# THE RETERO PROJECT: 3R MOTIVATED RISK ASSESSMENT METHODS FOR DOWNSTREAM FISH PASSAGE THROUGH HYDRAULIC STRUCTURES

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**ABSTRACT**

Barriers to downstream fish migration, in particular hydropower installations, pose a persistent and global threat to aquatic biodiversity. To evaluate site-specific injury and mortality risks for fish during downstream passage live fish experiments remain as the common assessment method. The RETERO (Reduction of live fish testing through science and technology) project aims to develop new methodologies to estimate the risk of injury and mortality for fish passing downstream through turbines, gates, weirs, bypasses, and upstream through pumps. The goal is to significantly reduce – and in the long-term replace – live animal testing following the Replacement-Reduction-Refinement (3R) principle in animal research. Ethohydraulic research is the first pillar of the project and has been conducted in a lab flume with live fish outfitted with sensors while their movements were tracked in 3D. The second pillar is based on experimental tools. These tools include both, passive and active sensor systems. Miniature biologgers with pressure and inertial sensors provide new insight into the fish kinematics during downstream passage and can be used to determine thresholds for injury mechanisms. This allows for a reduction of the number of individuals to validate the numerical models. Finally, actively propelled sensor probes will be used to explore the negative effects of active swimming during downstream passage, as shown by tests comparing actively swimming with anesthetized fish. As a third pillar, numerical behavioral models based on the laboratory observations have been implemented using two approaches, probabilistic and agent-based models, both in combination with CFD simulations. The broad range of new numerical and physical tools being developed in RETERO provide innovative methods for design improvements, but also the assessment of existing facilities. They are of high interest for the planning and operation of hydropower schemes for different stakeholders, including hydropower industry but also environmental experts. In this presentation we provide an overview of the RETERO project's aims, approaches, methods and current outcomes.

*Keywords:* ***3R Principle, fish injury and mortality risk, hydraulic structures, ethohydraulics***

## 1 INTRODUCTION

### 1.1 Status quo in mortality and injury risk assessment for fish in hydraulic structures

Only 10% of German rivers are in a *good ecological state* in terms of the European Water Framework Directive (EU-WFD). This is mostly due to the river's obstruction from roughly 190,000 technical barriers [1], leading to discontinuity, hindering fish migration and sediment transport. The 8,000 hydropower facilities installed in German rivers result in high mortality rates for migrating fish currently estimated as 22%, and which strongly depend on turbine type and size [2]. In accordance to the EU-WFD, monitoring and assessment of hydropower facilities and their impact on fish migration is mandatory for new installations and re-licensing in Germany. State of the art methods use live fish tests in order to quantify the mortality and injury risks for fish in such sites. In Germany alone, up to hundreds of thousands, mostly wild fish are deployed in such tests with a peak of 459,755 individuals in 2015 [3]. On the European level, 2.3M fish (not including commonly studied zebra fish in the lab) were used in 2018 in live tests of which 5,7% were lethal (non-recovery) , 9.9% led to severe and 33.9% to moderate damage. The exact amount of live fish used for hydropower sites assessment is not listed, but 895,767 individuals were deployed for transferable and applied research, 98,200 for "protection of the natural environment (..)", 7,545 for regulatory use and 84,720 for species conservation [4].

Analytical and empirical model development is not new and started already in the 1950s. Several models and sensor systems have been developed in the past years in order to provide alternatives to live-fish tests, such as the sensorfish from PNLL [5] and more advanced devices from TalTech [6] as part of the EU FITHydro project. Numerical tools, such as BioPA [7], use Computational Fluid Dynamics (CFD) to estimate the injury risk of turbine downstream passages. However, these numerical fish models and sensor devices behave fully passive, more like a wooden stick than a fish, and are sometimes even treated as mass-less particles. These model characteristics obviously provide a very limited representation of the behavior or the swimming characteristics of fish. Additionally, Geiger *et al.* (2020) proved in experiments that fish behavior is crucial for the mortality and injury risk assessment during turbine downstream passage. Electrically anesthetized fish showed a significant lower damage risk with a reduction of about 55% [8]. Even though fish can obviously not escape in a flow regime featuring velocities with more than 5 or 6 m/s, it has to be expected that they can partly control their position and extend the drifting time through the dangerous rotor region while trying to escape and swimming against the flow. In this case, behavior and active swimming has to be included in experimental and numerical studies. The RETERO project (retero.org), addresses these challenges and develops a new generation of methods for the assessment of hydropower facilities and technical installations in rivers with respect to the fish's behavior. The project aims for a significant reduction of live animal tests and in long term, the full replacement of live-fish tests by surrogate models and sensors. Those will have to provide reliable quantifiable assessment data, obviously necessary for a rigorous species protection and the conservation and recovery of the the river's biodiversity.

### 1.2 The 3R principles and the RETERO project

The RETERO project (Reduction of live fish testing through science and technology) consists of an interdisciplinary consortium including researchers from civil, environmental, mechanical and electrical engineering, as well as biology and informatics from five partner institutes and companies from Germany and Estonia. To achieve the project goals the consortium fully relies on the 3R principle introduced by Russel & Burch in 1958 [9]. In their concept, the three *R* stand for (1) a *Replacement* of the animals, e.g. by surrogate models or new methods, (2) a *Reduction* of the amount of animals deployed in the studies, e.g. by the development of more advanced methods to gain improved data and data quality from each animal deployed, and (3) the *Refinement* of the methods which shall reduce the suffering of the animals to an absolute necessary measure. The project addresses all three principles with a multitude of methods and sensors systems subsequently presented. In the development process, the work is based on three pillars: (1) ethohydraulic research, to gain insights into the behavior of fish in artificial, hydraulic environments (2) experimental tools, such as non-invasive biologgers mounted on dorsal fins or active probes and (3) numerical tools, such as probabilistic methods which forecast the fish behavior by analyzing the flow field.

## 2 ETHOHYDRAULIC RESEARCH

Ethohydraulics is the study of both ethology (behaviour) and hydraulics with a focus on the stimulus response relation for flow velocity, pressure or their derivatives. The project aims at understanding behavioral-triggering at the entrance of hydraulic installations. There, the flow field commonly features high velocities, gradients and turbulence intensities. This will provide valuable insights to predict fish behavior in models. The focus on the intake is a consequence of the assumption, that fish will reproducibly control their descend location and speed.. Observations from the RETERO laboratory investigations show that trout will successively lose their control, triggering specific behavior.

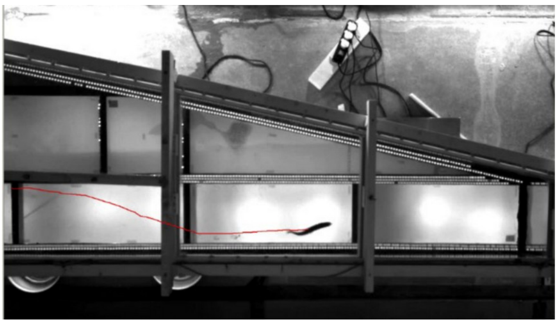

*Figure 1: 3D Tracking of the fish paths allows for a correlation of hydraulic field and fish behavior*

To the knowledge of the authors, there is sparse data available on the behavior of live fish during turbine passage. Field studies of turbines commonly treat them as as a "black box" because they cannot be physically accessed optically or acoustically while laboratory studies are limited to physical environments with reduced scale. Biologists commonly compare the physiological conditions of fish before and after the passage which allows for the statistical estimation of the damage, but provides limited insights into the mechanisms causing injury and mortality and the fish behavior during the passage. The ethohydraulic experiments performed during the project runtime on a flume installation and therefore only provide a first step allowing for the estimation of the necessary behavioral rules to create numerical fish surrogate models.

To achieve this, a set of three hypotheses was postulated and three designs were installed [10]. The first two hypotheses state that a longitudinal flow gradient will trigger behavior when a critical flow speed is reached under daylight and darkness. To this purpose, a maximum speed of 3 m/s was reached in the end of the flume. Brown trout (*Salmo trutta*), partly equipped with biologgers, were injected to the flume and their path were tracked with 3D video tracking (Fig. 1). The evaluation of the fish tracks combined with numerical simulations of the flow quantities allow for a determination of flow speed thresholds and other triggering parameters. The camera recordings were based on IR light, invisible for the brown trouts.

The third hypothesis considered transversal flow speed gradients. The flume installation was adapted and a strong transversal gradient of up to $1 s^{-1}$ (m/s/m) was achieved. Brown trouts were injected to the flume. First results show a significant behavioral change due to the spatial velocity gradient when normalized to the fish's body length. Other behavioral rules such as a clear preference to the bottom and the wall regions could also be derived from the studies.

## 3 EXPERIMENTAL TOOLS

Two sets of sensors are developed during the project runtime. The first is a non-invasive biologger system, called back packj sensors placed on the dorsal fin of fish with a weight of 3-5 g and a size of 25x14x4mm³ (LxHxW). Comparison tests showed a minor change in the swimming capacities and negligible change in downstream passage time for rainbow trouts larger than 250 mm body length. The sensors record pressure, accelerations and orientation with up to 2048 Hz. This allows for the detection of barotrauma risks, but mostly for the tracking of swimming activities and collisions. The RETERO backpack sensors are perfectly suitable for both hydropower plant assessment and ethohydraulic studies, delivering new and important insights in the behavior during the passage of hydraulic structures. First tests with eels and roach were performed in a large Archimedean Screw in Belgium and showed significant behavioral effects and differences when comparing passive and fish mounted sensors (Fig. 2). Details of the biologger experiments and field studies were presented on the Fish Passage Conference 2022 [11].

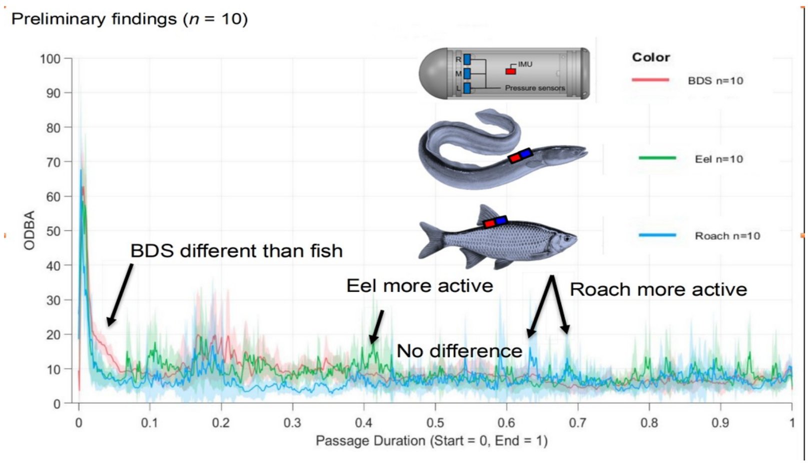


Figure 2: Preliminary biologger results from field tests on a large Archimedean Screw [11]

The second tool is a self-propelled sensor (Fig.3), that actively orients itself in the flow. These flexible fish robots with a soft tail perform a bio-mimicking fish-like motion pattern of a subcarangiform swimmer, driven by piezo-ceramic actuators with 5 degrees-of-freedom [12]. The sensors implemented in the robot are of similar technical capacities and design as the backpack sensors which are integrated in the microcontroller of the robotic device using I²C communication. In the current state navigation tests are performed after optimization of the motion law of the bio-inspired locomotion.

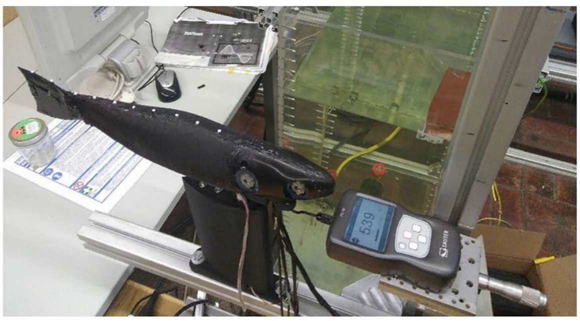

*Figure 3: Prototype of the self-propelled active sensor probe [12].*

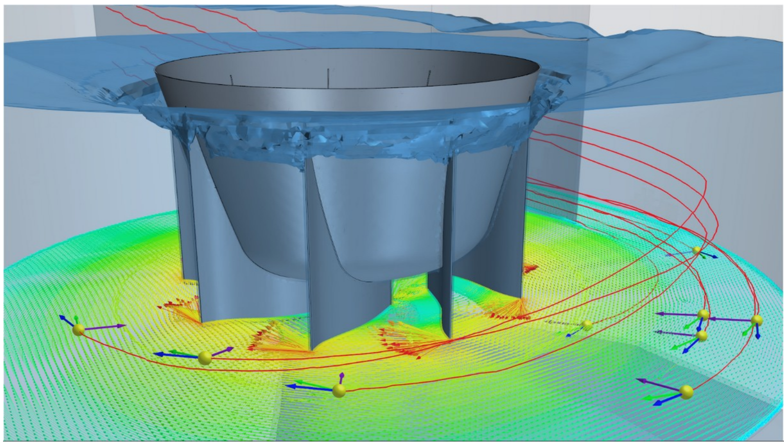

*Figure 4: Numerical model based on CFD/DEM with active fish behavior in an unsteadv flow field*

## 4 NUMERICAL TOOLS

The numerical tools developed are two-fold. (1) A probabilistic model based on the behavioral rules found in the ethohydraulic studies and implemented in the CASIMIR framework [13] determines the most probable paths of fish passing the device by evaluation of the fields, retrieved from steady-state simulations of the flow, and calculates the injury risks along the paths. The advantage of the model is its cost-effective approach, which makes it suitable for practitioners in the risk assessment community such as consultants and experts with background in biology and hydraulic engineering.
(2) A tool based on Computational Fluid Dynamics coupled with the Discrete Element Method (CFD/DEM). In the current approach, an additional swimming force is added to the mass-laden particles (Fig. 4). This additional force allows for the application of an individual behavior for each particle and the implementation of agent-based system to mimic fish behavior. Details of the methodology can be found in [14].

## 5 OUTLOOK, FUTURE WORK AND COLLABORATIONS

In the second project phase, our ethohydraulic research will be extended from salmonides to percides and cyprinides, additional behavioral rules are to be developed to improve the existing numerical models. The biologgers will be tested in field studies in Europe, while the self-propelled sensor is under further development. The numerical tools developed in the project were already deployed in parallel studies with partners from industry aiming for improvements in the fish compatibility in the design and development process of hydraulic machinery. Industrial collaborations will be further extended in upcoming projects to provide and to test the methods developed with practitioners and the community.

## 6 DATA AVAILABILITY

The RETERO Project commits itself to open science. Findings and research data are published on the open science repository at University Otto von Guericke Magdeburg. The links can be found on the project website; https://retero.org

## 7 ACKNOWLEDGMENTS, APPENDICES, AND REFERENCES

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