The potential of water spray to attract Atlantic salmon kelt (*Salmo salar*) in a regulated river

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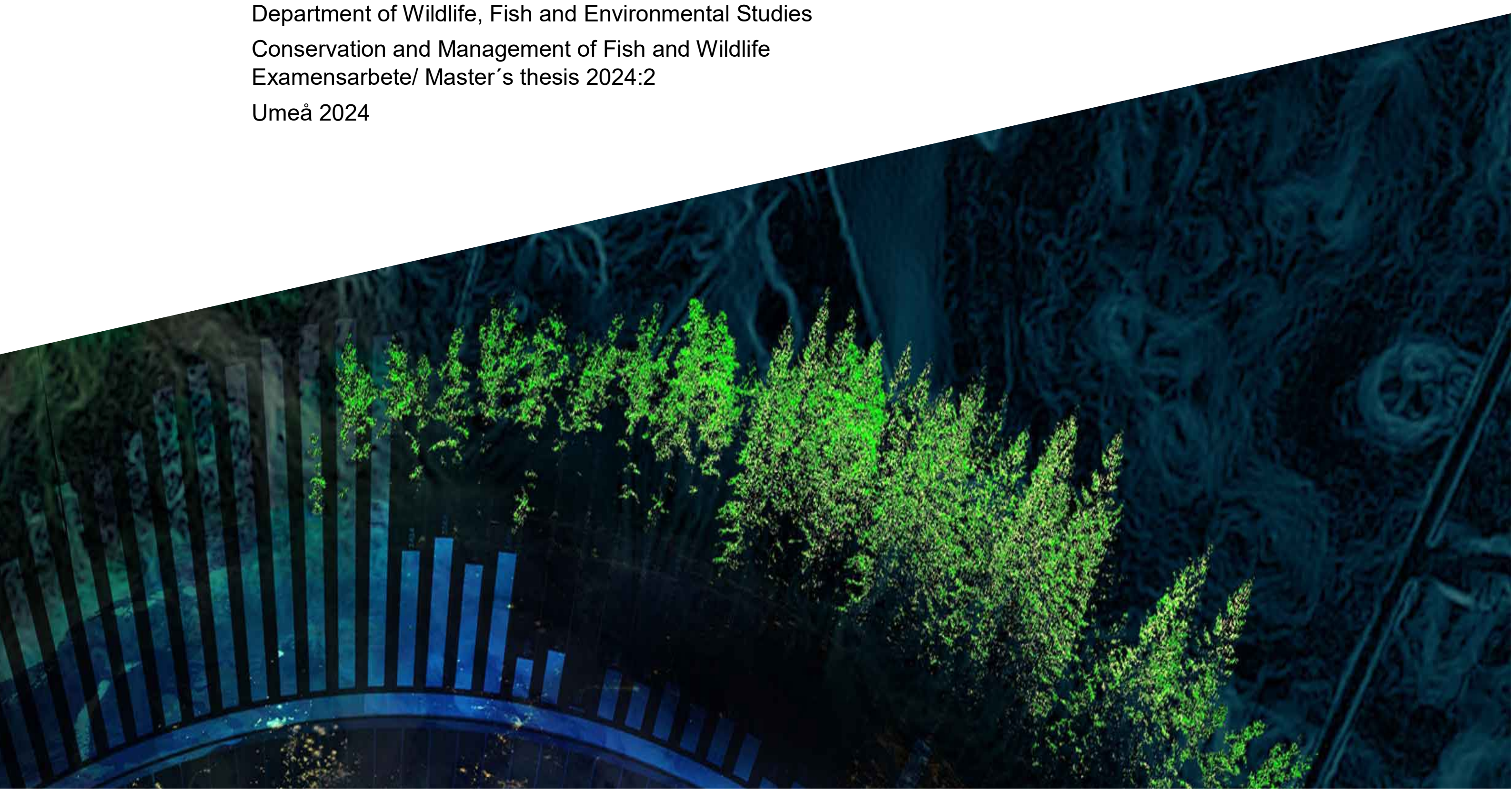

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Abstract

This study investigates the downstream migration challenges faced by Atlantic salmon (Salmo salar) during the post-spawning kelt life stage at hydropower dams. Surviving kelts can live on to spawn multiple times, and those repeat spawners can be of great importance because they can increase recruitment and population resilience. However, kelt migrating downstream are unlikely to survive passage through the turbines of a hydropower dam. In this study, sonar and acoustic telemetry were employed above the Stornorrfors hydropower dam to evaluate the effectiveness of water spray as a potential attractant for kelt. If successful, such a method could potentially be used to facilitate methods to either capture or guide kelt towards safer passages.

The findings of our study only partially support the hypothesis that surface spraying would attract salmon kelt. Sonar data, which do not allow differentiation between species, revealed that larger fish exhibited longer residence times near the active spray. While this indicates that water spray might hold the attention of larger fish, further results were more nuanced. Specifically, a significant decrease in fish count when the spray was on during twilight hours suggested a possible repellent effect. While such a decrease was not observed during daylight, the daylight data did not indicate a significant positive effect of water spray on fish count. Telemetry data revealed a non-directional increase in swimming speeds when the spray was active, which could potentially also be linked to a repellent effect. Notably, the pump feeding the water spray was found to produce a great amount of noise, potentially triggering a flight response. Furthermore, the mean delay time from first to last detection was 19.2 minutes, which is considerably shorter than reported by previous studies (> 20 h), questioning the impact of overwintering conditions, physiological factors, and environmental conditions. These short delay times in effect lead to a decreased sample size, limiting the generalisability of the results.

However, our results serve to increase the understanding of kelt behaviour in the intake channel, highlighting locations where future measures could be best implemented, and suggesting how experimental setups could be improved in the future.

Keywords: *Atlantic salmon, iteroparous, kelt, hydropower, water spray, attraction*

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1. Introduction

Atlantic salmon (*Salmo salar*) are of immense ecological, economic, and cultural importance, serving as a keystone species in various ecosystems (Myrvold et al., 2019). In recent decades, Atlantic salmon populations have faced significant declines, due to factors such as overharvesting, habitat loss, and the presence of migration barriers, such as hydropower dams (Ahlbeck-Bergendahl et al., 2019; Dadswell et al., 2022).

One of the many fascinating aspects of some Atlantic salmon populations is their anadromous life cycle, which involves migration between saltwater and freshwater habitats (Berg, 1985; Thorstad et al., 2011). However, this complexity contributes to the vulnerability of these populations and presents challenges for the management of Atlantic salmon (Thorstad et al., 2008). A distinct feature of some populations of Atlantic Salmon is iteroparity, a life history trait that allows fish to potentially spawn multiple times (Bordeleau et al., 2020). These repeat spawners, as described by Thorstad et al. (2008), play a crucial role in improving population resilience by acting as a buffer and significantly improving recruitment (Baktoft et al., 2020). Female repeat spawners can comprise up to 20% of the spawning population in unregulated rivers and contribute a disproportionately large number of eggs, exceeding first-time spawners by a factor as high as 2.8 (Bordeleau et al., 2020; Thorstad et al., 2008).

The upstream migration obstacles of Atlantic salmon have received considerable attention from researchers and governments, and successful mitigation measures, such as fish ladders at hydropower dams, have been widely established (Larinier and Travade, 2002). Although the challenges associated with downstream migration during the post-spawning kelt life stage have been recognised, they have been addressed to a lesser extent (Larinier and Travade, 2002; Vikström et al., 2020). Therefore, in both anadromous and iteroparous populations, salmon can reach their spawning habitats, but when migrating back to the sea, they likely perish when encountering hydropower turbines (Byström, 2020; Vikström et al., 2020). While physical barriers, such as weirs and baffles, have been successful in guiding kelt towards safer passages under certain conditions, their feasibility decreases in larger rivers because of lower efficiency and economic constraints (Larinier and Travade, 2002; Leander et al., 2023). Alternative methods using bubbles, light, or sound to guide smolt and kelt have been explored to varying degrees, but significant knowledge gaps persist, particularly for larger rivers and the kelt life stage (Knudsen et al., 1994; Leander et al., 2023, 2021; Lindberg, 2011).

This study aims to address the issues of salmon kelt downstream migration obstacles caused by hydropower dams. Specifically, to assess the potential of employing water spray above the Stornorrfors power plant to attract kelt, as well as to monitor fish behaviour using sonar and acoustic telemetry. The successful attraction of kelt using water spray would serve as a foundation for developing new methods and solutions, to safeguard their downstream migration, such as capturing them or guiding them toward safer downstream passages. Previous studies have found that kelt hesitate in the intake channel at Stornorrfors for more than 20 hours, on average, before passing through the turbines (Byström, 2020; Lundqvist et al., 2015). This period of hesitation can potentially be used to provide a stimulus to the kelt and to gain their attention. Additionally, Calles et al. (2012) documented kelt actively searching for safe passages at hydropower dams, indicating their potential responsiveness to directed stimuli. Furthermore, studies have shown that if surface spill gates are present, kelt often opt to pass via these routes rather than navigating through the turbines, further emphasising the potential of surface-orientated methods (Calles & Greenberg, 2005; Calles & Greenberg, 2009). It is conceivable that the noise and physical disturbance created by a surface spillway may have similarities to those produced by water spray on the surface, thus potentially gaining the attention of kelt during their search for a safe passage. Therefore, our central hypothesis posits that water spray on the surface of the river can be a method to attract kelt above the Stornorrfors power station.

2. Methods

2.1 Study site

The study site was situated at the intake channel of the Stornorrfors power station, located below the confluence of the Vindelälven and Umeälven rivers, approximately 20 km from the coast (Figure 1). Vindelälven, the largest tributary of Umeälven, plays a crucial role in the ecosystem, offering accessible spawning grounds to Atlantic salmon due to the absence of man-made obstacles (Lundqvist et al., 2008; Östergren and Rivinoja, 2008). The Stornorrfors power plant is the only dam obstructing salmon migration to Vindelälven. Upstream of the study site, the Umeälven river system presents impassable obstacles for salmon (Lundqvist et al., 2008). Although the Stornorrfors dam allows upstream migration via a fish ladder, downstream migrating kelt still face challenges (Leander et al., 2021; Lundqvist et al., 2008). A downstream guidance structure has been installed above the fish ladder in Stornorrfors, however, data from Passive Integrated Transponder (PIT)-tagged kelt using the bypass downstream suggest that passage efficiency is low (Lundqvist et al., 2015). Interestingly, previous studies have highlighted notable kelt behaviour patterns in the Stornorrfors dam intake channel. Specifically, research indicates that kelt exhibit a hesitancy before passing through the turbines (Byström, 2020; Lundqvist et al., 2015). This observed behaviour underscores the suitability of the location to test our hypothesis. Furthermore, the chosen site offered road access and a flat space on the shore, facilitating the transportation of the equipment and placement of the storage container housing the data collection equipment. The site was advantageous not only due to its physical characteristics but also due to the availability of electrical power, essential for the operation of our equipment.

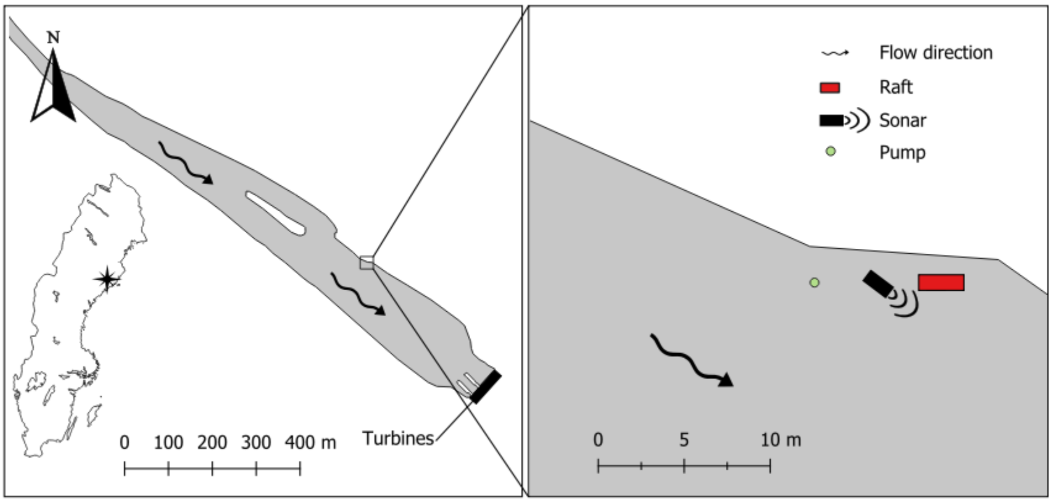

Figure 1. Map of the intake channel at the Stornorrfors power station (light grey) and turbines (black square, left tile). The black star on the map inset in the left tile shows the geographical location in Sweden. The right tile shows the experimental setup with spray raft, pump, and sonar.

2.2 Spray raft

A spray raft measuring 2.2 x 4.8 metres was placed along the bank of the Stornorrfors intake channel, approximately 360 metres upstream of the dam on the left channel side (Figure 1). This raft consisted of a spray nozzle mounted on a floating platform that was anchored to the bank using metal rods connected to concrete blocks on the shore (Figure 2). This anchoring mechanism was designed to maintain the raft's fixed position while accommodating fluctuations in water levels. The spray nozzle was connected to a water pipe that, in turn, received water from a submerged pump (WEDA D40N, 3.4 kW, 1320 l/min) positioned approximately 10 metres upstream of the raft. The pump was controlled by a smart switch (Nedis Smart Life SmartPlug, precision ±30 s) and operated on a schedule of one hour on and one hour off.

To assess the amplitude of pump noise relative to water spray and background sounds, hydrophone recordings were made adjacent to the raft at a depth of one metre (Zoom H5, Aquarian Audio H2d). Additional recordings were taken on the opposite side of the intake channel (Audacity 3.3.2, wave stats).

Figure 2. Spray raft during treatment (pump on). Concrete anchor block visible in the bottom right. Sonar is located underwater right (upstream) of the raft.

2.3 Sonar

On the upstream side of the raft, a Sound Metrics ARIS Explorer 3000 sonar device was deployed. The device was attached to a metal stand positioned on the riverbed. The sonar was configured to record at a rate of 5.6 frames per second (fps) and orientated to keep the surface disturbance caused by the spray within its field of view (FOV), at a range of approximately eight metres (Figure 3). The sonar has a range of 14 metres, allowing the monitoring of fish in proximity to the spray. Sonar data was continuously recorded from May 21st to June 26th. Due to the growth of water plants in the FOV and technical issues with the ARIS, only the first 30 days of sonar data could be used for analysis. On site, a computer was used to run the ARIScope software (version 2.7, Sound Metrics) for sonar data collection. Data were saved every hour to an external hard drive and automatically backed up to the cloud storage daily. While pike (*Esox lucius*) and brown trout (*Salmo trutta*) could potentially have generated echoes of similar size to salmon, extensive sampling did not detect any pike in the area (Leander et al., 2023). However, it is not feasible to distinguish between salmon and brown trout based on the sonar footage.

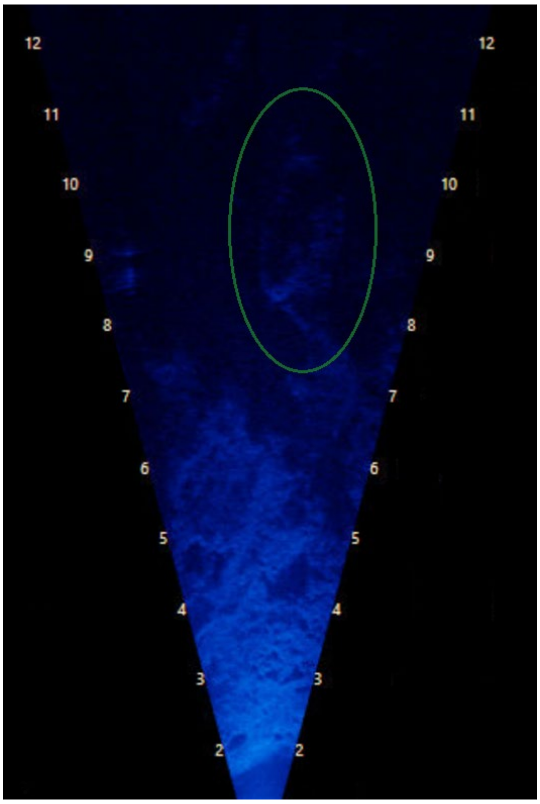

Figure 3. Screenshot of sonar, taken in ARISFish. Surface spray is marked (green ellipse) at a range of approximately eight to eleven metres.

2.3.1 Sonar data curation and analysis

Sonar data screening was conducted using the software ARISFish (version 2.6.3; Sound Metrics). To address the time constraints caused by manual screening, four hours of data (two hours of treatment and two hours of control) were selected from each day. The selected treatment hours were advanced by two hours each day, while the selected control hours were correspondingly regressed by two hours each day. This design aimed to minimise environmental bias, by analysing control and treatment hours during different times of day over the course of the study. Consequently, over a 30-day period, a total of 120 hours of data were analysed. However, it is important to note that not all sonar data selected for the analysis were complete: five hours (three treatment and two control) were incomplete, corrupt, or missing. In such cases, the data were replaced by selecting the closest available hour. Refer to Appendix 3 for a detailed schedule overview. Fish detections were marked when the echo was clearly identifiable as a fish that was sufficiently long (approximately 25 cm or greater) to be accurately measured using ARISFish. When a fish left the FOV of the ARIS, a subsequent encounter was treated as a novel detection. However, to assess the possibility that the same individual could be recorded multiple times, fish observations within a range of two minutes were screened for detections of a similar length (within a tolerance of ± 5%). The residence time was determined by calculating the time between the first and last detections of a fish within the FOV of the sonar.

2.3.2 Fish count

Sonar data used to evaluate fish count consisted of fish count per hour and size. Additionally, turbine flow data (subsequently referred to as “flow”) in m^3/s was provided in 5-minute resolution by Vattenfall. Relationships between fish count, treatment, and flow were explored using generalised negative binominal linear models. As our study was focused on the investigation of kelt, only fish with a length greater than 40 cm were considered for analysis. To better capture variations in diurnal behaviour patterns, the twilight hours (20:00-04:00) and daylight hours (04:00-20:00) were modelled separately. The count of fish greater than 40 cm served as a response variable in these models. Both models used the average flow (calculated from 5-minute data for each respective hour), spray status (treatment and control) and time (grouped into 4-hour blocks) as predictors. To further understand the behavioural responses of fish to the spray, both models were additionally run with modified data, excluding the first 10 minutes after the spray was activated or deactivated. This was done to determine whether the impact of spray would differ after potential immediate responses, such as a flight response.

2.3.3 Residence time

The relationship between residence time in the spray area and treatment was explored using a Mann-Whitney U test after testing the data with a Shapiro-Wilk test for normality. Due to time constraints and the focus on kelt, the analysis considered only the largest observed fish. Therefore, the 60 largest fish were selected to compare treatment (pump “on”, n = 30, mean (±1SD) = 68.06 ± 16.06 cm) and control (pump “off”, n = 30, mean (±1SD) = 79.81 ± 11.70 cm), respectively. The conducted test aimed to determine whether there was a statistically significant difference in the residence times of the fish between the spray being on versus off. All analyses were performed using R (version 4.3.1; R Core Team 2023).

2.4 Telemetry

In the autumn of 2022, a total of 45 salmon (wild, n = 17; hatchery-reared, n = 28; females, n = 17; males, n = 28) were captured utilising nets below the dam so they could spawn and subsequently overwinter in the hatchery. No feeding of the fish was carried out while they were kept in the hatchery (pers. com. Å. Forssen

21.12.2023). To monitor their downstream migration, the kelt were equipped with acoustic telemetry tags before being released in spring. During the tagging procedure, which took place on April 24th and 25th, the salmon were individually netted from the hatchery tank, transferred to an oxygenated tank, and anaesthetised with MS222. The transmitters (Vemco V9TP-2x, weight in air: 4.9 g, length: 31 mm) were then surgically implanted in the body captivity through an incision of approximately 15 mm in length. The fish were subsequently returned to a recovery tank and closely monitored until they had regained their equilibrium. The tagged kelts had a mean weight (M) of (±1 S.D.) 3.3 ± 1.8 kg (range= 0.7-8.96 kg) and total length (L) of (±1 S.D.) of 75 cm ± 14.5 cm (range = 49-110 cm). Condition factor (K) was calculated using the following formula:

$$K = 100 \cdot \frac{M}{L^3}$$

resulting in a mean (±1 S.D.) of 0.71 ± 0.09 (range = 0.51-0.91). Most kelts (n = 40) had also previously been PIT-tagged. Of the 45 tagged kelts, two did not survive until the release date, approximately four weeks after tagging. The remaining 43 kelt were released in the confluence area of Umeälven and Vindelälven, approximately 10 km upstream of the study site. Release took place on two consecutive days, the first half on May 22nd between 12:30 and 17:30 and the second half on May 23rd between 07:30 and 14:30.

2.4.1 Telemetry data curation and analysis

Telemetry data were filtered to remove instances where the swimming speed exceeded 5 m/s, the turning angles exceeded 165° (up to 0.5-metre track length), and 155° (up to 1-metre track length). This filtering was performed according to the Leander et al. (2019) telemetry data filtering method, to remove any false detections in the data set. Additionally, false track points laying outside of water were discarded. Initial plots were generated to determine swimming speeds, followed by colour-coding individual tracks according to their respective treatment or control conditions. This facilitated the assessment of the presence of kelt during the treatment (spray on) and control (spray off) phases.

2.4.2 Delay in the intake channel

Filtered telemetry data from the 35 kelt that were detected in the intake channel were analysed to investigate delay times. The delay time, defined as the difference between the first and final detection time of a kelt in the intake channel, was calculated for each individual. To analyse the impact of different variables on kelt residence times within the intake channel, a generalised linear model (GLM) with logarithmically transformed delay time as response variable was used. The model assessed the following variables on residence time: significance of the condition factor (K), flow during the first detection, length, sex, and origin (wild versus hatchery-reared).

2.4.3 Swimming speed

Our study aimed to explore whether differences in swimming speed could be a potential indicator of the reaction to water spray. The emphasis was placed on the direction of movement, with selection only of track segments pointing directly towards or away from the raft and including a 20-metre buffer zone around the raft. Furthermore, only track segments that began (direction away) or ended (direction towards) within a radius of 200 metres were considered (Figure 6). Four distinct groups were defined based on the combination of two factors: treatment state (control or treatment) and direction of movement (towards or away from spray raft). For this model, only individuals with observations in all four groups were considered (n = 3). After a square-root transformation of the response variable, a generalised additive model (GAM) was fitted. The response variable was modelled against the flow, individual ID, pump state, and direction. The model included smooth terms for flow by direction to address non-linear effects.

2.4.4 Movement in the intake channel

To improve the understanding of fish movement patterns within the intake channel, heat maps were generated to determine areas where tagged kelt spent the most time. To avoid individuals with longer delay times, and therefore more detections dominating the heat map, individuals were weighted according to the number of total detections.

Separate maps were created, differentiating between individual delay times of less than or more than one hour. This allowed an illustration of the spatial distribution difference of those fish that passed through the channel quickly and those fish that hesitated before entering the turbines. Furthermore, for fish with a delay of more than an hour, the data set was divided into two distinct groups: one for the treatment condition (spray on) and one for the control condition (spray off). This division allowed visualisation of whether the fish exhibited different location preferences in response to treatment versus the control environment (Figure 8).

3. Results

3.1 Hydrophone recordings

The hydrophone recording adjacent to the raft revealed notable acoustic characteristics; surprisingly, the sound of the water spray was indistinguishable from the pump noise. Notably, when the pump was activated the sound pressure level (ΔSPL) increased by 15.4 dB. This corresponds to an increase in sound pressure by a factor (z) of 5.88, calculated using the formula:

$$z = 10^{\frac{\Delta SPL}{20}}$$

3.2 Sonar data

A total of 1139 fish were detected and measured in the analysis of the 120 hours of sonar footage (treatment, n = 493; control, n = 646). Of these, 241 detections were of fish measuring more than 40 cm in length (treatment, n = 125; control, n = 116). A screening was carried out to assess the probability that the same individual was counted multiple times by comparing the sizes of the detected fish within a margin of ± 5% over a time span of two minutes. This method revealed that for the control condition, three individuals were potentially counted twice. Similarly, for the treatment condition, four individuals were potentially counted twice, and one individual was possibly recorded as many as three times.

3.2.1 Fish count

The count data revealed that the effect of treatment (spray on) on the fish count (> 40 cm) varied depending on the time of day (Figure 4). Separate GLMs using a negative binominal distribution were used to analyse the count data during daylight or twilight hours. During the twilight hours (20:00 - 04:00), a significant ($p = 0.006$) negative coefficient for treatment was observed, indicating that a decrease in fish count was associated with the spray being on.

In contrast, during daylight hours, a positive coefficient of treatment was detected. however, this coefficient was not statistically significant (p = 0.081). Both models determined that flow is not a significant predictor of fish count (Table 1).

Table 1. Results of the GLM daylight and twilight models, showing coefficients with fish count as response variable. The significant predictors (p) are shown in ***bold****.*

Coefficients	**Estimate**	**Std. Error**	**z value**	**Pr(>|t|)**
<u>Daylight</u>				
Treatment	0.408	0.277	1.713	0.081
Flow	<-0.001	<0.001	-0.950	0.341
<u>Twilight</u>				
Treatment	-0.732	0.268	-2.731	**0.006**
Flow	<0.001	<0.001	0.830	0.406

The modified analysis, where the initial 10 minutes post-spray change data were excluded to detect changes in count after a potential immediate response, continued to show a time-of-day dependent effect of the treatment on fish count. The flow remained a non-significant predictor of fish count for both modified daylight and twilight models (Table 2).

Table 2. Results of the modified GLM daylight and twilight models, omitting data of the first 10 minutes post-spray change. Showing coefficients with fish count as response variable. The significant predictors (p) are shown in ***bold****.*

Coefficients	**Estimate**	**Std. Error**	**z value**	**Pr(>|t|)**
<u>Daylight</u>				
Treatment	0.405	0.287	1.409	0.159
Flow	<-0.001	<0.001	-0.530	0.597
<u>Twilight</u>				
Treatment	-0.562	0.287	-1.957	**0.050**
Flow	<0.001	<0.001	1.262	0.207

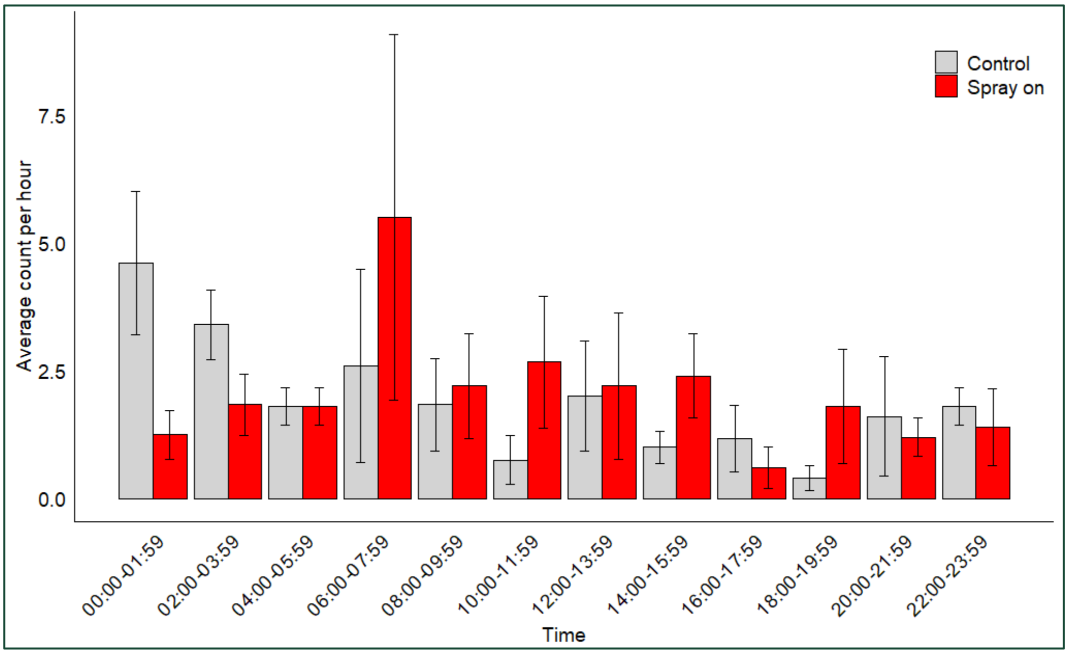

Figure 4. Average number of fish >40cm per hour, for control (grey) and treatment (red). Error bars showing ±1S.E.

3.2.2 Residence time

The average residence time in the FOV of the sonar for the 60 largest fish detected differed depending on whether the spray was on or off, with large fish spending more time around the spray when it was turned on, compared to when it was off (Figure 5). The Shapiro-Wilk normality test indicated that residence time data were not normally distributed ($W = 0.387$, $p = <0.0001$). Sequentially, a non-parametric Wilcoxon rank-sum test was chosen due to its suitability comparing differences between two independent samples when the data do not follow a normal distribution. When the spray was turned off, the recorded mean (±1 S.E.) residence time was 31.51 ± 10.62 seconds. In contrast, with the spray turned on, the mean (±1S.E.) residence time increased significantly to 116.42 ± 42.97 seconds (Figure 5), as indicated by a Wilcoxon test ($W = 208$, $p = 0.0003$).

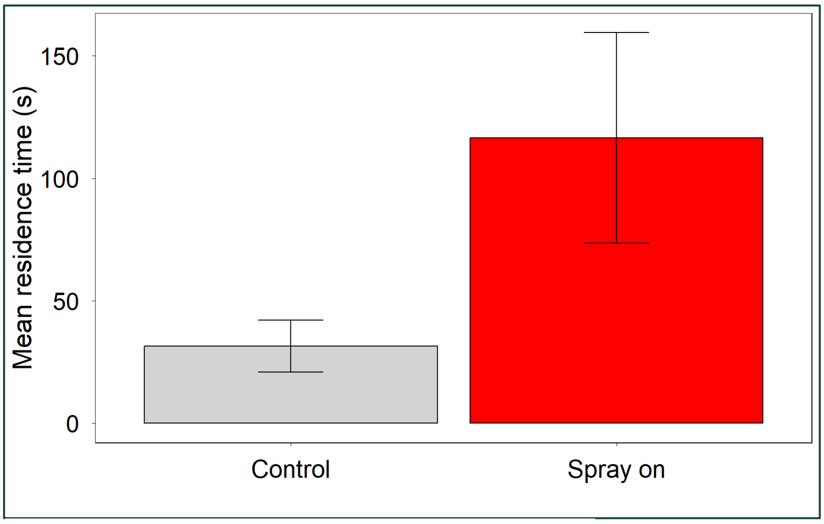

Figure 5. Mean residence time of 60 largest fish with spray turned off (control) and spray turned on (treatment). Error bars showing ±1 S.E.

3.3 Telemetry data

3.3.1 Delay time in the intake channel

Of the 43 kelt released, 19 % (n = 8) did not reach the intake channel during the study period and could not be considered for analysis. A total of 35 kelt successfully reached the intake channel, arriving over several days between May 22 and May 26 (Appendix 4). The data revealed a median delay from first to last detection of 19.2 minutes. The range was between 0.1 hours and 515.6 hours. Some 69% (n = 24) of the detected kelt had a delay time in the intake channel of less than one hour. Of the total number of tagged kelt reaching the intake channel, 37% (n = 13) were detected during both the treatment and control phases, 28% (n = 10) were detected exclusively in the control phase, and 35% (n = 12) were detected only in the treatment phase.

A GLM was fitted to the data of the 35 detected kelt to determine which factors might have impacted the delay time (response variable). The model considered the predictor variables of condition factor, flow, length of the fish, sex, and origin (wild vs. hatchery-reared). The results indicated that there were no statistically significant associations (Table 3).

*Table 3. Results of the GLM model, with delay time in the intake channel as response variable. The significant predictors (p) are shown in **bold**.*

Coefficients	Estimate	Std. Error	T value	Pr(>|t|)
Condition	-0.032	0.545	-0.059	0.954
Length	0.002	0.010	1.978	0.057
Sex	1.129	0.895	1.260	0.218
Origin	-0.042	0.119	-0.354	0.725
Flow	<-0.001	<0.001	-0.724	0.475

3.3.2 Swimming speed

The GAM was fitted to 537 track segments, considering only daylight data from individuals with track segments during both treatment and control, and swimming in both directions (directly towards and away from the spray). This limited the analysis to data from only three individuals (Figure 6).

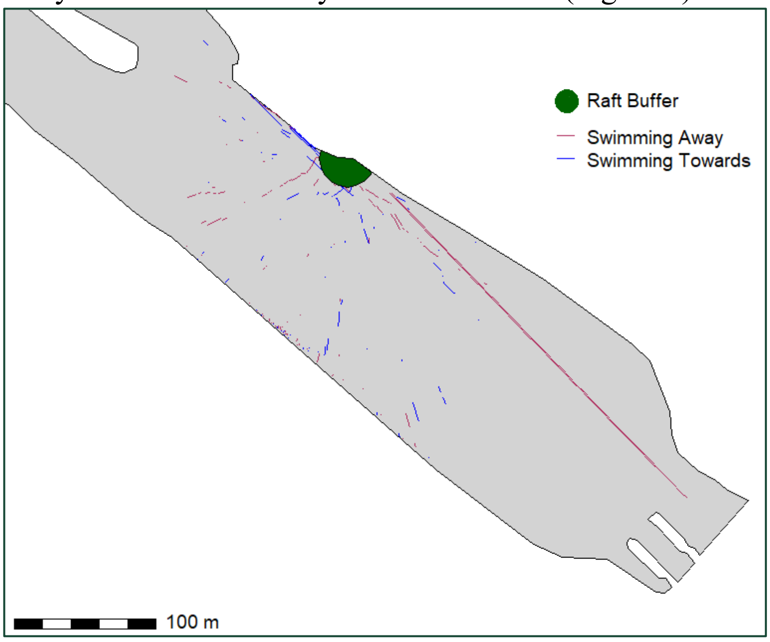

Figure 6. Track segments of an individual (ID:410) moving in the intake channel (grey), pointing directly towards (blue) and away (maroon) from the raft with a 20-metre buffer (green). Only track segments which either start or end within a 200-metre radius of the raft are considered.

The daylight data model indicated a significant relationship between flow and swimming speeds, both towards ($p = <0.001$) and away ($p = 0.005$) from the raft. Furthermore, treatment was found to have a significant effect ($p = 0.032$) on swimming speeds with a positive estimate. However, the interaction between treatment and direction of swimming was not found to be significant ($p = 0.482$). Therefore, the model indicates that while the spray on treatment significantly increases swimming speed, the effect was not found to be directional, indicating that swimming speeds both toward and away from the raft increased similarly when the spray was on (Table 4). A further model was fitted, considering 376 track segments of twilight data originating from the same three individuals. During the twilight hours, no significant impact of treatment on swimming speed could be detected ($p = 0.151$) (Appendix 1).

*Table 4. Results of the GAM model, daylight data, with swimming speed as response variable. Coefficients "Towards" and "Away" refer to swimming direction in relation to the raft position. Interaction terms are designated with ":", significant p-values are **bold**.*

Coefficients	**Estimate**	**Std. Error**	**T value**	**Pr(>|t|)**
Towards	0.112	0.094	1.194	0.233
Treatment	0.209	0.097	2.139	**0.032**
Treatment: towards	-0.082	0.117	-0.709	0.483
Smooth terms	**Edf**	**Ref.df**	**F**	**p-value**
S(Flow):away	3.054	3.570	5.276	**0.005**
S(Flow):towards	2.707	3.128	9.823	**<0.001**

3.3.3 Movement in the intake channel

A common pattern observed in our study was that the kelt swam relatively straight through the channel (Appendix 2). Interestingly, kelt with a residence time of more than one hour appeared to prefer areas closer to the dam (Figure 7). The raft area was not a preferred location during control or treatment. The left channel side, where the current was likely weaker and the riverbed shallower, appeared to be the preferred side.

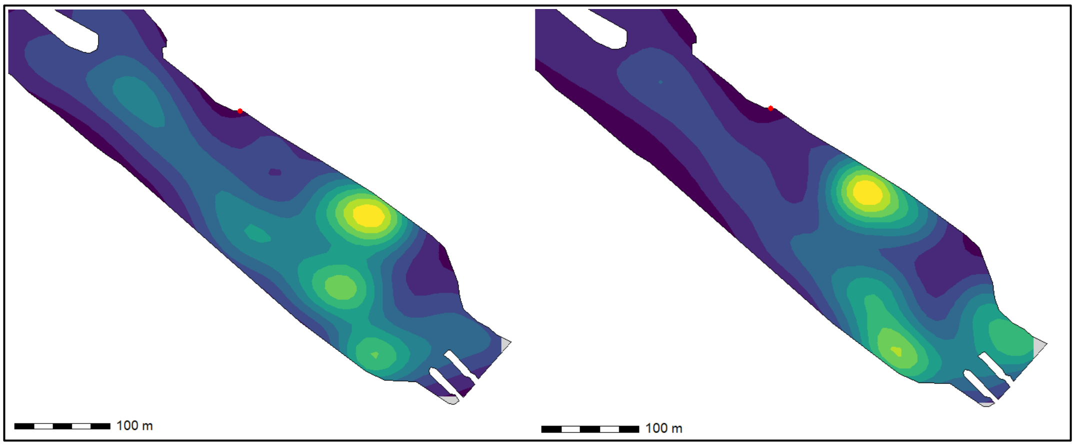

Figure 7. Showing weighted heat maps, including only kelt with a delay time of more than 1 h (n = 11) during treatment (left) and control (right). The raft position is represented by the red dot.

Furthermore, the acoustic telemetry data revealed that five tagged kelt passed between the raft and the opposite channel side during treatment. Of these fish, only one individual (ID:412) could be seen to clearly deviate from its route to investigate the spray (Figure 8). Notably, the pump was already turned on when the individual entered the channel.

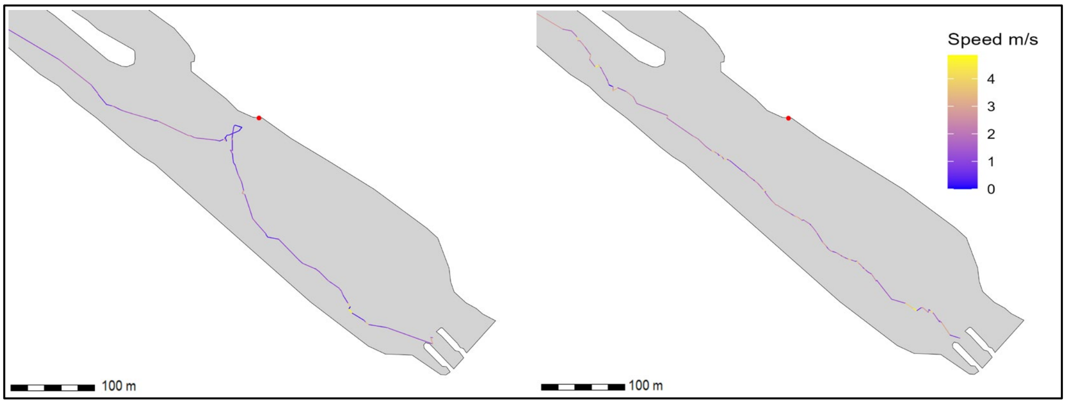

Figure 8. Left: Kelt (ID:412) passing through the intake channel, diverging towards the raft during treatment. Right: Kelt (ID:498) swimming straight through the channel, which was a common pattern. The position of the raft is indicated by the red dot. For further tracks, refer to Appendix 2.

4. Discussion

4.1 Attraction to water spray

The central hypothesis of this study was that surface water spraying could be used to effectively attract salmon kelt, thereby facilitating their capture or guiding them to safer downstream passages. This hypothesis is partially supported in this study by sonar data. Specifically, larger fish exhibited a significantly extended residence time in the vicinity of the spray raft when the water spray was turned on. This prolongation of stay among larger specimens is potentially indicative of a favourable response to the treatment. However, further results are more nuanced.

A significant decrease ($p = 0.006$) in fish count was observed within the FOV of the sonar when the spray was turned on during the twilight hours, indicating that the experimental setup had a repelling effect during this time of day. During the daylight hours, this effect was not observed. However, it is important to note that this coefficient did not reach statistical significance ($p = 0.086$). Despite the lack of statistical significance, it can be cautiously inferred that a repellent effect could not be detected during daylight hours. Nevertheless, this result should be interpreted with caution. The models omitting the first 10 minutes after a spray on/off event continued to show a time-of-day-dependent effect of the spray on fish count. In the twilight hours, the results indicate a less pronounced but still significant ($p = 0.05$) decrease in fish count when the spray was on. This suggests that, while there may be an initial flight response to spray activation, a negative response persists even after the initial 10 minutes after the spray is turned on.

The potential behavioural differences between salmon and trout could not be evaluated using the sonar data, as the species could not be distinguished. This limitation raises questions about species-specific behaviour, which could be addressed in future research.

Analysis of acoustic telemetry data provided further insight, revealing that swimming speeds directly towards and away from the raft were significantly higher during daylight hours when the spray was on. Although this indicates that the kelt reacted to the treatment, no significant directional bias was observed. Interestingly, this increase in swimming speed was not observed during the twilight hours. This can probably be attributed to decreased activity during the twilight hours. However, the tracking data revealed that of the 13 individuals present during both treatment and control in the channel, only three individuals had track segments towards and away from the raft in both treatment and control states within 200 metres from the raft. Therefore, due to the limited sample size, these results need to be treated with caution, and generalisability is questionable. Considering these data alone is not sufficient to draw conclusions about the potential of water spray to attract kelt.

A surprising finding of our study, however, adds another dimension to this discussion. We measured a significant level of pump noise adjacent to the raft using a hydrophone. A study by Knudsen et al. (1994) found that intense sound can potentially act as a deterrent to guide smolt away from unsafe passages at hydropower stations. Furthermore, Welton et al. (2002) found that acoustic barriers are more efficient in deflecting salmon smolt during night. According to Leander et al. (2021), this can probably be attributed to an increased repelling effect of sound treatment during the night. It is plausible that the repelling effect detected during twilight hours in this study may be due in part to the reduced visual perception of salmon in low light conditions, making them more dependent on and thus more sensitive to auditory cues. Additionally, experiments carried out on a salmon farm found that intense sound triggered a flight response in salmon, which coincided with increased swimming speeds (Bui et al., 2013). However, Bui et al. (2013) found that water spray on the surface did not trigger a flight response in farmed salmon. Considering this, the detected increase in swimming speed during daylight hours and the significantly lower fish count during twilight hours found in our study can potentially be attributed to an aversive response to pump noise, water spray, or a combination of these factors.

4.2 Delay time in the intake channel

Surprisingly, our study observed a mean delay time of only 19.2 minutes. These results differ considerably from those of previous studies, which reported delay times in excess of 20 hours at Stornorrfors (Byström, 2020; Lundqvist et al., 2015).

Specifically, Byström's study observed that the mean delay times of the two groups described were 37.5 hours (n = 13) and 21 hours (n = 23) respectively. However, unlike our study cohort, which was captured in autumn and released in spring, Byström captured and subsequently released the salmon in autumn. Notably, within Byström's study cohort, some fish migrated to spawning grounds and subsequently migrated downstream in the following spring, while others were fallbacks, aborting migration directly after tagging.

Nonetheless, Byström's results are in line with those of Lundqvist et al. (2015), who reported a median delay time of 26.7 hours (n = 18). However, the said study measured the delay time over a larger area, extending from the upper end of the fish ladder at Norrfors to the turbines. However, Lundqvist also specified that the mean travel time from Norrfors downstream to the turbines was approximately two hours, which, despite the larger area considered, still indicates a longer delay time compared to the kelt tagged in our study.

This discrepancy raises key questions about the impact of environmental conditions, overwintering locations, and physiological factors on delay times. Postspawning salmon that overwinter in the wild commonly do not regain their condition until they reach the sea (Baktoft et al., 2020). Similarly, our study fish overwintered in the hatchery before being released in spring, were not fed, and therefore did not improve in condition over the winter (pers. com. Å. Forssen 21.12.2023).

In addition to the overwintering in the hatchery, our study group was also distinct by the restricted release over two consecutive days. Telemetry data revealed that most of the kelt arrived at the intake channel in two clusters on two consecutive days (Appendix 4). Therefore, they had encountered similar conditions when they arrived at the intake channel.

Interestingly, our tagged fish displayed no significant variance in delay time based on size, sex, condition, flow at arrival or origin (wild/hatchery-reared). Therefore, the comparably short delay times may be the result of unaccounted physiological conditions or behavioural changes, possibly related to overwintering in the hatchery. They may furthermore be affected by environmental conditions that were either not measured or did not vary sufficiently during the time frame of the experiment. Furthermore, the spray experiment itself could have affected the delay time.

4.3 Movement in the intake channel

In this study, we used weighted telemetry data to create heat maps delineating the preferred locations of kelt with a delay time of more than one hour. Comparative analysis of these maps for treatment and control conditions revealed only marginal differences. Notably, the area in proximity to the raft seems to display no obvious variation between the treatment and control states (Figure 7).

Nonetheless, the heat maps were instrumental in identifying areas favoured by the kelt. During both treatment and control, the preferred areas begin approximately at the midpoint between the current raft position and the turbine entrance. This observation is pivotal as it highlights a potential location where kelt-spray encounters could be increased for future measures or experiments.

4.4 Future research

Future studies could benefit from a variety of improvements to build on our research. First, to further the knowledge of how a larger range of environmental conditions affect delay time, a more staggered release schedule should be implemented. An in-depth comparison of all available studies which recorded kelt delay times at Stornorrfors could yield invaluable insights into the factors impacting delay time.

Furthermore, results from our study have highlighted potential strategies for increasing kelt-spray interactions. In particular, the areas preferred by kelt began approximately at the midpoint between the current raft position and the turbine entrance. Therefore, by repositioning the raft approximately 150 metres downstream, the kelt-spray encounter rates could potentially increase, thus improving the sample size. However, relocating the raft would change the experimental parameters, and such a step should be carefully evaluated.

Our study observed a repellent effect of the spray/pump on fish count during twilight hours, which persisted when the first 10 minutes of data after the pump was turned on were omitted. This suggests that if fish adapt to the pump noise and/or spray, this adaption likely takes longer than 10 minutes. Investigating whether fish become accustomed to the treatment and behave differently over an extended period would be an intriguing avenue for future research.

Furthermore, for an in-depth analysis of acoustic influences on kelt behaviour, future studies should consider measurements with calibrated hydrophones to be able to relate absolute sound intensity and frequencies to previous studies. If similar experiments are to be conducted in the future, it is strongly recommended to reduce pump noise by placing the pump farther away from the raft or, preferably, out of the water.

Lastly, it could be beneficial to employ a more precise control system to manage and record pump operation. In our study, the timer relay used (Nedis Smart Life SmartPlug) had a precision of ±30 seconds. While functional, increasing the precision, ideally combined with a datalogger with RTC (real-time clock), would be beneficial to record the exact times of spray activation or deactivation. This would facilitate the precise correlation of pump state data with the telemetry data, allowing for monitoring of behavioural responses at the exact moments the pump is turned on or off.

5. Conclusions

Our analysis of the potential of water spray as an attractant for kelt at the Stornorrfors power plant revealed complex results. Although the sonar data suggested a partially attractant effect during daylight hours, with increased residence times for larger fish, they also indicated a potential repellent effect during the twilight hours. Telemetry data revealed higher swimming speeds during daylight hours in response to treatment, which is likely to be a further sign of a repellent effect. The unexpectedly short delay times compared to previous studies highlight the possible influence of environmental conditions during release, as well as individual physiological and overwintering conditions. In-depth comparative analysis of delay times is instrumental to further understanding the behaviour of kelt and would benefit future experiments by increasing the sample size. Moreover, heat map analyses suggest the relocation of the raft for future experiments to increase kelt-spray encounters. These findings further our understanding of the behaviour of salmon kelt in the context of the Stornorrfors dam. However, they also emphasise the need for further research to refine techniques and elaborate the influence of various factors on the behaviour of Atlantic salmon.

In summary, our study at the Stornorrfors hydropower plant provides new insights into the complex interactions between kelt behaviour, water spray, and hydropower dams. As the reliance on hydropower continues to be a global reality in the foreseeable future, the need for innovative and effective solutions to protect wild salmon populations is more urgent than ever. Our research contributes valuable knowledge, highlighting the importance of adapting management strategies to the complex behaviours of this species.

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Popular science summary – The water spray's siren song

The Atlantic salmon, a vital species for ecological balance, economic value, and cultural heritage, faces challenges due to overfishing, habitat loss and migration obstacles, such as hydropower dams. While the salmon's journey to spawning grounds are often hindered by hydropower dams, the construction of fish stairs has re-connected them to their ancient cradles. However, individuals in some populations can return to the sea after spawning, potentially returning to spawn multiple times. Those repeat spawners, also known as kelt, are of tremendous importance. Not only are they able to produce a substantial number of offspring, but they can also increase the resilience of a population.

This study focuses on such a population, particularly at the kelt life stage; post-spawning individuals that face perilous downstream migrations back to sea obstructed by hydropower dams. While young, small salmon smolt can pass the turbines of hydropower dams often unharmed, the substantially larger kelt likely perish at those obstacles. Previous research has found that kelt seem to hesitate for a day or more above the dam before entering the turbines, which opens a window of opportunity to help them on their way. We aimed to understand whether water spray above the Stornorrfors hydropower dam could be used to attract kelt during this key life stage. If successful, this could then be used to either capture or guide kelt towards safer passages, saving those gorgeous fish from a likely death. To test this theory, an experimental set-up with a spray nozzle on a raft, fed by a pump in the water, was positioned above the dam.

Valuable information on kelt behaviour was found with the help of sonar and acoustic telemetry data. The sonar data allowed the monitoring of all fish in the proximity of the spray, while the telemetry data yielded precise information on the movement of previously tagged kelt above the dam. While some data suggest that water spray may hold the fish's attention during daylight, other results show a significant decrease in the number of large fish in the proximity of the water spray during the night. The study also revealed surprising behavioural responses, with kelt showing increased swimming speeds during the day near the spray, possibly indicating an adverse reaction to either the spray, the associated pump noise, or a combination of the two. Interestingly, our group of tagged fish exhibited an unexpectedly short hesitation above the dam, swimming through the intake channel and entering the turbines in under 20 minutes on average. This determination of our group, combined with the adverse reaction to either the pump noise or spray itself, lead to a low number of kelt-spray encounters, limiting the generalizability of our results.

Nonetheless, this research provides valuable insights into kelt behaviour and suggests improvements to experimental set-ups for future studies. However, it also underscores the behavioural complexity of kelt and myriad of impacting factors.

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Appendix 1

Appendix 1 Model coefficients of GAM model speed, daylight, significant p are ***bold****.*

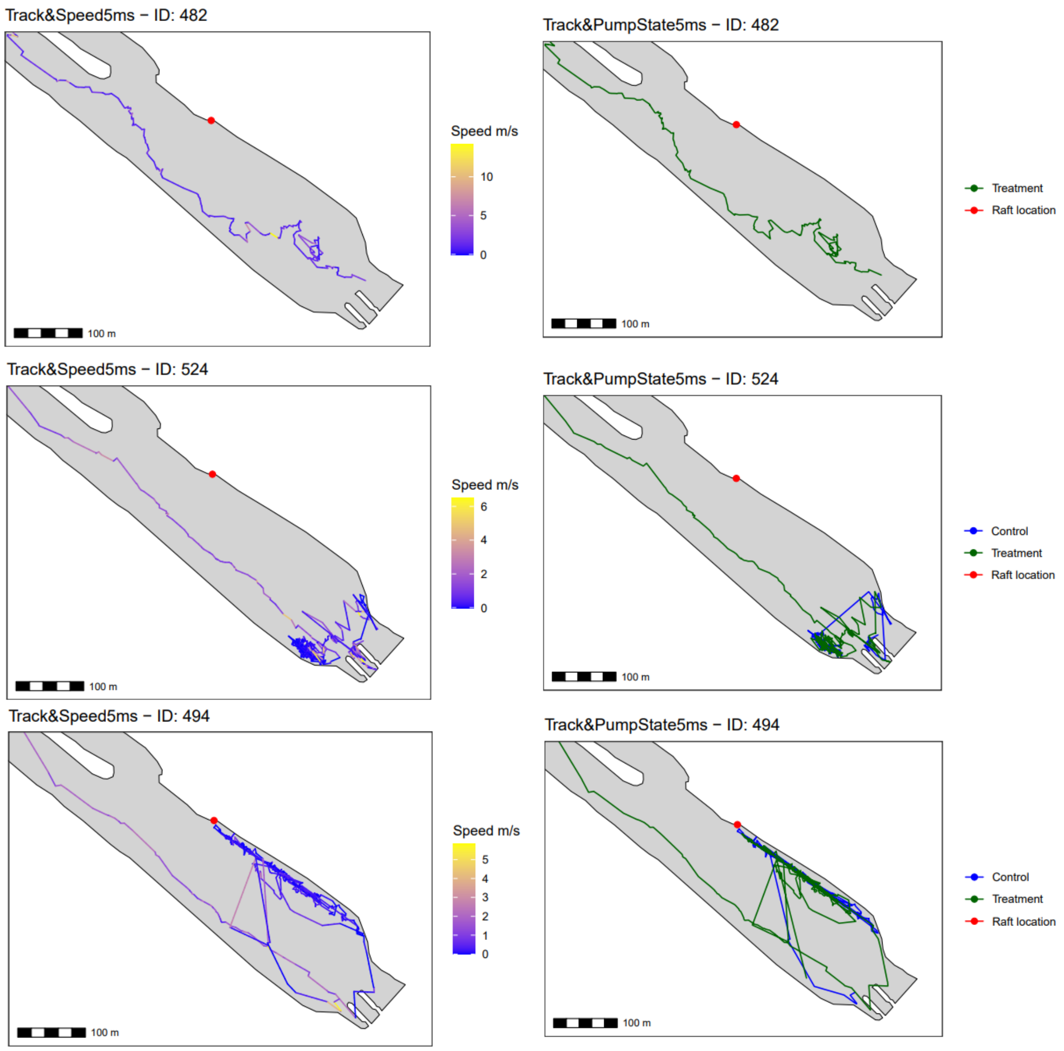
Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.57409	0.14734	-3.896	**0.0001**
Treatment	0.20896	0.09768	2.139	**0.0329**
DirectionToward	0.11289	0.09455	1.194	0.2331
Block4	0.20421	0.17391	1.174	0.2409
Block5	-0.19157	0.12269	-1.561	0.1191
Block6	0.78113	0.56136	1.392	0.1647
Block7	0.02058	0.15125	0.136	0.8918
Block8	-0.03423	0.169	-0.203	0.8396
Block9	-0.07925	0.18756	-0.423	0.6728
Block10	-0.81169	0.1448	-5.606	**<0.0001**
ID446	-0.65336	0.17803	-3.67	**0.0003**
ID494	-1.17455	0.5088	-2.308	**0.0214**
Treatment:DirectionToward	-0.08258	0.11753	-0.703	0.4826
Block4:ID446	-0.24852	0.20558	-1.209	0.2273
Block5:ID446	-0.15543	0.2871	-0.541	0.5885
Block6:ID446	-2.09842	0.61759	-3.398	**0.0007**
Block7:ID446	-0.80791	0.26018	-3.105	**0.0020**
Block8:ID446	-2.52554	0.6408	-3.941	**0.0001**
Block9:ID446	-1.95774	0.83845	-2.335	**0.0199**
Block10:ID446	1.74493	0.25399	6.87	**<0.0001**
Block4:ID494	0.75331	0.529	1.424	0.1551
Block9:ID494	1.29029	0.50554	2.552	**0.0110**
Block10:ID494	1.39886	0.5073	2.757	**0.0060**
Smooth terms	**edf**	**Ref.df**	**F**	**p-value**
s(Flow):DirectionAway	3.054	3.57	5.276	**0.0005**
s(Flow):DirectionTowards	2.707	3.128	9.823	**<0.0001**

Appendix 1 Model coefficients of GAM model speed, twilight, significant p are ***bold****.*

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-0.51907	0.14071	-3.689	0.000249
Treatment	0.11012	0.07664	1.437	0.15139
directiontoward	0.05782	0.05159	1.121	0.262918
Block24	0.15125	0.17484	0.865	0.387404
Block25	-0.18936	0.12321	-1.537	0.124944
Block26	-1.26848	0.79407	-1.597	0.110789
Block27	0.02608	0.1513	0.172	0.863234
Block28	-0.13425	0.16197	-0.829	0.407573
Block29	-0.25759	0.16416	-1.569	0.117251
Block210	-0.79516	0.14516	-5.478	**6.79E-08**
ID446	-0.64822	0.17226	-3.763	0.000187
ID494	-1.20689	0.7609	-1.586	0.113334
Block4:ID446	-0.10623	0.2114	-0.503	0.615524
Block5:ID446	-0.29172	0.2764	-1.055	0.291728
Block6:ID446	0	0.83366	0	1
Block7:ID446	-0.27232	0.25768	-1.057	0.291096
Block8:ID446	-2.10067	0.64654	-3.249	0.001234
Block9:ID446	-1.65802	0.85339	-1.943	0.052586
Block10:ID446	1.58625	0.2559	6.199	**1.18E-09**
Block4:ID494	0.76463	0.76863	0.995	0.320305
Block5:ID494	0	0	NaN	NaN
Block6:ID494	2.04482	0	Inf	< 2e-16
Block7:ID494	0	0	NaN	NaN
Block8:ID494	0.8762	0.87947	0.996	0.319587
Block9:ID494	1.39937	0.75302	1.858	0.063701
Block10:ID494	1.35279	0.75216	1.799	0.072685
Smooth terms	**edf**	**Ref.df**	**F**	**p-value**
(s)Flow:directionaway	3.247	3.444	5.408	**0.0009**
(s)Flow:directiontoward	3	3	9.636	**<0.0001**

Appendix 2

Appendix 2. Additional plots, showing different behaviour of kelt in the intake channel.

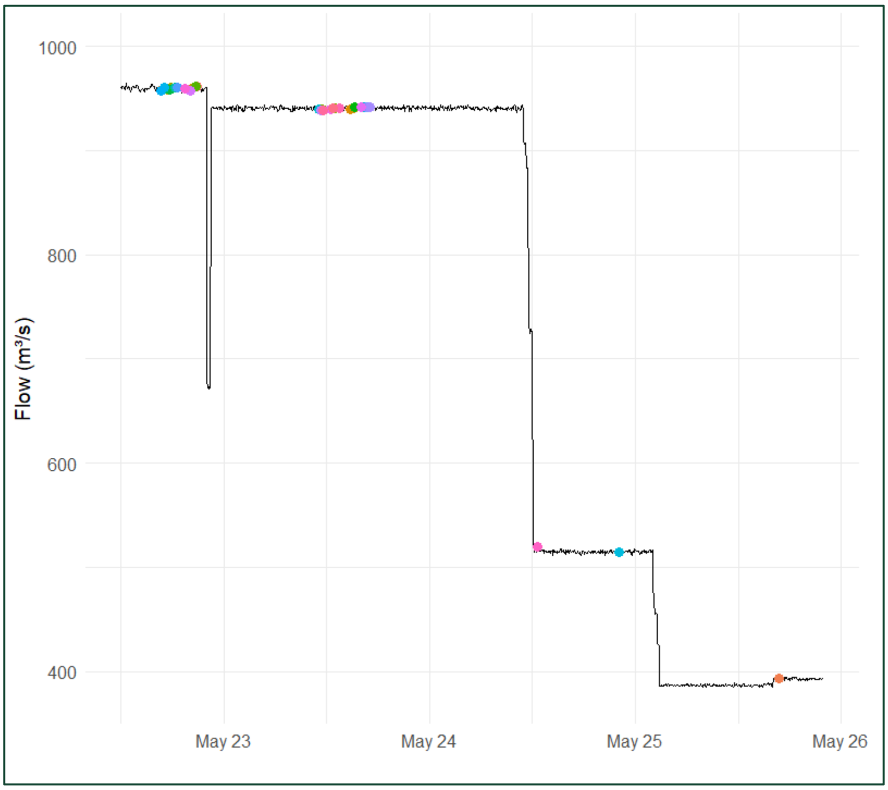


Appendix 3

Appendix 3 Sample schedule. Missing hours were replaced with hours marked in orange.

Day	On 1		On 2		Off 1		Off 2	
22/05/2023	00:00:00		12:00:00		05:00:00		17:00:00	
23/05/2023	02:00:00		14:00:00		03:00:00		15:00:00	
24/05/2023	04:00:00		16:00:00		01:00:00		13:00:00	
25/05/2023	06:00:00		18:00:00		23:00:00		11:00:00	
26/05/2023	08:00:00		20:00:00		21:00:00		09:00:00	
27/05/2023	10:00:00		22:00:00		19:00:00		07:00:00	
28/05/2023	12:00:00		00:00:00		17:00:00		05:00:00	
29/05/2023	14:00:00		02:00:00		15:00:00		03:00:00	
30/05/2023	16:00:00		04:00:00		13:00:00		01:00:00	
31/05/2023	18:00:00		06:00:00		11:00:00		23:00:00	
01/06/2023	20:00:00		08:00:00		09:00:00		21:00:00	
02/06/2023	22:00:00		10:00:00		07:00:00		19:00:00	
03/06/2023	00:00:00	02:00:00	12:00:00		05:00:00		17:00:00	
04/06/2023	02:00:00		14:00:00		03:00:00		15:00:00	
05/06/2023	04:00:00		16:00:00	10:00:00	01:00:00		13:00:00	09:00:00
06/06/2023	06:00:00	16:00:00	18:00:00		23:00:00		11:00:00	17:00:00
07/06/2023	08:00:00		20:00:00		21:00:00		09:00:00	
08/06/2023	10:00:00		22:00:00		19:00:00		07:00:00	
09/06/2023	12:00:00		00:00:00		17:00:00		05:00:00	
10/06/2023	14:00:00		02:00:00		15:00:00		03:00:00	
11/06/2023	16:00:00		04:00:00		13:00:00		01:00:00	
12/06/2023	18:00:00		06:00:00		11:00:00		23:00:00	
13/06/2023	20:00:00		08:00:00		09:00:00		21:00:00	
14/06/2023	22:00:00		10:00:00		07:00:00		19:00:00	
15/06/2023	00:00:00		12:00:00		05:00:00		17:00:00	
16/06/2023	02:00:00		14:00:00		03:00:00		15:00:00	
17/06/2023	04:00:00		16:00:00		01:00:00		13:00:00	
18/06/2023	06:00:00		18:00:00		23:00:00		11:00:00	
19/06/2023	08:00:00		20:00:00		21:00:00		09:00:00	
20/06/2023	10:00:00		22:00:00		19:00:00		07:00:00	

Appendix 4



Appendix 4. Showing first detections of tagged kelt at the intake channel (coloured dots) and corresponding flow. Arrival in two clusters over two days is apparent.

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