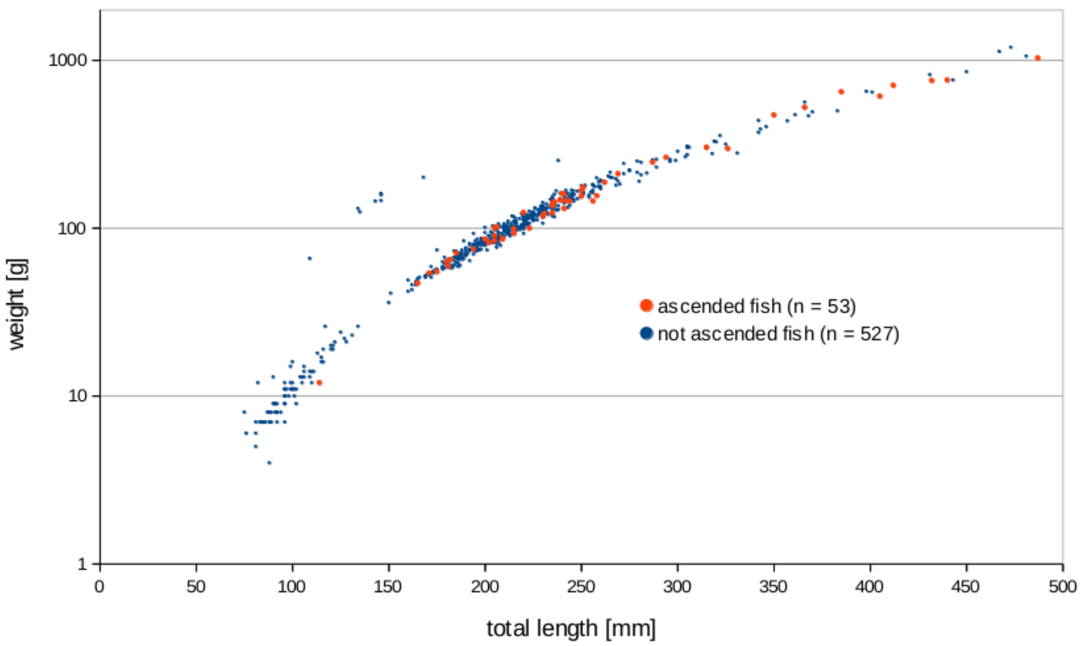


Figure 26: Semilogarithmic plot: weight vs. total length of the brown trout

With this data the condition factor CF, which tells us about nutritional condition and the fitness of the fish, can be calculated: $CF = 100 * W / L^3$ with W = weight in g and L = total length in cm (Neophitou, 1986). The median CF of all fish was 1.05, whereby some outliers in both directions exist (min 0.59, max 5.4). The median CF of the ascended fish was 1.04 with a minimum value of 0.86 and a maximum value of 1.17.

3.3 PIT-tagging

With the PIT-tags the migratory movements of the marked fish between the first and the second antenna within the fish pass could be examined. A total of 672 fish were marked, with total lengths between 66 mm (minnow) and 487 mm (brown trout). Overall, four fish species were examined (Table 3). As expected, only brown trout and a few minnows were registered in the fish pass, so the following description focuses on these species.

Between 11.09.15 and 04.01.16 86 fishes were registered at least at one of the antennae in the fish pass. Additionally, 49 of them were registered at the second antenna, indicating that they successfully passed the facility.

Four of the registered fish were detected at the second antenna only, but because all fishes had been released downstream, they must have passed the first antenna and therefore they are counted in following as "successfully passed fish" (n = 53). With these obviously missed four brown trout a detection probability could theoretically be estimated of approximately 92 %, probably due to tag size, insufficient energy supply of the batteries or similar. However, a correction of the statistic was not performed throughout this thesis.

Attraction efficiency

According to the definition (1.1.4), for assessing the attraction efficiency of Steffstep, only the fish which were released directly in the pool in front of the entrance are relevant (classification u1 and u2_u1). However, to gain additional information, efficiencies were also calculated for fishes released further downstream (classification u2, d3 and d4). These values also include information from the releasing sites up to the fish pass, therefore they will not be considered in detail in the following.

The attraction efficiency of Steffstep for brown trout was 28.4 % (n =155) (Table 4). The attraction efficiency for the minnows was only 11.8 %, whereby the sample size was much smaller (n =17). The three brown trout of the classification u2_u1 represents a special case. They were caught at the first and the second fishing day upstream and always released downstream of the fish pass, so they had already used the fish pass between the two fishing days. This classification had the highest attraction efficiency, but a very small sample size. The fish caught and released further downstream of the fish pass (classification d3, d4) had the lowest attraction efficiency.

Table 4: Attraction efficiency for brown trout and minnow

	released	registered at fish pass entrance	ratio [%] = attraction efficiency
brown trout, u1	**155**	**44**	**28.4**
brown trout, u2	210	27	12.9
brown trout, d3	79	5	6.3
brown trout, d4	136	6	4.4
brown trout, u2_u1	*3*	*2*	*66.7*
brown trout, u2_d4	*1*	*0*	*0.0*
brown trout, total	580	82	14.1
minnow, u1	**17**	**2**	**11.8**
minnow, u2	34	2	5.9
minnow, d3	4	0	0.0
minnow, d4	6	0	0.0
minnow, total	61	4	4.4

Passage efficiency

According to the definition the passage efficiency includes all fish which passed the facility regardless of their fish classification.

The mean passage efficiency of Steffstep for brown trout was 65 %, whereas no minnow passed the facility (Table 5). Again, it has to be considered that the sample size of the minnows was very small (n=4).

Table 5: Passage efficiency for brown trout and minnow

	registered at antenna 1	additionally registered at antenna 2	ratio [%] = passage efficiency
brown trout, total	**82**	**53**	**64.6**
brown trout, u1	44	33	75.0
brown trout, u2	27	13	48.1
brown trout, d3	5	2	40.0
brown trout, d4	6	3	50.0
brown trout, u2_u1	*2*	*2*	*100.0*
minnow, total	**4**	**0**	**0.0**

Similar to the attraction efficiency the passage efficiency was the highest for the special case of the fish with classification u2_u1 (100 %), which already had used the fish pass. Besides them the brown trout which were released in the pool (classfication u1) had the highest passage efficiency (75 %).

Size categories of the brown trout

The lengths of brown trout that were tagged and that ones that entered and ascended the fish pass differ (Table 6, Figure 27). On average, the ascended fish (248.7 mm) are bigger than the entered ones (226.1 mm). The entered ones in turn are bigger than the average of all tagged brown trout (209.4 mm).

The fish which were released in the pool (classification u1 and u2_u1) had the highest potential to use the fish pass because they were already near to the facility. In the following these fish are treated together as a separate group and their data is analyzed in more detail. It has to be kept in mind, that on average these fish are bigger than the mean lengths of all tagged fish.

Table 6: Mean and median of the different lengths of brown trout

	mean [mm]	median [mm]	number of fish
all tagged brown trout	209.4	211.0	580
entered brown trout	226.1	218.0	82
ascended brown trout	248.7	235.0	53
fish classification u1, u2_u1	246.4	230.5	35

Following, the brown trout are divided into two groups: the small fish (75 mm ≤ length ≤ 211 mm) and the big fish (211 mm < length ≤ 487 mm). The small fish had an attraction efficiency of 29.9 %, whereas the big fish had an attraction efficiency of 26.9 %. However, the passage efficiency is higher for the big fish (79.5 %) than for the smaller ones (47.4 %). Overall, most of the registered fish were between 16 cm and 27 cm long, reflecting the size range of all tagged fish (Figure 27).

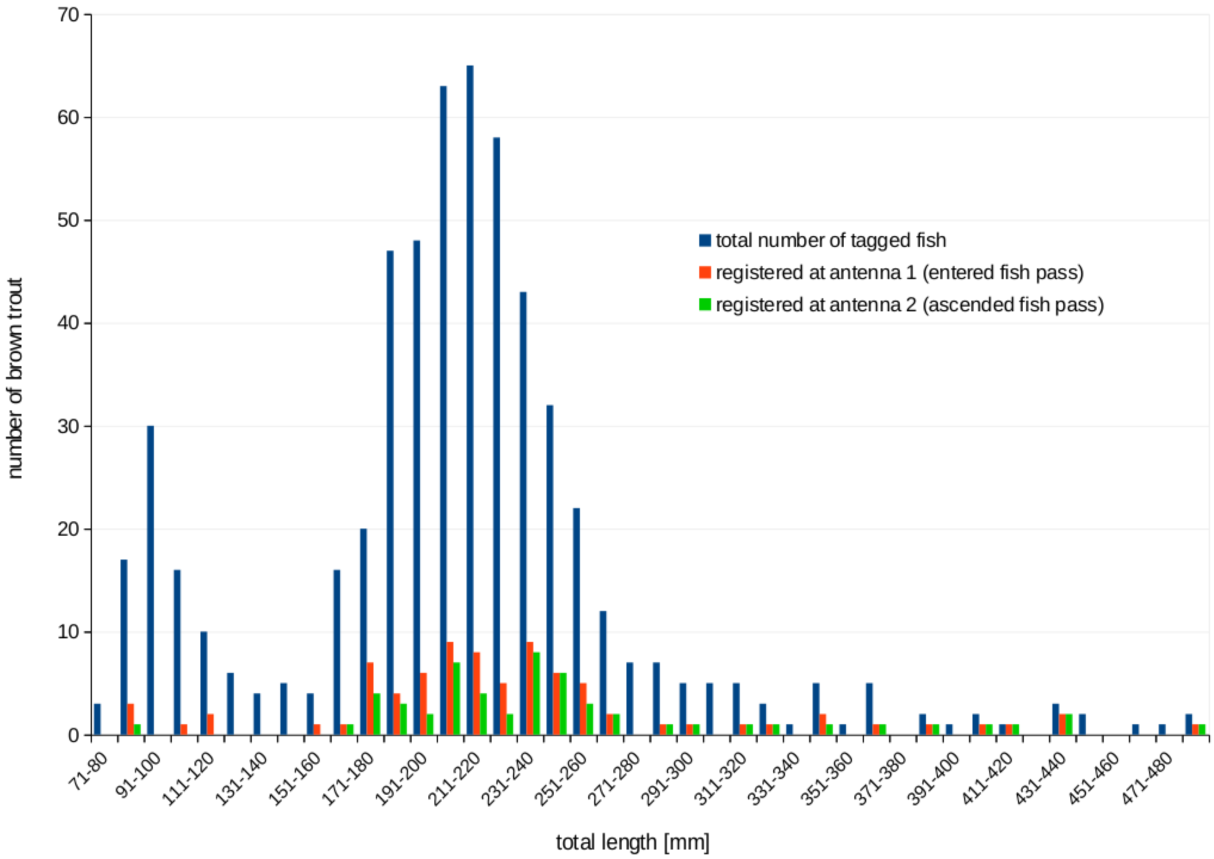


Figure 27: Size categories of tagged (n=580), entered (n=82) and ascended (n=53) brown trout

Efficiencies according to size categories

The small fish had almost the same attraction efficiency than the big fish, whereas the passage efficiency is higher remarkably higher for the big fish (Table 7). The total efficiency is depending on the attraction efficiency as well as on the passage efficiency and therefore also higher for the bigger fish. For the brown trout the total efficiency is 21.3 % (Table 7).

Table 7: Overview of the efficiency data of the brown trout [%]

	attraction efficiency	passage efficiency	total efficiency
considered fish classification due to definition	u1, u2_u1	all classifications	u1, u2_u1
small fish, n = 77 (87 mm - 211 mm)	29.9	47.4	18.2
big fish, n = 81 (211 mm - 487 mm)	26.9	79.5	24.4
total (all fish), n = 158	28.4	64.6	21.3

Migration time of the brown trout

The observed migration of tagged fish (upstream, n = 67 and downstream, n = 11) took place on 23 days. Nearly half of the upstream migrations (49 %) occurred on the same two days. Altogether no relationship between water temperature and fish migrations could be detected. The mean temperature on days with observed fish migrations varied between 5.8 °C - 16.6 °C (mean: 10.6 °C, median: 11.0 °C). Most of the brown trout migrated during daytime between 9 am and 8 pm (Figure 28).

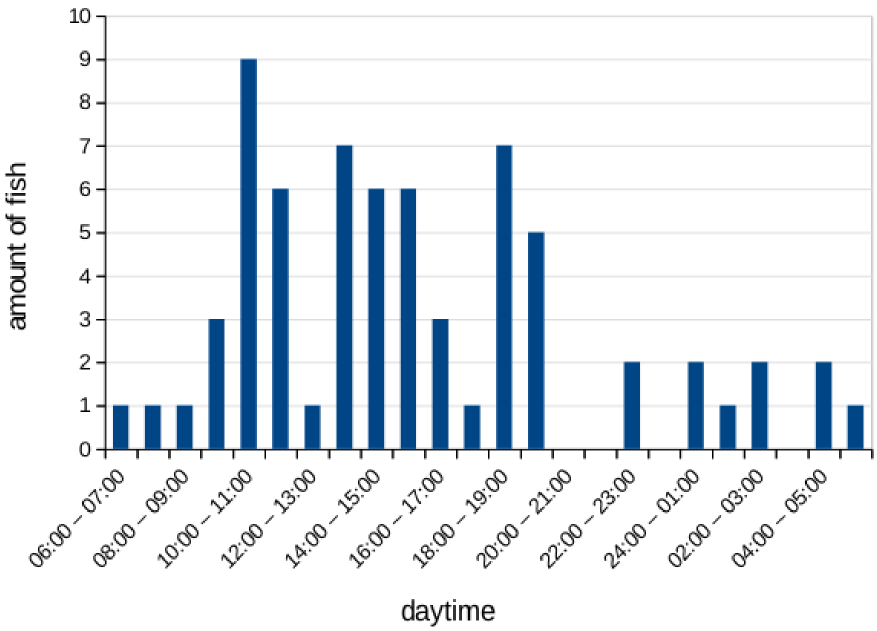


Figure 28: Daytime of the upstream fish migration of the brown trout (n=67)

Additionally, during almost the whole night some individuals passed the facility. More important than the daytime or the temperature seems to be the discharge. Most of the fish migrated at increased discharge in comparison to the days before (Figure 29). Often they passed the fish pass upstream either before or after a peak of the discharge. On 23.09.15 most of brown trout passed the fish pass, although the discharge only increased slightly. At the highest peak of discharge on 21.11.15, less than half of these brown trout swam upstream. Some fish also migrated upstream and downstream at constant discharge conditions.

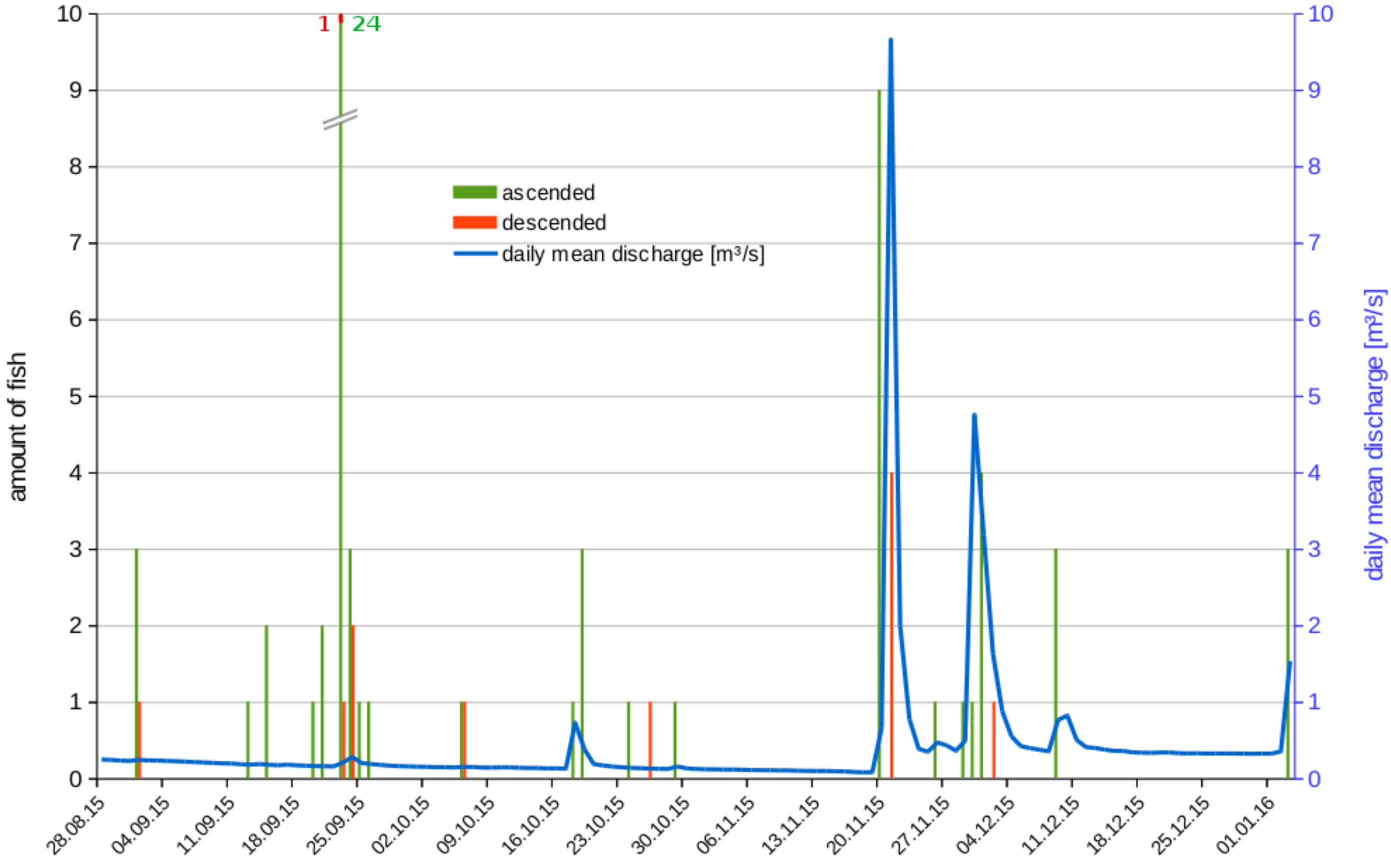


Figure 29: Fish migration in relation to the mean daily discharge over time

Frequency of fish migration and ascent speed of the brown trout

Most of the ascended fish were using the fish pass once, but some of them used it up to three times (Table 8). The 53 ascended brown trout individuals used the fish pass altogether 67 times to swim upstream and 11 times to swim downstream (Table 10). The fish which ascended more than once but did not pass the fish pass downstream must have been getting downstream over the obstacle.

Table 8: Migration frequency of the brown trout upstream and downstream

amount of migrations and direction	amount of migrating fish
1 time upstream	38
2 times upstream	4
3 times upstream	1
1 time upstream and 1 time downstream	3
2 times upstream and 1 time downstream	5
2 times upstream and 2 times downstream	1
3 times upstream and 1 time downstream	1
	53

To pass the prototype at the first time, the brown trout needed on average around half an hour (Figure 30, Table 9). The fastest fish needed only 10 minutes, whereas the slowest fish reached the top of the fish pass after 2.5 hours. Although the sample size of fish which entered the fish pass more than once was small (n = 13), it seems that at further ascents they passed the facility quicker than in the first run. On average they needed only 20 minutes for the further ascents.

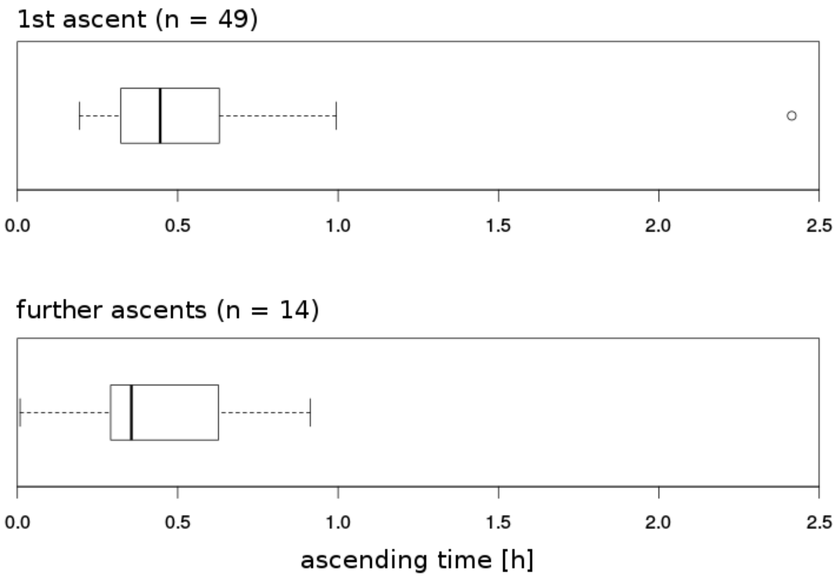


Figure 30: Ascending time of the brown trout at the first and the further upstream migrations

Table 9: Ascending time of the brown trout at the first and further ascents [hh:mm:ss]

	min	median	max	n
first ascent	00:11:35	00:26:42	02:24:50	49
further ascents	00:00:32	00:21:22	00:54:47	14

The ascending time seems to be depending on the fish size. Mainly bigger fish were slightly faster than smaller ones (Figure 31).

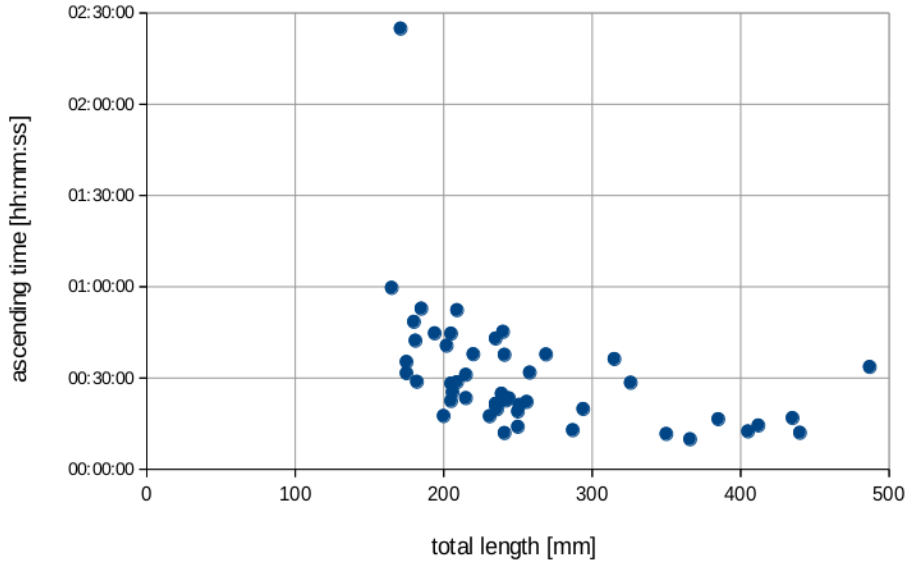


Figure 31: Relation of the total length and the ascending time of the migrating fish (n=49)

Downstream migration of the brown trout

Overall, ten of the ascended brown trout were also using the fish pass downstream (registered first at antenna 2 and then at antenna 1), one of them twice (Table 10). Four individuals swam downstream in one night with a peak of discharge around 22 m^3/s. Three individuals swam downstream during decreasing discharge and two during increasing discharge with regard to the discharge the hours before. Two big brown trouts swam downstream during a constant low discharge.

According to the median, the fish needed around 24 min to swim downstream, whereby the fastest fish just needed 1 min 14 seconds and the slowest 1 hour and 22 min (n =10). There was no relationship between the length of the fish and the time it needed to swim downstream.

Table 10: Length, migration time and discharge of downstream migrated brown trout

total length [mm]	time [hh:mm:ss]	discharge [m^3/s]	
194	00:10:15	3.0	decreasing
	01:03:50	0.2	increasing
215	00:36:47	0.3	increasing
230	00:23:24	0.3	decreasing
241	00:01:14	22.0	peak
269	00:12:24	22.0	peak
326	00:03:19	0.2	constant low
366	00:06:49	22.0	peak
412	00:09:48	0.2	decreasing
440	00:12:40	22.0	peak
487	00:21:56	0.2	constant low

General migration movements of the brown trout

Additional to the fish which successfully passed the fish pass, a lot of individuals just entered the facility without passing it. The 86 different fishes which were registered at the first antenna were overall entering the fish pass 132 times, thereof they passed the prototype 67 times upstream, 11 times downstream and 54 times they just entered it. The passage efficiency was calculated for the 86 individual brown trout independently how often they entered the facility.

Four brown trout entered the fish pass three times, but did not ascend. They were rather small: between 90 - 236 mm long. Additionally, three further brown trout entered the fish pass twice and did not swim upstream. They were between 84 - 216 mm long.

Half of the migration movements (51 %) were recorded during four days (Table 11). On 23.09.15 24 of the 25 entering fish also passed the facility. In contrast, on 18.10.15 only one fish passed the construction, whereas ten were registered at the first antenna, thus only entering without ascending. In November the highest peak of the discharge during the field study period occurred (Figure 22). One day before, during the increase of the water level, nine fish passed the prototype and ten just entered it. The difference of the minimum and maximum of the discharge shows, if the discharge was changing substantially.

Table 11: Amount of migration movements during four selected days

date	amount of ascending fish	amount of descending fish	amount of fish just entering the fish pass	discharge [m³/s]	mean of the daily water temperature [°C]
01.09.15	3	1	7	max 0.33, min 0.22	16.6
23.09.15	24	1	1	max 0.26, min 0.17	12.8
18.10.15	1	0	10	max 3.24, min 0.13	9.6
20.11.15	9	0	10	max 9.83, min 0.08	10.4

3.4 Fish trap

The fish trap was overall in use for 571 hours and controlled 37 times (Appendix B). During this time ten brown trouts with a length between 180 mm and 440 mm were caught (Table 12). All animals were trapped during night or during a time period over 24 hours in which the time of the actual catching can not be defined clearly.

In July it was very hot, a lot of bathers were swimming in the pool and climbing inside the fish pass and the discharge slowly decreased. In this time only one brown trout climbed the fish pass. In August an algae bloom in the wake of the high temperatures prevented the further use of the fish trap. In September and October the discharge was very low and leafs and twigs in the water blocked the fish trap so it was only in use at the end of October after rain but no fish was trapped. At the beginning of December the discharge finally increased and nine further brown trouts could be caught.

The fish migration always took place during increased water levels in relation to the days before. Sometimes the fish migrated during increased discharge and sometimes during decreasing discharge after a peak of “high water”.

The detection range of the big PIT-tags is around 1 m around the antenna. If fish were caught in the fish trap, they are partly inside of the detection range and can be registered several times. The comparison of the fish trap data with the data of the PIT-tagging showed that most likely six of the ten trapped brown trout were tagged individuals (marked bold in Table 12).

Table 12: Date and length of the caught brown trout in the fish trap

date	total length [mm]**	daily mean discharge [m³/s]*
06.07. / 07.07. 2015	350	0.78
30.11. / 01.12. 2015	**400**	3.98
01.12. / 02.12. 2015	180	2.42
	260	
	200	
	360	
09.12. / 10.12. 2015	**220**	0.80
	250	
	270	
	270	

* average of the two daily-discharge averages at measuring station Töss-Rämismühle (Appendix A)

** total lengths in bold are probably tagged fish

3.5 Video recordings

The video camera recorded over a span of 22 days overall 56 hours of footage at different daytimes, whereof 31 hours recorded inside the fish pass (Figure 20 camera position A) and 25 hours in front of the entrance (Figure 20 camera position B). At camera position A no fish could be detected (Appendix C, Table 21) from 04.08.15 until 21.10.15. At camera position B five fish could be recorded (Table 13) when they entered the fish pass, and at least nine distinguishable individuals could be observed in front of the entrance (Appendix C, Table 22). All detected fish were brown trout (Figure 32).

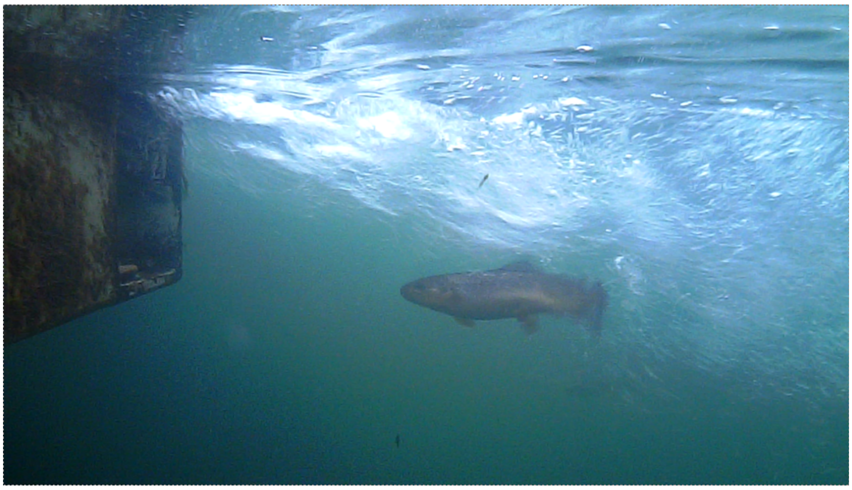


Figure 32: Brown trout is entering the fish pass on 09.12.15

The entering fish were all detected on the same day (09.12.15) between 3:00 pm - 4:30 pm and at an increasing discharge up to 1.8 m^3/s (AWEL, 2015 a). The fish in front of the entrance are difficult to distinguish and because the fish were swimming into the detection range of the video camera for several times the exact number of observed fish which did not enter the fish pass, could just be estimated. Seven of the observed individual fish were also recorded on 09.12.15 and two further fish were detected on 09.11.15 around five o'clock in the afternoon at a constant discharge of 0.1 m^3/s (AWEL, 2015 a).
The comparison of the camera-recorded fish, which entered the fish pass and the tagged ones, which were registered at antenna 1 that day, shows that most likely three of the five fish were tagged ones (Table 13).

Table 13: Comparison of the recorded and tagged fish

video recorded fish entering the fish pass		**fish registered at antenna 1**	
approximate time	amount of fish	time	total length [mm]
09.12.15 14:50	1	09.12.15 14:55	258
09.12.15 15:54	2*	09.12.15 15:58	215
09.12.15 16:06	1	09.12.15 16:08	256
09.12.15 16:25	1	-	-

* two fish entered the fish pass at the same time, one of them was tagged

3.6 Flow velocity and attraction flow

The flow velocities in and around the fish pass were measured on 08.12.15. The discharge this day was 380 l/s at the discharge measuring station Töss-Rämismühle (AWEL, 2015 a), which means that the fish pass was fully operational at this time. The flow velocity varied between 0.3 - 1 m/s in the center of the pool elements of the fish pass (measuring point 1) and between 0.6 m/s and 1 m/s in the slots (Table 14, Figure 33). At the inlet channel the flow velocity varied between 0.2 - 0.5 m/s.

The attraction flow directly in front of the fish pass entrance was 0.8 m/s. Where the attraction flow mixed with the flowing water entering over the obstacle, 80 cm from the entrance at a depth of 20 cm, the flow velocity was 0.9 m/s. The competing flow velocity of the river beside the obstacle was 0.6 m/s at a depth of 20 cm (Figure 33).

The pool elements are 60 cm high and were originally filled with 20 cm of substrate. During operation, the substrate was washed away directly after the slots and accumulated in the corners of the pool. So, over time, the height of the substrate varied inside the pools but the artificial stones still offered a rough surface of the bottom. The water depth was measured from the pool bottom without substrate (to have comparable values) up to the water surface and varied between 37 cm and 50 cm. The highest flow velocity of 1 m/s was measured at four vertical slots, irregularly distributed over the facility (Figure 33).

Table 14: Measurements of the flow velocity on 09.12.15

pool	measuring point 1 [m/s]	measuring point 2 [m/s]	water depth [cm]
15 = inlet channel	0.2	0.5	N/A
14	0.5	1.0	42
13	0.3	0.9	48
12	0.5	0.9	50
11	0.7	1.0	47
10	0.8	0.6	43
9	0.6	1.0	37
8	0.8	0.9	40
7	0.6	0.8	48
6	1.0	0.7	40
5	0.8	0.8	39
4	0.6	0.9	45
3	0.5	0.7	43
2	0.4	0.9	42
1	0.3	0.8	45

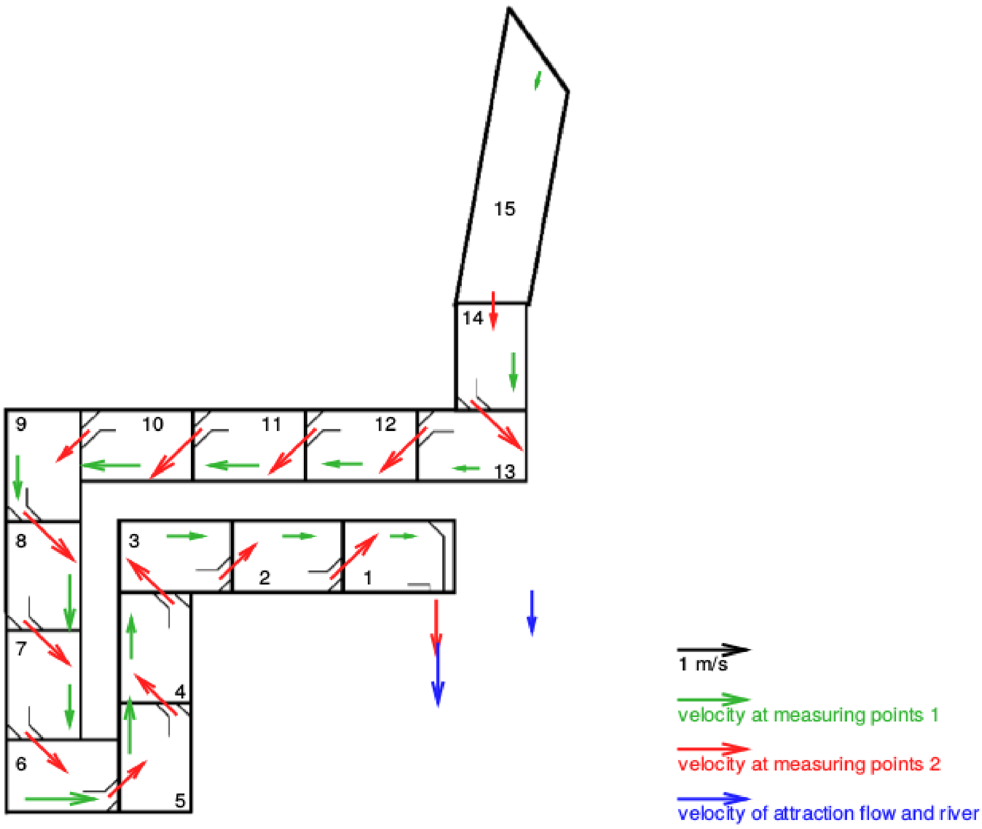


Figure 33: Overview of the flow velocities in the Steffstep prototype

4 Discussion

4.1 Context with literature and hypotheses

In the following the gained data is discussed and compared with results from similar studies. Additionally, the four hypotheses are tested.

4.1.1 Environmental conditions

Throughout this study fish migration via the fish pass Steffstep was found not to be constant over time but rather occurred in a strongly clustered manner. The comparison of PIT-data and measured discharge shows a clear relationship: the fish migrate favorably at an increased discharge (Figure 29). This result corresponds well with other studies. For example Weibel & Peter (2013) also determined a peak of fish migration of brown trout to pass a block ramp after heavy rainfall with an increased discharge. This might be explained as follows: On the one hand a high discharge allows the fish to pass small obstacles which are otherwise insurmountable. On the other hand an increase of the discharge often causes a turbidity of the water, which allows the fish to migrate without the risk to be detected by predators.
Theoretically, Steffstep needs a minimum discharge of 120 l/s to be functional. The PIT-analysis was performed during 129 days, whereof on 50 days the discharge was lower than 120 l/s and therefore the fish pass not fully operable. On 55 days the discharge was still smaller than 300 l/s (Figure 22). The low water level had made it difficult for fish which were released further downstream even to reach the fish pass. In general, it is suggested that the low discharge influenced the fish migration, which was concentrated on a few days with an increased discharge: 49 % of the upstream migrations occurred during two days and 51 % of all migration movements (upstream, downstream and only registered at antenna 1) took place on four days. According to Ovidio & Philippart (2002) such a behavior is typical for fish. If they are not able to pass an obstacle, they can wait downstream up to several weeks, until the environmental conditions improve (e.g. temperature of the water, increased discharge). It is interesting to see, that most of the fish migrated during the first increased discharge after they were released, although the difference of the discharge was just very small (Figure 29). This result matches with the data of Weibel & Peter (2013) at block ramps. They found that 40 % of the marked fish migrated upstream during the first night after translocation and another 29 % of the marked population passed the block ramps during the first increased discharge after one week.
Altogether, the low discharge had an impact on the registered fish migration. Especially the fish which were released further downstream (classification u2, d3, d4) had a low attraction efficiency (Table 4), whereby also other reasons are possible for this behavior as will be explained in more detail below.

The water temperature is one of the most important factors for the life of a fish. It influences all physiological and biochemical processes (Küttel et al., 2002). In each month of the year 2015, the mean water temperature of the River Töss was higher than in the past 31 years (Table 19). For the fishes, the maximum and minimum temperatures and the time when they occur are crucial. Additionally, the reaction of a fish to the water temperature is depending on its age-stage and the species. Küttel et al. (2002) summarized the temperature preferences of 32 Swiss fish species from global literature. The brown trout as a salmonidae prefer cooler water than the minnows, which belong to the cyprinidae (Table 15).

Table 15: Relevance of the water temperature to brown trout and minnow [°C]*

	brown trout			minnow		
	max	min	optimum	max	min	optimum
eggs	14	0	1 - 9	16	6	6 - 16
juvenile	28	0	7 - 14	23	-	-
adult	30	0	4 - 19	31	0	13 - 25
reproduction	13	1	1 - 10	22	7	11 - 22

*data from Küttel et al. (2002)

During the period of this study, the highest measured water temperature in the Töss was 19.9 °C and occurred in August. This value is five degrees above the optimum temperature of the juvenile brown trout and slightly above the optimum for the adult ones. The optimum range of the temperature is the preferred temperature of the animals, in which they show normal behavior, like eating (Küttel et al., 2002). The high water temperatures in summer suggest that the brown trout were stressed during this warm period but mortality should have been on a normal level, according to the values from Küttel et al. (2002). According to those values, the adult minnows should have had no problems with such temperatures and their spawning season was already finished at the beginning of the field study. By observing the spawning redds of the brown trout, the end of the spawning activities could be determined between 10.12.15 and 15.12.15. At this time, the daily mean water temperature was between 4 °C and 7° C. This lies within the optimal values given for reproduction from Küttel et al. (2002). The migration through the fish pass occurred independently of the water temperature in a range between 6 °- 16 °C. This matches with the values of the optimum temperature of the adult brown trout given by Küttel et al.

No data about water chemistry of the River Töss was taken for the evaluation, however, it is to consider that it also plays a role for the behavior of the fish.

Predation

The brown trout is a predator (see chapter 1.5.3), which is also known for cannibalism (Müller, 2015 a). In this master thesis, predation of the bigger brown trout individuals at the expense of smaller ones and minnows within the pool, the fish pass or the fish trap could not be excluded. Vice versa, there is no clear evidence that predation took place. Only one small fish (86 mm) inexpectedly passed the facility which might be explained as a detection of a bigger fish carrying the PIT-tag from this fish in its stomach.

In addition to intraspecific predation birds and especially grey heron (*Ardea cinerea*) and goosander (*Mergus merganser*) are a danger for the fish. Grey heron could be regularly observed near the fish pass but two investigation at typical sleeping places of these local birds could not prove that they had eaten some tagged fishes (no PIT-tags were found, which however is difficult as the tags have a relatively short detection range) and therefore no correction of the statistic was performed. Nevertheless the impact of the fish eating birds should not be underestimated.

4.1.2 Electrofishing

Many fish species, especially the brown trout, tend to return to their home site, when they were translocated or drifted downstream (Camenzind, 2008; Schläppi, 2011; Gardiner, 2015; Hinterhofer et al., 2015). This behavior is called homing or microhoming. To induce a motivation for the tagged fish to use the fish pass, a certain amount of fish was caught upstream and released downstream at different places (classification u, 62.9 % of all tagged fish). Other fish were caught and released downstream (classification d, 37.1 % of all tagged fish). According to the theory of homing, these fish have a lower urge to migrate and to use the fish pass. Of course the motivation of migration can be influenced by many more factors. For example, it was assumed that the spawning season of the brown trout during the study period affect migration. It could be shown fish with the classification u preferably migrated: From the 82 fish which were registered at the fish pass only 11 individuals (13.4 %) were of classification d. However, beside the reduced homing behavior this also depends on the very low discharge, which most likely prevented a migration of the fish from further downstream up to the fish pass.

On the two fishing days, 672 fishes were marked with PIT-tags. Some additional very small or injured animals were released again without a PIT-tag in order to spare these animals. The length and the weight of the caught fish were measured, from which the condition factor (CF) could be calculated. The median CF of all fish and the one of the ascended fish were nearly equal (1.05 ± 0.01), so that no difference of the fitness of the ascended and not ascended fish could be determined. The CF is depending on different parameters: age, sex, stage of maturation, season, elevation, amount of fat reserves and degree of muscular development (Barnham & Baxter, 1998; Burki Wildtier & Umwelt, 2009). This means that the CF is a flexible value which varies during the year. In literature values between 0.8 and 1.6 are found for salmonids (Bernet, 2000; Mendez, 2007; Michel, 2013). According to Burki Wildtier & Umwelt (2009) a CF value around 1.0 is an indicator value of a good condition for the trout region. Based on this statement it was concluded that most fish in the River Töss were in good condition. From all fish some outliers with a very low (0.59) or very high (5.4) CF were found, but it is suspected that these values are based on measurement inaccuracy or typing errors during the field study. Interestingly none of these fish ascended, so maybe there is a relationship to their unusual CF or it was just coincidence that these brown trout did not ascended. Four of the marked brown trout had some anomalies like loss of scale or a cloudy eye and three of the handled brown trout died after marking. These seven fish had no specifically low CF (0.97 - 1.88).

4.1.3 PIT-tagging

Practical scientific studies about the efficiency of fish passes are rare, and if conducted, mostly the effectiveness is examined. In the following, the results gained at the Steffstep prototype are compared with two papers, which reviewed some studies about the efficiency of different fish pass types. It has to be considered that these studies took place at different vertical-slot fish passes with different conditions (flow velocity, slope, height difference), with partly other species and different study designs, which is why they can not be directly compared to Steffstep However, the comparison allows a rough evaluation of the gained data. Additionally, a control site with similar environmental conditions and where no barriers exist would have been favorable for a comparison, but such river sections are rare in Switzerland and the effort for further examinations would have exceeded the scope of this study.

Attraction efficiency

The attraction efficiency for the brown trout was 28.4 %. As hypothesis 1.1 stated that the attraction efficiency was over 58 %, this hypothesis is hereby clearly rejected. This means that brown trout do not find and enter the fish pass sufficiently. The target value was taken from a review study with salmonids at 8 vertical-slot fish passes. There, the attraction efficiency varied between 12 % - 86 % (mean 54 %, median 58 %) (Bunt et al., 2012). Interestingly at the prototype the attraction efficiency for the small fish (75 mm - 211 mm) was with 29.9 % slightly higher than for the bigger ones (211 mm - 487 mm) with 26.9 %.

The attraction efficiency for the minnows was with 11.8 % also lower than hypothesized. The hypothesis 2.1 that 29 % of them will find and enter the fish pass is therefore also rejected. The target value was a rough estimation, because no comparable data was found in literature. However, in this case the sample size of the minnows was very small (n = 17), with a larger sample size the attraction efficiency of minnows might increase.

It is not surprising that the highest attraction efficiency was found for the fishes which were caught upstream and released directly in the pool or 100 m downstream (classification u1, u2_u1 and u2). These animals were already near the fish pass without additional obstacles and had the urge to go back to their original habitat because of their homing behavior. For this reason it can be expected that they have the highest probability for migrating upstream. Some studies showed the directed movement of brown trout after translocation. For example Camenzind (2008) figured out that 27 % of translocated brown trout came back to their original position (range of 20 m around their catchment area). This value is very similar to the attraction efficiency of 29.9 % found at the Steffstep prototype. Also Armstrong & Herbert (1997) showed that brown trout which were displaced returned to the area from which they were captured. The homing rate they found was as high as 86 %, whereby they only tested a small sample size (n =14). For the other classifications of fish, which were caught and released around 300 m downstream (classification d3 and d4) only a small attraction efficiency could be evidenced. This could be on the one side because their urge is smaller to move, because they were brought back to their habitat. On the other side they may have not reached the prototype because of additional obstacles or due to the low discharge, because of which growing gravel islands and very low water levels could have prevented their migration. Crook & Hinch (2013) mentioned that maybe not all individuals downstream of an obstacle had the motivation or need to migrate upstream as they would not be reproductively active or would use spawning habitats downstream of the obstacle. That some brown trout indeed used spawning habitats downstream of the obstacle was confirmed through the observation of five occupied spawning redds within the 300 m downstream of the fish pass. Otherwise brown trout are known to also migrate outside of the spawning season (Ovidio & Philippart, 2002), so spawning is not the only reason for migration. However, the motivation of fish captured and released downstream of a fish pass is always difficult to determine. Cooke & Hinch (2013) named the lack of information about the migration motivation of the fish as one of the greatest drivers of variation in efficiency as well as one of the greatest challenge for biologists.

Conclusion
The attraction efficiency of the Steffstep prototype was low (28.4 % for brown trout and 11.8 % for minnows). The facility has therefore to be optimized, some suggestions concerning optimization are described in subchapter 4.1.6.
The attraction efficiency was almost the same for the small (< 211 mm) and the big brown trout (> 211 mm): 28.4 % ± 1.9 %.
The fish with the classification d showed the lowest attraction efficiency (4,4 %, 6.3 %).

Hypothesis 1.1 was rejected: the attraction efficiency of the brown trout was smaller than 58 %
→ brown trout are not able to find and enter the Steffstep prototype sufficiently.
Hypothesis 2.1 was rejected: the attraction efficiency of the minnows was smaller than 29 %
→ minnows are not able to find and enter the Steffstep prototype sufficiently

Passage efficiency

At the prototype the mean passage efficiency of the brown trout was 64.6 %, which means that the hypothesis 2.1 is confirmed: the passage efficiency was higher than 53 % and therefore the brown trout is able to pass the facility. This target value was determined based on a review study about the passage efficiency of salmonids at vertical-slot fish passes (Noonan et al., 2012). However, Bunt et al. (2012), who also summarized the passage efficiency of salmonids at 8 vertical-slot fish passes, figured out that the median for the passage efficiency was 87 %. The difference could be a result of the different species or different technical parameters of the determined fish passes (e.g. slope, flow velocity). Considering the size of the ascended fish at the prototype, it is apparent, that the bigger brown trout had a higher passage efficiency (79.5 %) than the smaller ones (47.4 %). This matches with the results of Noonan et al. (2012). They also described that the upstream passage efficiency of salmonids increases with the total length of the fish.

At the Steffstep prototype the attraction efficiency of the smaller fish was almost the same as for the bigger ones, however, the bigger fish had a higher passage efficiency (Figure 27). This indicates that not the attraction efficiency divided between these groups but some parameters within the fish pass were relevant for the separation. The high flow velocity at some slots have very likely been insurmountable for smaller fish. Additionally, the brown trout had a low attraction efficiency but a relatively high passage efficiency at the prototype. This matches with some results from Bunt et al. (2012). They pointed out that for the examined fish passes the mean attraction efficiency was inversely related to the mean passage efficiency. Based on this statement one can conclude that the efficiencies are depending on the flow velocity: a high flow velocity results in a high attraction flow and therefore in a high attraction efficiency. At the same time the passage efficiency decreases because the faster flowing water is exhausting to pass for the fish.
Overall, the attraction efficiency for all fish at the Steffstep prototype was low which shows the need for some improvements of the facility. Additionally, the passage efficiency of the smaller fish has to be increased. To increase attraction efficiency, Bunt et al. (2012) recommended, among other things, supplemental attraction flows. This could be a way to increase the attraction efficiency of the Steffstep prototype without affecting the passage efficiency negatively. Also Noonan et al. (2012) described that higher water velocities attract more fish to the entrance of a fish pass. This is especially important at this study site where it has been very difficult for the fish to find the entrance, because competing water from the obstacle was dominating the attraction flow. This problem will be discussed in more detail in the subchapter 4.1.6.

As expected, not a single minnow passed facility, so hypothesis 2.2 that they are not able to pass the fish pass can also be confirmed. However, this result is statistically deficient because of the very small sample size of four individuals. The hypothesis was based on experiences at other field studies, where minnows seldomly passed fish pass facilities (Baumann, 2011; Weibel & Peter, 2012; personal communication Armin Peter, 04.01.16). Weibel & Peter (2012) who marked over 1000 minnows in a field experiment with block ramps suspected that one reason for this behavior could be, that minnows might generally not migrate outside of their spawning season - in contrast to brown trout. This is a probably a reason for this study, as it took place after the spawning season of the minnows. Other reasons why minnows did not use the fish pass for migration may include: too many predators (brown trout) in the pool and the fish pass, too high flow velocity within the fish pass, unsuitable arrangement of the fish pass (too many edges, unfavorable entry) or the way upstream was too big for them. However, Noonan et al. (2012) found that neither the flow velocity nor the length of the fish pass were crucial for the upstream passage efficiency. According to their results a higher slope of the fish pass was one of the important factors that decreased the passage efficiency significantly. In contrast to many conventional fish passes Steffstep has no continuous slope, but steps between the different pool elements. It is not known yet how this influences the passage efficiency.

Conclusion
The passage efficiency of the Steffstep prototype for the brown trout was suitable (64.6 %).
The bigger fish (> 211 mm) had a higher passage efficiency (79.5 %) compared to the smaller ones (< 211 mm) with 47.4 %, although they had almost the same attraction efficiency. Therefore, some optimizations of the facility in favor of the small fish are recommended.
No minnow passed the fish pass.

Hypothesis 2.1 was confirmed: passage efficiency of the brown trout was higher than 53 %
→ brown trout are able to pass the Steffstep prototype.
Hypothesis 2.2 was confirmed: passage efficiency of the minnows was 0 %
→ minnows are not able to pass the Steffstep prototype.

Total efficiency of the brown trout

According to Cooke & Hinch (2013) the attraction efficiency is as important for a fish pass as the passage efficiency. Therefore the total efficiency should be considered to decide which kind of fish pass is suitable for a specific scenario (Crook & Hinch, 2013). Based on the definition of the attraction efficiency used, before only considering the fish which were released in the pool, the total efficiency of the Steffstep prototype is 21.3 % for the brown trout. The bigger fish had a higher total efficiency than the smaller ones because of their higher passage efficiency. These values are clearly below the average of 44 % of the 29 examined vertical-slot fish passes which were examined by Bunt et al. (2012) and even much lower than the recommended 90 % - 100 % by Lucas & Baras (2001).

Comparison of Steffstep with block ramps

Block ramps are river sections with an increased slope and blocks of stones which fix the bottom of the river bed. They are built to reduce the channel erosion, similar to falls and swells, but allow migration of aquatic animals at the same time, if some hydraulic criteria are considered (Weibel et al., 2012). Nowadays they are often built with considerable costs to replace artificial falls (Weibel & Peter, 2013). As Steffstep is an alternative way to improve migration at artificial obstacles, its total efficiency is compared to the one of block ramps in the following.
The efficiency of a block ramp is depending on the type of block ramp and the fish species (Weibel et al., 2012). Weibel & Peter (2013) found that especially for brown trout the total efficiency is also depending on the fish size and the slope. If the slope is more than 6 % only brown trout which are bigger than 200 mm can pass it. At five block ramps examined in Switzerland the total efficiency for brown trout bigger than 200 mm was between 33 - 83 % (mean 51.8 %, median 44.4 %) and for brown trout smaller than
200 mm between 4.3 - 33.6 % (mean 19.6 %, median 25.0 %) (Weibel & Peter, 2013). Analogously, the total efficiency of the prototype was selective with respect the size of the brown trout. Brown trout from the pool which were bigger than 211 mm passed the construction with a mean total efficiency of 24.4 %, whereas the smaller ones only had a mean total efficiency of 18.2 %. Additionally, some small brown trout entered the fish pass on different days but did not ascend.
Overall, the total efficiencies for the brown trout are smaller at the Steffstep prototype than at the examined block ramps. The difference of the efficiency is especially high for the bigger fish. A likely reason is the high attraction efficiency of block ramps (approximately 100 %), which is a result of their construction over the whole cross section of the river. So an upstream migrating fish necessarily hits upon a block ramp, whereas the entrance of a fish pass has to be found.
Small fish like bullheads or minnows are not able to pass block ramps with a slope higher than 6 %, according to Weibel & Peter (2013). The authors therefore recommended to build ramps with a slope less

than 6 % to allow migration of all species and age-stages (Weibel et al., 2012). These results match with the findings of Schläppi (2011). For minnows he found a total efficiency of 7 % at a block ramp of 4.2 m lengths and a slope of 4.8 %. At the Steffstep prototype no minnows passed the facility, the possible reasons for which are discussed above.
For bullheads, Schläppi (2011) examined the total efficiency at four block ramps with a length between 3.5 - 22 m and a slope between 3 - 9 %. At two of the ramps no migration of the bullheads took place and at two of them only 4 - 6 % of the marked bullhead passed the ramps. For stone loach he found a total efficiency of 25 % at a block ramp with a length of 4.3 m and a slope of 4.6 %. The prototype of the Steffstep in Kollbrunn had no connection to the bottom of the river bed and hence no migration of bullheads or stone loach was possible. It is therefore recommended to test also Steffstep with such a connection.

Altogether, the total efficiency of block ramps is higher than the total efficiency of the Steffstep prototype for brown trout. Nonetheless, it has to be considered that a Steffstep and a block ramp do not fulfill the same function. The best ecological solution is to rehabilitate river sections and to give them more space. But most of the rivers have been straightened during the last centuries and nowadays it is often not possible to expand the river bed at the expense of human infrastructure (settlements, agriculture and similar). In order to improve the situation in terms of migration it is possible to build block ramps instead of the existing barriers. A block ramp also reduces erosion and additionally it is allowing migration of fish. Their implementation is expensive and needs a lot of time. In contrast, Steffstep aims to enable a fish migration over an existing barrier in a short time without removing the obstacle and for relatively low costs. In this way it is feasible to make as many barriers as possible passable for fish until the obstacles get removed or replaced by a block ramp. The challenges to build block ramps can be seen at the example in Kollbrunn: Installing a block ramp with a slope of 6 % instead of the existing barrier would result in a construction of nearly 64 m length. Such an installation would cause big structural changes to the river section at very high costs. It depends on the specific situation what kind of improvement will be done and in which time frame. Steffstep expands the current available solutions for a free fish migration.

Conclusion
The total efficiency of the Steffstep prototype for the brown trout was rather low (21.3 %), mainly because of the low attraction efficiency. Therefore, at the moment the total efficiencies for brown trout are higher at block ramps or other examined vertical-slot fish passes compared to Steffstep. However, these facilities do not fulfill exactly the same function as Steffstep.

Size categories of the brown trout
As it could be shown above the fish pass Steffstep is selective to the size of the fish. The smaller fish had always a lower passage efficiency than the bigger ones. Additionally, only one brown trout smaller than 16 cm reached the second antenna. It is likely that this brown trout of 86 mm length had been eaten by a bigger one and so its PIT-tag was in the stomach of a bigger fish, which then passed the facility. Five small fish entered the fish pass, two of them three times on different days. It looks like they tried to pass the facility. Because only two antennae were used, it is not known how far the small fish ascended. For further investigation it is recommended to use a third antenna placed in the lower third of the Steffstep prototype. Noonan et al. (2012) also showed that the upstream passage efficiency of salmonids increased with total fish length in their review paper. Additionally, Weibel & Peter (2012) pointed out that the total efficiency of block ramps increases with an increasing length of the fish. One reason for such a selectivity can be the microhoming behavior, which also increases with the length of a fish (Camenzind, 2008).

However, this is contrary to the fact, that the attraction efficiency for the small brown trout was slightly higher than the attraction efficiency for the bigger ones. Therefore, the low total efficiency has to have its basis within the fish pass: the flow velocity at certain slots may have been too high for small fish or the way through the fish pass was too big and they had not enough strength to pass all 14 pool elements. These assumptions are supported by the fact, that of the fish that ascended the smaller ones needed longer to pass the facility than the bigger ones (Figure 31).

Migration time of the brown trout

Overall, the brown trout migrated at all times of the day with a preference between 9 am and 8 pm (Figure 28). The data from the video recordings shows that the five ascending fish entered the fish pass just before dusk. The fish trap delivered no data about the migration time. Weibel & Peter (2013) found that the migration of brown trout to pass a block ramp normally started in the afternoon and ended in the morning, with a peak of migration before midnight. Laine (1990) tested the migration of hatchery-reared brown trout in a fish pass in Finland and found that they preferable migrated during nightfall. However, Noonan et al. (2012) found that in 16 of 17 studies the salmonids used the fish pass preferably during daytime. Altogether, brown trout do not seem to have strong preferences for the time of the day to migrate. A very likely explanation is that the migration time is mainly a result of the discharge - rather independent of the daytime (Figure 29).

Frequency of the fish migration and ascent speed of the brown trout

It is not yet fully established if fish are able to learn how to use a fish pass but it is assumed (Cooke & Hinch, 2013; Castro-Santos, 2015 b). Some data from this study supports this hypothesis: From the 54 ascended brown trout eleven used the fish pass more than once to pass the obstacle upstream. This shows that the fish had found the entrance, whereby no information exists if they had found the entrance faster than the first time. However, it could be shown, that between the first and the second antenna the fish were mostly faster at the second than at the first run to swim upstream (Figure 30). Additionally, the fish with the classification u2_u1, which already used the fish pass, have a very high attraction efficiency of 67 % and even a passage efficiency of 100 %. But it has to be recognized that the sample size is too low to draw meaningful conclusions (n = 3 and n =2).
The bigger fish which ascended the Steffstep prototype were slightly faster than the small ones (Figure 31). This was expected because in general, the distance which a fish travels per beat increases with an increased amplitude of the tail, which again increases with an increased length of the fish (Bainbridge, 1957). If the fish swim upstream directly, the bigger fish therefore have to be faster.

Downstream migration of the brown trout

The data of the downstream migration has to be interpreted with caution because there are different ways, how downstream migration could have happened. Above a discharge of 10 m^3/s the inlet channel and the last pool of the Steffstep prototype got flooded and the excess water fell directly from the top of the fish pass into the first pool (Figure 34). Therefore it is theoretically possible that fishes were washed away with the water and directly fell from the top in the first pool element or besides it. This could explain the short migration time of one brown trout, which only needed one minute downstream at a high discharge of around 22 m^3/s. Another explanation could be that the fish at a high discharge were swimming downstream directly over the obstacle but next to the fish pass and were registered by the second antenna, and then moved inside the fish pass below and got registered by the first antenna. There is evidence that the fish were swimming downstream across the obstacle, because some of them were registered more than once using the facility upstream but not downstream. This was only possible at an increased discharge, otherwise all water was fed into the fish pass and about 1.5 meter of the river on top of the obstacle were completely dry. Additionally, no downstream migration through the fish pass was possible during the use of the fish trap, because it shut off the inlet channel. Steffstep is mainly suitable for non-power station-related obstacles. At these obstacles it is less important that the fish to use a fish pass downstream than at the hydropower stations, where the fish have to be prevented swim downstream through the turbines. However, the data shows that the fish swim downstream over the obstacle as well as sporadically through the Steffstep prototype.

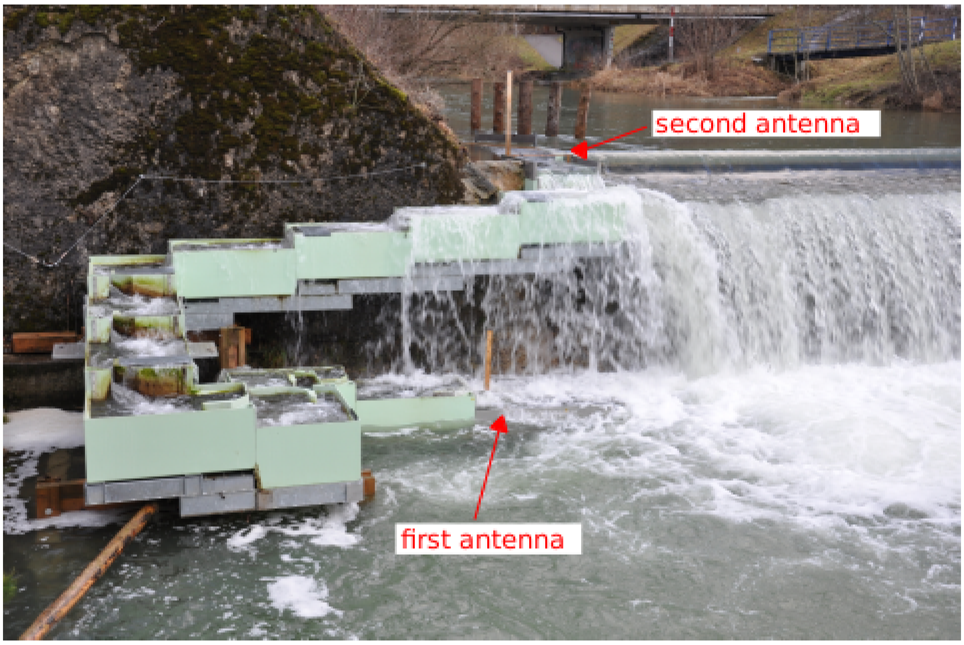


Figure 34: Steffstep with a discharge around 10 m³/s at 12.01.16

4.1.4 Fish trap

In general, it has to be considered that a fish trap can discourage some fish to enter the fish trap and therefore not all fishes which would pass the fish pass without the trap are counted (DWA, 2014). At the prototype the fish trap was not in use so much time and additionally the unfavorable water conditions led to less data than hoped for. Furthermore, the comparison of the trapped fish with the tagged ones was more difficult than expected: The wound caused by the PIT-tags was not visible any more and moving the fish trough the antenna made no sense because of the proximity of other tagged fish causing signals. For further investigation the use of a handheld reader for PIT-tags is recommended. The length of the caught fish differed from the associated tagged fish up to a maximum of 35 mm. This could be because the tagged fish were measured very accurately in a narcotized condition, while the trapped fish were measured directly in the water with a ruler and rounded to centimeters. A further issue is, that birds may have eaten some of the trapped fish and therefore the data results inconsistent. Fresh bird droppings could be found several times directly on the wooden board at the inlet channel.

4.1.5 Video recordings

The two recording times of the tagged and recorded fish are not exactly the same (deviations up to four minutes), because the camera did not record the time itself. It is calculated from the noted beginning of the recordings and the frame frequencies, whereas the time at the PIT-antenna was exactly recorded. All tagged and recorded fish had a big tag with a detection range of 1 m, which is why it is assumed that all fish which entered the fish pass with such a tag are immediately registered. Therefore it is very likely that actually three of the five fish were tagged.

The video recordings show that all five fish, which were recorded during their entrance to the fish pass, took many attempts before they finally entered the Steffstep prototype. First they swam through the attraction flow from several directions and some of them touched the fish pass with their snout. In addition, two different ways of entering the fish pass have been observed: First, the fish approached the attraction flow frontally at high speed. If the fish was close to the surface it struggled with the high flow velocity and the turbulences but finally entered the fish pass. Second, the fish came from the depth close to the entry but outside of the attraction flow and just at the end scurried from below into the fish pass. It looks like that the fish could feel the attraction flow but hesitate to enter the facility. The observed smaller fish were more hesitant to enter the fish pass than the big ones. These observations show, that the fish pass may cause a delay of the fish migration, which is not desired. With an optimized attraction flow the delay could be reduced.

4.1.6 Flow velocity and attraction flow

Normally fishes migrate within a river with a sustained speed which costs only little resources. DWA (2014) defines the mean sustaining speed to be about twice the length of the fish per second. If it is necessary the fishes can increase their speed which indeed is more exhausting and only possible for a certain time. This, so called prolonged speed, is defined by DWA as about five times the length of the fish per second. The maximum speed of a fish is also called its sprinting speed which is depending on the frequency of tail beating (DWA, 2014). The maximal possible frequency of tail beating decreases with increasing size of the fish. That means, that the smaller the fish, the faster is its relative sprinting speed (Bainbridge, 1957). The maximum performance is only possible for a few seconds and afterwards a regeneration time of several hours is necessary. In literature different values for the sprinting speed exist, but for salmonids and cyprinids it is about ten times the length of the fish per second at good environmental conditions (DWA, 2014). Another aspect that should be mentioned is that the distance which a fish can swim with constant effort decreases with increasing water velocity (Weibel & Peter, 2013). Additionally, environmental conditions, especially the temperature of the water, play an important role for the swimming capacities of the fishes (Ovidio & Philippart, 2002; Ovidio et al., 2007). For given environmental and physiological conditions, mainly the maximal flow velocity in a fish pass and its total length determines its passage efficiency (DWA, 2014).

In the prototype the highest measured flow velocity was 1 m/s and occurred at four locations in the fish pass. In consideration of the sprinting speed by DWA only fishes which are longer than 10 cm have theoretically the possibility to pass the facility as it would otherwise exceed the sprinting speed of the fish. This is consistent with the results of the tagged fish where basically no fish below a length of 16 cm was able to ascend. However, it has to be considered that the theoretical values are for optimal conditions (e.g. temperature of the water), but in the fish pass the flow velocity occurs irregularly, additional turbulences exist and that the measurements of the flow velocity are imprecise. Additionally, the fish has to pass 15 slots with increased flow velocity which is a huge effort for the animal. As it is shown in the PIT-tagging results (Figure 29) fish migrated preferably at increased discharge but the measurements were taken at “normal” water conditions. So the flow velocities most likely have been even higher than measured during the fish migrations. Additionally, the impeller is not easy to handle in a standardized way and the water flow in the fish pass is in reality not laminar. This may be possible reasons why also fish which have been bigger than 10 cm did not pass the facility. For further investigation it is recommended to do such measurements at different discharge to get discharge-dependent information about the maximum flow velocities within the fish pass.

The attraction flow is crucial to guide the fish into the fish pass. If the attraction flow is too high smaller fish are hindered to enter and if the attraction flow is too low the fish can not find the entrance. At the Steffstep prototype it was 0.8 - 0.9 m/s, whereas the competing flow velocity of the river was around 0.6 m/s. According to DWA (2014) a theoretical attraction flow of around 2.0 m/s is ideal for salmonids. But since this would hinder small fishes with low swimming capacities to enter the fish pass, there are other value recommendations for practical use: DWA suggests 1.0 m/s, the Russian norm "Stroitel'nye normy i pravila" (SNIP) suggests 0.8 m/s and in the USA 1.2 m/s are recommended (DWA, 2014). So the measured attraction flow of the prototype is at the lower end of the range of the recommended values. The fact that the attraction efficiency is still low seems to depend on the arrangement and therefore suggesting that the fish just did not find the entrance. The obstacle is about 25 m broad and at good migration conditions (increasing discharge) the whole obstacle gets flooded so that the attraction flow is not apparent any more (Figure 35). Even if the discharge is slightly increased, various water falls exist producing currents which compete with the attraction flow (Figure 36). In this situation it is therefore difficult for the fish to find the entrance of 16 cm width. Even at low water conditions competing water movements to the attraction flow exist (Figure 37). Additionally, downstream of the obstacle on both river sides an artificial widening of the riverbed serves as protection against floods. The water is nearly not flowing here and like a "blind spot" for the fish. The entrance could be too close to this area with the opposed flow irritating the fish.

Figure 35: Steffstep on 12.01.16 with a high discharge of 10 m³/s

Figure 36: Steffstep on 30.01.16 with a medium discharge of 4.2 m³/s

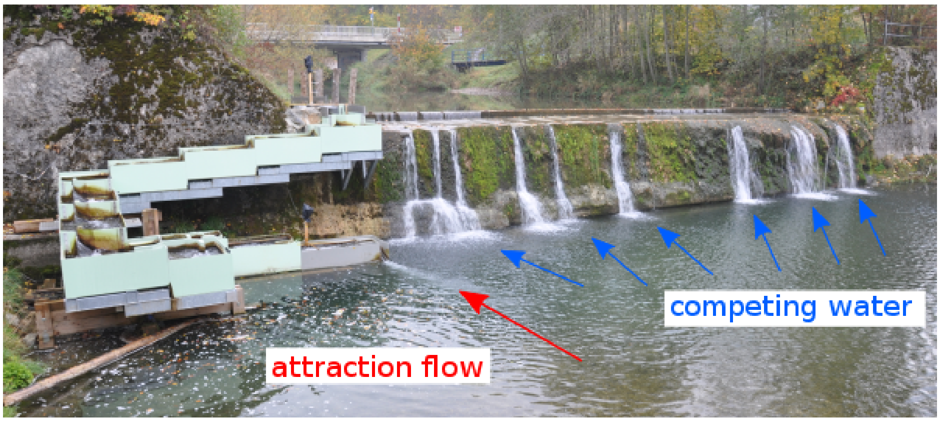


Figure 37: Steffstep on 20.10.15 with a low discharge of 0.2 m³/s

4.2 Methodological comparison

The major and most reliable data was gained from PIT-tagging. The energy for the PIT-measurements was first supplied by two car batteries. This resulted in a significant amount of work as well as few detection errors. A continuous power supply solved those issues. The marking of the fish and the installation as well as the tuning of the antennae was relatively quickly done. In contrast, the data from the fish trap and the camera was disappointing. The idea was to get some additional data to allow a statement about migration of the non-tagged fish. But the fish trap could only be used at clear water conditions without much debris and algae in the water. It has to be controlled at least once a day. Altogether, only ten fish could be caught during 37 days of use (Table 20). For the video recordings two simple cameras were used which only had a recording time of four hours. After the first few weeks one of the cameras broke down and the second had a reduced recording time. This caused a high personal effort to make and analyze the recordings. Some fish migrated during dusk or night, so it was not possible to record them. In the end on 51 hours of film material five fish could be observed during their entrance to the fish pass (Tables 21, 22). During the dry season numerous fishes from adjacent drying out tributaries, were released in the pool next to the fish pass. It was expected that this would result in movements downstream and upstream of some individuals to avoid the high competition. However, no evidence for this hypothesis was found. Overall, the six additional non-tagged fish in the fish trap and on the video recordings do not allow valid statements about the fish migration in the River Töss.

Recommendations for further ecological monitoring

This extensive field study showed, that for an ecological monitoring of a fish pass not all methods are equally suitable. To determine the efficiency of a fish pass the use of PIT-tags with a continuous power supply is highly recommended. The installation of the system and the marking of the fish needs a one-time effort. Further presence at the field site is normally only needed for occasional reparations after flood events. In contrast are the use of a video camera or a fish trap much more time consuming. Additionally, data evaluation is much easier and the individuals can be distinguished. However, it has to considered that in Switzerland a permission for PIT-tagging is necessary, the costs of the material is higher and this method only makes sense in long-term studies (minimum a few months). The material costs of all other measuring methods with a comparable information value are much higher (acoustic telemetry, radio telemetry, sonar) (Peter, 2013). To get additional data and an insight into the behavior of the fish, the use of a video camera with a permanent power connection is recommended. However, because the animals migrate preferably at high and increased discharge which normally results in a turbidity of the water it is only recommended as an additional method. The video recordings could be optimized with a motion detector or even an artificial lighting to record also at dusk and night but this would result in higher costs and potential disturbance of the animals.

4.3 Suggested technical improvements

The field study has shown, that a potential for an optimization of the fish pass Steffstep in different points exists. The attraction efficiency in general and the passage efficiency for small fish should be improved by adjustments at the Steffstep prototype. In the following the major suggestions concerning the attraction flow, flow velocity, design of the slots, cover and the substrate are presented.

First, the attraction flow could be reinforced by an additional pipe to increase the probability that the fish find the entrance. At this site in Kollbrunn, with such an installation the attraction flow could be directed more towards the depth of the pool, were most fish may be present. For a further installation of Steffstep, the entrance should be closer to the obstacle, allowing the fish to better find the entrance. At Kollbrunn it was not possible because of the defined length of the pool elements and the height difference between the obstacle and water surface. If this would be considered at the beginning of a new project the lengths of the pools could be adapted directly to fit the site.

Second, the results show that small fish did not pass construction. Therefore, the flow velocity within the fish pass should be adapted. This could be reached either with an optimization of the slot design: e.g. replace the round “nose” of the slots which accelerate the water with orthogonal edges or with a different arrangement of the slots after a turnaround of the fish pass (Figure 38). With the current design the water gets accelerated in the corner elements and therefore impedes the migration of fish with a small swimming capacity (Figure 38). Sometimes in this context the furnishing of resting areas with the possibility to hide and to regain strength is discussed, but in general a fish pass should enable a rapid crossing for the fish to let them continue their migration without delay (Thorncraft & Harris, 2000; Larinier & Marmulla, 2003). White et al. (2011) summarized some literature about resting pools and came to the conclusion that there is no justification for including such areas. Such pools could interrupt the ascent of the fish and observations showed, that the fish even avoid such areas (White et al., 2011). Additionally, it could be occupied by predators which then decrease the amount of migrating fish.

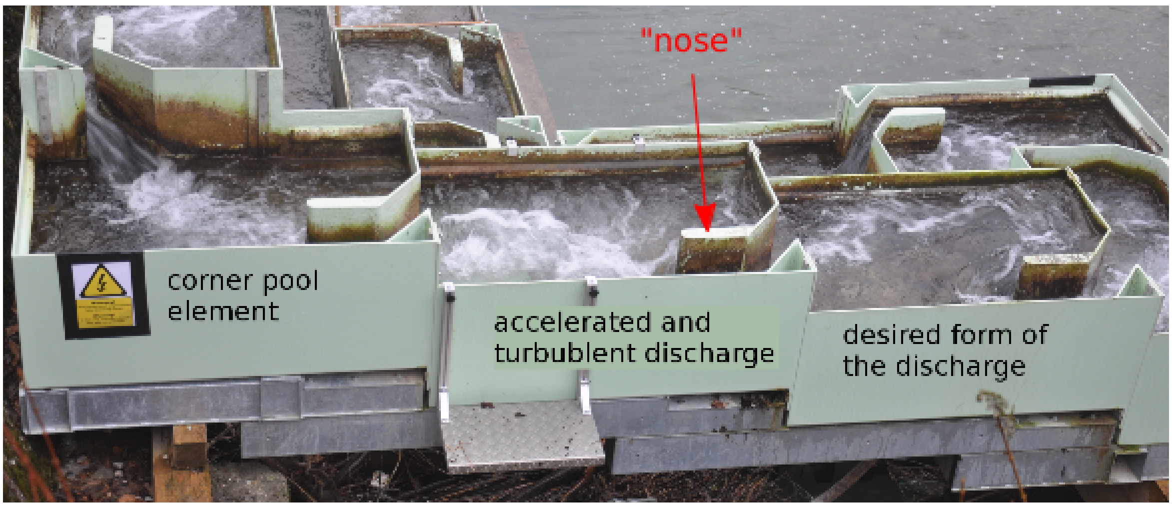


Figure 38: Different forms of the discharge within the Stefstep (picture from 05.12.15)

Third, if a fish trap is used, covering the inlet channel would reduce stress of the fish which are trapped until they get released. Such a cover could also prevent the predation by birds.

Fourth, substrate of the Töss was used to fill the fish pass, but the small stones were washed into the corners and out of the facility. So in future, the artificial stones should be curved against the flow direction so that the substrate gets caught there and bigger stones should be used to cover the bottom surface of the fish pass.
Fifth, a connection of the fish pass to the riverbed is desirable. Although no data about the efficiency of such a connection exists, it is recommended by experts (DWA, 2014). In Kollbrunn this could enable a migration of bull head and maybe even of stone loach, which live on the ground. This was not realized so far because of the technical challenge of the deep pool and the low discharge. The problem of a second entrance is the required amount of water and a possible competition between the two attraction flows. A second entrance, which is only functional at an increased discharge, could be a solution for this problem.
Further investigation in the field and the laboratory will be needed to test these suggestions.

5 Potential application of Steffstep

This master thesis was made possible through the financial support of the FOEN. In return the FOEN obliged me to investigate the potential application of Steffstep in Switzerland. Therefore in the following, first the ideal conditions for using a Steffstep and its benchmarks are described. After that three approaches for further detailed analyses are proposed and then a theoretical application of Steffstep at the River Töss is discussed to roughly estimate the potential on an exemplary basis. Finally a short description of the situation in Europe rounds off the chapter.

For the big picture it is important to know that in Switzerland 4'000 river kilometers should be rehabilitated until 2090, in addition to the restoration of the fish migration at 1'000 obstacles caused by hydropower stations until 2030 (Bammater et al., 2015). These ambitious aims are a huge challenge for the following generations. It will need a lot of time and money to realize them. For the endangered fish species additional rapid solutions are necessary. According to Gouskov et al. (2015) fish passes mitigate the negative effects of artificial barriers on fish population connectivity, especially to small populations, but the effects are not annihilated by them (Gouskov et al., 2015). However, Mills & Allendorf (1996) described that between 1 and 10 migrants per generation into a subpopulation would be sufficient to allow divergence in allele frequencies and therefore minimize the loss of genetic diversity. As will be shown below the fish pass Steffstep can help at certain sites to reach a connectivity of the now fragmented fish populations. As soon as a few migrating individuals enable a gene flow the actual presented biodiversity of fish can be preserved or even increased. So overall, Steffstep can speed up the preservation of the biodiversity of the fish fauna and thus deliver a part of the solution on the way to fully rehabilitated rivers. This master thesis is just one step on this way.

5.1 Ideal conditions for using Steffstep

As it is described in chapter 1.4.2, the fish pass Steffstep has a lot of unknown parameters. During the field study the parameters which were estimated by the WRH AG at the beginning of the project were tried to be verified. Because of the unfavorable environmental conditions, with a minimum of discharge over a long time, the significance of this study for the application of the fish pass is smaller than expected. However, the data is a good basis for further investigation.

Suitable river parameters

The WRH AG estimated that Steffstep is suitable for rivers up to an annual average discharge of 10 m³/s (Table 16). In the River Töss the mean annual discharge is 3.31 m³/s (average 1988 - 2014) (AWEL, 2014 a). For the application of such a fish pass in the profile of a river the flood conditions are more crucial than the mean discharge. It has to be prevented that the construction is carried away during a flood and increases the danger of flooding at another site (e.g. at bridge piers). To avoid such situations a close collaboration with the local hydraulic engineering of the cantons is mandatory. During the field study unfortunately no flood occurred. The highest discharge was 32 m³/s but this was just a fraction of the potential high water conditions of the River Töss. According to AWEL (2010 b) a high water which could occur all 30 years (HQ30) is determined at this site to be 205 m³/s. A HQ50 could be 240 m³/s and a HQ100 even 390 m³/s (AWEL, 2010 b). Whereby it has to be discussed which level of high water Steffstep should resist and which other solutions are possible to reduce the threat of log jams. For example predetermined breaking points are possible to integrate into the facility. At the River Töss five tree trunks protected the Steffstep prototype against driftwood and the majority of the construction was protected against floods behind a retaining wall (Figure 11). Because not more data about the behavior

during high water conditions was available during the time of this study further investigation is strongly recommended.
The minimum amount of water which a Steffstep with the standard size of 150 cm x 100 cm x 80 cm need to be theoretical functional is 120 l/s. If the discharge is lower, the fish may not able to pass the facility.
Because the fish pass has some edges and the substrate can not slide through the facility, small rates of the bed-load are favorable. Otherwise the substrate causes a high maintenance workload. In the Töss naturally small rates of the bed-load of around 30 $m^3/(km^2*y)$ occur. Through anthropogenic extraction of the bed-load actually, the rate is only 19 $m^3/(km^2*y)$ (AWEL, 2010 a).

Table 16: Suitable river parameters

	values estimated by WRH AG	measured values at the River Töss
size of the river	small to middle-sized rivers up to 10 m^3/s annual average discharge	annual average discharge 3.31 m^3/s
flood conditions	the flood protection have to be adapted to the given river	the maximal high water conditions with 32 m^3/s caused no damage (but this was just 16 % of HQ30)
minimum amount of water in Steffstep	-	120 l/s
bed-load	-	19 $m^3/(km^2*y)$

Suitable fish fauna

In general, Steffstep is suitable for all fish species with a swimming capacity that allows crossing the steps between the pool elements and therefore the size of the pools can be adapted to the local fish fauna. The attraction and the passage efficiency of a fish pass is depending on the fish species but the aim should be that all species and age stages are able to pass the facility. Until now, only connectivity data of the Steffstep for the brown trout and the minnow exists. In this master these the target values for the efficiencies were derived from field experiences so far and therefore it was assumed, that the brown trout will be able to pass the Steffstep prototype but the minnows will not be able to do so.
The aim value for the attraction efficiency for the brown trout as well as for the minnows could not be reached (Table 17). However, the estimated passage efficiency for the brown trout could be exceeded, especially for the brown trout bigger than 211 mm (median of all tagged fish).
The results show, that overall the attraction efficiency as well as the passage efficiency for the small fish have to be optimized. Some improvements of the hydrological conditions and the arrangement are listened in subchapter 4.3, therefore future versions of Steffstep might even enable migration of minnows. It is also recommended to test another Steffstep with further fish species to optimize it.

Table 17: Suitable fish fauna

	values estimated by WRH AG	measured values at the River Töss
brown trout [%]	attraction efficiency: > 58 passage efficiency: > 53	attraction efficiency: 28.4 passage efficiency: 64.6
minnow [%]	attraction efficiency: > 29 passage efficiency: 0	attraction efficiency: 11.4 passage efficiency: 0
other fish species [%]	-	not examined

Suitable obstacle parameters

Steffstep can be implemented at virtually any obstacle. Through the self-sustaining structure the fish pass is independent of the constitution and material of the obstacle and its surroundings. For the installation of the pool elements a crane is necessary, so the costs are reduced by a good accessibility. The main idea of Steffstep is to bridge the gap until a rehabilitation takes place. Therefore the potential application is particularly high at special sites, where the following two criteria are fulfilled: the obstacle will not be rebuilt within the next 10 years and it fragmented fish habitats. The following exemplary obstacles, which additionally fulfill these criteria, have a high potential:

- obstacles near to estuaries into a lake with lake trout populations,
- obstacles which prevent the migration of endangered species to their spawning grounds,
- obstacles which are under monumental protection,
- obstacles at infrastructure objects, like bridges, which are complex to remove,
- obstacles with protections walls like at the site in Kollbrunn,
- obstacles in urban areas, where Steffstep has lower costs, needs less space and cost-benefit ratio is favorable compared to classic solutions,
- weirs at small hydropower plants with "ehehaftem Recht" (= remaining rights from an old legal system which allow hydropower utilization without present constraints)

5.2 Benchmarks of Steffstep

Costs, maintenance and lifetime

The purchase price of a new Steffstep is depending on the size of the pool elements (which is depending on the fish fauna), the height difference of the obstacle and the site conditions. The costs are composed by the material costs of the pool elements and the inlet channel as well as the ancillary costs which are depending on the accessibility, depth of the pool behind the obstacle, constitution of the surrounding walls and similar. Existing prototypes have shown that the ancillary costs are about 1.5 times the material costs as a rule of thumb. At the prototype in Kollbrunn a lot of things were hand-made and part of the adaptive development, so the costs of this prototype are higher than the prospective Steffstep (Table 18).

Similar to other fish passes Steffstep has to be maintained. The effort for the maintenance is depending on the bed-load, debris in the river and amount of waste by humans. The more people spend their leisure time at the river the more waste can be found in the water. It is recommended to control the fish pass once per month at minimum, preferably more frequently. Surely the fish pass has to be checked after each flood event (removing of twigs, leafs, waste and ensure a uniform distribution of the bed-load) to ensure a free fish migration. At the Töss it could be seen, that on some days almost all entering brown trout also ascended, whereas on another day nearly nine of them were registered at the top of the Steffstep prototype (Table 11). It is possible that in such a case one of the slots was blocked by a peace of driftwood or similar. After high water conditions 4 man-hours were necessary to clean the fish pass..

According to WRH AG, the lifetime of the material is at minimum 50 -100 years. This could not be verified in the short field study of 8 months. After one month the whole fish pass was covered with algae, however, this did not influence the efficiency. For detailed data about the behavior of the material with the water and the solar radiation a Steffstep has to be used for several years.

Table 18: Benchmarks of Steffstep construction

	values estimated by WRH AG	measured values at the River Töss
costs [CHF]	4'300 / pool* (which corresponds to 21'500 / meter elevation gain) + 5'500 inlet channel + 20'000 - 100'000 ancillary costs	5'500 / pool + 5'500 inlet channel + 114'400 ancillary costs → in total 197'000 for 3 m elevation gain
maintenance	depending on bed-load and debris; controls after each flood event necessary	Steffstep was at least weekly controlled and after flood conditions 4 man-hours were needed to clean it
lifetime of the material	~ 50 - 100 years	prototype stands 8 months without damages

* with the masses 150 cm x 100 cm x 80 cm, including substructure and man-made stones

Advantages and disadvantages

The advantages of Steffstep are its relatively low costs, the quick installation time and the flexible construction. Additionally, the material can be reused at further sites, when an obstacle finally gets rehabilitated. Therefore it is possible to enable a fish migration at obstacles which will not be considered with other solutions in a foreseeable time.

The disadvantages are its maintenance workload and the unknown behavior during flood events. At the prototype in Kollbrunn the attraction efficiency for brown trout and minnows is too low and has to be optimized. Additionally, the passage efficiency for small fishes (< 211 mm) has to be increased. For other fish species at the moment no information exists.

Recommended approach for detailed analysis

Because the data which was gained during this study are not encompassing but rather a basis for further investigation, in the following three approaches for a detailed analysis are described.

To take into account the problematic status of the Swiss rivers (compare chapter 1.3.1), the new law (BGF) obliged all cantons to outline their rehabilitation plans. The first planning stage for the rivers had to be finished at year-end 2014 and includes a time horizon of 20 years. Every 12 years the cantons have to revise their planning for the next 20 years (VBGF, Art. 41d). With the assistance of this planning it is now possible to see which river sections will get rehabilitated in the following years and which will not.

Based on this information, three approaches exist to estimate the potential application of Steffstep:

1. River sections within the rehabilitation planning
   Through the preparatory work of the cantons a solid database exists. Within the rehabilitation planning the ecological potential and the cost-benefit ratio were determined and aligned with interdisciplinary expert opinions. The obstacles that will not be removed or otherwise rendered passable for fish in the next ten years are a potential site for Steffstep.
2. River sections beyond the rehabilitation planning
   All river sections which are not in the rehabilitation planning will surely not be improved within the next 20 years. These are potential Steffstep sites as well.
3. Independently of the rehabilitation planning
   All obstacles which are very expensive to removed but where a Steffstep has the best cost-benefit ratio to allow a free fish migration.

Regardless of whether the first or the second approach is taken the potential obstacles have to be prioritized. Therefore different guidelines from the FOEN, individual cantons or neighboring countries exist which are nicely summarized in the master thesis of Fahrni (2011). Which guideline to follow is depending on the available data. Fahrni (2011) recommended the following steps for a useful prioritization: First, collection of the deficits (physiological, biological and chemical), second, detection of potential of the recreation (hotspots and connectivity) and third, test of the feasibility (costs, high water protection, adjustments of the infrastructure). The third approach is the pragmatic way just to build a Steffstep at each site where it is surrendering. Therefore Steffstep should be a part of a portfolio of possible solutions.

For a quantitative evaluation of the potential application of Steffstep further studies are necessary.

- GIS-analysis with the data of the rehabilitation planning of the cantons with the framework conditions from chapter 5.1
- further efficiency monitoring with different fish species at several sites
- construction at a suitable site or in a laboratory to test the reaction at different flood conditions (HQ30, HQ50, HQ100)

For the systematic implementation a prioritization of the potential obstacles should be done to decide where Steffstep has the biggest impact. Therefore the focus should lay on sites with a high ecological potential for a better connectivity, e.g. spawning grounds, streams with less obstacles and similar. With the help of such further investigation the potential of the application of Steffstep could quantitatively be defined with a number of potential obstacles.

5.3 Theoretical application in the canton of Zurich

In the canton of Zurich the river system amounts a total of 3564 km. Of that 1606 km (45 %) are structurally strongly affected, artificial or piped (compare chapter 1.3.1). To comply with the VBGF the cantons have to rehabilitate one quarter of these problematic river sections (in the canton of Zurich around 400 km) in the next 80 years. Until 2035, they have to rehabilitate at least the first 100 km. In addition to the already defined 100 km of prioritized rehabilitated river sections, the canton prioritized 85 important obstacles which should be passable for fishes within the next 20 years. These obstacles are defined by the fishery authorities (AWEL, 2015 c). The list of obstacles is not yet exhaustive and further investigation will examine exactly which obstacles get rebuilt. This study is expect to be finished within one to two years, according to Stephan Suter, AWEL, head of section hydraulic engineer planning (personal communication, 06.11.15). The 85 obstacles are just a tiny fraction of the existing barriers: altogether there are more than 30'000 man-made falls and nearly 12'500 structures in the canton of Zurich (personal communication, Simone Knecht, AWEL, head of spatial planning, 11.12.13). How many obstacles are getting removed during the rehabilitation is not officially known.

As a full assessment of the potential of Steffstep fish passes would by far exceed the scope of this study, it was decided to roughly estimate the potential on an exemplary basis in the River Töss, as a typical river in the canton of Zurich. For this purpose the obstacles were examined that are on the prioritization list of the canton for the next 20 years. The three obstacles are downstream of the investigated prototype in Kollbrunn (Figure 39).

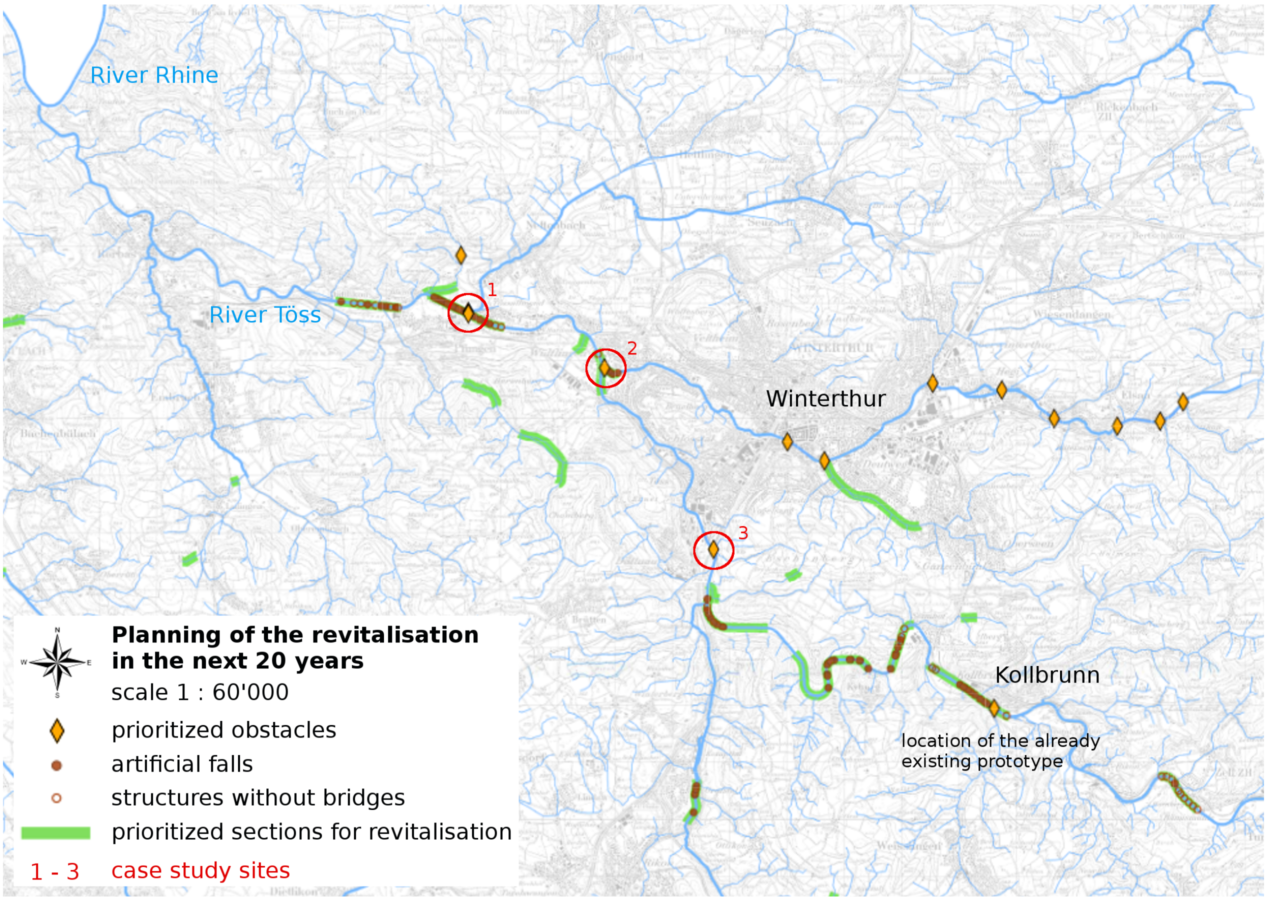


Figure 39: Extract of the rehabilitation map of the canton of Zurich (AWEL, 2015 c, modified)

Case 1: Riverbed ramp around 50 cm (E 8° 39.141 N 47° 31.139)*


Figure 40: Obstacle 1 in the River Töss

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* ARE, accessed on 02.12.15 *http://maps.zh.ch/*

This ramp in the River Töss is an old fall about 50 cm high with a riverbed ramp in the middle. In this river section numerous other artificial falls exist, which prevent a free fish migration. A Steffstep with a few pool elements could be built, but because there are so many falls in a row, it most likely would have the best cost-benefit ratio to remove them all together instead a Steffstep at each barrier. A Steffstep for an obstacle of 50 cm high at this site would cost approximately CHF 35'000 (including installation). In addition it has to be recognized, that all the fish passes will have to be maintained. In 2025 a rehabilitation of this river section will take place (AWEL, 2015 c).

Case 2: Artificial fall around 40 cm (E 8° 41.027 N 47° 30.599)*

Figure 41: Obstacle 2 in the River Eulach, tributary of the River Töss

This fall is the first barrier in the River Eulach, a tributary of the River Töss. It is only 40 cm high and could theoretically easily be bridged by a Steffstep, again with costs of around CHF 35'000. However, this is not useful, because no habitat would be accessible thereby. The River Eulach has been rigorously straightened and therefore no patchiness of different structures (dead wood, pools, riffles), which is necessary to provide a habitat for aquatic animals, exists. A high structural diversity is especially necessary for potential spawning grounds (Tunesi, 1996). To get a healthy river a rehabilitation has to be done, which includes the removal of this obstacle. According to AWEL (2015 c) such a rehabilitation will be done in 2025.

Case 3: Riverbed ramp around 170 cm (E 8° 42.517 N 47° 28.868)*

Figure 42: Obstacle 3 in the River Töss

The third obstacle is a river ramp of around 170 cm height. On the right side (in flow direction) an old pool fish pass with falls around 30 cm between the individual pools exists. It is very doubtful whether the pool fish pass or the ramp are passable for fish, most likely only for taller brown trout. This is a perfect site to build a Steffstep, because the ramp prevents a potential fish migration and the already existing pool fish pass could be used as a substructure for a Steffstep. Next to the obstacle a parking site exist, so the installation would not prove to be too complicated. In this river section the same four species as at the prototype near Kollbrunn are present (Eawag & BUWAL, 1995). According to their fish size this obstacle could be bridged with a Steffstep of eight pool elements with the dimension 150 cm x 100 cm x 80 cm. This would result in costs at around 85'000 CHF, of which approximately CHF 35'000 would be the costs of the material and approximately CHF 50'000 of the adjustments at the site.

This river section is not in the rehabilitation planning of the canton of Zurich, but the obstacle is one of the 85 prioritized ones (AWEL, 2015 c) and will therefore be further investigated in the upcoming study of the canton of Zurich.

These three obstacles, which were chosen on the basis of the rehabilitation map of the canton, shows clearly that Steffstep is not advantageous for all existing obstacles, although it would be technically feasible. The overall situation has always to be considered, e.g. if suitable habitats would be connected. However, Steffstep is one of many other solutions to reconnect fragmented rivers. If any kind of obstacle should be made passable for fish it is a serious alternative to classic solutions. Thanks to Steffsteps advantages obstacle which are not feasibly and in a foreseeable time bridged through other solutions, can nevertheless made passable for fish with a Steffstep. Overall, it is assumed at least each hundredth obstacle in Switzerland fulfill the criteria for a potential application of Steffstep: small to middle-sized river, suitable fish habitats are fragmented through an obstacle, which will not getting removed within the next ten years. This would result in a few thousands potential sites for Steffstep.

5.4 Situation in Europe

A look beyond Switzerland's borders reveals that also many other countries are facing huge problems with disconnected rivers and prevented fish migration. Today only one of the twenty largest European rivers, the Northern Dvina (Russia), is freely flowing. Mostly it looks like the following impressive example from France: One of the least regulated French river networks is the Garonne with 920 man-made barriers, 803 man-made waterfalls and 90 dams (Hildrew & Statzner, 2009) over its length of 647 km (Wikipedia, 2015). Like in Switzerland the politicians of the European Union recognized the problem of fragmented rivers and enacted the EU Water Framework Directive to improve the situation (WFD, 2000). This law obliges the member states to prevent a deterioration and to protect and improve the condition of the aquatic ecosystems (WFD, Art. 1). This requires a good coordination between the economical and ecological interests (ENVI, 2012). Theoretically all member states should have achieved a “good ecological potential” of the artificial and heavily modified rivers until 2015 (WFD, Art. 4, Par. 1a, i & ii). This “good ecological potential” includes connected rivers, which allows unrestricted migration of aquatic organisms and sediment transport (WFD, Appendix V). To reach this potential the member states have to develop a river basin management plans all six years (WFD, Appendix VII), comparable with the rehabilitation planning of the cantons in Switzerland. In 2012, the Committee on the Environment, Public Health and Food Safety of the European Commission (ENVI) elaborated a report about the status of the implementation of the WFD. This report showed that the aim of a good condition of the rivers until 2015 was illusory. Especially regarding the existing hydropower stations stronger efforts are needed to reduce their negative impacts on the streams. Because of this initial condition the member states recieved a deadline extension until 2027. As it is mentioned above, Switzerland plans to improve the negative effects of the hydropower stations until 2030 and to rehabilitate its most affected rivers until 2090 (Bammater et al., 2015).

The statements above show that in whole Europe countless obstacles are present which prevent a free fish migration and that there are laws which demand to remove them within the next century. In principle, the potential to build Steffstep fish pass types is existent all over Europe. The framework conditions differ between the countries. Switzerland has a particularly large number of obstacles, because it has a lot of streams, large height differences and invested early on a great deal of money in river engineering. Therefore a lot of obstacles exist, which enable a reasonable application of Steffstep. Other countries, for example Germany, has more large rivers with high ecological potential to connect the streams at the hydropower stations and less small disconnected rivers, which are mainly suitable for Steffstep.

6 Conclusion and outlook

In this master thesis, a new kind of fish pass called Steffstep was examined with respect to its connectivity and potential application in Switzerland. The data was gained during a field study at a Steffstep prototype in the River Töss and discussed with comparable data from literature. The values measured and calculated in this study are first of all valid for the deployed prototype. Further Steffstep implementations will depend on the same design and hence will the passage efficiency be similar. The attraction efficiency, on the contrary, depends on the setting in the specific river as a whole, wherefore fish will react in a not fully predictable manner at each site and for each customized Steffstep construction.

6.1 Efficiency of the Steffstep prototype

- The Steffstep prototype located in Kollbrunn could not sufficiently attract brown trout (28.4 % attraction efficiency) and minnows (11.8 % attraction efficiency). In order to increase the attraction efficiency, the Steffstep needs to be optimized in a way that the entrance can easily be found by the fish, e.g. with an additional attraction flow or a different arrangement of the entrance.
- The mean passage efficiency of this Steffstep is sufficient for brown trout (64.6 %).
- A low passage efficiency was observed for small brown trout (< 211 mm), that means the fish pass is size-selective. In order to increase the passage efficiency for the small fishes, Steffstep needs to be optimized, e.g. through lowering flow velocity within the fish pass or changing the pool arrangement.
- The total efficiency for the brown trout is rather low compared to other vertical-slot fish passes or block ramps. However, it needs to be considered, that those facilities focus on other functionalities than Steffstep. The low total efficiency is mainly a result of the aforementioned low attraction efficiency.
- The minnow is not able to pass this Steffstep. In the field study, though, the sample size was very small and it is therefore strongly recommended to increase the sample size in further investigation. However, as shown in other field studies, minnows are widely known for not using conventional fish passes or block ramps. Therefore, the fish pass design needs to be optimized for minnows as well as for small brown trout.
- Fish migration was observed mainly during increased discharge. Therefore, flow conditions or positions of sandbanks during such conditions necessarily need to be considered for the arrangement of a fish pass. During the field study, a very low discharge influenced the fish migration. Especially fish released further downstream were observed to migrate less.
- Fishes are probably able to learn using a fish pass. This is indicated by the fact that some fish used the fish pass more than once.
- Some brown trout used the fish pass also downstream. This is especially important for obstacles related to hydropower stations, in order to prevent fishes swimming downstream through turbines. However, the main application of Steffstep is at non-power station-related obstacles.
- In order to improve data collection in further investigation, PIT-tagging in combination with a video camera instead of a fish trap is recommended for monitoring.

6.2 Potential application of Steffstep

The potential application of Steffstep in Switzerland can not conclusively be answered. However, this extensive field study on the Steffstep prototype has revealed, besides it efficiency in general, some weakness of the present implementation. In order to reach a broader application field, these weaknesses, namely attraction efficiency and flow velocity in the slots, need to be addressed with an optimized version, potentially implementing the proposals suggested in this study.

In general, Steffstep has a high potential application in small to middle-sized rivers, where suitable fish habitats are fragmented through an obstacle that will not to be removed within the next ten years. Sites which met those criteria were estimated to add up to a few thousands within Switzerland. Further investigation, with respect to the existing rehabilitation plans of the cantons, is recommended. Especially the response of other fish species to Steffstep (also regarding a connection of the fish pass to the bottom) and the application of the fish pass at high water conditions should be examined. Therefore a close collaboration of the FOEN, the cantons, the WRH AG and ideally scientific institutes (like Eawag, VAW) is advisable.

6.3 Outlook

Is the fish pass Steffstep eventually a solution for disconnected rivers? The target condition is a fully rehabilitated river, without artificial aids for fish migration, which indeed will need decades to accomplish. Based on the results of this study it can be concluded that in the mean time Steffstep is a serious extension to the existing solutions to re-enable fish migration, according to preserve their diminishing biodiversity.

Certain optimizations for the construction have to be made to enhance its efficiency. This being done, Steffstep will be a suitable solution for the brown trout in particular. More research needs to be done facing other fish species and the reaction of the facility to high water conditions.

Nevertheless, Steffstep should already be part of the ongoing rehabilitation process.

List of Figures

Unless otherwise specified all pictures are made by Eva Baier, 2015.

List of Tables

Bibliography

The list of abbreviations can be found on page 6.

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Appendix

A) Measuring station 520 Töss-Rämismühle

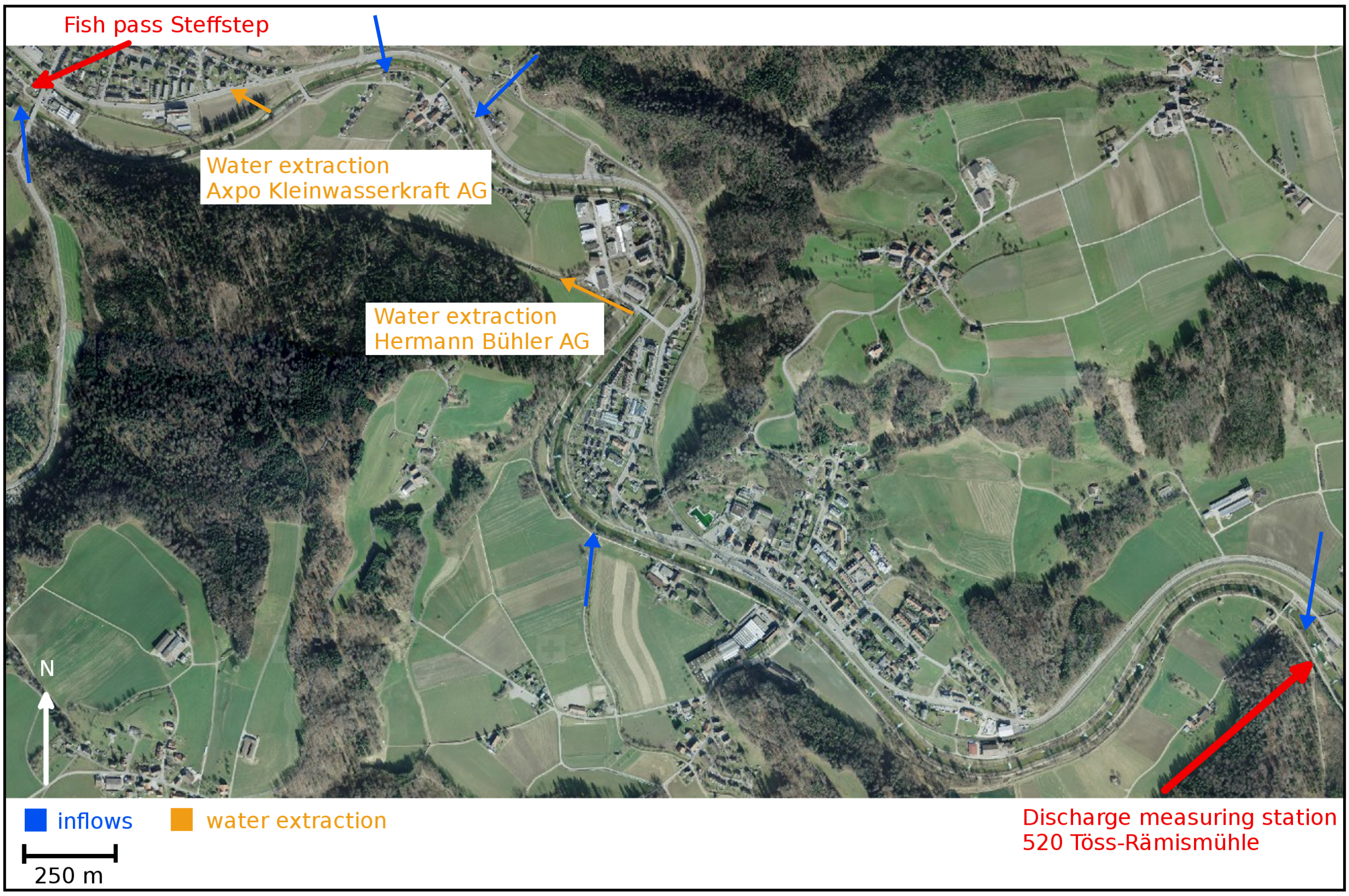

Figure 43: Map of measuring station Töss-Rämismühle (swisstopo (JD100042/JA100120), 2015, mod.)

During the field study the discharge data of the ARE discharge measuring station 520 Töss-Rämismühle was taken as reference (AWEL, 2015 a). This data correspond not exactly to the actual discharge at the fish pass due to in- and outflows between measuring station and the study site but was a rough approximation.

The measuring station is located around 5 km upstream of the fish pass Steffstep (Figure 43). Between the measuring station and the fish pass are two water extraction sites for electricity production. The Hermann Bühler AG only extracts water from the River Töss, if the stream carries a minimum of 5 m^3/s (personal communication, Andreas Birsner, Hermann Bühler AG, 07.12.15). The Axpo Kleinwasserkraft AG provides no information about the amount of extracted water or the timing, however a similar behavior can be assumed. Therefore at low water conditions the data of the measuring station complies relatively accurate to the ones at the Steffstep prototype. Besides a lot of small tributaries (like drainage gutters) five little streams feed the River Töss between the measuring station and the fish pass. After all the discharge at the fish pass can actually be considered slightly higher as measured at the discharge measuring station.

The data of precipitation is also taken from this measuring station (AWEL, 2015 b) and it is assumed that it matches with the values at the fish pass, because of the low distance between the measuring station and the Steffstep prototype.

B) Water temperature of the River Töss

Table 19: Comparison of the temperature of the River Töss 2015 and the last 31 years

	August	September	October	November	December
maximum temperature [°C]					
1984 - 2014*	19.8	17.8	15.1	11.9	9.6
2015	19.9	17.7	14.5	11.8	8.9
difference	+0.1	-0.1	-0.6	-0.1	-0.7
monthly mean temperature [°C]					
1984 - 2014*	14.4	12.7	10.6	7.5	5.4
2015	16.2	13.6	10.9	8.2	5.6
difference	+1.8	+0.9	+0.3	+0.7	+0.2

* AWEL (2014 b)

C) Results of the fish trap

Table 20: Overview of the fish trap data

Beginning	End	Duration [h]	Day / Night	Species	Total lenght [mm}
02.07.15 09:00	02.07.15 19:00	10	D	0	
02.07.15 19:00	03.07.15 08:00	13	N	0	
03.07.15 08:00	03.07.15 10:00	2	D	0	
03.07.15 19:00	04.07.15 08:00	13	N	0	
04.07.15 08:00	04.07.15 11:00	3	D	0	
04.07.15 19:00	05.07.15 08:00	13	N	0	
05.07.15 08:00	05.07.15 12:00	4	D	0	
06.07.15 19:00	07.07.15 08:00	13	N	BT*	350
07.07.15 08:00	07.07.15 10:30	3	D	0	
13.07.15 08:00	13.07.15 19:00	11	D	0	
13.07.15 19:00	14.07.15 08:00	13	N	0	
14.07.15 18:00	15.07.15 08:00	14	N	0	
15.07.15 08:00	15.07.15 10:00	2	D	0	
15.07.15 19:00	16.07.15 08:00	13	N	0	
16.07.15 08:00	16.07.15 10:00	2	D	0	
23.07.15 20:00	24.07.15 08:00	12	N	0	
24.07.15 08:00	24.07.15 19:00	11	D	0	
24.07.15 19:30	25.07.15 08:00	13	N	0	
03.08.15 08:00	03.08.15 13:00	5	D	0	
21.10.15 09:15	21.10.15 17:00	8	D	0	
21.10.15 17:00	22.10.15 09:00	16	N	0	
22.10.15 09:00	23.10.15 09:00	24	D/N	0	
23.10.15 09:00	24.10.15 09:00	24	D/N	0	
24.10.15 09:00	25.10.15 08:00	23	D/N	0	
25.10.15 08:00	26.10.15 09:00	26	D/N	0	
28.10.15 19:15	29.10.15 15:00	20	D/N	0	
29.11.15 16:00	20.10.15 16:00	24	D/N	0	
30.11.15 16:00	01.12.15 09:00	17	N	BT	400
01.12.15 09:00	02.12.15 13:30	29	D/N	BT	180
				BT	360
				BT	200
				BT	260
02.12.15 13:30	03.12.15 09:00	21	D/N	0	
03.12.15 09:15	04.12.15 09:15	24	D/N	0	
04.12.15 09:15	05.12.15 10:15	25	D/N	0	
05.12.15 10:15	06.12.15 12:15	27	D/N	0	
06.12.15 12:15	07.12.15 10:00	22	D/N	0	
07.12.15 10:00	08.12.15 09:00	23	D/N	0	
08.12.15 13:30	09.12.15 13:45	24	D/N	0	
09.12.15 13:45	10.12.15 15:45	26	D/N	BT	270
				BT	270
				BT	230
				BT	250
		571		**10**	

**BT = Brown trout*

D) Results of the video recordings

Table 21: Data of the video recordings, first camera position A

Beginning	End	Duration [h]	Visible fish
04.08.15 18:00	04.08.15 21:00	3.00	0
05.08.15 16:30	05.08.15 19:00	2.33	0
07.08.15 09:00	07.08.15 10:15	1.33	0
29.08.15 19:30	29.08.15 21:30	2.00	0
30.08.15 13:15	30.08.15 17:15	4.33	0
31.08.15 17:00	31.08.15 20:40	3.67	0
04.09.15 11:00	04.09.15 14:00	3.00	0
04.09.15 14:00	04.09.15 17:00	3.00	0
04.09.15 17:00	04.09.15 18:10	1.17	0
11.09.15 16:00	11.09.15 16:00	0.00	0
13.09.15 17:00	13.09.15 17:00	0.00	0
18.09.15 17:30	18.09.15 17:30	0.00	0
28.09.15 17:30	28.09.15 18:40	1.17	0
18.10.15 15:15	18.10.15 15:15	0.00	0
20.10.15 10:00	20.10.15 12:50	2.83	0
21.10.15 17:00	21.10.15 20:10	3.17	0
		31.00	**0**

Table 22: Data of the video recordings, second camera position B

Beginning	End	Duration [h]	Entering fish	Visible fish
23.10.15 09:15	23.10.15 11:40	2.42	0	
25.10.15 09:30	25.10.15 11:40	2.17	0	
27.10.15 09:15	27.10.15 11:25	2.17	0	
02.11.15 11:00	02.11.15 13:30	2.50	0	
07.11.15 11:15	07.11.15 13:25	3.17	0	
09.11.15 16:30	09.11.15 21:30	5.00	0	2
03.12.15 09:00	03.12.15 13:15	4.25	0	
09.12.15 13:45	09.12.15 19:00	3.33	5	7
		25.00	**5**	**9**

E) Recommendations to FOEN

F) Declaration of originality