FIThydro

Description of a Test Case:

Impact of an Archimedes screw hydropower plant on fish and the local fish population

Shipping canal and ship lock complex of Ham (Kwaadmechelen) - Belgium

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Picture: De Vlaamse Waterweg NV

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Table of Contents

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List of Figures

List of Tables

1. Description of the Test-Case

1.1. Description of the water bodies related to the hydropower plant (HPP) and ship lock complex of Ham (Kwaadmechelen, Belgium).

The shipping lock complex and accompanying HPP studied here is located in the Albert Canal in the municipality of Ham (Kwaadmechelen, Belgium; Figure 1 and Figure 2). The Albert Canal is one of the most important shipping routes of Flanders as it connects the River Scheldt via the Port of Antwerp, with the River Meuse and the Juliana Canal. It is dug in the 1930's.

The canal bridges a 60 m height difference between the river Meuse (highest) and the river Scheldt (lowest; Figure 2). The 60 m head is covered by six ship lock complexes on the Albert canal, of which the ship lock complex of Ham (Kwaadmechelen) is one (Figure 1 and Figure 2). The ship lock complex of Ham is situated at 77,2 km of the river Meuse. The other ship lock complexes are located in Wijnegem (closest to Antwerp and 119,8 km of the river Meuse), Olen (95,9 km of the river Meuse), Hasselt (50,2 km of the river Meuse), Diepenbeek (45,7 km of the river Meuse) and Genk (41,5 km of the river Meuse; Figure 1 Figure 2). The ship lock complexes of Ham, Olen and Hasselt are by-passed by a small channel that runs through a hydropower station. The hydropower station contains the largest Archimedes screws in the world, which can not only pump, but also turbinate water (two operational modes for one and the same screw; see further details below). The construction of these by-pass channels and accompanying hydropower stations are as well planned for the three other ship lock complexes of Wijnegem, Diepenbeek and Genk.

The canal and its side-canals are almost entirely fed by water of the river Meuse, and are directly connected to it in the city of Liège (Wallonia, Belgium; Figure 1 Figure 2). The water in the Albert Canal is used for shipping, industry, drinking water supply, irrigation, and cooling of the nuclear power plant of Antwerp. The discharge of the Canal is regulated and depends on the discharge of the river Meuse. Back in 1995 The Netherlands and Belgium agreed upon the amount of water that can be directed to the Albert canal and its side-canals, versus the river Meuse and the Dutch canals, in function of the amount available in the River Meuse at periods of low water supply (Maas afvoerverdrag 17 January 1995).

The river Meuse not only provides water for the Albert canal and its side-canals, but also for the Juliana canal going to the Netherlands (not indicated on the maps). The Meuse discharge is not constantly equally divided over all the canals and the Meuse itself. Depending on the water supply, more or less water is going to one or the other canal, or the river Meuse itself.

At the downstream side, the Albert canal meets the river Scheldt via the Port of Antwerp (Figure 1 and Figure 2). The canal is separated by the Port of Antwerp by a sluice that regulates the run off from the canal to the port (Figure 2). The river Scheldt itself is a tidal river with an open connection to the North Sea. At the location of the Port of Antwerp, the water is brackish. Unique to the Scheldt estuary is the freshwater tidal part between the city of Ghent and Antwerp. Although the Scheldt River is divided from the Albert canal through the Port of Antwerp and minimally one sluice, it is possible that fish migrate from the Scheldt River to the Albert canal. Therefore, it is possible that upstream migrating fish from the Scheldt River pass the Archimedes screws in pumping mode at specifically the most downstream ship lock complexes, and the one in Ham. Nevertheless, the probability of it is estimated to be low, and much lower than the probability that downstream migrating fish from the river Meuse pass the Archimedes screws in turbine mode.

In this respect, it is believed that the impact of the hydropower plant of Ham (Kwaadmechelen; and generally also the others in Olen and Hasselt) mainly affects the fish populations in the canal itself and its side-canals, as well as downstream migrating diadromous fish, going from the canal itself and the Meuse river to sea.

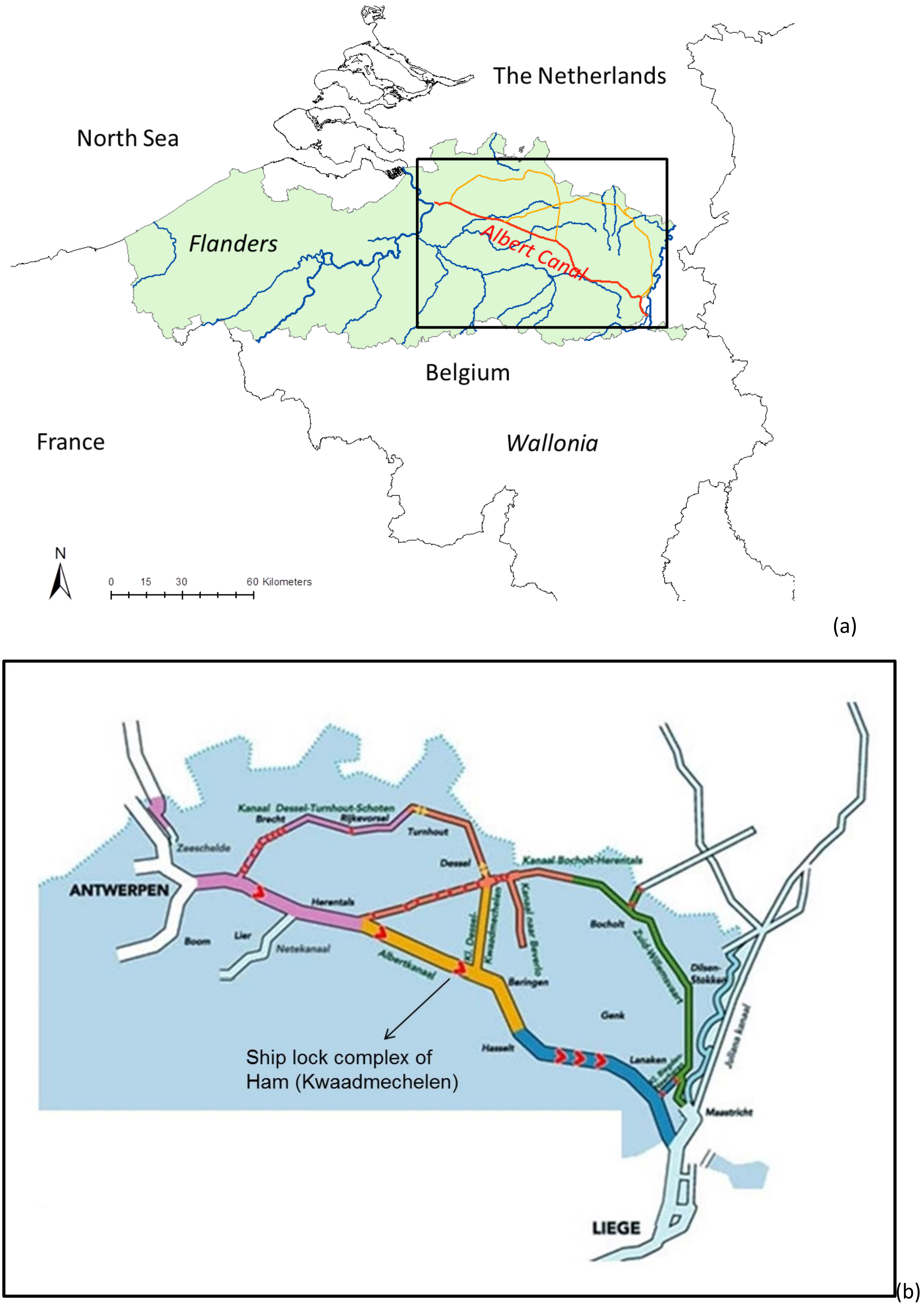

Figure 1: a) Related water bodies and location of the ship lock complex and hydropower plant of Ham (Kwaadmechelen) in Flanders (Belgium; thick blue lines: the river Scheldt (left) and the river Meuse (right), thin blue lines: other large rivers in Flanders, orange lines: the shipping canals connected to the Albert Canal and red line: the Albert Canal. b) Location of the ship lock complex and hydropower plant of

Ham in the Albert Canal and indication of the 5 other ship lock complexes (red arrows; source of figure b: Logistiek Platform Limburg (POM)).

1.1.1. Ecological and biological status

Albert canal

(to be continued)

River Meuse

(to be continued)

1.1.2. Hydrology of the Albert canal and Meuse River

Meuse River

The river Meuse is a typical rain fed river that stretches from France through Belgium ending up in an embanked estuary in The Netherlands with a total fall of 409m. This 935km long river has a discharge area of 36.000km^2 and its mean discharge is 230m^3, peaking up to tenfold after long and heavy rainfall. Besides the initial French part of the river and a stretch of 45km along the border between Belgium and The Netherlands, the river is highly regulated for navigation and therefor multiple sluices and calibration efforts were made. In total 45 barriers are present now of which 17 are equipped with hydropower turbines (http://www.meuse-maas.be/, retrieved 1st of December 2014). The total installed hydropower capacity downstream the city of Namur is around 75MW. The river also provides water to a number of canals that expanse the navigation network. This derived water is also used for irrigation, industrial processes and the production of drinking water. The Albert canal is one of these.

Albert canal

The hydrology of the Albert canal is entirely artificial and controlled by humans for shipping and other purposes. As indicated above, the canal is split in eight canal sections, divided by six ship lock complexes (with present or planned pumping/hydropower station) and one ship lock complex without pumping/hydropower station; Figure 2 Figure 3). The water level in each canal section depends on the water supply from the Meuse river, besides rainfall and the shipping/ship lock activity, the withdrawal of water for irrigation, drinking or cooling water, and the use of water for electricity production by the Archimedes screws in the pumping/hydropower station(s). Although the hydrology is highly artificial and water even sometimes flows from the Albert canal to the Meuse River, there mainly exists a net flow to the Port of Antwerp (Figure 1b).

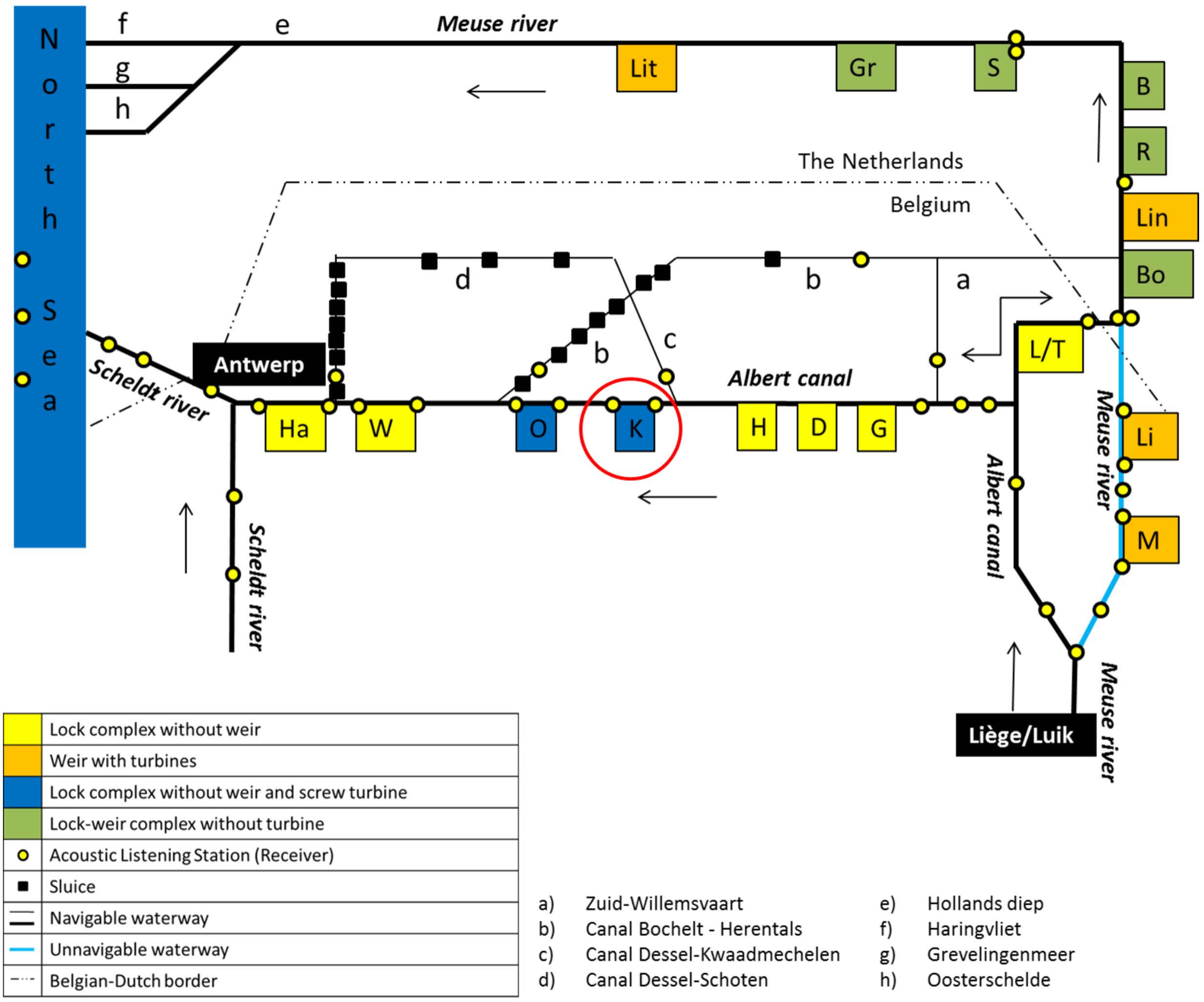

Figure 2: Schematic overview of Figure 2b, showing the Albert canal, the study site (red circle; ship lock complex with hydropower plant of Kwaadmechelen), its surrounding waterways and the location of ship lock complexes, weirs, sluices and hydropower stations. Additionally, the locations of the acoustic listening stations (ALSs or receivers) are indicated that are used to evaluate eel and salmon migration from the Meuse River to the North Sea. Arrows indicate flow direction (source: adapted from Raf Baeyens).

Figure 3: Lock complex in the Albert Canal (Ham) on the left and a weir complex with hydropower plant (Linne) on the right. (Source: http://nts.flaris.be/ and http://www.microhydropower.net/)

Seen the highly artificial nature of the water flow and discharges in the canal sections, it is out of the question to deduce general discharges during migration periods for silver eel and salmon smolts.

Figure 4 shows the discharges for the period of April-October 2014 at two locations in the Albert canal, and two locations in the Meuse River, close to their split.

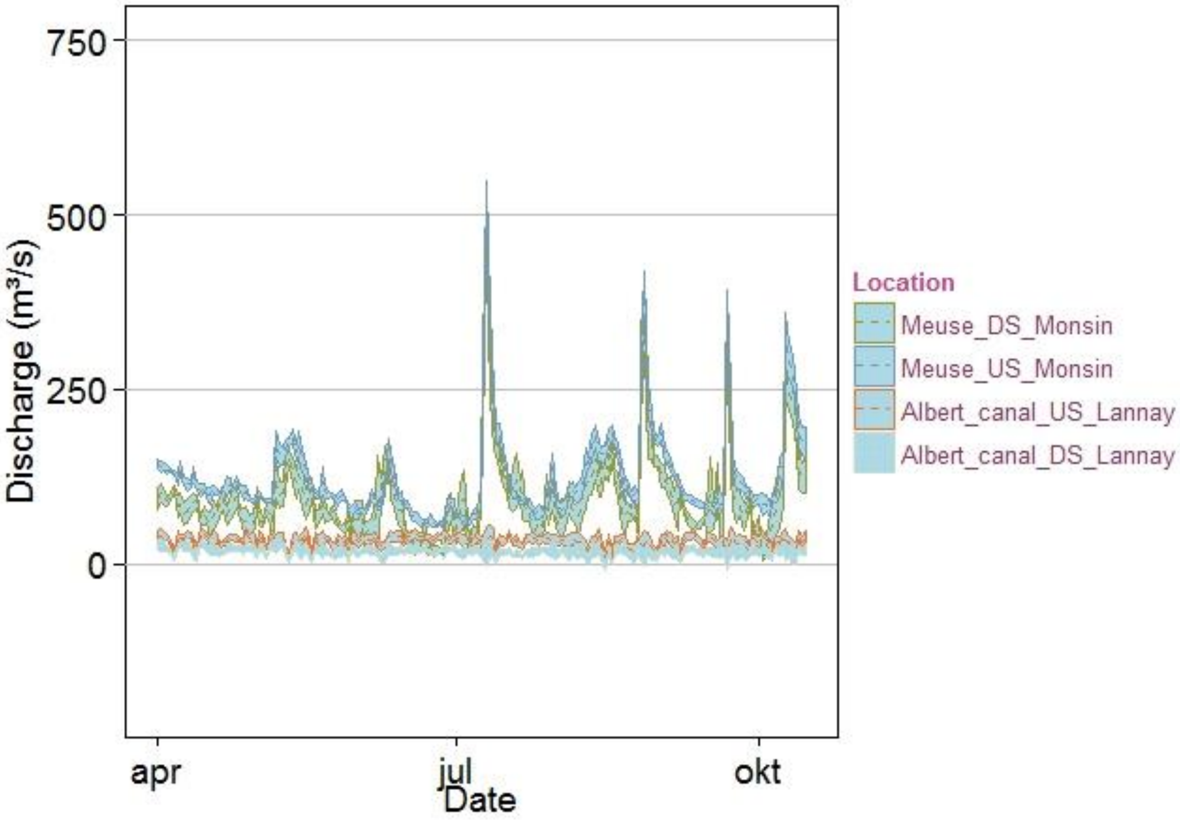

Figure 4: Mean discharge and 95% confidence interval, in the Meuse river upstream of the sluice complex in Monsin (Mo in Figure 2 ; Meuse_US_Monsin), downstream of Monsin (Meuse_DS_Monsin), and in the Albert Canal downstream of Monsin and upstream of the sluice complex in Lannay (La in Figure 2; Albert_canal_US_Lannay) and downstream of Lannay (Albert_canal_DS_Lannay) from April till October 2014 (source of the data: Service Publique de Wallonie, Direction générale opérationnelle de la Mobilité et des Voies hydrauliques, Département des Etudes et de l'Appui à la Gestion, Direction de la Gestion hydrologique intégrée, Namur).

1.1.3. Main pressures

The main pressures and measures described below (Table 1 Table 2), focus on the Albert canal itself, specifically on the hydropower plant and ship locks and their effect on fish of the canal itself and of the neighbouring, connected water bodies. Hence, it does not include the pressures and measures on the neighbouring water bodies an sich.

Table 1: Main pressures on the fish of the Albert canal and surrounding, upstream water bodies

Fish damage	It is investigated in this case study how harmful the hydropower plant (and pumping station) with this type of Archimedes screws is to fish passing the station, and what the impact is on the total fish population. Apart from the (potential) damage caused by the hydropower plant, parallel on-going research hypothesizes a potential harm of the ship lock complex as well in terms of fish damage.

Migration delay	A study of the migration behaviour of eel and salmon in the canal indicates serious downstream migration delays caused by the artificial hydrology of the canal, as well as the ship locks. Eventually and potentially preventing fish to successfully survive and reproduce.
Pollution (non-significant)	The water in the Albert canal is not of good quality, however, the water quality is a rather insignificant pressure on the local or passing fish, compared to the (potential, is being investigated here) detrimental effect of the hydropower plant, the artificial/controlled and highly unnatural hydrology, and the potential detrimental effects of the ship lock complexes on fish by delaying their migration as well as harming them during passage.
Morphology (high)	The Albert canal is an artificial water body. It is constructed for economic purposes and the question is if measures exist that can: 1) prevent the water body from harmful effects on neighbouring nature (fish coming from semi-natural water bodies that are connected to it), and 2) be used (spatially) as "extra" local habitats for plants, fish, macroinvertebrates, or as a safe-enough corridor between the river Scheldt and the river Meuse.

Table 2: Potential measures to prevent fish damage by hydropower

Fish migration measures	Bar screens or other fish guidance structures or methods (e.g. strobe light fish deterrence) that prevent fish from entering either the hydropower plant, either the by-pass channel leading to the hydropower plant.
Technical measures	Adaptations to the Archimedes screws to increase the fish-friendliness of the screw. E.g. closed screw that can serve as turbine, preventing fish from being squeezed between the blades and the housing. Other potentials are to be investigated, and are investigated through the experiments with the barotrauma detection sensors (BDS sensors) in this case study.
Operational measures	As long as fish damage by the screws is substantial, prevent high hydropower activity during downstream migration season of fish (specifically Silver eel and salmon/trout smolts). If there is a relation between the turbinated discharge and fish damage, then one or the other operational scenario (e.g. lower discharge for longer period, or higher discharge over shorter period) could be more fish friendly and should be taken into account. The research on the relation between discharge and fish damage is one of the

	major goals of this case study and is on-going at the time writing.

The technical and operational measures might have an effect on the hydropower production. Fish deterrence structures or methods at the entrance of the by-pass channel are not expected to have an effect on the hydropower production.

1.2. Presentation of the HPP

1.2.1. Rationale

As indicated in section 1.1, the Albert canal is almost entirely fed by the river Meuse, and in periods of low water supply, The Netherlands and Belgium decide how much (how less) water can flow to the Albert Canal.

The prevalence of dry periods is predicted by scientists to occur more frequently in future. Hence, this poses a threat to economy, as low water levels restrict the shipping capacity by restricting ship lock complex activity and lowering the vessel draft in the canal. To lift a ship in a ship lock from a lower to a higher canal section, a large amount of water is needed from the higher canal section, and is transported to the lower canal section. Consequently, to prevent economic loss following from a diminished shipping activity in dry periods, six pumping stations are to be built on the Albert canal. These pumping stations will enable to pump water from the lower to the higher canal section at each of the six ship lock complexes. The stations exist of three open Archimedes screws with a head of 10 m (see section 1.2.3 for further details), and in Ham as well one closed Archimedes screw that can only serve as pump and is supposed to be fish-friendly. To regain part of the energy cost of the pumping activity, the Archimedes screws are developed so that they can turbinate besides pumping, gaining electricity. So, the pumping stations serve as hydropower stations in periods of a high enough water supplies (discharge).

To date (June 2018), three pumping/hydropower stations have been built and are in use. This case study investigates the impact of the pumping/hydropower station in Ham (Kwaadmechelen), which was the first of these three and the first hydropower plant in Flanders (Belgium). The hydropower station in Ham is the only of three that has one closed Archimedes screw. This screw has his housing attached to the blades, preventing fish from being squeezed between the blades and the housing. This screw, which is supposed to be fish-friendly, can only pump water and cannot serve as turbine. The other two pumping/hydropower station were built in the cities of Olen and Hasselt (Figure 1). None of the pumping/hydropower stations in the Albert canal have Kaplan turbines, they only have Archimedes screws.

1.2.2. Location

The hydropower station, which also serves as pumping station, is located in a by-pass channel (380 x 6 meters) bridging the ship lock complex of Ham (Kwaadmechelen, Belgium; Figure 5). The location of the ship lock complex is indicated in the previous section and Figure 1 Figure 2.

Fish can freely swim from the Albert canal to the by-pass channel. Only during the time of this case study, the hydropower plant is disconnected for fish from the Albert canal at it’s’ outlet by a large fish cage (Figure 5). The cage is used to catch studied fish that passed through the turbines, either naturally or by forced experiments, to evaluate fish mortality and injury caused by the screws of the pumping/hydropower station.

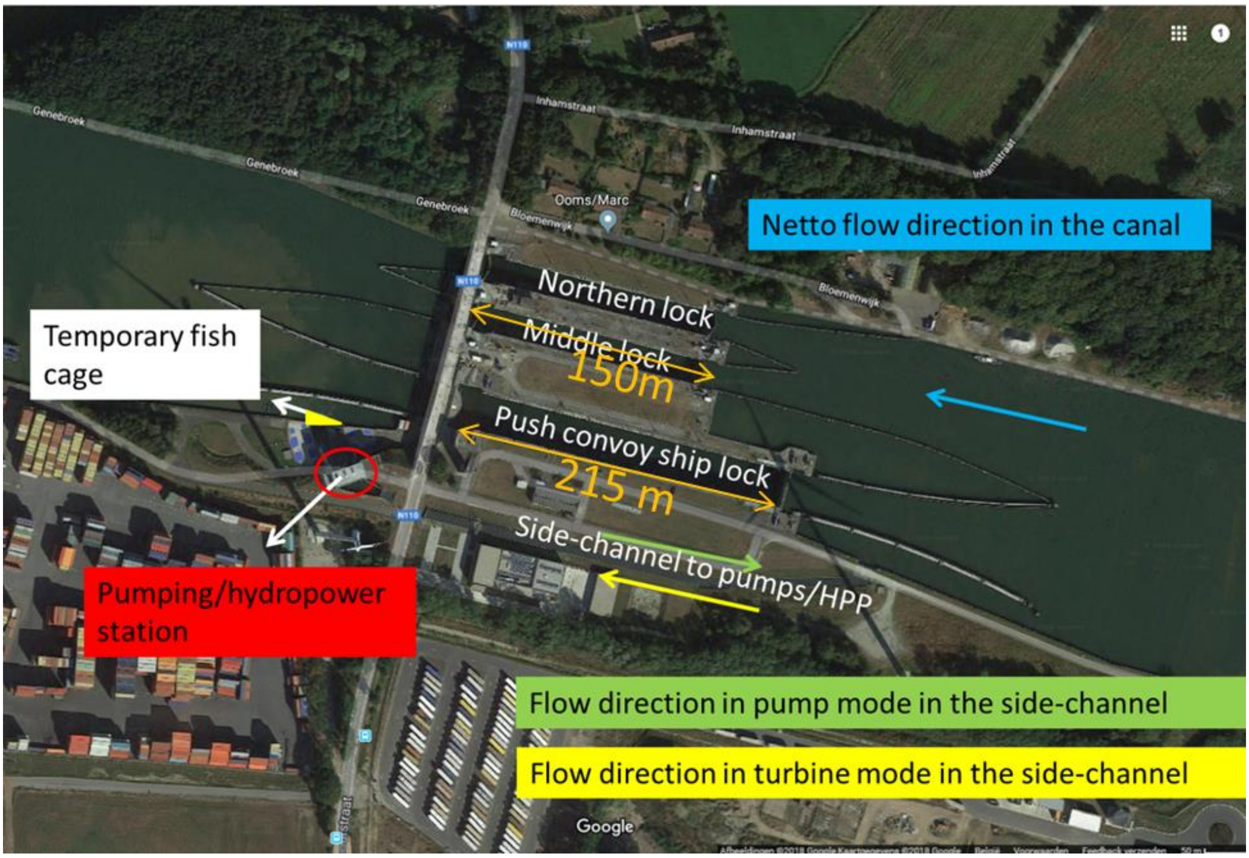

Figure 5: Aerial view on the ship lock complex of Ham (Kwaadmechelen, Belgium) and the location of the pumping/hydropower station.

1.2.3. Main characteristics

Albert canal

As indicated earlier hydropower is generated in the Albert canal by means of Archimedes screws that work efficient in situations with a low water head (height of dam/weir) and a high flow. Besides generating electricity, these facilities can also pump up water in times of water scarcity. These screws have a length of 22 m, a diameter of 4,3 m, an inclination angle of 38° and a weight of 85 tons. Each screw facility has a combined maximum output power of 1,2 MW. Installation and maintenance costs of a screw turbine are lower compared with propeller types and they are believed to be more fish friendly (Figure 6, Figure 7, Figure 8, and Table 3). The highly efficient Archimedean screw is able to generate electricity 24 hours a day, whilst maintaining the natural flow of a river (Elbatran et al. 2015). At the time writing three of six sluice complexes are provided with an Archimedes screw facility. The sluice complex and its screw facility in Ham are used to look after the possible impact on eel migration.

Figure 6: The pictures on the left apply on the Albert canal and visualize the pumping/hydropower station of Ham (top left), and one of the screws during its construction phase (bottom left). In contrast, the pictures on the right visualize the hydropower station of Lixhe on the Meuse river (top right) and its type of propeller (a propeller from a Straflo turbine; bottom right; sources: INBO, http://edfluminus.edf.com/ & http://www.dvo.be/)

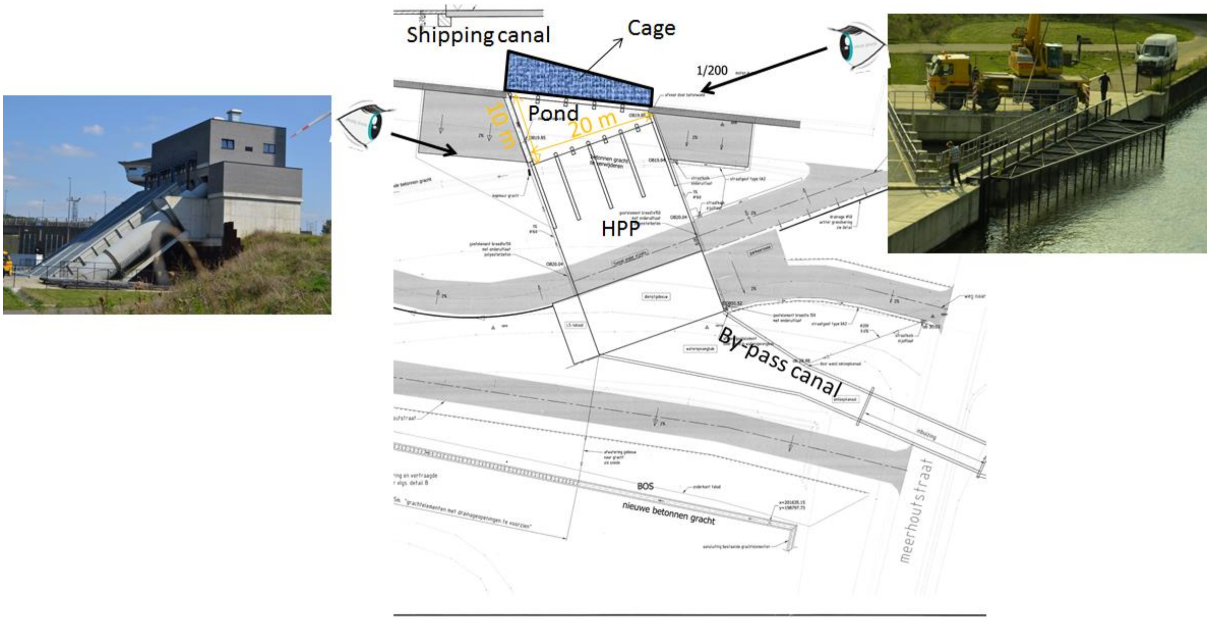

Figure 7: Map of the hydropower plant (HPP, picture on the left) and its location along the shipping canal, indicating the fish cage (picture on the right).

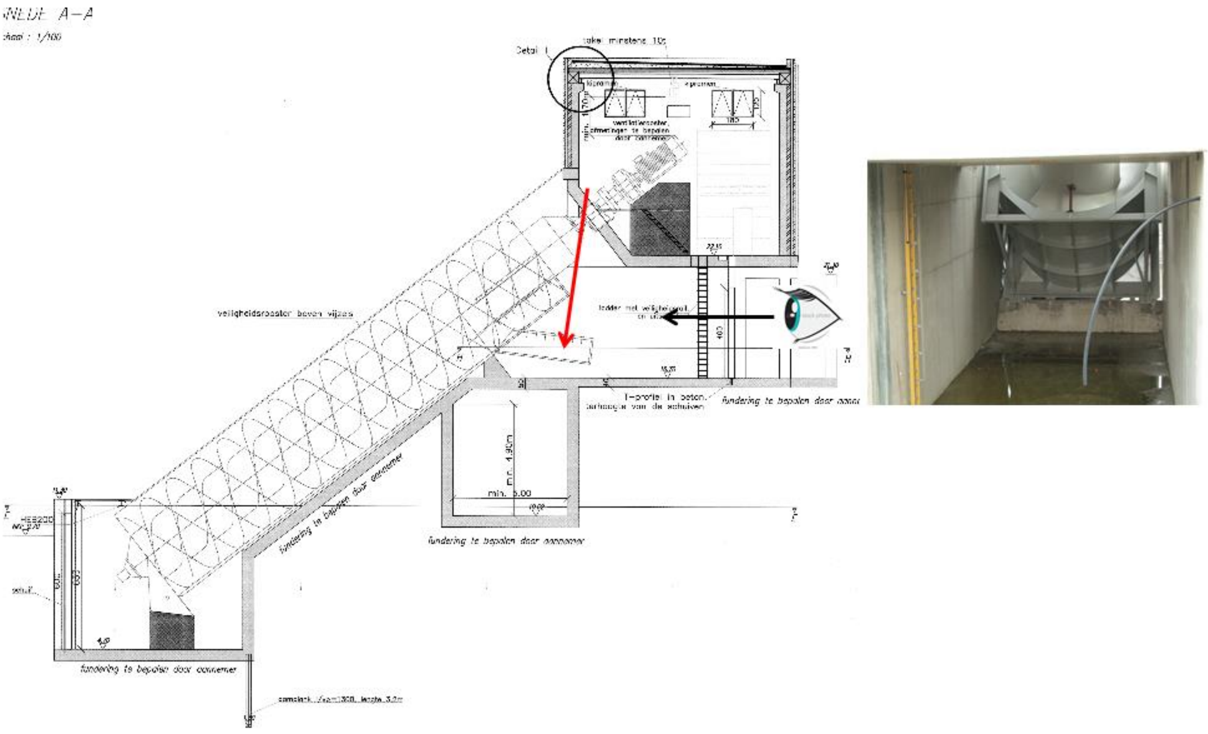

Figure 8: Side view on the hydropower plant and one of its open Archimedes screws. Red arrow indicating the injection tube through which fish is injected into the turbine for experimental tests on their impact on fish. Black arrow indicates the point of view of the picture on the right, of a closed turbine valve.

Table 3: Main characteristics of the HPP of Ham (Kwaadmechelen)

Watercourse	Albert canal
Situation :	Village of Ham (part of the municipality of Kwaadmechelen)(address: Meerhoutstraat 44A, Ham, Belgium)
Operator	De Vlaamse Waterweg (former NV De Scheepvaart)
Capacity of HPP	1,2 MW at maximal turbine discharge
Capacity of one Archimedes screw/turbine	8000 W
Maximum turbine discharge:	15 m^3/s with three screws (5 m^3/s per screw; 48 Hz or 19,95 rpm)
Minimum turbine discharge	3 m^3/s (3 m^3/s per screw; 33Hz or 13,71 rpm)
Head of one screw	10 m
Length screw/blades	22 m
Length screw/blades plus central axis	28 m
Diameter of one Archimedes screw	4,3 m
Weight of one Archimedes screw	85 ton
Inclination of the screws	38°
Length of bypassed reach/bypass channel leading to the HPP:	~350 m
Width of bypassed reach/bypass channel leading to the HPP:	~47 m

Species concerned :	European eel, Atlantic salmon/Trout, Bream, Roach and all other fish species present in the canal
Species studied (impact HPP)	European eel, Trout, Bream, Roach
Species studied (downstream migration by acoustic telemetry)	European eel (yellow and silver eels), Atlantic salmon (salmon smolts)

Principles of the Archimedes screw as pump/turbine

When the screw turns, water is taken up or down in portions in between the blades. The portions of water go up when the screw is pumping and go down when hydropower is generated. The water flows out either at the top and the bottom of the screw, respectively. Pumping requires an opposite turning direction of the screw.

When water is pumped, the screw is driven by an engine, and the rotation speed of the blades corresponds to a certain amount of water to be taken upwards (the pumped discharge).

When water is turbinated, the water pushes the screw to turn. The amount of water that flows into the screw is controlled by the controlled opening of a valve at the top of the screw. To prevent the screws from ‘running’ (acceleration of the rotation speed), the screw rotation has to be slowed down. This is done by the engine that serves as a generator, producing the energy.

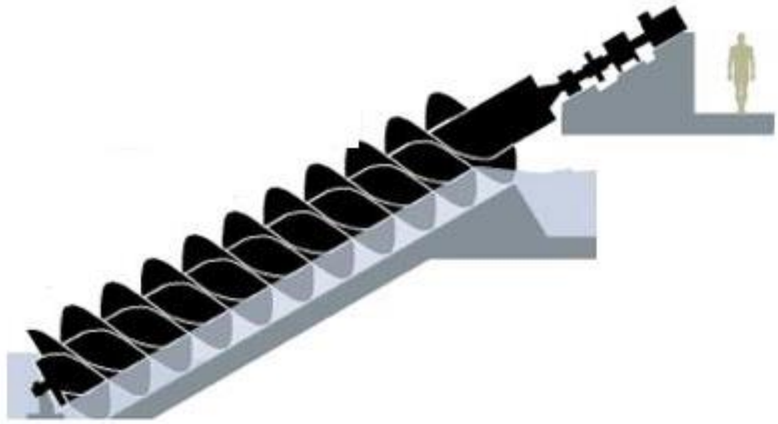

Figure 9: Schematic side view on an Archimedes pump/turbine screw.

Meuse River

This short paragraph on the hydropower on the Meuse River is just to contrast the Archimedes screw type hydropower stations with Straflo turbine propeller type, and Kaplan type hydropower stations, as the ones located on the Meuse River.

Three of four turbines downstream of the city of Liège in the River Meuse are Kaplan type turbines (two horizontal bulb types and one vertical one). The fourth one is of the Straflo type, a Kaplan-based turbine-concept where the flow also passes in horizontal direction (Figure 6). They all have blades with a diameter ranging between 3,55 and 5,6 m and their rotation speed ranges from 65 to 120 rpm. The power output ranges from 11,5 to 20 MW. All these propeller turbines are ideal in riverine situations that are characterized by a low water head (height of dam/weir) and a high discharge, but efficiency drops quickly when flows are less than provided (Okot 2013).

2. Objectives on this Test Case

The objectives of this test case (what are we planning?)

The aim of this test case is to apply BDS sensors on the largest Archimedes screws in the world serving as turbines. On the one hand, these BDS sensors are further developed and improved based on the application. On the other hand, the BDS sensors are used to define the impact of the Archimedes screws on downstream migrating fish (eel, bream, roach and trout). The research results are further interpreted with tests on life fish in another project, commissioned by the hydropower operator, "De Vlaamse Waterweg NV", which aims to investigate:

1. The impact of the hydropower station (3 open Archimedes screws as turbines) on fish that pass the screws, by evaluation of mortality and injury of fish that passed the screws in turbinating mode (and pumping mode, beyond the scope of this test case but tested in a parallel study).
2. The impact of the hydropower station on fish by evaluation of several pressure-related parameters by BDS sensor tests that pass the screws.
3. The impact of the hydropower plant on the local fish population and downstream migrating eel and salmon, by evaluation of the (relative) number of acoustically tracked eel and salmon that pass the sluice complex in the downstream direction by the by-pass channel and hydropower station (instead of taking the 'route' of the ship locks in the canal).

Although the focus of the research in this test case as part of Fithydro was on the application and development of the BDS sensors, the experiments with life fishes commissioned by the hydropower operator are reported here as well.

Why are we planning this on this Test case?

The pumping/hydropower station of Ham (Kwaadmechelen, Belgium) has (the largest) Archimedes screws (in the world) that serve as pump and turbine. This makes this site specifically interesting to investigate. Moreover, studies on the harmfulness of these types of screws are rare. Additionally, the pumping/hydropower station has a closed screw (used for pumping only), which is designed to prevent fish from being squeezed in between the blades of the screw and its housing. In a parallel study, the expected fish friendliness of this design is evaluated. The study is not part of the test case for Fithydro, because it focuses on pumping instead of hydropower. However, might be interesting for hydropower operators as well, specifically if they design pumps that can as well generate power in times of high water supply.

What are we expecting?

It is expected that the Archimedes type hydrodynamic screws are more fish-friendly than other turbine types, such as Kaplan turbines or propellers of the Safro-turbine type. However, it is as well expected that the impact on fish is still > 0%. Consequently, research on the precise reasons of the impact is needed, to further improve the design of the screws to screws with the lowest fish-damage possible. Furthermore, it is believed that the results of the fish tracking will further indicate the potential impact on the (local) fish population, and might help in finding successful measures to minimalize this impact.

Relevance (in Fithydro)?

This research gives unique insight into the fish-friendliness of this type of turbine, which is relevant information for hydropower operators who need to install new hydropower plants.

The Barotrauma Detection System sensors time series data from this test case are specifically relevant to (I) to determine statistical properties of the passage conditions at the Archimedes screw under three different operational conditions operations, (II) to advance in understanding of the effect of screw operation on fish passage, (III) to evaluate fish passage through the screw (as an operational measure for downstream fish passage), and (IV) to create recommendations for fish friendly passage at large Archimedes screws.

3. Presentation and results of activities in Fithydro

3.1. Study of survival through Archimedes screws

The aim of this part of the study was to investigate the impact of the hydropower station on fish that pass the screws by:

(1) forced fish pass experiments were performed in which four species were inserted at the top of one of the three screws, to pass it.

(2) Barotrauma Detection System Sensors (BDS sensors) were inserted at the top of one of the three screws, to pass it. The sensors measured the total water pressure, pressure changes and nadir pressure, linear acceleration, rotation rate, magnetic field intensity and absolute orientation

The BDS sensors are developed at the Tallinn University of Technology (TUT).

3.1.1. Methodology

Fish experiments

The species investigated in the forced fish passage experiments were European eel, Roach, Bream and Trout. Tests with hatched fishes of these species were performed for all three possible operational modes of the screws. These correspond to a capacity of 5, 4 and 3 m^3/s water discharge, which corresponds to rotational speeds of the screws of 19,95, 16,62 and 13,71 rpm. Per species and per operational mode three repetitive tests with each 100 individual fish were performed. Hence, in total 900 hatched fishes of each species were forced to pass the screws. Upon recapture, each tested fish was weighted, measured and its state was evaluated by observation. The fish was classified as either being dead, dying or alive and the presence of injuries was carefully checked. The state was daily evaluated again after to investigate delayed mortality. Fish injuries were divided into three categories: (1) injury free; (2) minor superficial scratches for eel and scale loss for over maximally 25% of the body surface, and fin injuries; and (3) (internal) bruising (further named contusion), swelling or bleeding, scale loss over minimally 25% of the body surface and the presence of cuts/slashes, decapitation or divided into parts (Figure 10). Category two was viewed as slight injuries, whereas category three was defined as severe injuries.

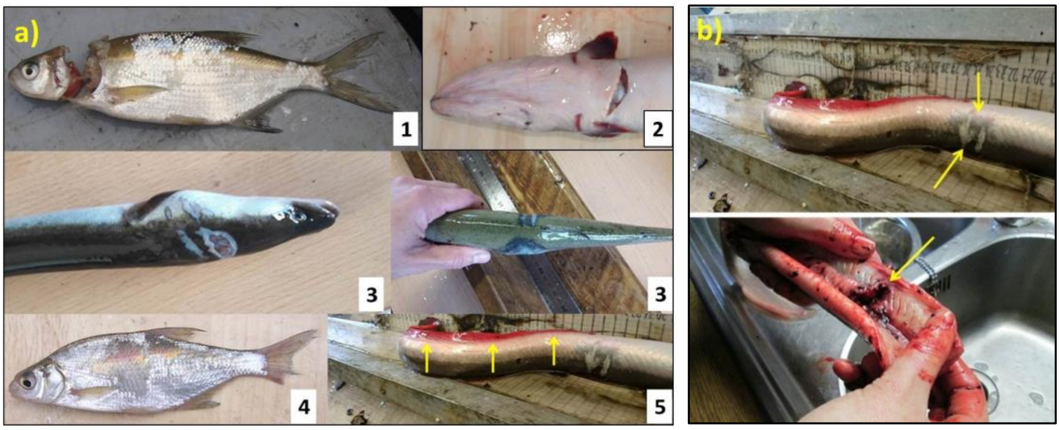

Figure 10 a) Images per category of fish injury: 1) decapitation, 2) cut, 3) contusion/swelling/bleeding, 4) scale loss and 5) fin damage. b) Internal damage of a contusion, where the contusion in the top panel corresponds to severe damage of the underlying muscle (bottom panel).

Not all fish could be caught from the basin after forced screw passage due to the dimensions of the basin and the relatively large distance of the cage to the screw outflow (Figure 7; Figure 11). Hence, fish that were not caught after screw passage stayed in the basin and their state could not be evaluated. The results described for the life fish tests were hence exclusively based on the observations on the number of caught individuals. To maximise the catch efficiency after turbine passage, the turbines were kept operative for one to a few hours daily and for up to one week after a test was performed. Unfortunately, still a substantial part of the tested fishes could not be evaluated due to low capture rates, meaning that the results of the experiments would be a complete underestimation of the impact of the screws if the fate of these was a heavy injury or dead. Hence, additional experiments with pre-killed fishes were performed to account for this. These tests were evaluated per species at an operational discharge of 5 m³/s.

Figure 11 Picture of the installation of the cage to catch tested fish after screw passage (see also Figure 7).

Beside the two types of tests described above (those with the hatched individuals of four species that were forced to pass the screws, and those with pre-killed fishes), wild fish that passed the screws were caught and evaluated as well. For this evaluation, additional tests were performed in which number of wild fish per species and their state and observed injuries were evaluated during several 24 hour screw operation tests. Hence, those fishes were not forced into the turbines, but naturally passed it on their way down in the canal/by-pass channel, and so could be of any species that is present in the canal. The measurements were performed on all fish that passed the screws during one 24h cycle of hydropower generation with three screws on 5 m³/s. The natural-passage experiments (as we call them in this report) were repeated four times (four 24h cycles, covering a total of 96h of hydropower generation). These experiments suffered the same catchability problems as encountered with the forced fish pass experiments, as the catch method was the same for both tests.

Data analysis

The proportions of observed fish having a certain type of injury were defined based on worst and best case observations of three repeated tests per species and discharge. Beside the specific type of injuries, the proportions of living, not damaged fish, lightly damaged fish, heavily damaged fish and dead fish were defined. This classification gives an estimate of the proportion of fish that are lost from the reproducing population due to screw passage, where lost fishes are defined as heavily injured and killed fishes.

In addition to the observed proportions, the chances were modelled that a fish of the tested species would die and/or get heavily injured due to screw passage. This come down to the chance that a fish is lost from the population due to screw passage as we assumed that heavy injuries prevent a fish from taking part in reproduction. Also the potential effects of the operational discharge (3, 4 or 5 m^3/s) and fish length were evaluated in these models.

The results of the experiments with pre-killed fishes were used to calculate the chance for a fish to die due to screw passage. This chance was then compared to the proportions of observed tested fish that died. The chance to die was calculated as follows:

$$\boldsymbol{P(D) = \frac{P(D|V) * P(V)}{P(V|D)}}$$

where P(D) is the chance for a fish to die due to screw passage, P(D|V) is the chance that captured test fish were dead due to screw passage, P(V) is the chance that a test fish was captured after passage, and P(V|D) is the chance to capture dead fish (so the pre-killed fish) after screw passage.

The formula entails that the lower the chance for dead fish to be caught, the higher our underestimation of the chance for a fish to die due to screw passage. We assumed that if the calculated chance did not deviate much from the observed proportions of dead tested fish, our results reported here are not an underestimation of the impact of the screws and that the fate of not evaluated tested fishes was similar to that of observed tested fishes.

Barotrauma Detection System sensor experiments

The objective of the fieldwork with the barotrauma sensors was to record 30 data sets per operational mode (3, 4 and 5 m^3/s). The sensors were deployed in the identical manner as the live fish in the forced fish-pass experiments (Figure 12C), and are recaptured downstream with a hand-held fish net (Figure 12D). Balloon tags were attached to each sensor and were set to inflate 1minute after deployment in the Archimedes screw tail water. Metadata for each deployment were recorded including the time of deployment, passage duration, noticeable scratches, dents or if the sensor was crushed. The BDS collect the time series at 100 Hz including the total pressure, linear acceleration, rotation rate, magnetic field as well as the absolute orientation of the sensors during their passage through the screws.

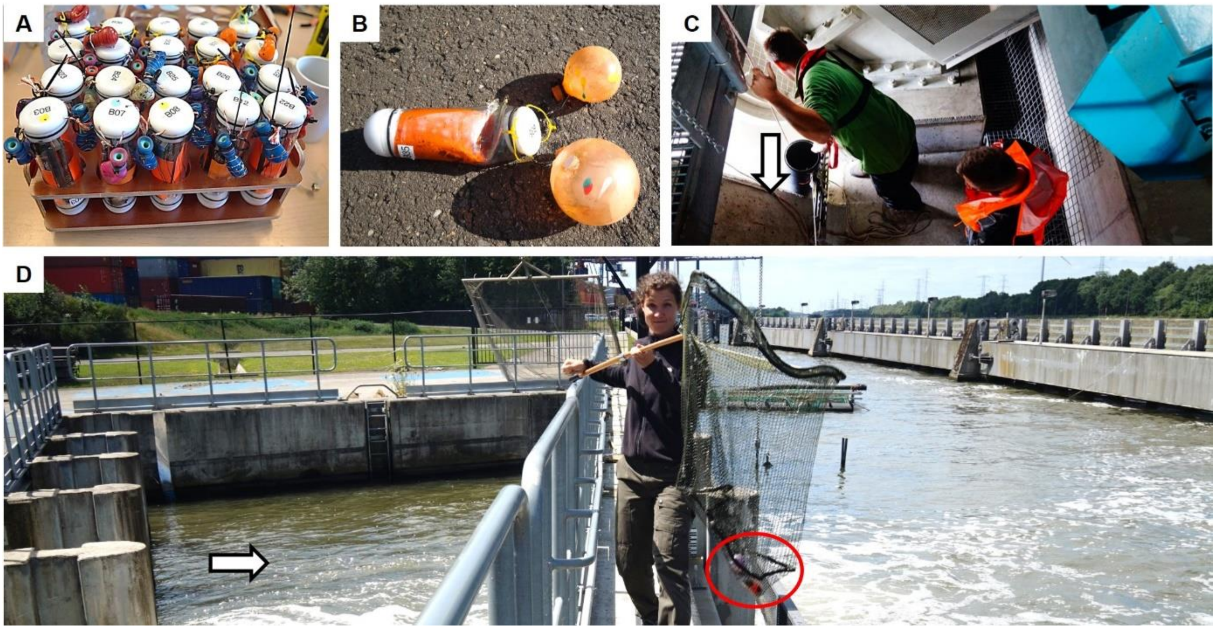

Figure 12: BDS deployment at Ham from 20-22.06.2018. A) Sensors outfitted with balloon tags ready for deployment. B) Sensor destroyed by crush event. C) Deployment of BDS into the Archimedes screw. D) Recovery downstream via balloon tags in a hand net.

Data analysis

After sensor recovery the data were downloaded and the sensor tube was inspected on the occurrence of scratches and crushes. Three different discharge scenarios were investigated based on a total of 124 sensor deployments, producing 91 usable data sets for (statistical) analysis (The analysis of damaged sensor housings revealed that the majority of recovered sensors did not have physical damage (Table 7). The statistical assessment of crushing and scratching events showed that there was a significant relationship between damage vs. no-damage, however it cannot be concluded that this relationship is defined by the three discharges investigated. Furthermore, there were no significant differences between discharge scenarios based on the pressure data metrics used in this study (see below). Finally, it was observed that each sensor deployment exhibited unique probability distributions. Therefore, we question the use of simple statistical metrics for the assessment of screw turbines, which appear to be a deterministic-stochastic environment.

The larger question is whether or not the uniqueness of the sensor data is related to the biological findings? If fish are expected to exhibit more complex behavior than a passive sensor during Ham screw passage, then it is our hypothesis that similar to the sensors, there will be no significant differences in injury and mortality across operational scenarios.

Table 7).

Damage to the sensor housing was visually inspected and noted as no damage, crushed or scratched and marked with a black permanent pen. A statistical assessment of crushing and scratching events vs. no damage was performed using a chi-squared test for independence. A contingency table for the number of no damage vs. damage (crushed or scratched sensors) for the three discharge scenarios was evaluated at the 1% significance level, $\chi 2(2, N = 124) = 9.92, p < .01$), indicating that a significant relationship exists between discharge and the occurrence of sensor damage. Specifically, the difference were between the expected and observed counts of no damage vs. damage for the two flow scenarios Q = 4 m^3/s and Q = 5 m^3/s.

The barotrauma datasets collected by the sensors where then firstly truncated based on pressure time series and visual inspection of start and stopping times. The time period of analysis corresponds to the data collected immediately after impact with the screw and just before it is carried along with the outflow from the screw in the tailrace. Next, *statistical parameters* were attempted to be calculated. However, preliminary analysis of ensemble statistics revealed that the Ham screw data were highly non-stationary. In contrast to previous works on turbines and pumps, the time series for individual deployments under the same operational conditions were highly variable. Because the time series are non-stationary, the Anderson-Darling test (α=0.05) for empirical distributions was used. The H0 hypothesis was that individual pressure time series under constant operating conditions were from the same population. Statistical tests to evaluate H0 were carried out on two empirical distributions: 1) the truncated total pressure for each operational scenario, and 2) the truncated pressure deviations based on median filter with window size of 0.5 s (n = 50 for each observation as the sampling rate is 100 Hz). Examples for each operational condition are shown in Figure 13.

The deviations were calculated to remove effects of periodic motion on the sensor data. This was done because in contrast to Kaplan or Francis turbine tests, the dynamics of the sensor body are not strongly coupled to the kinematics. Standard turbine types produce flow streamlines along which the sensor can travel, and a core assumption of passive sensor analysis is that the Lagrangian motion of the sensor is therefore highly correlated with the streamlines.

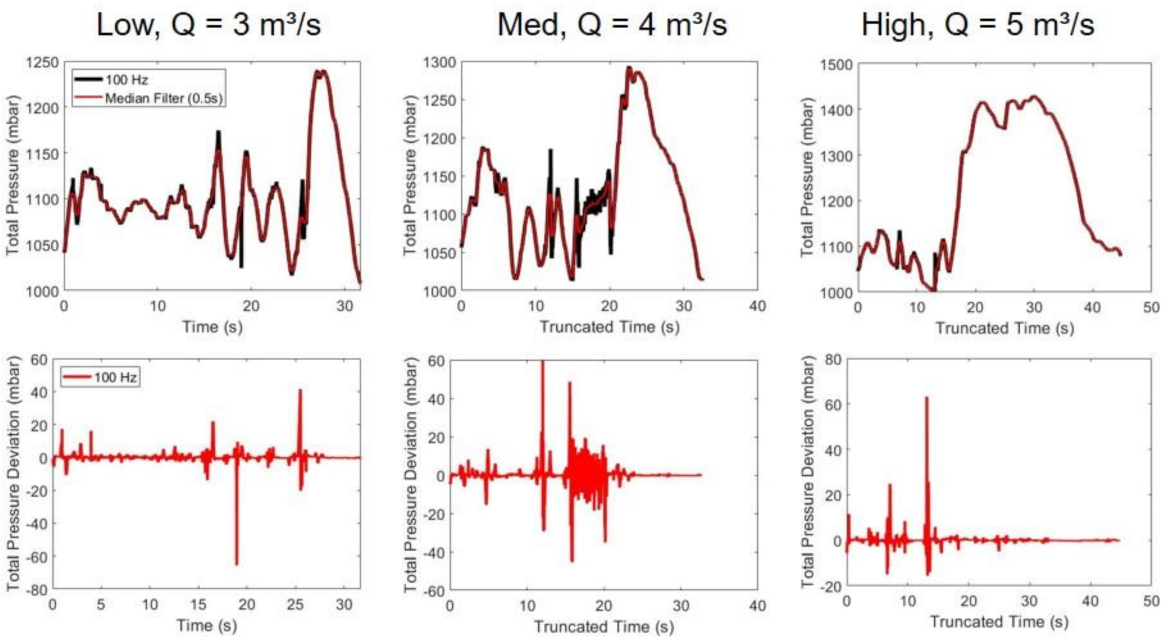

Figure 13 ***Top: Time series plots of example deployments for each of the three operational scenarios. Bottom: Corresponding time series plots of the pressure deviations using a median filter with 0.5 s window.***

Further, *ensemble statistics (min, max, med, mean, sd, Q1 and Q3)* were calculated for all parameters measured by the sensors. Lastly, the nadir (lowest) pressure, pressure maximum and the rate of pressure change (RPC) were evaluated, as is frequently done in sensor passage research (Pflugrath et al. 2019). The RPC is used to assess the risk of barotrauma, defined as the largest magnitude of rapid decompression fish may experience during passage (Boys et al. 2018). It is calculated as the ratio of the acclimation pressure of the fish upon entering the turbine to the nadir pressure. At the Ham site, fish enter the screw near the water surface at a shallow depth, which corresponds to the minimum rate of pressure change (RPC). The minimum RPC was calculated for each deployment as the ratio of the reference atmospheric pressure (100.0 kPa) to the nadir pressure recorded by the BDS (e.g.100.00 ÷ 98.1 = 1.02). All analyses were performed per operational discharge to investigate potential differences. Data were analysed in the software Matlab (The Mathworks, Inc. MATLAB, Version 9.6 2019).

3.1.2. Results

Fish experiments

Unfortunately not all tested fish could be caught and evaluated. The catch ratios for bream were even below half of the tested fish (Figure 4).

To exclude an underestimation of the harmfulness of the screws due to low catch ratios, tests with pre-killed fish were performed for all three species at 5 m/s. The results of this test (Table 6 and described further below) indicated that conclusions made based on the observed proportions of caught fish could be extrapolated and are no underestimation of the harmfulness of the screws.

Table 4 Mean, minimal and maximal recapture rates per species over all tests (three repetitive tests per one of three operational discharges)

	Mean	**Range**
Bream	42	34-49
Eel	60	51-68
Roach	72	59-100

Most caught bream, eel and roach were alive after screw passage and were still alive during the days after as indicated by delayed mortality evaluations. The proportions of fish showing a specific type of injury was similar for all three species (Figure 14). The type of injury that was observed the most was scale loss for less than 25% of the body surface. Heavy injuries were mostly determined as contusions. Other types of heavy injury were observed as well, unless scale loss over more than 75% of the body surface. Except for a small proportion of bream, decapitations were not observed (Figure 14; Figure 15).

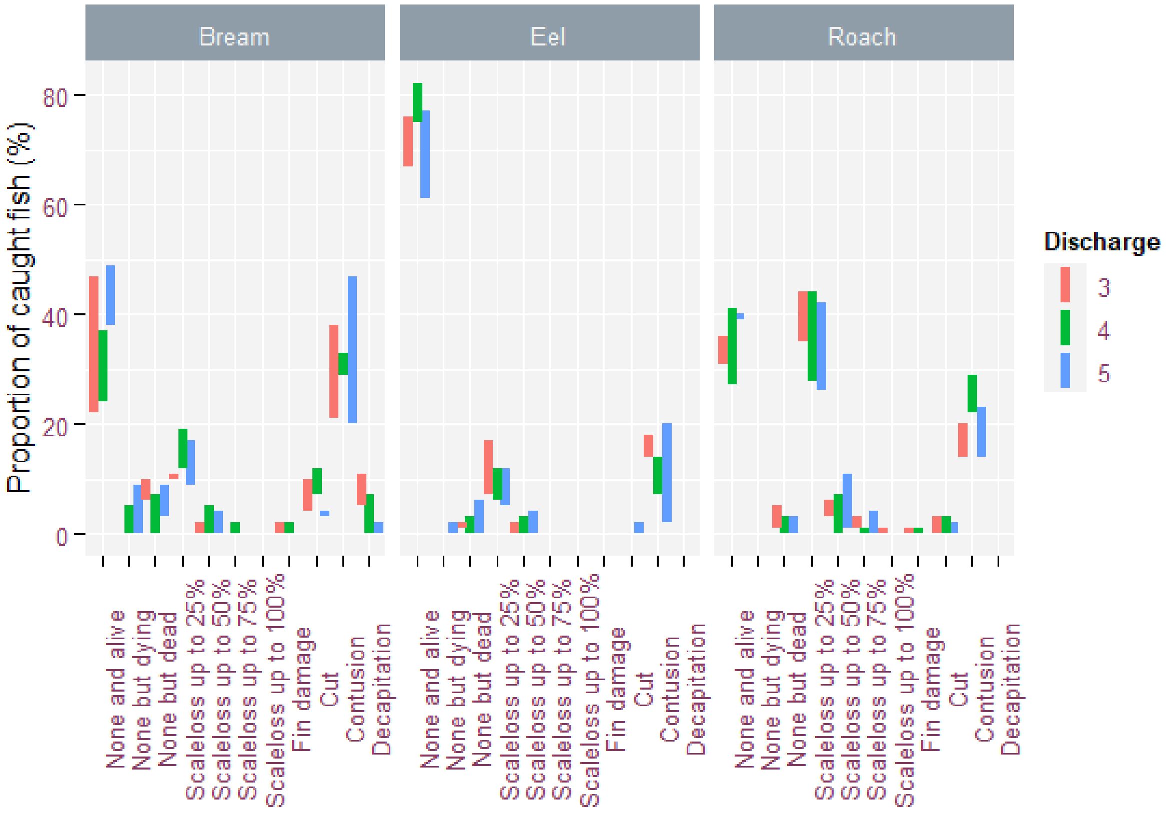

Figure 14 Proportions of caught fish per state (alive, dead or dying) and injury type for the three operational modes of the tested Archimedes type hydrodynamic screw: 3, 4 and 5 m³/s.

Figure 15 Examples of the most common injuries observed during fish experiments at the HPP of Ham: scale loss (top left), contusion (top right) and decapitated bream (bottom).

Based on the observed proportions of caught fish as well as the modelled proportions, we found that still on average 55% of bream died or got heavily injured due to screw passage, 17% of eel and 34% of roach (Table 5). In the best cases, 26% of the observed bream, no eel and 12% of the observed roaches were killed by the screw. Worst observations showed 35, 6 and 16% of killed bream, eel and roach, respectively. These observations were in line with the calculations of chance to die based on the results of the pre-killed fish tests. Hence, the observed numbers are not an under- or overestimation of the impact of the screws on passing fish and tested fishes that could not be caught after passage were certainly not all killed by screw passage (Table 6).

Table 5 Proportions of bream, eel and roach that died and/or got heavily injured (got lost from the reproducing population) due to screw passage, averaged over all tests at three operational discharges of 3, 4 and 5 m³/s. The range indicates the minimal and maximal proportions found. The averages and ranges account for the faith of not caught test fish through statistical modelling and tests with pre-killed fishes (see method section for further details).

Proportions of lost fish			
Species	Mean proportion (%)	Range (%)	Statistical relation with screw operational discharge
Bream	55	43-64	Significant effect

			where 4 m^3/s results in slightly higher loss
Eel	17	11-24	Significant effect where 3 m^3/s results in slightly higher loss
Roach	34	30-36	

The results of the statistical models were in line with the observations on caught fish. Furthermore, they indicated a significant but slight effect of the operational discharge of the screws on the chance to survive or not get lost due to screw passage. However, the operational mode that was worst or best differed per species. For roach such an effect was not found. Hence, we do not believe that operational management of the screws can be advised as mitigation measure.

The statistical models further indicated a significant effect of fish length on their chance to die or get heavily injured by screw passage for all three species. Specifically, large bream and roach are more prone to injury and loss than small once. In contrast, larger eels have a significant lower chance to get lost due to screw passage than smaller eels.

Table 6 Results of tests with pre-killed fish (column 4; P(V|D)) and calculations of the chance to die due to screw passage, based on the observed chance that a caught test fish was dead (column 2; P(D|V)), and the catch ratio of tested fish (column 3;P(V)). Worst and best case scenarios were based on the minimum and maximum observed results of three repeated tests on forced passage of hatched fish per species.

Species	P(D|V) (%)	P(V) (%)	P(V|D) (%)	(P(D/V)*P(V))/P(D)	**P(D) (%)**	**Observed proportion of dead fish**
Bream	26-35	34-46	66	Best case	Best case: **13**	**26**
				(26*34)/66=13,4		
				Worst case	Worst case: **24**	**35**
				(35*46)/66=24,4		
Eel	0-6	54-64	46	Best case	Best case: **0**	**0**
				(0*54)/46=0		
				Worst case	Worst case: **8**	**6**
				(6*64)/46=8,3		
Roach	12-16	65-74	53	Best case	Best case: **16**	**12**
				(12*65)/53=15,7		
				Worst case	Worst case: **22**	**16**
				(16*74)/53=22,3		

Barotrauma Detection System sensor experiments

The preliminary results of the sensor data are provided in the form of summary statistics in the following tables. Data post-processing and comparison with biological data and literature on Archimedes screws are currently still on-going. A peer-reviewed journal publication from the Ham BDS and live fish data set is under preparation and will be submitted in 2020.

The analysis of damaged sensor housings revealed that the majority of recovered sensors did not have physical damage (Table 7). The statistical assessment of crushing and scratching events showed that there was a significant relationship between damage vs. no-damage, however it cannot be concluded that this relationship is defined by the three discharges investigated. Furthermore, there were no significant differences between discharge scenarios based on the pressure data metrics used in this study (see below). Finally, it was observed that each sensor deployment exhibited unique probability distributions. Therefore, we question the use of simple statistical metrics for the assessment of screw turbines, which appear to be a deterministic-stochastic environment.

The larger question is whether or not the uniqueness of the sensor data is related to the biological findings? If fish are expected to exhibit more complex behavior than a passive sensor during Ham screw passage, then it is our hypothesis that similar to the sensors, there will be no significant differences in injury and mortality across operational scenarios.

Table 7 BDS sensor deployment summary for the Ham screw turbine, all sensors were recovered. Sensors with damage were visually inspected and afterwards classified as either crushed or scratched.

Discharge Scenario (m^3/s)	Number of total deployments	Number of recovered data sets (% total)	Number of sensors crushed in screw (% recovered)	Number of sensors scratched in screw (% recovered)
3.0	45	30 (67)	4 (13)	9 (30)
4.0	39	28 (72)	3 (10)	13 (46)
5.0	40	33 (83)	1 (3)	3 (9)

From the statistical analysis on correlation of passage events and their statistics it appeared for the Ham screw that the flow in the screw is *not random, but deterministic*: sensor data are bounded and highly correlated over short time periods, and the ranges of ensemble values remain constant over the entire passage event between sensor deployments and for all ensemble statistics. The time scale over which sensor data is correlated was found by taking the zero crossing point of the autocorrelation from the ensemble of pressure data for each operating condition and is shown in Figure 16. Furthermore, phase portraits using delay coordinate embedding of individual pressure time series were created for each operational condition in order to determine if the data were bounded and had defined trajectories. Unbounded data would indicate that the measurements are part of a uniform random process. However, bounds are well-defined and can clearly be seen for all Ham screw operational conditions.

The Ham screw produces *chaotic conditions*: sensor data have no correlation over longer time periods; there is no statistical similarity between single deployments under the same operating conditions, and no similarity between single deployments and ensemble statistics for constant operating conditions.

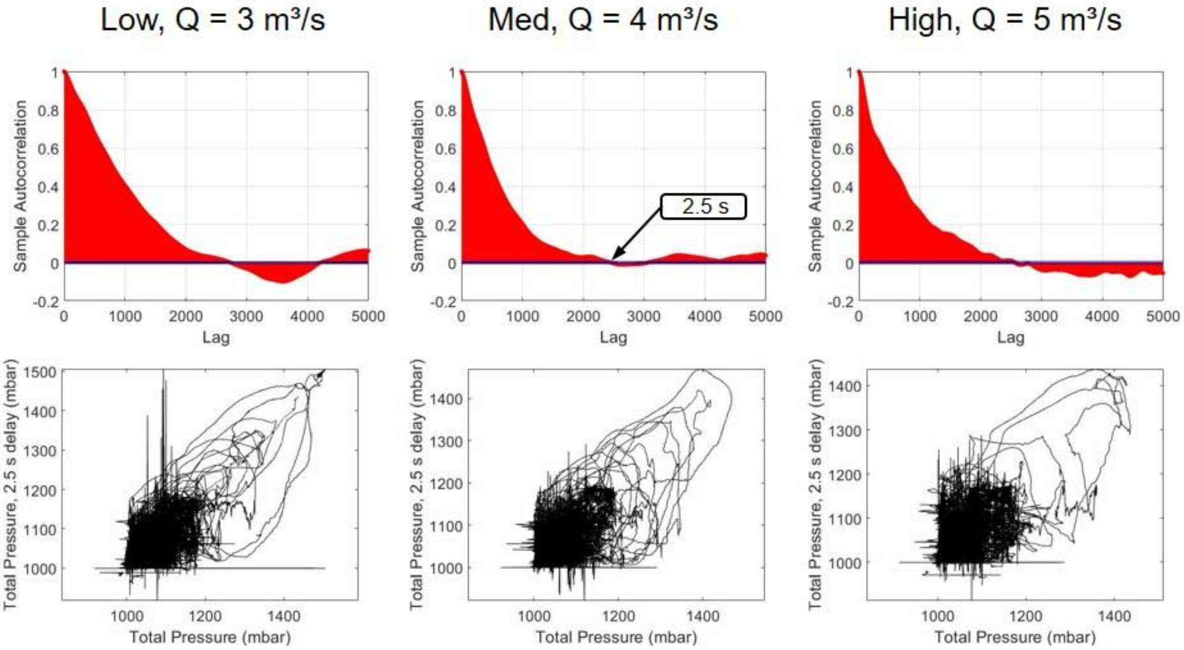

Figure 16 ***Top: Autocorrelation of the ensemble pressure time series for each of the three operational scenarios. Data remain positively correlated for a period < 0.5 s, and zero correlation occurs for all operational scenarios after 2.5 s. Bottom: Corresponding phase portraits of the pressure time series with a delay of 2.5 s. The results show that before the loss of correlation, the systems have common trajectories, are bounded by the same range of values, thus the data are from a chaotic process.***

It was found that the individual sensor measurements, even from the same scenario, are statistically not from the same sample population. The results for each scenario clearly result in the finding that even when the operational scenario is constant, the resulting pressure sensor time series are highly varied, and cannot be compared using standard ensemble methods (e.g. ensemble mean, sd dev. etc). Histograms of the resulting ensembles corresponding to each operational condition are shown in Figure 17. A comparison of the ensemble truncated pressure data as well as the ensemble truncated pressure deviations also failed the Anderson-Darling test (α=0.05), thus the ensemble data of the scenarios also represent unique populations.

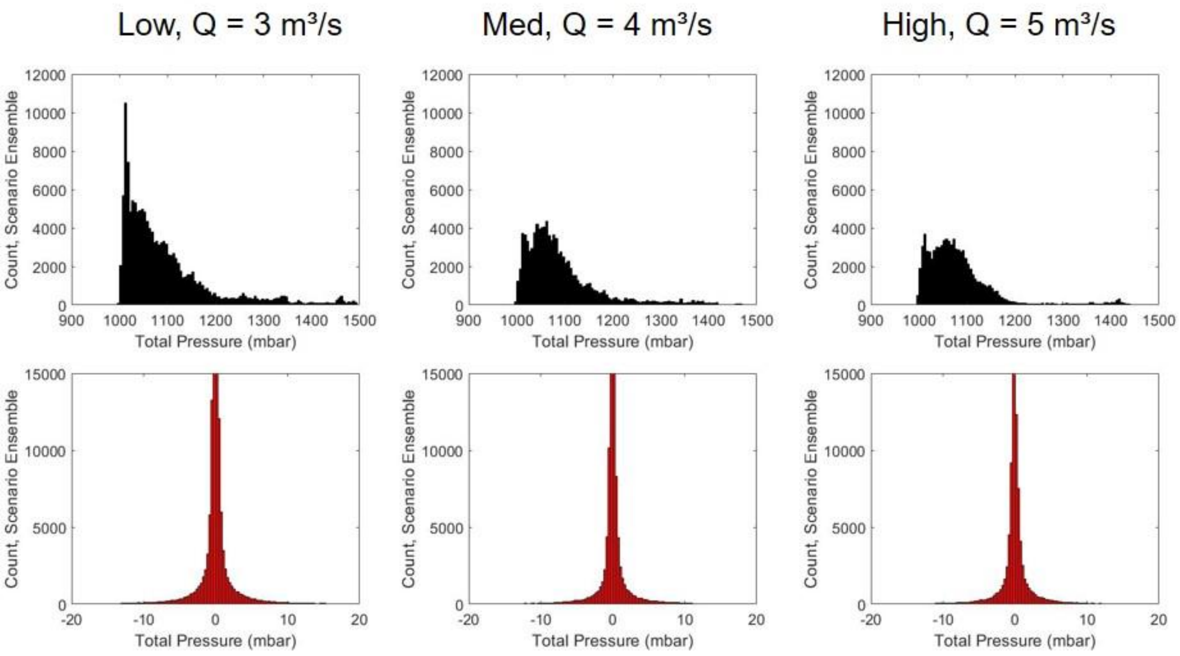

Figure 17 ***Top: Histograms of the truncated pressure time series data for each of the three operational scenarios. Bottom: Histograms of the pressure deviations from the median filter with 0.5 s window. None of the histograms passed H0 using the Anderson-Darling test.***

The preliminary results from the BDS investigation at Ham are provided in the following tables (Table 8, Table 9 and Table 10).

Table 8: Ensemble statistics of BDS deployment at Ham (n = 30), Q = 3 m³/s.

	PL (hPa)	PC (hPa)	PR (hPa)	Euler X (deg)	Euler Y (deg)	Euler Z (deg)	Acc X (m/s²)	Acc Y (m/s²)	Acc Z (m/s²)	Rot X (deg/s)	Rot Y (deg/s)	Rot Z (deg/s)
Min	983	989	985	0	-86	-181	-30	-33	-29	-959	-1717	-1009
Max	1229	1229	1227	362	87	182	31	30	30	1044	1723	979
Mean	1069	1068	1067	186	-1	79	0	-6	-2	15	-4	-3
Median	1047	1045	1045	191	-2	103	0	-8	-3	9	-1	-1
STD	58	58	58	104	26	78	4	5	5	137	185	138
Q1	1025	1024	1024	95	-16	60	-2	-9	-5	-38	-51	-53
Q3	1100	1098	1099	276	13	125	2	-4	0	67	48	50

Table 9: Ensemble statistics of BDS deployment at Ham (n = 28), Q = 4 m³/s.

	PL (hPa)	PC (hPa)	PR (hPa)	Euler X (deg)	Euler Y (deg)	Euler Z (deg)	Acc X (m/s²)	Acc Y (m/s²)	Acc Z (m/s²)	Rot X (deg/s)	Rot Y (deg/s)	Rot Z (deg/s)
Min	972	979	978	0	-86	-181	-32	-34	-34	-1099	-1786	-1017
Max	1227	1228	1226	360	86	182	33	27	32	1108	1748	984

Mean	1069	1069	1069	181	0	74	0	-6	-3	18	-1	-1
Median	1053	1053	1052	183	0	101	0	-8	-3	13	1	2
STD	56	56	56	104	30	89	5	5	5	169	220	162
Q1	1023	1024	1023	94	-19	55	-3	-9	-6	-52	-64	-68
Q3	1100	1100	1099	268	19	130	3	-4	0	88	67	69

Table 10: Ensemble statistics of BDS deployment at Ham (n = 33), Q = 5 m^3/s.

	PL (hPa)	**PC (hPa)**	**PR (hPa)**	**Euler X (deg)**	**Euler Y (deg)**	**Euler Z (deg)**	**Acc X (m/s^2)**	**Acc Y (m/s^2)**	**Acc Z (m/s^2)**	**Rot X (deg/s)**	**Rot Y (deg/s)**	**Rot Z (deg/s)**
Min	980	983	978	0	-87	-181	-31	-34	-34	-1012	-1750	-1010
Max	1191	1193	1192	361	85	182	32	28	31	1028	1681	1076
Mean	1052	1053	1052	185	-1	73	0	-7	-3	22	0	2
Median	1033	1034	1033	188	-2	92	0	-8	-3	18	3	3
STD	47	48	48	106	31	82	5	5	5	170	231	173
Q1	1016	1016	1015	97	-22	50	-3	-9	-6	-58	-70	-75
Q3	1081	1082	1081	274	19	126	3	-4	0	104	76	80

So, the evaluation of BDS event-based statistics using the Andersen-Darling test (α = 0.05) revealed that none of the pressure-based statistics followed a normal distribution, and we were thus unable to follow the approach taken in Pflugrath et al. (2019) using T-tests. We evaluated differences between the three discharge scenarios using Kruskall-Wallis tests (α = 0.05). Specifically, the dependent variables were the nadir pressures, pressure maximum and minimum RPC and the three discharge scenarios were the independent variables.

The results of the nadir and minimum RPC values are identical (p = 0.42) and clearly indicate that there was no significant difference between pressure minima across the three discharge scenarios. Similarly, a comparison of the pressure maximum (p = 0.28) failed to indicate a significant difference at the Ham study site. Considering the pressure-based statistics nadir, maximum and minimum RPC there were no differences detected across discharge scenarios.

The values of the pressure-based statistics are similar to those reported in Boys et al. (2018). The nadir values in both studies remained close to atmospheric pressure, where the overall range observed in the Ham screw turbine tended to be slightly higher (minimum nadir 93.5) than the screw turbine investigated in Boys et al. (2018) (minimum nadir 81.8). Unsurprisingly, the larger Ham screw turbine had deeper troughs, and also was able to discharge sensors deeper into the tail water, and therefore the mean maximum pressures at Ham (118.7-112.4 kPa) exceeded those at the Boys et al. (2018) test site (116.7 kPa) for both discharge scenarios. The mean minimum RPC for both screws remained nearly unity for all test cases (Ham 1.00-1.01, Boys et al. 2018 0.98-0.99). This is a clear reflection of the physical conditions in an Archimedes screw, where fish and sensors are exposed to low pressure maxima due to low water depths, as well as limited nadir pressure due to the turbine being exposed to atmospheric pressure along its length. Therefore, the results of this study further substantiate those by Boys et al. (2018) where it was pointed out that barotrauma or pressure-related injuries remain unlikely at Archimedes screw turbines.

Table 11 Summary of pressure variables (reference atmospheric pressure 100.0 kPa) from BDS deployments at Ham. Where available, all data are reported as ensemble means ± their standard deviation (SD) followed by the variable's range in parentheses.

Pressure-based statistic	Q = 3.0 m³/s Mean ±SD (range)	Q = 4.0 m³/s Mean ±SD (range)	Q = 5.0 m³/s Mean ±SD (range)
Nadir (kPa)	99.6 ± 1.1 (97.1-101.5)	99.1 ± 1.9 (93.5-101.3)	98.9 ± 1.8 (94.7-103.4)
Maximum (kPa)	122.4 ± 11.8 (106.7-149.3)	122.3 ± 9.5 (110.6-146.9)	118.7 ± 7.8 (108.0-143.7)
Minimum RPC	1.00 ± 0.01 (0.98-1.03)	1.01 ± 0.02 (0.99-1.07)	1.01 ± 0.02 (0.97-1.06)

3.2. Fish tracking by acoustic telemetry

3.2.1. Methodology

The impact of the hydropower plant on the local fish population and downstream migrating eel and salmon is investigated by one- and two-dimensional acoustic telemetry on downstream migrating European eel and salmon smolts in the Albert canal.

Acoustic telemetry is a technique that makes use of the propagation of sound through water. It is much like speaking and listening under water. An acoustic tag emits a sound with regular or irregular time intervals. The sound is propagated through water as sound-waves and can be received by an underwater antenna or hydrophone. The hydrophone is part of what is called a receiver or acoustic listening station (ALS). The sound that is emitted/transmitted by the acoustic tag is unique and encodes a unique series of numbers, called the ID code of the tag. When the tag is in the detection range of an ALS, the ALS hears and decodes the sound and logs the resulting ID code and precise timing of the detection.

In one dimensional acoustic telemetry an autonomous ALS is placed under water to evaluate the potential presence of an acoustic tag within its detection range. The detection range is a spherical area around (but not below) the antenna of the hydrophone (Figure 18).

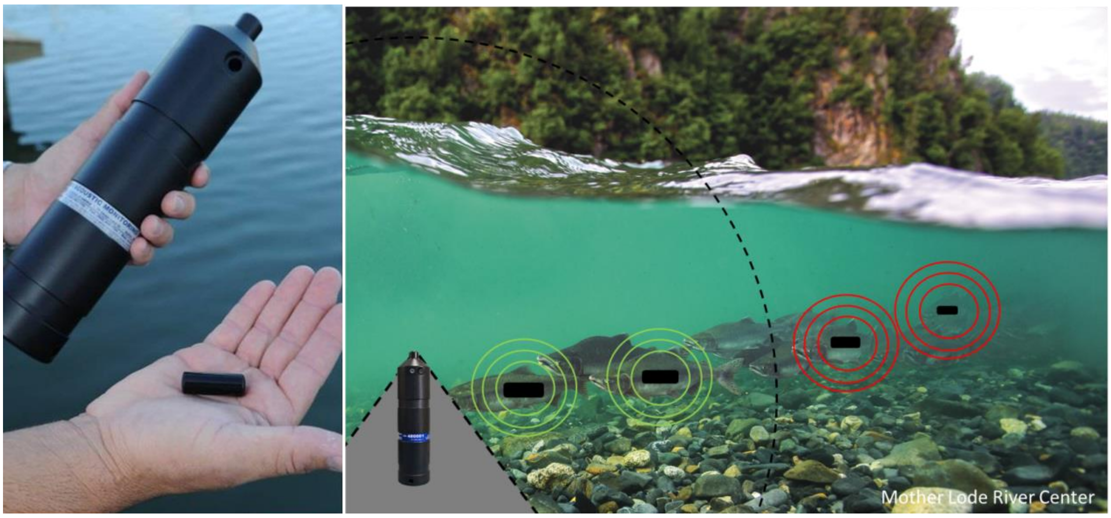

Figure 18 a) Acoustic Listening Station (ALS, receiver) (left hand) and acoustic tag (right hand), and b) schematic view of the detection range (the not grey area within the dashed circle) of one autonomous ALS fixed at the bottom of a river. Tagged fish that are within the detection range (green encircled tags) are logged (ID code) as being present at each time stamp that their emitted signal is heard by the ALS. ID codes of tagged fish outside of the detection range of the hydrophone are not logged at those time

stamps because they are not heard by the ALS and are thus assumed absent. One ALS can only define presence/absence and not the exact position of the tag within its detection range (one-dimensional acoustic telemetry).

In 2- and 3-dimensional acoustic telemetry, autonomous receivers are installed in a configuration so that every location in the area of interest is covered by the detection range of at least three receivers.

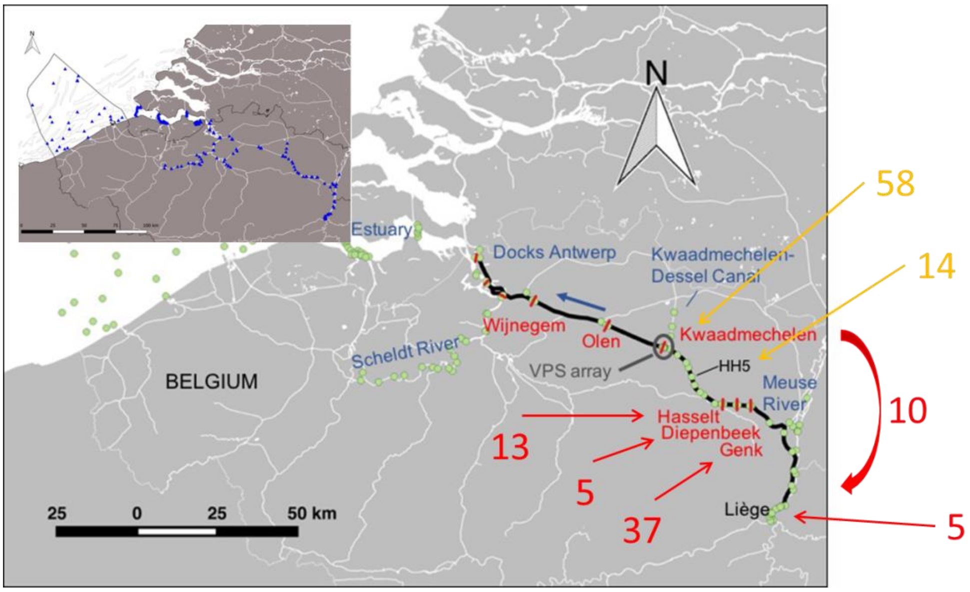

Figure 19 Map of the study area and indication of the number of tagged silver eels (red), salmon smolts (green) and their release location. The Albert canal runs from the Meuse River (city of Liège) to the Port of Antwerp in the North of Belgium. The study site in Ham (Kwaadmechelen) is located halfway between the Meuse River and Antwerp. Green dots indicate the locations where receivers were mounted to detect the tagged silver eels and salmon. The names and lines in red indicate the presence of the other five ship lock complexes on the Albert canal. VPS array refers to the array of receivers used for two-dimensional fish tracking near the sluice complex of Ham.

In total, 156 silver eels and 72 salmon smolts were tagged, released and tracked. Of the 156 eels, 15 were released in the Meuse River in the city of Liège to evaluate their choice for either migrating to sea along the Albert canal or the Meuse River. Fifty five were released at the ship lock complexes of Hasselt (), Diepenbeek () and Genk (), to evaluate their migration behaviour through the Albert canal, and another 86 eels were released upstream of Ham (downstream of Hasselt) to evaluate the route choice at the ship lock complex of Ham in detail with two-dimensional telemetry (Figure 19). The salmon smolts were all released between Hasselt and Ham to evaluate their route choice at the ship lock complex of Ham and beyond (Figure 19).

The tagged eels and salmons were released upstream of the sluice complex of Ham (Figure 19) and their downstream migration route was evaluated:

- at the scale of the entire shipping canal, including the Meuse river by one-dimensional telemetry
- at the small scale in an area of 300 m directly upstream of the ship lock complex and hydropower plant by two-dimensional telemetry.

The first evaluation was performed to indicate the route choice of eels coming from the Meuse River and eels released in the shipping canal. Specifically their choice to migrate to sea along the Albert canal or Meuse River was assessed. The second evaluation was performed to evaluate if and how migrating salmon smolts and silver eels passed the sluice complex of Ham and the proportion of them that would migrate along the hydropower plant. Fish can pass the ship lock complex of Ham by swimming into the side channel leading to the hydropower plant and pass the screws, or stay in the shipping canal and pass via the sluices by entering through open sluice gates or the inlet of the filling system during sluice filling.

The evaluation of migration behaviour and route choice gave insight in the proportion of fish that pass the hydropower station, and are thus potentially harmed by the Archimedes screws. The results of this part of the study may also give further insight into potentially successful mitigation measures, such as the need to install fish deterrence systems at the side channel entrance or the sluice filling system inlets. We focus on the results of the fine scale evaluation and route choice at the sluice complex of Ham as part of the evaluation of the impact of the hydropower plant on migratory fish in the canal. Parts of the results of the study at the large scale were published in Verhelst et al. (2018).

3.2.2. Results

The results indicated that only 14% of 86 tagged eel passed the hydropower plant on their way down to the sea through the shipping canal (Figure 21). In contrast, none of the tagged smolts passed the hydropower plant, but 5% of them were never detected by the two-dimensional receiver array (Figure 22). Figure 20 shows one two-dimensional fish track and CFD modelled stream velocity. The tracks indicated what route a fish took to pass the complex and how it entered the sluices if it did so. The final route was as well indicated by detections on receivers in the sluices, in the by-pass channel to the hydropower plant and downstream of the sluice complex. Further details on:

- how the studied fish approached the ship lock complex;
- how they entered the ship locks;
- how successful they were on finally passing on to the next ship lock downstream and eventually the Scheldt river to migrate to sea,

was investigated in PhD research and published in (Vergeynst et al. 2019, Vergeynst 2020).

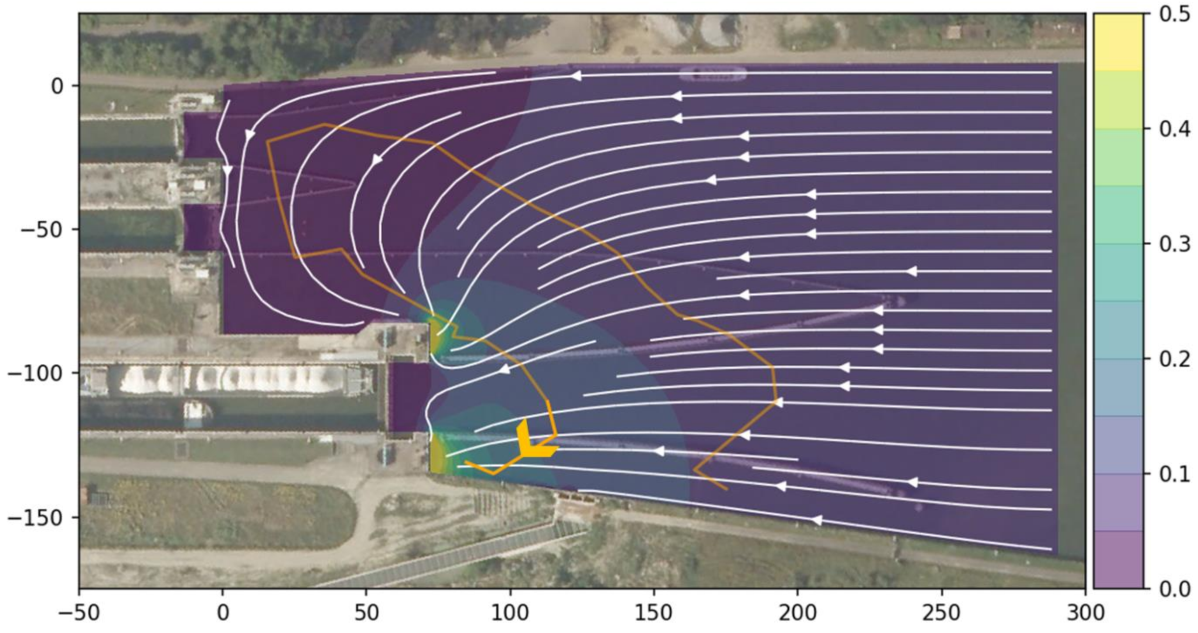

Figure 20 Aerial view of the area directly upstream of the ship lock complex and CFD modelled stream lines (white arrows), and one swim track (orange line/arrow) of an eel finally passing the sluice complex through the pushed convoy lock via the left inlet of the filling system of the sluice during sluice filling (Vergeynst 2020).

The total impact of the HPP on migrating eel and salmon is defined as causing no loss of migrating salmon (as none of the tagged ones passed the HPP), and is defined as a 2% loss of all migrating silver eels. The total impact is calculated as the percentage of the tagged fish that passed via the HPP on their way passed the ship lock complex of Ham, times the direct impact of the screw defined as a 17% eel loss and 61% salmon loss (Table 12). This ship lock complex is one of six that fish that take the shipping canal as a short cut to sea, have to pass. Consequently, the relatively low impact of the hydropower plant on passing eels thanks to the relatively low proportion passing via the hydropower plant adds up and the total impact cannot be neglected (Table 12). Installation of fish deterrence systems at the intakes of the side channels leading to the hydropower plants is advised to mitigate the measured impact of the Archimedes type hydropower screws at the ship lock complexes of the Albert canal in Belgium. At the time of writing only three of the six ship lock complexes are equipped with such hydropower installations, but the construction of the remaining three is planned for the near future.

Table 12 Calculation of the total impact of the HPP at Ham on migrating eel and salmon by the percentage of tagged animals that passed the HPP and the direct impact of the screw (columns 2 to 4). The cumulative impact over all six HPP installations on the Albert shipping canal (column 5).

	% HPP use	**% HPP mortality**	**% Total HPP loss**	**% Cumulative loss (6 HPP's)**
Salmon smolt	0	61*	0	0
Silver eel	14	17	2	11

*) this number has to be treated with caution as it was based on failed experiments with trout.

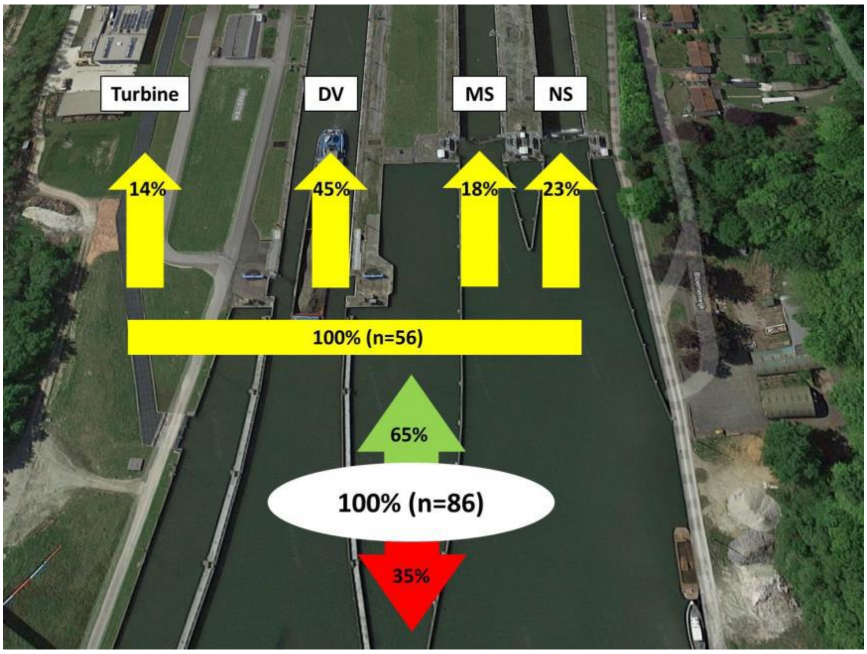

Figure 21 Route choice of 86 tagged silver eels at the ship lock complex of Ham (Kwaadmechelen, Belgium). DV: push convoy lock, MS: middle lock, NS: northern lock. Turbine refers to a hydropower installation equipped with three large (10 m head) Archimedes type hydrodynamic screws.

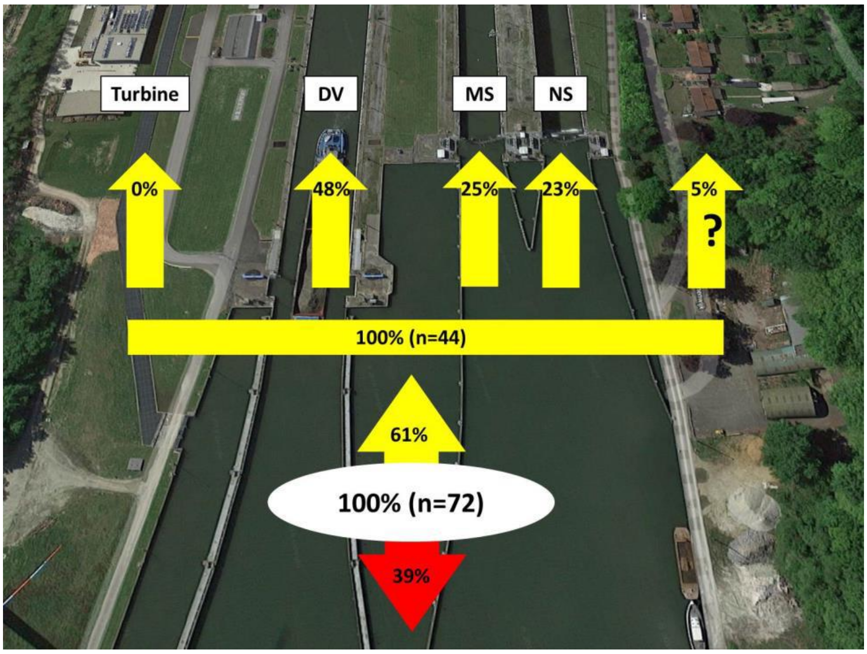

Figure 22 Route choice of 72 tagged salmon smolts at the ship lock complex of Ham (Kwaadmechelen, Belgium). DV: push convoy lock, MS: middle lock, NS: northern lock. Turbine refers to a hydropower installation equipped with three large (10 m head) Archimedes type hydrodynamic screws.

4. Conclusions and future work

Generally, Archimedes type hydrodynamic screws are regarded fish friendly and the few fish studies performed on this type of screws subscribed this (Kibel 2008, Schmalz 2010, Bracken and Lucas 2012, Havn et al. 2017, Piper et al. 2018). In contrast, the study performed here shows that the chances to die or get heavily injured for a fish that passes the Archimedes type hydrodynamic screws at the study site of Ham (Belgium) are substantial for bream and roach and should not be neglected either for eel.

If fish are injured, they mostly show scale loss for less than 25% of their body surface and heavy injuries are mostly contusions. Also a minor proportion of 3 to 13% of the sensors got crushed somewhere in the screw. No injuries were observed that could immediately be directed to pressure related problems, which for instance cause popped-out eyes.

The data collected with the BDS sensors revealed indeed that pressure is not an issue in these type of screws, and this is in line with similar research of Boys et al. (2018). The BDS sensor tests however also revealed that no two of the individual tests performed, were drawn from the same distribution. The behaviour of the sensors in the screws was thus an entirely chaotic process. It is therefore difficult to deduce from these data where heavy injuries such as for instance contusions or decapitations (for bream) occur in the screw. For instance is it caused exclusively at the first blade when entering the screw, or is it possible that fishes are crushed somewhere else along the screw, where the gap between the blades and the housing is up to 2 to 4 cm wide? Nonetheless, a small proportion of sensors were crushed as well and heavily damaged, although they are developed with the hardest plastic in the world. The statistical tests on crushing and scratching indicated a relation between damaged and not-damaged sensors, but no relation with operational discharge was found. Although significant differences were found for bream and eel, the resulting discharge that was more or less harmful differed between species and was small anyway. We conclude from these observations that operational discharge is not influencing the harmfulness of the screws to passing fish and we do not recommend it as a mitigation measure.

Moreover the next question to be solved will be whether or not the uniqueness of the sensor data is related to the biological findings? If fish are expected to exhibit more complex behavior than a passive sensor during Ham screw passage, then it is our hypothesis that similar to the sensors, there will be no significant differences in injury and mortality across operational scenarios.

Next, the observation of contusions on fish and crushes of sensors indicate that fish and sensors were squeezed between the blades and the screw housing. It was not possible to investigate where contusions and crushes happen and if it happens exclusively in the beginning at the first blade when fish and sensors enter the screw. Further research could be dedicated to finding the exact origin of these types of severe injuries to further adapt screw design and improve fish friendliness.

From the tracking study on eel and salmon, we concluded that the overall impact of the screw on migratory fish in the canal is relatively low, since relatively few eel and no salmon entered the HPP in this study. Nonetheless, the numbers of harmed migratory fish will add up on the scale of the entire canal, since six hydropower stations (as the one investigated here) will be present.

Further, the studies of Vergeynst et al. (2019, 2020) and Verhelst et al. (2018) on these data revealed the vast delay that migratory eels encounter due to the presence of the shipping lock complexes and HPP’s, how the fish are influenced by it and how few individuals eventually reach the sea. Moreover Vergeynst et al. (2020) found that the filling systems of the ship lock complexes potentially harm passing fish as well. Future work could test this hypothesis. However, most importantly, more fish species could be tracked and their chances of entering the HPP could be evaluated to further clarify the total impact of the HPP on the local fish population and how fish can be deterred from the inlet to the HPP at the entrance of the by-pass channel.

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