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Report

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Authors:

Mauro Carolli, Prof. Jeffrey Tuthan, Sahra Sabil,
Jon Museth and Atle Harby

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Hafslund Kraft AS and Glomma Kraftproduksjon AS

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SINTEF

Project report

SINTEF Energy Research
Postal address:
Postboks 4761 Torgarden
7465 Trondheim, Norway
Switchboard: +47 45456000
energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

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AUTHOR(S) Mauro Carolli, Prof. Jeffrey Tuthan, Sahra Sabil, Jon Museth and Atle Harby	
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Abstract

Downstream migrating fish face injury and mortality risks from turbines and hydraulic structures due to cavitation, pressure drops, blade strikes, and hydraulic shear. Waterproof autonomous sensors measured these risks by tracking pressure changes and strike events. The study, conducted at the Funnefoss and Kongsvinger power plants in the Glomma River, evaluated Nadir pressure, pressure rate of change, and strike events, comparing results to known mortality thresholds, particularly for grayling. The study found low risk of fish mortality at the two power plants. Future research should focus on varying turbine flows, different river conditions, and better understanding fish migration patterns in the Glomma River.

PREPARED BY Mauro Carolli	SIGNATURE Mauro Carolli Mauro Carolli (Jun 24, 2024 13:07 GMT+2)
CHECKED BY Markus Först	SIGNATURE Markus Foerst (Jun 24, 2024 13:30 GMT+2)
APPROVED BY Knut Samdal	SIGNATURE Knut Samdal Knut Samdal (Jun 24, 2024 13:35 GMT+2)

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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 runners at hydropower plant depending on the acclimation depth and pressure Nadir at the runner.
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.
Conduction current	The flow that should lead fish to fish ladders.
Ecological condition	The health or state of an ecosystem, referring to the water framework directive.
Ecological potential	The ability of an ecosystem to support various species and functions, 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.
Life stage of fish	Different developmental stages of fish, often categorized by size or age. Abbreviations used in this report: 0+ for newly hatched fish, L1 for first larval stage, L2 second larval stage, J1 juvenile stage, L6 late juvenile stage.
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 a number is from zero, 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.
Outliers	Data points that are significantly different from other observations.
Pressure Nadir	The lowest pressure point in a given area or system, here within the passage through the turbine.
Pressure rate of change	How quickly pressure decreases 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 that occurs in both directions: upstream and downstream.
Validation	Checking if data or results are accurate or reliable.
Water column	The pressure that is 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.

Prosjektoppsummering

Fisk som vandrer nedstrøms står i fare for å bli skadet eller drept når de passerer gjennom vannkraftturbiner og luker på grunn av trykkfall, kavitasjon, slag fra turbinblader og andre konstruksjoner. For å studere dette ble vanntette autonome sensorer brukt for å måle fysiske forhold som trykkendringer og slag som en fisk kan oppleve på sin vei forbi kraftverk. Denne studien ble utført ved kraftverkene Funnefoss og Kongsvinger i Glomma, der vi evaluerte tre nøkkelparametere: minimumstrykk som en fisk vil kunne oppleve ved passering gjennom turbinen (nadirtrykk), hastighet på trykkendringen og slaghendelser. Resultatene ble sammenlignet med kjente terskelverdier fra tilsvarende studier andre steder for å estimere risiko for fiskedødelighet.

Målet med denne studien var å undersøke de fysiske forholdene fisk vil kunne møte når de passerer turbiner på forskjellige dyp og vannføringer ved Funnefoss og Kongsvinger kraftverk. På Funnefoss undersøkte vi også fysiske forhold ved passering gjennom en luke som brukes til å lede fisk forbi dammen.

Hovedfunnene

- **Funnefoss kraftverk:** Resultatene indikerte lav risiko for fiskeskader og dødelighet. De fleste trykkmålingene var under kritiske verdier. Ved én kombinasjon av vannføring og dybde på Funnefoss falt noen få verdier innenfor risikoområdet for minimumstrykk for voksen harr, men de var fortsatt ikke kritiske for ungfisk. Det var få registreringer av slag. Bare én kombinasjon av vannføring og dybde viste at 15 % av sensorene ble truffet, mens for resten av forsøkene ble under 10 % av sensorene truffet av slag.

- **Kongsvinger kraftverk:** Resultatene fra Kongsvinger viste lignende lav risiko, der kun én av 116 trykkavlesninger oversteg risikoterskler for voksen harr. Variasjonen i resultater var høyere ved den største vannføringen gjennom turbinene, noe som tyder på at turbinvannføring kan påvirke risikoen.

Sammenligning med andre studier

Resultatene ble sammenlignet med en studie ved det sveitsiske kraftverket Bannwill, som viste tilsvarende minimumstrykkverdier og trykkendringer som ved Funnefoss og Kongsvinger. Hastigheten på trykkendringer gjennom klappeluka ved Funnefoss var betydelig lavere enn ved Bannwill, noe som tyder på at vannføringsforholdene påvirker trykkendringer.

Anbefalinger for fremtidig forskning

1. Variasjon i turbinvannføring: Ytterligere eksperimenter bør utforske effektene av ulike turbinvannføringer

2. Sammenligning av vannkraftverk: Undersøke forholdene ved ulike kraftverk i Glomma for å identifisere risiko og avbøtende tiltak for vandrende fisk.

3. Overløp og luker: Vurdere forholdene ved overløp og luker, da de under gitte forhold kan være like eller mer skadelige enn gjennom turbiner.

4. Vandringsmønstre: Mer forskning er nødvendig for å kartlegge vandringsmønstre for fiskesamfunn i Glomma.

5. Terskelverdier: Det er behov for mer kunnskap om terskelverdier (spesielt trykk og trykkendringer) for overlevelse til ulike livsstadier og størrelser av ulike fiskearter

Konklusjon

Studien målte og analyserte effektivt de fysiske forholdene fisk kan oppleve under nedstrøms vandring gjennom turbiner og luker ved to norske kraftverk. Resultatene peker på at risikoen for skade og dødelighet for fisk er generelt lav, men enkelte kombinasjoner av vannføring og svømmedyp viser en viss risiko som trolig enkelt kan unngås ved tilpasning av driften. Videre forskning bør fokusere på hvordan ulike kombinasjoner av turbinvannføring og svømmedyp påvirker forholdene. I tillegg er det viktig å forbedre forståelsen av fiskevandringsmønstre i Glomma.

Summary

Downstream migrating fish face risks of injuries and mortality from turbines and hydraulic structures due to cavitation, pressure drops, blade strikes, and hydraulic shear. To study these risks, waterproof autonomous sensors were used to measure the physical conditions fish experience, such as pressure changes and strikes from turbine blades or other structures. This study focused on the Funnefoss and Kongsvinger power plants in the Glomma River system, evaluating three key parameters: lowest pressure passing through the turbine (Nadir pressure), how quickly pressure change over time (pressure rate of change), and strike events. The results were compared to threshold values from literature to estimate fish mortality risk, with a focus on the grayling.

The objectives of this study were to examine the physical conditions fish encounter while passing turbines at different depths and flow conditions at both power plants. At Funnefoss we also investigated the conditions while passing through a tilting gate also used to direct fish downstream.

Key findings

- **Funnefoss power plant**: The study indicated low risk for fish injury and mortality. The majority of pressure readings were below known critical thresholds, though one of the experimental scenarios at Funnefoss showed only few values in the risk range for minimum pressure for adult grayling, which were still not critical for juvenile grayling. Strike events were minimal, with only one scenario showing 15% of hits, and the rest below 10%.
- **Kongsvinger power plant**: Similarly, experiments at Kongsvinger showed low risk, with only one of the pressure reading exceeding risk thresholds. The data variability was higher at maximum turbine discharge, suggesting that managing discharge levels could influence risks.

Comparison with other studies

The results were compared to a study at the Swiss power plant Bannwill, showing similar minimum pressure values and rates of pressure change to Funnefoss and Kongsvinger. The pressure rate of change during tilting gate passage at Funnefoss was substantially lower than for a similar structure at Bannwill, suggesting that tailwater discharge conditions influence pressure changes.

Recommendations for Future Research

1. Turbine flow variability: Further experiments should explore the impact of different combinations of swimming depth and turbine flow
2. Hydropower Plant Comparison: Investigate conditions at various power plants in the Glomma catchment to identify risks and mitigation measures for migratory fish.
3. Weirs and Spill Gates: Assess the conditions at weirs and spill gates, as they might be equally or more harmful than turbines.
4. Migration Patterns: More research is needed to understand the migration patterns for different fish species in the Glomma River, particularly for species like grayling.
5. Threshold values: More research is needed to validate the critical threshold values, especially for pressure and pressure changes, for survival for different fish species and life stages.

Conclusion

The study effectively measured and analyzed the physical conditions experienced by fish during downstream migration through turbines, gates and weirs at two Norwegian power plants. The findings indicate that the risk of fish mortality is generally low, but certain scenarios highlight areas where improvements could be made. Future research should focus on varying turbine flows, conducting studies during different river flow conditions, and gaining a deeper understanding of fish migration patterns in the Glomma River system.

1 Introduction

Downstream migrating fish may experience adverse impacts as they pass through turbines and hydraulic structures due to cavitation, pressure drops, blade strikes and hydraulic shear (Pracheil et al., 2016; Colotelo et al., 2016; Cada et al., 1999). To quantify the hydraulic conditions which may lead to injury and mortality, waterproof autonomous sensors can be deployed to collect information on the pressure and inertial changes that fish experience (Deng et al., 2014). Using repeated measurements with multiple identical sensors, pressure and acceleration time series can be averaged to create data-driven representations of the expected physical conditions experienced by fish during downstream passage (Schneider et al., 2017). In this study, barotrauma detection system (BDS) sensors for pressure measurements and strike events counting, and dummies for strike events counting, were deployed at the Funnefoss and Kongsvinger power plants. A dummy consists in a neutrally buoyant wood piece that resembles the weight of the sensors. They are used to test the experiment protocol and count the number of strikes during the turbine passage. BDS sensors are described in detail in Section 1.1. The data from the BDS sensors were averaged, and four physical parameters known to cause an increased risk of injury and mortality were evaluated: the Nadir pressure (Deng et al., 2014; Deng et al., 2017), the pressure rate of change (PRC) (Boys et al., 2018), the 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 known threshold values of each parameter based on 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 turbines at the Funnefoss power plant at different depths;
2. investigate the physical conditions that fish experience passing the tilting gate at the Funnefoss power plant;
3. investigate the physical conditions that fish experience passing turbines at Kongsvinger power plant at different depths and water flow.

Fish migration at power plants within the Glomma River system have been an important topic for environmental authorities, hydropower companies and fishing interests for decades (e.g. Qvenild 2008), and improving the conditions for fish migrations are identified as important measures in order to improve the ecological conditions in the different water bodies in the Glomma river system (www.vann-nett.no). However, the fish communities are complex, and knowledge of their migration activity remains limited. In this study, we used BDS sensors to investigate the physical conditions fish are likely to experience during downstream migration. Whereas the BDS sensors are expected to give highly relevant data on the different parameters for pressure change, the number of strike events is expected to increase with increasing length (Vikstrøm et al., 2020).

1.1. Barotrauma Detection System (BDS)

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). 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 at up 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 2nd order algorithm. All sensors were tested against a HOBO reference pressure sensor under static and dynamic conditions in a laboratory barochamber from 100 kPa to 500 kPa (Figure 2).

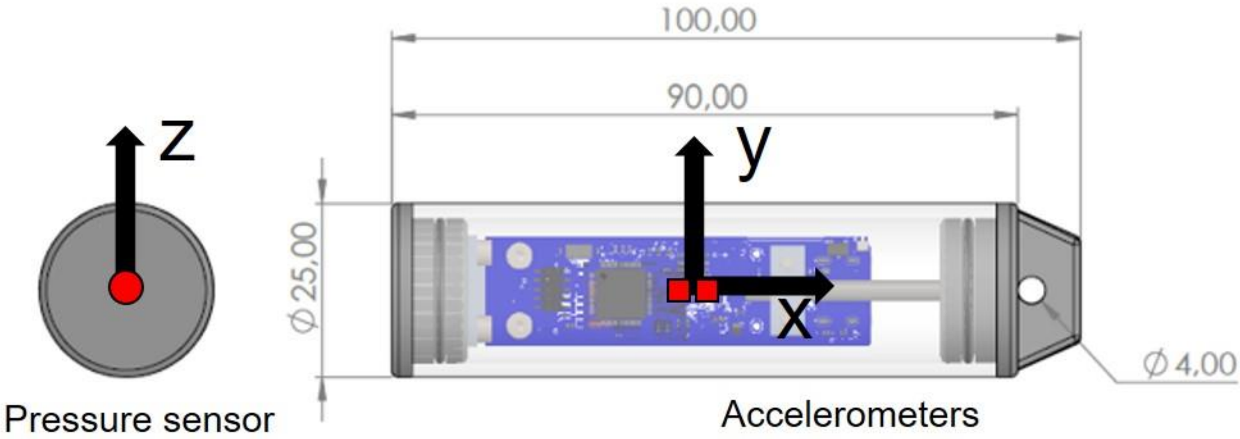

Figure 1: Schematic and dimensions of the BDS, showing the locations of the pressure sensor and the accelerometers. Left: view of sensor endcap with pressure port (red circle). Right: top view showing the location of the two identical accelerometers (red squares). The BDS are equipped with an atmospheric 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.

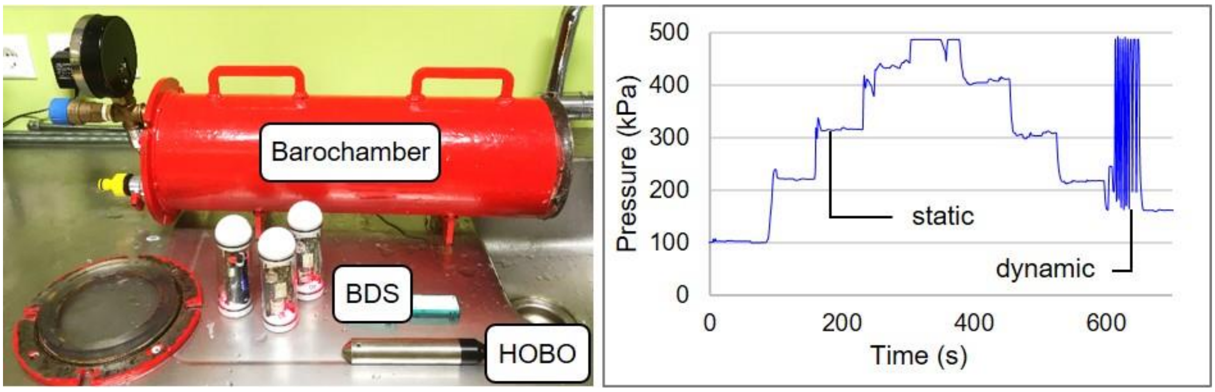

Figure 2: Left: Laboratory pressure testing setup. A maximum of 20 BDS can be simultaneously pressure tested up to 45 m H2O in the barochamber. The HOBO pressure sensor was used for validation. Right: Example of a test data set showing the up and down ramping of the static pressure testing and several rapid events for dynamic pressure tests.

After electronics testing and mechanical assembly, all pressure transducers were calibrated against a 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). 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 up 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

Physical and sensor specifications	Values
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).

Figure 3 a) illustrates typical data recorded by the BDS sensors during a typical turbine passage. It shows how the different stages (injections, turbine passage and tailwater) can be identified using the pressure data. Figure 3 b) shows a detail of the graph, highlighting which are the parameters relevant for our studies. The description of the parameters is detailed in the glossary at the beginning of the document.

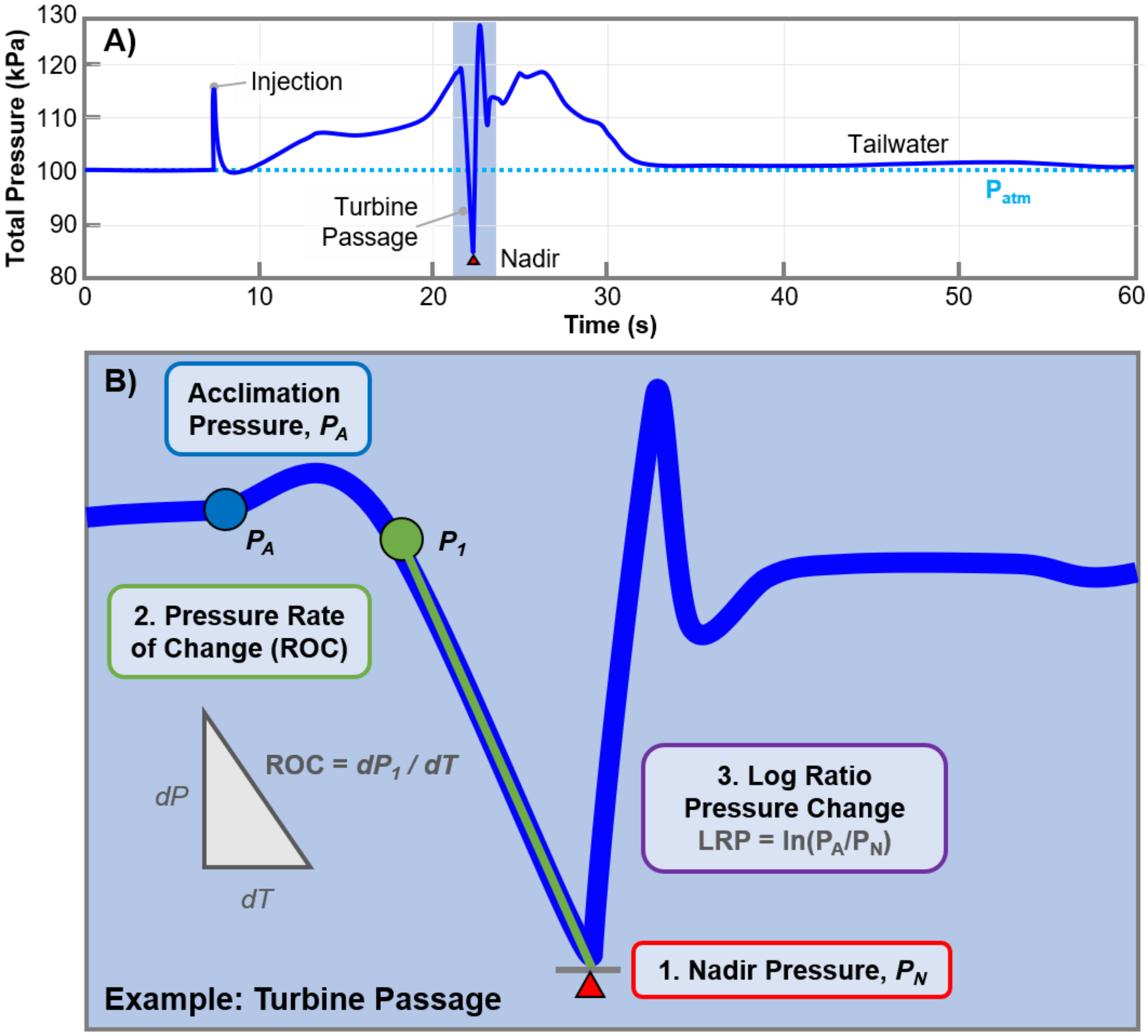

Figure 3: A) BDS pressure sensor time series during a typical turbine passage. B) The three parameters used to evaluate the risk of mortality to fish caused by rapid decompression are the Nadir pressure (1), the pressure rate of change (2) and the log ratio pressure change (3).

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 a 10%.

Physical parameter	Fish species / test site	Thresholds of injury or mortality	Threshold used in this study	Literature source
Nadir pressure (kPa)	Nase (L1, 0+), Roach (L6/J1) European Perch (0+) / surface acclimated European Perch (L6/J1), Roach (0+) / surface acclimated European Perch (L1), European grayling (L1/2) / surface acclimated European grayling (0+) / depth-acclimated at 251 kPa	50 kPa (some injury) 40 kPa (some injury) 20-25 kPa (some injury) 15 kPa (some injury) 42 kPa (94% mortality)	**50** **(values smaller than this threshold may result in a >10% risk of mortality)**	
	Chinook salmon (*Oncorhynchus tshawytscha*) Bluegill sunfish (*Lepomis macrochirus*)	70 kPa (no injury) 70 kPa (49.1.8% injury)		(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		(Brown et al., 2012)

Physical parameter	Fish species / test site	Thresholds of injury or mortality	Threshold used in this study	Literature source
		(sensor data only)		
	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 (-)	Nase (L1, 0+), Roach (L6/J1) European Perch (0+) / surface acclimated European Perch (L6/J1), Roach (0+) / surface acclimated European Perch (L1), European grayling (L1/2) / surface acclimated European grayling (0+) / depth-acclimated at 251 kPa	1.0 (some injury) 1.5 (some injury) 2.0 (some injury) 0.9 (47% mortality) 1.8 (94% mortality)	**0.5 (values larger than this threshold may result in a >10% risk of mortality)**	
	Juvenile Chinook salmon (*Oncorhynchus tshawytscha)*	0.92 (10% mortality)		(Carlson et al., 2012)
	Walleye (*Sander vitreus)* Tiger Muskie (*Esox luciusX E.Masquinongy)*	0.94 (10% mortality) 0.82 (10% 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 Study sites

The investigation of potential turbine passage damage to fish was conducted at two study sites. The first is at the hydropower plant Funnefoss, which is situated in South-Norway at the River Glomma and the second is at the hydropower plant Kongsvinger, which is located about 30 km upstream of Funnefoss. An overview of the location of the study sites is shown in Figure 4.

Figure 4: Location of the study sites.

The ecological potential at this river section is categorized as poor, mainly due to erosion and run-off from agricultural land, but also due to the barrier effects of hydropower dams. Improvements of conditions for fish migration are identified as adequate mitigation measures (www.vann-nett.no).

2.1 Funnefoss

The Funnefoss hydropower plant was commissioned in 1973 and put into operation in 1975. The hydropower plant has a capacity of 40 MW and an annual generation of 205 GWh. The head is 11 m high, and the maximal flow rate is 440 m^3/s. The average turbined flow over the whole year is 337 m^3/s. The dam has, from right to left, one tainter gate, four tilting gates, a weir and a tilting gate for the fish ladder and the turbines inlet. The main fish ladder close to the power station consists of 35 pools. The fish ladder in the dam consists of 10 pools. Figure 5 shows an overview of the hydropower plant.

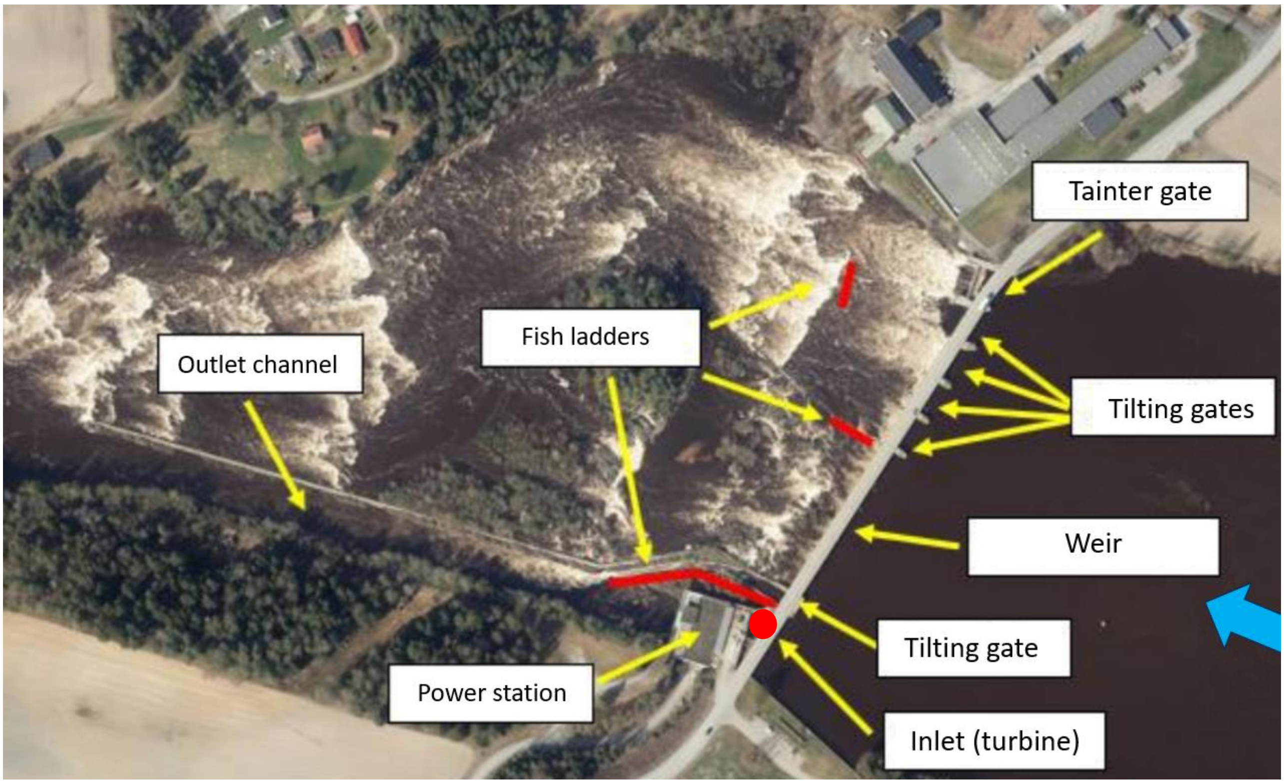

Figure 5: Overview Funnefoss hydropower plant (Akershus Energi, 2023). The sensors were deployed by the turbine inlet and the tilting gate close to the fish ladder (see the red dot).

At Funnefoss, fish migrate upstream and downstream. While fish who migrate upstream will seek the conduction current that leads them to the fish ladder (the actual functionality/efficiency of the fishway is not known), fish who migrate downstream follow the mainstream and are often expected to end up in the turbines (but depends on the ratio between discharge in the turbines and spill water gates). At Funnefoss two bulb turbines are installed, which are believed to be more “fish- friendly” than other turbines (Akershus Energi, 2023). The turbine intake has a trash rack with bar spacing of 100 mm and this means that relatively large fish can swim through the bars.

2.2 Kongsvinger

The Kongsvinger hydropower plant was commissioned in 1973 and put into operation in 1975, and expanded in 2011. It has a capacity of 42.7 MW and an annual generation of 200 GWh after expansion in 2011. The head is 10.25 m (GLB, Eidsiva, ØKAS, 2019). Two identical bulb turbines are operating in the hydropower plant. The turbines operate with a discharge of 70 to 252 m^3/s. The hydropower plant is shown in Figure 6.

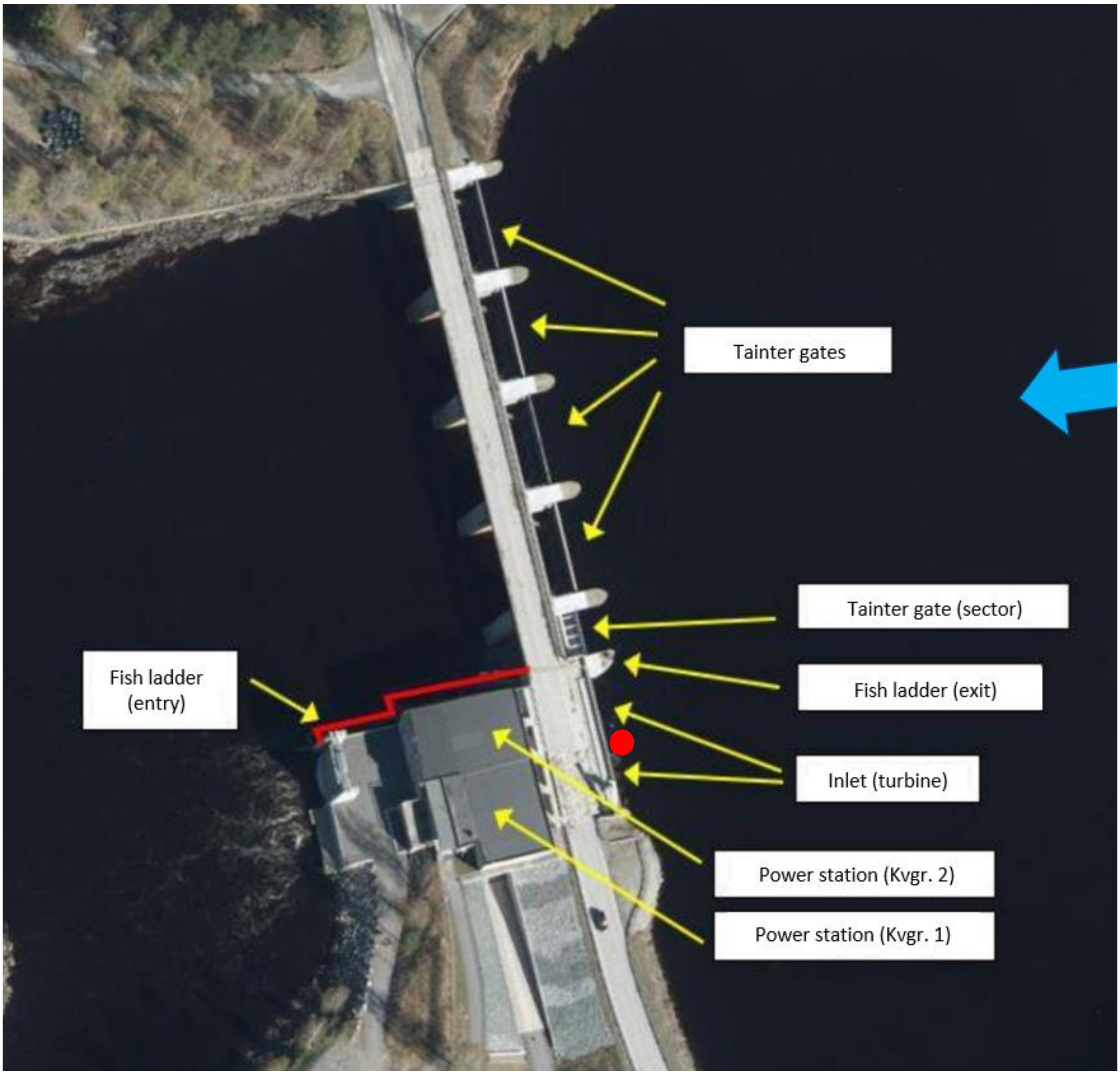

Figure 6: Overview Kongsvinger hydropower plant (GLB, Eidsiva, ØKAS, 2019). The sensors were deployed by the turbine inlet (see the red dot).

The turbine intake has a trash rack with bar spacing of 100 mm. and this means that relatively large fish can swim through the bars.

2.3 Fish community structure

The knowledge about two-way fish migrations in Glomma past Funnefoss and Kongsvinger power plants is limited, but some experiments with fish-traps in the fish ladders in the 1980s documented upstream migration of the following species:

- Funnefoss power plant: Brown trout (Norsk: Ørret; Lat.: *Salmo trutta*), European grayling (Norsk: Harr; lat.; *Thymallus thymallus*), common dace (Norsk: Gullbust; Lat.: *Leuciscus leuciscus*), common bleak (Norsk: laue; Lat.: *Alburnus alburnus*), ide (Norsk: Vederbuk; Lat.: *Leuciscus idus*) and chub (Norsk: Stam; Lat.; *Leuciscus cephalus*) (Linløkken 1989)
- Kongsvinger power plant: Brown trout, European grayling, common dace, roach (Norsk: Mort; Lat.; *Rutilus rutilus*), Norhern pike *(*Norsk: Gjedde; Lat.: *Esox lucius*), common bleak and ide (Qvenild 2008). In 2021 and 2022, video recordings in the fish ladder documented upstream migration of perch (Norsk: Abbor; Lat.: *Perca fluviatilis),* Norhern pike, chub, common bleak and common bream (Norsk: brasme; Lat.: *Abramis brama*) (Trond Taugbøl, pers. com.).

The fish community in adjacent river sections to Funnefoss and Kongsvinger power plants has hardly been monitored. Boat electrofishing in Glomma downstream (2011 & 2012) and upstream (2015) Kongsvinger power plant recorded in total 11 fish species (Museth et al. 2014, 2016). Hence, the fish communities in Glomma at the two sites studied in this project are consistent with other large Norwegian rivers, but site-specific knowledge about downstream migration at the two studied sites is low (e.g. which species and what time of the year do fish migrate downstream). A key assumption used in this report is that the fish species known to occur at the test site migrate both up- and downstream at the hydropower plants.

3 Method

At both study sites, Funnefoss and Kongsvinger, passive sensors were deployed to measure the pressure as well as dummies to count the number of strike events. The sensors and dummies were released at the intake of the hydropower plant. Alternative scenarios (see below) were analyzed to investigate different conditions for fish passage through the turbines and tilting gate (Funnefoss, overshot). At both power plants, the dummies and sensors were deployed using the trash-rack cleaning machine, equipped with a special box that allowed to release the sensors at the selected depth. At Funnefoss, four scenarios have been investigated. The dummies and sensors have been released at the inflow of turbine 1. For the four scenarios the BDS sensors have been deployed at different depths and during different discharges, representing fish which swim into the turbines at varying depths and discharges. Table 3 shows the different approximate injection depth and discharges for each scenario at Funnefoss. In Scenarios I-III, the sensors have passed through the turbines, whereas in Scenario IV, they have passed by the tilting gate.

Table 3: Overview of the four different scenarios at Funnefoss.

Scenario	Approximate depth (m)	Discharge (m^3/s)
I	26 (max depth)	400
II	16 (mid depth)	400
III	7 & 8 (min depth)	400
IV (Gate Overshot)	0	20

At Kongsvinger, four different scenarios have been investigated. All scenarios have been conducted at the same turbine, where the sensors and dummies have been released into the water at their corresponding water depth upstream the intake. The scenarios differ in depth of BDS deployment and in the discharge. The sensors and dummies have been released approximately at the depth of 21 m (max depth) for scenario I, the depth of 12 m (mid depth) for scenario II, the depth of 5 m (min depth) for scenario III and the depth of 21 m for scenario IV. While the discharge of Scenario I to III discharge is 208 m^3/s, the discharge of Scenario IV amounts to 148.8 m^3/s. An overview of the scenarios is shown in Table 4.

Table 4: Overview of the four different scenarios at Kongsvinger.

Scenario	Approximate depth (m)	Discharge (m^3/s)
I	21 (max depth)	208
II	12 (mid depth)	208
III	5 (min depth)	208
IV	21	148,4

4 Results

4.1 Funnefoss

To ensure statistical cross- comparability field study results, the number of deployed sensors should be approximately 30. The quantity of sensors and dummies that have been deployed, lost, destroyed, and hit are listed in Table 5. Also, information about data and unusable data is provided in the table. For Scenarios I, II, and IV over 30 data series have been collected (Table 5 in bold), while for Scenario III the amount of data series was low (n = 4) and was therefore not large enough for further analysis. The cause of the small sample size for Scenario III is that the deployment of the sensors at 7-8 meters depth was difficult due to the low intake velocity at that depth: the sensors were not entering the turbine and often resurfacing upstream of the power plant. Therefore, it was not technically possible to reach the minimum number of data necessary for the statistical robustness of the analysis. In total, 107 data series were collected, corresponding to a recovery rate of 93.9 % considering all deployed sensors. Neither dummies nor sensors were destroyed at this site. However, 6.8 % of the released BDS sensors did sustain strike events. The BDS strikes occurred during Scenarios I (14,9%) and IV (4,9%).

Table 5: Data quantity of each scenario at hydropower plant Funnefoss.

Scenarios	Category	Deployed	Lost	Destroyed	Strike	Data	Unusable Data
Scenario I	Sensors	46	7	0		34	5
	Dummies	8	0	0		0	0
	Total	54	7	0	**7**	34	5
	Percentage		13,0 %	0,0 %	14,9 %	87,2 %	12,8 %
Scenario II	Sensors	36	1	0		33	2
	Dummies	0	0	0		0	0
	Total	36	1	0	0	33	2
	Percentage		2,8 %	0,0 %	0,0 %	94,3 %	5,7 %
Scenario III	Sensors	8	4	0		4	0
	Dummies	0	1	0		0	0
	Total	8	5	0	0	4	0
	Percentage		62,5 %	0,0 %	0,0 %	100,0 %	0,0 %
Scenario IV	Sensors	36	0	0		36	0
	Dummies	5	0	0		0	0
	Total	41	0	0	**2**	36	0
	Percentage		0,0 %	0,0 %	4,9 %	100,0 %	0,0 %
Total	Sensors	126	12	0		107	7
	Dummies	19	0	0		0	0
	Total	145	12	0	9	107	7
	Percentage		8,3 %	0,0 %	6,8 %	93,9 %	6,1 %

The pressures upstream, in and downstream of the turbines have been measured by the sensors and give valuable information about the conditions for fish transversing through the turbines. While the minimum measured pressure is usually measured while releasing or recovering the sensors, the Nadir, the Pressure Rate of Change (PRC) and the maximum pressure are measured inside of the turbine. The statistical values of the entire data are listed individually for each scenario in Table 6 to Table 8. They include Mean, Median, the Maximum, the Minimum, the Range, the third Quartile, the first Quartile, the Interquartile Range, the Standard Deviation, and the Mean Absolute Deviation. The values are in millibars.

Table 6: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario I (Turbine, max depth, discharge: 400m³/s) at Funnefoss.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	1041.2	1130.7	1485.3	438.8	1046.5	1218.2	859.3	358.9	262.2	196.7
PRC	1904.1	1840.5	2450.5	1427.7	1022.8	2022.7	1747.0	275.8	260.5	138.7
Max Pressure	3057.2	3078.7	3366.1	2396.1	970.0	3211.5	2967.5	244.1	226.1	126.7
Min Pressure	904.0	985.9	999.5	438.8	560.7	997.9	859.3	138.7	146.3	13.3

Table 7: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario II (Turbine, mid depth, discharge: 400m³/s) at Funnefoss.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	963.5	976.6	1243.8	642.2	601.6	1092.0	809.7	282.3	165.7	122.1
PRC	1716.6	1706.8	2304.3	1236.5	1067.8	1852.5	1573.4	279.1	211.0	139.3
Max Pressure	2777.2	2816.8	3115.8	2433.0	682.8	2885.5	2633.3	252.2	171.1	99.6
Min Pressure	909.3	976.6	999.5	642.2	357.3	997.5	809.7	187.8	113.0	22.9

Table 8: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario III (Turbine, min depth, discharge: 400m^3/s) at Funnefoss.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	891.5	900.9	961.9	802.3	159.6	944.4	848.1	96.3	72.8	49.3
PRC	1523.0	1522.5	1590.5	1456.5	134.0	1586.6	1458.8	127.8	75.0	64.4
Max Pressure	2417.0	2411.5	2448.6	2396.3	52.3	2426.0	2402.5	23.4	23.0	11.1
Min Pressure	891.5	900.9	961.9	802.3	159.6	944.4	848.1	96.3	72.8	49.3

Table 9: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario IV (Gate, discharge: 20m^3/s) at Funnefoss.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	947.5	947.7	993.4	871.1	122.3	965.5	936.2	29.3	28.2	14.1
PRC	133.4	135.4	224.4	34.0	190.4	167.5	96.7	70.8	50.9	37.3
Max Pressure	1168.3	1136.7	1455.4	1049.1	406.3	1207.1	1102.1	105.0	100.9	38.2
Min Pressure	947.5	947.7	993.4	871.1	122.3	965.4	936.2	29.2	28.2	14.1

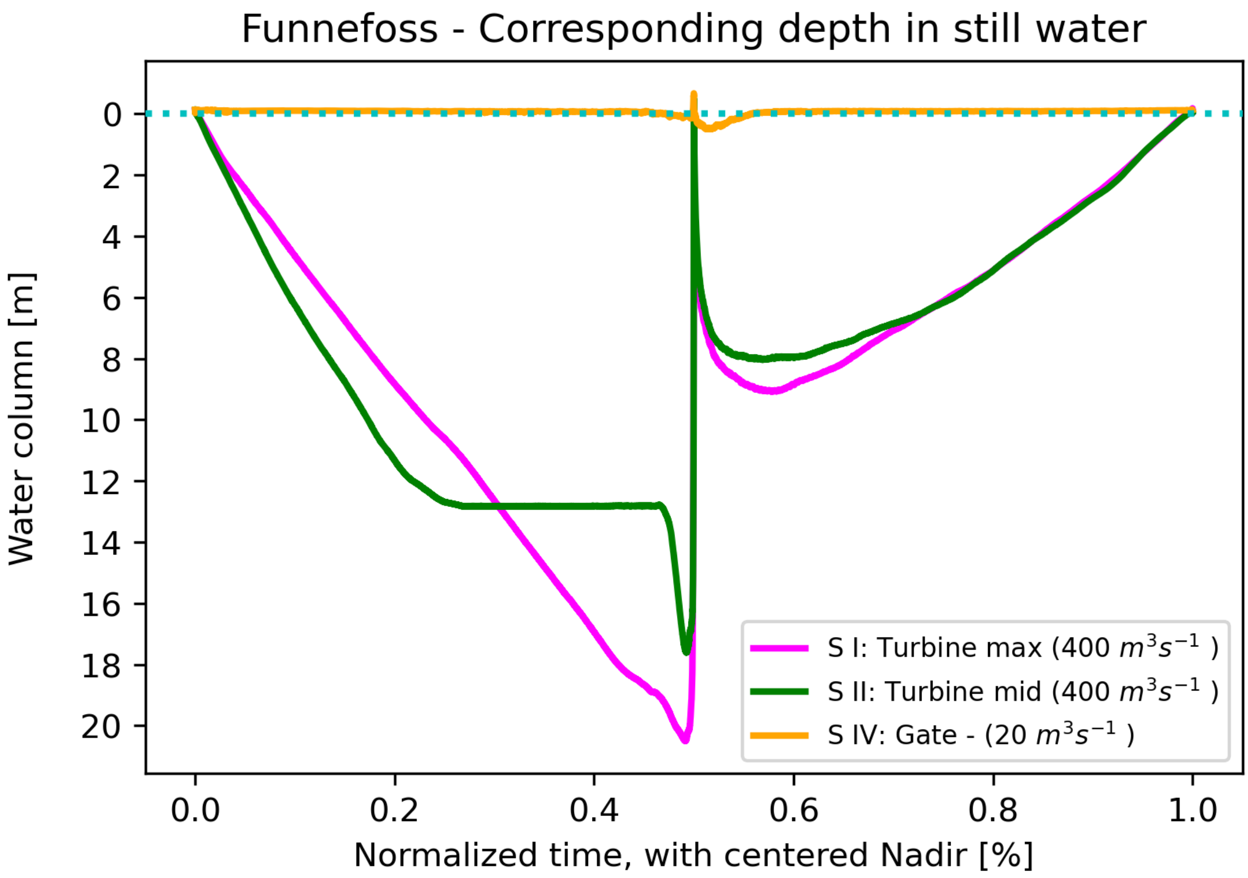

Figure 7: Average measured pressure converted in water columns [meter] are segmented into pre-Nadir and post-Nadir event across all scenarios at Funnefoss; The dotted light blue line indicates the water level.

The pressures of three scenarios are visualized in Figure 7. We excluded Scenario III because of insufficient data. The X-axis represents the normalized time with the Nadir pressure of the turbine/ on the tilting gate being at the 50% of the total time for each scenario. Time normalization enables a direct comparison between the different scenarios. The Y-axis represents the measured pressure in water column, expressed in meters as an approximation of the water depth. The solid lines represent the values of each scenario, averaging the respective measurements among the various sensors, while the dotted blue line at value 0 represents the water level.

As the sensors are deployed, the depth increases and so the water column values decrease. As they arrive at the scenarios' selected depth, the water column does not correspond to their exposed depth, due to the pressure-reducing effect of the velocity. An approximately horizontal line can be seen when the sensors reach the deployment depth. Once the sensors flow through the turbine, the pressure suddenly rises to the maximum pressure, drops to the Nadir, while passing though the turbine and rises again, when arriving to the tailwater. As the sensors pop up to the surface, the pressure reaches atmospheric pressure (0 depth).

The orange line corresponds to the scenario IV, in which the sensors have been sent in the channel downstream the tilting gate and differs from the other scenarios. As it is released on the surface, it does not cross the turbine. Small changes of water column are shown while flowing over the tilting gate. Note that the time is normalized and distorted, which means that the graphs do not show real time. Looking into the raw data, the sensors need less time to Nadir in Scenario IV, but more time between the Nadir and the tailwater than the sensors crossing the turbines.

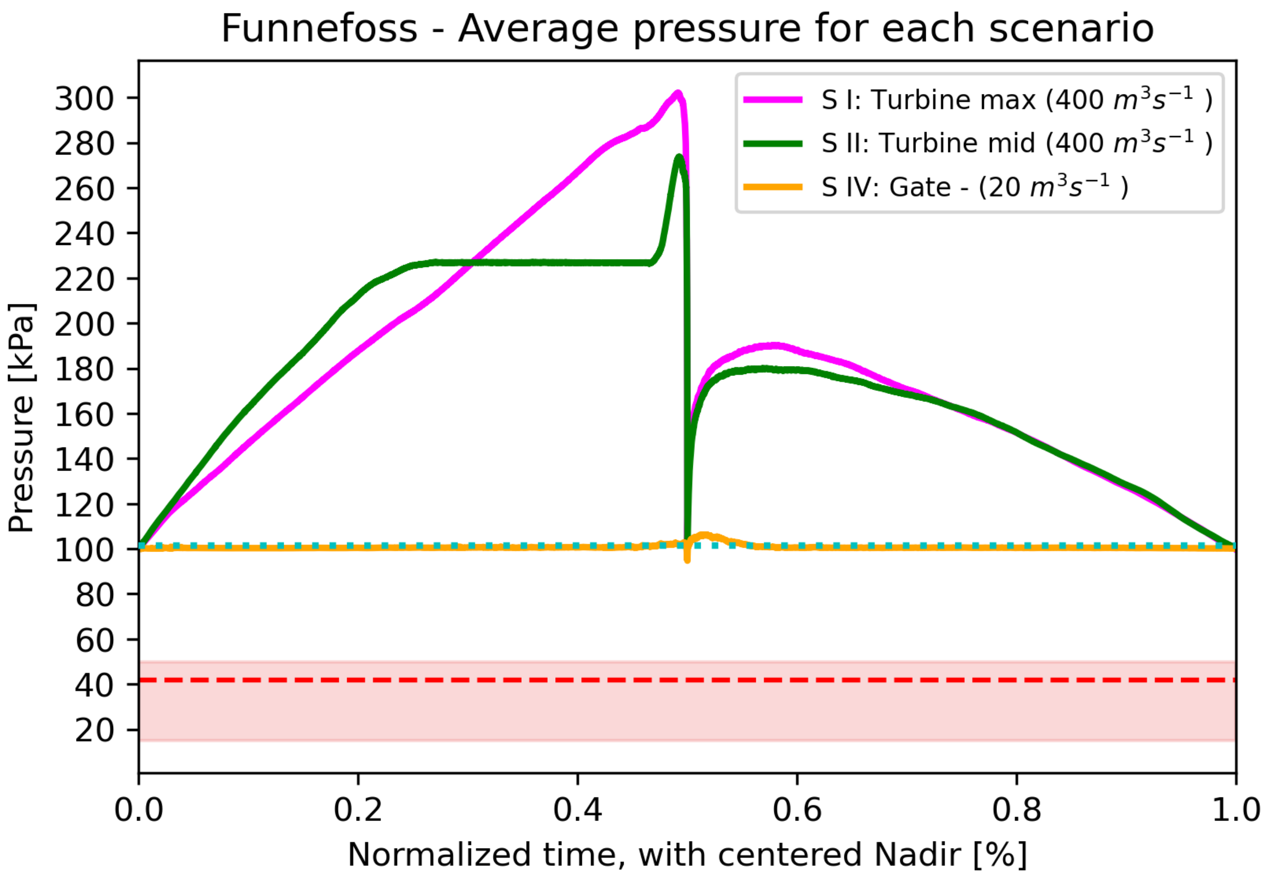

Figure 8: Average pressure values in kilo Pascal are segmented into pre-Nadir and post-Nadir for all scenarios at Funnefoss; The light blue dotted line indicates atmospheric pressure, while the red strikethrough line denotes the threshold for European grayling 0+.

Figure 8 shows the pressure of each scenario and is similar structured to Figure 7. On the X-axis, time is normalized with the Nadir inside the turbine or downstream the tilting gate set at 50%, facilitating direct comparison across scenarios. Meanwhile, the Y-axis represents pressure measurements in kilo Pascals. The scenarios are represented with solid lines, and the blue dotted line represents the atmospheric pressure at 101.325 kPa. The red area represents the threshold for different fish species defined using literature with an upper value of 50 kPa and a lower value of 15 kPa. While Nase (L1, 0+) and Roach (L6, J1) have a threshold of 50 kPa, European Perch (L1) and European grayling (L1/2) have a threshold of 15 kPa. In our case studies, the European graylings (O+) is the most interesting and relevant species, with the strikethrough line indicating the species' threshold at 42 kPa. The increase and drop of the pressure are better visualized in Figure 8. The first nearly horizontal line is upstream the turbine, indicating the starting depth, the steep pressure inclination indicates the entrance into the turbine, the pressure Nadir, is the maximum pressure drop that occurs during energy production phase transformation. As the sensors enter the tailwater, the pressure rises again and when the sensors come back to the surface, the pressure goes towards 0. Regarding the averaged values, the threshold for European grayling in the life stage 0+ is not exceeded.

As the two pressure related thresholds for fish are the Nadir pressure inside the turbine and the Pressure Rate of Change, it is essential to not only consider the average data of each scenario but perform a detailed analysis of the entire datasets. The following boxplots visualize those data more in detail.

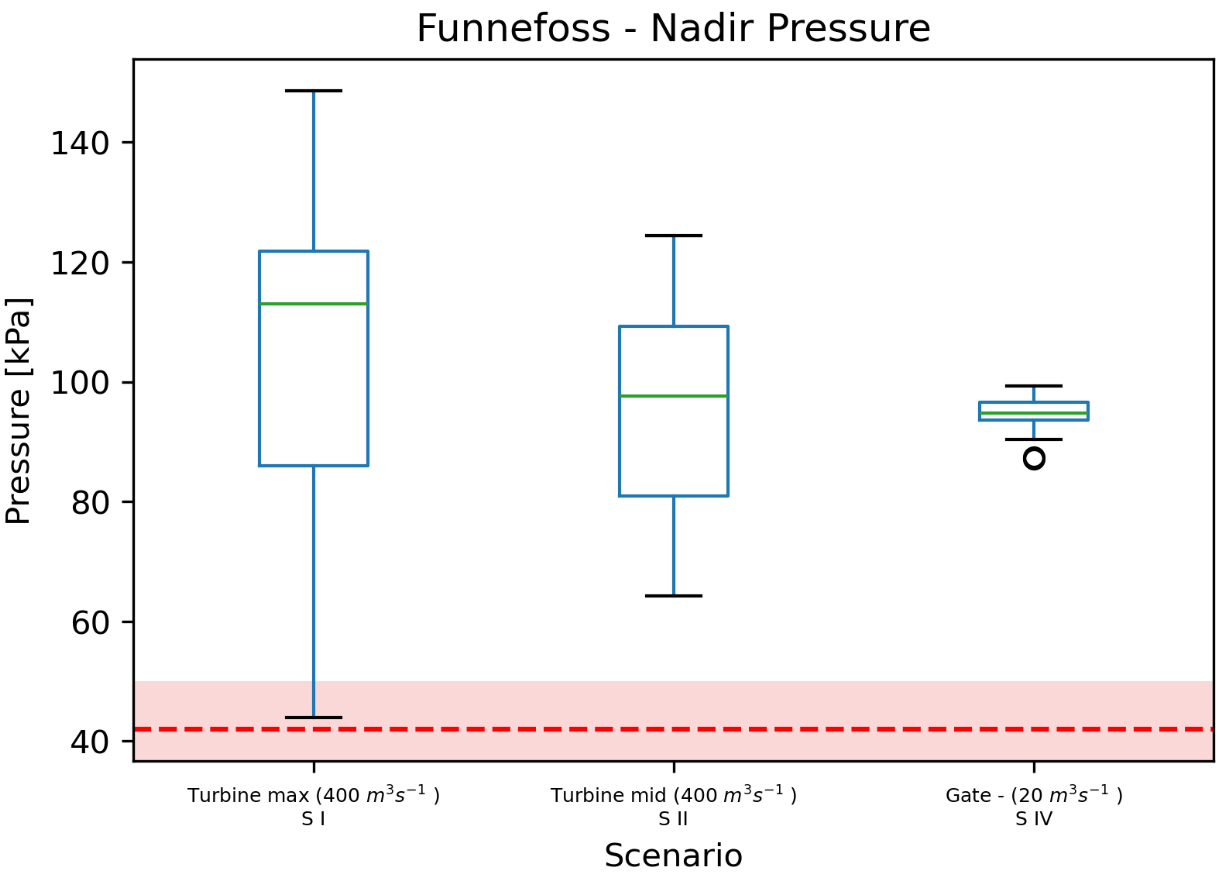

Figure 9: Boxplots represent the statistic values for the Nadir pressure in kilo Pascal for all relevant scenarios at Funnefoss, the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red strikethrough line corresponds to the threshold for fish.

In Figure 9 the boxplots for the three relevant scenarios are plotted. Scenario IV (depth: 8 m; discharge: 400 m³/s), has not been plotted as not enough data could be collected for this scenario for reliable statistical analysis. The green line at the centre represents the median, while the blue horizontal lines represent the first and third quartiles. It means that 50% of the data, which corresponds to the interquartile range, lay in the blue plotted box. The small black lines indicate the whiskers, which can be calculated through the first/ third quartile -/+ 1.5 times the interquartile range of the data. Circles denote outlier data, which lay outside of the whiskers. The red strikethrough line and the red area corresponds to the fish species thresholds. The data range of Scenario I (Depth:26 m; Discharge 400 m^3/s) is the largest along all three scenarios and some of the recorded data are in the range for which the mortality is assumed higher than 10 %. This means that the fish have a slightly higher risk passing though the turbine in these conditions and at this depth, compared to other scenarios, the interquartile range of data, of Scenario IV (Depth: 0; Discharge 20 m^3/s) is the narrowest and also the farthest away from the fish threshold. Passages through the tilting gate is safer for fish, and the pressure data highlight that the threshold for this parameter is exceeded only in a limited number of cases.

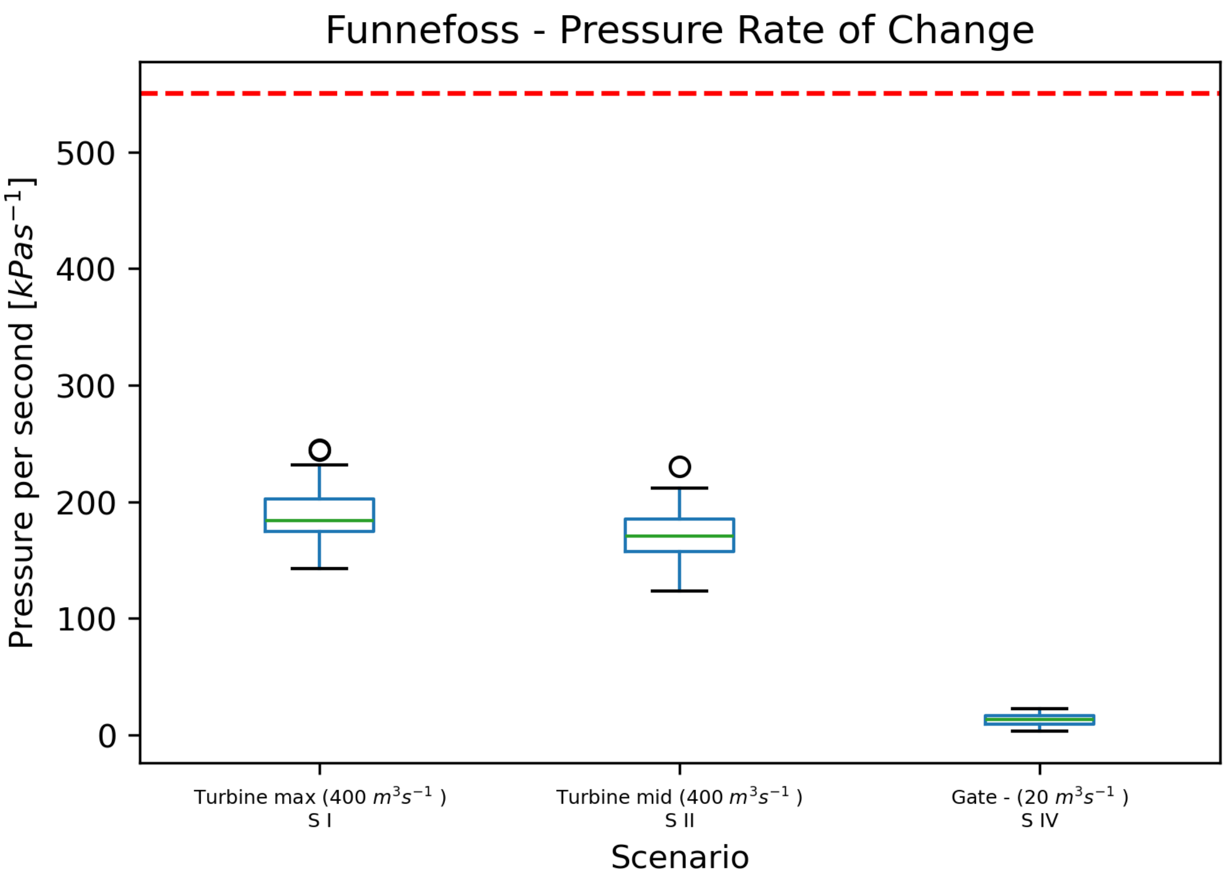

Figure 10: The pressure rate of change in kilo Pascal per seconds for all relevant scenarios at Funnefoss are plotted as Boxplot; the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red strikethrough line corresponds to the threshold for fish.

Figure 10 shows the statistical values of the Pressure Rate of Change in kilo Pascal per seconds as boxplots for Scenario I – II and IV The boxplots are structured the same as in Figure 9. The threshold for fish lays at 550 kPa/s and has never been exceeded. The interquartile range of data is the smallest for the scenario IV. As for the Nadir pressure, this means that letting the fish pass through the tilting gate is the most predictable and safest scenario. Unlike the Nadir pressure, the interquartile range of data of the Scenarios I and II are more similar to each other and very narrow. The interquartile range of data is not too high and the threshold for fish is twice as high and does not show any threat. The data show that the passage through the turbine is safe for the fish if we consider this parameter.

4.2 Kongsvinger

Table 10 shows the number of sensors and dummies have been deployed, lost, destroyed, or hit and how many data series and unusable data have been collected for each scenario. Approximately 30 data series are recommended to provide summary statistics for cross-comparison between scenarios and sites. Based on this criteria, Scenarios I, II and IV (Table 10, in bold) were measured successfully in the field for further evaluation. Scenario I have 30, Scenario II has 26, Scenario III only 10, and Scenario IV 31. In Scenario III, the sensors did not enter successfully the turbine, therefore we decided to change the experiment settings. The statistical values of Scenario III are therefore not representative, and similarly to Funnefoss case study we decided to exclude it from detailed analysis. In total 89 data series were collected. It is notable that neither dummies nor sensors were destroyed, and only 3 % of all deployed objects have been hit. Those hits occurred only during Scenario I.

Table 10: Summary of the data quantity of each scenario at the Kongsvinger hydropower plant.

Scenario	Category	Deployed	Lost	Destroyed	Hit	Data	Unusable Data
Scenario I	Sensors	38	5	0		30	3
	Dummies	14	2	0		0	0
	Total	52	7	0	**3**	30	3
	Percentage		13,5 %	0,0 %	6,7 %	90,9 %	9,1 %
Scenario II	Sensors	34	1	0		26	7
	Dummies	12	1	0		0	0
	Total	46	2	0	0	26	7
	Percentage		4,3 %	0,0 %	0,0 %	78,8 %	21,2 %
Scenario III	Sensors	6	2	0		1	3
	Dummies	4	0	0		0	0
	Total	10	2	0	0	1	3
	Percentage		4,3 %	0,0 %	0,0 %	25,0 %	75,0 %
Scenario IV	Sensors	36	1	0		31	4
	Dummies	8	0	0		0	0
	Total	44	1	0	0	31	4
	Percentage		2,2 %	0,0 %	0,0 %	88,6 %	11,4 %
Total	Sensors	116	9	0		89	18

Scenario	Category	Deployed	Lost	Destroyed	Hit	Data	Unusable Data
	Dummies	42	3	0		0	0
	Total	158	12	0	3	89	18
	Percentage		7,6 %	0,0 %	2,1 %	83,2 %	16,8 %

At the Kongsvinger study site, pressures have been measured and documented the same way as at Funnefoss. They measurements have been conducted upstream, within, and downstream of the turbines offering significant insights into the conditions affecting fish passage through the turbines. The Nadir pressure, the Pressure Rate of Change (PRC) and the maximum pressure are taken inside the turbine. Statistical summaries of the entire dataset for each scenario are presented in Table 11.

Table 11: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario I (Turbine, max depth, Discharge: 208m^3/s) at Kongsvinger.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	1241.6	1266.8	2814.5	731.1	2083.4	1330.2	1096.1	234.1	343.8	113.2
PRC	1464.3	1543.6	1921.7	47.8	1873.9	1635.4	1465.5	169.9	336.3	92.5
Max Pressure	2934.6	2945.3	3209.4	2236.4	973.0	3002.2	2936.0	66.3	177.1	23.7
Min Pressure	965.6	993.6	997.8	731.1	266.7	995.9	986.7	9.2	72.2	3.2

Table 12: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario II (Turbine, mid depth, Discharge: 208m^3/s) at Kongsvinger.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	1110.3	1067.7	2236.0	97.8	2138.2	1252.4	913.1	339.3	414.4	165.5
PRC	1247.4	1261.6	2142.2	15.2	2127.0	1440.6	1133.2	307.5	419.8	139.0
Max Pressure	2461.7	2407.8	2882.3	2239.2	643.1	2584.4	2311.5	272.9	172.3	115.2
Min Pressure	915.5	994.5	999.2	97.8	901.4	997.0	913.1	83.9	186.9	3.5

Table 12 and Table 13 provide key metrics such as Mean, Median, Maximum, Minimum, Range, third Quartile, first Quartile, Interquartile Range, Standard Deviation, and Mean Absolute Deviation. All values are reported in units of millibars.

Table 13: Statistical values in millibars for the measured Nadir, pressure rate of change, maximal pressure and minimal pressure at Scenario IV (Turbine, mid depth Discharge: 148.4m^3/s) at Kongsvinger.

Meas	Mean	Median	Max	Min	Range	Q3	Q1	IQR	STD	MAD
Nadir	1440.2	1449.6	1647.3	1197.4	449.9	1522.4	1334.2	188.1	129.9	108.6
PRC	1179.9	1159.0	1698.5	850.1	848.4	1304.4	1046.8	257.6	206.2	129.9
Max Pressure	2959.6	2951.0	3046.2	2936.0	110.2	2955.9	2947.1	8.8	24.7	4.7
Min Pressure	994.2	995.5	999.5	980.4	19.1	997.4	992.7	4.8	4.4	2.1

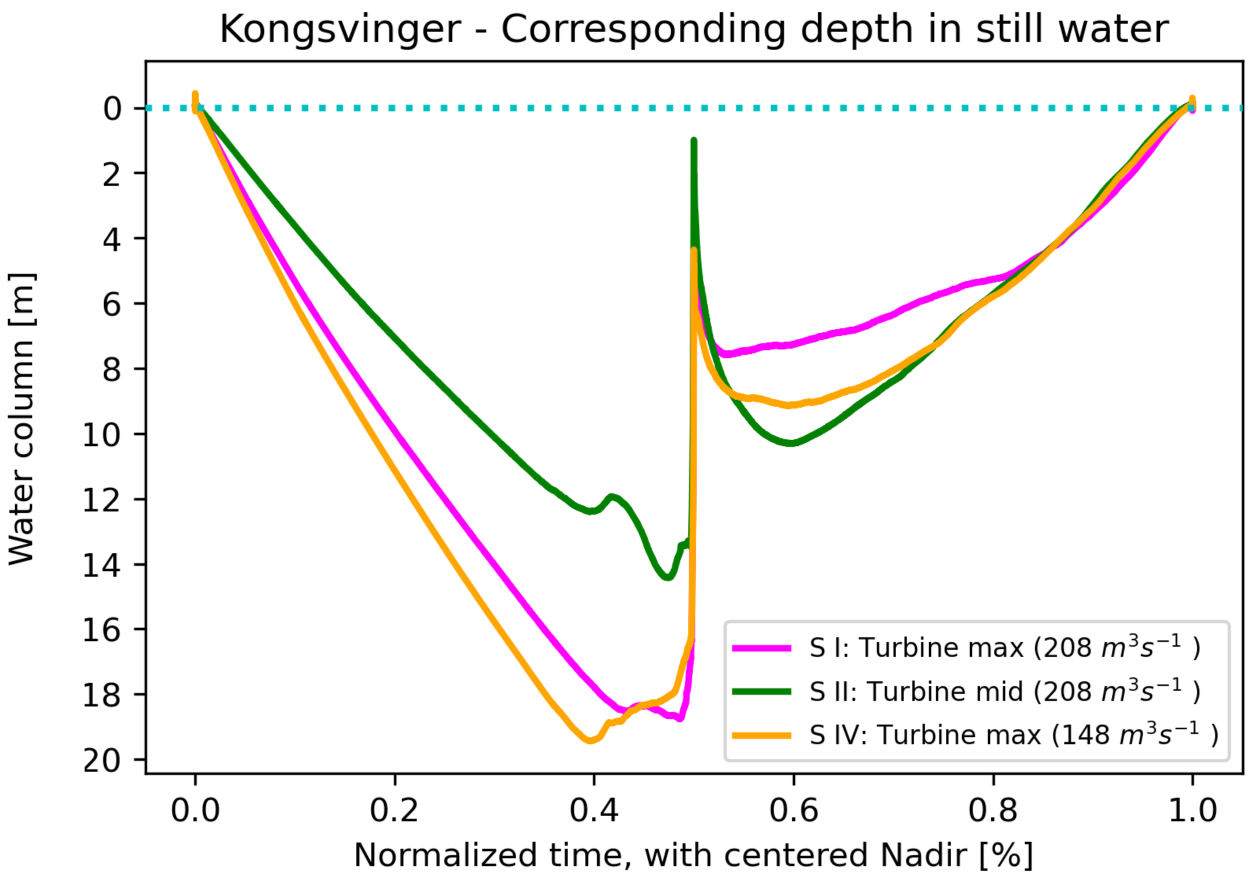

Figure 11: Average measured pressure converted in water columns [meter] are segmented into pre-Nadir and post-Nadir passage across all scenarios at Kongsvinger; The light blue line indicates the reference water level surface, which is given a default value of "0m".

For the Kongsvinger study site, Figure 11 displays the pressure readings for all four scenarios and is structured the same way as Figure 7. The X-axis represents normalized time, with the turbine's Nadir set at 50%. This setup facilitates direct comparison among the scenarios. Note that the values before and after the 50% time point are rearranged and do not correspond to equal time intervals. The Y-axis represents water pressure measured in meters of water column. Solid lines represent the average values of each scenario, while a blue dotted line depicts the water level.

As sensors are released, they descend, thus the depth increases. Compared to Funnefoss, the maximum water column of the scenario upstream the turbine is represented by the local maximum and more difficult to identify. Upon entering the turbine, pressure suddenly rises to maximum- and it drops to the Nadir the passage. Finally, it rises again upon exiting into the tailwater. As sensors resurface, the water column approaches zero.

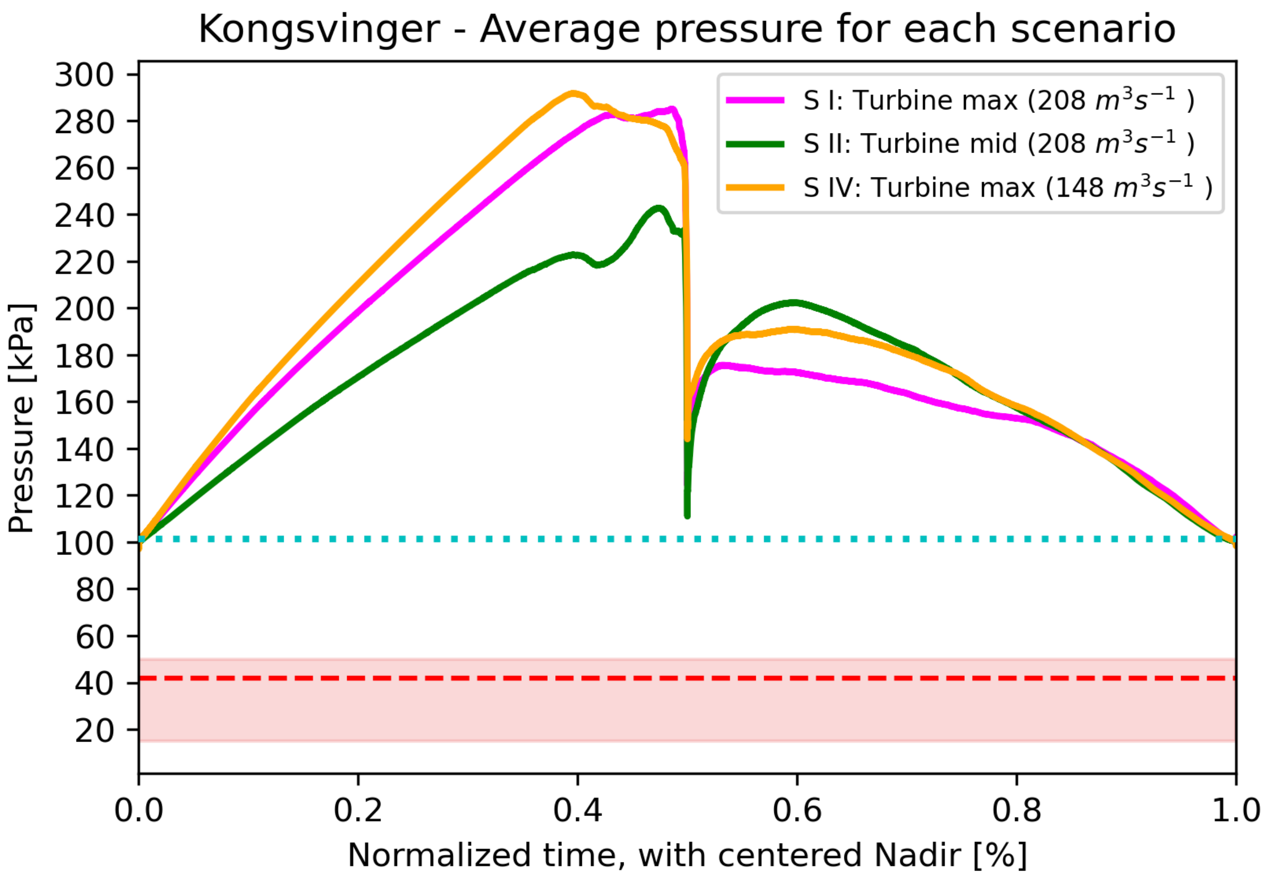

Figure 12: Average absolute pressure values in kilo Pascal are segmented into pre-Nadir and post-Nadir for all scenarios at Kongsvinger; The light blue dotted line indicates atmospheric pressure, while the red strikethrough line denotes the threshold for European graylings 0+.

As for Figure 11, Figure 12 visualizes the pressure of each scenario. On the X-axis, time is normalized with the Nadir positioned within the turbine or through the tilting gate, set at 50%, which facilitates direct comparison across scenarios. It's noteworthy that values before and after this midpoint are rearranged and do not follow an equal time distribution. Meanwhile, the Y-axis indicates pressure measurements in kilo Pascal. Solid lines represent the scenarios, the blue dotted line symbolizes atmospheric pressure at 101.325 kPa, and the red strikethrough line denotes the threshold for European grayling 0+. The red area shows the upper threshold of 50 kPa and the lower threshold of 15 kPA, representing the range of values for different species.

As for the Funnefoss case study, the following part shows a more detailed analysis of data, by visualizing all the data series. The averaged values do not surpass the threshold for European grayling in the 0+ life stage.

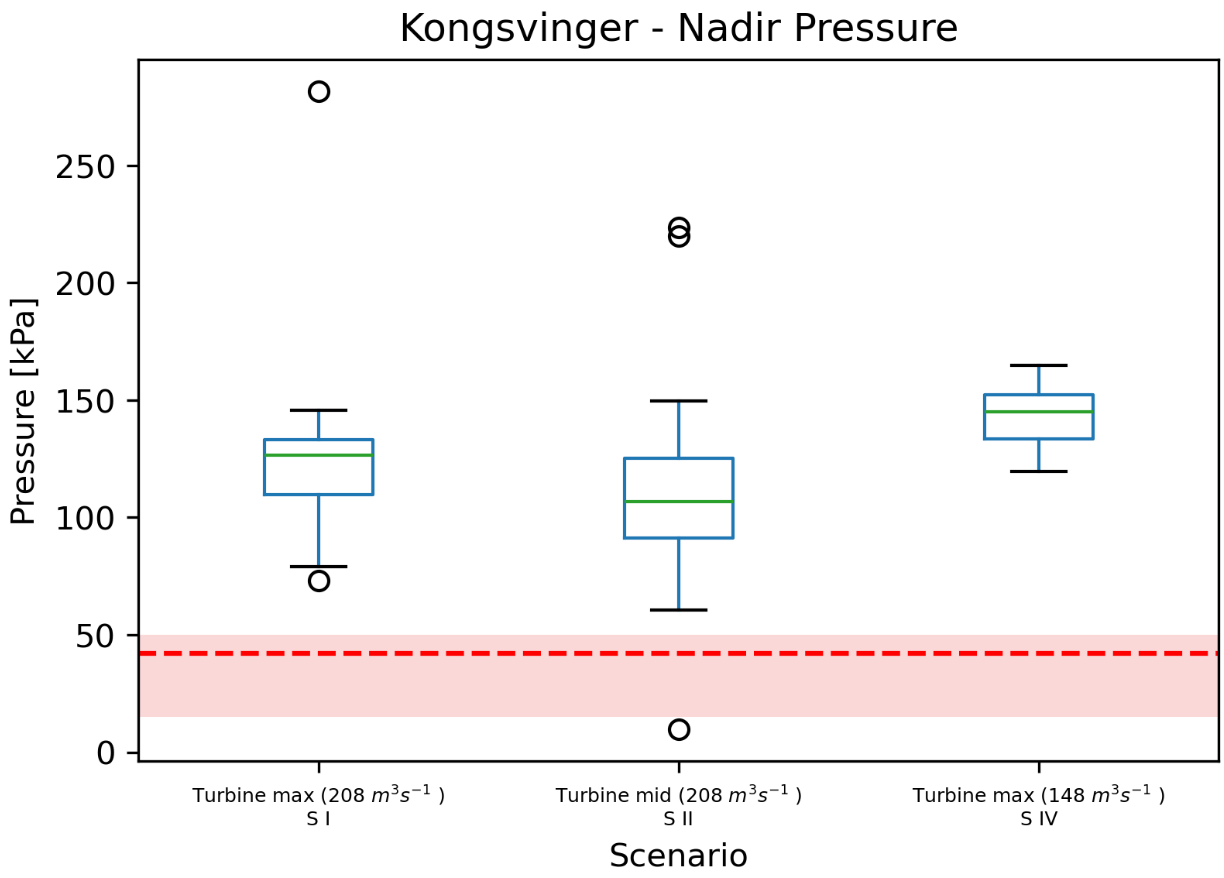

Figure 13: Boxplots represent the statistic values for the Nadir pressure in kilo Pascal for all relevant scenarios at Kongsvinger, the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red strikethrough line corresponds to the threshold for fish.

Figure 13 displays boxplots for three pertinent scenarios. Scenario III, with a depth of 5 meters and discharge of 208 cubic meters per second, is omitted due to insufficient data for reliable statistical analysis. Each boxplot features a green line representing the median, and blue horizontal lines denoting the first and third quartiles. These quartiles encapsulate 50% of the data, forming the interquartile range within the blue box. Whiskers, indicated by small black lines, extend from the quartiles and are determined by the interquartile range multiplied by 1.5. Outlier data points, lying beyond the whiskers, are depicted as circles. Additionally, a red strikethrough line and the red area mark the fish thresholds. The interquartile range of data is narrow for all three scenarios. Scenarios I and II show a higher variability of the data, with several outliers, while Scenario IV (lower discharge) is the farthest away from the fish threshold and no outliner data have been registered. Scenario II is the closest to the fish threshold and includes outlier data that exceed the threshold. The presence of outlier required a consolidation of the data series: after a keen review of the raw data, the data do not show any measurement error. In particular, the outlying data series which lays under the threshold of all life stages of the grayling is correct. It is interesting to highlight as the critical Scenario at Funnefoss is the deepest scenario, while at Kongsvinger is the shallowest.

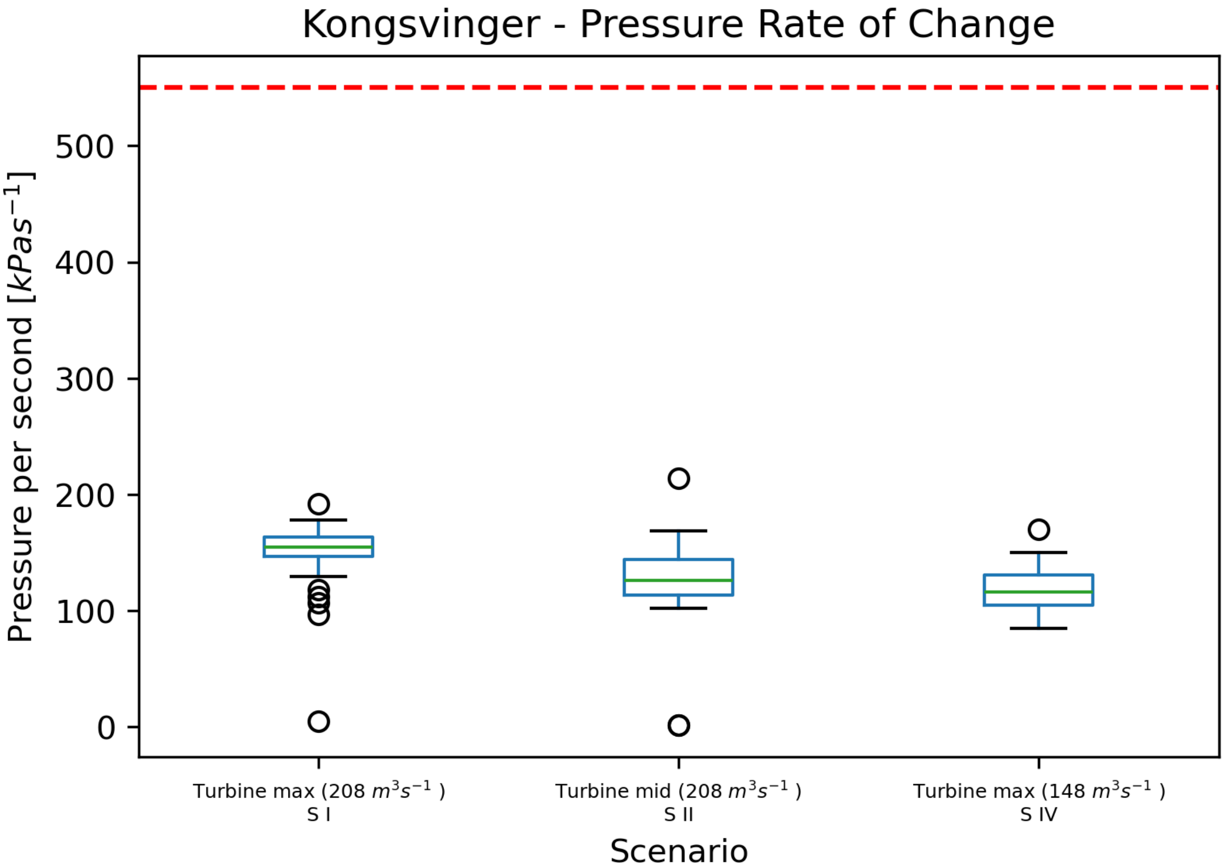

Figure 14: The pressure rate of change in kilo Pascal per seconds for all relevant scenarios at Kongsvinger are plotted as Boxplot; the green line in the middle indicates the median, the blue lines indicate the first and third quartile, the small black lines indicate the outliers, and the circles indicate outlier data; the red strikethrough line corresponds to the threshold for fish.

Figure 14 illustrates the statistical representation of the Pressure Rate of Change in kilo Pascals per second through boxplots for Scenarios I, II and IV. Scenario III (depth: 5 m; discharge: 208 m^3/s) is excluded due to insufficient data for reliable analysis. The boxplot format is identical to that of Figure 13. Notably, the fish threshold of 550 kPa/s remains unexceed for all three scenarios and the data are well below the threshold.

5 Discussion

This experiment represents a first attempt to study the pressure conditions and the number of hits that fish species might experience when migrating downstream through the turbines at Funnefoss and Kongsvinger power plants. The analysis does not highlight any critical situation regarding the strikes. The number of hits registered in the turbines in both case studies and the tilting gate in Funnefoss is low, with only Scenario I in Funnefoss with 15% of hits, and all the other scenarios under 10%. The number of hits are expected to be higher for fish species and life stages of a bigger size than the sensors: in case more information is desired, the use of a rubber fish designed by TalTech is suggested.

The Nadir pressure data from the sensors also do not highlight any critical situation, with 100% of the values never exceeding the known critical thresholds for selected fish species in most scenarios. Although the distribution of the data for Scenario I in Funnefoss shows that at least part of the data fall in the risk range, they never exceed the threshold for the European grayling which is, to the best of our knowledge, one of the most relevant species in the catchment (see below for a discussion about the fish community). The other scenarios in Funnefoss do not show any value in the risk range. For Kongsvinger, only one outlier exceeds the risk thresholds for all species including the grayling. However, these data series is an outlier which by definition represents only a small percentage of the statistical distribution. For the Kongsvinger case study it should be mentioned that the scenarios at maximum discharge (208 m^3/s) show highest variability of the data, compared to the scenario at lower discharge (148 m^3/s) but with the same injection depth. This offers some insights into management strategies for case studies with critical conditions: lowering the discharge during the migratory period might mitigate risk, although lower flows increase hit probabilities.

The pressure rate of change data does not indicate a critical situation in any of the investigated scenarios, where all pressure data remained below threshold values reported in Table 2 (550 kPa/s).

The thresholds used in this report have been identified from literature and applied in several similar studies conducted by TalTech, as part of the Swiss project ”Fish Downstream Migration“(Tuhtan and Toming, 2023). Tolerance data and dose-response curves for each fish species and life-stage for each of the analysed parameter would be desirable, but they are currently not available for the majority of European fish species and life stages. The horizontal Kaplan turbine at Bannwill, Switzerland (28,5 MW, Q = 450 m^3/s, h = 5,5 – 8,5 m) had mean Nadir pressures ranging from 72,3 to 92,2 kPa and mean pressure rates of change of 152,2 to 165,7 kPa/s. The Nadir values from the Swiss study are similar to, but generally lower than those in Funnefoss and Kongsvinger, and the rates of pressure change for the Swiss and Norwegian sites are similar.

At Bannwill, overshot weir tests were also conducted, with mean Nadir pressures of 98,2 kPa and mean pressure rates of change of 239,9 kPa/s. When compared to the overshot weir at Funnefoss, it was found that both sites had similar Nadir pressures, and the pressure rate of change during the tilting gate passage at Funnefoss was substantially lower than that at Bannwill. This is likely due to the difference in discharge conditions during the tests at each field site; in the Swiss study at Bannwill, the tailwater was maintained at minimum flow, whereas in the Norwegian case, tailwater conditions corresponded to a flood event.

Boat electrofishing in Glomma downstream (2011 & 2012) and upstream (Kongsvinger power plant in 2015 recorded in total 11 fish species (Museth et al. 2014, 2016). Hence, the fish communities in Glomma at the two sites studied in this project is quite complex, but the knowledge about downstream migration at the two studied sites is especially low (e.g. which species and what time of the year do fish migrate downstream).

The number of strike events estimated in both case studies was low. It is worth noting that the observed number of strike events recorded by the 10 cm/ 46 g BDS sensors are expected to be higher for larger individuals of brown trout, northern pike, grayling and other species. The four Swedish Kaplan turbines at Lanforsen (39 MW, Q = 620 m^3/s, h = 10 m) were found to have a strike-based mortality of live fish (juvenile Atlantic salmon and brown trout) with a mean body length of 17,3 of 1,3% (Vikström et al., 2020). Another Swedish Kaplan study at the Sikfors hydropower plant (40 MW, Q = 270 m^3/s, h = 19 m) estimated strike mortality probability for smolts of Atlantic salmon (mean length = 14,8 cm) and sea trout (17,5 cm) as well as kelts (Atlantic salmon mean length = 78,4 cm, sea trout = 64,0 cm). In this study, the mortality rates for smolt ranged from 7,7% (Atlantic salmon) to 9,7% (sea trout) and for kelts from 37% (sea trout) to 45,3% (Atlantic salmon), illustrating the increase in probability in relation to the increase in total body length (Ferguson et al., 2008). In a previous study, Engström (2021) estimated fish mortality rates during turbine passage at the Kongsvinger and Braskereidfoss hydropower plants. Mortality rates were calculated for various fish lengths: the mortality once the fish has entered the turbine is dependent on the fish size and discharge. The estimated mortality is higher at low discharges and for larger individuals due to increased probability of being hit by turbine blades. The estimated mortality rate is two times higher for discharges under 150 m^3/s than for discharges over 150 m^3/s, the highest mortality rate is 70 % and applies to 100 cm long fish, that pass through the turbine during low discharge. Fish with a length of 10 cm have a mortality rate lower than 10 % at all different discharges (Engström, 2021).

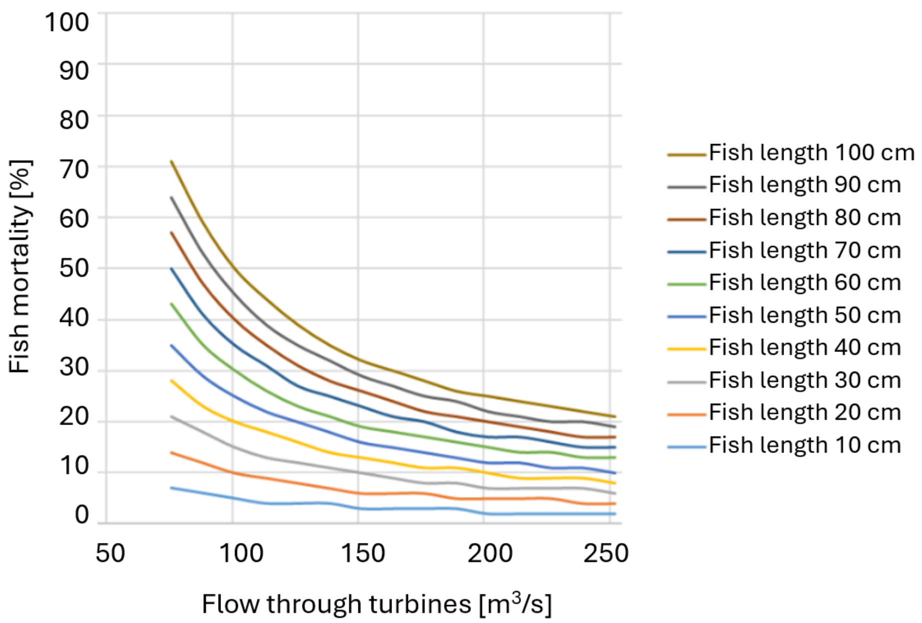

Figure 15: Estimated fish mortality at Kongsvinger, dependent on discharge and fish length (Engström, 2021).

6 Conclusion

The objectives of this experiment were to sample the physical conditions experienced by fish in passage through turbines during downstream migration in two power plants in the Glomma River catchment. The mortality thresholds for different species and life stage are reported in Table 2: while site specific data for the species in this river are not available, we relied on data from live fish observations and sensor studies in the literature to determine pressure-based physical parameters.

For the Funnefoss power plant, two turbine scenarios with same discharge but at different depths and one for the tilting gate have been analysed. Considering the impact of pressure-based physical factors, the mortality rate of fish passing downstream through the turbine or the tilting gate in Funnefoss, is estimated to be under 10% due to pressure and change in pressure, although it might be higher for large individuals. Scenario I shows some potentially critical values falling into the risk range for the Nadir pressure, although they were not found to be critical for juvenile grayling.

For the Kongsvinger power plant, three scenarios (two at different depths and one at different discharge) were analysed. Taking into account the influence of pressure-related physical conditions, the estimated mortality rate for fish migrating downstream through the turbine in Kongsvinger is less than 10%. Only one outlier Nadir measurement during Scenario II was found to have a pressure-induced risk of mortality.

7 Recommendations

Future studies to estimate the risk of injury and mortality during hydropower plant passage may benefit from adopting one or more of the following recommendations:

- The only scenario for which we could change the discharge, highlighted that there are differences in pressure in case the fish enter at the same depth but different discharge. For management strategies, this could be investigated more in detail by repeating the experiment at a different discharge.
- The experiments have been conducted at high flow conditions. It could be relevant to conduct experiments during lower flows (or reduce the load), when it is not possible to load the turbine at maximum discharge.
- In the Glomma catchment there are several hydropower plants. It might be interesting to investigate which one shows the worse conditions for migratory fish, in order to target it with potential mitigation measures.
- Weirs and spill gates in some cases have worse conditions than the turbines itself. It could be interesting to investigate potentially critical weirs in the catchment.
- Partial and complex migration system; we do not know which life-stages, and the time of the year, the different fish species that migrate downstream. It is known from other studies in the river system that grayling fry drift downstream after emergence from the gravel (van Leeuwen et al. 2017), and this is probably also the case for other fish species, e.g. whitefish. In general, there is very little knowledge about the fish community and the migration system in the Glomma River.

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