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Hybrid fish protection for intakes at headrace tunnels in reservoirs

Calvin Frees(1), Jonas Haug(2), Ruben Tutzer(3), Barbara Brinkmeier(4), Markus Aufleger(5)

(1,2,3,5) University of Innsbruck, Innsbruck, Austria,
calvin.frees@uibk.ac.at, jonas.haug@uibk.ac.at, ruben.tutzer@uibk.ac.at, markus.aufleger@uibk.ac.at,
(4) HyFish GmbH, Innsbruck, Austria
barbara.brinkmeier@hyfish.com

Abstract

Hybrid fish protection systems are based on the combination of mechanical and behavioral barriers. The hybrid fish protection system FishProtector is combining a mechanical barrier with the behavioral barrier of an electric field. This enables effective fish protection with bar clearances at trash racks of several centimeters preventing operational problems and reducing hydraulic losses. The University of Innsbruck and the academic spin-off company HyFish GmbH from Innsbruck have developed multiple fish protection systems using this technology. For this purpose, extensive research and tests with fish have been carried out in the past years. The technology is suitable for usage at reservoirs with dams, for the inlets at pumped storage power plants and at the inlets of cooling water systems of thermal power plants. The first project at a reservoir has already been realized in Italy. In autumn 2021, ethohydraulic tests were performed for this purpose at a test facility in Austria. Further projects are in preparation. The present manuscript shows important outcomes of the development work, technical details of the pilot projects and an overview of the conducted ethohydraulic tests. In addition, an outlook on numerous applications in practice is given.

Keywords: Fish protection; Reservoirs; Hydropower; Electrical barriers; Water intake;

1. INTRODUCTION AND BACKGROUND

Water is withdrawn from reservoirs for various reasons. Typically, reservoirs are standing water bodies and consequently the hydraulic conditions change only in the close surrounding of these structures. This distinguishes water intakes at reservoirs from those of run-of-river hydropower plants. Examples for water intakes from reservoirs are nuclear or thermal power plants as well as high head storage hydropower plants. Water intakes for these purposes are known to be a source of danger for fish due to entrainment and impingement (Chow et al., 1981).

One specific purpose of water withdrawal from reservoirs is to generate energy that is flexible in time by high-head storage hydropower plants. Storage hydropower plants currently represent the most important technical option to store energy on a large scale. They enable to balance fluctuations of energy consumption and energy production in the power grid on an interregional level by a wide range of energy production rates combined with short lead times (Giesecke et al., 2014). The benefits are however accompanied by several ecological impacts such as hydropeaking, water withdrawal, altered sediment transport (Gurung et al., 2016). The discharge of cold water in river systems is known to have an impact on the water temperature and consequently also on the local composition of fish species and is therefore also known as “cold water pollution” (Schwevers and Adam, 2005).

Furthermore, there is also the possibility of direct fish entrainment at the water intakes of reservoirs. In the case of high-head storage hydropower plants, the chances of fish survival are minimal due to the large penstock and the corresponding Pelton turbines of these types of hydropower plants (Schwevers and Adam, 2020). At some pumped storage hydropower plants water is directly withdrawn from rivers as lower reservoirs which leads to the possible entrainment of fish from the river during the pumping cycle (Schwevers and Lenser, 2016). In comparison to river power plants fish protection measures at reservoirs gain less attention, due to their neglectable impact on fish migrations. Nevertheless, official approval procedures are often setting up requirements for the new construction of water intake structures to fulfil the goals of the European Water Framework Directive. Since there is no state-of-the-art specified for fish protection measures, there is also no legislative framework and individual considerations are necessary.

Water withdrawal from reservoirs into the headrace tunnels is carried out by water intake structures which typically are submersed several meters below the water level. The main function of these structures is to discharge the water with low hydraulic losses into the headrace tunnel and therefore to slow down the flow velocity at the entrance of the water intake structure. This is often achieved by an expanded discharge cross-section of the headrace tunnel at the entrance (Giesecke et al., 2014). Trash racks at water intakes of reservoirs are often realized as vertical bar racks consisting of flat steel bars and with a total flow section between 50 – 200 m² (Figure 1).

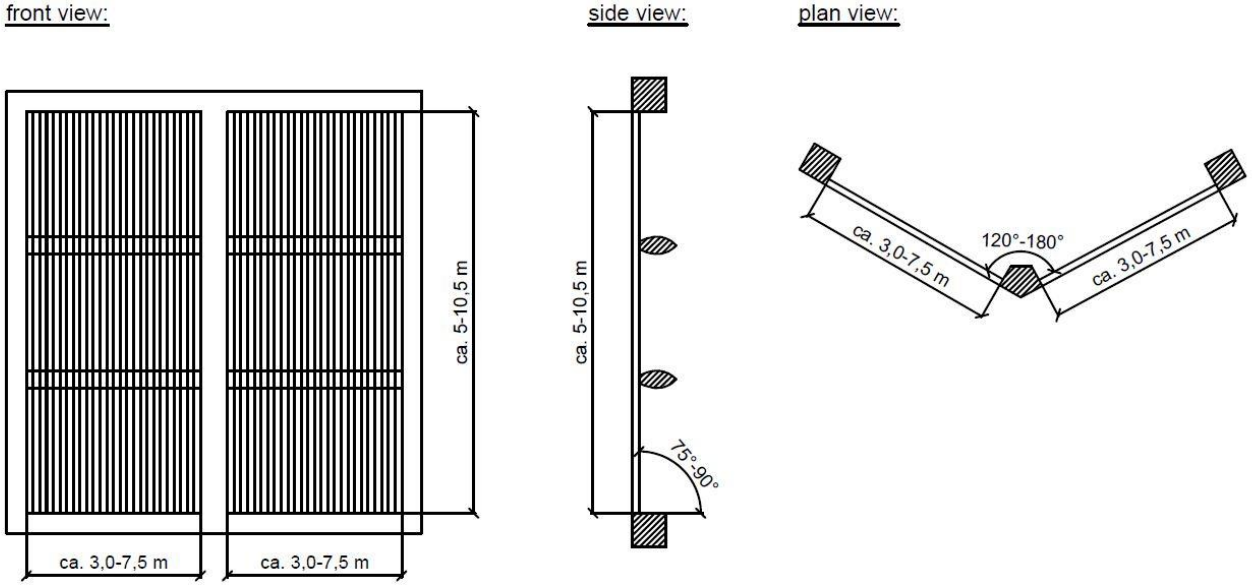

Figure 1. Common geometries of water intake structures at Austrian reservoirs

In general the design and dimensioning of these trash racks strongly depends upon the type of reservoir, the submersion depth, the penstock velocity, the sensibility of the machines in the power house as well as the accessibility for cleaning (Johnson, 1988; Giesecke et al., 2014). Design considerations of these trash racks have to be made in regard to achieve the required load capacities, low maintenance effort and low hydraulic losses (Johnson, 1988). Trash racks of high-head storage hydropower plants might have to withstand velocities up to the penstock velocity depending on the geometry of the intake. The outflow phase of the structure marks the most challenging hydraulic loading for the trash racks of pumped storage hydropower plants and has led to several static failures of trash racks (Johnson, 1988). These factors lead to bar clearances that are not suitable to avoid the entrainment of fish in a physical or behavioural manner. Installed bar clearances of water intake structures at Austrian reservoirs range between 50 and 100 mm with an average value of around 70 mm.

In 2016 a survey was carried out investigating the state-of-art of fish protection measures at pumped storage hydropower plants in Germany and the neighbouring countries. The outcome of this investigation was that no fish protection measures are implemented at any of the pumped storage hydropower plant for which information was given (Schwevers and Lenser, 2016). It has to be considered that the upper or lower reservoirs are not always natural habitats of fish and therefore fish protection measures are unnecessary in many cases. In general, lower and upper reservoirs in alpine regions are often artificially constructed in high altitudes and contain therefore no fish population unless fish are stocked for recreational fishing purposes.

Nevertheless, in less mountainous regions it often occurs that especially lower reservoirs are connected to natural water systems and consequently fish protection measures are required by legislative regulations (Schwevers and Lenser, 2016).This is especially important when new power plants are constructed along water systems which are designated as protected areas by the Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Unlike for small to medium scale river power plants there are no effective mechanical barriers available for the purpose of fish protection at reservoir intakes. This is also a consequence of the operational requirements, the static loading from both sides due to the changes in flow direction (for pump storage power plants only) as well as the relatively fast flow velocity in front of the bar racks (Schwevers and Adam, 2016). Reducing the bar clearance of bar racks to achieve fish protection based on physical properties is no option at reservoir intakes due to operational requirements, clogging with floating trash and increasing hydraulic losses.

The differences between water intake structures of reservoirs and those of river power plants are obvious. At river power plants there are potentially migrating fish species which aim to get downstream of the power plant and therefore orient themselves on the main current and consequently passing through the turbines (Ebel, 2013; Böttcher et al., 2015). Generally spoken this is not the case for the resident fish species in reservoirs. Of course, there are exceptions for example if water is extracted directly from a river which is inhabited by migratory fish species. Focusing on reservoirs in the form of standing water bodies it can be considered that fish in reservoirs approach water intake structures rather accidently while foraging and not on purpose. If the flow velocity at the trash rack exceeds the swimming capacity of the fish, these individuals are likely to get entrained up into the headrace tunnel.

Efforts to ensure fish protection at water intake structures of reservoirs could potentially be realized by reducing the approach velocity, creating a less attractive habitat in the forebay of the water intake and creating a barrier to prevent fish passages. Since mechanical barriers with narrow bar clearance are not suitable for this purpose due to high hydraulic losses and static issues (Schwevers and Adam, 2016), mechanical barriers with moderate bar clearance could be additionally equipped with a behavioral barrier.

2. ELECTRICAL BARRIERS FOR FISH PROTECTION AT WATER INTAKES

The first electrical barriers to prevent fish from entering water intake structures have been developed around hundred years ago (Hocutt, 1980). These early systems became widely spread in the following years and often contained two rows of vertical electrodes and used AC or DC (Beaumont, 2016).

Subsequently, a large amount of studies has been conducted to evaluate the effectiveness of these systems with varying results. Even though electrical barriers showed the potential to prevent fish from passage also concerns were raised about the reliability at differing conditions and fish species compositions (Hocutt, 1980).

The development of electrical barriers continued and in recent years several studies with modern systems have been conducted showing promising results for an improvement of fish protection at power plants (Rost et al., 2014; Egg et al., 2019; Tutzer et al., 2021). This modern generation of electrical barriers is using pulsed direct current (pDC) and lower voltages to induce an electric field in the water. The benefits of pDC are founded in a lower power demand as well as less harmful effects on the fish. Fish entering the electric field show an avoidance behaviour which is dependent upon the electrical potential the fish is absorbing across its body (Beaumont, 2016).

Positive effects on avoidance behaviour can be achieved in a hybrid system which is combining a mechanical barrier with an electrical behavioural barrier. Visual and hydraulic stimuli lead to carefully approaching fish (positive rheotaxis) which consequently sense the electric stimuli and show an avoidance reaction by swimming in upstream direction (Tutzer et al., 2019). Limited visibility due to darkness or turbidity have shown potential negative impacts on the effectiveness of hybrid barriers using electricity due to a reduced visual stimulus (Haddering and Jansen, 1990).

The application of an electrical barrier using electricity to prevent fish from entering the headrace tunnel of a reservoir is a complicated task. Multiple aspects have to be considered to fulfill the operational requirements on the one hand and to ensure a reliable improvement in fish protection under different boundary conditions on the other hand. To minimize hydraulic losses and the formation of vortices at the trash rack the components of the electrical barrier have to be aligned with the bars of the rack. Due to the shielding effect of the rack, electrodes can only be mounted on the front side of the bars facing upstream.

The static stresses that trash racks of reservoirs have to withstand are considerably higher than those of river power plant (Johnson, 1988). These hydraulic loadings lead to the need for a safe and durable mounting of the electrodes on the bars without increasing hydraulic losses due to additional fixation materials. Water intake structures of lower reservoirs are often equipped with a trash rack cleaner which grasps in between the bars to remove washed up trash of the bars. Therefore, the electrodes and their fixation need to be space saving or the trash rack cleaner has to be adapted. Electrical insulation between the electrodes and the bars has to be ensured (short circuit).

Water intake structures might be inaccessible due to the submersion depth and thus need to be durable for long service intervals and low maintenance. The current flow between the electrodes of an electrical barrier leads to an accelerated corrosion of the anodes. To slow down this process several design considerations have to be made to fulfill the goal of low maintenance. Factors influencing the corrosion are the material of the electrodes, the pulse length of the pDC, the applied voltage as well as the polarity of the electrodes.

The fish protection effectiveness of a hybrid barrier also depends upon the visibility of the mechanical barrier. Water intakes of reservoirs are often located in depths of several meters where light incidence is comparably low. The visibility is also limited in natural water systems with high amounts of suspended sediment loads. To prevent fish from passaging the rack as a consequence of a wrong directional avoidance reaction due to lacking visual stimuli the front side of the bars could be additionally lighted. To prevent attracting fish from the further surroundings the visibility should be limited to the direct proximity of the rack.

Another challenge for the design of an electrical barrier for a water intake of a reservoir is the sheer size of the trash racks up to 200 m² and even more. As a consequence, the electrical current increases and the electrical equipment has to be able to deliver such large electrical currents.

3. TECHNICAL CONCEPT OF THE BAR SCREEN FISHPROTECTOR

In order to satisfy the need for a cost-efficient and versatile fish protection mechanism the Unit of Hydraulic Engineering at the University of Innsbruck developed a fish protection system, the ´Flexible Fish Fence´ (Aufleger and Brinkmeier; Böttcher et al., 2014). The system consists of horizontal tensioned steel cables which are angled to the current in order to achieve a guiding effect on fish towards the bypass (Böttcher et al., 2014). In 2014, the first ethoydraulic experiments were conducted at the HyTEC (Hydromorphology and Temperature Experimental Channel) facility of the University of Natural Resources and Life Sciences in Lunz am See. The aim of these studies was to evaluate the fish protection effectiveness and the guiding efficiency of the system. The oscillation of the steel cables showed a neglectable behavioral effect on fishes and consequently the system could not fulfill the requirements for an effective physical barrier (Kammerlander et al., 2020). To improve the guiding efficiency of this system the next experiments were conducted at the same facility with an electrified flexible fish fence, the Flexible FishProtector. The results of this system showed a significant improvement of the fish protection effectiveness with cable clearances of 60 mm in the electrified setups compared to not electrified setups (Tutzer et al., 2019; Tutzer et al., 2021).

Even though the Flexible FishProtector is a widely applicable solution for newly constructed power plants, there is also the necessity for a system that can be used for retrofitting existing water intake structures. In this context the Bar Screen FishProtector was developed as an adaption of the Flexible FishProtector. This new system consists of electrodes which are mounted on the upstream side of a bar rack. The electrodes are connected to a pulse generator. By applying pulsed direct current (pDC) on the electrodes an electric field in the upstream surrounding of the trash rack is created. This electric field improves the fish protection effectiveness of the physical barrier by adding a behavioral barrier analog to the Flexible FishProtector and enables an increase of bar clearance of bar racks while maintaining the same fish protection rate (Frees, 2021).

The electrodes are screwed into boreholes in the flat steel bar (Figure 2) to enable a durable and strong fixation which is able to withstand the stresses that occur during the inflow and the outflow phase. The cross section of the electrodes is designed to match the width of the flat steel bars. This enables the application of a trash rack cleaner which can grasp in between the bars to remove trash. Plastic dowels between screws and steel bars as well as a continuous insulating layer ensure the avoidance of electric current flow on-to the bars. The top ends of the electrodes are connected to wires which lead to the pulse generator.

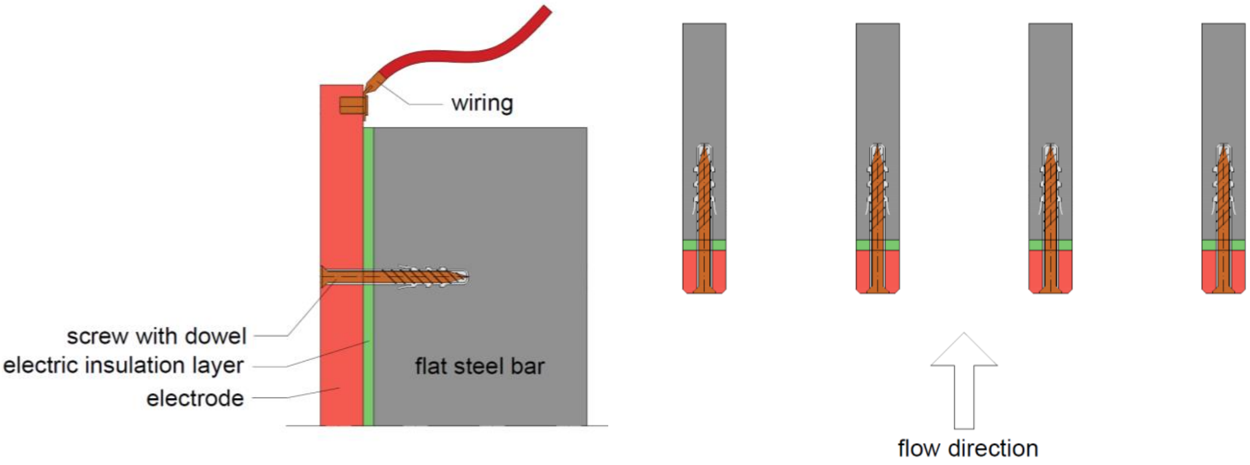

Figure 2. Electrode fixation of the Bar Screen FishProtector (patent pending)

The output voltage of the system can be set individually depending on the water conductivity since this factor is influencing the effect of the electrical field on fish (Beaumont, 2016). In case of a moderate water conductivity (~300 µS/cm) the output voltage is set to 80 V. The pulse generator creates pulses in a square waveform with a duration of less than a millisecond. These short pulse durations lead to low power demand as well as a slower corrosion process. In order to improve the durability in the context of corrosion the polarity of the electrodes is changing frequently. The frontside edges of the rod electrodes can be trimmed or rounded to minimize hydraulic losses. The total installation of the Bar Screen FishProtector is expected to have no negative influence on the hydraulic losses of the bar rack.

The clearance of the rod electrodes can be varied according to the bar clearance of the trash rack. The arrangement of the electrodes is one of the most influential parameters on the strength and the form of the electric field. In order to maximize the extensions of the electric field in the upstream area of the Bar Screen FishProtector, the polarity of the electrodes is arranged to alternating sets of three same polarized electrodes. This means that three anodes are followed by three cathodes and so on.

4. ETHOHYDRAULIC STUDIES AND REALIZED PROJECTS

In the year 2020, the first ethoydraulic experiments were conducted with an electrified vertical bar rack, the Bar Screen FishProtector, at the HyTEC facility. The experimental bar rack consisted of 10 mm wide and 40 mm deep flat steel bars which were electrified by mounting 8mm steel rods on the front side of the bars. Bar clearances were varied in multiple setups from 30 mm up to 150 mm. Two different hydraulic boundary conditions were included in the studies with flow velocities of 0.23 m/s and 0.55 m/s. Experiments were conducted with three different fish species in each experiment (Grayling (*Thymallus thymallus)*, Chub (*Squalius cephalus)* and Brown Trout (*Salmo trutta fario)*) and a number of 15 individuals per species. A pulse generator was used to generate pulsed direct current with a voltage of 80 V and a square waveform. Fish were stocked in the upstream area of the bar rack and no bypass was installed in the experimental setup. Fish interactions with the electrified and not electrified bar rack were recorded with underwater cameras and afterwards analyzed (Figure 3). Three trials of each experimental setup were conducted. The results of these ethoydraulic experiments showed a strong fish protection effectiveness and low rack passage rates at bar clearances of 30 - 70 mm compared to the not electrified reference setups. Bar clearances above 70 mm resulted in a decreased fish protection effectiveness due to visual and hydraulic stimuli (Frees, 2021).

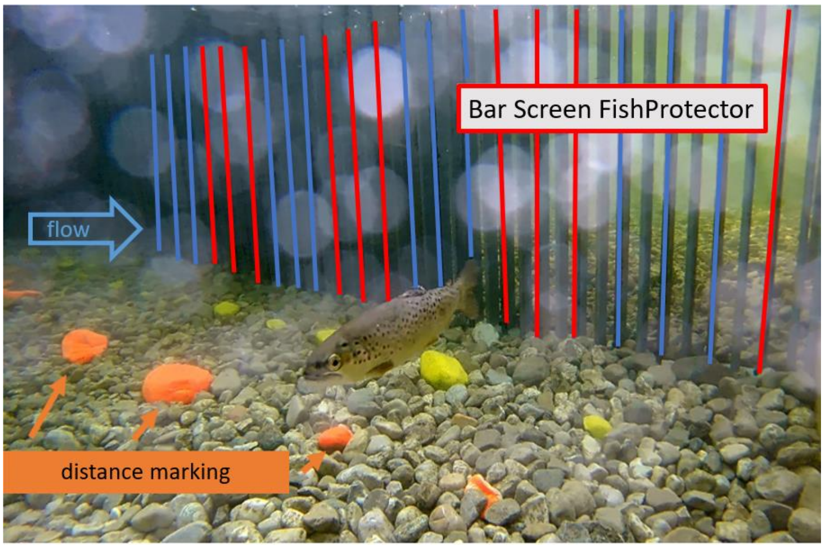

Figure 3. Visualization of the ethohydraulic experiments in the HyTEC facility.

To investigate the fulfillment of the operational requirements of the Bar Rack FishProtector the system has been installed at the cooling water intake of a nuclear power plant. Sample electrodes have been mounted on to the front side of the bars with an insulating layer in between (Figure 4). Different fixation options were tested to evaluate the durability, the trash rack cleaning effectiveness as well as overall operational issues. The trash rack cleaner had to be modified due to the additional cross section of the electrodes on the bars. The electrodes were installed in 2020 and the functional tests are still ongoing without any problems or operational issues so far. After one year, the condition of the electrodes, the fixation and the insulating layer will be assessed to draw a conclusion in regard to the durability and maintenance of the system.

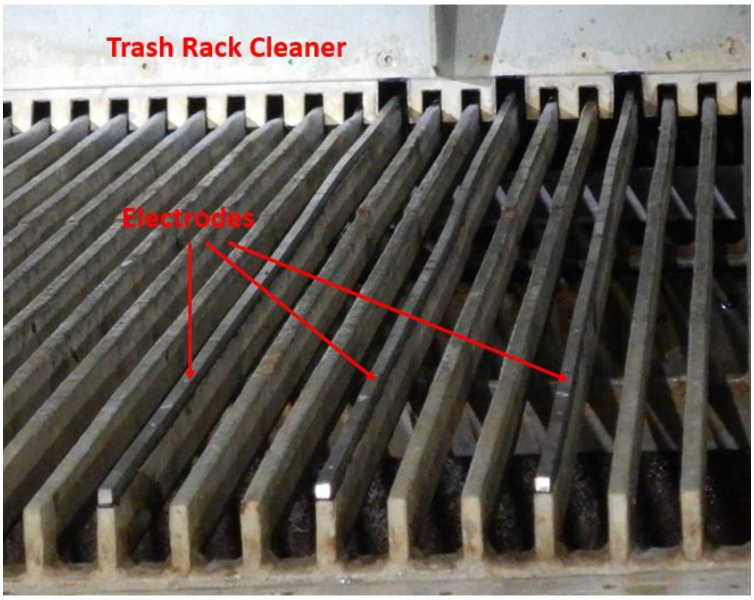

Figure 4. Fixation of electrodes for functional tests at the water intake of a nuclear power plant.

In 2021, the hydraulic engineering research group at the University of Innsbruck was approached by an operator of a storage hydropower plant in Italy to design a fish protection system for a reservoir. The upper reservoir of this power plant is stocked with different species of salmonids to enable recreational fishing. Fish have been observed approaching the water intake and getting entrained into the headrace tunnel.

To prevent the loss of stocked fish the aim was to install a hybrid barrier in front of the intake. This system consists of a frame in which electrified steel cables are tensioned (Figure 5). These steel cables are used as a mechanical barrier as well as electrodes for the electric behavioral barrier.

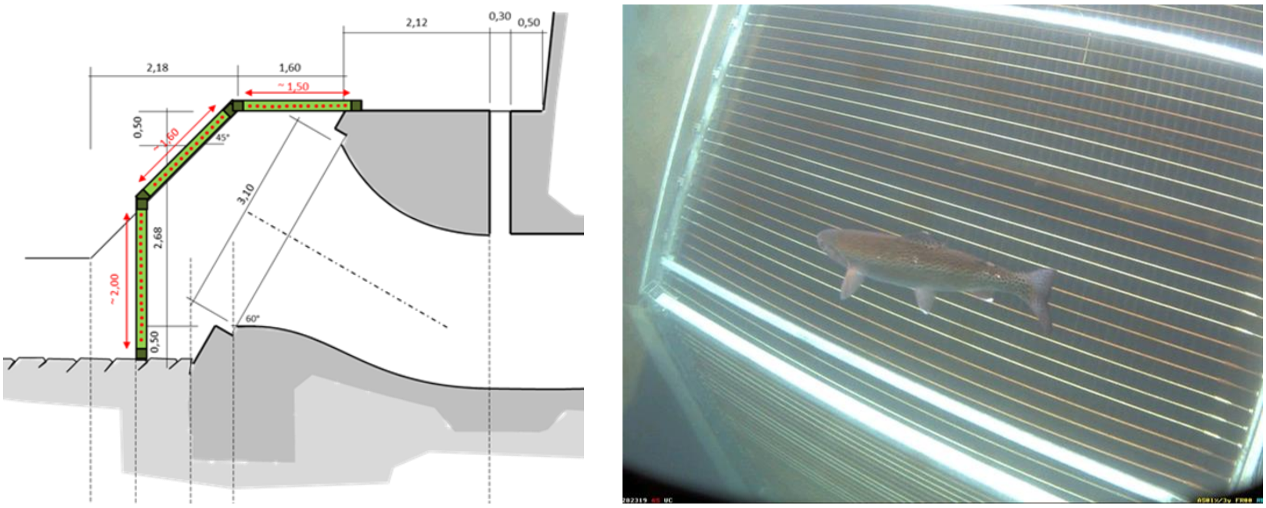

Figure 5. Newly installed Fixed FishProtector at a water intake of a reservoir in Italy.

The biological effectiveness to prevent fish from entering the water intake was surveyed by an underwater camera (HydroCam, I Am Hydro GmbH, Germany). The analysis of the recorded footage is still ongoing but the first impressions seem to validate the fish protection effectiveness of the FishProtector system.

Plans exist to equip a trash rack at a water intake of a pumped storage hydropower plant with the Bar Screen FishProtector. Therefore, ethohydraulic experiments have been conducted at a flood control structure on the shore of the river Donau in the autumn of 2021. This structural facility only served as a very suitable site for the investigation and had no direct local connection with the planned PSHP. An unscaled section model of a trash rack with a length of 7.0 m was installed in a channel with a water depth of 0.8 m (Figure 6). In the experimental setup the fish were confined in the upstream area of the bar rack which was bordered by a net upstream. The aim of the experiment was to record the rack passages of the electrified and non-electrified bar rack over time. Even though the experimental setup is different to applications at water intakes where fish have much more freedom of movement the retaining rate under confined space enables to draw important conclusions on different setups. Flow velocities along the rack varied between 0.25 – 0.55 m/s due to the geometric boundary conditions of the channel. Three PIT antennas were installed in the channel, one antenna upstream and two antennas downstream of the bar rack. Multiple fish species were used in each trial (barbel *(Barbus barbus)*, bream (*Abramis brama)*, roach (*Rutilus rutilus)* and perch (*Perca fluviatilis)*) with an average stock of 90 individuals. The fish were tagged with PIT tags to record when and which individual fish is passing through the bar rack. A total of 12 experiments were conducted whereof eight were performed with an electrified setup and four with the not electrified reference setup. The duration of the experiments was set up to eight hours to examine the development of the rack passages over time and to include potential familiarization effects into the study. Four experiments were performed at night to evaluate the impact of a different activity level and a decreased visibility of the physical barrier.

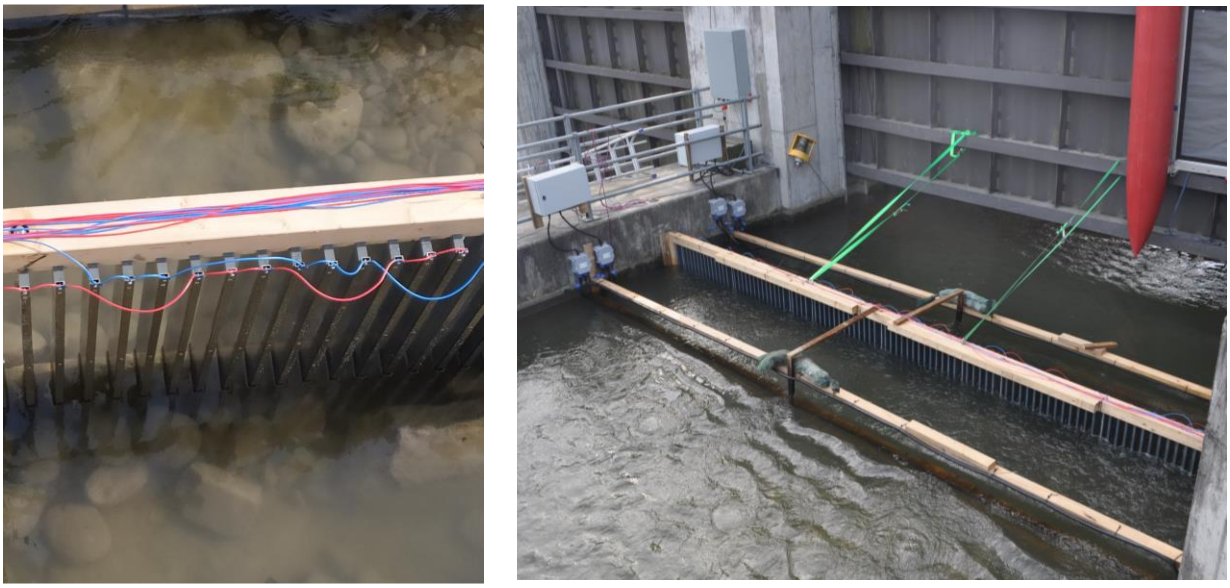

Figure 6. Setup of the ethohydraulic experiments with a 7 m long model of the Bar Screen FishProtector

The analysis of the collected data is not finished yet, but the preliminary results show an improvement of the retaining rate in the electrified setups. Furthermore, higher activity levels and decreased visibility seem to have an impact on the retaining rate of the Bar Screen FishProtector at night. Nevertheless, retaining rates could be improved by applying electricity during day and night.

5. OUTLOOK

The concept of the Bar Rack FishProtector offers many application possibilities at multiple types of water withdrawal structures such as reservoir water intakes and cooling water intakes. The Unit of Hydraulic Engineering at the University of Innsbruck and the spin-off company HyFish GmbH have planned several future projects where the FishProtector will be installed.

Future research will investigate the biological effectiveness of the system at real sites in the form of functional tests at differing boundary conditions as well as possibilities to slow down the corrosion of the electrodes.

6. ACKNOWLEDGEMENTS

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