DOWNSTREAM FISH PASSAGE EVALUATION USING BAROTRAUMA DETECTION SENSORS

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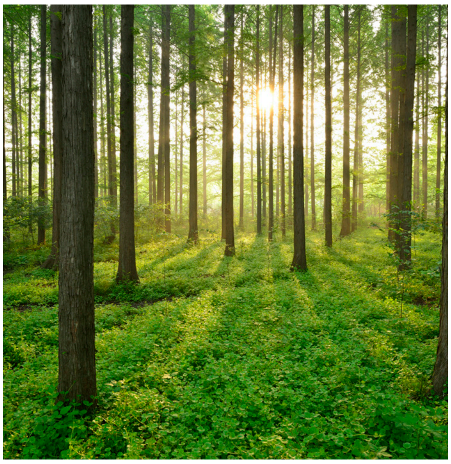

HYDROPOWER ENVIRONMENTAL RESEARCH PROGRAM

Energiforsk

Downstream Fish Passage Evaluation Using Barotrauma Detection Sensors

Ätrafors and Lanforsen case studies

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Foreword

It is urgent to increase the knowledge about the risks that extreme pressure drops and blade strikes pose to downstream migrating fish when passing through hydropower turbines, as well as to find methods to minimise these risks, especially for species such as eel and salmon.

In this project, experiments were carried out with sensors that were passed through the hydropower plants Lanforsen and Ätrafors to measure the pressure conditions and blade strikes that downstream migrating fish can be exposed to during turbine passage. The study shows that the risks for downstream migrating fish can be reduced through continuous monitoring and optimisation of turbine operations, with the aim of maintaining pressure conditions above critical minimum levels and reducing the number of turbine blade strikes.

The project has been carried out by Mauro Carolli, Sahra Sabil, Håkon Sundt and Atle Harby, Sintef, and Olle Calles, Kau, within the Hydropower Environmental Research Program, which aims to provide fact-based knowledge for decisions on environmental improvement measures in hydropower. The programme is coordinated by Energiforsk and financed by Vattenfall Hydropower, Fortum, Uniper/Sydkraft Hydropower, Statkraft Sverige, Skellefteå Kraft, Holmen Energi, Jämtkraft, Tekniska verken i Linköping, Mälarenergi, Karlstads Energi and Jönköping Energi.

The project has been followed by the programme's steering group consisting of Marco Blixt (Fortum), Erik Sparrevik, Lo Persson and Henrik Viklands (Vattenfall), Johan Tielman (Uniper/Sydkraft Hydropower), Susann Handler and Sara Friberg (Jämtkraft), Jakob Bergengren (Tekniska verken i Linköping), Angela Odelberg and Anders Bergman (Statkraft), Fredrik Ölvebo (Mälarenergi) and Sandra Åström (Skellefteå Kraft).

Marco Blixt, Fortum, and Johan Tielman, Uniper/Sydkraft Hydropower, have assisted the project with technical support and access to research facilities and data. Help from technical personnel at Fortum and Uniper has also been crucial for the successful completion of the experimental work.

Bertil Wahlund, Energiforsk

Stockholm, april 2025

Summary

The report summarizes a study on the impact of the physical conditions during turbine passage experienced by downstream migrating fish, by measuring the pressure conditions and strike events using pressure sensors. Despite measures like bypasses and screens, many fish still pass through turbines, facing risks such as extreme pressure drops and blade strikes. The study used Barotrauma Detection System (BDS) sensors to investigate the physical conditions (strike and pressure), encountered by fish passing through turbines. This study was conducted at Ätrafors where the results were interpreted in relation to downstream eel migration, and at Lanforsen where the results were interpreted in relation to downstream salmon smolt migration.

In terms of methodology, sensors were deployed at both power plants to measure pressure and count strike events. Dummies were used to test the experimental setting and count strike events, while sensors were measuring pressure data. Different scenarios with varying discharge rates in different turbines were assessed. The data was analysed using a one-way Kruskal-Wallis ANOVA, followed by Dunn's test for post-hoc comparisons.

At Ätrafors, different scenarios showed that pressure levels are maintained in the safe range for eels at the Nadir pressure, which is the lowest pressure in the turbine passage and a critical moment for fish. However, the number of strike events was relatively high. At Lanforsen, none of the scenarios (different turbine and discharge) showed pressure levels exceeding the critical thresholds for salmon safety. The rate of pressure change was also within safe limits, and no strike events were recorded.

The discussion highlights that despite safe pressure conditions at Ätrafors, the high number of strike events indicates a significant risk of injury and mortality for fish. Modifications to inlet racks have significantly reduced eel mortality by preventing the fish to enter the turbines. The pressure levels and rates of change at Lanforsen were within safe limits for salmon, indicating a lower risk of injury. The absence of strike events confirms findings from literature for fish of similar size to the dummies: the number of strikes in this site is very low. The comparison with other case studies highlights that more data are needed to identify the most relevant factors and enable generalized conclusions.

The use of sensors in measuring pressure conditions can contribute to evaluate environmental conditions for fish during downstream passage. Continuous monitoring and optimization of turbine operations are necessary to minimize risks to migrating fish.

Keywords

- Downstream eel and salmon migration
- Turbine passage
- Pressure conditions
- Barotrauma injuries
- Strike events

- Nedströms ål- och laxvandring
- Passage genom turbin
- Tryckförhållanden
- Skador på grund av tryck och tryckändring (Barotrauma-skador)
- Bladträffar

Sammanfattning

Rapporten sammanfattar en studie där man använt sensorer för att mäta tryckförhållanden och bladtäffar vid turbinpassage, något som kan påverka nedströmsvandrande fisk. Trots åtgärder som avledningsanordningar för nedströmsvandring och anpassade galler, passerar många fiskar fortfarande genom turbiner och utsätts för risker som extrema tryckfall och bladträffar. I studien användes Barotrauma Detection System-sensorer (BDS) för att undersöka dessa förhållanden (bladtäffar och tryck) som fiskar utsätts för när de passerar genom turbiner. Studien genomfördes vid Ätrafors (fokus ål-migration) och vid Lanforsen (fokus laxsmolt-migration).

Försöken genomfördes genom att sensorer och dummies användes vid båda kraftverken för att mäta tryck och räkna antalet bladträffar. Dummies användes för att testa den experimentella uppsättningen och räkna slaghändelser, medan sensorerna mätte tryckförhållanden. Olika scenarier med varierande flödeshastigheter i olika turbiner utvärderades. Data analyserades med hjälp av en envägs Kruskal-Wallis ANOVA, följt av Dunns test för post-hoc jämförelser.

Vid Ätrafors visade olika scenarier att trycknivåerna hölls inom det säkra intervallet för ål vid Nadir-trycket, vilket är det lägsta trycket i turbinpassagen och en kritisk punkt för fiskarna. Dock var antalet bladträffar relativt högt. Vid Lanforsen visade inga av scenarierna (olika turbiner och flöde) att trycknivåerna föll nedanför den kritiska gränsen för lax. Tryckförändringstakten var också inom säkra gränser, och inga bladträffar registrerades.

Diskussionen belyser att trots säkra tryckförhållanden vid Ätrafors, innebär det höga antalet bladträffar en betydande risk för skador och dödlighet hos fiskarna. Modifieringar av intagskanaler har minskat åldödligheten avsevärt genom att förhindra fiskarna från att komma in i turbinerna. Trycknivåerna och tryckförändringarna vid Lanforsen var inom säkra gränser för lax, vilket indikerar en lägre risk för skador. Avsaknaden av bladträffar bekräftar resultat från litteraturen för fisk av liknande storlek som dummies: antalet bladträffar på denna plats var mycket lågt. Jämförelsen med andra fallstudier belyser att mer data behövs för att identifiera de mest relevanta faktorerna och dra generella slutsatser.

Att använda sensorer för att mäta tryckförhållanden kan bidra till att utvärdera tryck- och slagriskförhållandena för fisk vid nedströmspassage. Kontinuerlig övervakning och optimering av turbindriften är nödvändiga för att minimera riskerna för migrerande fiskar.

List of content

Glossary of terms

Technical terms	Short explanation
Annual generation	The total amount of energy produced in a year.
Barotrauma	Injuries caused by rapid changes in the water pressure. Fish swim bladders are acclimated to the water depth before entry into the hydropower plant and then undergo inflation or deflation when passing the turbine.
Boxplot	A graphical representation of the distribution of a dataset, showing quartiles, median, and outliers.
Capacity	The maximum amount of electricity that can be produced.
Calibration	Adjusting or setting instruments to ensure accuracy.
Cavitation	Air bubbles that are forming and collapsing in water, often near fast-moving objects like turbines.
Attraction flow	The flow that should lead fish to fish ladders.
Ecological condition	The health or state of an ecosystem, referring to the water framework directive.
First Quartile	The value above 25% of the data falls.
Flap gates	Gates along a dam that open or close by swinging on a hinge.
Gyroscope	A device used to measure orientation and angular velocity.
Head	The difference in height between the source and discharge points of water in a hydraulic system.
Hemispherical	Shaped like half of a sphere, rounded on one side.
Interquartile Range	The range between the first and third quartiles.
Magnetometer	A device used to measure the strength and direction of magnetic fields.
Maximum	The highest value in a set of numbers.
Mean	The average value of a set of numbers.
Mean absolute deviation	The average of the absolute deviations of each value from the mean. Absolute deviation is how far from zero is a number, regardless of its sign.
Median	The middle value of a set of numbers when they are arranged in order.
Minimum	The lowest value in a set of numbers.
Nadir pressure	The lowest pressure point in a given area or system, here during the passage through the turbine.
Outliers	Data points that are significantly different from other observations.

p-value	Statistical measure that helps determine the significance of your results in a hypothesis test
Pressure rate of change	The velocity which pressure is changing over time.
Range	The difference between the maximum and minimum values in a set of numbers.
Relative error	The difference between a measured value and the true value, expressed as a percentage of the true value.
Resurfacing	Coming back to the surface of the water after being submerged.
Spill gates	Gates or openings in a dam or reservoir used to release excess water.
Standard deviation	A measure of the dispersion or spread of a set of numbers.
Tailwater	The water downstream of a dam or other structure.
Third Quartile	The value below which 75% of the data falls.
Two-way fish migration	Fish movement occurring in both directions: upstream and downstream.
Validation	Checking if data or results are accurate or reliable.
Water column	The pressure identical to the pressure of a vertical column of water stretching from the water surface to the point of measurement.
Whiskers	Lines extending from a boxplot indicate variability outside the upper and lower quartiles.

1 Introduction

Downstream migrating fish can face significant harm when passing through turbines and hydraulic structures due to factors such as cavitation, pressure drops and blade strikes (Pracheil et al., 2016; Colotelo et al., 2016; Cada et al., 1999).

Fish typically follow the main current to conserve energy, which often leads them towards turbine inlet at hydropower plants (Fjellstad et al., 2018). To mitigate the risk of entering the turbine, various barriers are installed upstream of the turbine inlets to redirect fish to bypass routes. Physical barriers like bar or mesh screens prevent larger fish from passing through, while behavioural barriers use stimuli (e.g., electricity, light, sound) to encourage fish to avoid the area. Recent developments include hybrid barriers that combine physical and electric obstacles.

Downstream corridors, including surface and full-depth bypasses, aim to provide safe routes for fish, ensuring they reach the tailwater unharmed. Additional structures such as flushing channels and fish passes, originally designed for upstream migration, can also assist downstream movement. Recent findings indicate that large fish may pass through physical barriers more often than predicted, highlighting the importance of understanding turbine conditions for safe downstream migration (Knott et al., 2023).

To measure the hydraulic conditions that may cause injury and mortality, waterproof autonomous sensors can replace the use of live fish and can be used to gather data on the pressure and inertial changes (Deng et al., 2014). By taking repeated measurements with multiple identical sensors, researchers can average pressure and acceleration time series to create data-driven representations of the physical conditions fish encounter during downstream passage (Schneider et al., 2017). The pressure changes fish face during turbine passage are highly predictive of their survival, with the ratio of acclimation pressure to Nadir pressure, which is the lowest pressure while passing the turbine, being particularly critical in determining the impact on fish, especially smolt survival (Trumbo et al., 2014).

In this study, Barotrauma Detection System (BDS) sensors for pressure measurements and strike event counting, as well as dummies only for strike event counting, were deployed at the Lanforsen (Dalälven; N=139) and Ätrafors (Ätran; N=111) power plants in Sweden. A dummy is a neutrally buoyant wooden piece that mimics the weight of the sensors and is used to test the experimental protocol and count strike events during turbine passage.

The data from each BDS sensor was combined in scenarios, and four physical parameters known to increase the risk of injury and mortality were evaluated: Nadir pressure (Deng et al., 2014; Deng et al., 2017), pressure rate of change (PRC) (Boys et al., 2018), log ratio pressure change (Boys et al., 2016), and the number of strike events (Amaral et al., 2015; Saylor et al., 2020). The sensor data were compared to established empirical threshold values from the literature to estimate the risk of fish mortality exceeding 10% (Interkantonale Aareplanung, 2014). The objectives of the present study were to:

1. investigate the physical conditions that fish experience passing through different turbines at the Ätrafors power plant, with special focus on downstream eel (*Anguilla anguilla*) migration
2. investigate the physical conditions that fish experience passing through different turbines at the Lanforsen power plant, with special focus on downstream Atlantic salmon (*Salmo salar*) smolt migration.

The report is divided in different sections: after the introduction (Section 1), Section 2 briefly describes the sensors we used for the experiment, Section 3 provides details about the study sites, Section 4 describes the experimental setting and the different scenarios, Section 5 presents the results which are discussed in Section 6. Section 7 summarizes the conclusions of the study.

2 Barotrauma Detection System (BDS)

The data collection was conducted using dummies for experimental setting and blade strikes count, and sensors for blade strike counts and pressure data.

2.1 Sensors

The BDS sensor housing consists of two POM plastic end caps and a 2.5 cm outer diameter polycarbonate plastic tube, with a total length of 10 cm, and mass of 46 g (Figure 1 and Figure 2).

Figure 1 Last version of the BDS sensors. The black circle above the "B32" label marks a strike from a turbine.

Neutral buoyancy of the BDS is achieved by screwing the flat end cap inwards or outwards to modify the total sensor volume. Each hemispherical end cap contains three digital total pressure transducers (MS5837-2BA, TE Connectivity, Switzerland) with a sensitivity of 0.0021 kPa (0.21 mm water column) and are linearly rated for 25 m of water depth (

Table 1). The sensors can however be deployed down to 45 m of water depth using a non-linear correction based on laboratory calibration. Each pressure transducer is equipped with its own on-chip temperature sensor, and pressure readings include real-time temperature correction using a 2^{nd} order algorithm. All sensors were tested against a commercial reference pressure sensor under static and dynamic conditions in a laboratory barochamber from 100 kPa to 500 kPa (Figure 3). The water logger is a HOBO commercial water level logger (U20-001-02, HOBO) from atmospheric conditions up to > 450 kPa (ca. 45 m water column). The HOBO pressure reference device was chosen as it is a calibrated commercially available device, identical to that used by the PNNL "Sensor Fish" device for pressure calibration (Deng et al., 2014).

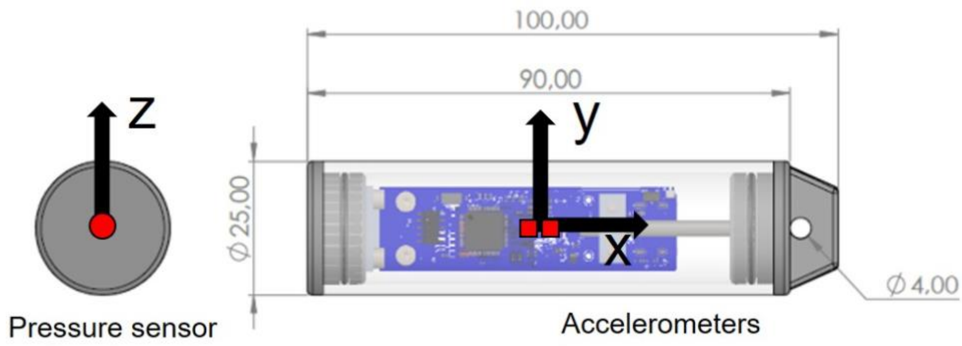

Figure 2 Schematic and dimensions of the BDS, showing the locations of the pressure sensor and the accelerometers. Left: view of sensor endcap with pressure port (red circle). Right: top view showing the location of the two identical accelerometers (red squares). The BDS is equipped with an atmospheric pressure calibration algorithm. Once the sensors have been activated using a magnetic switch, data from each pressure transducer is logged for 15 seconds. The atmospheric pressure, including the sensor-specific offsets, are recorded internally. Afterwards, all three pressure transducers are set to a default value of P_{atm} = 100.0 kPa at local atmospheric pressure. This auto-calibrates all sensors to local changes in the atmospheric pressure which occur during the day. This feature removes the necessity of manually correcting pressure sensor readings after deployment.

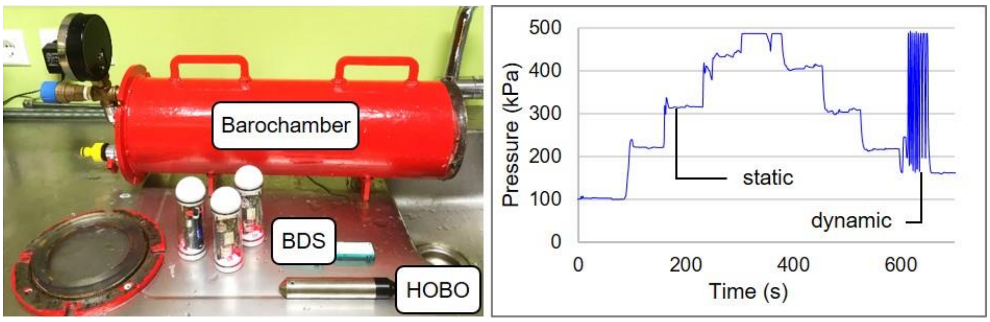

Figure 3 Left: Laboratory pressure testing setup. A maximum of 20 BDS can be simultaneously pressure tested up to 45 m H_2O in the barochamber. The HOBO pressure sensor was used for validation. Right: Example of a test data set showing the up and down ramping of the static pressure testing and several rapid events for dynamic pressure tests.

After electronics testing and mechanical assembly, all pressure transducers were calibrated against the HOBO water logger. The accuracy of all pressure transducers was < 2% relative error. The barochamber used for all pressure experiments is a custom-built device used for marine testing applications for depths down to 50 m.

It consists of a 0.5 m long welded steel tube with an outer diameter of 0.158 m and wall thickness of 0.005 m. One end of the device can be removed and sealed via an o-ring and includes a glass viewing window. Prior to pressure testing, the chamber was tilted onto one end and water was flushed through the system for 30 s to remove entrained air.

Table 1 Technical specifications of the BDS sensors deployed in this study.

Physical and sensor specifications	**Values**
Physical dimensions	100 +1.25 x 25 mm (adjustable)
Density	1.0 mg / mm³ (adjustable)
Excess mass (wet weight)	+/- 0.5 g
Sensor sampling rate	Pressure and IMU 100 Hz Accelerometer 2000 Hz
Maximum sampling duration	240 min
3D acceleration range	+/- 400 g
3D rotational velocity range	+/- 2067 °/s
Pressure range	+/- 2941 kPa
Temperature sensor	-20 - 85 °C (temperature correction on each pressure sensor)

In addition to the three pressure transducers, the BDS sensor also contains a digital 9 degree of freedom inertial measurement unit (IMU) model BMX160 (Bosch Sensortec, Germany) integrating linear accelerometer, gyroscope and magnetometer sensors. A detailed reporting of the IMU capabilities, its settings and specifications can be found on the datasheet provided at the manufacturer's web page (Bosch Sensortec GmbH, 2024).

Each sensor returns one pressure data series, one acceleration data series and the duration of the data collection (here expressed in percentage). The typical pressure data recorded by the BDS sensors can be broken down into different stages (injections, turbine passage and tailwater, Figure 4a). The injection is when the sensors are released in the water, either manually launched into the turbine inlet or deployed with other methods (e.g., using the rack cleaner). Turbine passage is clearly identified by a sudden increase followed by a sudden drop in pressure, and the tailwater stage is when the pressure stabilizes towards the atmospheric pressure. The parameters relevant for the studies are the Nadir pressure, the lowest pressure point in a given area or system, here within the passage through the turbine, and the pressure rate of change, defined as the velocity which pressure is decreasing over time (Figure 4b).

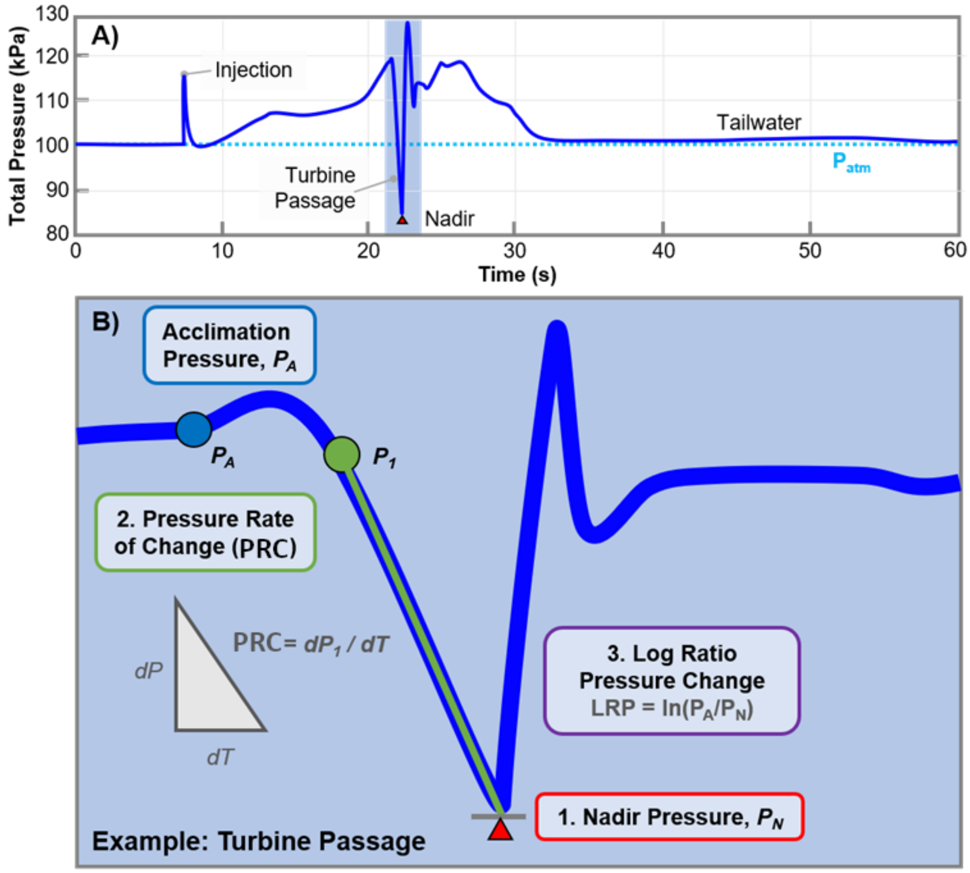

Figure 4 A) BDS pressure sensor time series during a typical turbine passage. B) The three parameters used to evaluate the risk of mortality to fish caused by rapid decompression are the Nadir pressure (1), the pressure rate of change (2) and the log ratio pressure change (3).

The thresholds for Nadir pressure and pressure rate of change used for the analysis of the data are empirical and derived from the literature work listed in Table 2 (Abernethy et al., 2003, Becker et al., 2003). We emphasize that the pressure must stay above the Nadir pressure thresholds and remain below the pressure rate of change limits to reduce the risk of injury and mortality due to pressure changes.

The focus for Ätrafors power plant was the European eel, thus we used the thresholds proposed for the American (silver) eel for the Nadir pressure (2.7 kPa. Pflugrath et al., 2019 in Table 2). For the pressure rate of change, we used a limit of 550 kPa/s which is a conservative value used for all fish species, derived from literature and applied in other similar experiments (Brown et al., 2012, Odeh, 1999). In Lanforsen the focus was the Atlantic salmon smolts. Since thresholds for this species are not yet available, for the Nadir pressure we adopted a conservative approach by doubling the maximum value obtained from the literature for Chinook salmon (*Oncorhynchus tshawytscha*,10 kPa), for a final value of 20kPa (Becker et al., 2003). For the pressure rate of change, we used the limit of 550 kPa/s as for European eel (Brown et al., 2012, Odeh, 1999).

Table 2 Summary of pressure-related physical parameters and corresponding threshold values used in this study. The threshold values were used to estimate the risk of fish mortality in exceedance of 10%.

Physical parameter	Fish species / test site	Thresholds of injury or mortality	Threshold used in this study	Literature source
Nadir pressure (kPa)	Chinook salmon (*Oncorhynchus tshawytscha*) Bluegill sunfish (*Lepomis macrochirus*)	70 kPa (no injury) 70 kPa (49.1.8% injury)	**20 for the salmon, 2.7 for the eel (values smaller than this threshold may result in a >10% risk of mortality)**	(Abernethy et al., 2003)
	Chinook salmon (*Oncorhynchus tshawytscha*) Rainbow trout (*Oncorhynchus mykiss*) Bluegill sunfish (*Lepomis macrochirus*)	2-10 kPa (some mortality) 2-10 kPa (some injury) 50 kPa (some mortality)		(Becker et al., 2003)
	American eel, yellow-phase American eel, silver-phase (*Anguilla rostrata*)	2.4 kPa (no mortality) 2.7 kPa (no mortality)		(Pflugrath et al., 2019)
pressure rate of change, PRC (kPa/s)	Brook lamprey (*Lampetra richardonii*) Pacific Lamprey (*Entosphenus tridentatus*)	1.05 kPa/s (no mortality) 0.73 kPa/s (no mortality)	**550 (values larger than this threshold may result in a >10% risk of mortality)**	(Colotelo et al., 2021)
	Bonneville Dam Ice Harbor Dam	62.0 kPa/s (sensor data only) 5784.7 kPa/s (sensor data only)		(Brown et al., 2012)
	ARL fish-friendly turbine runner guidelines	<550.3 kPa/s (at 1100.6 kPa/s injury is assumed)		(Odeh, 1999)
Log ratio pressure change, LRP (-)	Juvenile Chinook salmon (*Oncorhynchus tshawytscha)*	0.92 (10% mortality)	**0.5 (values larger than this threshold may**	(Carlson et al., 2012)

Physical parameter	Fish species / test site	Thresholds of injury or mortality	Threshold used in this study	Literature source
Log ratio pressure change, LRP (-)	Walleye (*Sander vitreus)* Tiger Muskie (*Esox luciusX E.Masquinongy)*	0.94 (10% mortality) 0.82 (10% mortality)	**result in a >10% risk of mortality)**	(Brown et al., 2015)
	Juvenile American shad (*Alosa sapidissima)*	0.64 (10% mortality)		(Pflugrath et al., 2020)
	American eel, silver-phase (*Anguilla rostrata*)	2.23 (no mortality, 13.3% injury)		(Pflugrath et al., 2019)

2.2 DUMMIES

Dummies are pieces of wood that resemble the weight and size of the sensors (Figure 5). They are mainly used to assessing the field conditions and providing insights about the time and place of the resurfacing of the sensors after they pass through the turbines. They can also be used to count the number of strikes. The number of strikes is visually counted when the dummies (and the sensors) are retrieved. Each sensor and dummy can experience multiple strikes during the same passage, although we did not record this type of event during this experiment. When counted, each strike is marked with a permanent marker to avoid double counting after the following passage or experiment.

Figure 5 Dummy with fully inflated balloons.

3 Study sites

3.1 ÄTRAFORS

The River Ätran, located in southern Sweden, stretches approximately 240 km, originating in Gullered, Västergötland, and flows into the Kattegat at Falkenberg. The river's drainage basin covers an area of 3,343 km^2, predominantly forested, with lakes, bogs, fields, and other land types contributing to its landscape. The river's average discharge is around 47 m^3/s, with historical records showing variations from 5 to 275 m^3/s. Major tributaries like Högvadsån, Assman, and Kalvån significantly contribute to the river's flow and ecological diversity. The river is heavily utilized for hydropower, with 35 stations along its course.

The focus in this case study is the European eel. The river supports a variety of fish species but the results from the sensors and dummies were related to the European eel. The eel migration dynamics have been already studied in Calles et al. (2010, 2013). The facility is equipped with racks and traps for descending silver eels in the upper part of the intake channel. As described in Calles et al., 2013, the racks have been improved from 2010 to 2013 to reduce mortality during eel migration.

Figure 6 shows the location of Ätrafors power station, which is a hydroelectric plant on the Ätran River, about 23 kilometres upstream from Falkenberg. Owned by Sydkraft Hydropower AB, a company in the Uniper group, and maintained by One, it began operation in 1918, with the current structure completed in 1930.

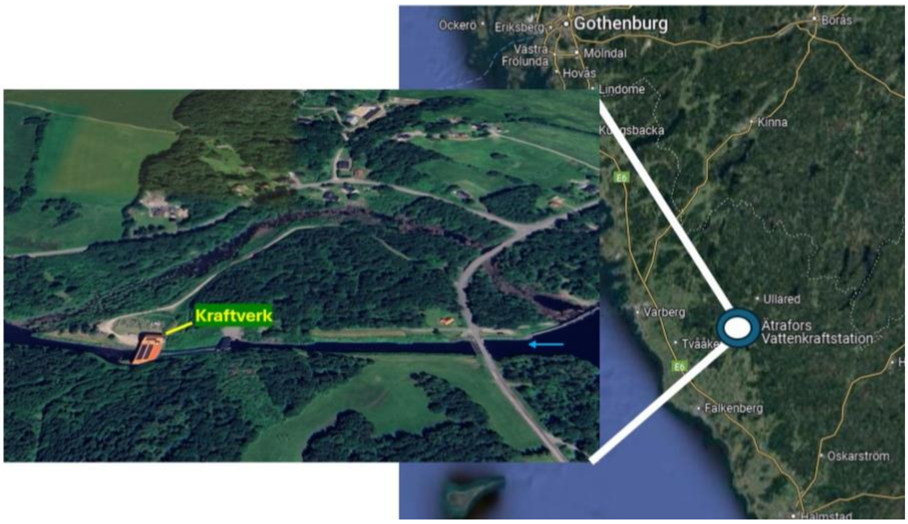

Figure 6 Location of Ätrafors powerstation (Google Earth, 2024)

Originally, the site was developed by damming the historic fishing location at Rävigeforsen (mainly sawmills and mills), leading to the construction of the first power station with an 18-meter head, generating 2.5 MW. In 1922, Yngeredsfors Kraft AB acquired the plant, initiating a significant upgrade that concluded in 1930. This resulted in a second plant with a 23.5-meter head, producing 13 MW from three Francis turbines.

3.2 LANFORSEN

The Dalälven River is one of Sweden's major rivers, flowing through the central part of the country. It stretches approximately 520 kilometres, originating from the confluence of the Österdalälven and Västerdalälven rivers in Dalarna County and eventually emptying into the Baltic Sea near the town of Älvkarleby. Historically, the Dalälven River has been an important waterway throughout Swedish history, with several historical sites and towns located along its banks. It is also a popular destination for recreational activities such as fishing, boating, and hiking. The river basin is rich in biodiversity, supporting various species of fish, birds, and other wildlife. Conservation efforts are in place to protect and restore the natural habitats along the river, ensuring the sustainability of its ecosystems.

The river is notable for its numerous hydropower stations, including the Lanforsen Station, which is located about 23 kilometres from the river's mouth. This station generates 39 MW of power using four Kaplan turbines and operates at a head of 10 meters with a discharge capacity of 620 m³/s. The location of the power plant is shown in Figure 7.

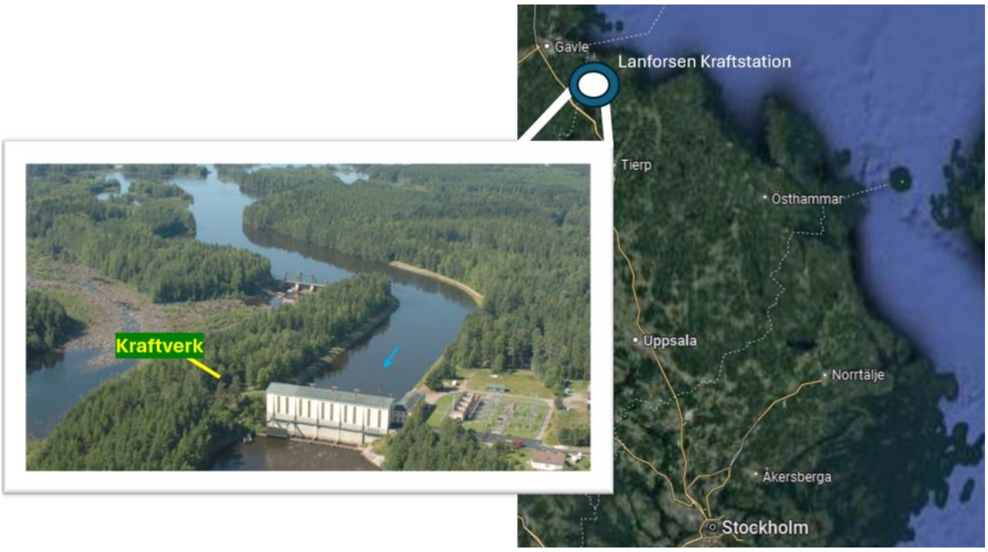

Figure 7 Location of Lanforsen power plant (Santiago, 2021).

Lanforsen is a hydroelectric power plant and former waterfall located on the Dalälven River at Älvkarleö, between the Untra and Älvkarleby power plants in Älvkarleby Municipality.

The power station was constructed between 1919 and 1931 with three Kaplan turbines. In the 1940s, a fourth unit, also equipped with a Kaplan turbine, was added. The plant has a capacity of 42 MW and a head of 9.25 meters. It primarily functions as a run-of-the-river power station. Initially, the plant was owned one-third by Sandvikens Ironworks and two-thirds by the City of Stockholm, which utilized power from Lanforsen through a 145-kilometer transmission line, partly parallel to Untra. In 1982, Sandvikens Ironworks sold its share to Stockholm Energi (Wikipedia, 2024b). The current owner and operator of the Lanforsen HPP is Fortum.

4 Method

4.1 EXPERIMENTAL SETTING

At both study sites, Ätrafors and Lanforsen, dummies were deployed to test the experimental design and to preliminary count the number of strikes. While the pressure was actually measured by the sensors, the strikes were visually evaluated and counted after retrieving both sensors and dummies. The sensors were deployed to measure the pressure. At both power plants the dummies and the sensors were deployed inside the rack, to ensure that the sensors could enter the turbines and not resurface upstream. Alternative scenarios (S from hereon, Table 3 and Table 5) were analyzed to investigate different conditions for fish passage through the turbines. Scenarios related to the combination of several factors: discharge, turbine number (unit), and turbine type. Discharge denotes the flow through the turbines during the experiment, turbine number indicates in which turbine we performed the experiment, the turbine type if a turbine is Kaplan or Francis. Even if two turbines are of the same type and have the same discharge, the hydraulic conditions inside the turbine might not be the same and they might lead to different pressure measurements.

Each scenario starts with the deployment of the dummies. The deployment of the dummies had multiple objectives: evaluating if the dummies were passing through the turbines intact, setting the timing of the inflation of the balloons and helping the personnel retrieving the sensors to identify in which areas sensors and dummies are resurfacing. The timing of balloon inflation is crucial and requires careful calibration: if the balloons inflate too early, the sensors may resurface upstream, while inflating too late could cause them to surface too far downstream, making retrieval impossible.

Ätrafors power plant is equipped with three Francis turbines (Turbine 1, 2 and 3), Lanforsen with four Kaplan turbines (Turbine 1, 2, 3, 4). The flows were determined by the hydropower operations during the days of the experiments (23-24/10/2023 for Ätrafors, 17-18/06/2024 for Lanforsen).

Table 3 Overview of the two different scenarios at Ätrafors

Scenario	Turbine type	Turbine nr.	Discharge (m^3/s)
I	Francis	1	25
II	Francis, external	3	16

Each experiment has been considered statistically robust if the scenario included at least 25 usable data series from individual sensors. Unusable data series were discarded. Usable data series means that the data collected by the sensors follows a specific distribution (see Figure 4), visually assessed by the researcher during data consolidation. Unusable data series mostly include sensors that resurfaced upstream without passing through the turbines.

Across both scenarios, a total of 111 units were deployed, with 76 sensors and 35 dummies (Table 4). 6 sensors and 1 dummy were lost, with no sensor or dummy being destroyed, but 25 were struck. Despite these strikes, most of the data collected was usable (57 data series), with only 5 data series deemed unusable. The dummies had a minimal impact on overall results, with only 1 loss reported and only 2 strikes in SI.

Table 4 Data collected for each scenario.

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
SI	Sensors	41	5	0	7	27	5
	Dummies	25	1	0	2	0	0
	Total	66	6	0	9	27	5
SII	Sensors	35	1	0	16	30	0
	Dummies	10	0	0	0	0	0
	Total	45	1	0	16	30	0
Total	Sensors	76	6	0	23	57	5
	Dummies	35	1	0	2	0	0
	Total	111	7	0	25	57	5

For Lanforsen case study, we conducted deployments at four scenarios (Table 5). For the first two scenarios (SI Turb. 2 80 m³/s and SII Turb. 3 80 m³/s), 25 usable data series were collected. We included also the results from a scenario representative of a higher discharge (SIII Turb.3 100 m³/s) even with less data series. For this scenario, the lack of data was due to the limited amount of time the power plant operated at a discharge of 100 m³/s. Maintenance operations in the upstream and downstream hydropower plants led to production and time restrictions, resulting in the loss of seven sensors. In Lanforsen we tested also an additional scenario (SIV), but the deployment of the sensors was not successful because all the sensors resurfaced upstream due to local physical and hydraulic conditions.

Table 5 Overview of the different scenarios at Lanforsen

Scenario	Turbine type	Turbine	Discharge (m³/s)
I	Kaplan	2	80
II	Kaplan	3	80
III	Kaplan	3	100
IV	Kaplan	1	100

Across all scenarios, a total of 139 units were deployed, including 103 sensors and 36 dummies (Table 6). Overall, 13 sensors were lost (7 only in SIII Turb.3 100 m³/s), with no sensors destroyed or struck in any scenario. Most of the data collected (70 sensors) was usable.

Table 6 Data collected for each scenario at the Lanforsen hydropower plant.

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
SI	Sensors	32	1	0	0	25	6
	Dummies	11	0	0	0	0	0
	Total	43	1	0	0	25	6
SII	Sensors	40	1	0	0	31	7
	Dummies	2	0	0	0	0	0
	Total	42	1	0	0	31	7
SIII	Sensors	22	7	0	0	14	1
	Dummies	5	0	0	0	0	0
	Total	27	7	0	0	14	1
SIV	Sensors	9	1	0	0	0	8
	Dummies	18	1	0	0	0	0
	Total	27	2	0	0	0	8
Total	Sensors	103	10	0	0	70	22
	Dummies	36	1	0	0	0	0
	Total	139	13	0	0	70	22

4.2 STATISTICAL ANALYSIS

We conducted a one-way Kruskal Wallis ANOVA with the scenario as grouping factor. The hypothesis was to test if pressure variables (Nadir pressure and pressure ROC) were statistically different among the scenarios. The Kruskal-Wallis test can be used with uneven samples because it is a non-parametric method. Instead of analyzing the raw data values, the test focuses on ranking all the data points across the groups and then comparing the average ranks. This ranking approach allows the test to minimize the impact of differing sample sizes, making it robust to variations in group sizes. Additionally, the Kruskal-Wallis test does not assume that the groups have equal variances, which is a requirement for parametric tests like one-way ANOVA. This means that even when the number of observations in each group differs significantly, the test remains valid. Its ability to handle such situations makes the Kruskal-Wallis test a practical choice for analyzing our data, as the sample size of each scenario is different and especially SIII (Turb.3 100 m^3/s) in Lanforsen has a small sample size. After performing the Kruskal-Wallis test and finding a significant result, we conducted a post-hoc test to determine which specific groups differ from each other by applying Dunn's test. We ran the test for both Nadir pressure and pressure rate of change variables. We did not compare the two case studies because of the many differences in discharge rates, target species, and turbine types making a comparison non-statistically robust.

5 Results

5.1 ÄTRAFORS

Descriptive statistics for Nadir pressure and pressure rate of change (PRC) in both SI (Turb.1 25 m^3/s) and SII (Turb.3 16 m^3/s) reveal moderate clustering of values around the mean. In SI (Turb.1 25 m^3/s), shown in Table 7, Nadir pressure and PRC display standard deviation (STD) and interquartile range (IQR) values that suggest the data are relatively well-distributed around the mean without large variability, as reflected in the limited range of values. Table 8 shows that SII (Turb.3 16 m^3/s) follows a similar pattern, with low STD and IQR values for both variables. This consistency between SI (Turb.1 25 m^3/s) and SII (Turb.3 16 m^3/s) points to stability in pressure dynamics across different discharge and different turbines.

Table 7 General statistics for the Ätrafors SI (Turb.1 25 m^3/s) for Nadir pressure and pressure rate of change. Statistics are Mean, Median, Maximum, Minimum, Range, 25th and 75th percentile, Interquartile range (IQR), Standard deviation (STD)

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	43.1	43.8	57.6	19	38.6	49.1	40.4	8.6	9.4
PRC (kPa/s)	258.7	256.5	282.7	237.8	44.9	266.6	251.6	15.1	11

Table 8 General statistics for the Ätrafors SII (Turb.3 16 m^3/s) for Nadir pressure and pressure rate of change. Statistics are Mean, Median, Maximum, Minimum, Range, 25th and 75th percentile, Interquartile range (IQR), Standard deviation (STD)

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	43	44.7	52.8	29.1	23.7	49.6	37.6	12.1	7.6
PRC (kPa/s)	248.5	247.2	275.4	229.1	46.3	253.2	242.2	10.9	11.6

Analyzing the water column, both scenarios exhibit a similar overall pattern where the water column height decreases to a minimum before recovering, as shown in Figure 8. However, there are notable differences between the scenarios. SI (Turb.1 25 m^3/s), with a higher flow rate, shows a more gradual and less pronounced drop in water depth, reaching a shallower Nadir pressure point. In contrast, SII (Turb.3 16 m^3/s), with a lower flow rate, causes a steeper drop in water depth, indicating more significant fluctuations. After reaching the Nadir, there was a recovery in pressure at both scenarios, but with different behaviors. SII (Turb.3 16 m^3/s) exhibits a sharp peak just after the Nadir pressure, temporarily exceeding the initial water level before stabilizing. On the other hand, SI (Turb.1 25 m^3/s) recovery is smoother, with a more controlled return to stable water levels.

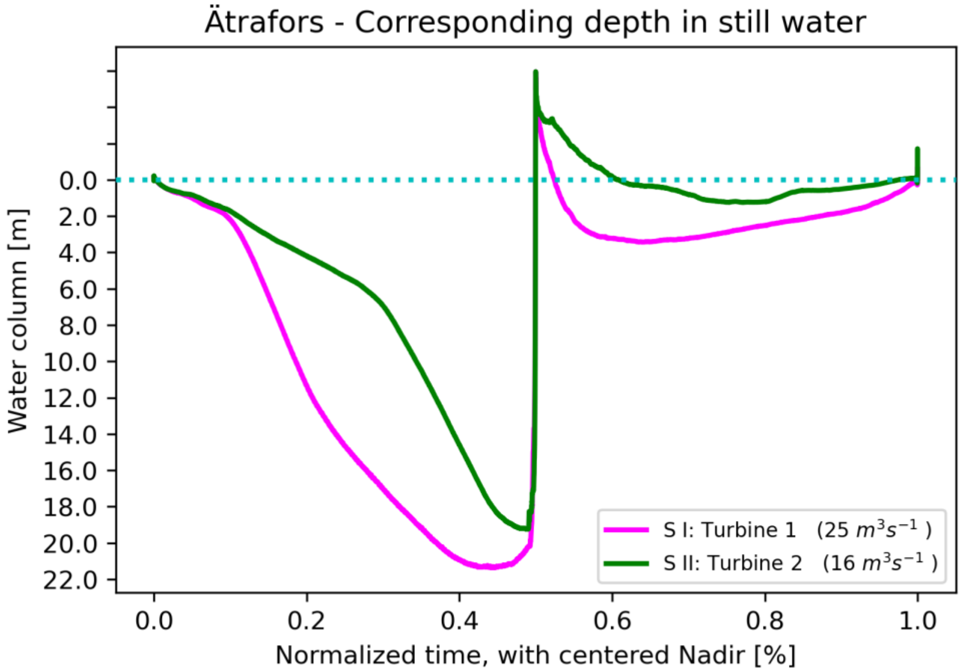

Figure 8 Average measured pressure converted in water columns [meter] are divided into pre-Nadir and post-Nadir event across all scenarios; The dotted light blue line indicates the surface. The X-axis represents the normalized time, where 0.5 (or 50%) likely marks the Nadir—the point of minimum pressure converted in water depth. The Y-axis shows the water column height in meters, demonstrating the fluctuations in water levels as the sensors travel through the turbines.

In both scenarios, the pressure initially rises steeply from the baseline value of approximately 100 kPa, reaching different peak pressures (Figure 9). SI (Turb.1 25 m^3/s) shows a steeper increase, peaking at around 310 kPa, while SII (Turb.3 16 m^3/s) peaks at a lower pressure of approximately 240 kPa. After reaching the peak, both curves exhibit a sharp drop. Nadir pressure drop is more pronounced in SI (Turb.1 25 m^3/s), where the pressure falls below 50 kPa, while in SII (Turb.3 16 m^3/s) it drops to about 80 kPa. After the Nadir point, the pressures gradually rise again and eventually return to the baseline value of around 100 kPa by the end of the normalized period. The red dotted line representing the pressure threshold for eels at 2.7 kPa, assumed to be a critical threshold. During the Nadir phase of the pressure curves, the Nadir values in both scenarios never fell below this threshold.

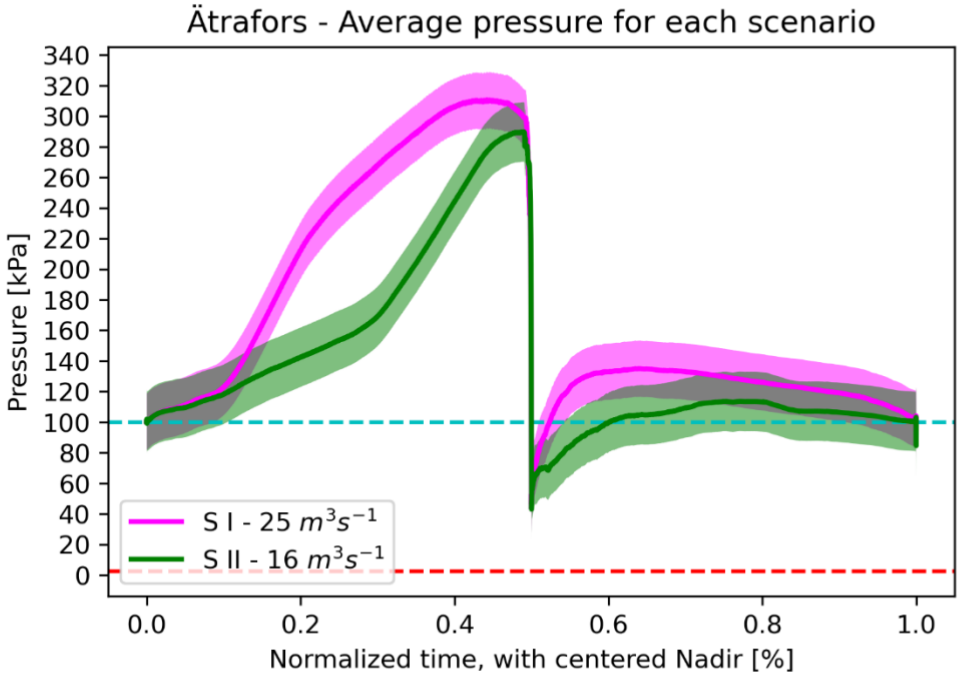

Figure 9 Average pressure values in kilo Pascal are divided into pre-Nadir and post-Nadir for all scenarios; The light blue dotted line indicates atmospheric pressure, while the red dashed line denotes the threshold for eels. The shaded area represents the confidence interval (95% equal to 1.96 standard deviations) of the distributions.

For SI (Turb.1 25 m^3/s), the boxplot shown in Figure 10 indicates a median pressure slightly above 40 kPa. The IQR for this scenario extends from around 35 kPa to 50 kPa, with whiskers stretching from approximately 30 kPa to 57 kPa. Interestingly, there are two outliers below the lower whisker, with pressure values just above 20 kPa. These outliers suggest that there are occasional dips in pressure that, while notable, do not approach the critical threshold for eels. SII (Turb.3 16 m^3/s) exhibits a similar distribution of Nadir pressures, with a median pressure again slightly above 40 kPa. The IQR and whiskers for this scenario are almost identical to those of SI (Turb.1 25 m^3/s), with the IQR spanning from about 35 kPa to 50 kPa and whiskers extending from 29 kPa to 53 kPa. However, no outliers are present in this scenario, indicating a more consistent pressure distribution without any significant drops.

Both scenarios maintain pressure levels well above the Nadir threshold for eels, with the median pressures and the entire range of the IQRs remaining far from the critical level. This suggests that the operational pressures of both turbines, under the given scenarios, are unlikely to pose a threat to eel safety, as the Nadir pressures remain comfortably within a safe range. For the Nadir pressure, the Kruskal Wallis ANOVA did not detect significant differences between the two scenarios, with a p-value of 0.86.

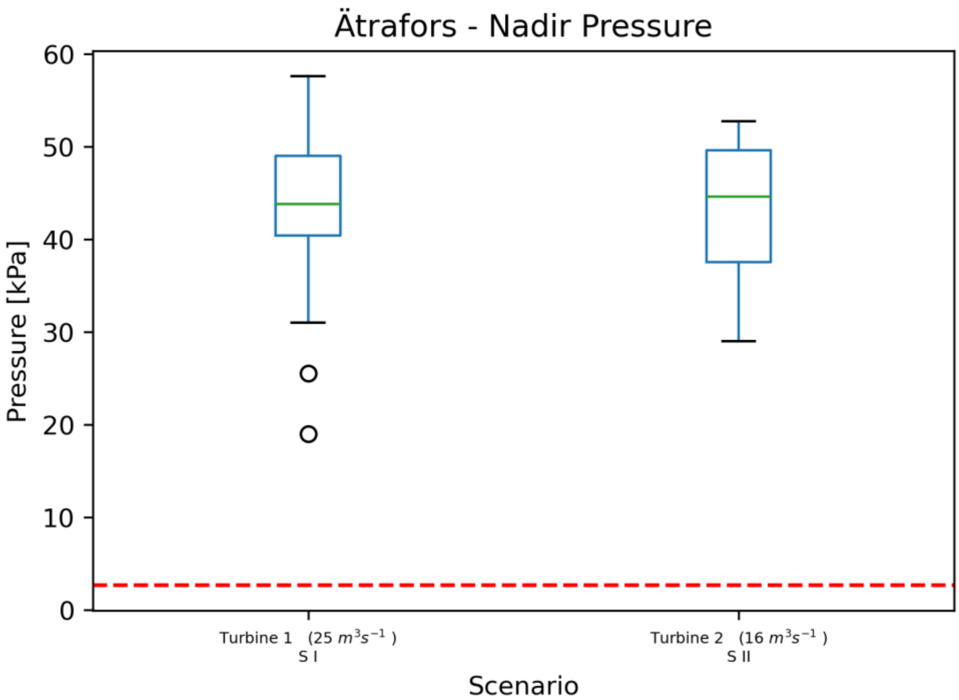

Figure 10 Boxplots represent statistic indicators for the Nadir pressure in kilo Pascal for all relevant scenarios: the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outlier. The red dashed line denotes the threshold for eels (see Table 2).

For SI (Turb.1 25 m^3/s), the box-and-whisker shows that the median pressure rate hovers around 300 kPa/s, with an IQR spanning from approximately 275 kPa/s (lower quartile) to nearly 325 kPa/s (upper quartile). The whiskers extend down to around 250 kPa/s and up to nearly 350 kPa/s. Notably, there are no outliers indicated for this scenario (Figure 11). In contrast, SII (Turb.3 16 m^3/s) exhibits a slightly higher median pressure rate—just above 300 kPa/s. Its IQR extends from approximately 275 kPa/s (lower quartile) to just under 350 kPa/s (upper quartile). The lower whisker drops close to around 275 kPa/s, while the upper whisker reaches approximately 400 kPa/s. Additionally, an outlier is depicted slightly above the upper whisker at about 400 kPa/s.

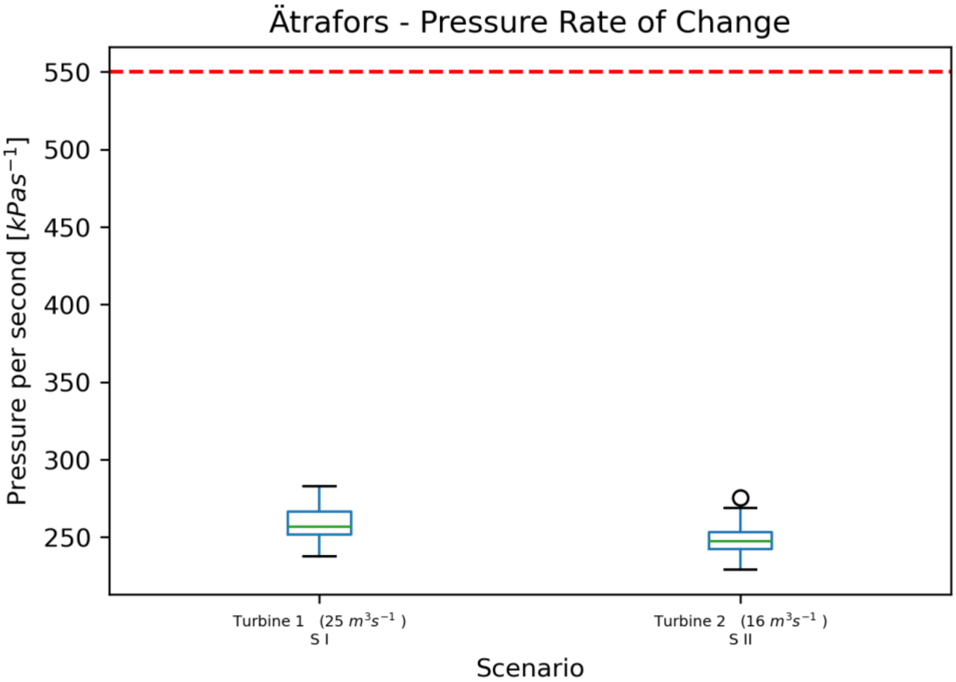

Figure 11 The pressure rate of change in kilo Pascal per seconds for all relevant scenarios are plotted; the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red strikethrough line corresponds to the threshold for a generic fish species.

There was a higher pressure rate of change in turbine 1 at 25 m^3/s compared to turbine 2 at 16 m^3/s; the difference was statistically significant (Kruskal Wallis ANOVA with a p-value of 0.003). In this case the value of the Dunn's post-hoc test is the same as for the Kruskal Wallis because only two scenarios are considered. However, as highlighted by the red dashed line (Figure 11), which represents the threshold described in Section 2.1, the pressure rate of change is well-below the threshold considered harmful for fish entering the turbines in both scenarios.

In this experiment, we recorded some strike events during the turbine passage in both scenarios. We didn't record any multiple strike events (e.g., one unit is struck more than once during the same passage), thus number of strikes corresponds to number of struck units. In SI (Turb.1 25 m^3/s), the percentage of strikes relative to total deployments is 15.0%, in SII (Turb.3 16 m^3/s), the percentage increased to 36.4%.

5.2 LANFORSEN

The data across three scenarios SI (Turb. 2 80 m^3/s), SII (Turb. 3 80 m^3/s), and SIII (Turb. 3 100 m^3/s) for Nadir pressure and PRC at Lanforsen display some notable differences in pressure values and variability. In SI (Turb. 2 80 m^3/s), the mean Nadir pressure is around 63 kPa, ranging from approximately 19 to 79 kPa, as shown in Table 9. The PRC has a mean of nearly 83 kPa/s with values spanning from 45 to 126 kPa/s, showing moderate variability in both metrics. The IQR for both variables indicate some dispersion but without extreme outliers, and the standard deviations also reflect moderate clustering around the means.

Table 9 General statistics for Lanforsen SI (Turb. 2 80 m^3/s) for Nadir pressure and pressure rate of change. Statistics are Mean, Median, Maximum, Minimum, Range, 25th and 75th percentile, Interquartile range (IQR), Standard deviation (STD)

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	63.4	66.2	78.6	18.9	59.6	74.8	58.3	16.5	14.7
PRC (kPa/s)	82.7	80.9	125.5	45	80.5	86.8	74.3	12.5	15.5

For SII (Turb. 3 80 m^3/s), shown in Table 10, the mean Nadir pressure is higher, close to 73 kPa, with a range extending from about 35 to 99 kPa. The PRC mean is slightly lower than in SI (Turb. 2 80 m^3/s), at around 78 kPa/s, yet the range widens substantially from 0.7 to 112 kPa/s. Both variables in SII (Turb. 3 80 m^3/s) demonstrate a more substantial spread in their values, as indicated by their respective IQRs and slightly lower standard deviations than S I.

Table 10 General statistics for Lanforsen SII (Turb. 3 80 m^3/s) for Nadir pressure and pressure rate of change. Statistics are Mean, Median, Maximum, Minimum, Range, 25th and 75th percentile, Interquartile range (IQR), Standard deviation (STD)

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	72.8	75.2	99.4	34.7	64.7	80.1	67.8	12.3	11.7
PRC (kPa/s)	78.4	79.4	112.1	0.7	111.4	86.6	73.2	13.4	18.8

In S III, the mean Nadir pressure is roughly 40 kPa, with values between 24 and 63 kPa, indicating a tighter distribution around the mean, which can be seen in Table 11. PRC in SIII (Turb.3 100 m^3/s) has a higher mean than in previous scenarios at about 104 kPa/s, with values ranging from 78 to 124 kPa/s. In S III, turbine 3 and 100 m3/s, the Nadir pressure varied more compared to the other scenarios with lower discharge. On the contrary the pressure rate of change showed less variability.

Table 11 General statistics for Lanforsen SIII (Turb.3 100 m^3/s) for Nadir pressure and pressure rate of change. Statistics are Mean, Median, Maximum, Minimum, Range, 25th and 75th percentile, Interquartile range (IQR), Standard deviation (STD).

Variable	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD
Nadir (kPa)	40.1	33.7	63	23.6	39.4	53.3	29.6	23.7	13.9
PRC (kPa/s)	104.3	108.8	124.5	78.1	46.4	113	92.7	20.3	14.5

These values collectively reveal different degrees of variability and clustering across scenarios, reflecting how pressure and PRC conditions vary in each setting.

The fluctuation of water depth over time shows a pronounced decrease in the centre indicating a significant drop in water level (Figure 12). All three scenarios exhibit similar patterns: starting at an elevated level on the left side of the graph before sharply descending into a trough around the midpoint—the Nadir—and then ascending back up on the right side. SIII's (Turb.3 100 m^3/s) line slightly diverges from SI (Turb. 2 80 m^3/s) and SII (Turb. 3 80 m^3/s) after passing through the Nadir point.

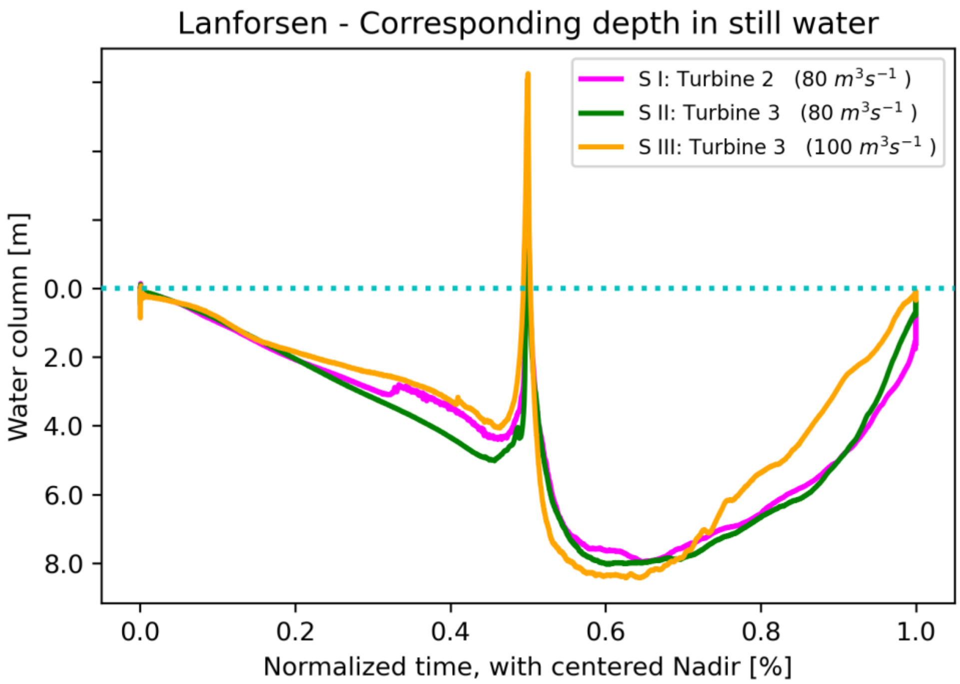

Figure 12 Average measured pressure converted in water columns [meter] are divided into pre-Nadir and post-Nadir passage across all scenarios; The dotted light blue line indicates the reference water level surface, which is given a default value of "0m".

For the average pressure, all three scenarios follow a similar pattern (Figure 13 and Figure 14): they start at the atmospheric pressure, rise slightly and drop sharply to their lowest point (the Nadir) during the passage through the turbines, and finally rebound and gradually decrease in the tail race. The red dashed line, which represents the pressure threshold for salmon, is set at 20 kPa. It is evident that in none of the three scenarios the pressure drops below this threshold. The comparison between the scenarios highlights the possible impact of different discharge on pressure levels. SIII (Turbine 3 at 100 m³/s) appears to have a slightly higher pressure recovery compared to the other scenarios (80 m³/s), but it still does not fall below the threshold.

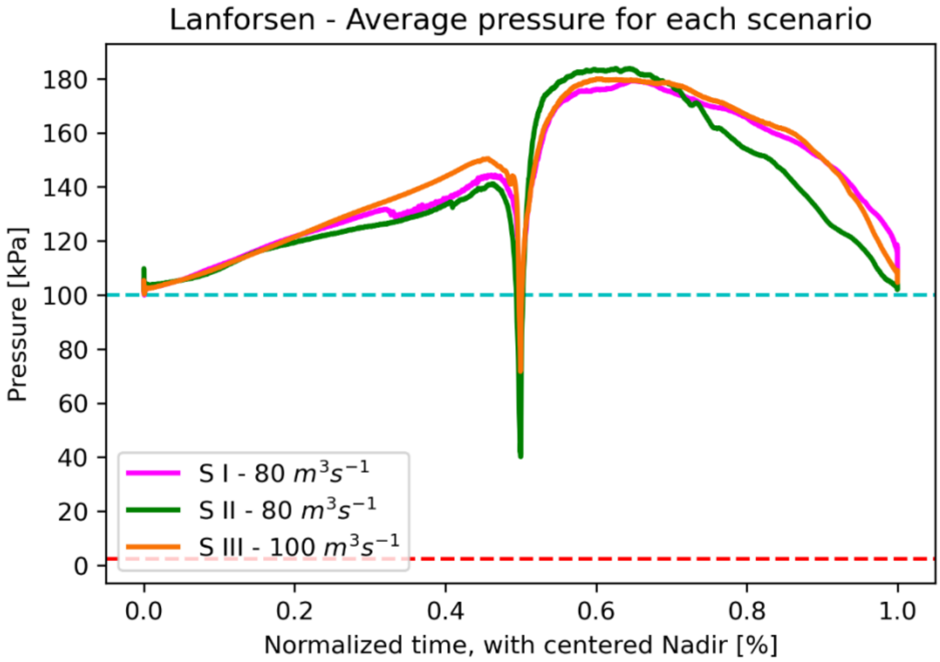

Figure 13 Average absolute pressure values in kilo Pascal are divided into pre-Nadir and post-Nadir for all scenarios; the light blue dashed line indicates atmospheric pressure, while the red dashed line denotes the threshold chosen for the Atlantic salmon.

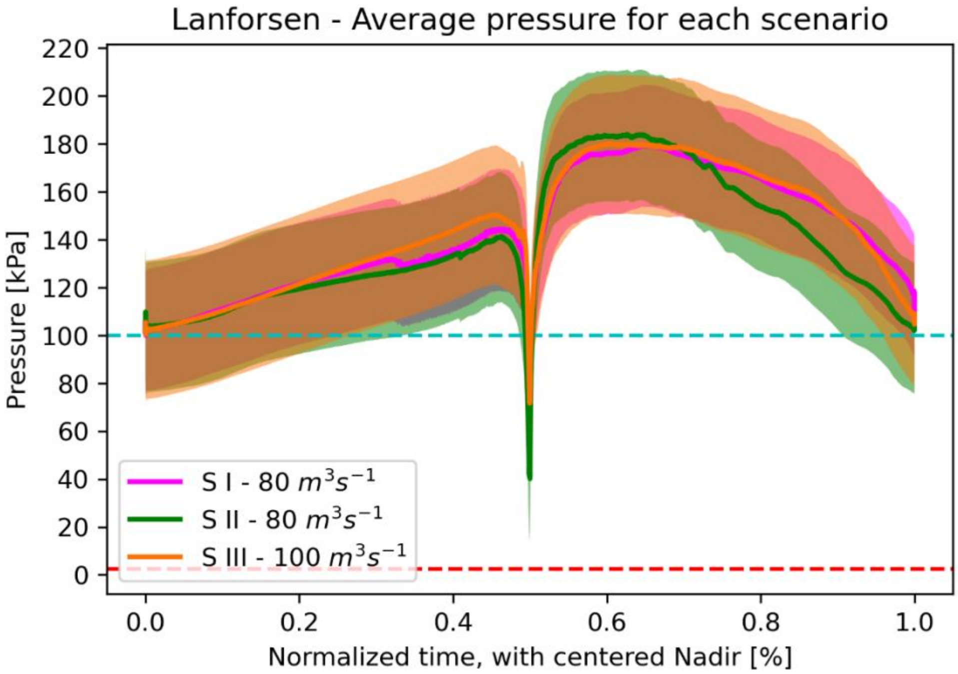

Figure 14 Average absolute pressure values in kilo Pascal are divided into pre-Nadir and post-Nadir for all scenarios; the light blue dashed line indicates atmospheric pressure, while the red dashed line denotes the threshold chosen for the Atlantic salmon. The shaded area represents the confidence interval (95% equal to 1.96 standard deviations) of the distributions.

As shown in Figure 15 for SI (Turb. 2 80 m³/s), where Turbine 2 operates at a flow rate of 80 m³/s, the pressure values range from around 40 kPa to 80 kPa, with a median near 60 kPa. While most of the pressure readings are well above the salmon safety limit, there is an outlier below 20 kPa. This suggests that in this scenario, the pressure dropped below the safe threshold at least once, potentially endangering salmon.

SII (Turb. 3 80 m³/s), with Turbine 3 also operating at 80 m³/s, exhibits slightly higher pressure values compared to Scenario I, with a median just under 80 kPa. The pressure range is narrower, indicating more consistent pressure levels.

In Scenario III, where Turbine 3 operates at a higher flow rate of 100 m³/s, the median pressure drops to around 40 kPa, and the overall pressure range is wider. The lower whisker is close to the 20 kPa limit, but there are no outliers below this threshold. Although this scenario does not show any instances where pressure fell below the salmon safety limit, the overall lower pressures suggest it operates closer to the critical threshold.

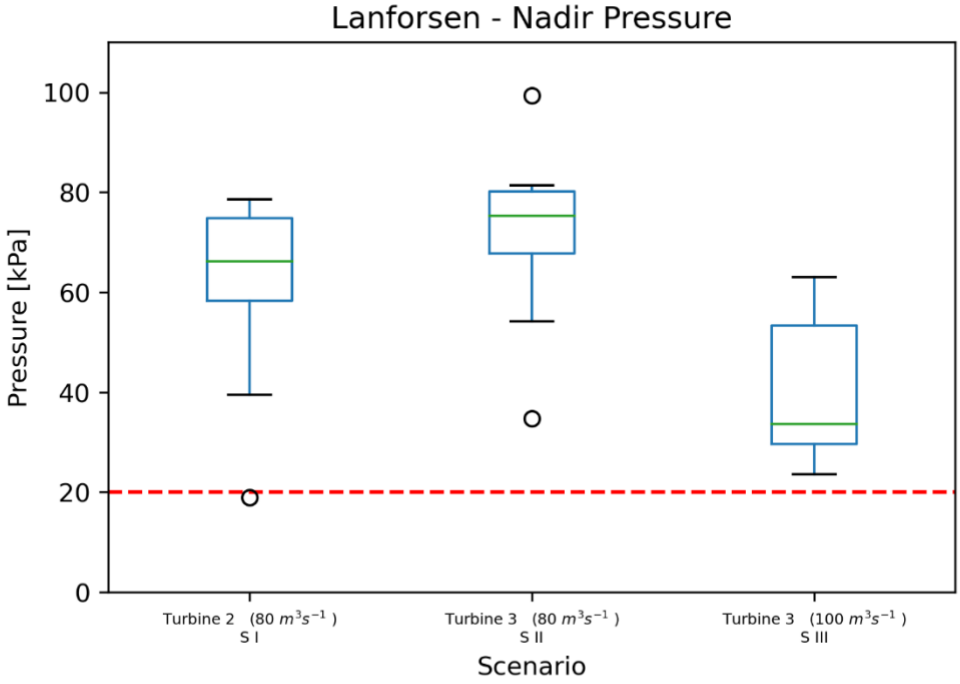

Figure 15 Boxplots represent the statistic values for the Nadir pressure in kilo Pascal for all relevant scenarios, the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red dashed line corresponds to the threshold for fish.

The results of the Kruskal Wallis ANOVA for Nadir pressure are significant. Dunn's test shows that there is no statistically significant difference between Scenario I and Scenario II (same discharge), as their p-value is 0.06, slightly above the standard significance threshold of 0.05. However, both SI and SII where the discharge is 80 m^3/s have significantly higher range in Nadir pressure compared to SIII where the discharge is 100 m^3/s (SI vs. SIII, $p = 0.004$, SII vs. SIII, $p<0.001$). For PRC, shown in Figure 16, in SI (Turb. 2 80 m^3/s) the pressure rate of change clusters around a median just below 100 kPa/s. The values are mostly consistent, ranging between 90 kPa/s and 110 kPa/s, with two outliers—one slightly above 100 kPa/s and another significantly below 50 kPa/s. Importantly, all values are well below the safety limit, indicating that this scenario poses no immediate risk to salmon due to pressure rate changes.

SII (Turb. 3 80 m^3/s) shows a similar distribution to SI (Turb. 2 80 m^3/s). The median rate of change remains just below 100 kPa/s, with a slightly broader range of values. The outliers are consistent with those in Scenario I, and, like the first scenario, all the observed pressure rate changes stay safely under the threshold.

In SIII (Turb.3 100 m^3/s), the pressure rate of change has a slightly higher median, closer to 110 kPa/s. However, the range and pattern of values are similar to the previous scenarios, with no outliers exceeding the safe limit. All the recorded pressure rates of change remain well below 550 kPa/s, indicating that this scenario is also safe for salmon.

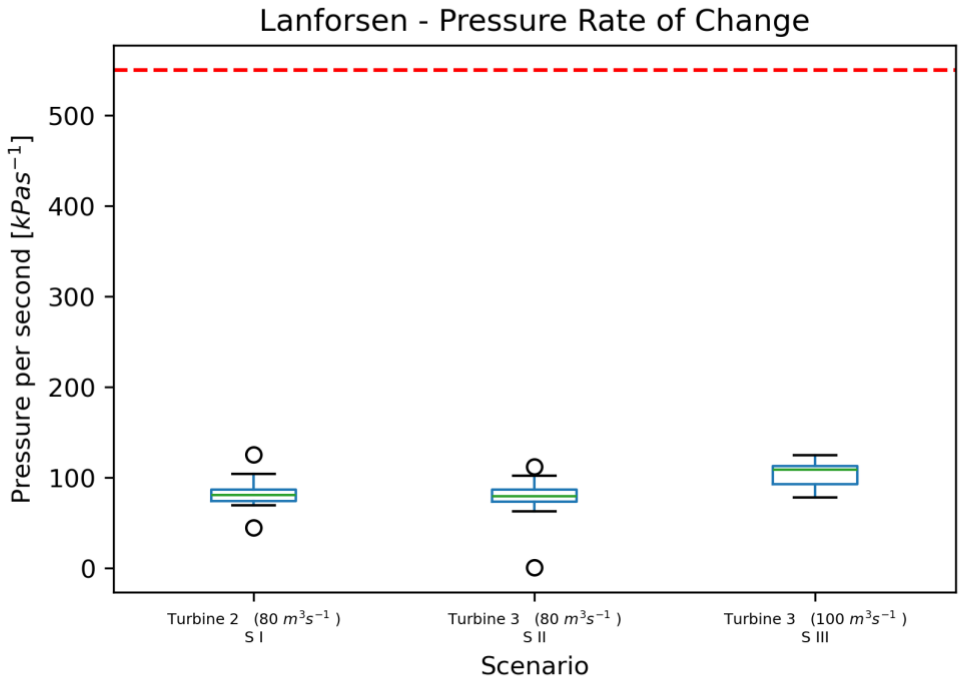

Figure 16 The pressure rate of change in kilo Pascal per seconds for all relevant scenarios are plotted as Boxplot; the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red dashed line corresponds to the threshold for fish.

The analysis of all three scenarios shows that the pressure rate of change is consistently below the critical limit. Despite the presence of outliers, none of the scenarios approach a level that would pose a threat to salmon, making the conditions safe across all three scenarios with respect to pressure fluctuations.

For the pressure rate of change, the Kruskal Wallis ANOVA highlighted significant differences. Similarly to the Nadir pressure variable, Dunn's test results indicate that there is no statistically significant difference between SI (Turb. 2 80 m^3/s) and SII (Turb. 3 80 m^3/s), as their p-value is 1, showing that their distributions are very similar. However, both SI and SII with a discharge of 80 m^3/s had a significantly lower pressure rate of change compared to SIII where the discharge is 100 m^3/s (SI vs. SIII $p = 0.001$, SII vs SIII $p < 0.0001$). The analysis for SIII (Turb.3 100 m^3/s) should be interpreted with caution due to the smaller sample size relative to the other scenarios but it indicates that higher discharge might result in larger pressure rate of change across the turbines in Lanforsen, with values remaining well-below the critical threshold.

5.3 COMPARISON WITH OTHER CASE STUDIES

The case studies outlined earlier in this report were compared with data from two additional case studies in Norway: Funnefoss and Kongsvinger hydropower plants, which are equipped with large Kaplan turbines (see Carolli et al., 2024 for further details). The comparison of Nadir pressure does not show a consistent pattern based on turbine type (see Figure 17). While Nadir pressure indicator is generally lower for the Francis turbine, the value for the Lanforsen S III (100 m^3/s)

is more comparable to the Francis turbine at Ätrafors than to the Kaplan turbines in the Norwegian case studies. In these cases, discharge levels were 200 m³/s at Kongsvinger and 400 m³/s at Funnefoss, double the discharge at Lanforsen S III. It appears discharge is the most important factor that influences Nadir pressure (higher discharge – lower Nadir pressure). However, Lanforsen S III lacks sufficient data for statistical comparison, as does the Francis vs. Kaplan turbine factor, for which only two Francis turbines are available. In another case study in Switzerland (Tuthan and Toming, 2023), a horizontal Kaplan turbine recorded Nadir pressure similar to, though generally lower than, those observed at Funnefoss and Kongsvinger. Therefore, additional data would be needed to enable a more robust analysis. Data from the downstream migration structure indicate that pressure remains consistently close to atmospheric levels, as expected.

For the Ätrafors and Lanforsen SIII (Turb.3 100 m³/s) case studies, the Nadir pressure values fall below the threshold for the grayling (0+ life stage). Although this species was not the focus of the study, this pattern could suggest a potential risk for certain species passing through the turbines.

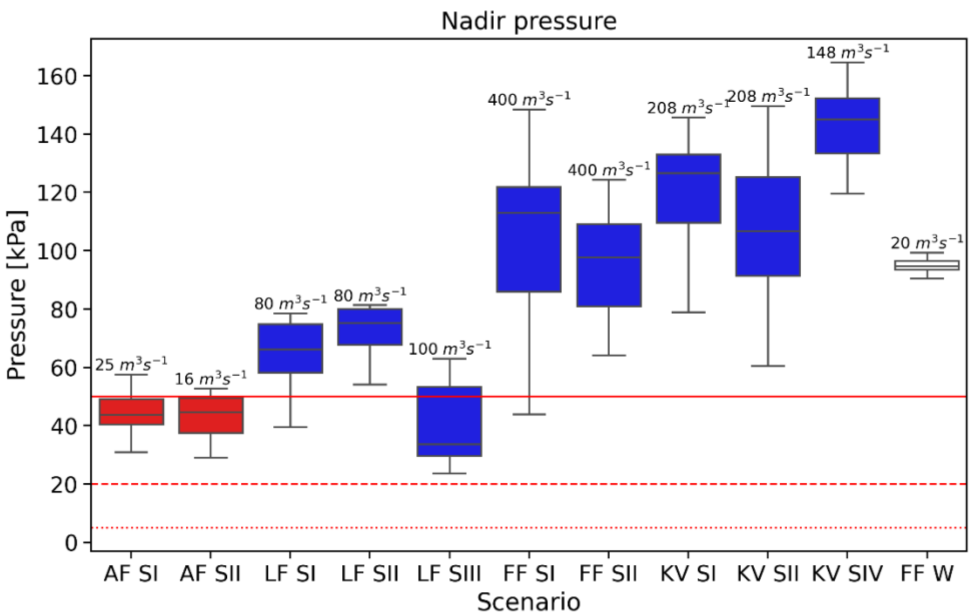

Figure 17 Comparison between the Nadir pressure in the scenarios for the case studies in Ätrafors (AF) and Lanforsen (LF), and the case studies from a former project in Funnefoss (FF) and Kongsvinger (KV) in Norway. The colors represent the turbine types: red for Francis turbines, blue for Kaplan and white for a downstream migration structure. The continuous red line represent the threshold for grayling (50 kPa) applied in the Norwegian case studies, the dashed red line the threshold for the Chinook salmon (20 kPa) and the dotted line the threshold for the eel (2.7 kPa). Discharge values for each scenario are shown at the top of each boxplot's whisker.

The pressure rate of change (Figure 18) shows a clearer pattern compared to the Nadir pressure: this indicator is higher for the Francis turbine, highlighting a higher risk for fish passing through these turbines. For this indicator, the most relevant factor appears to be the turbine type. In the Swiss case study, the pressure rate changes are comparable to the Norwegian sites. However, additional data are still required for a more robust assessment. The PRC remains highly stable and consistently low during the downstream migration passage.

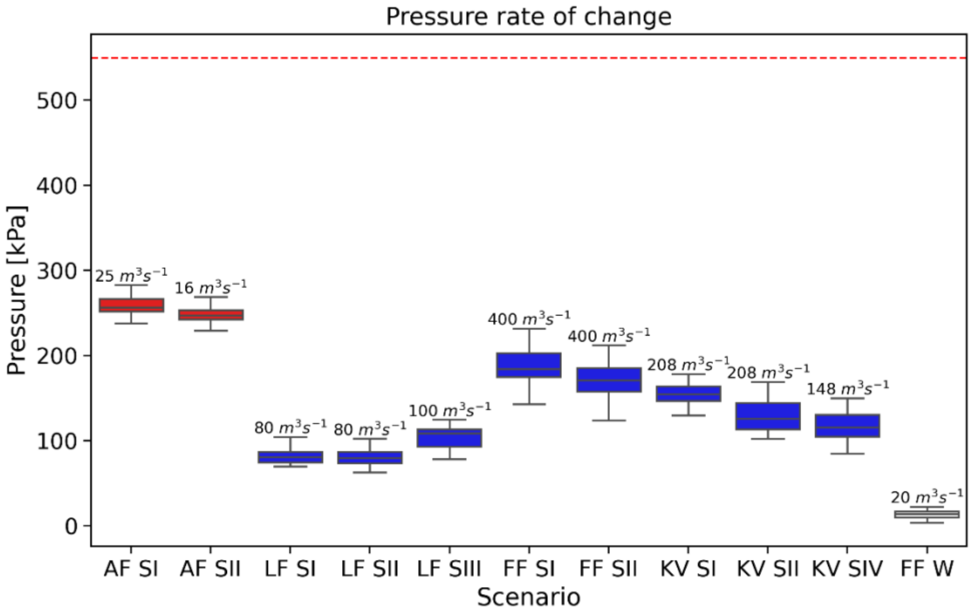

Figure 18 Comparison between the pressure rate of change in the scenarios for the case studies in Ätrafors (AF) and Lanforsen (LF), and the case studies from a former project in Funnefoss (FF) and Kongsvinger (KV) in Norway. The colors represent the turbine types: red for Francis turbines, blue for Kaplan and white for a downstream migration structure. The dashed red line represents the threshold (550 kPa) for grayling, Chinook salmon and eel. Discharge values for each scenario are shown at the top of each boxplot's whisker.

The comparison with the available case studies does not clearly identify the most relevant factor. For Nadir pressure, it appears that discharge is more significant, while for PRC, turbine type seems to play a larger role. Additionally, other factors, such as turbine speed, may also be important for the analysis. To gain a clearer understanding of the driving factors, further data collection is necessary.

This experiment was conducted in turbines; however, the sensors can also be applied in spillways or migration passages to measure pressure as for the case in Norway. The sensors are equipped with an accelerometer, and data analysis is currently underway to determine whether the accelerometer data can be used to assess collisions with structures.

6 Discussion

Maintaining pressure changes above the species limit helps prevent physical injuries and reduce mortality such as barotrauma (Abernethy et al., 2003; Becker et al., 2003; Pflugrath et al., 2019; Colotelo et al., 2021; Brown et al., 2012; Odeh, 1999; Carlson et al., 2012; Brown et al., 2015; Pflugrath et al., 2020). Exceeding the pressure threshold can have severe implications. Fish may suffer from significant physical injuries, leading to immediate or delayed mortality.

Behavioural changes due to stress and disorientation can disrupt their migration patterns and reproductive success (Brown et al., 2012). Adhering to this threshold might contribute to the conservation of eel populations, threatened by various environmental factors. In Ätrafors, SI (Turb.1 25 m^3/s), with a higher flow rate, showed more stable pressure and smoother recovery, while SII (Turbine 2 16 m^3/s), with a lower flow rate, experienced more substantial fluctuations and a higher percentage of sensors being struck. Despite these differences, both scenarios maintained pressure levels well above the critical threshold for eel safety (i.e., Nadir pressure levels are not harmful for eels), ensuring that the operational pressures of both turbines were unlikely to pose a threat to eel populations. Given that eels have been observed down to 2000-meter depth (Sebert et al., 2009), eels are expected to tolerate significant pressure differences, although they may require more time to adapt to these variations compared to the pressure variations in the turbines. The pressure rate of change threshold of 550 kPa/s has never been exceeded in this study, with values well-below this threshold (max value 283 kPa). However, the number of strikes in this case study were relatively high with 15% and 36 % in SI (Turb.1 25 m^3/s) and SII (Turbine 2 16 m^3/s), respectively.

For Francis turbines, the number of strikes might be high, leading to high injury and mortality during the passage (Vikström et al., 2020; authors' observation). Calles et al. (2013) have previously highlighted high mortality rates (60%) for fish passing through the turbines in this Ätrafors. Eels are particularly vulnerable to turbine passage due to their elongated bodies, which increase the risk of being struck by turbine blades. Before rack modification eels often suffered from impingement on inlet racks and injuries from turbine blades (Calles et al., 2010). After the modifications made to the inlet rack, eel mortality has been significantly reduced (Calles et al., 2013). Despite the improvements, some eels still pass through the turbines. Of the five eels that entered the turbines after modification, three were killed, resulting in a 60% turbine-induced mortality rate for those individuals (Calles et al., 2013). The high number of strike events recorded during the experiment, even with sensors considerably smaller than the eels (10 cm), seems to confirm that the number of strike events in these turbines might be high and lead to high mortality rates. In the experiment described in Calles et al. (2013), the eels killed in the turbines had escaped through holes in the nets that were used in the study. To prevent these events, nets have been replaced with steel cages.

The potential consequences for the salmon in the Lanforsen scenarios were related to the Nadir pressure and the rate of pressure change they could experience if they pass through the turbines. The Nadir pressure threshold for salmonids is set at 20 kPa based on previous studies of Chinook salmon. According to literature (Becker et al., 2003) pressure level below 2-10 kPa can be harmful, potentially causing barotrauma or increase mortality. We opted for a threshold of 20 kPa as a conservative value because the only values available in literature are for the Chinook salmon in the range of 2-10 kPa. Due to the absence of data in the literature for the Atlantic salmon, we opted for using a particularly conservative value. In the scenarios analysed, none of the pressure levels dropped below this threshold, indicating that the salmon would not be exposed to dangerously low pressures. The pressure variations in the scenarios show that while there were significant drops in Nadir pressure during turbine passage, the pressures recover and remain above the 20 kPa threshold, suggesting that the salmon are likely to avoid severe pressure-related injuries during their passage through the turbines.

In all scenarios, the pressure values were generally safe, with only one outlier below the 20 kPa threshold (SI Turb. 2 80 m^3/s), suggesting a small risk of exposure to harmful pressures. It is worth mentioning that the comparison between SI (Turb. 2 80 m^3/s), SII (Turb. 3 80 m^3/s) vs SIII (Turb.3 100 m^3/s) could indicate a trend: an increase in discharge (from 80 to 100 m^3/s) could lead to a decrease in Nadir pressure values, and a further increase in discharge might lead to a drop of Nadir pressure below the critical value. However, it was not possible in this experiment to collect sufficient data to validate the observed trend. Overall, the consequences for the salmon in these scenarios are relatively positive, as the pressure levels and rates of change remain within safe limits. This means that the salmon are unlikely to experience significant harm from pressure-related factors as they pass through the Kaplan turbines tested in this experiment. The safety limit for the pressure rate of change is set at 550 kPa/s. In all scenarios, the pressure rate of change remained well below this limit, indicating that the salmon are not subjected to harmful rapid pressure changes. As previously noted, the results of Scenario III should be interpreted with caution due to the smaller sample size relative to the other scenarios.

In Vikström et al. (2020), the mortality rate for salmonid smolts (aggregated brown trout and salmon) passing through the Kaplan turbines in Lanforsen was found to be 0%, based on data for 68 fish. In our experiment, we did not detect any strike event in Lanforsen, with the caveat that the sensors have a slightly smaller size (10 cm for the sensors and the dummies vs a range of 17.3 ± 7.4 cm, 68 smolt specimen). In contrast, Francis turbines at Stornorrfors, Umeälven River, showed a mortality rate of 11.9% for smolt and 56% for adults (Vikström et al., 2020). Our experiment further supports the low mortality probability for smolt as detected by field data and modeled by blade strike model in Vikström et al. (2020), showing a mortality rate of 1.3%. To obtain more robust findings regarding the impact on larger life stages and species, we recommend using rubber fish that replicate the size of adult fish, developed and produced by the same institute which produces the sensors. This would involve a similar experimental setup for deployment and retrieval, but with a different tool.

In the previously mentioned study by Vikström et al. (2020), at Lanforsen the discharge values were similar to the values tested in this study: the average discharge value is 97 m^3/s, with a maximum of 130 m^3/s and a 10th percentile of 78 m^3/s (indicating that discharge exceeds this value 90% of the time). The 10th percentile discharge for turbine number 4, which was not tested in this study, is lower (67 m^3/s). These values are similar to the discharge levels tested during the sensor experiment, supporting the conclusion that the turbines in Lanforsen have a minimal impact on salmon smolts. However, since discharge values above 100 m^3/s are common, it is recommended to verify if the trend of decreasing Nadir pressure with increasing discharge is consistent in the event of detected increases in salmon mortality. As mentioned, Vikström et al. (2020) highlighted as the mortality rate for salmon (smolt and adult) was much higher in a power plant equipped with Francis turbines (Stornorrfors) compared to the Kaplan turbine in Lanforsen. The sites differ in factors beyond turbine type: the turbines operate at higher speeds, with greater head and more blades, all of which may contribute to the higher mortality in Stornorrfors. Vikström et al. (2020) also indicate that the observed mortality was significantly higher at Stornorrfors than predicted only by the turbine strike model, suggesting that barotrauma may contribute to the elevated mortality rate at this site. Unfortunately, data from experiments of this type remain limited, and a comprehensive comparison is not yet feasible. A database containing these data is currently under development. It is possible to make a preliminary comparison with data from studies conducted by SINTEF Energi on Kaplan turbines.

The uncertainty in pressure observations can be represented by the standard deviation for each scenario, and the variability shows notable differences between case studies with similar turbines. Fu et al. (2016) analyzed 10 Francis turbines with higher heads and larger discharges than Ätrafors, showing a wide variation in Nadir pressure across sites, ranging from approximately 25 to 175 kPa. As a comparison the Nadir pressure variations at Ätrafors, was from 19 to 59.6 kPa. In a case study in Norway, with Kaplan turbines larger than Lanforsen (maximum load 400 m^3/s), the Nadir pressure varies between 89 kPa and 124 kPa, and the pressure rate of change varies between 124 and 190 kPa, both values higher than the data from this study in Lanforsen. With the current available data, it is difficult to draw conclusion about turbine type or discharge that can be generalized. However, a comprehensive dataset including other experiments is under construction. If publicly available, this dataset could contribute to the development of a model to predict, to a certain extent, the probability of barotrauma injuries based on few known factors and variables.

To optimize hydroelectric facilities for power generation while minimizing ecological impact, it is essential to understand the hydraulic conditions and physical stresses that fish encounter when navigating complex hydraulic environments such as the turbines. To study the effects of turbine passage on fish, both field and laboratory experiments are needed, and different methods are available. One field method is the balloon-tag recapture technique, where live fish are tagged with balloons that inflate when injected with water, bringing the fish to the surface for recapture (Heisey et al., 1992). This method allows for the identification of injuries and possible injury mechanisms, but it does not locate the exact source of injury. Another approach is biotelemetry, such as acoustic telemetry, which tracks fish survival and behavior through receivers placed upstream and downstream of a dam (McMichael et al., 2010). This method provides detailed information on fish location, behavior, and survival, but it cannot detect non-lethal injuries, nor can it identify precisely the location of injuries (e.g., passing through turbine, fish passage, spill-way) a capability that the sensors can provide.

Identifying specific locations within turbines and operations where conditions are intense enough to cause injury or mortality, can also be done with the deployment of sensors such as the BDS used in this study or the Sensor Fish (Deng et al., 2014), used in this study. Although field studies using live fish are valuable for assessing some of the events (e.g., blade strikes), the use of live fish raises both experimental and ethical issues. From an empirical perspective, live fish studies cannot be used to accurately measure the pressure variations that fish experience or to identify harmful conditions, which may stem from various factors (e.g., turbine type, discharge rate, specific turbine conditions). From the ethical perspective, experiments should be conducted by applying the Three Rs principles—refinement, reduction, and replacement, and the use of alternative methods should be encouraged (Schaeck et al., 2013). The use of BDS sensors overcomes these limitations and enables experiments to be conducted across different countries, each with varying legislation regarding the use of live animals in scientific research (Directive 2010/63/EU for EU and EEA countries).

The primary limitation in using the sensors arises from the experimental conditions. If, due to technical reasons such as the structure of the power plant or the inlet, or the conditions in the outlet, it is not possible to deploy or retrieve the sensors, the experiment cannot be conducted. Another potential limitation, which can be addressed by conducting separate experiments with live fish, is that the use of sensors does not allow for the determination of injury or mortality pressure thresholds for the fish species. Thresholds are taken based on life-stage and species-specific studies available for live fish (Abernethy et al., 2003; Becker et al., 2003; Pflugrath et al., 2019; Colotelo et al., 2021; Brown et al., 2012; Odeh, 1999; Carlson et al., 2012; Brown et al., 2015; Pflugrath et al., 2020). In Europe, there are to-date no openly available barochamber studies to establish threshold nadir pressures, rates of change or ratio pressure changes. The methodology of comparing pressure-related parameters to estimate the risk of barotrauma injury and mortality can be substantially improved through the inclusion of barochamber laboratory studies of live European fish species in order to establish thresholds for the nadir pressure, rate of change and ratio pressure change.

7 Conclusions

The study conducted at the Ätrafors and Lanforsen power plants in Sweden provides valuable insights into the conditions that downstream migrating fish experience when passing through turbines.

At the Ätrafors power plant, the experiments revealed non-harmful pressure changes in the turbines, which is beneficial for eels' safety. However, the number of strike events was relatively high, indicating that despite the generally safe pressure conditions, there is still a significant risk of injury and mortality for eels passing through the turbines, which was confirmed by previous studies using telemetry (Calles et al., 2013). To reduce the number of fish entering the turbines, the number of strikes and enhance the overall safety of fish passage, the modifications of the rack have been already proven as being effective. The data collected across the various scenarios exhibit a high degree of similarity, indicating that variations in discharge rates and different turbines do not significantly influence the pressure values observed. Additionally, the incidence of strike events remains notably high in both scenarios, suggesting that the operational differences between the turbines and discharge conditions do not mitigate the frequency of these events.

The Lanforsen power plant scenarios showed pressure levels exceeding the critical threshold for salmon safety across all tested conditions only in one case. The rate of pressure change was also within safe limits, indicating that the turbines at this site pose a lower risk to salmon, which confirmed the results of previous telemetry studies (Vikström et al., 2020). The absence of strike events in the Lanforsen scenarios further supports the conclusion that the hydraulic conditions at this power plant are relatively safe for fish passage. Pressure values across the scenarios show a high degree of similarity, indicating that variations in discharge rates and turbine do not significantly affect the pressure values. However, in Scenario III, where the discharge rate was higher, 100 m^3/s, there was a noticeable decrease in Nadir pressure values. This suggests that further increases in discharge could potentially be harmful to migrating salmon. The Nadir pressure in Lanforsen decreases when discharge increases (SIII (Turb.3 100 m^3/s). Additional experiments with increasing discharge are recommended to further investigate this possible trend.

Further studies combining laboratory and field data should be conducted to enable direct comparisons and a better understanding of lethal and injury thresholds under both laboratory and field conditions.

Overall, the study underscores the need for continuous monitoring and, in case of unexpected increase of fish mortality, possible optimization of turbine operations to minimize the risks to migrating fish. By maintaining pressure conditions above critical thresholds and minimizing strike events (e.g., optimization of protection racks), it is possible to improve the survival rates of fish passing by hydropower plants. These research findings help identify pressure problems and high number of strike events during turbine passage, highlighting environmental drivers that might lead to population bottlenecks, and contribute to plan measures such as appropriate flow values that could minimize the risk for fish.

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DOWNSTREAM FISH PASSAGE EVALUATION USING BAROTRAUMA DETECTION SENSORS

The report provides a study on the impact of extreme pressure drops and blade strikes pose downstream migrating fish when passing through hydropower turbines. The report focuses on species such as eel and salmon. The study was conducted at Ätrafors (downstream eel migration) and at Lanforsen (downstream salmon smolt migration).

Experiments were carried out with sensors that were passed through the hydropower plants at Lanforsen and Ätrafors to measure the pressure conditions and blade strikes that downstream migrating fish can be exposed to during turbine passage.

At Ätrafors, different scenarios showed that pressure levels are maintained in the safe range for eels at the Nadir pressure. However, the number of strike events highlighted some possible risks. At Lanforsen, none of the scenarios (different turbine and discharge) showed pressure levels exceeding the critical thresholds for salmon safety. The rate of pressure change was also within safe limits, and no strike events were recorded.

The study shows that the risks for downstream migrating fish can be reduced through continuous monitoring and suggest that they could be managed through optimization of turbine operations.