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Fish behavior and movement in front of hydropower plants and hydro engineering installations

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Abstract

The present thesis used sonar-based technology (Adaptive Resolution Imaging Sonar, ARIS Explorer 3000) to understand fish movement and behavior in front of hydropower plants (HPP) and hydro engineering installations (HEI). In a first phase, the sonar-based system was tested against the state of the art net-based monitoring technique in order to detect a potential bias in the record of quantitative downstream fish movement and consequently validate this new monitoring approach. According to this study (Chapter 3), the sonar-based system demonstrated a 62% detection rate compared with the net-based technique. Moreover, the sonar-based system revealed an size and species specific limitation in detecting fish < 100 mm and the high suitability for migration studies of fish with characteristic body shapes like the elongated European Eel (*Anguilla anguilla, L.* 1758). In a second phase, the findings were used to observe the natural downstream migration of the European Eel at a HPP during two consecutive years. In this study (Chapter 4), rising discharge and decreasing water temperatures < 9° C were identified as major triggers for the onset of the downstream migration of this critically endangered species. The lunar cycle and air pressure did not affect the migration behavior. The observed behavior patterns of the migrating Silver Eels in front of the HPP were used in the decisions to modify the flow regime. The opening of an undershot sluice gate modified the flow regime and successfully attracts the Silver Eels to this new alternative corridor. Taking advantage of this new corridor, 190 Silver Eels could successfully pass the hydropower plant in one night, during the observation period, making this approach highly promising for European Eel conservation. Additional to the usage of attraction flows for the successful guidance of fish individuals, this thesis tested the potential of electric stimuli to guide or block fish of certain corridors. Consequently an electric fish fence (Aufleger et al. 2014) was mounted in front of one of the biggest pumping stations in Bavaria in order to observe the fish behavior and their response to the electric stimuli in front of this structure. The findings of this study (Chapter 5) confirmed the functionality of the fish fence as a behavioral barrier. The fish turning rate measured up to 72% under realistic field conditions. Consequently, the promising results of this chapter might change the general pessimistic European perspective concerning the functionality of electric fish fences. In a holistic view, this thesis explored and applied new monitoring techniques under field conditions that generated new findings about fish behavior which have since successfully been applied in fish conservation means in front of HPP's and HEI's.

Zusammenfassung

In der vorliegenden Dissertation wurde mithilfe neuester Sonartechnologie (Adaptive Resolution Imaging Sonar, ARIS Explorer 3000) das Verhalten von Fischen vor Wasserkraftanlagen und wasserbaulichen Anlagen untersucht, um Rückschlüsse über die Funktion von Fischschutzmaßnahmen zu sammeln und neue Ansätze auf Grundlage von Verhaltensmustern für die Praxis bereitzustellen.

In einem ersten Schritt (Kapitel 3) wurde die Eignung des Geräts für verhaltensbasierte Untersuchungen unter Freilandbedingungen untersucht. Ziel war es mögliche Einschränkungen des Geräts, wie größen- oder artspezifische Detektionsfehler, im Vorfeld herauszustellen und so zukünftige Untersuchungen methodisch abzusichern. Hierfür wurde der „Stand der Technik“ in Form einer netzbasierten Methode (Multimaschen-Hamennetz) mit der infrage kommenden innovativen sonar- und kamerabasierten Technologie verglichen. Hierbei ergab sich für das sonarbasierte System im Vergleich zum Stand der Technik eine Detektionsrate von 62%. Des Weiteren zeigte sich, dass mit dem sonarbasierten System Fische < 100 mm nicht sicher detektiert werden konnten und Fischarten mit ähnlichen sich überschneidenden Körperformen nicht klar differenziert werden konnten. Einzig Fischarten mit charakteristischen Körperformen, wie der schlangenförmige Aal konnten einwandfrei bestimmt werden. Diese Erkenntnisse wurden in einem zweiten Schritt dazu verwendet, die flussabwärtsgerichtete Wanderung der Blankaale (adulte Form von *Anguilla anguilla,* L. 1758) mittels des sonarbasierten Systems vor einem nachträglich nachgerüsteten „fischfreundlichen“ Wasserkraftwerk über zwei Jahre hinweg zu untersuchen.

Im Zuge dieser Untersuchung (Kapitel 4) konnten einerseits der steigende Abfluss des Gewässersystems in Verbindung mit sinkenden Wassertemperaturen (< 9° C) als Hauptauslöser für den Beginn der Wanderung dieser stark bedrohten Fischart Richtung Meer identifiziert werden, wohingegen der lunare Zyklus und der Luftdruck eine untergeordnete Rolle spielten. Darüber hinaus konnten die beobachteten Verhaltensmuster dazu verwendet werden, die Passierbarkeit der Anlage durch die Öffnung eines turbinennahen Leerschützes signifikant zu erhöhen und damit die „Fischfreundlichkeit“ der Anlage und Kleinwasserkraftanlagen generell zu steigern. Durch die konsequente Anwendung der in dieser Studie gesammelten Erkenntnisse und der Öffnung des turbinennahen Leerschützes konnten alleine in einer Nacht 190 Blankaale bei der erfolgreichen Wanderung in das Unterwasser des Kraftwerks nachgewiesen werden.

Neben der in Kapitel 4 aufgeführten Möglichkeit Fische durch Änderungen im Strömungsregime in passierbare Korridore abzuleiten, wurde zudem der Effekt von elektrischen Impulsen in Form des elektrifizierten Seilrechens (Aufleger et al. 2014) und dessen Eignung als Verhaltensbarriere untersucht (Kapitel 5). Dazu wurde der Seilrechen vor das Einlaufbauwerk eines der größten bayerischen Pumpwerke installiert und das Fischverhalten mithilfe des sonarbasierten Systems untersucht. Die Ergebnisse dieser Studie bestätigten zum ersten Mal die Funktionalität des elektrischen Seilrechens als Verhaltensbarriere unter realistischen Feldbedingungen mit einer Ableitrate von bis zu 72%, was in einem klaren Kontrast zu den bisherigen meist negativen Bewertungen über die Funktionalität von elektrischen Fischscheuchanlagen in Europa steht.

Zusammengefasst konnten durch die Erkenntnisse dieser Dissertation, durch die Etablierung einer neuen sonarbasierten Monitoringmethode und deren konsequente Anwendung vor Wasserkraftanlagen und wasserbaulichen Anlagen, neue bislang unbekannte Erkenntnisse über Fischverhalten vor Wasserkraftanlagen generiert werden, welche in Form von Managementempfehlungen zum Betrieb von Wasserkraftanlagen und wasserbaulichen Anlagen umgesetzt wurden und so den Fischschutz vor Wasserkraftanlagen und wasserbaulichen Anlagen signifikant steigern konnten.

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I'm thankful to my supervisor and Doktorvater Prof. Dr. Jürgen Geist for supporting me with scientific input and encouraging me to go further at every state of my PhD. Moreover, I want to thank my colleagues Dr. Joachim Pander and Dr. Melanie Müller for simply being such nice people. During the times of decreasing motivation and increasing distraction you two helped me to stay focused to my goal.

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1 General Introduction

Since the first hydropower plant (HPP) was built in Northumberland/England in 1880, this technology has become one of the most common ways to generate electricity today, accounting for over 16% of the worldwide electricity production (Worldbank 2017). Hydropower captivates through its technical simplicity and the widespread availability of running water within the temperate and the tropical zone making it also the most important renewable energy source worldwide (Bratrich et al. 2004). Hydropower is not actively generating carbon dioxide nor consuming fossil fuel making this technology eco-friendly at a first glance. However, the usage of hydropower also results in the modification, fragmentation and degradation of freshwater ecosystems (Habit et al. 2007). These rare ecosystems are covering only 0.8% of the earth surface, contrary these systems inhabitant more than 15,000 fish species, which is in turn one quarter of all living vertebrates species worldwide (Dudgeon et al. 2006). Beside their potential energy source, these ecosystems are a fundamental requirement for human prosperity at the same time, due to their richness of drinking water and food. Consequently, freshwater biodiversity is directly connected with human needs and is suffering far more than the terrestrial systems around the globe (Sala et al. 2000). As a result, the IUCN considers freshwater fish as one of the most threatened group of vertebrates with almost 40% of the species listed (Reid et al. 2013).

Expanding hydropower implies the transformation of dynamic river systems into highly modified water bodies. The banks are straightened, longitudinal barriers and static flow regimes focused on energy production efficiency, while affecting fish populations due to habitat and connectivity loss (Pander et al. 2018). The resulting crucial decline in fish population and biodiversity caused by hydropower is widely known and investigated (Morita & Yamamoto 2002, Ebel 2013, Bierschenk et al. 2018). Despite the huge impact on fish populations the International Energy Agency is expecting that hydropower will be doubled until 2050 due to the attractiveness for developing countries (IEA 2012). Since hydropower is an established way to generate electricity, new fish protection approaches are needed to minimize the potential impact on fish populations caused by hydropower.

The direct impacts on fish populations caused by hydropower occur worldwide and are permanent. Firstly, the fragmentation of rivers through hydropower plants and hydro engineering installations (HEI) present a major problem for long distance migrating fish species such as the European Eel (*Anguilla Anguilla,* L. 1758) and the Atlantic Salmon (*Salmo salar,* L. 1758*)* and is the most detectable one for the laymen (Figure 1). Weirs and hydropower plants along the rivers are blocking their natural migration routes, resulting in the inaccessibility of spawning grounds and lower reproduction rates for such species. A famous example for the negative correlation between the blocking of rivers by HPP's and the crucial decline of diadromous fish species is the construction of the Iron Gate in Serbia/Romania and the disappearance of the former wide spread Beluga Sturgeon (*Huso huso,* L. 1758) in the upper and middle Danube (Hensel & Holcík 1997).

The longitudinal blocking of HPP's also affects the non-migrating species due to the loss of life cycle depended sub-habitats and the reduction of the natural compensatory capacity in cases of naturally occurring catastrophic events e.g. climate change, floods, predation (Gouskov et al. 2016). Additionally, the severe change in flow regime eliminates peak flows and is changing the seasonal flow regime, which are assumed as major triggers for migration events (Figure 1) (Egg et al. 2017). The headwater of a HPP is characterized through low current velocities, high water depths and a strong layer of fine substratum, while the tailwater shows high current velocities at the turbine outlet (Egg et al. 2017). The artificial flow regime of HPP sites has changed from dynamic seasonal changes to homogenous main currents running through the turbine. This in turn, encourages most of the downstream migrating fish to enter the turbine passage. In order to distract approaching fish of entering the turbine, attraction flows in front of bypass systems and low current velocities in front of fish protection screens could be a promising solution (DWA 2014). However, due to the usage of water for attraction flows and the resulting loss for electricity generation, this issue creates a perceived financial loss for the HPP operator, which in turn might complicate the realization of fish protection means. Individuals that find a way throughout the barrier are facing the threat of turbine blade impingement and sudden changes in pressure while passing the turbine passage (Boys et al. 2018). Fish that pass the turbine passage can receive simple injuries like cuts or scale loss to severe injuries such as amputations, internal injuries or even death (Ebel 2013). Especially, the cumulative effect of several turbine passages can cause mortality rates of up to 100% for certain species (Doenni et al. 2001, Dumont 2005, Dumont 2006).

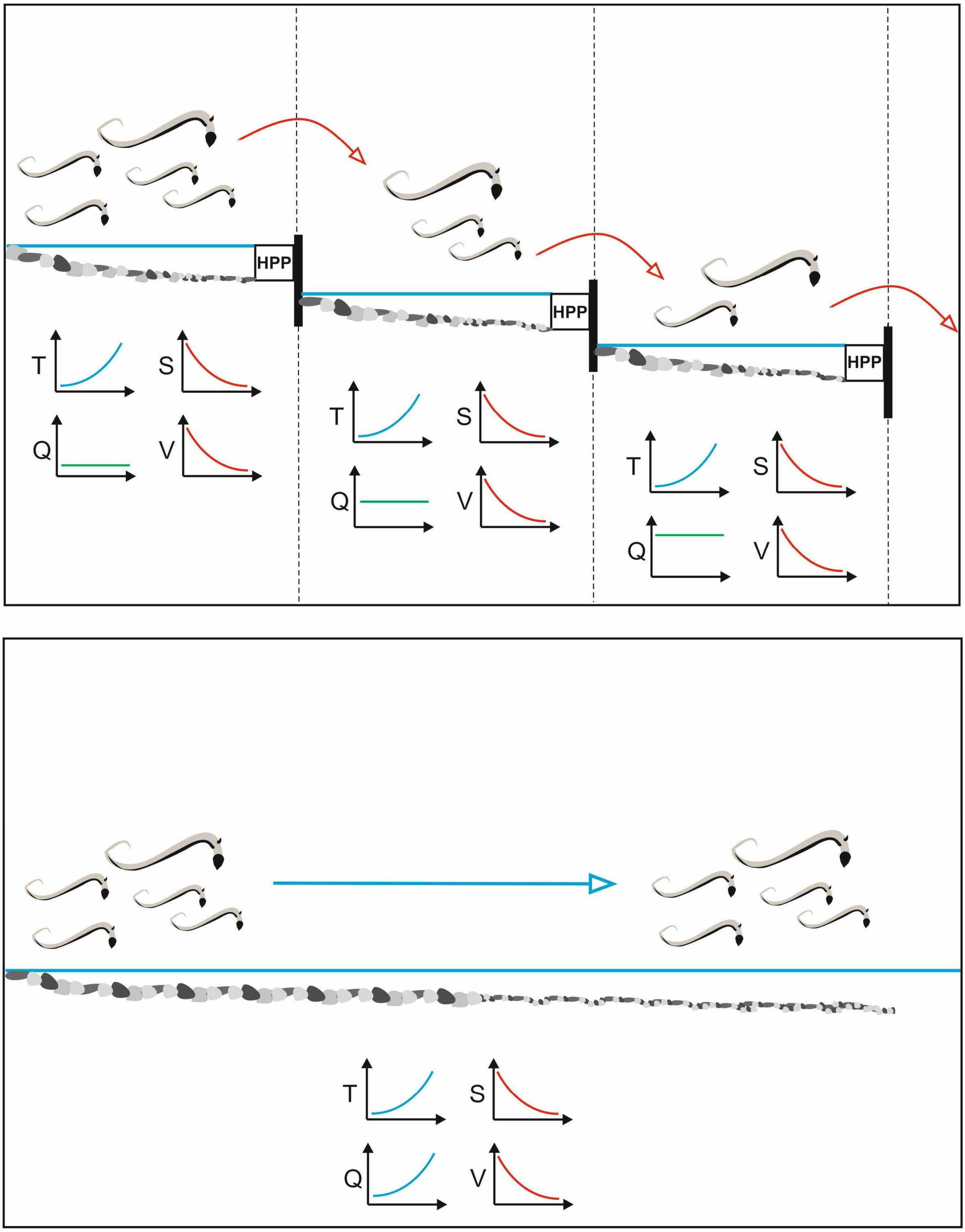


Figure 1: Schematic view of a blocked and unblocked river system. On top: Blocked river system with multiple changing abiotic conditions and the fragmentation of the longitudinal connectivity. T = water temperature, S = sediment fraction, Q = discharge, V = current velocity. Cumulative mortality caused by hydropower of downstream migrating Silver Eels is symbolized by the declining number of Silver Eels on their downstream migration towards the Sargasso Sea. On bottom: Unblocked river system with one single natural abiotic gradient along its route and with undisturbed longitudinal connectivity without cumulative mortality caused by hydropower. T = water temperature, S = sediment fraction, Q = discharge, V = current velocity.

In order to minimize the chance of turbine passage, several techniques have been invented in the past. Mechanical barriers like fish protection screens present a simple way to hinder certain fish sizes of entering the turbine passage, while bypass systems at HPP's and HEI's provide alternative corridors for fish migration (Figure 2). According to Calles and Bergdahl (2009) screens with a gap sizes of ≤ 18 mm showed the potential to prevent Silver Eels of entering the turbine passage, whereas other authors describes a gap size of ≤ 20 mm (Travade et al. 2010, Dumont 2005, Cuchet & Rutschmann 2014). However, even fish protection screens with a maximum gap size of ≤ 18 mm cannot prevent small fish individuals and drifting juveniles passing the turbine, while this size class can inhabitant most individuals of a rivers population (Grenouillet et al. 2002). The effect of turbine passage for the juvenile life stage is currently unknown and should be considered in future studies. Beside the size specific limitations of these structures, fish protection screens with small gap sizes are only feasible at sites with low discharge and low amounts of debris, due to the risk of clogging. Consequently, this technique is only useful for small-scale hydropower plants. Another approach to increase the efficiency of fish protection screens is their position within the river like inclined and horizontal screens (Ebel 2013). These systems can cause higher guidance effects to migrating fish individuals with increasing downstream migration rates (Adam et al. 2002).

Next to the mechanical barriers, behavioral barriers with higher or no gap sizes can be another approach to hinder fish entering the turbine intake (Figure 2). Advanced screen systems can also guide fish to bypass systems while forcing them not to enter the turbine intake (Aufleger et al. 2014, Egg et al. 2019). Those systems are using electricity, sound, light or air bubble curtains to create a potential behavioral barrier in front of HPP's and HEI's which should, in theory, prevent fish of entering the turbine passage (Sager et al. 1987, Knudsen et al. 1994, Bullen & Carlson 2003, Heimerl 2017). The usage of electrified vertical cables presented the novel approach to use electricity in order to create behavioral barriers. The functionality of these first generation electricity-based fish protection structures was investigated in the past, especially at cooling water intakes of thermal power plants (Heimerl 2017).

However, the observation that these first generation electric fish fence structures were not as efficient as expected resulted in poor acceptance of these technologies in Europe (Turnpenny & O'Keeffe 2005, Larinier 2008). In contrast to the European perspective, electricity-based systems are widely used at the Great Lakes (USA) to avoid the spreading invasive fish species like Common Carp (*Cyprinius carpio*, L. 1758) or Sea Lamprey (*Petromyzon marinus*, L. 1758)

(Verrill & Berry 1995, Swink 1999, Noatch & Suski 2012). Encouraged by that, several study groups in Europe are currently focusing on the improvement of the first generation electric fence with the potential to change the European perspective (Aufleger et al. 2014).

After the reduction of the likelihood of turbine passage by mechanical and/or behavioral barriers, a high variety of downstream-bypass systems have been invented (Figure 2). Surface flow bypasses, like on top spillways are widely studied under field conditions for migrating salmonids of the northwest pacific coast of the USA (Scruton et al. 2007, Wertheimer 2007). The finding of species specific migration behavior patterns, such as, the primarily use of distinctive water columns for migrators has highly improved bypass systems for salmonids around the world. According to that, smolts (downstream migrating life phase of anadromous salmonids) are mainly migrating close to the water surface, enabling engineers to adapt species specific solutions for the downstream migration. In contrast to this salmon specific behavior, other species show different migration behavior. According to the expertise of professional fishermen, eels are known to catch in traps near the bottom leading to the conclusion of a bottom oriented migration behavior.

The European Eels autecology is still poorly understood due to massive migration route of up to 12,000 km and their hidden way of life. Consequently, there is only contradictory and unconfirmed information about the onset of their migration and the related triggers. Nevertheless, bottom oriented downstream bypass systems like the zig-zag shaped eel bypass are available and used in Europe (Hassinger & Huebner 2009). This system should allow the unharmed downstream migration of Silver Eels by a zig-zag shaped tube with opening holes that guide the Silver Eels to an outlet within the tailwater of the HPP. This system is developed and validated under laboratory scale with limited use of knowledge transfer into natural rivers or field sites. One the one hand, laboratory conditions with homogenous flow regime, the loss of any natural variable (e.g. debris) seems to strongly differ from realistic river conditions. On the other hand, laboratory conditions may strongly affect the migration behavior of fish individuals itself. Fish that might have already stopped their migration behavior due to the catch or hatchery before the flume experiment. In order to close this gap, this thesis tries to understand abiotic triggers of the migration and to test a bottom near bypass systems during the migration period for the first time under field conditions.

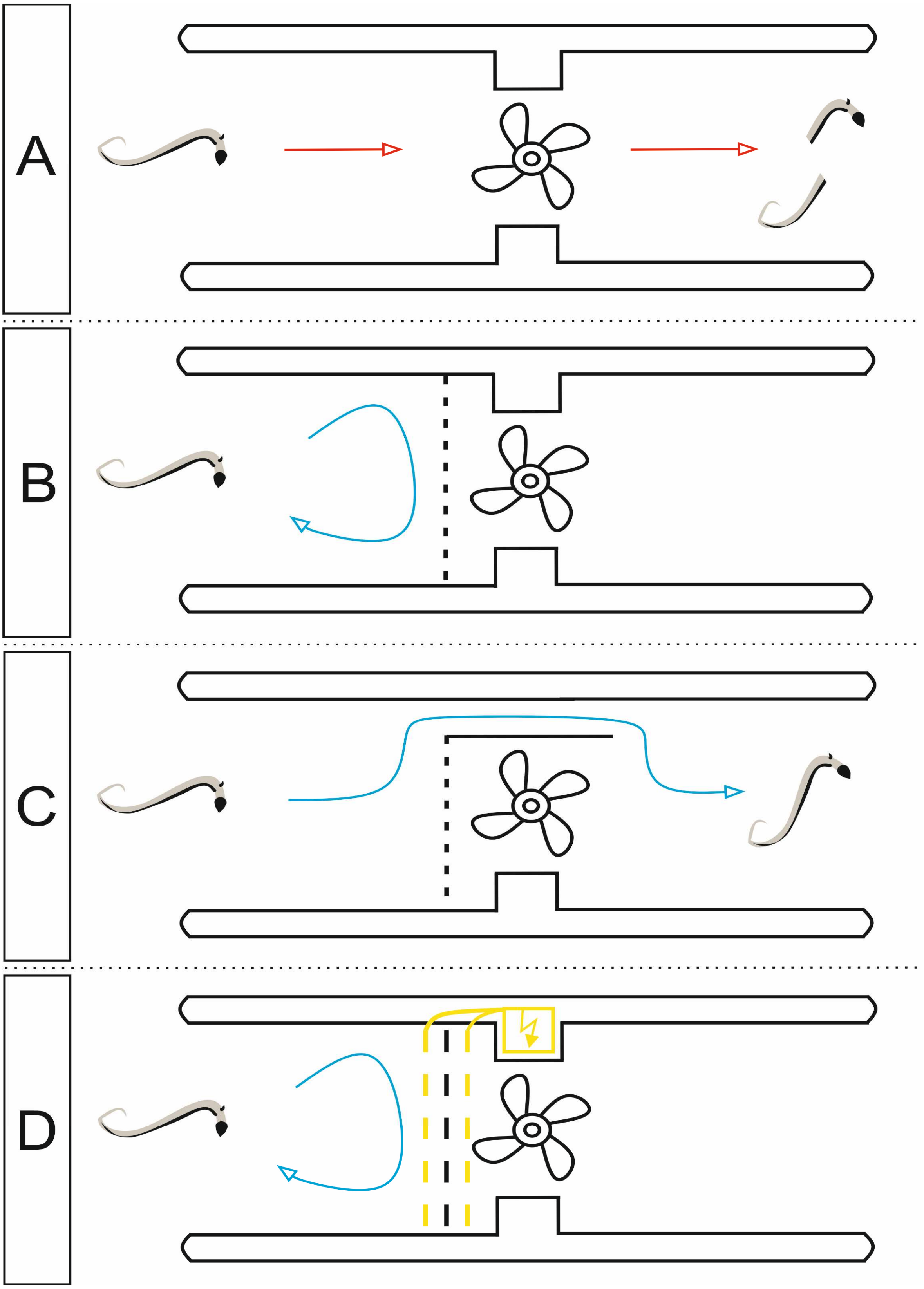


Figure 2: Schematic view of fish protection concepts in front of hydropower plants studied within this thesis. A: Hydropower plant without fish protection concept and the resulting damage of passing fish. B: Mechanical barrier with small gap size (Fish protection screen). C: Mechanical barrier (Fish protection screen with a bypass system for the successful downstream passage). D: Behavioral barrier (Electric fish fence) with high gap size.

Suitable methods are needed to observe undisturbed natural fish behavior during downstream migration within river systems. Those methods need to be non-invasive in order to record the natural migration behavior. After this limitation, telemetric systems present an elegant way of observing migration behavior. However, this system requires a pre-processing of fish individuals and medical intervention plus state approval in many countries. As a result, fish have to be caught and a surgery is necessary to implant the transmitter which could potentially affect the behavior at least for a period of time. Moreover, telemetric systems do not deliver the needed accuracy to visualize minimal behavior patterns like small scale change of directions or abrupt stops that could be potentially used for a better understanding of HPP's and HEI's. Since camera-based systems deliver a high accuracy while not affecting the behavior itself, they can be a promising solution while being affordable at the same time. Due to the light-based functional principle, cameras without artificial lights, that may affect the natural behavior, are only usable during daylight and clear water conditions (Egg et al. 2018). The position of the sun and the resulting angle of incidence can negatively affect the usability of the recorded data. Taking this into account, according to Knott et al. (2019), the movement of some fish species like Topmouth Gudgeon (*Pseudorasbora parva*; Temminck & Schlegel 1846), European Grayling (*Thymallus thymallus,* L. 1758), European Eel (*Anguilla anguilla*; L. 1758) and Pike-Perch (*Sander lucioperca*; L. 1758) mostly occur during night. So this system is not able to monitor every desired species under every condition without an artificial source of light.

In order to observe natural fish behavior even under poor visibility, hydro acoustic solutions could be a very promising technology. This method has experienced a big technology leap, from the snap shot creating single beam technology to the real-time video created by multi beam technology. This thesis used a "Adaptive Resolution Imaging Sonar" (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) with the latest technology available on market (2019), in order to understand fish behavior patterns in front of HPP's and HEI's. This tool was originally developed by the Army Corps of Engineers for detecting underwater threats for military underwater vehicles. Contrary to its warfare origin this system is widely used in freshwater field research and is capable to detect fish and their behavior in general. The transducer can operate with a maximum frequency of 3.0 MHz (Manufacturer specification: Identification frequency) by using 128 beams and a nominal effective range of 5 m. Ideal for the identification of structures or even fish species at small underwater structures. Additionally, the transducer can operate with a minimum frequency of 1.8 MHz (Manufacturer specification: Detection frequency) by using 64 beams and a nominal effective range of 15 m for the detection of big underwater structures and fish presence and their movement. For a precise underwater aiming of the system under minimal fish disruption this thesis used a two-axis control system (ARIS Rotator AR2, Soundmetrics, Bellevue, WA, USA). The system works effectively independent of light and turbidity conditions of the water body while delivering high resolution real-time videos of the underwater scenery. Consequently, this tool opens up new opportunities for fish behavior studies under realistic field conditions. However, there is a controversy debate about the possibilities of this technique considering the species identification. According to Langkau et al. (2012) even under best case scenario conditions a species identification is only partly possible, while Hately & Gregory (2006) suggest that only characteristic species like the European Eel can be detected by this technology. The debate continues when talking about the accuracy in measuring of fish lengths by the sonar system. According to Burwen et al. (2010) the recorded length of one Salmon (900 mm in their study) can vary about 130 mm while other authors do not make this issue a subject of the discussion at all. As a result, a validation of this outstanding new sonar system is needed in order to clarify the device-based scientific findings.

1.1 Objectives and Hypothesis

The core objective of this thesis was to investigate fish behavior in front of HPP's and HEI's, in order to reveal specific behavior patterns that could be useful to decrease the impact to fish individuals and to fish populations caused by HPP's and HEI's. These findings were used to give specific management recommendations to HPP operators to improve fish protection at hydropower plants. In a first phase, this thesis is examined the advantages and disadvantages of innovative monitoring systems considering their suitability for fish movement and behavior studies. Therefore this thesis compared innovative systems (e.g. Adaptive Resolution Imaging Sonars and High Definition Cameras) with a conventional system (multi-mesh stow net) in order to identify the potential bias concerning the number, length and species composition recorded by those methods under realistic conditions (Chapter 3). The results of this chapter provide a foundation for the subsequent chapters within this thesis.

The gained knowledge about this method was used in a second phase to investigate behavior patterns of Silver Eels at the Franconian Saale during their migration. Over two subsequent years the study identified abiotic triggers for the onset of their migration that can be used to set timeframes for eel conservation strategies (Chapter 4). Additionally, a bottom near bypass system was tested under field conditions and a new method to facilitate downstream migration for Silver Eels was discovered. This new approach showed its potential to significantly improve the escapement rate of this threatened species and is simultaneously supporting the Eel Management Plan of the European Union (Regulation Council of the European Union 2007). The thesis also tested (Chapter 5) the functionality of a new generation of electrified fish fence developed by Aufleger et al. (2014), as a behavioral barrier in front of one of the biggest pumping stations in Germany.

In particular, this thesis hypothesized that there are no significant differences in the detected number of fish, the measured size and the recorded species composition among the innovative monitoring systems (Adaptive Resolution Imaging Sonar, High Definition Camera) and the conventional net-based system. Additionally, this thesis hypothesized that significant higher number of Silver Eels migrate through the opened undershot sluice gate compared to the zig-zag shaped Eel bypass system. Moreover, this thesis hypothesized that the electrified fish fence created a significantly higher number of turning behaviors compared to the non-electrified state.

2 Material and Methods

The thesis at hand used the ARIS Explorer 3000 (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) in every chapter in order to study fish behavior in front of HPP's and HEI's. The consequent development of this method during the thesis enabled new insights in fish behavior and has been translated into concrete management recommendations.

2.1 Functional principle of sonar systems

Sonars (So und Na vigation and R anging) are using sound waves in order to detect underwater targets. Due to the high density of water, sound waves are moving five-times faster underwater compared to atmospheric conditions. Taking advantage of this effect, sonars are transmitting sound waves that are moving across the water body until they reach an underwater obstacle (Figure 3). The sound wave gets reflected by the surface of the respective obstacle and the echo is moving back to the source. Due to the time that the sound wave needs to return, the sonar is able to calculate the distance to the obstacle. Moreover, the sonar is able to calculate the size of the source by the echo signal. Since, sound wavelengths underwater are two-thousand times longer than the ones of visible light, sound is able to ignore little particles within the water body that would block the wavelengths of visible light. As a result sonars can even "see" under dark and turbid underwater conditions.

The high frequency sound impulses of the sonar did not cause any response behavior of fish individuals. However, one famous example of avoiding behavior towards sound impulses are known for members of the Clupeidae. Based on the co-evolution of members of the Clupeidae and the sound generating dolphins, this family developed this kind of avoiding behavior to sound impulses (Goetz et al. 2015).

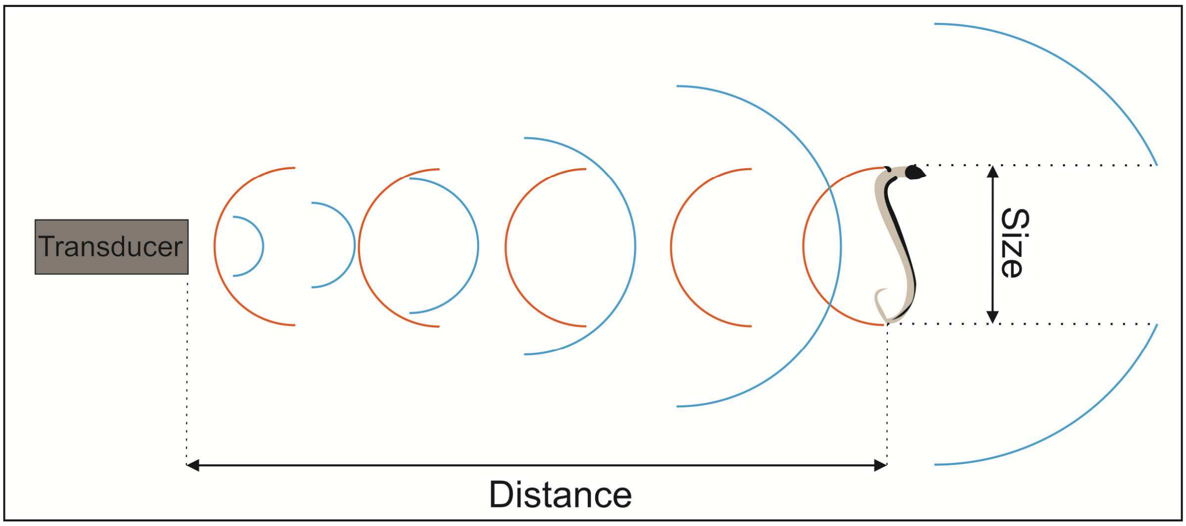


Figure 3: Functional principle of sonar systems. The transducer is sending a sound impulse (blue semicircles). The obstacle (Silver Eel) is sending back an echo (red semicircles) to the transducer.

2.2 Sonar systems for riverine research

Different research questions need different sonar-based methods. Generally, three types of sonars can be distinguished for riverine aquatic research.

The widely known single beam sonar (fish finder) is the simplest concept of a sonar system. The transducer is sending one sound impulse (beam) towards the bottom of the water body. Targets that are within this signal are sending back an echo to the transducer, resulting in the information of the target position within the water column (water depth) and the size of the target. However, no information is given about the targets horizontal position within the sound impulse or the targets swimming direction (Figure 4).

Another type of sonar represents the split beam sonar (Figure 4). This sonar is sending a predetermined number of sound impulses (beams) towards the bottom of the water body. The classification in quadrants allows the sonar to determine the horizontal position of targets within the water column. Similar to the fish finder the split beam is able to detect the position within the water column (water depth) and the size of the target. Additionally, this system can distinguish in which quadrant the fish was located and in which it is moving. Thus, the swimming direction can be determined and more information can be generated compared to the fish finder.

In the evolution of sonars for riverine aquatic research, imaging sonars represent the fittest and most innovative available level and generate the highest number of information for the researcher. This system is using a high number of parallel arranged vertical sound waves (128 beams for the ARIS Explorer 3000 in 3.0 MHz mode). This high density of beams is able to visualize the detailed underwater scenery in real time. Fish that are within the ensonified area can be counted and measured. Moreover, fish that is swimming through the ensonified area is unconsciously passing the parallel arranged vertical sound waves (Figure 4, Figure 5) generating a high number of information about the swimming speed, the swimming direction and the body shape. Due to the correct information about the range (x-axis) and the cross range (y-axis) the target can be followed during time, resulting in fish trails (Figure 5).

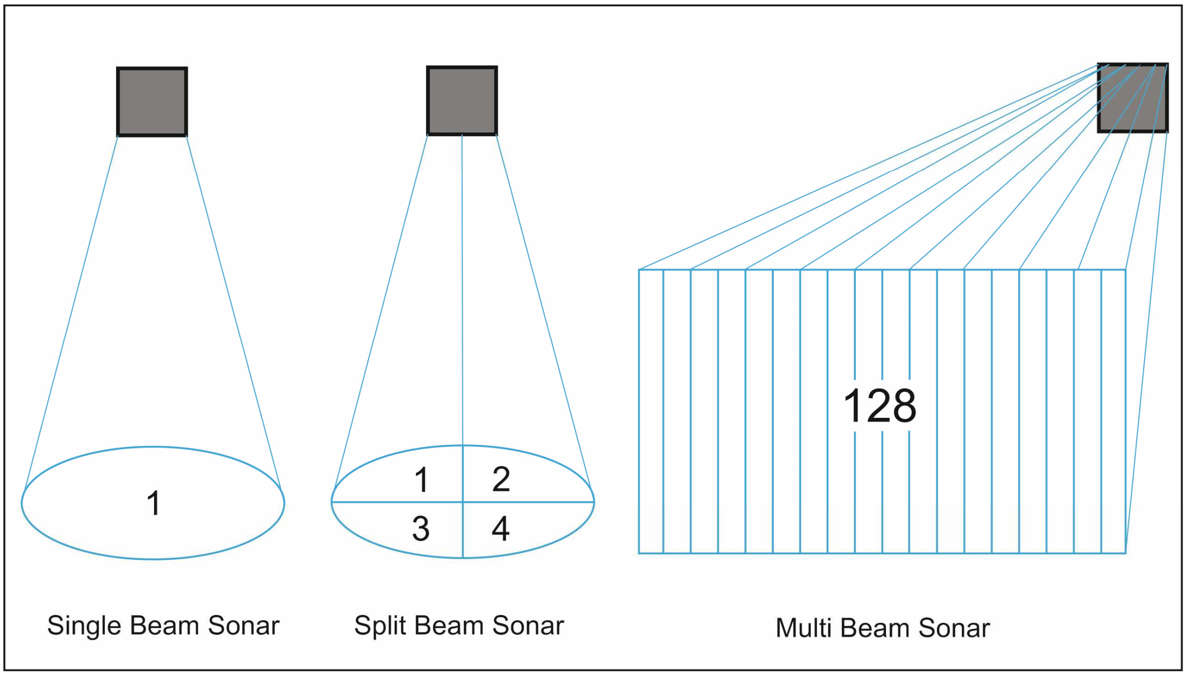


Figure 4: Schematic view of the three different types of sonars for riverine aquatic research. Grey square: Transducer of the respective type of sonar.

2.3 Imaging sonars

At the end of the 20^{th} century the U.S. Navy was developing a new underwater acoustic camera, which was able to generate real time videos even under dark and turbid water conditions. The idea behind this was to clearly identify and follow enemy underwater threats in order to eliminate these. After years of development, the first generation DIDSON Sonar (Dual Frequency Identification Sonar) (DIDSON 300 m, Soundmetrics, Bellevue, WA, USA) was introduced in 2002 and mainly used by Military services and the Oil-Industry. This system was able to visualize e.g. offshore oil pipelines for maintenance purpose, missed persons or material to a maximum depth of 300 m. Besides this, more technical usage, the DIDSON got applied in Fish Biology and Fisheries Science.

The DIDSON is using 1.8 MHz during identification mode and 1.1 MHz during detection mode. Moreover the sonar is transmitting 96 vertical beams during the identification mode and 48 vertical beams during the detection mode. Due to its capability of generating underwater real time videos the sonar was used to investigate the upstream migration of the North-American salmon species concerning the number and length of the migrators. Moreover, the DIDSON was used to test the efficiency of fish bypass systems. Beside the new findings in fish movement of characteristic big fish like Salmons the DIDSON also showed its limitations. Especially the accuracy and the low resolution of the videos did not allowed species identification. Moreover, the DIDSON revealed a high bias within measurement data. According to Burwen et al. (2010) measurement data about the same adult salmon (900 mm) can vary about 130 mm during a full tail cycle.

Consequently, Soundmetrics introduced the ARIS Explorer 3000 (Adaptive Resolution Imaging Sonar) (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) as the second generation of Imaging Sonars. This milestone in hydro acoustics is able to use 3.0 MHz during the identification mode and 1.8 MHz during the detection mode. Moreover, the ARIS is using 128 vertical beams within the identification mode and 64 vertical beams during the detection mode. The increase of wavelength and vertical beams resulted in a higher resolution compared to the DIDSON. The ARIS is now able to deliver high resolution videos of the underwater scenery. Compared to the first generation DIDSON sonar, the ARIS sonar is delivering a higher resolution enabled a more detailed view in underwater scenery due to the higher accuracy and resolution.

The ARIS is sending 128 vertically arranged beams towards the desired underwater structure. Within the identification mode the sonar is emitting 3,000,000 sound impulses per second that are reaching the underwater structure. As described in Figure 3 the structure reflects those sound impulses and the transducer is receiving those. The high amount of received echoes is creating a picture of the underwater scenery and is translated to a top view video by the manufacturer's software ARISScope (Soundmetrics, Bellevue, WA, USA).

Fishes that are swimming through the ensonified area are passing the vertically arranged beams resulting in a value on the cross range (Figure 5). Additionally, due to the distance between the transducer and the target, the range can also be determined. Together these two variables are generating a full fish track. This fish track contains the swimming direction e.g. towards a certain corridor, the swimming speed, the residence time within the ensonified area, the tortuosity, the size of the fish and the thickness. These values can be used during the post-processing of fish behavior data.

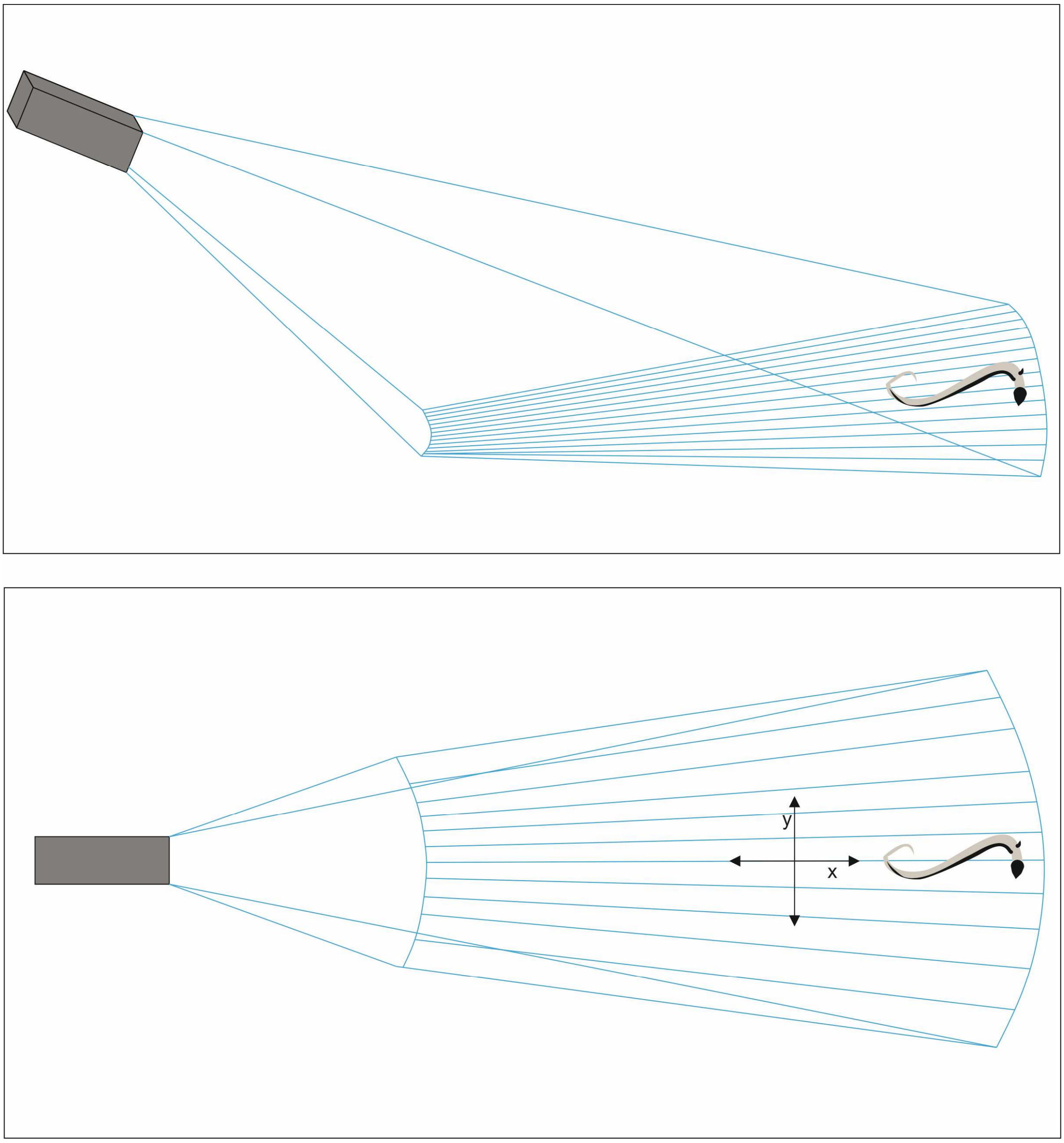


Figure 5: Schematic view of the functional principle of the ARIS Sonar. Grey box. ARIS Explorer 3000, Blue lines: vertically arranged beams. y: cross range, x: range.

2.4 Application to river conditions

Sonar systems are high-end technologies that should be handled with extra caution. However, the distributors are not delivering practical solutions to bring the sonar in front of HPP's or HEI's. In order to monitor fish behavior under realistic field conditions new mounting solutions are needed. In the context of this thesis two different mounting solutions have been developed.

Module I was the first development in the beginning of this thesis in order to mount the sonar system safely onto walls in the front of HPP's and HEI's. The module was made out of steel in order to endure the water pressure of the current of a river. The sonar was mounted to a square tube that was running in a rail in order to change the position within the water column, when needed. Since, this module is firmly fixed with a wall the sonar is not changing its position. This module is most appropriate for long time observations of the same structure in front of HPP's and HEI's and was used within Chapter 3. However, this solution turned out to be not flexible enough for realistic field conditions with changing flow conditions.

As a result, Module II was developed in order to react to changing condition during field work. Therefore eight floating pontoon elements (JETFLOAT International GmbH, Salzburg, Austria) were fixed together. On top of those a steel outrigger was fixed simultaneously to the Module I, where a square tube was running in a rail. Beneath the ARIS Explorer 3000 was fixed to the outrigger. The decisive advantage lies in the flexible change of the position during a study. The position can be hold due to the usage of ropes. Moreover, a boat engine can be attached allowing also long distance change of position.

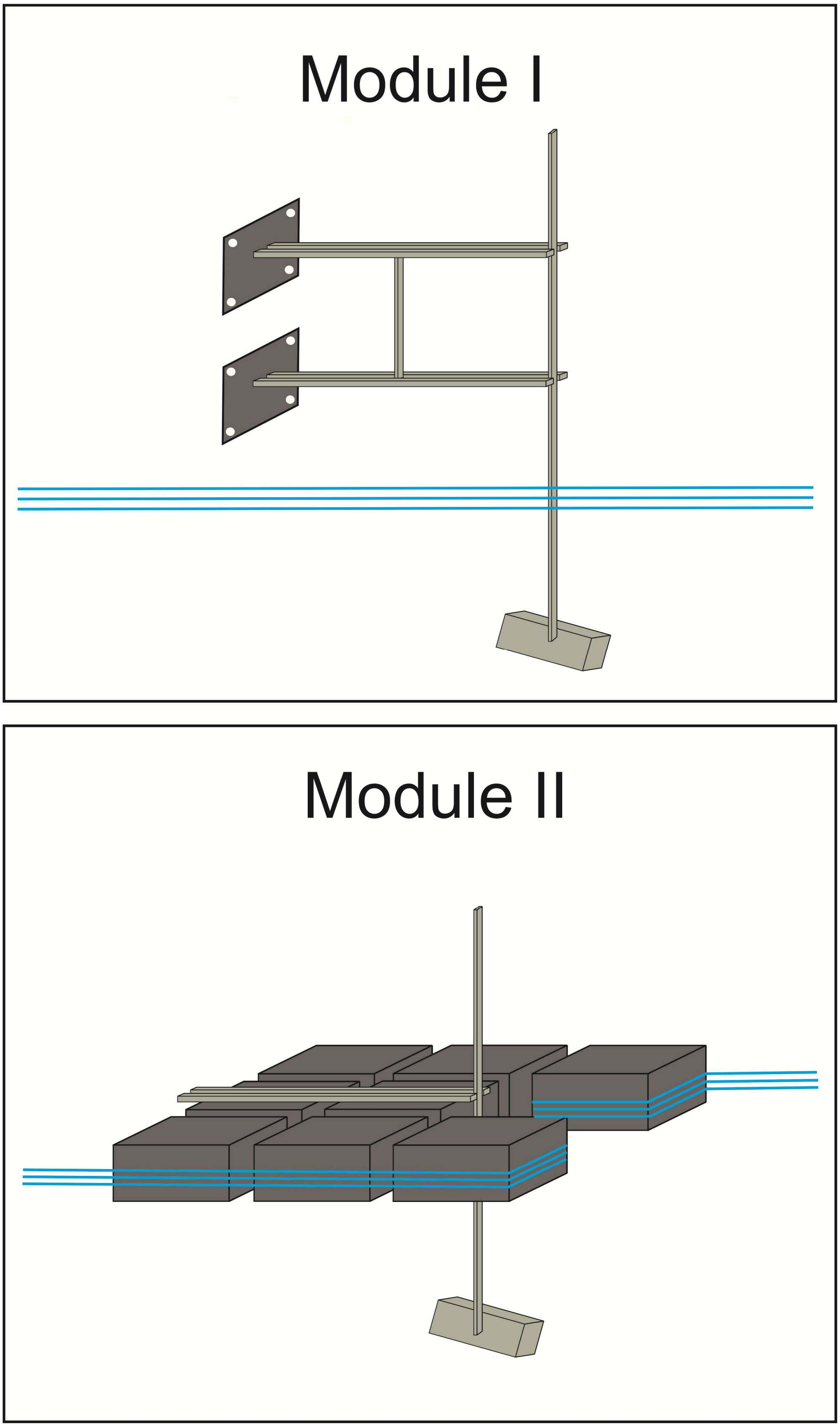


Figure 6: Schematic view of Module I and Module II. Blue lines: water surface.

2.5 Post-processing of sonar data

Beside the practice oriented problems like the application to river conditions the post-processing of sonar data and the resulting quantification of behavior patterns is the most challenging part within hydro acoustic studies. Within this thesis a manual and a semi-automated approach was used. In every case, the video data was standardized over time. Depending on the fish occurrence and the research question this thesis used 0.25 h intervals (Chapter 4 and Chapter 5) or 0.75 h intervals (Chapter 3).

The manual approach implies the manually watching of every video file by an expert and the counting of pre-defined criteria. In order to minimize the personal bias in such data, Chapter 4 used four experts that independently watched every video without detailed information about time and place. For further calculations the mean value was used making this manual approach on the one hand highly time consuming but on the other hand highly effective concerning the quantification of video data.

For the semi-automated approach this thesis used Echoview 6.0 - 8.0 (Myriamax, Hobart, Australia). This software represents a milestone in the post-processing of sonar data due to the user-oriented interface and the staggered treatment of the video files. Thus, it is possible to delete the static background of the video file in order to visualize only the movement within the videos. As a result the movement of fish individuals can be tracked across time generating various meta data e.g. swimming speed, swimming direction and fish size that can be used for further calculations. However, the fine adjustment of this semi-automated approach needs a lot of experience and knowledge about hydro acoustic under field conditions. Moreover, even during the semi-automated approach the decisions made by the software need to be verified by an expert.

3 Comparison of sonar-, camera- and net-based methods in detecting riverine fish-movement patterns

This chapter was also published in: Egg L., Pander J., Mueller M. & Geist J. (2018). Comparison of sonar-, camera-and net-based methods in detecting riverine fish-movement patterns. Marine and Freshwater Research. 69 (12). 1905-1912.

3.1 Abstract

Monitoring of fish movement is important in understanding and optimizing the functionality of fishways and in restoring riverine connectivity. This study compared fish monitoring data (ARIS sonar-based and GoPro camera-based), with catches in a multi-mesh stow net following downstream passage in a small river in Bavaria, Germany. In terms of the number of individuals, the sonar-based system (detection rate = 62.6% of net-based catches) outnumbered the counts of the camera-based system (45.4%). Smaller specimens of < 100 mm and < 150 mm were under-represented with the sonar and the camera-based systems respectively. Species identification based on the camera system was similar to that for net-based catch, whereas no proper species identification could be performed with sonar data. In conclusion, the sonar-based system can be recommended for the counting of fish >100 mm during night and turbid conditions, unless species identification is necessary. During daylight and with clear water, cameras can be a cheaper and promising option to monitor species compositions of fish > 150 mm.

3.2 Author contributions

EL, PJ, MM and GJ designed the concept of the experiment; EL organized and conducted the field work; EL processed the dataset; EL watched the video data; EL and MM analyzed the results. EL wrote the initial draft of the manuscript under supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

3.3 Introduction

European rivers have experienced strong changes in their connectivity, with dams and weirs being considered a main problem for fishes, particularly for diadromous long-distance migrating species such as eel and salmon (Kareiva et al. 2000, Dauble et al. 2003, Thorstad et al. 2003, Sheer & Steel 2006). In the context of the European water framework directive, the restoration of connectivity and of fish migration is considered the main target to achieve a good ecological state or potential of riverine systems (European Commission of the European Parliament and of the council 2000). So as to evaluate the success of restoring connectivity and to study fish migration, validated tools for the monitoring of fish movements in rivers are necessary. Several studies have used sonar- and camera-based approaches to assess fish movement, by recording the numbers, lengths and species (Santos et al. 2002, Davidsen et al. 2005, Baumgartner et al. 2006a, Burwen et al. 2007). However, little attention has been paid to validate data from such monitoring systems by comparing them with 'state of the art' net-based catch.

Net-based methods such as multi-mesh stow-net catches deliver the pre-eminent results concerning fish counts, fish lengths and the species composition. However, these net-based systems require a high personal as well as financial effort and are highly vulnerable to being damaged, e.g. during discharges with high loads of floating debris. This is particularly problematic for monitoring during fall when migration peaks of species such as the European eel (*Anguilla anguilla*, L. 1758) and the Atlantic salmon (*Salmo salar* L. 1758) coincide with enhanced discharge conditions (Jonsson et al. 1997, Durif & Elie 2008, Egg et al. 2017). Beside these restrictions, net-based approaches are always invasive and can cause damage or death to the fish. Especially sensitive species such as Northern grayling (*Thymallus thymallus*, L. 1758) were shown to have high mortalities up to 80% if emptying intervals of nets are 12 h (Pander et al. 2018).

Sonar-based systems have the potential to observe corridors with less effort, simultaneously minimizing fish disturbance. For instance, sonar systems such as single-beam sonars, split-beam sonars and multi-beam sonars have been used in monitoring fish movement and passage (Daum & Osborne 1998, Steig & Iverson 1998, Lilja et al. 2003, Egg et al. 2017). Especially high-frequency multi-beam sonars have been methodologically assessed concerning accuracy and precision of fish count data, mostly on the basis of precursors of the ARIS sonar (Holmes et al. 2006, Burwen et al. 2007). Despite their high price, sonar systems are easily mounted and do not need much personnel compared to the net-based monitoring systems. Additionally, they are able to count and measure regardless of the turbidity of the river and are not that vulnerable to high amounts of floating debris. The main weakness of these systems seems to be the correct species identification. Previous studies have shown that sonar-based DIDSON systems can identify only some species under artificially modified conditions (Langkau et al. 2012). Such conditions are difficult to generate in field experiments, significantly increase experimental effort and may affect fish behavior. In contrast, the higher resolution of the ARIS-sonar compared with DIDSON, along with provision of an 'identification frequency', may potentially increase accurate species identification.

Visual systems such as conventional cameras are another potentially useful approach to monitor corridors (Davidsen et al. 2005). Analogously to sonar-based approaches, these systems are installed under the water surface. Despite the small price and the simple usage of these systems, there are several restrictions. Conventional camera systems cannot operate during night, during periods of high turbidity or high loads of floating debris.

Whereas there have been several studies employing sonar- and camera-based systems, there is a lack of studies that compare results from visual detections with net-based catches. As an explicit novelty, this study compared the number, length and species composition of fish applying the latest sonar technique (ARIS) with those applying cheaper alternatives. To the best of our knowledge, no study has yet compared the accuracy of simultaneous sonar- and camera-based fish monitoring with the catches of a multi-mesh stow net, so as to validate the comparability of these approaches.

Thus, the core objective of the present study was to test to what extend sonar and visual systems are able to correctly record fish movement at a riverine corridor, compared with the net-based catches, considering the number of fish, their average lengths and the species identification. We hypothesized that there are no significant differences in the (1) recorded number of fish counts, (2) lengths recordings and (3) species detections among the sonar-, camera- and net-based method.

3.4 Material and Methods

3.4.1 Study site

The study was conducted at the Moosach River in Freising in Bavaria, Germany (48°39'42.1"N, 11°72'35.4"E), where previous experiments on the accuracy of net-based systems were conducted (Pander et al. 2018). The source of the Moosach is located in the city of Munich and drains into the Isar River after 35 km. For a characterization of the river, see Auerswald and Geist (2018). The Moosach has a mean annual discharge of 2.53 m^3 s^{-1}, a mean low water discharge of 1.87 m^3 s^{-1} and a mean flood discharge of 5.6 m^3 s^{-1}, recorded at the water gauge in Freising (5 km downstream of the study site: 48°24'29.8"N, 11°46'8"E). The study site was located at a weir, where the river runs through a 2.5 m wide sluice gate (Figure 7). At this site, fish passage can occur only from upstream to downstream, making this an ideal study site for comparison of different catch and detection methods.

The field work was performed in summer (4 July - 11 July 2016) at a mean discharge of 2.36 m^3 s^{-1}. Four methods (net-based, sonar-based optimistic, sonar-based pessimistic and camera-based) were simultaneously conducted during day- and night-time, so as to test their efficiency under different light conditions. Daytime was defined from sunrise to sunset (day: 0500 to 2100 hours, night: 2100 to 0500 hours). During the whole study period, the sluice gate was constantly open. The environmental conditions were constant throughout the study period (Table 1).

3.4.2 Environmental variables

Three times per day, environmental values were recorded; current velocity (ms^{-1}) in front of the sluice gate was measured with an electromagnetic water flow meter (Ott MF Pro, Ott, Kempten, Germany) 10 cm below the water surface, in the middle of the water column and 10 cm above the river bottom; in addition, turbidity (NTU) (Turbidity meter, WTW, Weilheim, Germany), oxygen (mgL^{-1}), pH, conductivity at 20° C (μScm^{-1}) and temperature (° C) (Multimeter, WTW, Weilheim, Germany) were measured in the headwater of the weir.

Day	1	2	3	4	5	6
Temperature [°C]	15.6 ±1.0	16.3 ±0.7	16.2 ±0.4	13.5 ±3.2	16.3 ±0.7	18.0 ±0.7
Dissolved Oxygen [mgL^{-1}]	11.76 ±1.18	11.72 ±0.87	11.45 ±0.66	11.63 ±0.78	11.79 ±0.66	11.06 ±0.54
Electric Conductivity at 20°C [μScm^{-1}]	781 ±2	781 ±2	783 ±2	781 ±1	781 ±1	778 ±1
pH	8.5 ±0.8	9.5 ±0.1	9.8 ±0.4	9.3 ±3.4	9.5 ±0.4	9.5 ±0.4
Turbidity [NTU]	2.54 ±0.32	2.86 ±0.40	3.13 ±0.34	4.18 ±0.55	3.94 ±0.34	3.26 ±0.28
Current velocity near surface [ms^{-1}]	0.48 ±0.03	0.47 ±0.11	0.44 ±0.08	0.43 ±0.06	0.41 ±0.07	0.33 ±0.10
Current velocity middle [ms^{-1}]	0.54 ±0.07	0.48 ±0.09	0.43 ±0.06	0.44 ±0.05	0.37 ±0.05	0.48 ±0.17
Current velocity above bottom [ms^{-1}]	0.45 ±0.16	0.41 ±0.10	0.34 ±0.08	0.34 ±0.09	0.27 ±0.08	0.34 ±0.05
Discharge [m^3s^{-1}]	2.50 ±0.00	2.39 ±0.06	2.36 ±0.00	2.36 ±0.00	2.36 ±0.00	2.23 ±0.00

Table 1: Abiotic habitat characteristics during the 6-day study period. All values are given as arithmetic means ± standard deviation.

3.4.3 Net-based monitoring

So as to record downstream fish movement, the study used a knotless multi-mesh stow net of decreasing mesh size and narrowing diameter (length: 6.5 m, mesh sizes: 30, 20, 15, 10 and 8 mm), which was directly mounted behind the outtake of the sluice gate, as used in Pander et al. (2018). The stow net was emptied with a boat every 0.75 h. To ensure that all fish that passed the sluice gate were caught in the net, the area between the sluice gate and the stow net was electrofished (3 kW, single anode, EFKO, Leutkirch, Germany) before and at the end of every interval (Figure 7). Immediately after the electrofishing, the full stow net was lifted out of the water with a pulley. After emptying the net, every specimen was identified to species level and the total length and weight were measured. To determine the catch efficiency of the stow net, we performed a net validation every second day. For this reason, a total of 40 soft plastic fish imitations of different lengths (5 and 10 cm) and different buoyancy (swimming and sinking) were put in front of the sluice gate and, subsequently, caught in the stow net (Figure 8). The validation resulted in recapture rates of 100% for these plastic fish imitations.

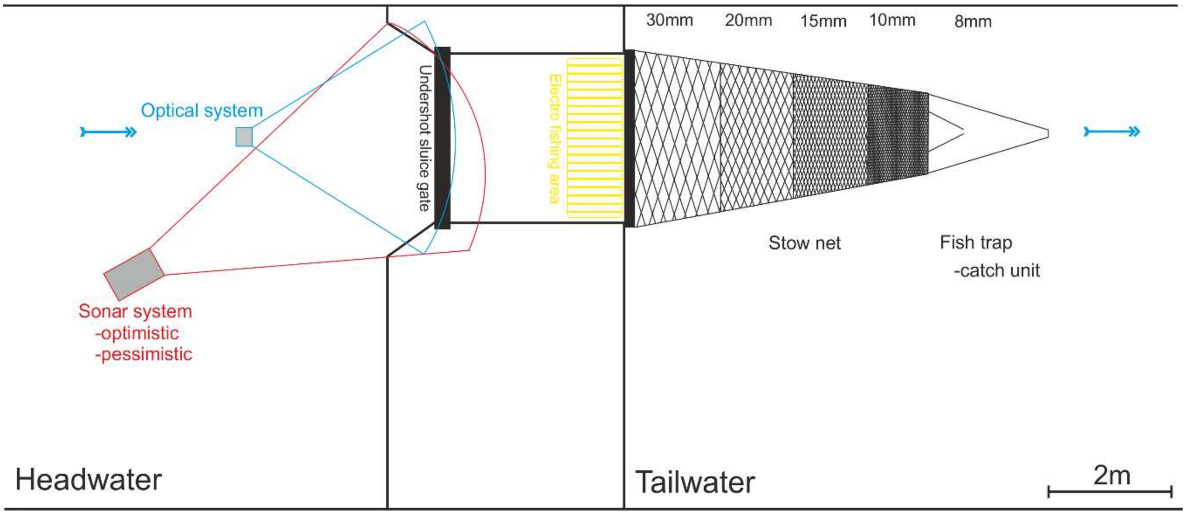


Figure 7: Top view of the study site (headwater, sluice gate and tailwater). Blue arrow indicates the main current. Stow net with the different mesh sizes on top (30, 20, 15, 10 and 8 mm). Area where electrofishing was performed so as to force the fish that already passed the sluice gate but had not yet entered the stow net, to do so (yellow).

3.4.4 Sonar-based monitoring

For the sonar-based monitoring of fish movement, this study used an Adaptive Resolution Sonar (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA). The sonar was operated with a horizontal beam angle of 28°, a vertical beam angle of 14° and was set to the identification frequency of 3.0 MHz according to the manufacturer specification. The sonar was mounted in the headwater of the weir on the orographic right-hand side. During the whole study period, the sonar was 20 cm below the water surface and was set to -7.70° pitch and -10.48° tilt. Sonar data were subsequently analyzed with two different processing approaches (optimistic and pessimistic). For both approaches, every 0.75 h, video data were watched with 20 frames per second (FPS). The optimistic approach involved counting and measuring of all objects resembling fish shape with the Software ARISfish (Soundmetrics, Bellevue, WA, USA). In contrast, the pessimistic approach counted objects as fish only if an additional tail-beat frequency was observed on the echogram (Mueller et al. 2010).

3.4.5 Camera-based monitoring

For the visual monitoring of fish movement, we used an underwater high-definition camera (GoPro 4 Hero, San Mateo, CA, USA), which observed the entire corridor (Figure 7). The camera was operating with a resolution of 1280 × 720 pixels. Analogously to the sonar data, every generated 0.75-h video was watched afterwards with 20 FPS. Fish that passed the gap of the sluice gate were counted, measured and the species were identified if possible. To allow comparison with the sonar-based approach, the camera was synchronised with the sonar. The data were stored and subsequently analysed with the software GoPro Studio (San Mateo, CA, USA).

3.4.6 Statistical analyses

The recorded number of fish per 0.75 h and the determined average lengths (mm) were compared among the different monitoring approaches by using univariate statistics. Because the data did not fulfil the assumptions of normality, Kruskal–Wallis test and Bonferroni-corrected post hoc pairwise Mann–Whitney U tests were used (software R ver. 3.4.0, www.r-project.org, 1 July 2017). Moreover, species and length composition were compared with multivariate statistics. Permutational multivariate ANOVA (PERMANOVA) was used to test the dataset for differences in species composition that was visualised in non-metric multidimensional scaling (NMDS). Additionally, we used Similarity percentage (SIMPER) analysis to detect the most persistent size classes per method, by using Primer (ver. 6, Plymouth Marine Laboratories, UK, http://www.primer.com). In all statistical testings, significance was accepted at $P < 0.05$.

3.5 Results

3.5.1 Recorded number of fish

Both the sonar- (optimistic = 62.6%, pessimistic = 57.8%) and the camera-based system (45.3%) showed lower detection rates than did the net-based counts (Table 2). Even though the average count of fish per 0.75 h caught with the net-based system was 1.5-fold higher than the average count detected with the sonar-based optimistic approach, no significant difference could be detected (Figure 8), which is in line with Hypothesis 1. The average count of fish per 0.75 h detected with the sonar-based pessimistic approach (8.61 ± 5.67) was 1.7-fold lower and that detected with the camera-based approach 2.2-fold lower than were the net-based catches (Figure 8, Table 2). Contrary to our hypothesis, the study detected significant differences between the pessimistic sonar and camera-based counts compared with the net-based catch (Table 2). Additionally, the catches of the net-based system showed the highest variability, with a maximum of 44 fish per 0.75 h (Table 2).

	Sonar-based optimistic	**Sonar-based pessimistic**	**Camera-based**	**Net-based catch**
Total number	503	465	364	804
Mean number/0.75h	9.31 ±5.81	8.61 ±5.67	6.74 ±5.87	14.88 ±10.89
Maximum number/0.75h	26	26	27	44
Minimum number/0.75h	0	0	0	0
Mean size [mm]	128.52 ±76.13	130.93 ±77.78	147.11 ±119.10	116.42 ±85.96
Maximum size [mm]	709	709	900	840
Minimum size [mm]	40	40	40	31
Number of fish <50mm	11	10	5	29
Number of fish >50-100mm	227	203	162	502
Number of fish >100-150mm	132	124	81	115
Number of fish >150-200mm	61	56	45	50
Number of fish >200-250mm	31	31	41	57
Number of fish >250-300mm	27	27	21	38
Number of fish >300mm	14	14	9	13
Alburnus alburnus [%]	0.0	0.0	6.0	13.1
Anguilla anguilla [%]	0.0	0.0	1.6	0.5
Esox lucius [%]	0.0	0.0	0.8	0.7
Gasterosteus aculeatus [%]	0.0	0.0	0.0	1.0
Pacifastacus leniusculus [%]	0.0	0.0	0.5	0.9
Perca fluviatilis [%]	0.0	0.0	0.5	0.2
Rhodeus amarus [%]	0.0	0.0	0.0	2.5
Rutilus rutilus [%]	0.0	0.0	3.0	6.6
Salmo trutta [%]	0.0	0.0	69.0	66.8
Scardinius erythrophthalamus [%]	0.0	0.0	6.3	7.5
Tinca tinca [%]	0.0	0.0	0.0	0.2
Unknown [%]	100.0	100.0	12.1	0.0

Table 2: Catches and detections based on the different monitoring approaches. The mean values are presented with the standard deviations.

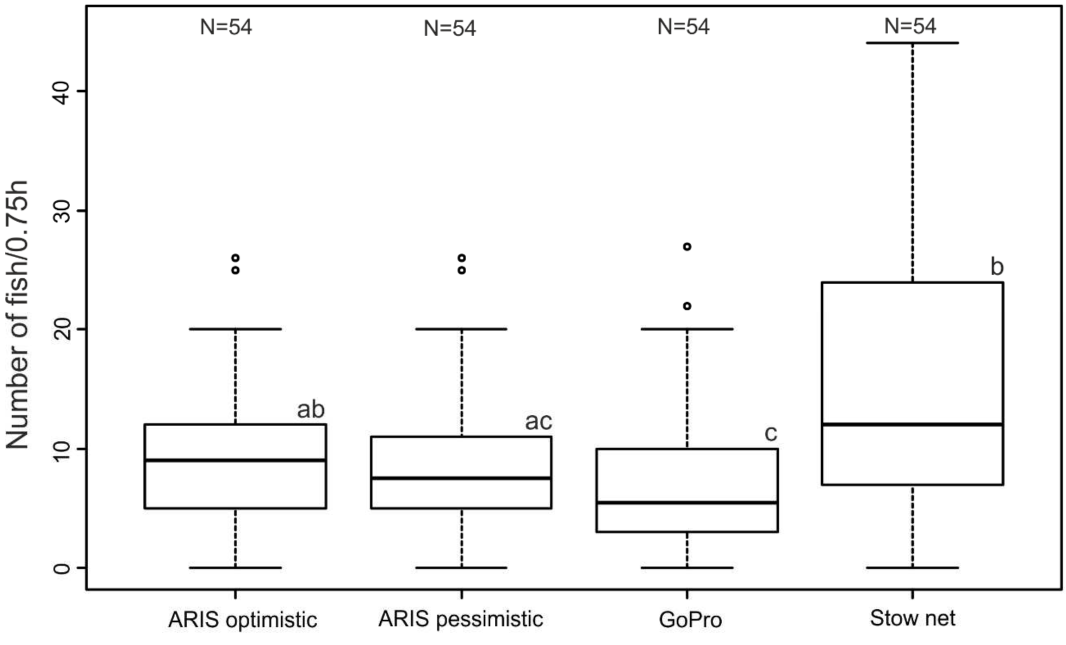


Figure 8: Boxplot of number of fish per 0.75 h detected during downstream passage through the sluice gate with the different methods, including sonar-based optimistic (ARIS optimistic), sonar-based pessimistic (ARIS pessimistic), camera-based (GoPro) and the net-based system (Stow net). Box indicates 25% quantile, median and 75% quantile; whisker indicates minimum and maximum values; and outliers (outside of the 1.5× interquartile range interval from the whiskers) are indicated by circles. Significant differences are shown by different letters (a, b, c).

3.5.2 Recorded lengths of fish

Contrary to the second hypothesis (2), the sonar- and camera-based systems measured greater total lengths than did the net-based system (Table 2, Figure 9). In the net-based system, the lowest mean size was recorded compared with the other systems. Analogously, as for the recorded number of fish, the sonar-based systems (128.52 ± 76.13 mm) obtained a result that was the most similar to the net-based catch (116.42 ± 85.96 mm), followed by the sonar-based pessimistic approach (130.93 ± 77.78 mm) and the camera-based system (147.11 ± 119.10 mm), with the latter showing the highest standard deviation. The camera-based (maximum 900 mm) and the net-based (maximum 840 mm) systems identified fish lengths > 710 mm, which were not detected by the sonar-based systems.

The net-based system recorded a 3-fold higher total number of fish of the Size class < 50 mm than did the sonar-based systems, and a 6-fold higher count of fish of this smallest size class than did the camera-based system (Table 2, Figure 10a). The Size class > 50-100 mm showed similar results, with a 2-fold higher count of specimens caught with the net-based system than with the sonar-based systems, and a 3-fold higher count than with the camera-based system. Both sonar-based and net-based systems recorded a similar number of fish for the Size class > 100-150 mm, whereas the underestimation of the camera-based system was also evident in the next size class. Considering the relative contribution of the total counts, both sonar-based approaches recorded a 1.8-fold higher proportion in this size class than did the net-based system. All of the systems recorded similar numbers of fish for the Size class > 150 mm, still resulting in shifts when considering relative contributions (Figure 10b). The net-based system caught a 2-fold higher count of fish than did the sonar-based systems in the Size class > 200 mm. In contrast, the camera-based system showed a 1.6-fold higher relative contribution for the Size class > 200-250 mm (Figure 10b). For the Size class > 250-300 mm, a 1.7-fold higher number of fish were recorded in the net-based system than in the two sonar-based systems (Figure 10a), whereas the percentage distribution was overlapping. In the largest size class (> 300 mm), the sonar-based and the net-based systems recorded almost identical values, whereas the values in the camera-based system were 1.4-fold lower than those in the net-based system. The relative contribution of the total counts showed a 1.5-fold greater fish count in the sonar and camera-based systems than in the net-based system.

Among the sonar and camera-based methods, SIMPER analysis identified the greatest dissimilarity between the net-based and camera-based systems (average dissimilarity = 70.68), followed by the sonar-based pessimistic (average dissimilarity = 62.84) and the sonar-based optimistic (average dissimilarity = 61.94) systems. Over all monitoring methods, the Size class > 50-100 mm showed the greatest contribution for the respective dissimilarity (camera-based: Size class > 50-100 mm = 50.23%; sonar-based pessimistic: Size class > 50-100 mm = 48.60%; sonar-based optimistic: Size class > 50-100 mm = 48.37%).

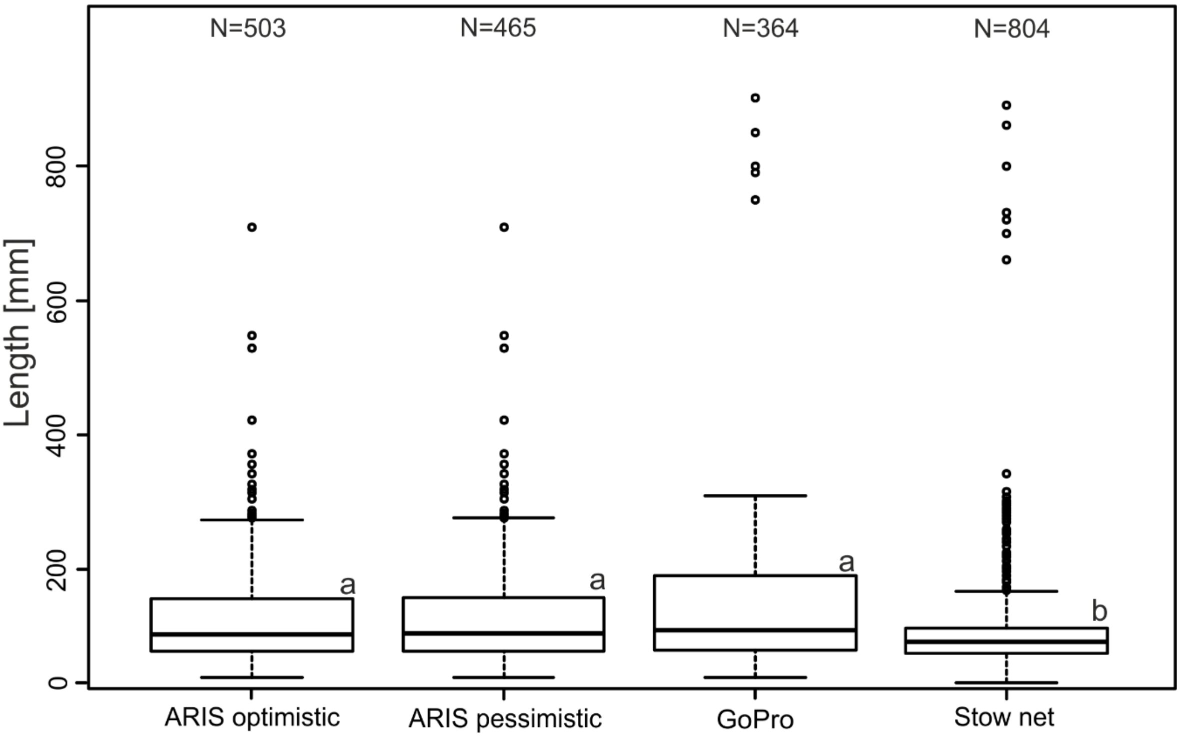


Figure 9: Boxplot of the average total fish lengths recorded by the different monitoring approaches, including sonar-based optimistic (ARIS optimistic), sonar-based pessimistic (ARIS pessimistic), camera-based (GoPro) and the net-based system (Stow net). Box indicates 25% quantile, median, 75% quantile; whisker indicates minimum and maximum values; outliers (outside of the 1.5× interquartile range interval from the whiskers) are indicated by circles. Significant differences are shown by different letters (a, b, c). The smallest caught specimen was 31 mm (Stow net).

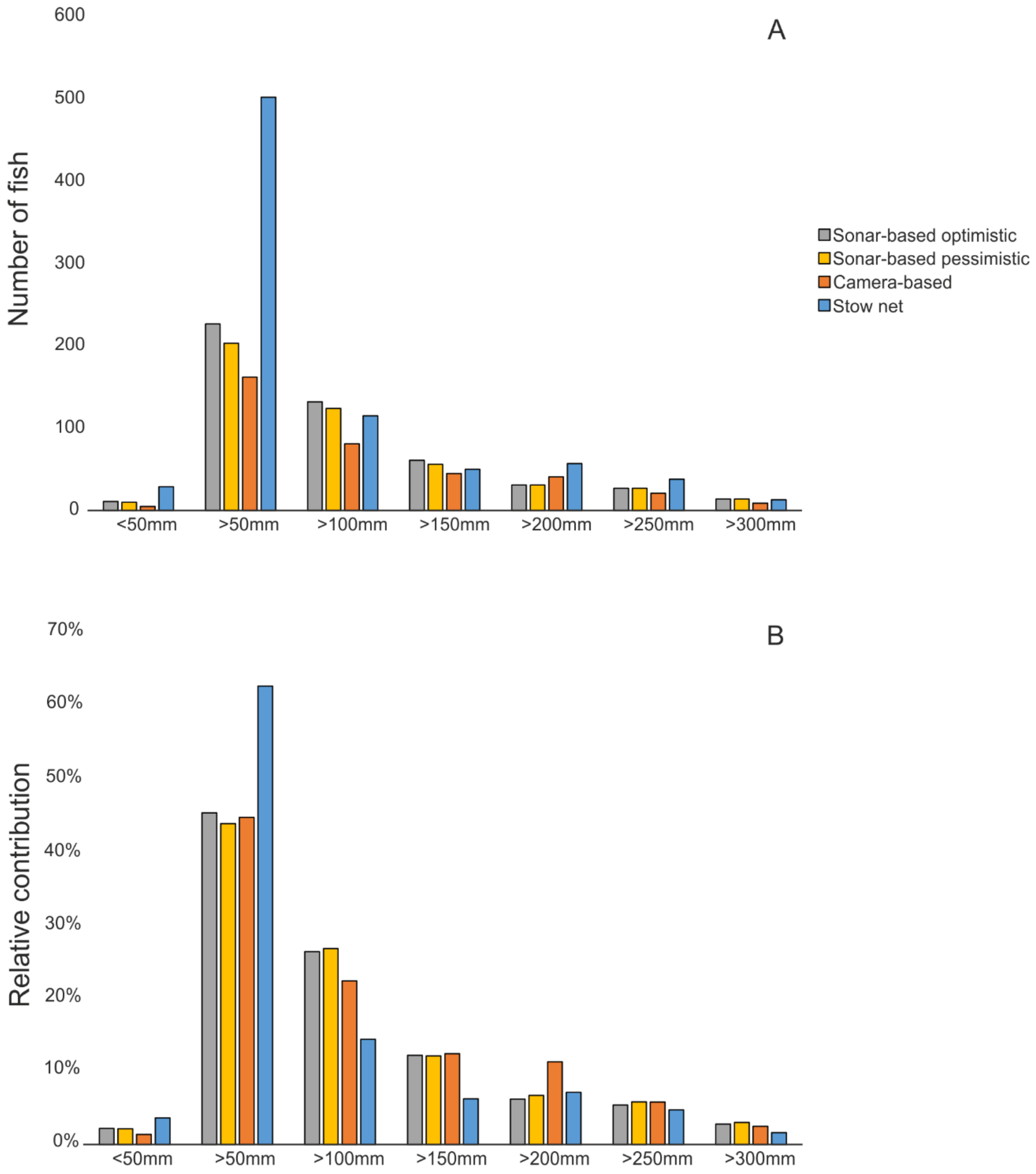


Figure 10: (a) Total number of recorded fish subdivided into seven size classes (<50, >50–100, >100–150, >150–200, >200–250, >250–300 and >300 mm). (b) Relative contribution of total counts subdivided into seven size classes. Net-based (blue), camera-based (orange), sonar-based optimistic (grey), sonar-based pessimistic (yellow).

3.5.3 Recorded species composition

In total, 11 fish species were detected using the net-based system over the 6-day study period (Table 2). In contrast, the camera-based system identified only 8 species, with 12.1% of specimens remaining unidentified. With the sonar-based data evaluation, no fish could be determined to species level. Thus, all sonar detections were assigned to 'unknown' species.

In line with the third hypothesis (3), the results of the recorded species composition between the net-based system and the camera-based system showed marginal differences. The most persistently detected fish species with both systems at a proportion over 60% was brown trout (*Salmo trutta,* L. 1758) (Table 2). Additionally, the camera-based system showed differences in the recorded number of certain fish species. Specifically, the camera-based system detected a 2.5-fold lower percentage of bitterling (*Rhodeus amarus,* Bloch 1782), and 2-fold lower percentages of bleak (*Alburnus alburnus,* L. 1758), roach (*Rutilus rutilus,* L. 1758) and stickleback (*Gasterosteus aculeatus,* L. 1758), which are all small-bodied species (Table 2).

The PERMANOVA showed a significant difference in the recorded species and size composition between the net- and camera-based systems (pseudo-F = 9.197, p (perm) = 0.001), yet some overlap in species and size composition was evident among both approaches in the NMDS (Figure 11). This overlap was largely explained by similar identification of larger specimens, whereas smaller individuals of < 150 mm often remained undetected with the camera-based system.

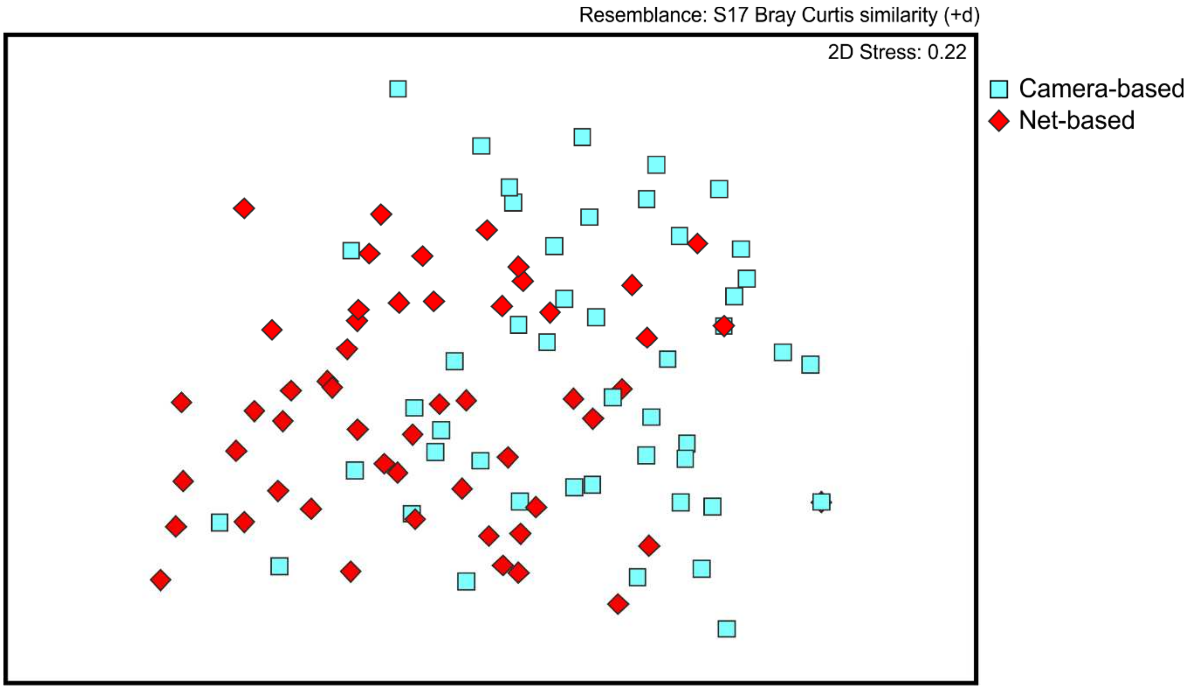


Figure 11: Non-metric multidimensional scaling (NMDS) plots based on Bray–Curtis similarity of the entire fish community recorded with the camera- and net-based monitoring techniques at downstream passage through the sluice gate. Two-dimensional stress is non-metric stress.

3.6 Discussion

Monitoring of fish movement in river corridors plays an important role for assessing river connectivity. Given the novel finding of the present study, sonar- and camera-based systems showed limitations in accurately recording the number, length and species composition. In addition, the performance of the tested monitoring methods ultimately also depends on light and turbidity conditions (camera-based), debris clogging and mesh size (stow net-based) as well as false automated detections inferences (sonar-based). These specific limitations of each of the tested methods need to be considered when selecting the most appropriate monitoring tool for the research question of interest and when interpreting the results.

3.6.1 Recorded number of fish

The lower number of fish in sonar- and camera-based records than the net-based catches indicated that the results of these methods are influenced by false-negative detections. This can result from fish being too small to be detected with the resolution of the respective systems, fish moving in the dead corner of the sonar or camera or from the two-dimensional picture in which an object can cover another object behind it. The latter is particularly relevant for downstream moving fish schools, resulting in an underestimation of individual numbers because of the overlapping of shadows and individuals in sonar as well as camera data (Becker et al. 2011). Regarding the camera-based systems (< 50% of the net-based catch), light conditions and turbidity can limit the detectability of fish as well. Because the present study was conducted under clear water conditions (maximum turbidity 4.18 NTU), turbidity can be excluded as a limiting factor. However, during the whole study period, the camera-based system detected zero counts after sunset, whereas the other systems continued recording.

Besides false-negative detections, false-positive detections could potentially affect sonar-based studies by, for example, erroneously counting debris as fish (Hateley & Gregory 2006). Because fish counts were lower for the sonar-based system than were the net-based catches, it can be assumed that this effect is not very pronounced in the dataset herein. Moreover, it can be assumed that false-positive detections are unlikely if the occurrence of tail-beat frequencies is being considered as applied in the pessimistic sonar-based approach. Accordingly, the high similarity between optimistic and pessimistic approach (deviation < 5%) suggests that this effect is negligible. With the camera-based system, false-positive detections are highly unlikely because of the additional information of color and structure of the fish in the high-definition video data. However, particularly in sonar data, it may also be that false-positive detections are leveled out by a high number of false-negative detections, which could at least partly explain the differences in size representation.

3.6.2 Recorded lengths of fish

Differences in the recorded specimen numbers can be largely explained by differences in the detection of small size classes among the methods. This is supported by the recorded higher average length of the sonar- and camera-based systems than the net-based system. Considering the different detection rates of the size classes, the sonar- and camera-based systems underestimated the number of fish (sonar-based < 100 mm and camera-based < 150 mm) compared with the net-based catches. The false-negative counts in this size class may result from high measurement errors of the respective method. Measurement conducted within the net-based system suggests a marginal error of ± 10 mm, owing to the movement of the fish during the measurement procedure. In contrast, the direct error of fish-length measurements by the sonar-based system seems to results from the position, the behavior and the angle of the fish within the ensonifed area. Burwen et al. (2010) demonstrated that even a measurement of the same adult salmon (900 mm) can vary ~ 130 mm during a full tail cycle. According to this measurement error, the chance to detect a fish < 100 mm decreases with a disadvantageous position within the ensonified area. Their study also highlighted that an adequate measurement was increasing when the fish was sinusoidal in shape, rather than straight and perfectly perpendicular (Burwen et al. 2010). Therefore, the overestimation of the sonar-based measured average size could be explained by species and individual specific swimming behavior during the downstream passage. Moreover, the chosen frequency of 3.0 MHz, which is recommended as 'identification frequency' by the manufacturer, seemed to be inadequate for certain size classes. Especially fish > 200 mm appeared smaller than they really were and the full body was not displayed on the echogram. As a result, the high-frequency setup is not recommendable during studies focusing on fish of > 200 mm, whereas Egg et al. (2017) conducted a successful survey with 1.8 MHz on European Eels of > 200 mm. In contrast to the software-based measuring of the sonar data, the evaluation of the camera-based data was performed manually estimating the size of the fish, without having a tool or scale bar. Surprisingly, the camera-based and the sonar-based measurement still showed highly similar results. This may be explained by the close position of the camera to the corridor (< 1 m), whereby adequate estimations could be conducted. Additionally, the corridor itself could be used as a size-reference during the evaluation. According to the present study, the camera-based system recorded a 1.4-fold lower number of fish than did the net-based system in the Size class < 150 mm. Consequently, the camera-based system indicated a minimum threshold of 150 mm and is, according to the present study, not recommendable for the monitoring of fish specimens < 150 mm.

3.6.3 Recorded species composition

The relevance of length-specific detection rates of the sonar- and the camera-based systems can be particularly problematic in surveys focusing on the demographic structure and on small species. The results of the present study indicated that sonar-based techniques are unsuitable for proper fish species identification, which is in line with the findings of Horne (2003). Only the very characteristic body shape of a few species, such as the elongated body shape of the European eel (*Anguilla anguilla*, L. 1758), allows a precise identification (Hateley & Gregory 2006; Egg et al. 2017). However, sonar images of river lampreys (*Lampetra fluviatilis*, L. 1758) could still be misidentified as eels in rivers where both species occur simultaneously (Belcher et al. 2001). In the present study, the net-based system caught five cyprinid species, which generate an overlap of body shapes during the sonar-data evaluation. Therefore, sonar-based migration studies should be conducted only in rivers, where an overlap in size and species shape is not crucial. Langkau et al. (2012) could successfully identify species by using the acoustic shadow and the body shape of four fish species on plates in an experimental setup. Because of the high effort, this setup is difficult to create under field conditions. In contrast, the camera-based system was able to produce a reasonable basis for a correct fish identification. However, as for the recorded counts and lengths, the camera-based system underrepresented the proportion of small species. In line with the finding of the minimum-size threshold of 150 mm for the camera-based system, the percentage of bleak (*Alburnus alburnus*, L. 1758; net-based mean size: 91 mm), bitterling (*Rhodeus rhodeus*, Bloch 1782) (43 mm) and roach (*Rutilus rutilus*, L. 1758; 76 mm) was two-fold smaller than with the net-based method. Therefore, camera-based systems can be recommended only for studies focusing on species composition of fish > 150 mm.

3.7 Conclusion

Sonar-based and camera-based systems provide a non-invasive approach to monitor fish movement without creating harm or disturbance to fishes, but are restricted in species and size-class representation and their dependency of power supply. In contrast, the net-based systems can most effectively record the fish movement among the different methods studied herein, with the highest number of recorded fish and the best representation of the species inventory. However, this monitoring method creates the highest disturbance for fish and is technically limited by the river discharge and the amount of floating debris. The sonar-based system can be used even during floods and turbid conditions, under which the camera-based system reaches its limits. However, the sonar and camera-based systems have their pros and cons concerning the counting and measuring of fish and the identification of the species. The sonar-based system can be recommended for the counting of fish movements of individuals > 100 mm, if an assignment of individuals to species is not necessary. During daylight conditions and in clear water, even low-priced camera-based systems represent an adequate substitute for net-based catches for fish > 150 mm, also allowing species identification. So as to extend this system for the usage during night, a combination with infrared light seems to be promising. In contrast, the movement of fish < 100 mm can be adequately monitored only by using net-based techniques.

4 Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant

This chapter was also published in: Egg L., Mueller M., Pander J. & Geist J. (2017). Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant. Ecological Engineering. 106. 349-357.

4.1 Abstract

Hydropower plants have been linked with high mortality and passage impairments during Silver Eel (*Anguilla anguilla*) downstream migration, but there is still a lack of effective and economically viable management options for safe power plant passage. This study used an Adaptive Resolution Imaging Sonar (ARIS) to investigate how undershot sluice gate management at a small-scale hydropower plant affects Silver Eel behavior during downstream migration. Not a single eel of out of 1323 counts used the eel bypass system, which is currently considered a technical standard. Instead, Silver Eels approached the opening of an undershot sluice gate and effectively used this corridor during their downstream migration. The opening size of the undershot sluice gate and the resulting higher current velocities in front of this corridor were identified as the most important triggers. Migration occurred primarily at night and peaked with rising discharge. This study suggests that undershot sluice gates can be used as a cost-effective downstream migration pathway and should be operated at night on rising discharge during the peak migration period for eels

4.2 Author contributions

EL, MM and PJ conceived the concept of the paper in discussion with GJ; EL organized and conducted the field work; EL processed the dataset; EL, MM, PJ and KJ watched the video data; EL and MM analyzed the results. EL wrote the initial draft of the manuscript under the supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

4.3 Introduction

Migrating fish species are considered the most critically imperiled faunal elements in aquatic ecosystems (Dudgeon et al. 2006). In particular, populations of long-distance migrating diadromous fish species such as the European Eel (*Anguilla Anguilla,* L. 1758) have had strong population declines, often beyond sustainable levels (Limburg & Waldmann 2009). This prompted the IUCN to classify the species as critically endangered (Jacoby & Gollock 2014). After hatching in the Sargasso Sea, *A. anguilla* undertakes one of the longest migrations in the animal kingdom, to the European continent (approximately 6,000km) (Schmidt 1922; van Ginneken & Maes 2005). After several years in freshwater habitats, mature European Eels (Silver Eels) migrate back to the Sargasso Sea for the completion of their life cycle, where all specimens die after spawning. During the past centuries, migration routes within most rivers have strongly decreased in longitudinal connectivity due to the construction of hydropower plants (HPP) and other barriers. Some authors have directly linked the observed decline in eel populations to Silver Eel damage during turbine passage (MacNamara & McCarthy 2014). Due to their elongated body shape, Silver Eels are much more susceptible to turbine blade impingement compared to other species, resulting in reported cumulative Silver Eel mortalities after multiple turbine passage of up to 100% (Doenni et al. 2001, Dumont 2005, Dumont 2006). As a means of conservation, the European Parliament issued an Eel Management Plan (Regulation Council of the European Union 2007). According to this plan, the escapement rate of Silver Eels should be at least 40% of the potential biomass a river system could produce in the absence of anthropogenic modification. Strategies to fulfill this plan and to facilitate downstream migration of Silver Eels currently include a diversity of management options such as the catching of Silver Eels and their transportation to the sea ("Trap-and-Truck") (McCarthy et al. 2008), identifying activity patterns at the onset of migration ("Migromat") (Adam 1999; Bruijs et al. 2009) for shutting down turbines, as well as technical measures to facilitate downstream movement (e.g. "Hassinger tube system") (Hassinger & Huebner 2009). However, to date there is a lack of information on the usefulness of many of those approaches. Some of the options such as shutting down turbines during migration or "Trap-and-Truck" approaches are either costly or not sustainable and thus not well accepted. Moreover, several factors that govern migration patterns and eel behavioral responses are not yet fully understood. For instance, management of sluice gates at existing hydropower facilities is a currently unexplored management option to facilitate downstream migration of eels that could be easily realized with little or no cost due to the comparatively small water volumes needed.

Most of the existing hydropower plants are equipped with sluice gates, which are primarily used for spilling of debris, offering a great potential for fish conservation if they were effective in attracting and guiding downstream migrating fish.

An evidence-based aquatic conservation approach requires evaluating different management options against predefined criteria to identify optimal solutions (Geist 2015). Thus, we tested if undershot sluice gate management affects Silver Eel behavior and downstream migration at an existing small-scale HPP considering season, daytime versus nighttime, and different flow conditions. Additionally, the functionality of the installed eel bypass system was tested during the migration period of *A. anguilla*. Specifically, we hypothesized that (i) Silver Eels recognize and use an undershot sluice gate as migration corridor, (ii) and that attraction of Silver Eels to this migration corridor depends on the opening width of the undershot sluice gate. Conversely, we hypothesized (iii) that Eel Activity in front of the fish protection screens upstream of the turbines decreases with the opening of the undershot sluice gate due to the attraction of *A. anguilla* to this alternative corridor.

4.4 Material and Methods

4.4.1 Study site

This study was conducted at a HPP at the Franconian Saale in Bad Kissingen in Bavaria, Germany (N50°10'47.5" E10°04'24.8"). As a tributary of the Main, the Franconian Saale belongs to the Rhine catchment, which is part of the natural distribution area of *A. anguilla.* The Franconian Saale is an anthropogenically modified river with a mean low water discharge of 2.9 m^3s^{-1}, a mean discharge of 12.1 m^3s^{-1} and a mean flood discharge of 114.0 m^3s^{-1} recorded at the nearest water gauge in Bad Kissingen (10km downstream of the HPP: N50°10'47.5" E10°04'24.8"). The hydrograph of the river is characterized by floods in fall and late winter, as well as periods of low water during summer. The entire river (136 km) is regulated by 17 weirs. The small-scale HPP is equipped with a Kaplan turbine with a maximum capacity of 280 kW and a horizontal fish protection screen with a gap size of 15 mm. During the eel migration events recorded in this study, the turbine was run at a mean capacity of 157.3 ± 95.7 kW. The HPP is equipped with an eel bypass system in front of the horizontal fish protection screen (Hassinger & Huebner 2009), which is intended to guide the eels unharmed into the tail water of the HPP. The Silver Eels can potentially enter this structure through holes in a zig-zag shaped tube, which is placed on the ground of the river in front of the fish protection screen.

After swimming through this structure, the Silver Eels reach the tailwater of the river by sliding down a flume. In close proximity to the turbine intake, a sluice gate exists (length: 6.25 m, height: 3.75 m). This undershot sluice gate is additionally equipped with an overshot spillway in order to lead floating debris into the tail water. The undershot sluice gate only operates during high flow conditions to guide large floating debris into the tail water. The water level of the headwater is regulated by a 17.65 m wide shutter weir on the orographical right side of the Franconian Saale. Since the turbine intake is limited to a maximum discharge of 10.0 m^3s^{-1}, any additional water in the river is lead over the top of the shutter weir. This results in almost constant current velocity conditions in front of the fish protection screen during rising flood levels. The study was carried out in two consecutive years (2015 and 2016).

The study was performed during a period of low flow conditions in late summer (Reference I: 28 September 2015 and 01 October 2015) and during the expected Silver Eel migration period, initiated by the first flood in late fall 2015 (Event I: 20-21 November 2015). Subsequently, during low flow conditions in fall 2016 (Reference II: 07-09 November 2016 and Reference III: 11-12 November 2016) and during high flow conditions (Event II: 24-26 October 2016 and Event III: 16-18 November). The weather situation and the lunar phase were recorded during the study period and are illustrated in Figure 12. Daytime was defined from sunrise to sunset (summer: Day=07:01a.m.-07:00 p.m.; Night=07:01p.m.-07:00 a.m.; fall: Day=07:31a.m.-4:30p.m.; Night=4:31a.m.-07:30a.m.). At the study site, the Silver Eels could only use two possible corridors for their downstream passage (eel bypass system and the opened undershot sluice gate) (Figure 12).

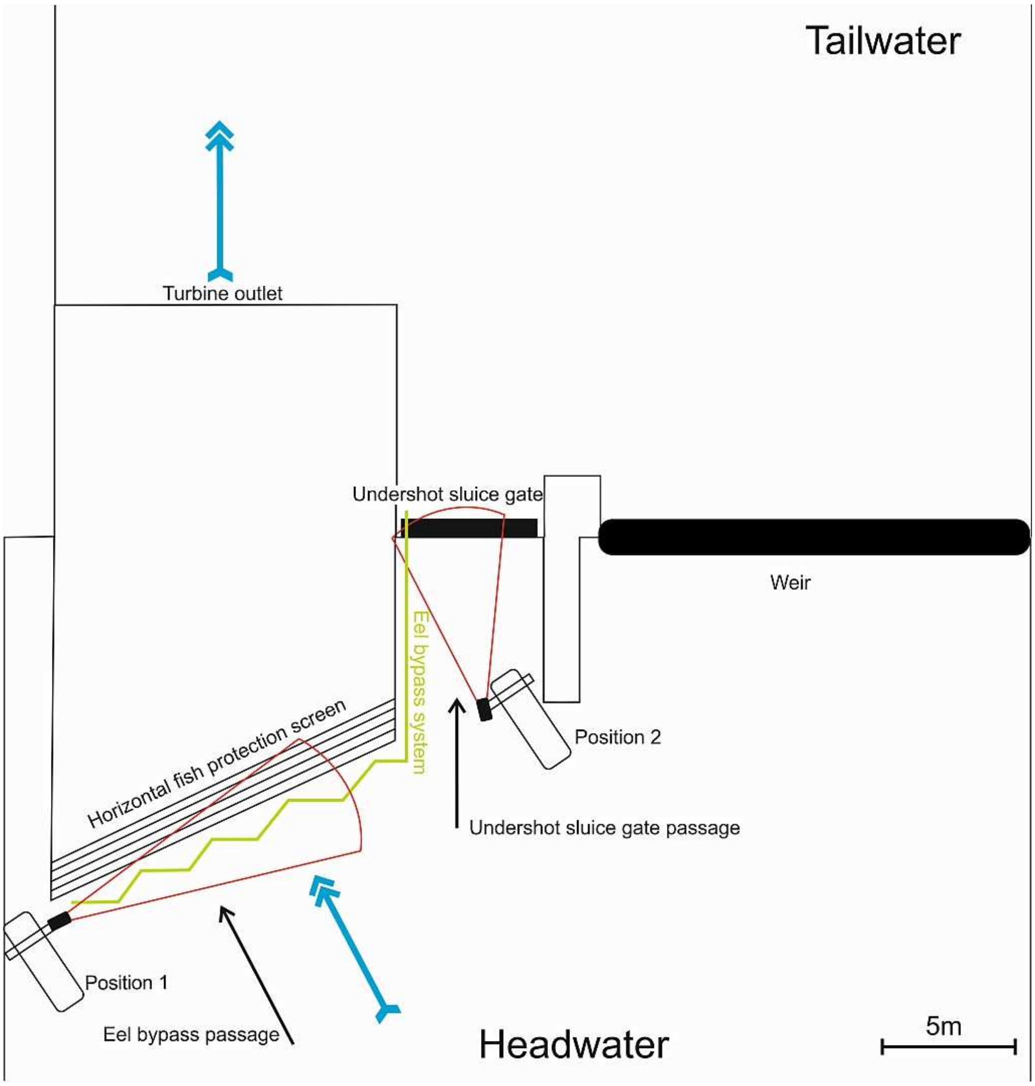


Figure 12: Top view of the study site (eel bypass system with the fish protection screen, opened undershot sluice gate and weir). Blue arrow=main current.

The opening width of this gate can be regulated and was manipulated in this study to test the effects of different opening widths on Silver Eel migration. Due to the installed fish protection screen (gap size 15 mm), no Silver Eels could enter the turbine passage.

4.4.2 Environmental variables

Current velocity [ms^{-1}] in front of the fish protection screen was recorded with an electromagnetic water flow meter (Ott MF pro, Ott, Kempten, Germany) 10 cm below water surface, in the middle of the fish protection screen and 10 cm above the river bottom twice a day. To be able to link eel behavior with current velocities in the undershot sluice gate, sonar measurements were used to calculate the specific current conditions of the different flow treatments in front of the undershot sluice gate. For this reason, the mean current velocity for each 0.25 h sample was calculated by the entrained debris, which passed this corridor, using the Software Echoview 6.0 (Myriamax, Hobart, Australia). Links between current velocity and Eel Migration intensity through the undershot sluice gate was then explored by correlation analyses. For a general characterization of the environmental conditions, different additional abiotic parameters were measured: turbidity [NTU] (Turbidity meter, WTW, Weilheim, Germany), oxygen [mgL^{-1}], pH-value, conductivity [µScm^{-1}] and temperature [° C] (Multimeter, WTW, Weilheim, Germany) twice a day at three measuring points in the head water of the HPP. The weather conditions (air temperature [° C], air pressure [hPa], rainfall [mm]) were recorded during the study period for every day by using the data of the meteorological station of the city of Bad Kissingen.

4.4.3 Acoustic detection of eels

Activity and downstream passage of Silver Eels were recorded with an imaging sonar (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) placed in two positions in front of the horizontal screen and the undershot sluice gate. The imaging sonar unit was operated with a horizontal beam angle of 28°, a vertical beam angle of 14° and a frequency of 1.8 MHz. The sonar was fixed on a small vessel (Carolina Skiff J14, Carolina Skiff LLC, Waycross, USA). The boat was swapped between the two different positions (Figure 12). The sonar was mounted 1.20 m under the water surface. The sonar provides video data which were saved in the field and subsequently analyzed.

4.4.3.1 Eel Activity

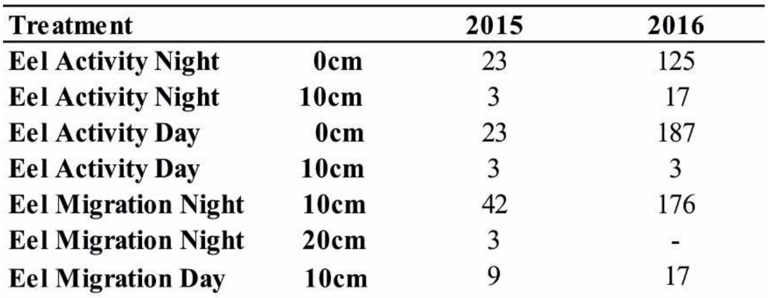
The first position (P1) was in front of the horizontal screen in order to record the Eel Activity (Figure 12). In this position the pitch was set to -16.4° and the tilt was set to -1.4°. Eel Activity was defined as follows: Every appearance of an eel inside of the ARIS video window was counted as one Eel Activity record. In order to test for diurnal patterns of the Eel Activity and the detected Eel Migration, both were recorded during daytime and nighttime. The Eel Activity in front of the screen was observed while the undershot sluice gate was closed during day and night in two consecutive years (2015 and 2016). In order to detect changes in the Eel Activity, the same area was recorded while the undershot sluice gate was opened during day and night in both study years. Due to the observed marginal Eel Activity during daytime, we only compared the different treatments (opened and closed undershot sluice gate) during nighttime. In order to validate the functionality of the eel bypass system, eels were counted visually and net-based with a fixed fyke net at the outlet of the tube slide, where the shallow water level allowed emptying the net. Visual observations at the tube slide were made for 0.25 h intervals every 1.50 h during the total observation period. For the visual observation, every Silver Eel was counted that was sliding down the tube slide.

4.4.3.2 Eel Migration

The second boat position (P2) was located directly in front of the undershot sluice gate in order to detect potential passing of Silver Eels (Figure 12). In this position, the pitch was set to -24.9° and the tilt was set to -29.3°. Eel Migration was defined as follows: Every eel on the video passing through the gap between the river bottom and the undershot sluice gate was counted as one Eel Migration record. Since no backward movement of the eels was detected through the undershot sluice gate, double counts can be excluded. The Eel Migration was observed during two phases of different opening widths in 2015 (20 cm and ≤ 10 cm) resulting in different current velocity conditions. Due to the lower discharge conditions in 2016 the undershot sluice gate operated only ≤ 10cm opening width.

4.4.4 Analysis of the sonar data

The total observation period (157.75 h) was subdivided into 0.25 h sample interval units (N=631). Eel Activity and the numbers of migrating eels were determined by an independent visual counting by four experts in order to eliminate personal bias. As a high consistency among the counts with no significant differences among observers was evident, the mean value of the four counts was used for the following analysis. Every expert watched the data independently with the Software ARIScope (Soundmetrics, Bellevue, WA, USA) and counted the Eel Activity and the Eel Migration. As a result, the study comprised 631 sample units of 0.25 h observation periods each (Table 3). However, technical constrains at the study site and the changing water level during the expected migration period of *A. anguilla* produced an uneven sample sized among the different treatments. A total of 52 sample units were recorded for the Eel Activity in 2015, comprising 23 sample units during daytime when the undershot sluice gate was closed and 23 sample units during nighttime when the undershot sluice gate was closed. Additionally, 3 sample units during daytime when the undershot sluice gate was opened and 3 sample units during nighttime when the undershot sluice gate was opened. Fifty four sample units of 0.25 h observation periods each were recorded for eel migration in 2015, comprising 9 sample units during daytime, 42 sample units during nighttime when the gap size of the undershot sluice gate was ≤ 10cm and 3 sample units during nighttime when the gap size of the undershot sluice gate was 20 cm.



Treatment		2015	2016
Eel Activity Night	**0cm**	23	125
Eel Activity Night	**10cm**	3	17
Eel Activity Day	**0cm**	23	187
Eel Activity Day	**10cm**	3	3
Eel Migration Night	**10cm**	42	176
Eel Migration Night	**20cm**	3	-
Eel Migration Day	**10cm**	9	17

Table 3: Replicates of the different Treatments.

In 2016 a total of 332 sample units were recorded for the Eel Activity, comprising 125 sample units during daytime when the undershot sluice gate was closed and 187 sample units during nighttime when the undershot sluice gate was closed. Additionally, the study comprised 3 sample units during daytime when the undershot sluice gate was opened and 17 sample units during nighttime when the undershot sluice gate was opened. One hundred ninety three sample units of 0.25 h observation periods each were recorded for Eel Migration in 2016, comprising 17 sample units during daytime and 176 sample units during nighttime. Due to the lower discharge conditions in 2016 the undershot sluice gate was not opened higher than 10 cm. For the analysis of the actual eel migration, only the sample units were used which could be clearly identified as a migration event. An actual migration event was defined by the first appearance of a Silver Eel.

4.4.5 Statistical analyses

In order to detect differences between the treatments we used univariate statistics. The dataset was analyzed with the software R (www.r-project.org). Each dataset was tested for normality and homogeneity of variance by using the Shapiro-Wilk-test and the Levene-test. The t-test was used if the data showed normal distribution. When data were not normally distributed, the Mann-Whitney-U-test was used to test for differences between the treatments. Spearman-Rank correlation and Power regression models were used to test for correlation between the mean velocity and the number of migrating Silver Eels in 0.25 h intervals. In all statistical testing, significance was accepted at $p < 0.05$.

4.5 Results

4.5.1 Observed Silver Eel migrations

A total number of 191 Silver Eels was recorded using the undershot sluice gate in 2015 (Event I: 20-21 October 2015). The great majority of them (96%) migrated during nighttime with a peak migration of up to 28 eels/0.25 h. During this migration peak, the water temperature reached 9.9 ± 0.4° C (mean ± standard deviation) and turbidity reached 17.3 ± 9.5 NTU. At the onset of the observed migration event the weather situation changed, with a 9° C decrease in air temperature, a 16h Pa decrease in air pressure and a 21 mm increase of rainfall within a day (Figure 13). The moon was in the first quarter of its phase with an up to 75.3% illuminated circle (Figure 13). Eel fishermen at the River Main, of which the Franconian Saale is a major tributary, confirmed that our study period exactly matched the predominant Silver Eel migration (Personal communication C. Schaetzl). In the following year, two migration events were recorded (Event II: 24-25 October and Event III: 17-18 November). During the first migration event in 2016 (Event II), a total of 23 Silver Eels were recorded using the opened undershot sluice gate. In this event, every Silver Eel migrated during nighttime (100%), with a peak migration of up to 6 eels/0.25 h. During this migration peak, the water temperature reached 9.3 ± 0.4° C and turbidity was 8.6 ± 0.2 NTU (Table 4). At the onset of the observed migration event the weather situation changed, with a 4° C increase in air temperature, a 15 hPa increase in air pressure and a 9 mm increase of rainfall (Figure 13). The moon was in the last quarter of its phase with an up to 34.2% illuminated circle (Figure 13). During the last observed migration event in 2016 (Event III) a total of 18 Silver Eels were recorded using the opened undershot sluice gate. As in Event II, every Silver Eel migrated during nighttime

(100%) with a peak migration of up to 3 eels/0.25 h. During this migration peak, the water temperature reached 4.8 ± 0.2° C and turbidity reached 4.9 ± 1.3 NTU (Table 4). At the onset of the observed migration event the weather situation changed, with an 11° C increase in air temperature, a 26 hPa decrease in air pressure and a 7 mm decrease of rainfall within a day (Figure 13). The moon was in the third quarter of its phase with an up to 95.0% illuminated circle (Figure 13).

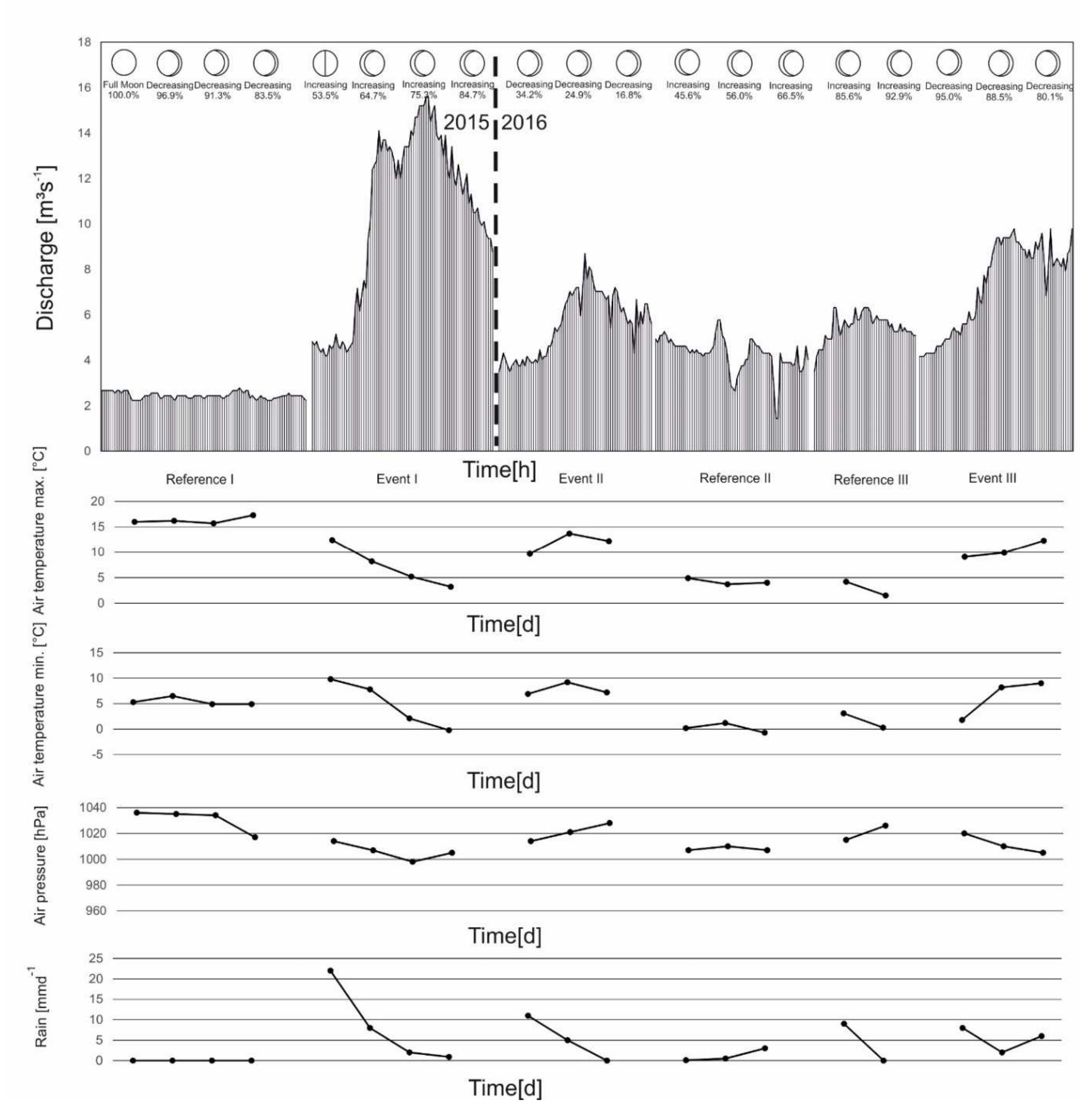
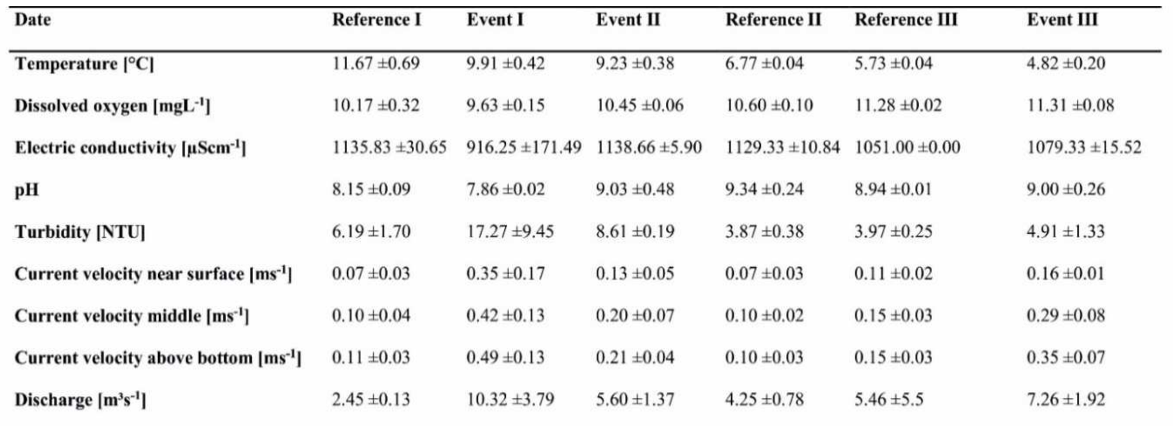


Figure 13: Lunar phase (percentage of the illuminated moon [%]) is shown on top of the figure. Discharge of the Franconian Saale during the study period.

Eel Activity as an indicator of an upcoming eel migration event revealed differences between the periods of low discharge and floods. During Reference I the Eel Activity in front of the fish protection screen was significantly lower (0.1 ± 0.4 eels/0.25 h) compared to Event I (64.2 ± 55.4 eels/0.25 h; Mann-Whitney-U-test: W = 9600; $p < 0.001$). During Event I in late fall the abiotic parameters changed, with a 1.8° C decrease in water temperature, three-fold higher turbidity, four-fold higher current velocity above bottom and a four-fold increase in discharge (Table 4).

As in 2015, during Reference II and Reference III the Eel Activity in front of the protection screen was significantly lower (0.0 ± 0.0 eels/0.25 h) compared to Event II and Event III (8.4 ± 7.4 eels/0.25 h; Mann-Whitney-U-test: W = 7772; $p < 0.001$). Event II showed a 3.0° C higher water temperature compared to Reference II and III, two-fold higher turbidity, two-fold higher current velocity above bottom and a 1 m^3 increase in discharge. Furthermore Event III showed different abiotic parameters compared to Reference II and Reference III conditions. Water temperature fell down to 4.8° C, turbidity raised up to 4.9 NTU, current velocity above bottom showed a three-fold increase and a 2.4 m^3 increase in discharge.



Date	Reference I	Event I	Event II	Reference II	Reference III	Event III
Temperature [°C]	11.67 ±0.69	9.91 ±0.42	9.23 ±0.38	6.77 ±0.04	5.73 ±0.04	4.82 ±0.20
Dissolved oxygen [mgL^{-1}]	10.17 ±0.32	9.63 ±0.15	10.45 ±0.06	10.60 ±0.10	11.28 ±0.02	11.31 ±0.08
Electric conductivity [µScm^{-1}]	1135.83 ±30.65	916.25 ±171.49	1138.66 ±5.90	1129.33 ±10.84	1051.00 ±0.00	1079.33 ±15.52
pH	8.15 ±0.09	7.86 ±0.02	9.03 ±0.48	9.34 ±0.24	8.94 ±0.01	9.00 ±0.26
Turbidity [NTU]	6.19 ±1.70	17.27 ±9.45	8.61 ±0.19	3.87 ±0.38	3.97 ±0.25	4.91 ±1.33
Current velocity near surface [ms^{-1}]	0.07 ±0.03	0.35 ±0.17	0.13 ±0.05	0.07 ±0.03	0.11 ±0.02	0.16 ±0.01
Current velocity middle [ms^{-1}]	0.10 ±0.04	0.42 ±0.13	0.20 ±0.07	0.10 ±0.02	0.15 ±0.03	0.29 ±0.08
Current velocity above bottom [ms^{-1}]	0.11 ±0.03	0.49 ±0.13	0.21 ±0.04	0.10 ±0.03	0.15 ±0.03	0.35 ±0.07
Discharge [m^{3}s^{-1}]	2.45 ±0.13	10.32 ±3.79	5.60 ±1.37	4.25 ±0.78	5.46 ±5.5	7.26 ±1.92

Table 4: Abiotic habitat characteristics during the study period. All values are given as arithmetic mean ± standard deviation.

4.5.2 Opening width of the undershot sluice gate

In line with our hypothesis, eels predominantly used the undershot sluice gate as a passage corridor in both years, with eel detections strongly depending on the opening width of the undershot sluice gate during Event I (opening width = 20 cm: 23.4 ± 5.5 eels/0.25 h; opening width ≤ 10 cm: 2.7 ± 1.6 eels/0.25 h). Despite a comparable low number of replicates (N=3) with an opening width of 20 cm, the detected Eel Migration was significantly higher at an opening width of 20 cm compared with an opening width of ≤ 10 cm (Mann-Whitney-U-test: W = 0; $p < 0.001$) (Figure 14).

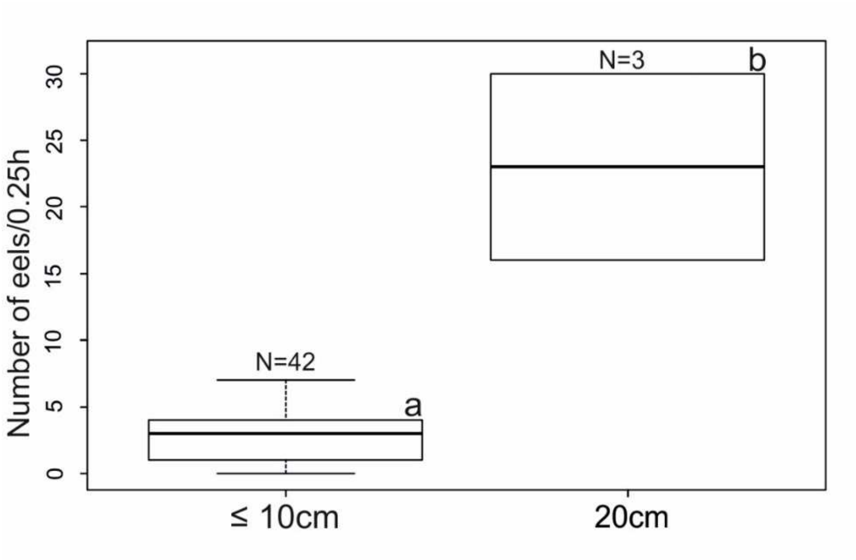


Figure 14: Boxplot of the detected Eel Migration/0.25h through the undershot sluice gate with an opening width of ≤10cm and an opening width of 20cm during Event I. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a,b).

Caused by the higher opening width of the undershot sluice gate, current velocity in front of this corridor increased by 26% during an opening width of 20 cm compared to an opening width ≤ 10 cm conditions (Opening width 20 cm: 0.5 ± 0.1 ms^{-1}; Opening width ≤ 10 cm: 0.4 ± 0.0 ms^{-1}). Current velocity was positively correlated with the amount of migrating Silver Eels/0.25 h (Spearman Rank correlation: S = 9811.202; $p < 0.05$; rho = 0.3537). Additionally the results of the Power regression model ($R^2 = 0.5545$) supported this outcome (Figure 15). The power regression model was mostly determined by the highest current velocity events at which the greatest Silver Eel passage occurred.

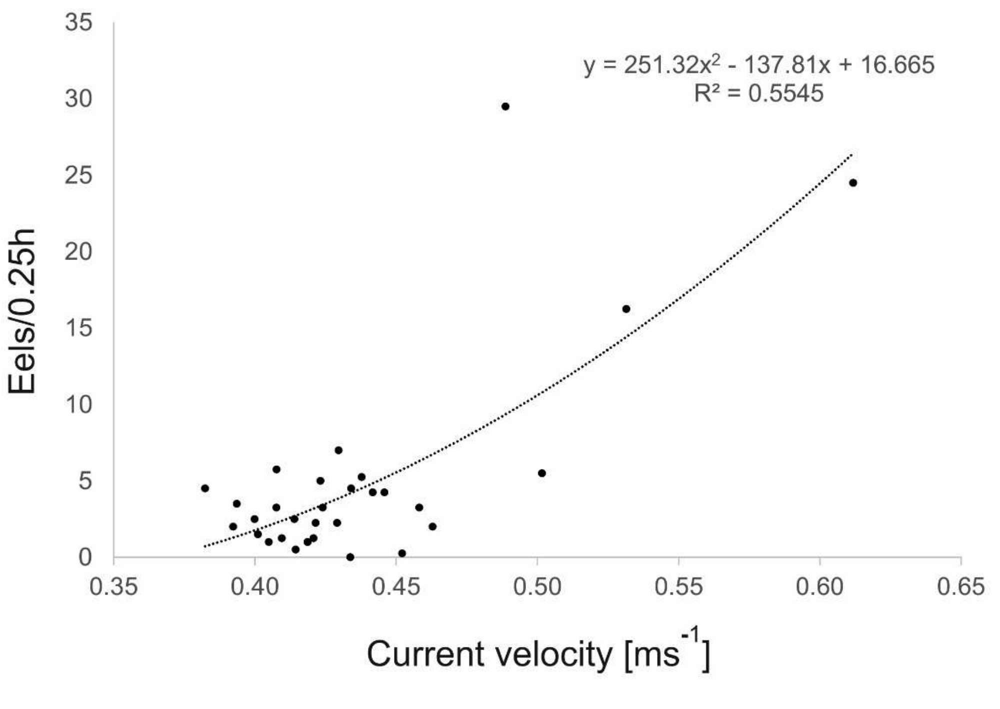


Figure 15: Power regression between the current velocity (x-axis) and the recorded number of migrated eels (y-axis). Each data point represents a 0.25 h time interval.

4.5.3 Screen approaches and gate operation

The analysis of nighttime Eel Activity in front of the fish protection screen of Event I revealed a response of *A. anguilla* to the opening of the undershot sluice gate. Following the opening of the undershot sluice gate, Eel Activity in front of the fish protection screen decreased (before opening of the sluice gate = 131.7 ± 15.9 eels/0.25 h; after opening of the sluice gate = 102.5 ± 20.1 eels/0.25 h) since eels were attracted to the alternative corridor. Due to the small number of replicates, the difference observed in 2105 was not statistically significant (t-test: t = 1.6094; df = 3.809; $p > 0.05$). In contrast, the analyses of Event II and Event III in 2016 revealed a significant response of *A. anguilla* to the opening of the undershot sluice gate (Mann-Whitney-U-test: W = 269; $p < 0.05$). The Eel Activity in front of the fish protection screen decreased significantly after the opening of the undershot sluice gate (before opening of the sluice gate = 10.6 ± 6.9 eels/0.25 h; after opening of the sluice gate = 5.6 ± 3.3 eels/0.25 h) (Figure 16).

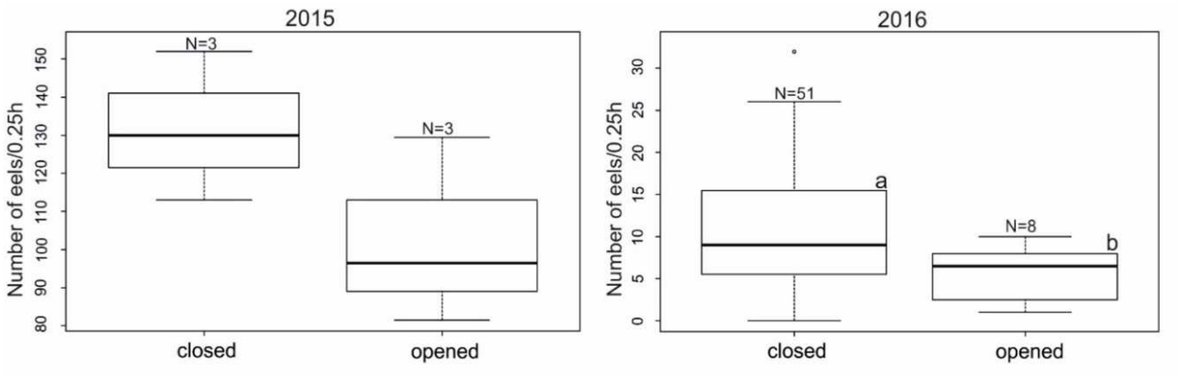


Figure 16: Boxplots of the recorded Eel Activity/0.25h in front of the fish protection screen for the opened and closed undershot sluice gate conditions during 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

4.5.4 Diurnal patterns of the observed eel migration

The results of this study revealed diel patterns of Eel Activity and Eel Migration over all migration events. During nighttime (117.1 ± 33.7 eels/0.25 h) the recorded Eel Activity in Event I was significantly higher compared to daytime (11.3 ± 3.5 eels/0.25 h; Mann-Whitney-U-test: W = 0; p < 0.001) (Figure 17). During an opening width of ≤ 10 cm, significantly more Silver Eels migrated through the opened undershot sluice gate during nighttime (2.6 ± 1.6 eels/0.25 h) compared with daytime (0.9 ± 1.1 eels/0.25 h; Mann-Whitney-U-test: W = 1682.5; p < 0.001) (Figure 18). In the following year, the Silver Eels revealed the same diel preferences. During Event II and Event III the recorded nocturnal Eel Activity was significantly higher compared to daytime (nighttime: 10.6 ± 6.9 eels/0.25 h; daytime: 0.6 ±1.3 eels/0.25 h) (Mann-Whitney-U-test: W = 10.5; p < 0.001) (Figure 18).

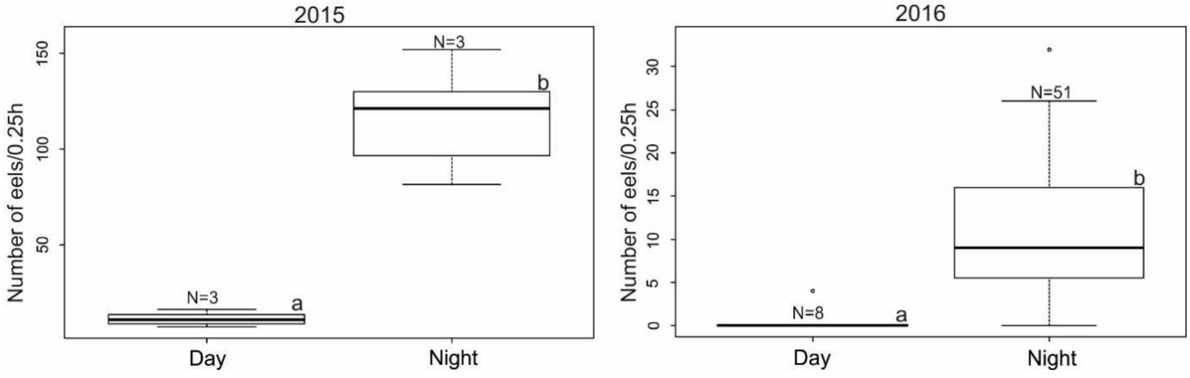


Figure 17: Boxplots of the recorded Eel Activity/0.25h in front of the fish protection screen during time period in 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

As in 2015, significantly more Silver Eels migrated through the opened undershot sluice gate during nighttime in 2016 (nighttime: 1.0 ± 1.0 eels/0.25 h; daytime: 0.0 ± 0.0 eels/0.25 h) (Mann-Whitney-U-test: W = 45; $p < 0.01$) compared with daytime (Figure 18).

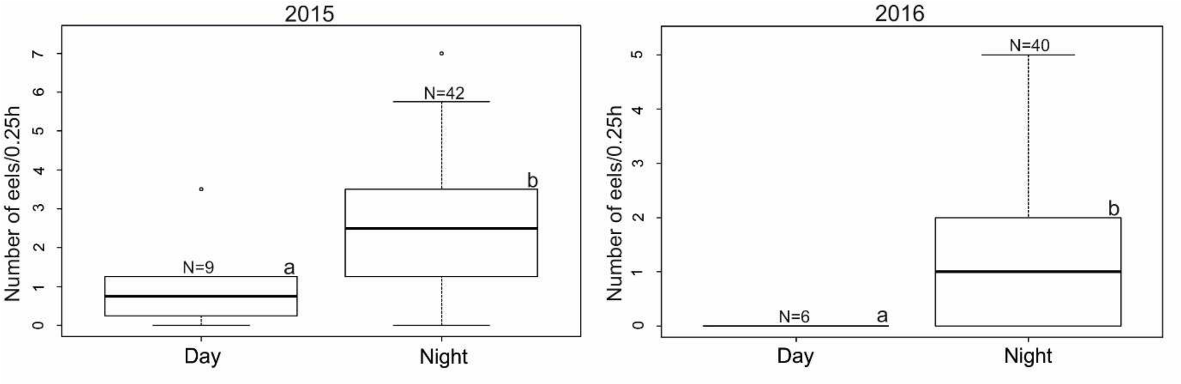


Figure 18: Boxplots of the recorded Eel Migration/0.25h through the undershot sluice gate during time period in 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

4.5.5 Eel bypass system

In contrast to the current perception on using the zig-zag shaped eel bypass tube as a technical standard to facilitate eel downstream migration, not a single Silver Eel out of a total eel count of 1323 over both years used this corridor. Particularly since 775 (in 2015) and 548 (in 2016) counts were recorded in front the fish protection screen which is located directly adjacent to the entrance of the eel bypass tube.

4.6 Discussion

The results of this study support that management of Silver Eel migration should primarily target a narrow time window during late fall and at nighttime, specifically during periods of increased water flow and increased turbidity. Undershot sluice gate management, which is currently hardly considered in facilitating the downstream migration of *A. anguilla*, appears to be a promising management approach at small-scale HPPs, since our data clearly suggest that the opening of these structures attracts Silver Eels. The opening size of the sluice gate and the resulting change in current velocity in front of this structure were the main parameters affecting its effectiveness as a migration corridor for Silver Eels. In contrast to the Silver Eel management approach proposed herein, currently used alternative management options, such as the methodology of "Trap and Truck", the "Migromat" and eel bypass systems (MacCarthy et al. 2008; Bruijs et al. 2009) are economically disadvantageous under most circumstances.

Silver Eels are generally known to follow the main current during their downstream migration (Gosset et al. 2005; Jansen et al. 2007; Travade et al. 2010) which can also explain the high activity of Silver Eels in front of the horizontal screen where the main discharge is located. The eel bypass system was originally expected to be a main corridor for the downstream migration of Silver Eel since previous laboratory studies by Hassinger & Huebner (2009) had suggested passage rates of > 90% through this type of system. However, none of the Silver Eels used this corridor at the field site studied herein, questioning the general applicability of this bypass. Based on our sonar observations, it is likely that the major reason for this is clogging by leafy debris, which is mobilized during flood events in fall. This debris accumulated in front of the entrance holes of the eel bypass system, in turn reducing the functionality of this corridor for the downstream migration of Silver Eels.

In contrast to the current perception that the orientation of the Silver Eels is restricted to the main current flow, the results of this study suggest that Silver Eels were able to detect and effectively use the opened undershot sluice gate as an alternative corridor, even though the discharge of this corridor was low compared to the main current. In this context, current velocity can play an important role for the detectability of alternative corridors by migrating Silver Eels as shown by Carton (2001). According to Baker and Montgomery (1999), Montgomery et al. (1995) and Montgomery et al. (1997) fishes are able to detect minimal changes in the current velocity with their lateral line. This is in line with the findings of this study, where a higher current velocity at the undershot sluice gate resulted in a higher number of Silver Eels using this corridor. After reaching the barrier of the fish protection screen, the Silver Eels started to actively search for alternative corridors and responded immediately to the opening of the undershot sluice gate.

According to Calles and Bergdahl (2009) and Adam et al. (2002), the maximum gap size of a screen should be 18 mm in order to prevent Silver Eels from entering the turbine passage. In addition to the narrow bar spacing of the screen, the positioning of the alternative corridor in direct spatial proximity to the main current can ensure optimal detectability for the migrating eels. The increase in migration activity with increasing opening size of undershot sluice gates likely results from the observed increase in current velocity, which acts as a trigger for Silver Eels to be attracted away from the main current. Consequently, it does not appear necessary to relocate the main current to the sluice gate, but the creation of an additional attraction flow seems to be advantageous, especially when combined with a fish protection screen that prevents Silver Eels from entering the turbine passage. According to Tudorache et al. (2015) the critical swimming capacity of mature *A. anguilla (*0.94 ms^{-1}) was not exceeded at the open end undershot sluice gate in this study (max. 0.61 ms^{-1}) Thus it can be assumed that the Silver Eels actively choose this corridor. In addition to their ability to detect changes in current velocity, fishes and especially *A. anguilla,* are also able to register minor changes of sound patterns (Slabbekoorn et al. 2010, Purser et al. 2016). Thus, a response of the Silver Eels to this signal can be an alternative explanation for the observed behavior.

Because a permanent opening of the sluice gate may be rarely possible, it would be beneficial to know over what environmental ranges the sluice may be best operated to maximize passage. Previous studies identified many factors (e.g. lunar circle, daytime, turbidity, temperature, and discharge) that were correlated with Silver Eel downstream migration (Reckordt et al. 2014, Barry et al. 2016, Behrmann-Godel & Eckmann 2003). Miyai et al. (2004) observed that the downstream migration occurred during new moon or in the moons last quarter. In line with this finding, the two migration events in 2016 (Event II and Event III) took place in the decreasing half of the moon phase. However, the migration event with the highest numbers of migrating Silver Eels in this study (Event I) was during the moon’s first quarter. Thus, it can be assumed that the lunar phase is not a major trigger for the Silver Eels to start their migration. Similar to this finding, no trend could be detected for air pressure as a trigger for the seaward migration of Silver Eels. According to Okumara et al. (2002) atmospheric depressions might be a major trigger for Silver Eels to start their migration (Figure 13). While Event I and Event III occurred during phases of decreasing air pressure, Event II took place in a phase of increasing air pressure. According to the present study, the increase in discharge and turbidity seem to be the most crucial triggers for the Silver Eel downstream migration at the Franconian Saale. Euston et al. (1997), Durif et al. (2003) and Behrmann-Godel & Eckmann (2003) also propose that the Silver Eel migration starts with the first increase of discharge in fall. Additionally, Silver Eels are supposed to reach a maximum migration rate at 9° C, whereas the migration rate decreases in both directions of higher and lower temperatures (Vollestad et al. 1986). This is partially supported by the findings of the present study, considering the discharge of the Franconian Saale and the mean temperature of Event I (9.2° C) and Event II (9.4° C). However, Silver Eels also migrated during Event III, when the mean water temperature reached 4.7° C. Consequently, it can be assumed that the migration period of *A. anguilla* is not strictly limited by lower water temperatures, even though the number of migrating Silver Eels was much lower compared to Event I and Event II. Since the ideal combinations of discharge and temperature only occur during narrow time windows throughout the year, the management of Silver Eel migration by opening undershot sluice gates can be limited to a few days per year and site, resulting in minimum disturbance of hydropower plant operation. Besides the measurement of environmental factors to predict eel migration events, visual observations of eel behavior using the Migromat system (Adam 2000) can improve the accuracy of the prediction of eel migration. Vollestad et al. (1994) showed that the migration of tagged Silver Eels is faster after sunset. According to Bruijs et al. (2003) and Miyai et al. (2004) most of the Silver Eels migrate during the night. This is also supported by our study, where Eel Activity as well as Eel Migration was higher during nighttime, indicating that undershot sluice gate management during the night could be sufficient to facilitate successful Silver Eel migration. Due to the increased water flow during a Silver Eel migration event, the additional water, which is anyway not useable for electric power production in the HPP, can be passed through an undershot sluice gate at no additional costs for the hydropower company. Boubèe and Williams (2006) recommend the opening of an alternative corridor during the whole migration period of the Silver Eels. Whereas an automated undershot sluice gate opening at rising water levels at nighttime during fall is likely to improve the successful migration of Silver Eel at the study site, and possibly elsewhere. Therefore, additional studies (e.g. net or telemetric based) should be carried out to validate the results of this study at different HPP's. However, it has to be considered that differences in water pressure caused by height differences at sluice gate structures have the potential to cause fish damage as detected in Baumgartner et al. (2006b) for fish larvae. Therefore, additional assessments of critical pressure differences should be carried out and compared to the potential damage of turbine passages. Additionally, an adequate downstream depth of plunge pools might be advantageous in order to dissipate energy and reduce the risk of striking downstream structures.

4.7 Conclusion

The approach of guiding Silver Eels through already existing technical structures of HPPs, revealed the potential to significantly improve the downstream migration of *A. anguilla*, at comparatively low economical cost. According to this study, Silver Eels used the opened undershot sluice gate as a corridor during their downstream migration in two consecutive years. After the opening of the undershot sluice gate, Eel Activity in front of the fish protection screen decreased. This leads to the conclusion that migrating Silver Eels were able to recognize the additional corridor, even if the main flow runs through the turbine passage. The detectability of the corridor was strongly dependent on the opening width of the structure and the resulting higher flow conditions in front of the alternative migration corridor. However, it is necessary to hinder the Silver Eels from entering the turbine passage. For that reason it is crucial that this corridor is blocked by an adequate fish protection screen (15 mm in this case). The results of this study confirmed that the migration of Silver Eels is a nocturnal event and measures with the aim of ensuring their migration should concentrate during nighttime. Additionally, the study identified discharge, the resulting increase of turbidity and the water temperature as the main triggers for the start of the migration. Management plans of HPP's should consider the opening of undershot sluice gates during the main migration period of *A. anguilla* at rising water levels at night and, and during fall months.

5 Effectiveness of the Electric Fish fence as a behavioral barrier at a pumping station

This chapter was also published in: Egg L., Pander J., Mueller, M. & Geist, J. (2019). Effectiveness of the electric fish fence as a behavioral barrier at a pumping station. Marine and Freshwater Research. 70 (10). 1459-1464.

5.1 Abstract

Dyke-based pumping stations have been linked with high fish mortalities during pumping events. Behavioral barriers like electrified fish fences have been proposed as a promising solution to prevent entrainment of fish into pumps. In order to test the effectiveness of such barriers, the intake of a pumping station was equipped with a new generation electrified fish fence while the fish behavior was observed with an Adaptive Resolution Sonar (ARIS) during non-electrified (reference) and electrified (treatment) operation modes. The results of this study revealed the functionality of the fish fence as a behavioral barrier with a fish turning rate of up to 72% at a mean water temperature of 4.3° C and a mean current velocity of 0.05 ms^{-1}. These case study field results suggest that new generation electrified fish fences may be a promising solution to reduce the impacts of pumping stations on fish.

5.2 Author contributions

EL conceived the concept of the paper in discussion with GJ; EL organized and conducted the field work; EL processed the dataset; EL, PJ and MM analyzed the results. EL wrote the initial draft of the manuscript under the supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

5.3 Introduction

Fish passage through technical structures like dyke-based pumping stations can cause a major threat for fish populations (McNabb et al. 2003, Buysse et al. 2014, Bierschenk et al. 2018). The occurring injuries can range from simple scale loss to cuts, amputations and death (Mueller et al. 2017). Since even so-called "fish-friendly" pumps (Pentair VPFI-600.200) can still cause high mortality rates of 25% under field conditions (Bierschenk et al. 2018), new concepts for passage prevention are necessary. In many cases mechanical barriers, like fish protection screens with a maximum gap size of 20 mm, are considered a successful way to hinder fish of larger size classes entering hydropower turbine structures (Ebel 2013). However, these concepts are inadequate for pumping stations due to the risk of screen clogging that can happen during flood events with high loads of floating debris from the hinterland of the dyke.

Besides mechanical barriers, behavioral barriers can be another approach to hinder fish entering the pumps. Behavioral guidance barriers, such as light, acoustics, bubble screens, and electricity offer an alternative to mechanical structures to reduce fish entrainment at pumping stations (Sager et al. 1987, Knudsen et al. 1994, Bullen & Carlson 2003, Noatch & Suski 2012). Compared to mechanical barriers these systems are not vulnerable to high loads of debris due to the sparse usage of physical components. However, the observation that these first generation electric fish fence structures were not as efficient as expected, resulted in poor acceptance of these technologies in the past (Turnpenny & O'Keeffe 2005, Larinier 2008).

Contrary to the concept of the first generation (Kreuzer 1986), the fish fence monitored in this study promises to combine the advantages of mechanical barriers with those of behavioral barriers while being at the same time unsusceptible for high loads of debris. Compared to the first generation of electrified barriers, the newly developed electrified fish fence (new generation fish fence) examined in this study is based on the concept of using horizontally tightened steel ropes with a gap size of 50 mm that are electrified with 80 V in a 3+/3- scheme (Aufleger et al. 2014). It has been proposed as a solution of using low voltage in a specific scheme focusing on high barrier effects without causing fish injuries. In contrast to the first generation, this fish fence uses steel ropes that can relaxed during periods with high amounts of floating debris to avoid clogging (Boettcher et al. 2013). According to the national report of Brinkmeier et al. (2016), this system seems to be promising on laboratory scale with blocking rates of up to 80% for several European fish species. The test here is to simply ask the question does this new design work to block fish. Therefore, the effectiveness of the new generation electric fish fence was tested as a corridor blocking behavioral barrier under field conditions at one of the largest dyke-based pumping stations in Germany, the Saubach station at the Danube in Deggendorf. The present study used an Adaptive Resolution Sonar (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) to record the fish behavior in the observation area in front of the electrified fish fence (treatment) and compared those results with a non-electrified state (reference). The present study aimed at assessing the functionality of the electrified fish fence as a behavioral barrier and at providing specific turning rates which can be used to support future management decisions. We hypothesize that fish will behaviorally respond to the horizontal electrified fish fence (i) and predict that significantly more fish will be deflected away from an intake pump when the fence is active (treatment) relative to when it is inactive (reference) (ii).

5.4 Materials and Methods

5.4.1 Study site

The study was conducted at a dyke-based pumping station at the Danube River in Deggendorf in Bavaria, Germany (N48° 48'45.9", E12° 57'51.6"). The pumping station was newly constructed for the purpose of flood protection. During periods of high discharge, it drains the hinterland beyond the dyke. In order to achieve this goal, the pumping station has four conventional pumps (Koester VPH 800) and one additional "fish-friendly" pump (Pentair VPF1-600.200) with a maximum performance of 0.4 m^3s^{-1}.

The newly developed electrified fish fence (Aufleger et al. 2014) with a gap size of 50 mm was installed in front of the water intake of the pumping station in January 2018. The fish fence consisted of a frame with horizontally tightened steel ropes covering the whole water intake, connected with a NEPTUN DC fish-guidance control system (PROCOM SYSTEM S.A., Wroclaw, Poland). It was operated according to the most effective setup previously identified in the laboratory study by Brinkmeier et al. (2016), i.e. operating at 80V and with a 3+/3- scheme as presented in Brinkmeier et al. (2016).

The "fish-friendly" pump ran at full speed during the experiment in order to study the effectiveness of the electrified fence under maximum suction and entrainment conditions. To observe the fish behavior in front of the electric fish fence, we used an Adaptive Resolution Sonar (ARIS Explorer 3000, Soundmetrics, Bellevue, WA, USA) running at 1.8 MHz and continuously producing 0.25 h videos. The sonar was mounted to a vessel in close proximity to the intake of the pump, 20 cm below water surface to observe the area in front of the electric fish fence as previously also applied in other behavioral studies (Egg et al. 2017, Egg et al. 2018) (Figure 19). The study was performed at three consecutive days, starting every day in the second half of the day during daylight until sunset (16th – 18th of January 2018).

5.4.2 Environmental variables

For an overall characterization of the environmental conditions, different abiotic variables were measured three times a day: turbidity [NTU] (Turbidity meter, WTW, Weilheim, Germany), dissolved oxygen [mgL^{-1}], pH-value, electric conductivity [µScm^{-1}], and temperature [° C] (Multimeter, WTW, Weilheim, Germany). Current velocity [ms^{-1}] in front of the fish fence was recorded with an electromagnetic water flow meter (Ott MF pro, Ott, Kempten, Germany) 10 cm below the water surface, in the middle of electrified fish fence and 10cm above the river bottom. Table 5 shows the abiotic habitat characteristics during the study period.

Day	1	2	3
Temperature [°C]	3.7 ±0.1	4.9 ±0.4	4.4 ±0.1
Dissolved oxygen [mgL^{-1}]	9.89 ±0.21	9.23 ±0.14	8.10 ±0.10
Electric conductivity at 20°C [µScm^{-1}]	522 ±1	563 ±1	561 ±7
pH	7.6 ±0.1	7.6 ±0.1	7.3 ±0.3
Turbidity [NTU]	4.91 ±0.15	5.56±0.20	6.88 ±0.15
Current velocity near surface [ms^{-1}]	0.05 ±0.02	0.05±0.01	0.07±0.02
Current velocity middle [ms^{-1}]	0.07 ±0.02	0.06 ±0.01	0.06 ±0.02
Current velocity above bottom [ms^{-1}]	0.03 ±0.01	0.05±0.01	0.06 ±0.02

Table 5: Abiotic habitat characteristics during the 3-day study period. All values are given as arithmetic means ± standard deviation.

5.4.3 Processing of the sonar data

In order to generate replicates (according to Boswell et al. 2008) the sonar was continuously running and generated 20 intervals à 0.25 h in which the fish fence was non-electrified (reference) and 16 intervals à 0.25 h in which the fish fence was electrified (treatment). In a first step, the raw data was pre-processed with the Software Echoview 8.0 (Myriamax, Hobart, Australia) in order to semi-automatically detect fish that entered the observation area (20 cm in front of the fish fence). In a second step, every potential fish track was manually assessed and the body shape and the individual behavior were identified. False positive detections made by the semi-automatic approach like large debris or interferences were deleted. In order to record the behavioral response of fish during their approach to the fish fence the specific change of fish behavior expressed in changes of swimming direction (horizontal turning angle [°]) of every fish was used. Fish that inverted their swimming direction (289-70°) after approaching the fish fence were classified as "turning behavior". Fish that continued their swimming direction after they approached the fish fence in an angle of 71-90° or 271-290° were marked as no reaction (Figure 20). Additionally every fish that passed the fish fence (91-270°) was marked as "passage" (Figure 19, Figure 20).

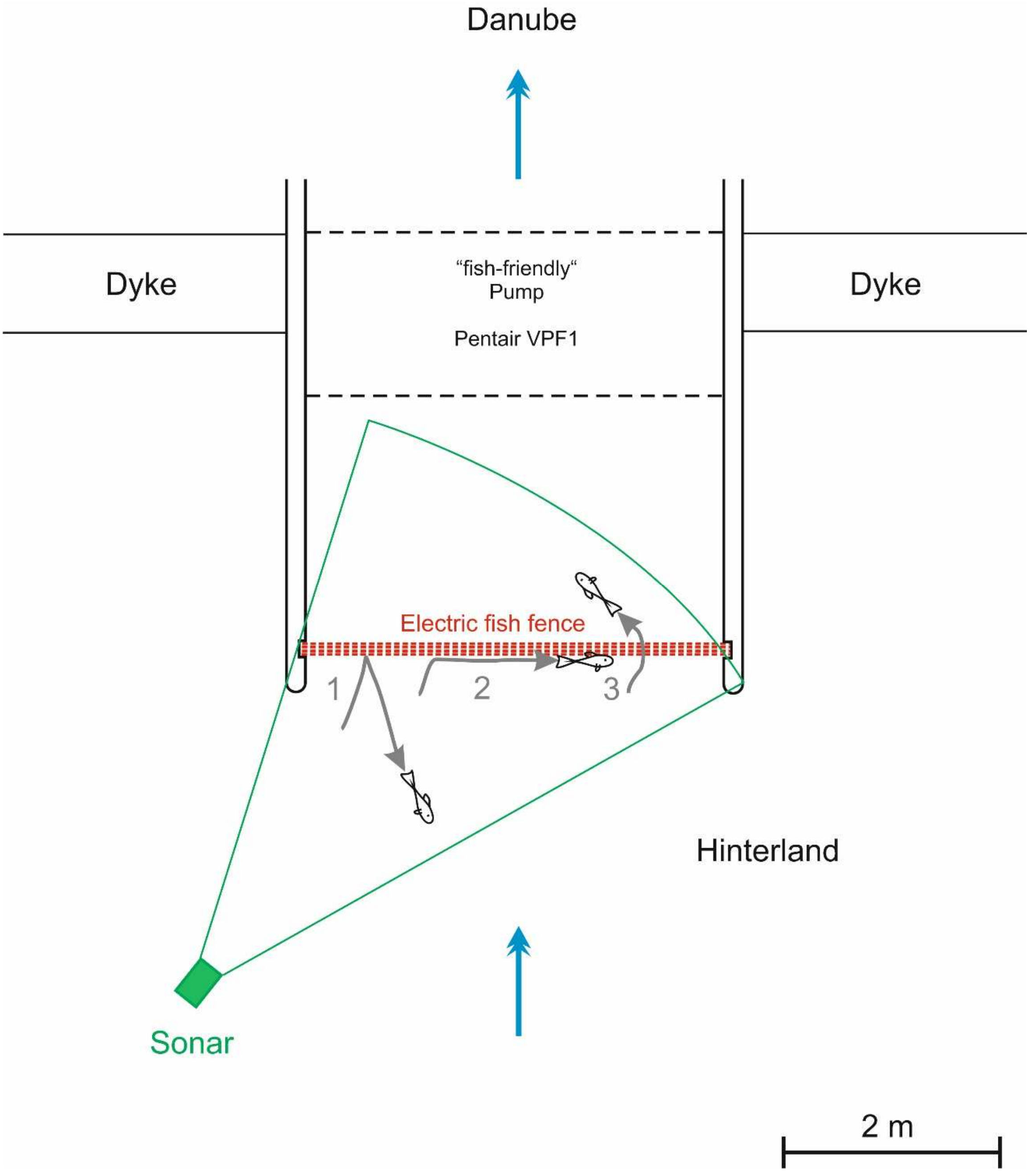


Figure 19: Top view of the study site (Hinterland, Electric fish fence, Pump and Danube). Blue arrow indicates the main current. Grey arrows = reaction types: 1 = "Turning behavior". 2 = "No Reaction". 3 = "Passage".

The number of the different reactions/ 0.25 h were counted and compared between the reference and the treatment. Due to uncertainties in the sonar-based species identification (Egg et al. 2018), only the body shape (deep-bodied and streamlined) and size (small = < 20 cm; large = ≥ 20 cm) were recorded. Using these data, we defined four morphotypes: large and deep-bodied body shape (LD), small and deep-bodied shape (SD), large and streamlined body shape (LS) and small and streamlined body shape (SLS). However, no fish of the morphotype SLS were recorded during the study period. In order to quantify the functionality of the fish fence the study present a specific turning rate (N turning behavior / N approached) of the fish approaching the device during treatment and reference conditions.

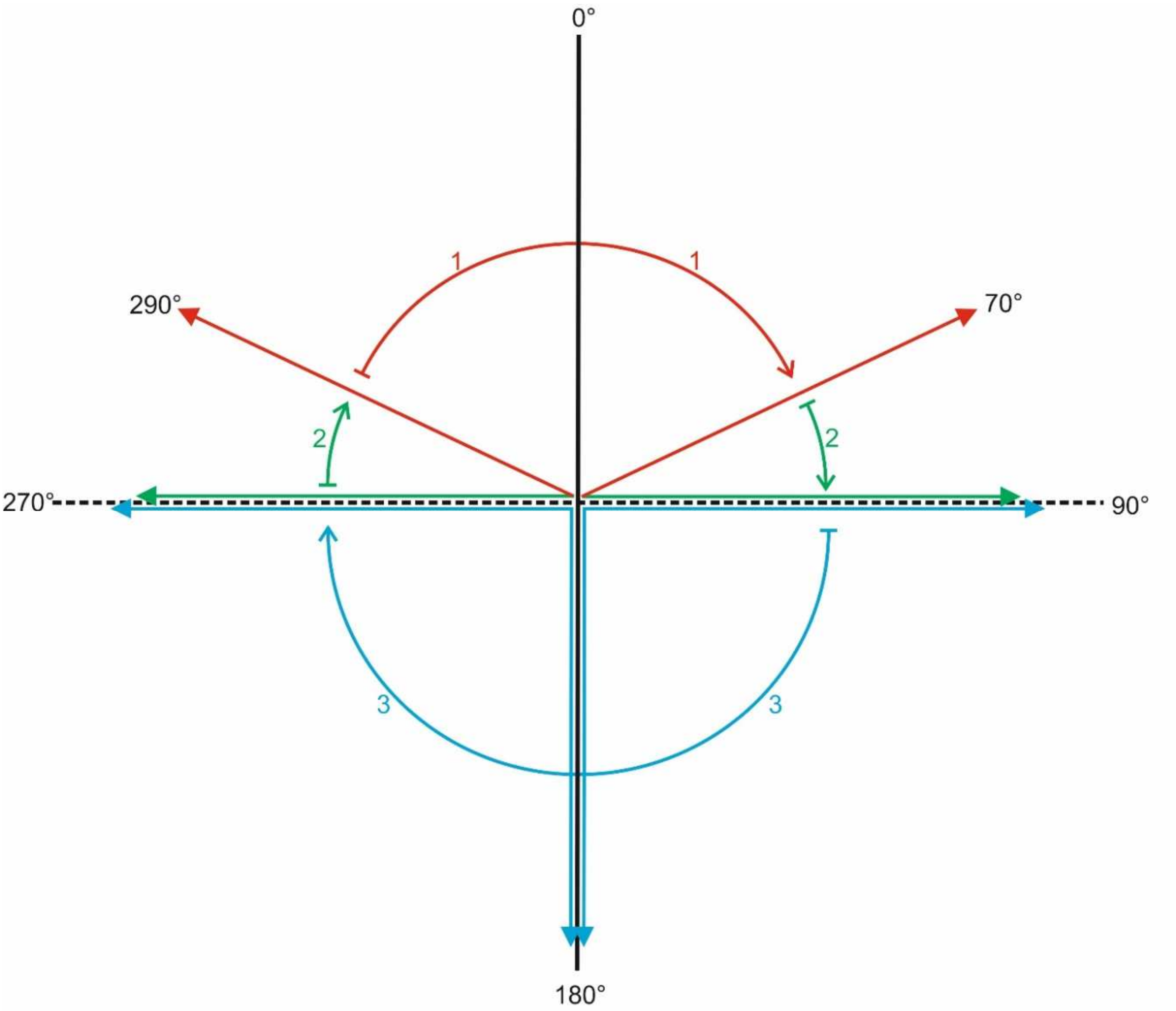


Figure 20: Definition of the different reaction types based on the horizontal turning angle, after approaching the fish fence (top view). The arrows are illustrating the swimming direction of fish after approaching the fish fence. Reaction types: 1 = "Turning behaviour", 289-70°; 2 = "No Reaction", 71-90° or 271-290°; 3 = "Passage", 91-270°. Dashed black line = Fish fence.

5.4.4 Statistical analyses

To test for differences between reference and treatment conditions, we used univariate statistics. The data was analyzed with the software R (R software, ver. 3.4.0, www.rproject.org). Each dataset was tested for normality and homogeneity of variance by using the Shapiro-Wilk-test and the Levene-test. Since every data set showed no normal distribution, the Kruskal-Wallis test and Bonferroni-corrected post hoc pairwise Mann–Whitney-U tests were used to test for differences of the behavior types (“turning behavior” and “no reaction”) between the treatment and the reference (electrified and non-electrified).

In order to highlight the proportions of the respective reaction types within every 0.25 h interval and to visualize possible overlaps between the reference and the treatment, multivariate statistics were used. The reaction and morphotype composition of each 0.25h observation interval were compared between reference and treatment conditions by using ANOSIM (Analysis of Similarities) and visualized in a NMDS (non-metric multidimensional scaling) based on Bray-Curtis Similarity (Primer ver. 7, Plymouth Marine Laboratories, UK, http://www.primer.com). In all statistical testing, significance was accepted at $p < 0.05$.

5.5 Results

During the study period, a total of 177 trails of fish movement were detected within the observation area of the electrified screen. Out of there, 57 fish were observed approaching the fish fence during the electrified state and 120 during the non-electrified state (Table 6).

Table 6: Sample size for each body type of fish and the respective number of reaction type during treatment and reference condition.

Body shape	Reaction type	Treatment	Reference
Large deep-bodied	*Turning behaviour*	17	0
	No Reaction	11	69
	Passage	0	0
Small deep-bodied	*Turning behaviour*	0	0
	No Reaction	0	13
	Passage	4	4
Large streamlined	*Turning behaviour*	21	0
	No Reaction	4	34
	Passage	0	0
Small streamlined	*Turning behaviour*	0	0
	No Reaction	0	0
	Passage	0	0

Out of the 177, eight fish were observed swimming through the screen (electrified = 4, non-electrified = 4). During the non-electrified state (reference) a seven-fold higher amount of the body shape LD and an eight-fold higher amount of the body shape LS without a reaction were recorded compared to the treatment. In contrast, turning behavior irrespective of body shape could only be observed during the electrified operation mode (Table 6). Figure 21 shows the number of reactions/ 0.25 h of the body shape LS within the observation area during reference and treatment conditions. During reference conditions, no "turning behavior" was detected, similar to the result of the group of "no reaction" where only four fish were counted during treatment conditions. During treatment conditions a significantly higher number of "turning behavior" were detected compared to reference conditions, whereas a higher number of "no reaction" were detected during reference conditions. The recorded fish behavior of the morphotype LD revealed similar patterns compared to the morphotype LS (Figure 21, Figure 22). However, overall a higher number of these morphotype were recorded during the study period resulting in a clearer distinction compared to morphotype LS. During the non-electrified state no "turning behavior" was recorded, whereas during the electrified state significant more "turning behavior" of the body shape LD was recorded (Figure 22).

Taking into account the results of the body shape LS and LD, the first hypothesis (i) was confirmed. Moreover, in line with the second hypothesis (ii) the results of the body shape LS revealed a significantly higher number of fish with "turning behavior" during the electrified state compared to the non-electrified state, whereas this could not be confirmed for the body shape LD. However, a total of 11 fishes were recorded showing "no reaction" within the observation area even though the fish fence was electrified.

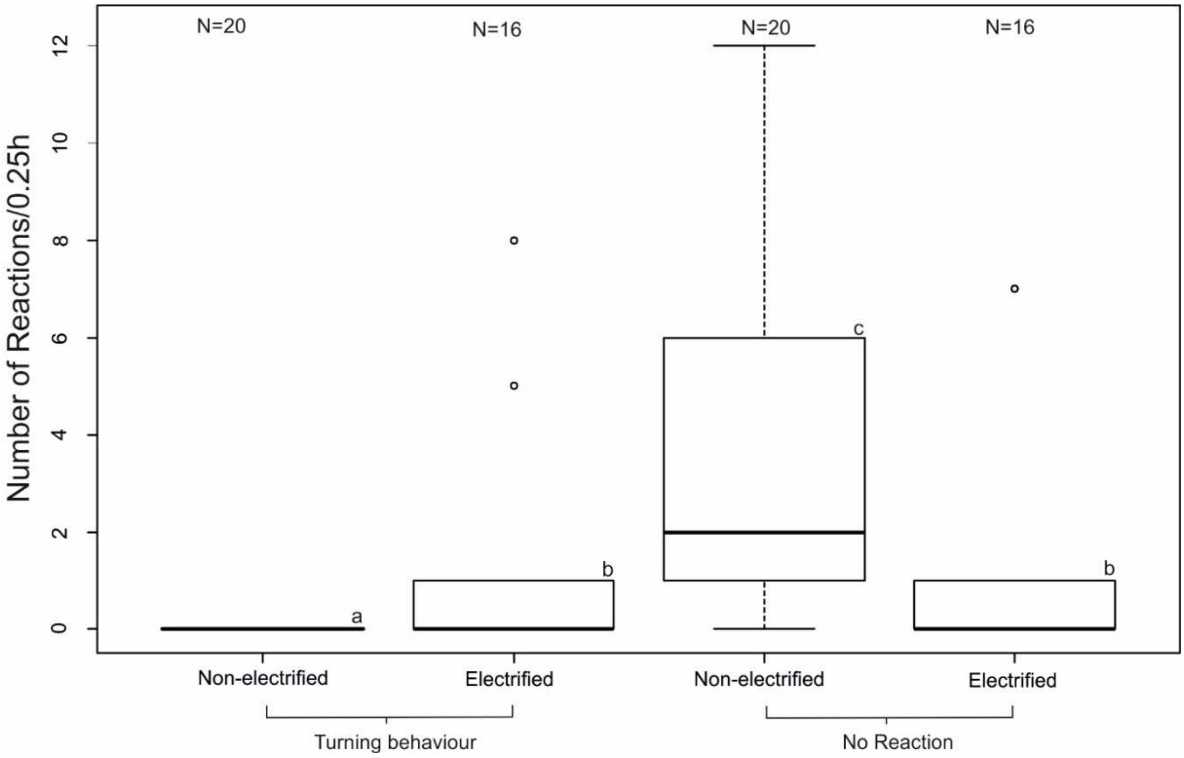


Figure 21: Boxplot of the detected number of reactions / 0.25 h of large and deep-bodied fish (LD) within the observation area of the electrified and non-electrified fish fence. Box: 25% quantile; median, 75% quantile; whisker: minimum and maximum value. Circle: Outliers. Significant differences were visualized by different letters (a,b,c).

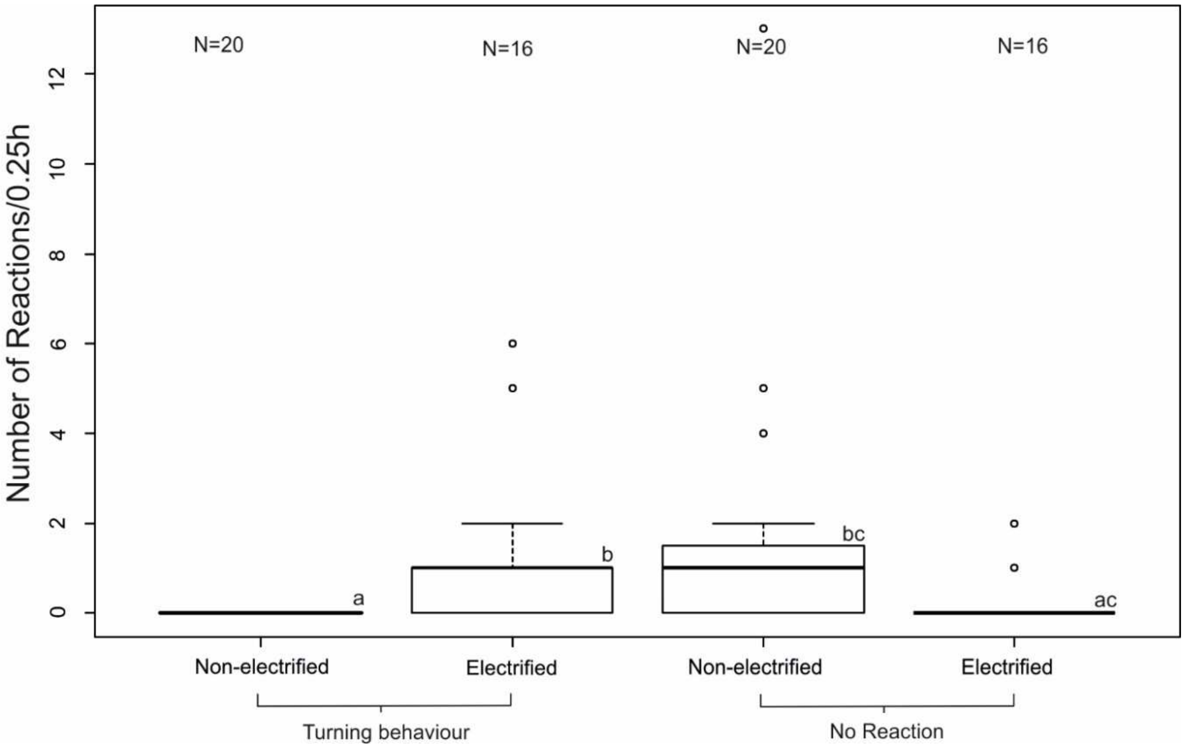


Figure 22: Boxplot of the detected number of reactions / 0.25 h of large and streamlined (LS) within the observation area of the electrified and non-electrified fish fence. Box: 25% quantile; median, 75% quantile; whisker: minimum and maximum value. Circle: Outliers. Significant differences were visualized by different letters (a,b,c).

In the multivariate analysis, no overlap was recorded between the fish behaviour of the two groups (reference and treatment) (Figure 23), supported by the results of ANOSIM which revealed significant differences between treatment and reference conditions (Global R = 0.355, p-value $\leq$ 0.001), supporting the first hypothesis (i). During the electrified state a lower average number of fence approaches (0.50 fence approaches/ 0.25 h) were recorded compared to the non-electrified state (0.85 fence approaches/ 0.25 h). During treatment conditions a higher average number of turning behaviour (0.79 turning behaviour/ 0.25 h) were detected compared to reference conditions (0.00 turning behaviour/ 0.25 h). In contrast the average number of “no reaction” was higher during reference conditions (1.93 no reactions/ 0.25 h) compared to treatment conditions (0.39 no reactions/ 0.25 h). During the study period, eight fish were observed passing the fish fence structure. During treatment conditions a marginally higher average number of fence passages (0.25 passages/ 0.25 h) were recorded compared to reference conditions (0.20 passages/ 0.25 h). In order to calculate a specific turning rate for the electrified fish fence, we considered only the morphotypes that were potentially able to pass the 50 mm fish fence (LS and SD). During treatment conditions a total of 29 fish were recorded approaching the observation area of the electrified screen, while 21 revealed the predefined reaction type of "turning behaviour", resulting in a turning rate of 72%. During reference conditions a total of 51 fish were recorded approaching the observation area, while none of those showed the reaction type "turning behaviour", resulting in a turning rate of 0%.

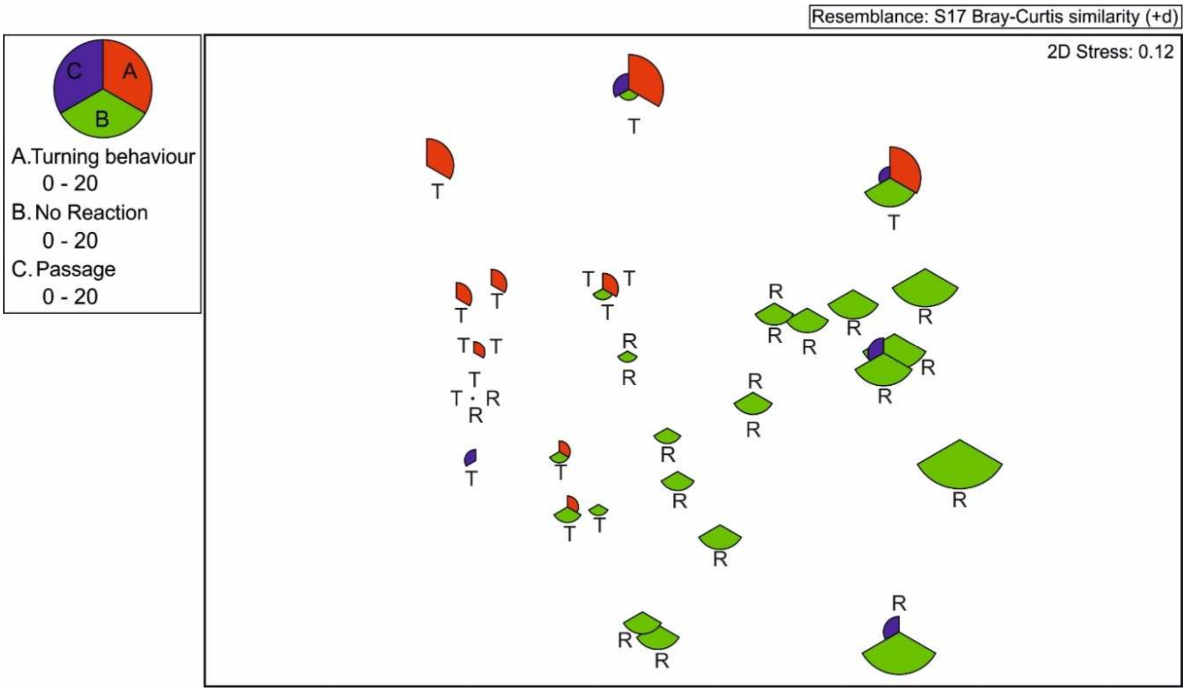


Figure 23: Non-metric multidimensional scaling (NMDS) plots of all 0.25h intervals based on Bray–Curtis similarity calculated from the counts of different fish reactions within the observation area of the electrified (Treatment) and non-electrified (Reference) fish fence. T: Treatment. R: Reference. Red: Number of turning behaviour. Green: Number of "No Reaction". Blue: Number of fish passage through the fish fence. Two-dimensional stress is non-metric stress.

5.6 Discussion

According to the results of the present study, the new generation electric fish fence significantly changed the behavior of fish within the observation area in the desired way. During the non-electrified operation mode the fish showed "no reaction" when approaching the fish fence, whereas during treatment conditions significantly more fish of the body shape LS revealed "turning behavior" and thus fled from the entrainment structure. Those fish showed a behavioral flee reaction towards the opposite direction of entering the electric field of the fish fence (i.e. against the current). Moreover, fish that showed this typical avoidance reaction once seemed to subsequently avoid this area. According to Topal and Csanyi (1999) mild electric stimuli, like the ones occurring within the observation area of the electrified fish fence, might explain such avoidance behavior. Therefore, the lower average number of fence approaches during the electrified compared to the non-electrified state could be explained by a learning effect as a result of negative experience.

Despite the change of behavior, a few fish fence passages were still observed during the study. Such fence passages do not only depend on the behavioral barrier effect, but also on the mechanical barrier effect that depends on the gap size. Berger and Lehmann (2017) recommend to combine a behavioral barrier with a mechanical barrier in order to increase the functionality. The chosen gap size of 50 mm in this study primarily affected the morphotype LD and resulted in a mechanical barrier for them potentially and in a higher blocking rate. Beside the effectiveness of the behavioral barrier, the mechanical barrier effect of the new generation fish fence should be considered as well. Moreover, the length of the used steel ropes and the resulting voltage loss could potentially affect the functionality of the electrified fish fence and should be examined in future studies. Generally, the turning rate of 72% observed in this field study is in line with the laboratory study of Brinkmeier et al. (2016) where a turning rate of 80% was observed. These findings of relatively high turning rates of new generation electric fish fences in laboratory and field studies are in contrast to earlier studies on old-generation fish fences (Kreuzer 1986, Larinier et al. 2008, Heimerl 2017). These first generation fish fences mainly differ in the setup of the anodes like vertical electrodes that can be configured as droppers from an overhead cable that can be lifted out of the way by passing debris or as floating steel cable electrodes mounted to bottom anchored cables. However, according to Gosset and Travade (1999) those systems revealed turning rates of only up to 15%. Also, Turnpenny and O'Keeffe (2005) and Larinier (2008) strongly advised against the first generation of electric fish fences in the past. The observed differences between old generation and new generation electrified fish fences may be attributable to structural and operational differences such as the different gap sizes and the different electrification modes.

Despite the promising results concerning the functionality of the new generation electrified fish fence, there are certain limitations that prevent generalization of our findings. First, this study was conducted at low water temperature (4.3° C) and at only one case study site with low current velocity and a given number of 33 fish species being present in the system (Bierschenk et al. 2018). Different reactions at higher water temperatures are likely at increased metabolic rates, although this may actually further increase turning rates compared to those in our study. The low current velocity in front of the fish fence within this study (0.05 ms^{-1}) is by a factor of ten below the maximum tolerable current speed in front of fish protection devices by national German standards (DWA 2005) and may allow even fish with weak swimming capacity to actively avoid screen collisions. It is likely that a higher current velocity in front of the fish fence can potentially cause higher entrainment rates, although this can be ruled out at the pumping station studied here which already operated at maximum pump performance throughout the experiment. Additionally, periods of high loads of debris and the resulting cleaning of the structure probably increases entrainment rates and needs to be examined in future studies. Another issue that needs to be addressed, is the functionality of the electrified fish fence under situations with different fish communities, and in particular during directed fish movement such as spawning migration of diadromous species. For instance, according to Heimerl (2017) turning rates for the migratory European eel can be much lower (ca. 30%) compared to other species. This may have resulted in an overestimation of overall turning rates at our study site where eel are not part of the native fish community within the Danube and they were not detected during the study.

In conclusion, the findings of our pilot field study on the effectiveness of the electrified fish fence suggest the usage of this device as behavioral barrier at the conditions tested in this study. In particular, the new generation electrified fish fence showed promising results concerning the desired change of the fish behavior during the electrified state, resulting in overall high turning rates even at low water temperature. However, these preliminary results need to be validated under different environmental conditions such as higher water temperature, higher current velocities in front of the fish fence and during high amounts of debris, as well as with other fish species such as eel.

6 General Discussion

The observation of fish behavior in front of hydropower plants and the understanding of specific behavioral patterns have the potential to improve fish conservation at HPP's and HEI's. However, due to the lack of suitable non-invasive technologies, most of the knowledge about fish behavior in front of HPP's and HEI's was gathered during laboratory conditions that could not been confirmed under realistic field conditions. After the launch of the second generation of High Resolution Imaging Sonars (Adaptive Resolution Imaging Sonar, ARIS Explorer 3000) a suitable technology for this interesting und undiscovered issue appeared, but it needed to be validated under realistic conditions first.

This thesis validated this innovative monitoring technique in the context of fish passage at HPP's and HEI's and applied these findings into concrete recommendation strategies for fish conservation in front of HPP's and HEI's.

Several conservation approaches like bypass systems and guiding structures are available on the market, which potentially improve fish conservation at HPP's and HEI's. The portfolio for ensuring upstream migration and movement ranges from natural bypass systems to technical vertical slot passes and lift solutions are all widely tested for functionality (Ebel 2013). In order to test for upstream movement efficiency, net-based and camera-based systems delivered previously unknown findings in understanding upstream movement and fish behavior for several fish species in the past (Alabaster 1970, Lucas & Batley 1996, Gowans et al. 2003). Contrary, solutions to ensure downstream migration of fish species are rare in general and the technical implementation reveal their limits when it comes to HPP's without sufficient fish protection screens that are capable to successfully guide fish into surface or bottom bypass system. According to Albayrak et al. (2018) there is a lack of effective fish protection solution for HPP's > 100 m^3s^{-1}. Due to the high amount of water running through the turbine these power plants cannot use fish protection means with narrow bar spacing and rely on guidance systems (Larinier 2008, Ebel 2013). However, due to a widespread skepticism on the side of public authorities and a lack of willingness by the hydropower operator to invest, guidance systems are rarely used in Europe and are consequently barely understood (Albayrak et al. 2018).

Moreover, downstream migration behavior and fish protection means are much less understood than the upstream solutions due to the lack of methods that are capable to monitor their effectiveness under realistic field conditions. Additionally, the state of the art net-based techniques for quantifying downstream fish movement is highly time and resource consuming, but with the needed sharpness of details concerning the number, size and species composition (Egg et al. 2018). However, this technique is not providing information about fish behavior that occurs prior to the entrance within a corridor. Additionally, this technique is vulnerable to high amounts of debris especially during high discharge conditions. Since most of the directed downstream fish movements (e.g. smolt migration of juvenile salmons and the Silver Eel migration of adult eels) are mostly situated during high discharge conditions, when this technique can barely generate reliable data. Moreover, flood periods are always accompanied by high turbidity which additionally excludes the usage of camera-based systems. As a result, a new innovative method is needed which is able to monitor fish movement and fish behavior at the same time to understand what fish individuals are doing in front of HPP or HEI structures and how many of them are reproducing the observed behavior patterns.

In order to identify a potential bias and to validate new monitoring technologies like camera- and sonar-based systems this thesis has tested those against a conventional net-based technique (multi-mesh stow-net), considering the recorded number of fish, the recorded length and the recorded species composition observed at a river corridor under realistic field conditions. Based on the results of this thesis, it turned out, that out of the innovative systems the sonar-based system showed its potential to monitor river corridors especially under difficult conditions like high discharge and/or during night. According to the results, sonar-based systems can be a great solution during turbid conditions and during the migration of fish > 100 mm. Beneath this determined minimal threshold, the sonar-based system was not able to record the amount of fish in an appropriate manner. Moreover, despite the disability of the sonar-based system to identify typical fish shapes, this primarily works with elongated and very characteristic body shapes like the European Eel, which could be clearly identified by the post-processing of the sonar data (Hately & Gregory 2006).

In a second step, the gathered knowledge about the sonar-based system was utilized to monitor the downstream migration and behavior of the highly threatened European Eel (*Anguilla anguilla,* L. 1758). The downstream migration of this catadromous species is known to be a nocturnal event, which additionally encourages the usage of sonar-based systems. Despite this assumption, the European Eels behavior and its migration are still mysterious in cases of temporal and abiotic triggers (Bruijs & Durif 2009). Several authors are still discussing about the direct role of lunar phases and air pressure conditions to the onset of the Silver Eel migration (Okumara et al. 2002, Cullen & McCarthy 2003, Tsukamoto et al. 2003). The results of this thesis highlights the role of rising discharges combined with temperatures below 9° C as one of the major triggers starting the spawning migration of the European Eel back to the Sargasso Sea, whereas air pressure and lunar phase were not influencing the migration behavior. According to the results, the prediction of the onset of the migration has become a tangible reality and conservation means can now be set in useful timeframes.

On the Silver Eels long-distance journey to their spawning grounds they have to approach several HPP's (Figure 1), resulting in high cumulative mortality rates with a significant decrease of the escapement rate which in turn violates the Eel Management Plan of the European Union (Regulation Council of the European Union 2007). Following the main current, Eels are accumulating at the turbine intake of the HPP. Therefore, these structures need to be equipped with fish protection screens which can effectively hinder mature Silver Eels entering the turbine passage. Moreover, the observation of the fish behavior in front of the fish protection screen revealed the irrepressible desire of the migrating Silver Eels to pass this structure. Therefore fish protection screens focusing on eel conservation should be ≤ 18 mm in order to reduce the chance of turbine passages of Silver Eels. Additionally, during their search for possible passage opportunities Silver Eels were even swimming in every water column layer which highly contradicts with another major assumption about Silver Eels being exclusively bottom oriented migrators. Even though the number of approaching Silver Eels was extremely high in close proximity to the bypass system, none of them were using this corridor by entering the bottom near the entrance holes. Consequently, the functionality of a widely accepted bypass system was disproven under field conditions during this study for the first time. This was very surprisingly due to a former laboratory study that revealed a passage rates for Silver Eels > 90% throughout this structure (Hassinger & Huebner 2008). Due to the high resolution of the sonar-based method the reason for the dysfunctionality was located in the natural dynamic process of a river during peak water flows in form of the remobilization of high amounts of sunken debris. It turned out, that the bypass system was not performing well due to a high amount of sunken debris in front of the HPP which was clogging the entrance holes of the bypass structure. As a result, the bypass structure might work under moderate discharge scenarios, while being inefficient under the typical conditions during the onset of the Silver Eel migration.

In contrast, the unconventional opening of an undershot sluice gate in close proximity to the turbine intake was generating a successful alternative corridor under low financial input and without any structural changes. The simple manipulation of the flow regime and the resulting attraction of the migrating Silver Eels enabled the successfully passage of 190 Silver Eels in one single night during a migration event. Moreover, this opportunistic change in behavior and the passage through an undershot sluice gate was observed for the first time, while opening gaps about 20 cm revealed higher passage rates compared to the opening widths of 10 cm. The finding of this alternative corridor and the resulting acceptance of the Silver Eels under field conditions might lead to the passage rate greatly exceeding 90 % and strongly supporting the Eel Management Plan of the European Union (Regulation Council of the European Union 2007).

In a last step, the sonar-based method was used to monitor fish behavior in front of a new generation electrified fish fence developed by Aufleger et al. (2014). This tool of behavioral barrier was stated to be inefficient and not being a recommendable device in Europe in the past, while being an accepted solution to block invasive fish in the United States (Swink 1999, Lavis et al. 2003, Jerde et al. 2013). The new generation of electrified fish fence developed by Aufleger et al. (2014) was used in front of the biggest pumping station in Bavaria in order to hinder fish of entering the pumping passage which can cause high mortality rates (Bierschenk et al. 2018). In order to go more in detail about the change in fish behavior patterns while entering the electrified fish fence, an advanced semi-automated post-processing approach was used (see Chapter 5). According to those findings, the turning angle of every fish that entered the fish fence was observed and analyzed with the Software Echoview 8.0 (Myriamax, Hobart, Australia). For the first time, the potential of the new generation electrified fish fence to significantly change fish behavior during the electrified state compared to reference condition has been confirmed under realistic field conditions. In contrast to the widely shared notion of being inefficient, this finding represents a paradigm shift in the discussion about the effectiveness of electrical fences in the European perspective.

The disproven functionality of a widely accepted bypass system, the misappropriation of an undershot sluice gate and the rehabilitation of a behavioral barrier technique raised the issue of whether our current knowledge about fish passage and behavior in front of HPP's and HEI's under realistic field conditions is sufficient enough to generalize assumptions and to state overall recommendations considering fish protection at HPP's and HEI's. Even though this thesis was not considering every issue, the uncovered novelties are giving valid reasons for scrutinizing the applicability of laboratory based results concerning fish passage to field conditions.

In the progress of the invention of innovative fish protection means in front of HPP's and HEI's, laboratory tests are necessary to collect first hydrological impressions of their functionality under flowing water conditions and represent the first pillar for effective fish protection means in front of HPP's and HEI's (Figure 24). In the case of promising hydrological conditions, a second step should be to test the functionality under the usage of experimental fish in order to collect data about the fish behavior in front of the structure. This includes also standardized assessments using caught wild fish or experimental fish from hatcheries. Hatchery fish are born and grown under artificial conditions implying a divergent fish behavior compared to wild fish what should be considered during the assessment of the functionality. According to that, hatchery fish can be helpful to collect general data about fish behavior like the reaction of certain fish species to electric stimuli (Topal & Csanyi 1999) but are unsuitable to collect data about migration behavior that only occur under realistic field conditions. As a result, the observed behavior patterns of hatchery fish might differ compared to wild fish leading to different assumptions considering the onset of a migration or the functionality of fish protection means during migration. At this point it is crucial to preference wild fish over the more easily available hatchery fish where possible. However, even if a study is using wild fish, like caught Silver Eels, the behavior of fish can also differ across time, abiotic water conditions and the state of the fish itself. The caught Silver Eels could stop their migration behavior due to the electric stimuli during the catch or by the change of abiotic conditions in the water tanks. Thus, those fish potentially show a different behavior in a flume under laboratory conditions, compared to a wild fish which was triggered by the change of abiotic conditions like the increase of discharge and turbidity (Egg et al. 2017). Nevertheless, laboratory studies represent an important tool in testing the functionality of new fish protection means. However, based on the results of this thesis, the next step of quality management has to be a validation under realistic field conditions representing the second pillar for effective fish protection means in front of HPP's and HEI's.

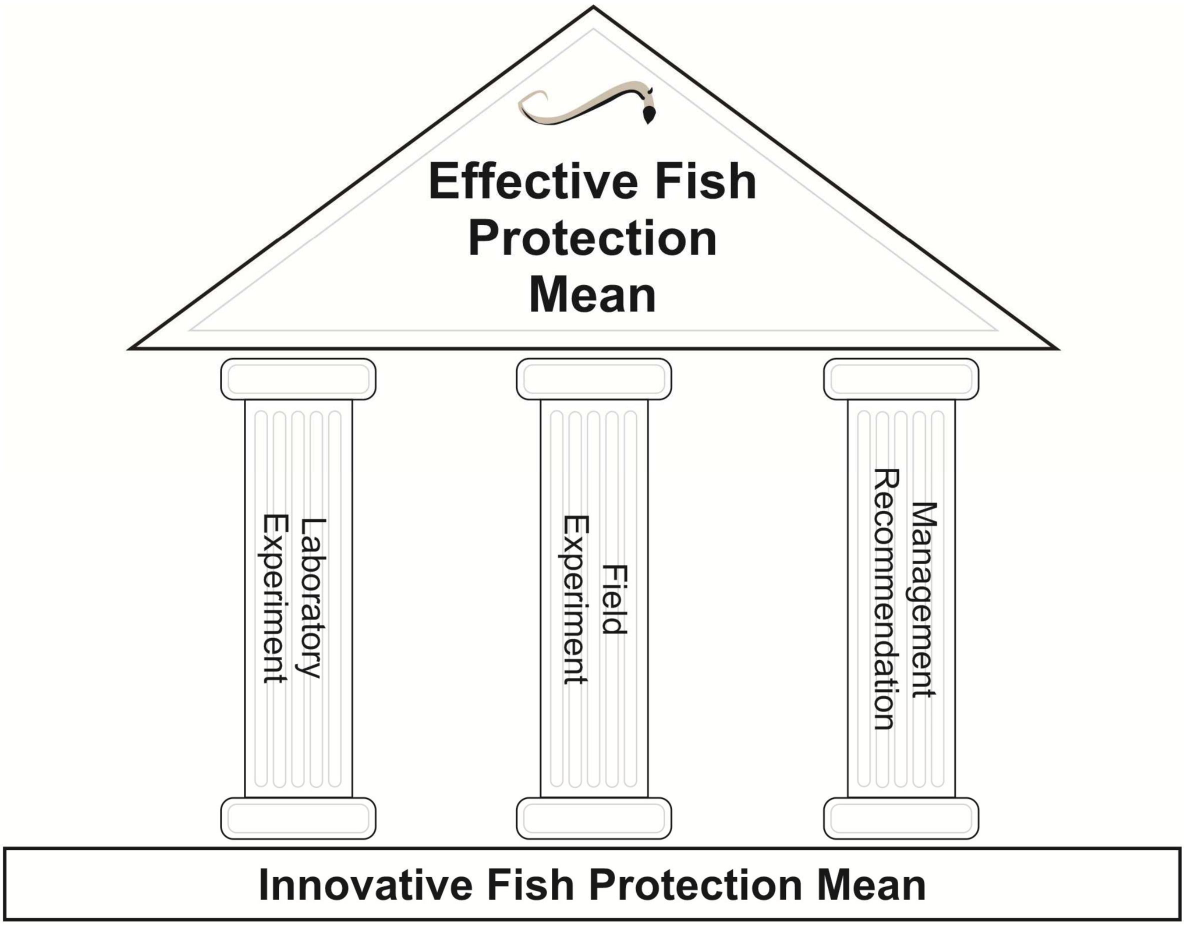


Figure 24: The three pillars for effective fish protection means in front of HPP's and HEI's.

The study has to fulfill the criteria of an evidence based study described in Geist (2015) and should be done within a relevant timeframe were migration events meet possible bottleneck of a bypass system or other corridors at HPP's and HEI's. Therefore a pilot site for the fish protection mean has to be chosen which should represent the average type of HPP's or HEI's in order to allow transferability of the collected data to comparable construction types. At this state the transferability of such a validation at one pilot site towards other HPP's or HEI's has to be critically scrutinized. Even if the construction of several HPP's in a river system is following one standardized construction plan (e.g. Lech River in Bavaria) the effectiveness of a fish protection mean can highly differ due to small construction deviations or changes in the flow regime as shown in Chapter 4. Ideally, the effectiveness of each fish protection means at every HPP should be tested under field conditions and the usage of a non-invasive method representing another important pillar of fish conservation on front of HPP's and HEI's (Figure 24). The choice of the method should be based on site specific conditions like the hydrological condition of a river (e.g. visibility, temperature, flood event etc.) the desired fish species (e.g. body shape) and the research question. Since the applicability of this very strict fine scale monitoring is not justifiable due to financial reasons but desired for effective fish conservation, the transferability of results to similar construction types is acceptable and necessary.

In the case of promising results within the laboratory scale and the field scale, those findings should be used to define concrete management recommendations that can be applied by the HPP or HEI operator in order to improve fish conservation at their sites (Figure 24). Moreover science seems to prefer just to deliver data or findings without being a part of the implementation of these. This last pillar for effective fish protection means represents the transition from the scientific world towards the practitioner world and deserves special attention.

Especially in Germany, there are a several guidelines and literature concerning the construction and the functionality of bypass systems and fish protection means (LAWA 2001, DWA 2005, DWA 2014). Those guidelines provide an important key tool for practitioners in the implementation of fish protection means. At the same time these guidelines go hand in hand with the duty to test for topicality and correctness of the respective content based on scientific studies. Consequently, there is a high requirement in the development of new methodological approaches that are able to test the assumptions under field conditions and under the site specific limitations. This thesis has highly demonstrated how the conversion of a cleaning structure (undershot sluice gate) can be a successful migration corridor, fish protection means can be unconventional but need to be validated especially under the site specific condition of every HPP or HEI.

In conclusion this highlights the important role of science in developing and testing new monitoring techniques and consequently detecting the deficits of already existing fish protection means at HPP's and HEI's. The results of this assessment then should be presented in front of all possible stakeholders on a local scale in order to discuss the site specific suitability of the fish protection means. In a next step the conclusions of this meeting need to be manifested in local modified management guidelines of the related HPP, highlighting once more the importance of site specific validation of fish protection means. After successfully testing the gathered findings at other HPP's with different hydrological and fish faunistic conditions, the management guidelines can be set to a national and more further to an international level.

However, when talking about the compatibility of HPP and HEI for fish populations, we need to remain at a realistic level. Turbines and pumping stations will remain as one of the major threats for fish population worldwide. The challenge right now is to improve HPP and HEI to minimize the potential threat for fish to a sustainable level that is not threatening the population. Consequently, following this way of improvement, the technical progress and the understanding of fish behavior is far enough to minimize the negative impact to fish populations. At the moment each technical structure has its own site specific problem with categories of impact that need to be examined with the described guidelines and improved or solved in a best case scenario. Therefore, we need a high understanding of fish behavior in front of HPP's and HEI's to recognize possible problems. Only the resulting scientific based in-depth knowledge has the potential to achieve this goal, because this enables to convince the often stubbornly one-sided opinion within the fisheries at the same time.

Despite the technical understanding of a HPP the understanding of the fish population within a river system is crucial to improve HPP and HEI technology. One remaining unsolved issue in fish conservation worldwide is the unknown size and quality of fish population within a river system. For instant, the actual impact to the Eel population resulted by the restoration of the longitudinal connectivity (Chapter 4) can only be estimated due to lack of knowledge about the real size and quality of the Eel population within the observed river system.

6.1 Outlook

The present thesis provides a new basis for the improvement of HPP's and HEI's regarding fish conservation. A new monitoring technique has been tested and at the same time established to observe and understand fish behavior in front of HPP's and HEI's. Moreover, this thesis provides a guide how to test the functionality of innovative fish protection means and highlights the transitions of the findings into concrete management recommendations for HPP's and HEI's operators.

The future of sonar-based monitoring methods and the constant improvement of the technology are going to increase the accuracy and the range of application while being more and more affordable. The market is open for sonar-based monitoring that is able to look into former unknown issues of fish conservation at HPP's and HEI's. However, there still needs further investigation of application possibilities and topics. The usage of higher frequencies and faster computer technologies has the potential to solve the problem of the correct identification of species in foreseeable timeframes. In this context the measurement accuracy will increase to a high level. Nevertheless, the present thesis can be used as a basis for future sonar-based studies that are focusing on fish behavior in front of HPP's and HEI's. The success of the present thesis should encourage scientists to continue the further development of the latest sonar-based technologies in order to create new monitoring approaches and to win new insights in fish behavior in front of HPP's and HEI's.

The management recommendation based on the findings within Chapter 4 to open undershot sluice gates during the main migration period of *A. anguilla* at water temperatures < 9° C, rising water levels, at night and during fall months could be transferred to similar HPP's around the globe. According to Pflugrath et al. (2019) high changes of pressure and shear can occur during an undershot sluice gate passage. Consequently, the management recommendation to open an undershot working as a successful corridor for downstream migration is limited to HPP's with heads ≤ 10 m. The opening of undershot sluice gates with heads > 10 m could cause major injuries to the migrator and is not recommendable. Nevertheless, the consequent application of this approach at suitable sites has the potential to significantly reduce the cumulative mortality caused by HPP's. This approach could also be an opportunity for the downstream migration of other fish species which should be considered in future studies.

Behavioral barriers like the tested electrified fish fence within Chapter 5, represent an actual new invention which is able to increase fish protection in front of HPP's and HEI's. Based on the findings of this thesis the electrified fish fence is able to hinder fish entering the pumping passage during the occurred abiotic conditions. In order to go further the electrified fish fence need to be tested under different abiotic conditions and different fish species. According to Aufleger et al. (2014) the electrified fish fence can also work as a guidance structure and is capable to successfully guide laboratory fish into a bypass system. Those guidance systems might be the only available solution to effectively increase fish protection at HPP's > 100 m^3s^{-1}. Consequently, this guidance system should be tested under realistic field conditions in order to transfer the findings in concrete management recommendation which can be applied by HPP operators.

The new findings, within this thesis highlight the importance of understanding fish behavior under field conditions. Looking into the fish behavior allows scientists to detect and understand behavioral patterns that can be used to improve bypass systems or other fish protection means. Applying the given guide for testing the functionality of fish protection means in front of HPP's can be a promising approach to improve HPP's on a worldwide range.

Scientific research and findings can only solve a small aspect of the conflict of hydropower and fish conservation. We must do away from the extreme positions that prevent constructive talks or compromises. Only through dialog can the fish passage topic be solved and new solutions can be discovered. Scientists need to be open for new fish protection means and the monitoring of these means with newly developed technologies. Especially at new sites, new ideas and compromises play the key role in improving HPP's and HEI's towards a tolerable level for fish population.

7 Publication list

7.1 Publication related to this thesis

Egg L., Mueller M., Pander J., Knott J. & Geist J. (2017). Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant. Ecological Engineering. 106. 349-357.

Egg L., Pander J., Mueller M. & Geist J. (2018). Comparison of sonar-, camera-and net-based methods in detecting riverine fish-movement patterns. Marine and Freshwater Research. 69 (12). 1905-1912.

Egg L., Pander J., Mueller M. & Geist J. (2019). Effectiveness of the electric fish fence as a behavioral barrier at a pumping station. Marine and Freshwater Research. 70 (10). 1459-1464.

7.2. Further Publications

Pander J., Mueller M., Knott J., **Egg L.** & Geist J. (2017). Is it worth the money? The functionality of engineered shallow stream banks as habitat for juvenile fishes in heavily modified water bodies. River Research and Applications. 33 (1). 63-72.

Geist J., Mueller M., Pander J., Knott J., **Egg L.**, Lohmeyer B., Genius D., Linde P. & Mayr C. (2018). Aktuelle Forschungsergebnisse Fischökologisches Monitoring an innovativen Wasserkraftanlagen. Erfassung der Einflussfaktoren auf Fischschäden und alternative Abstiegskorridore für den Aal. Der Flussmeister. Zeitschrift für Wasserwirtschaft. 19- 23.

7.3 Oral presentations

Egg L., Pander J., Mueller M., Knott J. & Geist J. (2017). Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant. Invited Talk. Bavarian Environment Agency. December 2017.

Egg L., Pander J., Mueller M. & Geist J. (2019). Comparison of sonar-, camera-and net-based methods in detecting riverine fish-movement patterns. Invited Talk. Fish Passage Conference Albury AUS. December 2018.

7.4 Poster presentation

Knott J., **Egg L.**, Mueller M., Pander J. & Geist J. (2015). Assessment of fish damage and habitat quality. Fish Passage Conference Groningen Netherland. June 2015.

8 Author contributions to the chapters

Chapter 3

EL, PJ, MM and GJ designed the concept of the experiment; EL organized and conducted the field work; EL processed the dataset; EL watched the video data; EL and MM analyzed the results. EL wrote the initial draft of the manuscript under supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

Chapter 4

EL, MM and PJ conceived the concept of the paper in discussion with GJ; EL organized and conducted the field work; EL processed the dataset; EL, MM, PJ and KJ watched the video data; EL and MM analyzed the results. EL wrote the initial draft of the manuscript under the supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

Chapter 5

EL conceived the concept of the paper in discussion with GJ; EL organized and conducted the field work; EL processed the dataset; EL, PJ and MM analyzed the results. EL wrote the initial draft of the manuscript under the supervision of GJ; MM, PJ and GJ made edits. All authors reviewed and approved the final manuscript.

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