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RESEARCH ARTICLE

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Imaging-sonar observations of salmonid interactions with a vertical axis instream turbine

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Abstract

Anthropogenic activities and their influences on aquatic systems is an important topic, especially considering the growing interest in using the earth's resources in a sustainable way. One of those anthropogenic activities is the introduction of renewable technologies into the aquatic environment such as instream turbines. Environmental studies around those technologies are often still ongoing due to their novelty. During the spring of 2018, juvenile individuals of two salmonid species, Atlantic salmon and brown trout were released upstream a vertical axis instream turbine in the river Dal (Dalälven) in eastern Sweden. The aim of this study was to investigate the swimming behavior of the salmonids around a small-scale prototype vertical axis instream turbine. The swimming pattern and the possible response of avoiding the vertical axis instream turbine were documented with a multi beam sonar. A control area, next to the turbine, was used as reference. No consistent results were shown for trout as they were passing the control area with a statistically high variation, and specimens were rarely observed in proximity of the turbine, neither if the turbine was operating nor at stand still. Salmon clearly avoided the operating turbine, but did not avoid the turbine when it was at stand still, and was often observed swimming straight through the turbine area. These findings indicate that operating this type of instream turbine in a river affects the swimming behavior of Atlantic salmon but is unlikely to affect its migration paths. For brown trout, the statistical results are inconclusive, although data indicate a response of avoiding the turbine. The species are in little risk to suffer physical harm as no fish entered the rotating turbine, despite very turbid water conditions.

KEYWORDS
Atlantic salmon, brown trout, collision risk, imaging sonar, marine current energy converter, multi beam sonar, salmonids, vertical axis instream turbine

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1 | INTRODUCTION

Ecological impacts from anthropogenic activities on the aquatic environment has become one of the primary questions in ecology (Komyakova et al., 2022). It has also been concluded that no area of the ocean and rivers has been unaffected by human intervention (Halpern et al., 2008). Development of renewable energy devices to harvest energy from rivers are among these human activities, and the idea is to substantially contribute to energy security and to combat climate change at the same time. In the past and up till now, the development and expansion of hydro power dams can be described as highly disruptive to river ecosystems, both during construction and in their day-to-day operation (Asmal, 2000; Schulz & Adams, 2019). Completed dams without passage-ways created insurmountable obstacles for aquatic organisms, notably for migrating fish (Kosnik, 2008) and fish species have been shown to disappear locally following the installation of dams (De Mérona & Albert, 1999; Parrish et al., 1998).

Hydrokinetic turbines present an alternative to building dams for electricity generation from hydro power in river systems. Hydrokinetic devices are free-standing, open structures installed in naturally flowing water currents, and fish may avoid these structures as they would any other hindrance, such as a trawl or a boat (Viehman & Zydlewski, 2015). They are fundamentally different from conventional hydro power designs, and are therefore likely to affect fish differently (S. Amaral et al., 2011; Brian Polagye et al., 2010). However, with many turbine designs being put forward, it is important to in depth assess the effects such technologies have on the local environment (Langhamer & Molander, 2018). The diversity of power take off designs also implies a diversity of environmental impacts (S. V. Amaral et al., 2015; Cada et al., 2007). Due to the spacial overlap of turbines and fish, interactions between the two are expected (Viehman & Zydlewski, 2015) and one potential impact common to many designs is the risk of collision between rotating parts of the structure and aquatic organisms (Wilson et al., 2007). Other identified stressor–receptor interactions can be exposure to underwater noise from operational devices, exposure to electromagnetic fields from power cables and energized devices, changes in habitats due to the presence of devices, renewable energy systems acting as fish aggregating devices, and displacement of fish populations (Copping et al., 2021; Seitz et al., 2011). The great concern with tidal and river turbines is the potential for animals to be injured or killed by collision with rotating blades, which is widely perceived as the primary environmental impact of hydrokinetic generation.

Brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*) are important economic and ecologic anadromous fish species in Sweden and elsewhere. Wild anadromous Atlantic salmon have declined demonstrably throughout their native range and many of these declines or extermination can be attributed climate change (Thorstad et al., 2021) to pollution (including acid rain), total dewatering of streams but especially to the construction of dams (Parrish et al., 1998). The interest and spread of hydrokinetic turbines has increased and fish might pass these structures by swimming around them, thereby avoiding what is widely perceived as the primary environmental impact of hydrokinetic turbines (Castro-Santos & Haro, 2015). The essential concern is still if fish are likely to be struck and injured by the devices (Bevelhimer et al., 2017; Copping et al., 2021) or if they could provoke avoidance behaviors. Avoidance behaviors hold their own risks, for example, fish may refuse to pass the structures, in which case access to habitat may still be blocked or only available at a reduced rate (Castro-Santos & Haro, 2015). Hydrokinetic turbines could have a lower environmental impact compared to hydro power dams, but, as with hydro power, interactions with migrating fish is one major concern and further investigation is needed.

Hydrokinetic turbine technology can be still classified as new, and few devices have been in the water for extended periods of time, in part because the environmental impacts of these turbines are not well known. This is one of the reasons why there are few field studies existing on fish-turbine interactions. In summary, laboratory and field studies have found a low risk of collision, and some have found that fish avoid tidal turbines (Berry et al., 2019; Copping et al., 2021; Hammar et al., 2013; Müller et al., 2023; Shen et al., 2016; Viehman & Zydlewski, 2015; Zhang et al., 2017). However, the risk that is of primary concern is whether fish or other large organisms that encounter these devices are likely to be struck and injured (Bevelhimer et al., 2017; Copping et al., 2021). The choices fish make when encountering a hydrokinetic turbine in their natural environment must be better understood to assess the effects of these devices on fish (Hammar et al., 2015). Due to risk of collision between fish and hydrokinetic turbines, it is important to better understand the behavior of fish within hydrokinetic sites (Hammar et al., 2015).

Technological advancements and improvements of methodologies have increased our understanding of the effects tidal and instream turbines can have on organisms. Despite these advances, there are still challenges in monitoring fish, especially in turbid, fast flowing aquatic environments. Detecting collision events or observing fish movement and behavior in relation to the underwater turbines are especially challenging. Conventional monitoring techniques may not work properly in harsh conditions, which can result in limitations for human safety and unreliable data acquisition. Common scientific methods for fish observations are; the use of optical cameras, acoustic tags, echo-sounders, capture, and diving (Bender et al., 2017; Geoffroy et al., 2016). These conventional techniques require substantial resources while incurring high risks for human life, equipment, and costs. However, these limitations can be overcome by utilizing alternative technologies such as high frequency sonar systems (Francisco & Sundberg, 2018; Kerrie et al., 2010). An example of high frequency sonars to be useful for monitoring the harsh environment surrounding hydrokinetic turbines is the multibeam sonar system (MBS), which is able to acquire photo-like acoustic images, similar to medical ultrasound.

Similar to optical cameras, light detection and ranging (LIDAR), radio detection and ranging (RADAR) and human-observations need clear water and natural or artificial light. The MBS can in turn be used in environmental monitoring studies in murky and turbid waters

(Bender et al., 2017; Bevelhimer et al., 2016; Francisco & Sundberg, 2019; Geoffroy et al., 2016; Kerrie et al., 2010; Sparling et al., 2016; Williamson et al., 2016) as a non-invasive tool that extensively gathers data such as the occurrence, behavior, size, and class of a variety of aquatic species coexisting within a designated habitat. MBS systems demonstrated to be capable of being tuned for use in environmental monitoring studies which observed fish and marine mammals at hydrokinetic sites (Bender et al., 2017; Bevelhimer et al., 2016; Francisco & Sundberg, 2019; Geoffroy et al., 2016; Kerrie et al., 2010; Sparling et al., 2016; Williamson et al., 2016). Although the technique to acquire data has been used in the recent years, the data acquisition and processing framework is still a novel challenge.

An MBS acquires acoustic images by emitting and receiving sound pulses in multiple angles across-track swath, typically with beams in fan-shape (Hovem, 2007; McGehee & Jaffe, 1996). Transducer elements are arranged in two dimensional arrays, each element transmits sound pulses individually in a crescent order, and the echoes are received simultaneously by all receivers. This setup effectively steers the beam in several directions simultaneously, and the transducer elements are organized in a spiral configuration so that the beam pattern fills the field of view (FOV). The use of several narrow beams, with a minimized transmit-pulse (beam spacing), maximizes the effective sampling volume covered in the entire swath in a single ping. Typically, an MBS can have up to 1500 beams emitted in angular sectors up to 180° of FOV and can operate in frequencies of 200 kHz up to 3 MHz, achieving range resolutions of up to 1 cm and an angular resolution of about 0.2°. One of the main limitations of using MBS for acoustic images is the high operating frequencies which restricts the range to less than 100 m, and increases sensitivity to background noise. Noise prevenient by the bottom substrata and surface turbulence can also disturb the signal, especially if targets are located at a greater distance than the bottom depth (Chu, 2011; Waite, 2002). Air bubbles within the swath can also cause intense disturbing background noise. MBSs generate large volumes of data. Processing and analysis of data can be complex and time consuming, making it difficult to automate the identification and classification of underwater targets.

The aim of this study was to investigate the swimming behavior of two salmonid species around a small-scale prototype vertical axis instream turbine deployed on the river bed in the river Dal (Dalälven) in the east of Sweden. For that purpose, individuals of brown trout and Atlantic salmon have been released upstream of the turbine while documenting their swimming pattern and possible reactions of avoiding vertical axis instream turbine with the help of an MBS.

2 | MATERIALS AND METHODS

2.1 | Study site and turbine specification

The Söderfors experimental site is located at the river Dal in the village of Söderfors, around 75 km north of Uppsala. The vertical axis instream turbine is deployed approximately 800 m downstream of a conventional hydro power plant operated by Vattenfall AB, see Figure 1, and has been deployed from a road bridge in March 2013 (Lundin et al., 2013).

The vertical axis instream turbine is comprised of a straight-bladed Darrieus type turbine connected to a direct-driven permanent magnet generator mounted on a tripod, deployed on the river bed consisting of stones and boulders at a depth of 6–7 m. The directly driven vertical axis instream turbine has a 7.5 kW installed capacity. The core structure of the turbine is made of steel, the blades are made of carbon fiber, measuring 3.5 m of height and 6 m of diameter (Figure 2; Lundin et al., 2013; Yuen et al., 2011). The designed maximal rotational speed is 20 rpm. The starter, load system and monitoring equipment is located in a measuring cabin onshore, 150 m away from the instream turbine.

2.2 | Study species

During the study, individuals of two native salmonid species were released by hand from a boat in the river Dal, the Atlantic salmon, and the brown trout (Figure 1c). The fish were individually tagged with passive integrated transponder (PIT tags), farmed and provided by the Fisheries Research Station in Älvkarleby run by Swedish University of Agricultural Sciences.

2.2.1 | Atlantic Salmon—*S. salar*

Fish were juveniles in their second year and transitioning into the smolt stage. Individuals had a total length of around 12 cm. At this time in their life cycle, and during the period of the year the study was conducted, the fish would begin their downstream migration toward the sea. A total of 90 individuals were released during the study (Table 1).

2.2.2 | Brown trout—*S. trutta*

Individuals had a total length of around 25 cm. At this time in their life cycle, and during the period of the year the study was conducted, the fish typically show a stationary behavior in that size and age range. A total of 87 individuals were released during the study (Table 1).

2.3 | Observation method and data analyses

One MBS was deployed at a depth of 0.5 m on a pole mount platform, in two distinct arrangements: (1) had the transducer orientated downwards, with a pitch angle of $\alpha_{MBS} = 10^\circ$ and a yaw angle of θ_{MBS} of 23° toward the turbine. The other arrangement (2) had the transducer oriented away from the turbine and toward the control site or the riverside, with same pitch angle but with a yaw angle of θ_{MBS} of -60° (Figure 1c). The MBS maximum range of the sonar was set to 30 m

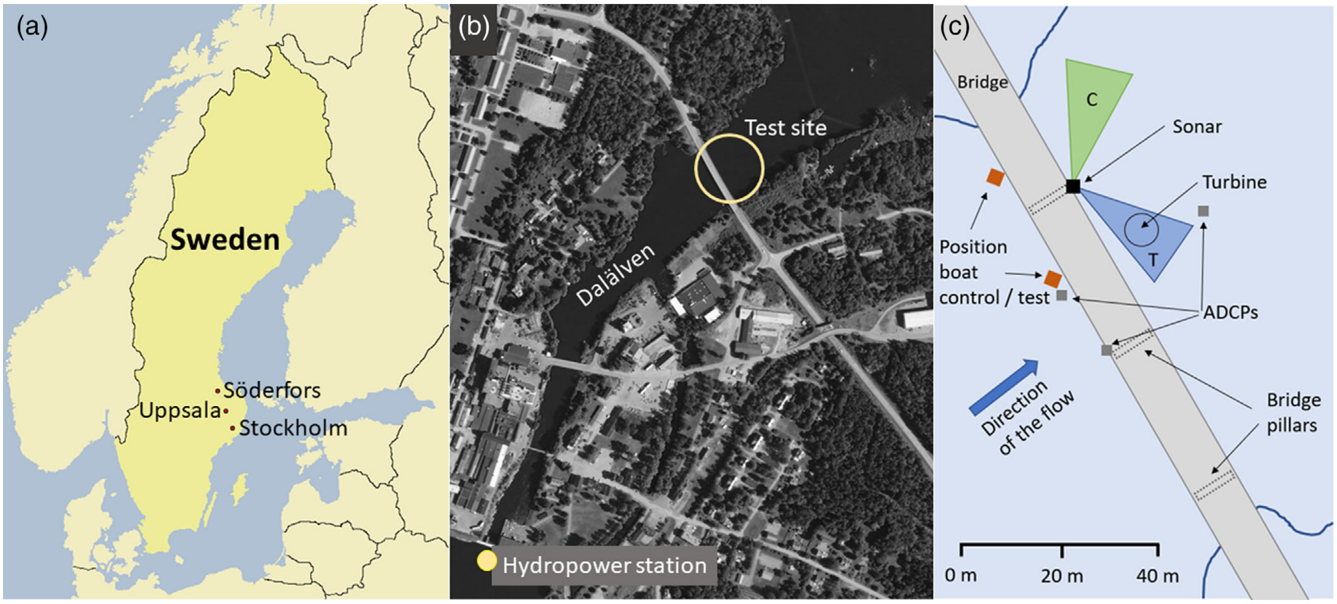


FIGURE 1 (a) Location of Söderfors, approximately 140 km north of Stockholm. (b) Bird's eye view of central Söderfors with the location of the hydro power station, the test side with the instream turbine and the measuring cabin, after Lundin et al. (2013). (c) Experimental setup in the river Dalälven. Location of turbine, sonar and ADCP's are indicated. The blue triangle indicates the field of view of the MBS pole arrangement *T* (test), the sampling conditions turbine on or off and the green triangle indicates the field of view of the control site MBS pole arrangement c (control). [Color figure can be viewed at wileyonlinelibrary.com]

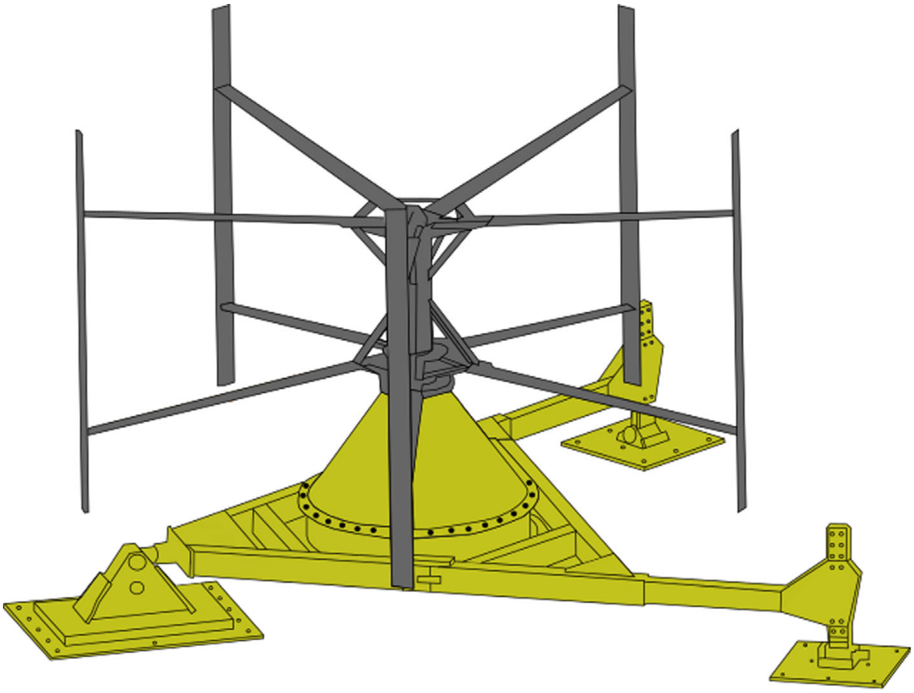


FIGURE 2 Image of the vertical axis instream turbine energy conversion unit mounted on a tripod (after Forslund and Thomas (2018)). [Color figure can be viewed at wileyonlinelibrary.com]

with a FOV with a prismatic shape and aperture of 20° horizontal by 130° vertical. The FOV covered the center of the turbine at a range of 19 m, and also a part of the riverbed and the surroundings (Figure 3a,b).

Juvenile brown trout and Atlantic salmon were released by hand one by one from a moored boat during May 3rd and 4th and May 30st and 31st 2018, respectively. Fish were released during three different conditions: Turbine ON, Turbine OFF (still turbine), and Control site (a nearby part of the river without turbine) for each of the three releases. At the Turbine ON and Turbine OFF, being the same site, passing fish were monitored using the MBS pole arrangement *T* (test), while fish passing the Control site were monitored using the MBS pole arrangement C (control; Figure 3b). For each condition, and for both species, three releases with 29 individuals for brown trout

TABLE 1 Total released juvenile brown trout and Atlantic salmon individuals during the three treatment, with each three replicates A1-3, B1-3, and C1-3.

Brown trout			
Date	**Release**	**Treatment**	**# individuals**
2018-05-03	A1, A2, A3	Turbine ON	Each release 29
2018-05-03	B1, B2, B3	Turbine OFF	Each release 29
2018-05-04	C1, C2, C3	Control	Each release 29
Atlantic salmon			
Date	**Release**	**Treatment**	**# individuals**
2018-05-30	C1, C1, C2	Control	Each release 30
2018-05-30	B1, B2, B3	Turbine OFF	Each release 30
2018-05-31	A1, A2, A3	Turbine ON	Each release 30

and 30 individuals for Atlantic salmon were released (Table 1). Acoustic doppler current profilers (ADCP) were not operating during sonar recordings as ADCPs are believed to cause interreference with the sonar.

2.4 | MBS data processing

MBS data was acquired as a succession of pings (echoes), each with 768 beams separated by 0.18°, at refresh rates of 4–8 Hz, and preprocessed in real-time conditions using *BlueView SDK 3.6* (Table 2). The formed acoustic images contain backscatter intensity, range, georeference, and velocity data of insonified targets. Acoustic images were submitted to further analyses using supervised classification of the backscattering intensity and range values using *ProViewer 4* and *Matlab* (Figure 4). In order to classify targets, a valid set of pixels were selected as the representation of a specific class of targets, namely fish, turbine, debris, top and bottom boundary layers. This process was repeated and improved several times in order to improve accuracy. However, random and systematic measurement errors are still present. The precision was estimated to be ±0.1 m of the measured distance between two points within the acoustic image reproduced in *ProViewer 4*. Following this procedure, targets were manually counted and tracked, resulting in two variables for analysis: *passage* defined as the number of fish passing through the detection zone in proportion to the number of released fish, and *proximity* defined as the closest distance between fish trajectory and the turbine area. Figure 4 shows the data acquisition and processing scheme after (Francisco & Sundberg, 2019).

2.5 | Statistical data treatment

Each species was analyzed with respect to the response variables *passage* (the proportion of released fish being observed in the detection zone) and *proximity* (the distance between passing fish and the turbine area).

For the *passage* variable, the statistical design included three treatment levels: Control (area without turbine), OFF (present turbine not rotating), and ON (present turbine in operation, rotating). Three releases were conducted for each treatment ($N = 3$). Data distributions did not satisfy assumptions for normality most likely due to small sample size, and instead the Kruskal–Wallis ANOVA non-parametric test was selected to conduct the data analysis.

The statistical design for analyzing *proximity* included the two treatment levels OFF and ON, with the factor of fish release group being nested. Each release group contained a variable number of observed fish individuals passing with an established distance (m) toward the turbine area. Brown trout data were transformed through a Box–Cox transformation to fulfill normality assumptions (Shapiro–Wilk normality test) and analyzed by nested ANOVA. After establishing no difference between release groups, data were pooled and one-way ANOVA was used to re-inventory differences between treatments (ON/OFF). For Atlantic salmon, data did not fulfill conditions for parametric test and Kruskal–Wallis ANOVA was used. Following post hoc test establishing significant difference between release groups from different treatments but not within each treatment, samples from the release groups were pooled and a Mann-*U*-Whitney non-parametric test were applied to further inventory the effect of the treatment factor (ON/OFF).

All statistical analyses were conducted using statistical software Statistica (version 13.5).

2.6 | Turbine speed and water speed

The average water speed on May 3rd at the upstream ADCP at around 14.30 was 1.75 m/s with variance 0.01 m/s (Figure 5). The rotational speed of the turbine was on average 0.53 m/s with variance 0.3 m/s (Table 3).

Variance in rotational speed occurs because during each rotation, the turbine has peaks of power output each time a blade passes its optimum power extraction point. For these experiments, the turbine was at the time of the experiments missing one blade, resulting in an unusually high variance in rotational speed. The tip-speed-ratio is defined as the speed of the tip of the blade relative to the water speed, and gives an indication of the instantaneous power absorption of the turbine. The optimal tip-speed-ratio for this turbine has been experimentally measured to be 3.1 (Lundin 16). The resulting tip-speed-ratio is 3.05 and at this speed each revolution of the turbine takes just below 4 s. Mean values of water speed, rotational speed, and tip-speed-ratio for the other sampling days can be found in Table 3. Water speed for May 30th was retrieved by direct contact to a hydrologist at SMHI database and no variance can be stated, since no field measurement of water speed was conducted on that day.

3 | RESULTS

A total of 264 brown trout and 270 Atlantic salmon individuals were released upstream of the vertical axis instream turbine to investigate

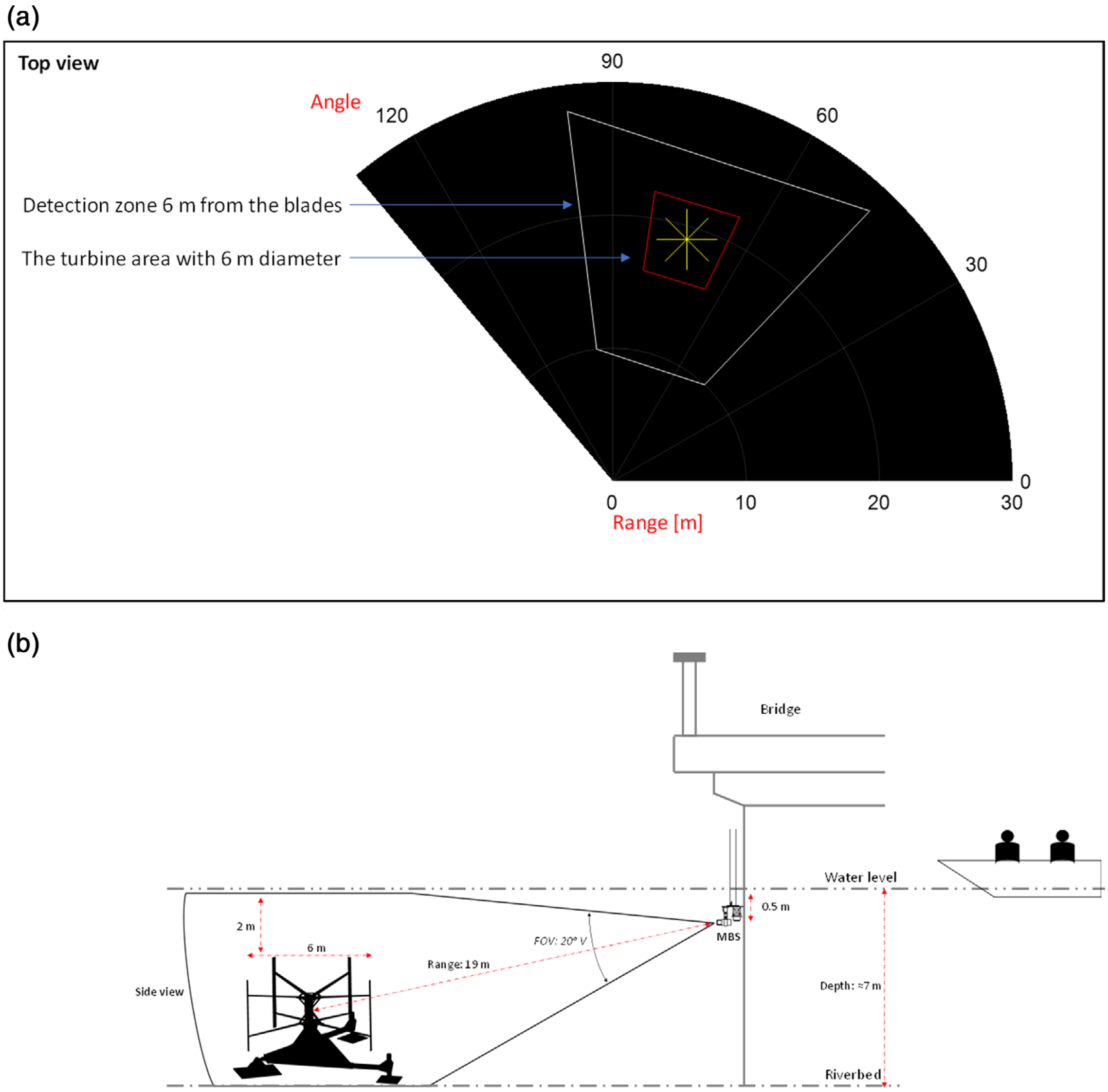


FIGURE 3 (a) Top view of the data acquisition acoustic setup arrangement T (test) using a multibeam sonar (MBS) at distances of 19 m from a hydrokinetic turbine deployed at Söderfors research site. Fish was manually released into the water from a small boat. (b) Side views of the data acquisition acoustic setup arrangement *T* (test) using a multibeam sonar (MBS) at distances of 19 m from a hydrokinetic turbine deployed at Söderfors research site. Fish was manually released into the water from a small boat. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Technical specifications of MBS used on the experiment.

Multibeam imaging sonar (MBS)	Specifications
BlueView	Frequency: 0.9 MHz (operational) Number of beams: 768 fps: up to 50 Hz (sample frequency) FOV: 132 × 20 (field of view) Resolution: 0.18°/2.54 cm Maximum range: 100 m

the swimming behavior and possible reactions of avoiding to the turbine of the two native anadromous fish species. No collisions were detected throughout the study.

3.1 | Brown trout

The number of observed brown trout in proportion to the number of released brown trout (variable: *passage*) was not significantly different between the control area and the area with the turbine, for operating and non-operating turbine (Kruskal–Wallis ANOVA: H $(2) = 1165$, $p = 0.558$; Figure 6a). Brown trout seemed to make little change in their swimming behavior between the presence of an operating or non-operating turbine compared to a control area. The box plot nevertheless indicates that more brown trout swam through the detection zone in the control area compared to the turbine area regardless of operation mode (ON/OFF; Figure 6a).

The *proximity* between brown trout swimming trajectory and the turbine area was not significantly different between the two turbine

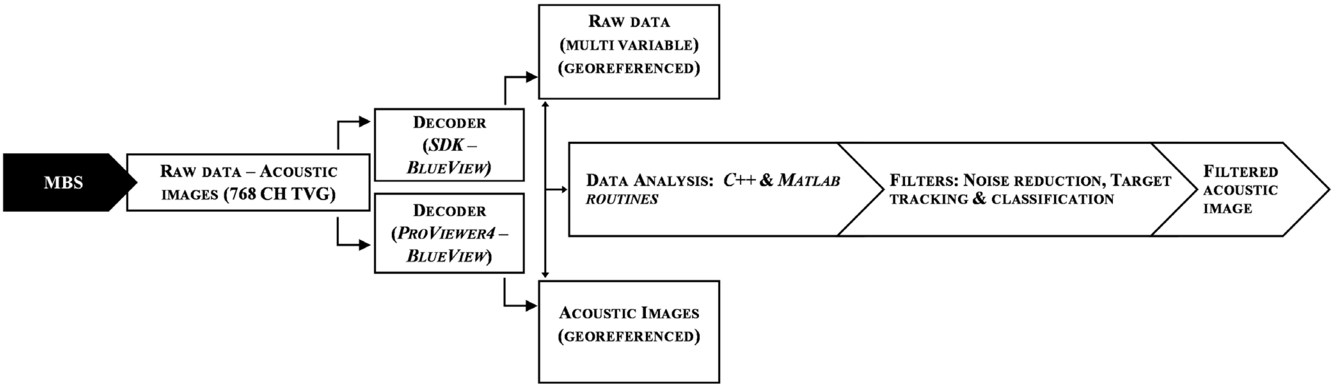


FIGURE 4 Scheme of data acquisition, processing and analysis used for the detection, track and classification of released fish within the hydrokinetic research site in Söderfors, after Francisco and Sundberg (2019).

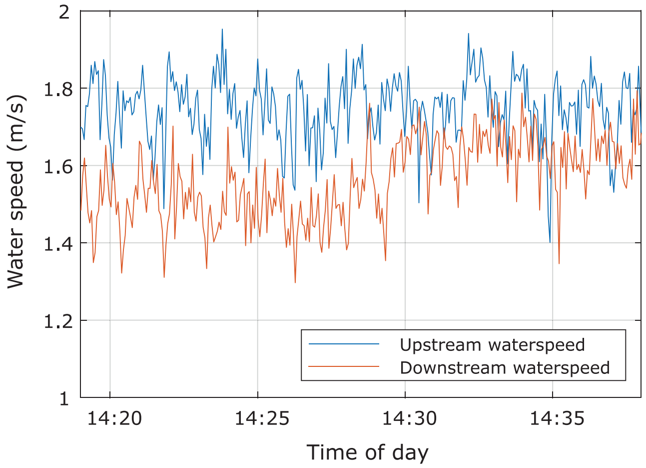


FIGURE 5 Water speed (m/s) for the sampling day May 3rd measured upstream and downstream of the turbine. [Color figure can be viewed at wileyonlinelibrary.com]

operation modes turbine ON and turbine OFF, neither in the nested design (nested ANOVA: $F = 0.010$, $p = 0.919$) nor with release groups pooled (one-way ANOVA: $F = 0.827$, $p = 0.367$; Figure 6b). The average distance to the operating turbine was 7.3 m, whereas the distance to the not rotating turbine was 7.9 m.

3.2 | Atlantic salmon

The Atlantic salmon clearly differed in their swimming behavior between control area and the operating turbine. The *passage* of salmon was significantly different between the control area and turbine in operation (Kruskal–Wallis ANOVA: H $(2) = 7.260504$, $p = 0.027$; Figure 7a). The proportion of observed fish in the control area was on average 0.9, in contrast to 0.1 for fish observed during turbine mode ON.

The proximity of Atlantic Salmon swimming trajectory to the turbine showed a difference between release groups from operation modes ON and OFF (Kruskal–Wallis ANOVA: H $[5] = 19.184$, $p = 0.002$; Figure 7b). The average distance to the operating turbine was 6.0 m, whereas only 1.9 m for the still turbine.

4 | DISCUSSION

Given the high turbidity in the (melt) water of the study site, the findings suggest that juvenile Atlantic salmon and brown trout are at minimal risk of physical injury from the investigated vertical axis instream turbine which is in accordance with previous studies (S. V. Amaral et al., 2015; Berry et al., 2019; Bevelhimer et al., 2017; Castro-Santos & Haro, 2015; Hammar et al., 2013; Zhang et al., 2017). No collisions of fish were recorded throughout the study.

A previous laboratory experiment by Berry et al. (2019) found that brown trout were less likely to avoid a vertical axis turbine than Atlantic salmon. The study presented here indicates a similar pattern, as Atlantic salmon did not seem to avoid the turbine much when it is not operating, but clearly avoids it during operation (Figure 7a). For brown trout, the results presented in this study are inconclusive, possibly due to the low number of replicates (releases; Table 1) and the high variation in trout observation during control conditions. But it is worth noting that the observation pattern indicates that trout avoids the turbine whether it is operating or not (Figure 6a). Trout and salmon show different behavior in parr and smolt stages which is reflected in our results (Armstrong et al., 2003; Peake et al., 1997).

These similarities with the previous results of Berry et al., 2019 is further supported by the observed swimming pattern and the proximity between fish and turbine. Brown trout generally kept a fair distance between 7 and 8 m to the turbine whether operating or not (Figure 6b). Atlantic salmon clearly swam closer to the turbine with an average distance of only 1.9 m, when the turbine was not operating and but kept an average distance of 6 m when the turbine was operating (Figure 7b). The proportion of observed fish during turbine mode ON was 0.1 for Atlantic Salmon (Figure 7a). An average of 10% of the released Salmon during turbine mode ON kept a fair distance during all three releases (Figure 7b). This finding indicates that 90% of the

TABLE 3 Summary of the results from the water speed, rotational speed, and tip-speed-ratio during the sampling days.

Date	Time	Water speed	Rotational speed	Blade tip speed	Tip-speed-ratio
2018-05-03	12.00	1.74 ± 0.001 m/s	Turbine off	Turbine off	
2018-05-03	14.30	1.75 ± 0.01 m/s	17.0 ± 9.5 (rpm)	5.34 (m/s)	3.05
2018-05-04	12.30	1.72 ± 0.01 m/s	Turbine off	Turbine off	–
2018-05-30	12.30	1.18 m/s	Turbine off	Turbine off	–
2018-05-30	15.30	1.18 m/s	Turbine off	Turbine off	–
2018-05-31	12.15	1.18 ± 0.01 m/s	13.1 ± 1.4 (rpm)	4.12 (m/s)	3.49

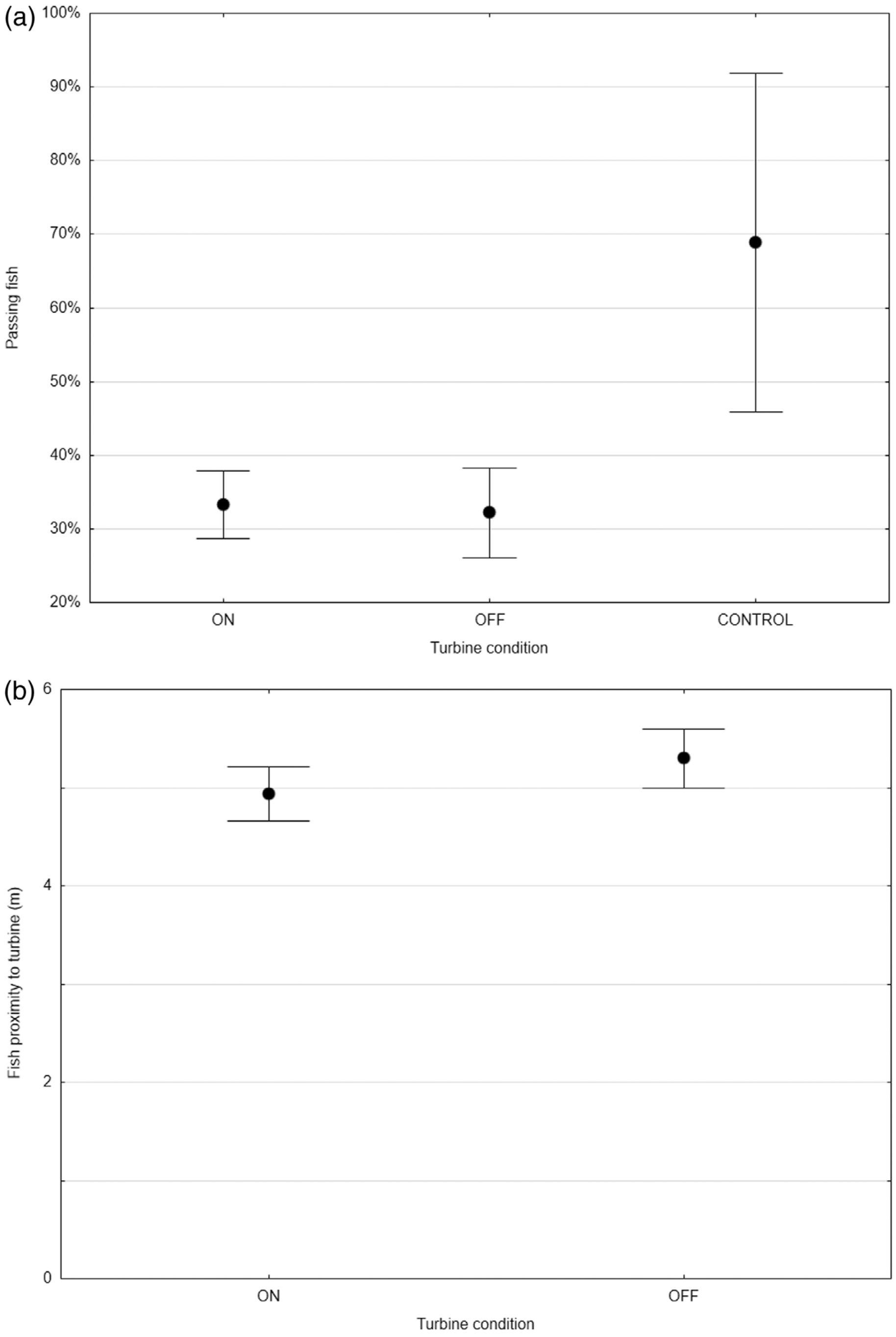
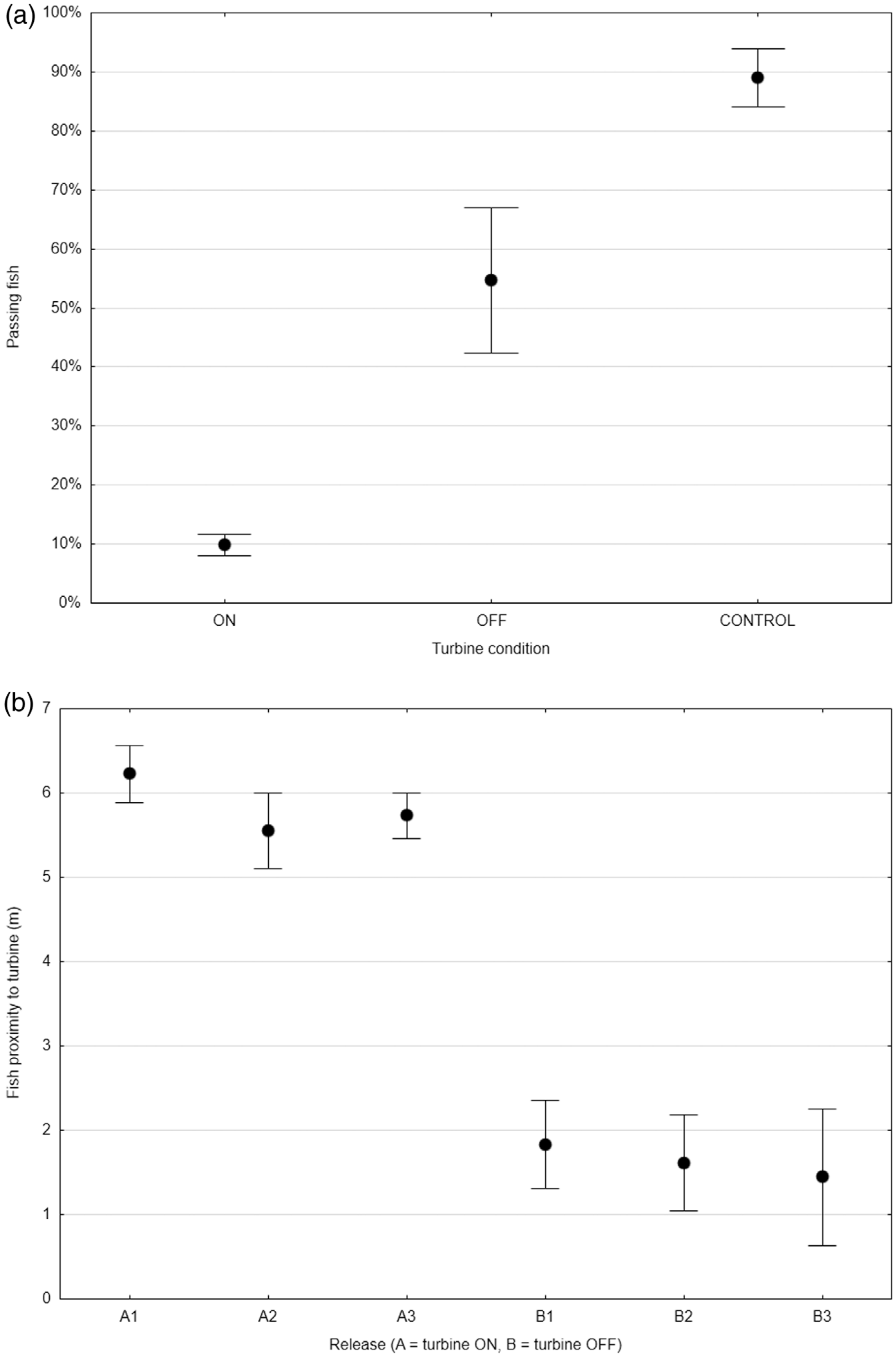


FIGURE 6 (a) Box plot of brown trout passage, showing the proportion of trout detected by the MBS for the three experimental conditions, turbine ON, turbine OFF and the control area. Number of released fish were the same in all three release groups (Table 1). (b) Plot of proximity (m) between turbine area and brown trout swimming trajectory as observed by the MBS, with all three release groups pooled for the two experimental conditions turbine ON and turbine OFF. Pooling of data was justified by post hoc test showing no difference among release groups within each treatment.

FIGURE 7 (a) Box plot of proportion of Atlantic salmon detected by the MBS for the three experimental conditions, turbine ON, turbine OFF and the control area. Number of released fish were the same in all three release groups (Table 1). (b) Box plot of proximity (m) of Atlantic Salmon to the turbine detected by the MBS of the three replicates of the two experimental conditions turbine ON and turbine OFF. A1-3 and B1-3 indicated the fish releases during Turbine ON and OFF, respectively.



fish of the three releases kept an even farther distance to the turbine than the 10% recorded Salmon.

One plausible explanation for the avoidance reaction is that fish were able to see or sense the vibrations or turbulence from the turbine as they approached, and therefore changed their direction. Near field avoidance of turbines by fishes due to visual cues are proved in studies from marine conditions (Hammar et al., 2013), but in rivers, sediment load and turbid waters may impair the visual recognition of rotating blades and impede behavior of avoidance of fish. Further research is needed to examine if and how fish respond to visual cues from moving parts associated with hydrokinetic turbine technologies or if other cues are responsible (Schweizer et al., 2011).

The lateral-line system is a sensory system that allows fish to detect water flow generated by biotic and abiotic sources and is used for orientation and collision avoidance. In turbid waters fish may rely on their lateral-line system for orientation. Fish measure the relative movements between their body and the surrounding water at each, of up to several thousand, sensory organs called the neuromasts. Rheophilic fishes, like many salmonids, spend most of their time in running water and are thus almost always exposed to background water flow (Mogdans, 2019). Velocity and vorticity of the flow depend on the amount of the water passing through a defined volume, on the nature of the habitat, including width, depth, and substrate conditions of a river and on obstacles such as a turbine within the flow. Turbidity also plays an important role because it reduces the effectiveness of vision, placing greater importance on the lateral-line system or the acoustic system. Different substrates (sand, gravel, stones) may cause different degrees of turbidity and thus affect the relative importance of non-visual modalities like the lateral-line system for orientation and collision avoidance (Mogdans, 2019).

A still turbine causes less hydrodynamic changes in the water than an operating turbine. Still, the hydrodynamic changes from a still turbine may trigger possible reactions of avoidance, but brown trout avoid the turbine in both scenarios. Brown trout may be more sensitized on a lower level to detect hydrodynamic changes but other cues are also likely to account for the reactions of avoiding of brown trout. Salmon showed a clear reaction of avoidance from the operating turbine and the fact that the avoidance behavior was not found when the turbine was not operating, suggests that it was the rotating turbine and changes in noise, hydrodynamics and other cues that was responsible for the avoidance behavior for this species.

Noise is a possible turbine-generated stimulus which could potentially affect the swimming behavior of fish around hydrokinetic turbines (Grippo et al., 2017). Species-specific sensitivity to noise is important to consider as fish with swim bladder are more likely to be affected. However, no noise studies are available for the vertical axis instream turbine investigated in our study. By necessity, hydrokinetic turbines are placed in areas that naturally have high flow and turbulence, thus representing an already noisy environment. The placement in these locations may reduce the ability of fish species to detect the noise from the turbine, and ambient noise may exceed the turbine noise, mask it, and thereby decrease the possibility for fish to detect it. Further research on influence of turbine noise is necessary to identify it importance in fish swimming behavior.

Conducting field studies always bear inaccuracies (Lemoine et al., 2016) and the manual counting of the target was likely affected by accuracy errors. Higher accuracy would have required a completely controlled setup in which the released fish were recaptured or recounted using other methods such as tags. An improvement of the study could be furthermore realized by larger sample sizes and replicate size to support statistical power and a refined study setup (Lemoine et al., 2016).

5 | CONCLUSIONS

None of the two species are likely to be exposed to physical harm by the studied kind of turbine as they seem to effectively avoid the rotating turbine, despite turbid water conditions. Similar results were found for Atlantic salmon and brown trout around a vertical axis hydrokinetic turbine in a stream aquarium (Berry et al., 2019) and rainbow trout around vertical axis hydrokinetic turbine in a stream aquarium (Müller et al., 2023). These findings indicate that operating this type of instream turbine in a river affects the swimming behavior of Atlantic salmon but is unlikely to affect its migration paths. For brown trout statistical results are inconclusive, although data indicate a response of avoiding the turbine.

With a better understanding of changes in the swimming patterns of fish around individual turbines, and eventually multiple turbines or arrays, the predictive power of the outcomes of encounters could lead to a wider strategic approach to monitoring. This could help reducing the required level of monitoring and thereby support and speed up of the sustainable development of hydrokinetic turbines and tidal energy in the future.

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DATA AVAILABILITY STATEMENT

Data will be available upon request.

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