Salmonid response to a vertical axis hydrokinetic turbine in a stream aquarium

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Abstract—**Hydrokinetic turbines are an industry with growing interest. With many varying designs being put forward it is important to assess in depth the effects such technologies are likely to have on the local environment. In this study, the response of two downstream migrating juvenile salmonid species (brown trout and Atlantic salmon) to a three-bladed vertical axis hydrokinetic turbine was assessed in an experimental setup. A large, flow-controlled tank was used for 15 minute individual trials, in which 80 individuals were tested (40 of each species). Four water velocity settings (0 m/s– 0.4 m/s) were assessed during the study with 10 replicates for each treatment. No direct collisions were observed. Behavioural responses to the turbine were analysed in terms of pass events and active avoidance. It was found that trout were less likely to pass the turbine than salmon. In the case of both species fish preferentially passed around the turbine rather than passing through the turbine structure. This could have implications for turbine placement.**

Keywords—**Vertical axis hydrokinetic turbine, stream aquarium, Salmonids, collisions risk, fish behaviour**

I. Introduction

An integral player in the fight against climate change is the development and implementation of devices that can extract energy from renewable sources. It has been established that reducing reliance on fossil fuels will help cut greenhouse emissions worldwide [1]-[3]. Technologies that can harness the energy available in our oceans and rivers are a large part of this.

Many recent advancements have been made in renewable energies. Wind and solar power enjoy widespread use, both commercial and private, and there is now an increasing focus on wave and tidal energy as well. Hydrokinetic turbines are examples of such devices; they utilize the energies of flowing water through river systems or tides converting it to electricity.

Paper number: 1488. Environmental impact and appraisal. This study was made possible by a grant from J. Gust. Richert foundation (to J.S.). M. Berry, J, Sundberg and F. Francisco are all at Div. of Electricity, Dept. of Engineering Sciences, Uppsala University. Box 534, S-751 21 Uppsala Sweden. *Corresponding author: jan.sundberg@angstrom.uu.se

Water, moving unidirectional in streams/rivers or bi-directional as tides along the coast, moves turbine blades, and the energy harnessed by this movement is used to generate electricity. Different renewable sources come with their own advantages and disadvantages. The potential energy gain from hydropower is massive compared to wind, for example; estimates have been made that as much as 60% more energy can be gathered from water movement as from air due to the greater density of water [4]. Tidal and wave energy is considered to be more predictable than wind, but the availability of appropriate sites is limiting [5]. The energy landscape in the future is likely to consist of a collaboration of sources, so the varying renewable energy industries need to be 'mutually reinforcing rather than rivals' [6]. It is hoped in the case of energy harvested from marine environments that as much as 7% of the world's electricity demand could be met by 2050 [7].

Fast-flowing rivers can provide a constant supply of energy, thus enabling a greater degree of energy security because of the predictability. This could be particularly useful in isolated communities, where turbines could bring electricity to remote off-grid areas near water sources such as rivers, streams and waterfalls [8]. Historically, electricity has been brought to these types of communities via diesel-driven generators but rising fuel prices is making this less feasible, especially as fuel is often transported long distances. Additionally, generators can bring a host of problems to the local environment namely pollution [4], and increase the global emissions of greenhouse gases. Field studies have been undertaken across the globe to assess the practicality of using turbines to bring power to remote places [4]. One such study in Brazil found that a turbine deployed in a fast flowing river ($2ms^{-1}$) was sufficient to power a nearby medical station [4], [9].

Hydrokinetic turbines also present an alternative to the building of dams; dams can be highly disruptive to river ecosystems both during construction and in their day-to-day operation, notably for migrating fish [2]. Fish species have been known to disappear locally following the installation of dams; in 1999 a study [10] found 20 species were lost following construction of the Petit Saut dam site in French Guiana. Dams have previously been the cause of

ISSN 2309-1983

depletions of Atlantic salmon stocks [11]. In comparison with hydropower dams, hydrokinetic turbines could have a lower environmental impact. Construction of new dams has partly been halted due to concern over the negative environmental impact [2], and it has been argued in some cases that existing dams should be deconstructed to aid restoration of natural environments [12]. This has left a gap for more environmentally friendly technologies to lead the way in riverine hydroelectricity.

Hydrokinetic turbines can be scaled depending on the installation site, they can also be placed in vast arrays or singularly depending on site and intended purpose. Several designs are currently being tested worldwide, but most fall into one of three categories: vertical axis, horizontal axis and reciprocating [5]. Vertical axis designs are gaining in popularity due to their simplicity and suitability in a wide range of scenarios [13]. The design of the vertical axis turbines means that there is no blade tip and in general the rotation speed will be lower; both of these factors reduce the potential danger to fish [14]. For maximum energy yield, turbines will likely be placed in the fastest flowing section of a river; in most cases this will be the middle of the river channel. This is also the portion of river used most often by migrating fish, as it allows them to conserve energy during their long journey [8]. As such it is likely that these fish will be exposed to turbines during their migration.

It is thought that the operational life of deployed turbines will be around 30 years [5, 15, 16], during which time a whole host of different animals are likely to encounter them. Thus, it is important to understand the likely impact on the surrounding environments, and their residents, of deployed turbines. Birds, aquatic mammals and fish are likely to be affected in some way [5], specifically in that they will be exposed to risk of collision with moving parts [12]. Mammals such as the harbour seal, *Phoca vitulina*, frequently use tidal channels to forage, although it has been suggested the chance of such species colliding with a turbine is low [17]. Diving birds also use turbid areas for foraging, e.g. [18], but few studies have assessed the impact of turbines. Diving birds, aquatic mammals and fish are the most likely organisms to be affected in some way [5].

Assessing the impact on fish is vital, and migratory species are of particular interest because of the likelihood of turbines being placed within migratory routes [19]. Atlantic salmon and brown trout are important anadromous species in Sweden both economically and ecologically [20, 21]. The primary concern is physical injury and mortality from direct collisions with turbine blades [12].

Earlier studies on fish have found this risk of blade strikes to be low including both tidal and instream species, e.g. [22, 23], and laboratory experiments, e.g. [19, 24-25], although in several studies fish entered and even passed through the turbine. Also, predictive models have been used in order to estimate collision risk, e.g. [26-28]. But a wide spectrum of other conditions are still to be considered, and thus, more studies are required in order to both fully establish findings and cover the multitude of factors of possible importance.

Of equal importance is to assess the risk of affecting natural behaviours [27]; any novel change to an environment can illicit alterations to behaviours of local organisms. Behavioural changes can be just as important as physical injury, and therefore fitness, markedly for migratory species. There are many ways turbines could potentially affect fish behaviour; they could act as a physical barrier for passage, noise disturbance could deter fish, and interference from electromagnetic fields could also have unforeseen implications [8]. If turbines influence fish such that they avoid passing a turbine altogether, migration could be severely affected and even halted. This could have dire consequences for local populations. Even small delays in migration could also drastically decrease fitness or survival likelihood of fish. Adjusted swimming behaviour in proximity of turbines has been seen in previous experimental studies [23]. If fish avoid areas containing turbines altogether this is equivocal to habitat loss. Another concern is that turbine structures could in fact attract small fishes seeking refuge from predators [5], [12]. The local loss of a species will certainly impact other species within that ecosystem as well [16].

Concern also surrounds the possibility that turbines could, in fact, attract animals. Small fishes may seek refuge from predators [5, 12], which could increase their risk of collision. Broadhurst & Barr [29] suggest that Atlantic pollock, *Pollachius pollachius*, use turbines for protection. Larger predatory species could in turn be attracted to the site by the increased abundance of prey, increasing the risk of collision to large species too. Recorded observations of schooling fish was found to increase at sites with a marine renewable energy installation (MREI), in comparison to a similar site with no MREI. The manner in which these schools utilised the water column was also affected [30].

Monitoring aquatic species *in situ* can be challenging, particularly at sites with energetic waters [5]. However, turbines will ideally be placed in exactly those type of sites. As a result of this difficulty, behavioural responses of fish to manmade objects in fast flowing waters is relatively unknown [5, 22]. It can also be problematic to assess subtle changes to populations for species with large ranges [5], such as migratory fish. Thus controlled experimental studies can be of great assistance when investigating these potentially nuanced changes to fish behaviour. This study will analyse the interaction between juveniles of two salmonid species and a vertical axis hydrokinetic turbine under a range of water velocities. An experimental set-up was used, specifically a stream aquarium with controllable water flow. It is expected that passes of the turbine and avoidance behaviours by fish are likely to differ across the varying water velocity treatments [31] and between the two species. Additional understanding of turbine fish interactions comes from modelling studies many of which exclude avoidance behaviours because of a lack of quantitative data [27], highlighting the importance of gaining greater understanding of fish behaviours exhibited near turbines. The model created by Hammar *et al*. [27] also state that the risk of blade strikes increases with current speed, which highlights the importance of gaining a greater understanding of fish behaviours exhibited near turbines.

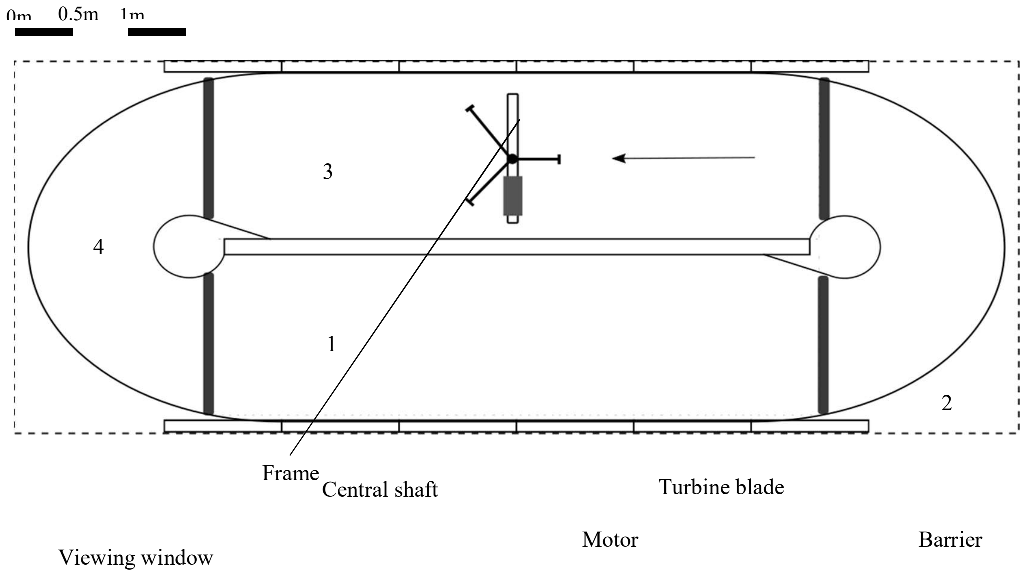

Fig. 1. Schematic of the experimental stream aquarium used in the study. The arrow indicates direction of water flow. 1: holding area, 2: release area, 3: trial area, 4: capture area. Groups of fish were kept in 1 to acclimatise. A single fish would then be guided into 2 prior to a trial. Fish would be released individually from 2 into 3 to begin a trial. 4 was used as an area to easily capture and remove fish after trial.

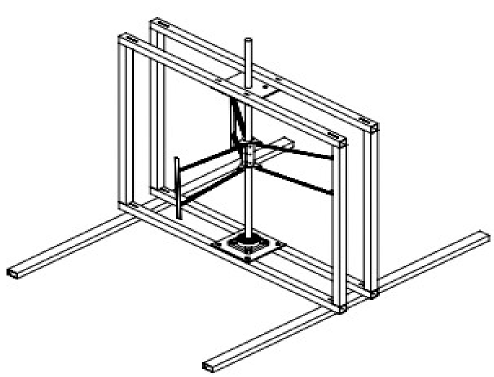

Fig. 2. Schematic drawing of the model vertical axis hydrokinetic turbine within a frame, used for this study.

II. METHOD

A. Stream Aquarium

The experimental stream tank used is located at the Fisheries Research Station in Älvkarleby, Dept. of Aquatic Resources, at the Swedish Agricultural University (SLU).
The 35,000 litre capacity tank (Fig. 1) was filled with a mixture of both groundwater and river water from the neighbouring river Dalälven. The water was approximately 80 cm deep. The incoming groundwater has a different chemical makeup compared to river water [25], which is the natural environment for the fish. However, it was necessary to add groundwater to improve visibility for monitoring during trials. The tank was supplied with a constant flow of new water at approximately 1 litre per second.

The floor of the tank in the holding and trial area is covered in a gravel substrate (approximately 30 cm deep). The other areas of the tank have a sheet-metal bottom. The tank was lit from above with alternate incandescent and fluorescent strip lights; the strip light directly above the turbine was turned off to reduce glare on the water interfering with video recording.

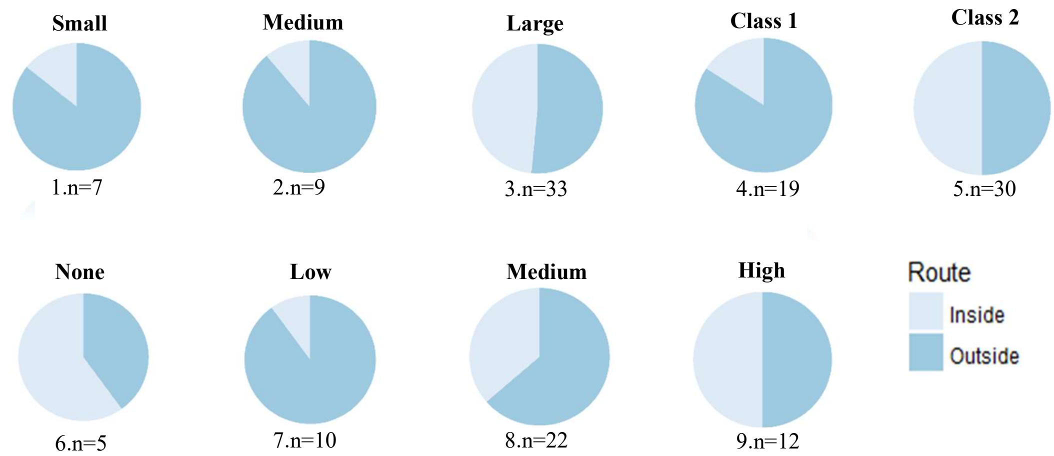

Fig. 3. Charts showing the significance of size, activity class and water velocity on route taken past the turbine. No. 1 to 3 shows how individuals from the three size classes (small, medium and large) differed in route taken. No. 4 to 5 shows how individuals from the two activity classes (class 1 and class 2) differed. No. 6 to 9 shows how route taken differed across the four water velocity treatments (none, low, medium and high). Sample sizes (n=) for all pie charts are shown for both species combined.

The tank has an adjustable, circular water flow. The settings used roughly correlate to 0 m/s, 0.1-0.15 m/s, 0.2-0.25 m/s and 0.3-0.4 m/s, as actual flow varied throughout the tank and was higher in the middle of the corridor where the turbine was placed. Higher water velocities could not be used because of the risk of disrupting the barriers put in place to separate the different areas of the tank as well as making direct observations difficult due to turbulence and the brownish water.

B. Turbine

A vertical axis hydrokinetic model turbine was used for this study, based on the technology developed at Uppsala University [33, 34] which is adapted for operation at low rpm. The turbine was three-bladed attached to a central shaft, which in turn sat within a frame (Fig. 2). The top of the frame sat above the water level and the stabilizing bottom bars were submerged under the substrate in the tank. The frame was positioned in the middle of the stream passage 3.2 m from the barrier separating the release and trial areas. The frame was placed such that its outer edges were 20.5 cm from the tank wall on the left side (facing the direction of the flow of water) and 16.5 cm from the right side wall. The base of the blades was approximately 20 cm from the gravel bottom. The blades were held 32 cm from the central shaft. The blades themselves were 35 cm in length. A motor and associated fan were attached to the top of the frame. The motor directly drove the turbine continuously and was set for 10 rpm for all trials. The rpm was checked weekly during the trial period to check for any motor malfunctions. Tests at the Söderfors site have shown that, for water velocities lower than 0.9m/s, a rotation of at least 10 rpm is needed for energy gain [35].

C. Study Species

Two salmonid species were used: brown trout, *Salmo trutta*, and Atlantic salmon, *Salmo salar*. The fish were farmed at and provided by the fish nursery in Älvkarleby, (SLU). Fish were juveniles in their second year and were transitioning into the smolt stage. 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 towards the sea.

Prior to testing, fish were kept in tanks separate to that of the experimental stream tank. In these, the feeding regime is controlled by an automated system and water was circulated with a constant flow of river water. As such, the temperature and chemical makeup of the water differ from that in the experimental tank. The fish were transferred from these tanks to the holding area of the experimental tank in groups of 5-10 of the same species (species randomly determined). Fish were left at least overnight in the holding area of the experimental tank to acclimatize to the conditions.

D. Trial Protocol

In total of eight different treatments were performed for the study, including two salmonid species and four water velocities), in a fully crossed design. Each treatment had 10 replicates totalling eighty trials. Timed 15 minute trials were conducted for each individual, with a total of 20 hours of observation time. As salmonid behaviour is known to vary depending on period of the day, trials were restricted to a period of 11:00-17:00. A random number generator was used to determine which of the four water velocity settings was to be used for each trial. The water velocity for the upcoming trial was set several minutes prior to allow the fish to adjust their swimming speed accordingly.

Water temperature measurements were taken before each trial using a weighted thermometer lowered into the tank via a rope. During most trails the temperature was between 13-15 C, but as low as 9 C in the first trails in May and as high as 20 C in the last trails in the end of August.

Fish were roughly categorized by eye into one of three size classes (small, medium and large). Small fish were approximately ≤ 10 cm, medium 11-15 cm and large >15 cm. The largest fish was ca 19 cm long. All size categorisations were conducted by the same individual observer. Fish were also taken and measured at random using a ruler, at regular intervals during the study period to reduce the chance of bias.

The fish were monitored throughout the trials by direct human observation (behind a hide) and video cameras at two positions around the turbine. Sony HDR-AS200V action cameras were used. A camera was suspended above the tank directly over the turbine and the other was placed on a tripod outside of the tank so as to view the turbine from the side through the viewing panes of the tank. Recordings were not taken from above during high velocity trials as the movement of the water, rippling and turbulence, made it impossible to see below the surface. During trials the observer was obscured by a hide as much as possible so as not to startle the fish. Recordings from the cameras were used later to confirm and refine data collected by the observer. The two cameras were synchronised and controlled remotely and were recording simultaneously.

Prior to a trial, an individual fish was corralled into the release area from the holding area (Fig. 1) using a net as a guide. To start a trial, a door in the barrier between the release and trial area was raised and the individual was gently corralled through. As soon as the fish crossed the barrier threshold the trial began and video recording started. On commencement of each trial the date and time was recorded. Any instances of active avoidance of the turbine were noted. Active avoidance behaviours included: sudden changes in swimming trajectories within 1m of the turbine; sudden halts in swimming within 1m of the turbine; sudden changes in position in the water column within 1m of the turbine; repeated swimming backwards and forwards up to the turbine (either along the length/width/height of the tank); and general evasive behaviour within 1m of the turbine. Any passes of the turbine were recorded and the time of pass (seconds since start of trial), alignment of the fish (head first or tail first), position relative to the turbine (over/under/around left side/around right side) were noted. Over and under passes were made within the frame of the turbine.

During the trials individuals were categorized into one of two activity classes: mostly explorative (class 1) and mostly timid (class 2). Individuals falling into class 1 spent more than half of the trial time exploring, foraging or being generally active. Those falling into class 2 spent more than half the trial seeking refuge among the substrate, generally still and only moving to maintain their position against the current.

After each trial the individual was corralled into the capture area, where it was caught using a net and transferred into a bucket. The individual was taken outside where it was released into manmade pools connected to the river Dalälven, allowing the fish to continue their natural migration to the sea.

E. Statistical Analysis

The time (seconds from the start of the trial) it took for an individual to pass (if it passed at all) was analysed by creating a linear model and conducting an ANOVA test. Only trials that had pass events were used in the analysis and therefore type III sum of squares was used to take into account the unbalanced nature of the data. To increase the sample size water velocity treatments were combined into low (no flow + low flow) and high (medium flow + high flow). Inspection of the residuals revealed a non-normal distribution and as such a square root transformation was performed on the pass times. Graphical inspection of the residuals as well as a Shapiro-Wilk test ($W=0.95$, $p=0.17$) revealed this was sufficient to normalise the data.

The route taken past the turbine was analysed with a generalized linear model that was assessed by analysis of deviance. During trials there were four possible outcomes for route, however for statistical analysis these were combined into inside the frame (under and over) the turbine and outside (left and right). All pass events were used including multiple passes from a single individual.
Because of the binary nature of the data a binomial distribution was defined. Two size class values were missing from the data (trial numbers 45 and 59); as a logistic regression requires a balanced design the missing values were replaced with the mode, in this case large, this was also done when creating subsequent models. A full model was created with all possible independent variables (date, time, species, water velocity, activity class, size, water temperature). Effect of individual was removed by adding trial number as a random effect to the model. Variables with low deviance (<1) were removed as they do not substantially improve the fit of the model; The model was tested with a logit link function, probit link function and cloglog function; the logit link yielded the lowest residual deviance and thus was used in the final model. A chi-squared test was conducted using single term deletions to remove the effect of factor order.

The active avoidance response was analysed with a generalized linear model that was assessed by analysis of deviance. Because of the binary nature of the data a binomial distribution was defined. A full model was created with all possible independent variables (date, time, species, water velocity, activity class, size, water temperature). The model was tested with a logit link function, probit link function and cloglog function; the logit link yielded the lowest residual deviance and thus was used in the final model. A chi-squared test was conducted using single term deletions.

Whether a pass event occurred was analysed with a generalized linear model that was assessed by analysis of deviance. Because of the binary nature of the data a binomial distribution was defined, a slight overdispersion

TABLE I
RESULTS FROM THE ANALYSIS OF DEVIANCE FOR WHETHER A PASS OCCURRED. FACTORS WITH LOW SCALED DEVIANCE WERE EXCLUDED FROM THE FINAL MODEL; IN THIS CASE, DATE (DEVIANCE = 0.4), WATER TEMPERATURE (DEVIANCE = 0.0006) AND TIME (DEVIANCE = 0.2) WERE DROPPED FROM THE MODEL. SIGNIFICANT RESULTS APPEAR IN BOLD.

	df	Dev.	LLR	p
Size	2	91.4	3.9	0.1
Activity	1	90.6	3.1	0.08
Species	1	94.8	6.8	**0.009**
Velocity	3	91.6	4.1	0.3

TABLE II
RESULTS FROM AN ANOVA TEST ON TIME TAKEN TO PASS (S). NO SIGNIFICANT EFFECT OF SPECIES, WATER VELOCITY OR AN INTERACTION BETWEEN THE TWO WAS FOUND.

	SS	df	F	p
Species	84.9	1	1.6	0.2
Velocity	11.2	1	0.2	0.6
Species x Velocity	167.11	1	3.2	0.09

TABLE III
RESULTS FROM THE ANALYSIS OF DEVIANCE FOR ROUTE TAKEN PAST TURBINE. FACTORS WITH LOW SCALED DEVIANCE WERE EXCLUDED FROM THE FINAL MODEL; IN THIS CASE IN THIS CASE WATER TEMPERATURE (0.005), TIME (0.9) AND SPECIES (0.05) WERE REMOVED.

	df	Dev.	LLR	p
Date	1	43.7	2.3	0.1
Size	2	51.8	10.5	**0.005**
Activity	1	47.2	5.9	**0.01**
Velocity	3	51.7	10.3	**0.02**

TABLE IV
RESULTS FROM THE ANALYSIS OF DEVIANCE FOR ACTIVE AVOIDANCE. SIGNIFICANT RESULTS APPEAR IN BOLD.

	df	Dev.	LLR	p
Date	1	74.2	2.8	0.09
Size	2	74.6	3.2	0.2
Activity	1	82.0	10.6	**0.001**
Temperature	1	72.4	1.1	0.3
Time	1	77.4	6.0	**0.01**
Species	1	73.3	2.0	0.2
Velocity	3	80.5	9.1	**0.03**

was detected so a quasibinomial distribution was used (dispersion factor of 1.2). A full model was created with all Whether a pass event occurred was analysed with a generalized linear model that was assessed by analysis of deviance. Because of the binary nature of the data a possible independent variables (date, time, species, water velocity, activity class, size, water temperature). Variables with low scaled deviance (<1) were dropped from the model as they do not improve the fit of the model. The model was tested with a logit link function, probit link function and cloglog function; the logit link yielded the lowest residual deviance and thus was used in the final model. A chi-squared test was conducted using single term deletions.

III. RESULTS

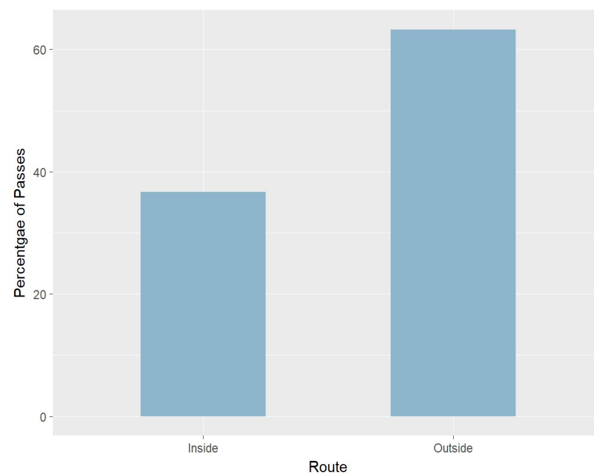

Fig. 4. Route taken, inside or outside the frame, for all passes over all treatments. Percentage of passes taken either inside (through turbine frame) or outside (around turbine frame) are displayed.

No collision or even close contacts between fish and the turbine was observed. General patterns on the influence of fish size, activity and velocity on fish passes are shown in Fig. 3. Whether an individual passed near the turbine at all during the trial was found to be significantly associated with species (LLR=6.8, p=0.009, Table I). More salmon passed the turbine than trout, 31 passes were recorded during salmon trials and 18 during trout trials.

When considering time taken for an individual to pass from commencement of a trial no significant effect of species (F=1.6, p=0.2) or water velocity (F=0.2, p=0.6) was found (Table II).

Generally, more passes were recorded outside of the turbine frame than inside (Fig. 4). Size of fish was found to be significant (LLR=10.5, p=0.005), and it appears that both small and medium individuals pass outside more whereas large individuals show less preference (Fig. 3, Table III). Activity class (LLR=5.9, p=0.01) was also found to be significant with more timid (activity class 1, Fig. 5. Table IV) fish passing outside of the turbine frame more frequently, more explorative fish were equally likely to pass outside as inside the turbine frame. Water velocity was also found to be significant (LLR=10.3, p=0.02); at no velocity fish swam inside the frame more often, at low and medium velocities fish swam outside more often, and at the highest velocity fish swam equally as often inside as outside the frame. No significance of date was found (LLR=2.3, p=0.1).

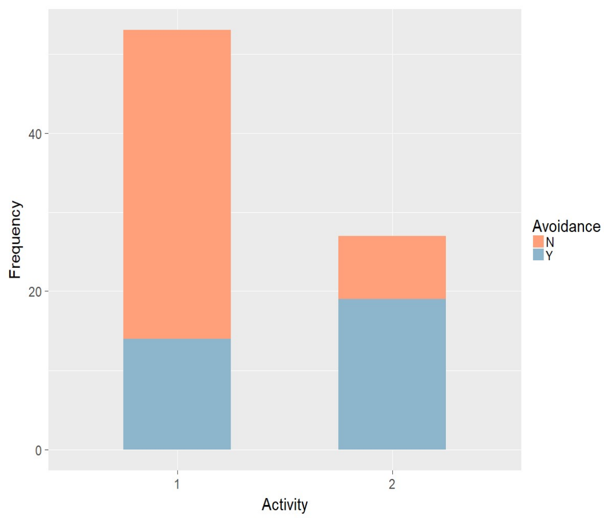

Fig. 5. Responses of active avoidance of the turbine varying across the two activity classes (Activity class 1 = timid, activity class 2 = explorative).

Instances of active avoidance were recorded and analysed, this yielded some significant results. Activity class was found to be significant (LLR=10.6, p=0.001), more timid individuals from activity class 1 were less likely to exhibit active avoidance of the turbine, more explorative individuals from activity class 2 exhibited active avoidance more often than not. Time was another factor found to have a significant effect on active avoidance (LLR=6.0, p=0.01), separating data from trials into hourly slots revealed less active avoidance earlier in the day (Fig. 6).

No significant result was found in the analysis for date (LLR=2.8, p=0.09), size class (LLR=3.2, p=0.2), water temperature (LLR=1.1, p=0.3) or species (LLR=2.0, p=0.2).

IV. DISCUSSION

A promising result was that no collisions were recorded throughout the study. This key finding suggests, at least for juvenile salmonids under these circumstances, that the risk of physical injury is minimal, this is in keeping with previous studies [19, 22-25]. The behavioural changes observed were a little more complex to assess, and several points were raised.

The two species behaved differently which suggesting species differ in response to turbine exposure and which may have implications in the planning for siting of turbines. In general, salmon were more likely to pass the turbine than trout; 31 passes were observed with salmon and 18 with trout. This could have been caused by the fact that trout swam closer to the bottom whereas salmon utilised more of the water column; perhaps the proximity of the base of the turbine blades to the tank bottom inhibited the trout. It could also be that as the salmon simply swam more than trout and there was therefore a greater chance they would pass during a 15-minute period. Either way, a low number of trout passes could have implications for deployment in areas with known trout populations. If the presence of turbines interferes with trout migration, local populations could decline. Placement of turbines would have to be carefully considered. Perhaps ensuring that enough space is left around turbines could combat this [22] this is also supported by the finding that both salmonid species preferentially passed around the turbine rather than swimming through it (Fig. 4). A suggestion could be to leave larger gaps underneath turbines to enable fish to pass. This would need to be investigated further. For both salmon and trout, more passes were observed swimming around the turbine as opposed to through the turbine

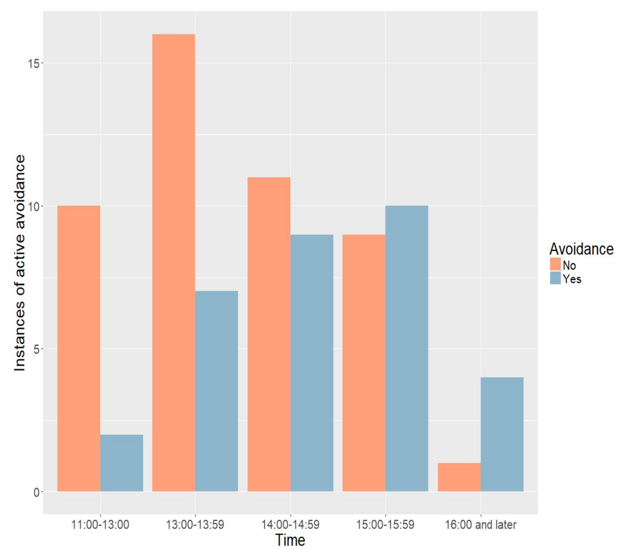

Fig. 6. The relationship between time of day and active avoidance. Time is blocked into hourly periods, a time block of three hours was used from 11:00h - 13:00 h because of there were much fewer trials conducted during this time, similarly all trials after 16:00 h were grouped (the latest trial was conducted at 17:10 h). The frequencies of active avoidance are shown in blue and number of individuals that showed no signs of active avoidance are depicted in orange.

structure (Fig. 2). This suggests that turbines should be placed with large gaps also on either side. Possibly, if arrays of turbines are to be deployed, sufficient room would have to be left between units to allow for fish to be able to swim around. Further tests with arrays would be needed to judge if behaviour differs when faced with multiple turbines. Modelling has shown that arrays are highly likely to alter tidal currents, specifically currents could increase directly to the sides of turbines [36], which was the area this study found to be most used by individual fish, albeit past a singular turbine only. A field study in Söderfors also found water velocities to decrease in the wake of a turbine [33]. This potential change in currents, when large arrays are deployed, could drastically change how a fish may behave when faced with an area of many turbines.

Fish were more commonly observed to swim along the inner tile wall in a tank. This could have been an experimental artefact if fish were reluctant to swim along the outer side, along the glass wall. This may also explain why they were more likely to swim around the turbine frame. This could also explain why more timid fish (activity class 2) were found to go around the turbine more often; the wall acted as a safer haven for the fish compared to the other glass side. This could also imply that turbines should be placed away from river edges. However, different species are known to utilise different parts of a river, e.g. [37], wherefore local species compositions may always have to be determined before localisations of turbines are determined. It was also found that the preference of swimming around the frame was weaker for larger fish, however it is worth bearing in mind that the sample sizes for both small and medium fish were small and as such this effect is likely to be irrelevant.

At middling water velocities (low and medium) fish tended to swim around the turbine frame as opposed to through. At high velocities this pattern seemed to disappear and for no velocity the sample size was too small for meaningful analysis. It could be that at higher velocities fish have less control of their swimming and thus could be forced through the turbine. It could also be related to the suggestion that in some cases fish activity sample varies less with increasing current speed [27]. However, it seems the fish retain enough control to manoeuvre past without coming into contact with any of the turbine components even at the higher velocity tested in this experiment.

Instances of active avoidance of the turbine were common although seemed to be influenced by both time and activity class. It is fairly intuitive that more active fish (activity class 1) avoided the turbine more often. More timid fish (activity class 2), showed less active avoidance of the turbine, but this is likely due to the reduced chance of even encountering the turbine; many trials with timid fish ended without the fish moving close enough to react to the turbine or even moving at all. As for the effect of time, it appears that fish were less likely to avoid the turbine in trials that took place earlier in the day, this was unexpected as the time period over which trials took place was reasonably restricted. This finding, of behaviour varying with time, also highlights the need for studies over different periods, as many species follow seasonal, dial and tidal cycles as exemplified by studies in tidal channels [38-40], affecting also numbers present at particular sites.

In many cases fish that exhibited avoidance behaviours did go on to pass the turbine. Though initially unsure of the turbine, they ultimately were not inhibited by it and passed. This seemed particularly true for salmon. Trout, however, did not seem to differ much in whether passing or not passing after active avoidance behaviour, but it is possible this was an artefact of the low number of trout passes total.

In terms of time (s), no significance was found for species or water velocity. This could imply that the reaction of the fish to the turbine is uninhibited to some extent by the relatively low velocities tested in this scenario. However, this should be interpreted with caution due to the large ranges in the data.

During the study period (May to August), fish were transitioning into the smolt stage. Towards the end of the study (from 27/07/18) significant silvering was noticed, indicating the fish were near completion of the transition to smolt. It is worth noting this could have influenced fish behaviour, although no significance of date was found during statistical analysis. Temperature also varied much more than anticipated due to the record highs in Sweden in the summer 2018, however this didn't reveal any significant effect during the study.

Some issues arose during the study around the experimental set up. From personal observation it seems fish were potentially disturbed by the noise of the motor. This is unlikely to be a problem in a real environment as turbines are likely to be deployed at sites with energetic waters with considerable ambient noise, which will mask any noise produced by the turbines themselves [5], however, others have noted effects on fish form turbine noise [41]. Once fish had been released into the trial area many would simply stay near the barrier and thus did not encounter the turbine. For future trials, the distance to the turbine could perhaps be reduced to encourage fish to interact.

Video footage was not as informative as initially hoped as there were problems with visibility. Condensation quickly built up on the viewing panes which affected video quality of the side view. Footage taken from above was frequently distorted by ripples and turbulence in the water. The quality of the videos sometimes made it difficult to identify the fish against the gravel bottom. However, the useable footage did match with the results gathered by the observer and could be further analysed in the future. It also provides a record that can be easily shared and compared against future trials with a similar setup.

Overall, this first study shows that the experimental setup is serving its purpose and highlights that downstream migrating juvenile salmonids are capable of avoiding physical injury from direct contact with a vertical axis hydrokinetic turbine under the conditions tested. This step forward in understanding the likely ecological effect of deployment of such devices is vital for the progression of renewable energies in the hydro sector. Fish were clearly aware of the turbine and exhibited subsequent behavioural changes. Ideally, a similar trial will be run with no turbine present to compare 'normal' behaviour with that of this study. It is worth bearing in mind that trials were limited to 15 minute periods. It would be preferential to consolidate experimental studies such as these with *in situ* studies under natural conditions over longer periods of time to fully gauge whether migration would be significantly affected.

Further studies are also required to assess in depth how salmonids, and other species, react under different conditions. Reduced line of sight under night conditions may result in more collisions or more course alterations in closer proximity to the turbines [22, 42]. In extremely dark conditions some salmonids may struggle to see an object until they are very close, especially in turbid conditions [43]. Migrating fish are known to be more active at night [44], as many species and age and size classes are in general, e.g. [45], further highlighting the need for night trials with Atlantic salmon and brown trout, specially, and other fish species in general. Though, most likely the use of pit tags will be needed for observations in darker light regimes, e.g. [19]. It will also be necessary to perform group trials to see how schooling behaviour affects rates of passage. This could be particularly interesting as Atlantic salmon are known to complete their journey downstream as smolts in kin groups [46].

ACKNOWLEDGEMENT

We would like to thank the personnel at the Fisheries Research Station in Älvkarleby, Dept. of Aquatic Resources, at the Swedish Agricultural University, and particularly Ann-Britt Florin and Erik Petersson. We would also like to thank two anonymous reviewer who's comment improved the manuscript. The experimental work, conducted under licenses no. 5.8.18-02928/2018, complied with the standards and procedures stipulated by the Swedish Ministry of Agriculture.

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