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RESEARCH ARTICLE

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Guiding downstream migrating Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) of different life stages in a large river using bubbles

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Abstract

Salmonid repeat spawners are precious individuals for wild populations due to their high fecundity and previous spawning experience, making them important in environmental policy. However, repeat spawners rarely exist above hydropower dams in regulated rivers as the mortality of post-spawners (kelts) when passing through turbines during downstream migration is very high. To mitigate this problem, there are different technical solutions that potentially guide fish toward available fishways. Bubble barriers represent one alternative to costly physical guiding structures, but the efficiency of bubbles for guiding downstream migrating kelts has not been tested. In this study, we evaluate a 100 m long bubble barrier in guiding salmonids—both smolts and kelts—away from the main current and toward an alternative fishway in Ume River, a large regulated river in northern Sweden. We used both acoustic telemetry and sonar to measure the guiding effect of the bubble barrier for downstream migrating fish. We found that more than twice as many salmonids chose the alternative fishway when the bubble barrier was turned on. This was true both for smolts and kelts, suggesting that bubble barriers can be used to guide salmonids of different life stages in rivers with flow rates over 500 $m^3 s^{-1}$. Indeed, our study indicates that bubble barriers are low-cost structures that could be rapidly applied in many regulated rivers to support salmonid migration.

KEYWORDS
Atlantic salmon, Brown trout, bubble curtain, fish migration, fish passage, hydropower

1 | INTRODUCTION

Most of the world's large rivers have human-made barriers (Nilsson et al., 2005) and their negative impact on freshwater connectivity constitutes a major threat to wild fish populations (Northcote, 1998). Rivers in Europe are among the most modified in the world (Belletti et al., 2020), with only one-third achieving "good ecological status" according to the EU-Water Framework Directive (Grizzetti et al., 2017). Large economic resources have been dedicated toward solutions that facilitate fish passages around migration obstacles, and the focus has so far primarily been on improving conditions for upstream migrating fish, for example, via fish ladders (Bunt et al., 2012; Lundqvist et al., 2008). However, passages during downstream migration are critical for fish survival, and hence this phase has gained increasing attention within ecological research (Nyqvist et al., 2017; Pelicice et al., 2015; Silva et al., 2016) as well as from a management perspective (Schwevers & Adam, 2020; Verhelst et al., 2018).

In regulated rivers, downstream migrating fish must often pass hydropower plants on their way to the sea, resulting in delayed migration and high mortality from turbine passage for both juveniles and adults of many fish species (Calles et al., 2010; Ferguson et al., 2006; Muir et al., 2001; Norrgård et al., 2013). Two fish species of high ecological and socioeconomical value, that often encounter hydropower plants, are Atlantic Salmon (*Salmo salar*) and sea-running brown trout (*Salmo trutta*). Both species are anadromous and iteroparous where adults can survive spawning and have the potential to reproduce again in future years. Salmon and trout experience two crucial downstream migration events during their life cycle: (i) migration as juveniles (smolt) from rivers to the sea; and (ii) migration as post-spawning fish (kelts) returning to the sea to grow and potentially return to the river the coming year as repeat spawners (Fleming, 1996; Jonsson & Jonsson, 2011). These repeat-spawning individuals have been highlighted as being of crucial importance for wild salmon populations. Studies have estimated that repeat spawners contribute a disproportionately higher number of eggs (by a factor of up to 2.8) relative to the maiden spawning counterparts (Bordeleau et al., 2020; Halttunen, 2011), and, due to their fast recovery to spawn again, may also buffer inter-annual variation in recruitment success (Bordeleau et al., 2020; Niemelä et al., 2006). However, survival of kelts passing through turbines is generally low, with large fish suffering up to 100% mortality, for example, 100%, Kaplan turbine (Scruton et al., 2007) and 81–100%, Kaplan turbine (Vikström et al., 2020). In comparison, much lower mortality rates (usually <15%) are reported for smolts during turbine passage due to their smaller size, for example, 13%–19%, Kaplan turbine (Ferguson et al., 2006) and 7%–15%, Kaplan turbine (Muir et al., 2001).

Current technical solutions for guiding downstream migrating fish toward safe passages mainly involve various forms of physical structures, for example, racks and weirs. Due to the high costs, practical challenges, and safety issues for large physical guidance structures, few existing examples are found in larger rivers. For example, Emanuelsson et al. (2017) calculated an installation cost between 28 and 35 million Euros, and a yearly maintenance cost of 0.32–0.37 million Euros, for a 165 m long physical barrier guiding downstream migrating fish in a large Swedish river. Extrapolating these cost over larger regions rapidly generate enormous costs: implementing physical guiding structures for only a fraction of the nearly 630,000 documented migration barriers in Europe alone (Belletti et al., 2020) would generate costs far above the budgets typically used for freshwater management. There is consequently a great need for considering efficient low-cost alternatives for guiding downstream fish. This is particularly urgent in Europe, where the revision of management around hydropower dams and regulatory options under the EU-Water Framework Directive (European Commission, 2018) is currently implemented across the European Union. Regardless of the cost, the efficiency of guiding structures must also be considered to understand their true value, especially if low-cost alternatives turn out to be less efficient. Furthermore, if low-cost alternatives are affordable enough to be used in a large number of locations, their general usefulness may outweigh potentially lower efficiency. The level of efficiency required to justify a certain cost of a guiding structure will likely vary with system characteristics and target species. Hence, to obtain those numbers, more detailed and system-specific studies are needed.

Bubble barriers have been shown to be efficient for guiding migrating fish of multiple species under different environmental conditions (Flammang et al., 2014; Noatch & Suski, 2012; Zielinski & Sorensen, 2016). Further, they do not alter water flow (i.e., decrease head loss) or catch debris like physical barriers, and therefore come with a considerably lower installation and maintenance cost (Clay, 1995). For salmonids, earlier studies have found that bubbles can guide both Pacific (Perry et al., 2014) and Atlantic salmon smolts (Leander et al., 2021; Welton et al., 2002). However, if downstream migrating salmonid kelts can be guided by bubbles remains untested.

Our aim with this study was to quantify the efficiency at which bubble barriers guide downstream migrating Atlantic salmon and brown trout kelts and to compare this efficiency with that for Atlantic salmon smolt. We also discuss the implications of the findings from a perspective of managing salmonid populations in European rivers. Typically in regulated rivers, downstream migrating salmonids follow the main current that leads through the hydropower turbines, whereas alternative, safer migration routes (e.g., fish ladders) have much lower water flow. Hence, our main hypothesis was that bubble barriers can be used to steer kelts away from the main current toward an alternative migration route.

2 | MATERIALS AND METHODS

To test our main hypothesis, we deployed a 100 m-long bubble barrier across a section of a large river, at the intake channel to a large hydropower station. The barrier covered the main river channel, where we aimed to guide fish toward an alternate channel with lower water flow and, hence, less used by migrating salmonids (Davidsen et al., 2005; Moore et al., 1998). We used two methods of data collection to compare fish movement with the bubble barrier turned on (treatment) and off (control): (i) acoustic telemetry provided information on fine-scale movements of tagged fish around the bubble barrier (high data resolution on a smaller sample size) and (ii) a sonar system was used to count the number of fish passages in the alternative fishway (low data resolution on a larger sample size).

2.1 | Study site

The study was conducted in Ume River, northern Sweden, from the 22nd of May to 5th of June in 2020, which corresponds to the peak of kelt migration and the beginning of smolt migration at the site (Östergren & Rivinoja, 2008). The river starts in the Scandinavian mountain range at the border between Sweden and Norway and drain

29,300 km^2 before entering the Baltic Sea in the east. The main stem of Ume River is regulated with 18 hydropower plants and does not support any production of wild anadromous salmonids. The biggest tributary, Vindel River, is free flowing and sustains wild populations of both Atlantic salmon and sea running brown trout. However, the Vindel River enters Ume River 11 km upstream of a large hydropower plant, Stornorrfors, which both upstream and downstream swimming salmonids must pass to complete their migration. We used the intake channel of Stornorrfors hydropower plant (63°51′25.1″N 20°2′20.9″ E) as the study site to test our hypothesis.

2.2 | Migration of salmonids in Ume/Vindel River

A technical fishway connects the river above the dam with the original river channel below (Figure 1, panel A), which today functions as a 9 km long bypass of the turbines, with a minimum discharge of 25 m^3 s^{-1} from 20th of May to 30th September, allowing fish to pass the dam and continue their migration to the spawning grounds further upstream. An automated fish counter has since 2008 registered upstream migrating fish with an average annual count of 9083 salmon and 401 brown trout (Å. Forsén, personal communication, April 12, 2021). Repeat-spawning salmonids in Vindel River are nevertheless few in numbers. Lundqvist et al. (2015) reported that only one out of 728 tagged salmon passed the fishway during upstream migration more than one spawning season. However, studies of radio-tagged fish have reported a high spawning and overwintering survival, that is, 38% (Lundqvist et al., 2015) and 84% (Östergren & Rivinoja, 2008) for salmon and trout, respectively, suggesting high potential for iteroparity in this river system.

2.3 | Bubble barrier

For this study, a bubble barrier was deployed in the Stornorrfors intake channel. This is a narrow part of the river where downstream migrating fish concentrate in a small area, which maximizes fish–barrier interaction. However, there is no available fishway directly at

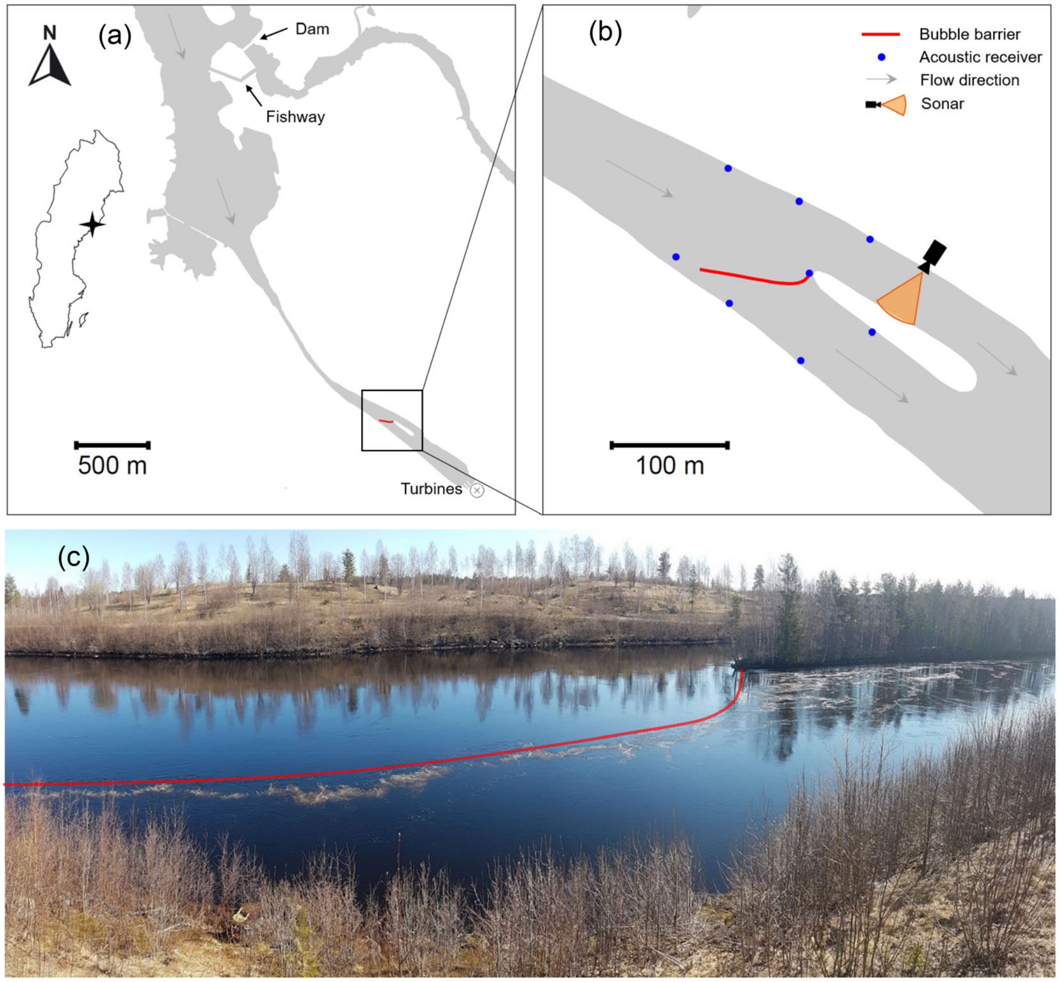

FIGURE 1 (a) Map of Ume River (light grey) around Stornorrfors hydropower plant, with geographical position (black star) of the study site at national scale of Sweden, (b) detailed map of the area around the island (white polygon), bubble barrier (red line), acoustic receiver positions (solid blue circles), and the sonar and its corresponding detection range (black camera and orange polygon, respectively), with dark grey arrows represent the flow direction. (c) panorama photo taken from the south shore, with the active bubble barrier (seen in parallel to the added red line) stretching from the shoreline to the island in the middle of the channel. [Color figure can be viewed at wileyonlinelibrary.com]

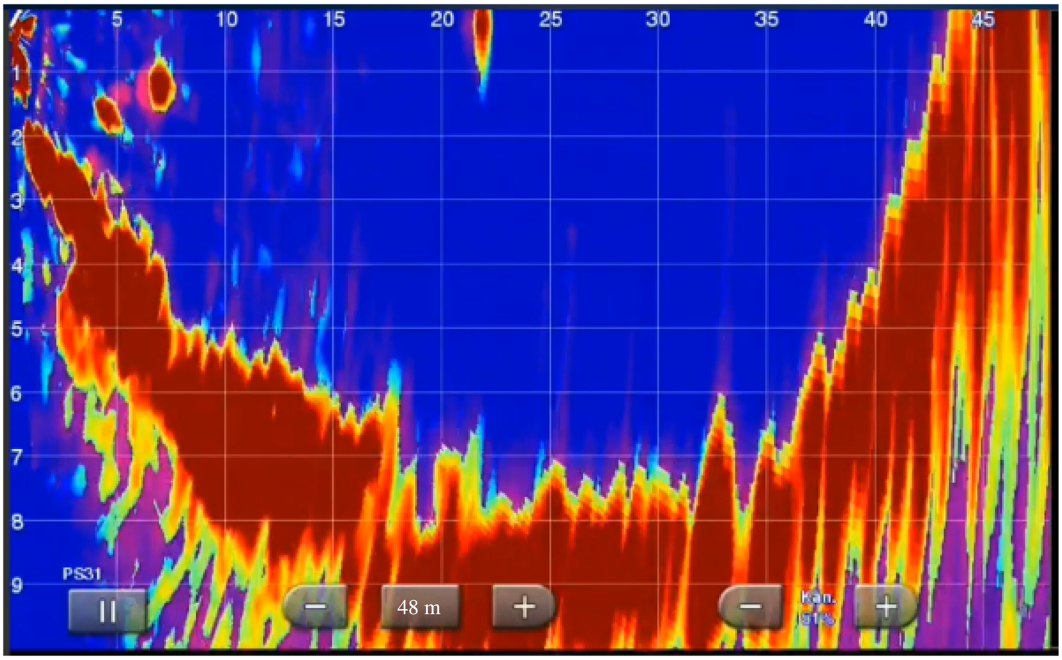

FIGURE 2 Example data from the sonar showing a cross section of the channel from the north side of the island where the axis represents the depth and width of the river in meters, y-axis, and x-axis, respectively. The sonar is positioned in the upper left corner of the cross section and covers the full width (43 m) and depth (8 m) of the u-shaped channel, portraying water as blue and other physical objects' bottom as yellow and red. Note the three clear echoes in the surface as results from fish passing at 4, 7, and 22 m from the sonar. [Color figure can be viewed at wileyonlinelibrary.com]

this site. The bubble barrier was situated between the south shore and the western tip of an island situated in the middle of the channel, creating a curtain of bubbles covering the channel at the south side of the island at approximately 45° angle with a slight downstream U-shape (Figure 1). A perforated hose was attached to an 11-mm steel wire anchored to the ground on each side and weighed down with ~80 kg of metal weights. This positioned the wire and hose at a depth ranging from 5 meters mid-channel to 2 meters closer to the shorelines, while the maximum water depth of the channel was measured at 9.8 m. Perforations were made using a 3-mm diameter needle, which created slits in the hose through which the air exited. Air flow through the perforations was tested in the laboratory before being used in the field. The size of the study did not allow for any large-scale trials before the actual study was initiated. The perforated hose was connected to a diesel compressor (Kaeser Mobilair M100) generating a working pressure of 7 bar at a flow rate of 10.2 m^3 min^{-1}. Both the perforated hose and compressor capacity were based on earlier studies in the laboratory and field by Leander et al. (2021).

2.4 | Sonar data curation

On the northern side of the island (i.e., the side without a bubble barrier), a sonar transducer (Garmin Panoptix PS31) was deployed to detect fish passages (Figure 1). The transducer was paired with a Garmin GPSMAP 922xs sonar which recorded and stored data. The sonar provided a rough estimate of fish size (an example is shown in Figure 2) but did not allow for species identification. Other than salmonids, a plausible species generating similar size echoes would have been northern pike (*Esox lucius*), but extensive sampling with rod and reel in the area (> 50-rod hours) generated no other fish than salmon (31) and trout (9) kelts. Hence, we referred to all sonar detections as either Atlantic salmon or brown trout kelts.

Sonar data were recorded from the 26th of May to the 4th of June 2020, from 09:12 to 22:20, when the bubble barrier was alternating turned on and off. A total of 36 h 20 min of sonar data were recorded when the bubble barrier was turned on, which was divided into seven replicates of lengths between 2.7 and 6.3 h. For each replicate when the bubble barrier was active, a corresponding control replicate with the same starting and ending time was recorded on another day during a period when the barrier was turned off. This pairwise design, with a total of 14 replicates, was done to prevent bias from any diurnal variation in migration intensity. Treatment (barrier on) and control (barrier off) replicates were alternated throughout the study to minimize differences in environmental factors within paired replicates. For further information on replicate distribution, temperature, and river discharge; see Figure S1 and Table S1.

2.5 | Telemetry data curation

Detailed information on movements of specific individuals at the study site was tracked using acoustic telemetry. Between 22nd of May and 2nd of June 2020, 40 wild kelts (31 salmon and 9 brown trout) were caught in the intake channel at Stornorrfors hydropower plant, using rod and reel. As kelts can tolerate more handling compared to fish that have recently entered the river, we expected low mortalities due to handling (Halttunen et al., 2010). After capture, fish were moved to an oxygenated tank holding 2 m^3 of river water (< 14°C) and transported 3 km upstream within 3 h. The 40 wild kelts ($TL = 67.4$ cm ± 2.0, mean ± 1SE) were surgically tagged using acoustic transmitters equipped with depth sensors (Vemco V7P-2x, weight: 1.2 g, length: 19 mm, signal delay; HR: 1.5 ± 0.1 s, PPM: 40 ± 8 s). Forty two-year-old salmon smolts acquired from a nearby hatchery were also tagged with acoustic transmitters (Vemco V5-2x, weight: 0.77 g, length: 12.7 mm, signal delay: HR: 0.9 ± 0.1 s, PPM: 30 ± 10 s, no depth sensor). Before tagging, fish were anaesthetized with tricaine mesylate (MS-222) until loss of equilibrium and measured for length. The transmitters were placed in the body cavity through a scalpel incision on the ventral side anterior to the pelvic girdle. The incision was closed using sutures and two surgeon's knots after which the fish were returned to either a flow-through tank (smolts) or a holding cage submerged in the river (kelts). After recovery and visual inspection of activity and flight behavior, to ensure that the fish were in good condition, the fish were moved to an oxygenated 1.5 m^3 transport tank, trucked 3 km upstream of the barrier, and released back into the river (Figure 1). All handling and tagging of fish were approved by the animal ethics board in Sweden (Dnr 5.2.18-3060/17).

We deployed 8 receivers (Vemco HR2) in a 1.5-hectare grid around the barrier, to detect signals from tagged fish. The average receiver spacing was 69 m, well below the detection range reported for the HR2 in similar settings (Leander et al., 2020). Fish positions were derived via hyperbolic positioning using the Vemco positioning system (VPS) as described by Smith (2013) and erroneous positions were filtered out using swimming speeds and turning angles, as described by Leander et al. (2020). The kelt transmitters sent signals with different time delays, but due to outdated firmware in the receivers, only the PPM signals were detected, and not the HR signal. Hence, we obtained a lower time resolution for the kelt.

2.6 | Sonar data analysis

Sonar data were quantified by human review with the same person for all data. Fish passages were defined as echoes generating a solid detection in red and given a timestamp (see example in Figure 2). Reference trials with dead fish towed in front of the transducer generated continuous sonar echoes. Hence, if echoes were absent for more than 10 s, the reappearance of an echo (also in the same area) was defined as a novel detection. Distribution for this data was tested with Shapiro–Wilk normality test. *T*-test was used to test for differences between control (barrier off, $n = 7$) and bubble treatment (barrier on, $n = 7$) in (i) the number of passages on the north side of the island, (ii) discharge, and (iii) temperature. To further explore how the bubble treatment, temperature, and discharge affected the number of passages on the north side of the island we performed a series of generalized linear models. Each factor was tested alone and in combination with the other (both with and without interaction terms) and model selection was based on the lowest AIC score. Values of discharge and temperature were provided from the hydropower plant and measured every 50 min. The sonar could only detect fish larger than approximately 30 cm; hence, this data provided information on kelts exclusively, and not on smolt.

2.7 | Telemetry data analysis

These data provided information on passages on both sides of the island and could therefore be used to analyze passage ratios (north vs. south) for smolts and kelts separately. Due to the low abundance of trout (9 out of 40 caught kelts) we did not analyze the species separately, hence data presented in this study does not explain any possible differences between the species. For individuals with few triangulated positions, we used raw data from the three receivers furthest downstream (the island functioned as a screen to block transmitter signals from one channel to the other; see Figure 1) to separate fish that passed on the north side from fish passing on the south side. If fish appeared on the site more than once, we only analyzed their first encounter.

Initially, we tested for any preference of passing the island on a specific side using tagged individuals entering the site when the bubble barrier was turned off. We used a chi-squared goodness of fit test and compared the observed ratio of passages (north/south) to an expected ratio of 0.5, that is, a random distribution. If significantly different from random, the observed control ratio was used as the expected ratio in second chi-squared goodness of fit test to be compared with the observed ratio of tagged individuals entering the site when the bubble barrier was turned on.

Similar to the sonar analysis, discharge and temperature were compared between control and treatment with t-tests. Each replicate (individual tagged fish) could be assigned a specific point in time, defined as the moment when that fish first passed a perpendicular line from the tip of the island. Corresponding data on temperature and discharge were assigned to each individual from the closest time stamp in the 5-min resolution data on environmental variables.

3 | RESULTS

3.1 | Sonar data

The sonar recorded 1319 fish detections throughout the study period and a Shapiro–Wilk normality test showed that the number of detections per hour had a normal distribution ($W = 0.890$, $p = 0.080$). When the barrier at the south side of the island was turned off, we observed on average 12.7 kelt passages per hour at the north side of the island. With the barrier turned on, we observed a significant increase of 94% to an average of 24.6 kelt passages per hour on the north side of the island ($t = -2.759$, $df = 9.288$, $p = 0.022$; Figure 3).

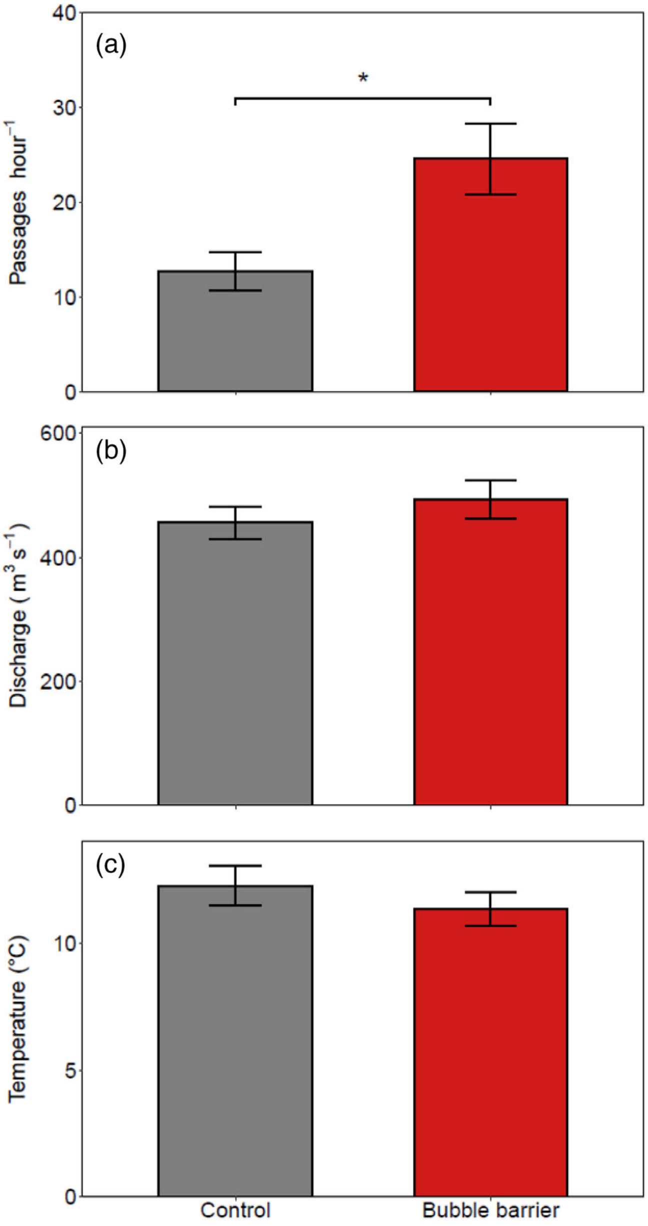

FIGURE 3 (a) Mean number of fish passages per hour on the north (alternative fishway without barrier) side of the island, (b) river discharge, and (c) temperature, for control (grey) and bubble treatment (red). Error bars showing ±1 SE and significant difference ($p < 0.05$) is indicated with *. [Color figure can be viewed at wileyonlinelibrary.com]

No difference in discharge ($t = -0.928$, df = 11.651, $p = 0.372$), nor water temperature ($t = 0.897$, df = 11.703, $p = 0.388$), was seen between treatments in the sonar data. The generalized linear model with the lowest AIC-score included the bubble treatment and temperature as explanatory variables with no interaction between them (Table S2). The bubble treatment showed a significant positive effect on the number of passages on the north side of the island ($p = 0.026$; Table S3), whereas temperature had a negative effect on the number of passages ($p = 0.032$).

3.2 | Telemetry data

Of the 80 fish released, six smolts and two kelts were excluded from the analysis because they never reached the study site, leaving 34 smolts and 38 kelts available for statistical analyses. After filtering the telemetry data, the median (± 1 SE) offset from a towed reference tag to a high-precision GPS track (i.e., accuracy) was 0.84 ± 0.07 m. The average (± 1 SE) swimming depth of the individual the kelt was 1.81 ± 0.19 m.

Both kelts and smolts had a preference for migrating south of the island when the barrier was turned off, with only 3 out of 18 kelts ($\chi^2 = 8.00$, $p = 0.005$), and 4 out of 20 smolts ($\chi^2 = 7.20$, $p = 0.007$) choosing the north side, indicating that the north side was a non-preferred migration route for the fish. These ratios were used as the expected values when the bubble barrier was turned on. Here, a significant increase of passages on the north side was observed for both age classes, where 8 out of 20 kelts ($\chi^2 = 7.84$, $p = 0.012$) and 8 out of 14 smolts ($\chi^2 = 12.07$, $p = 0.002$) chose the north side with the bubble barrier turned on (Table 1). No difference in water temperature was observed between periods when the barrier was turned on or off in the telemetry data (kelts: t = 0.246, df = 35.692, $p = 0.808$; smolts: t = 1.914, df = 19.688, $p = 0.070$), nor for the discharge during tagged smolt passages (t = −0.851, df = 25.079, $p = 0.403$). However, discharge during tagged kelt passages was significant higher during the bubble treatment, 581 m^3s^{-1}, compared to control, 492 m^3s^{-1} (mean values, t = −2.976, df = 30.340, $p = 0.006$; Figure 4). This was due to daily variance in turbine discharge and resulted in an average surface water velocity of approximately 1.1 m s^{-1} during control and 1.4 m s^{-1} during the bubble treatment (Figure S2), potentially reducing the efficiency of the bubble barrier by

TABLE 1 Expected and observed passages on the north side of the island for the different treatments (control, bubble barrier active) and age classes (kelts, smolts). The number of individuals expected and observed passages on the northern (untreated side) with corresponding chi-squared and *p* values are summarized for each group. Passages are given in both proportion of the total (prop.) and absolute numbers (abs.).

Treatment	Age class	Number of individuals	Expected passages north (prop. ∣ abs.)	Observed passages north (prop. ∣ abs.)	χ^2 value	*p* value
Control	Kelt	18	0.50 ∣ 9	0.17 ∣ 3	8.00	**0.005**
Bubble	Kelt	20	0.17 ∣ 3.4	0.40 ∣ 8	7.84	**0.012**
Control	Smolt	20	0.50 ∣ 10	0.20 ∣ 4	7.20	**0.007**
Bubble	Smolt	14	0.20 ∣ 2.8	0.57 ∣ 8	12.07	**0.002**

Note: The bold values are the *p*-values from the statistical test and represent the significance of the test.

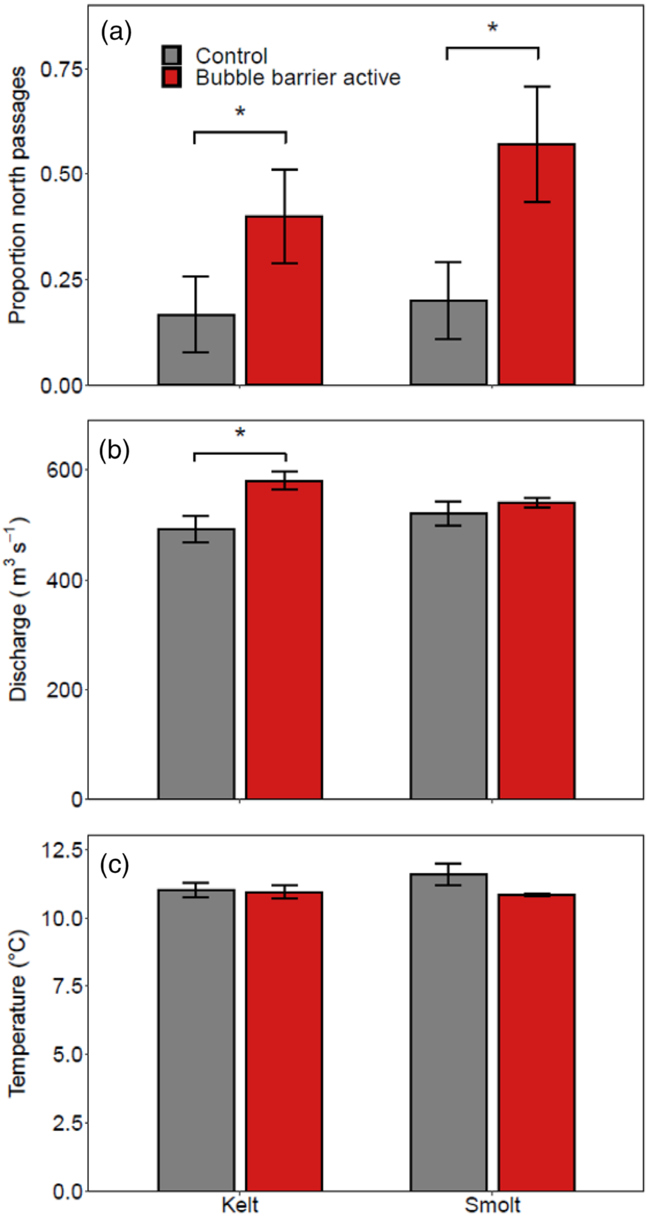

FIGURE 4 (a) Mean proportion of passages on the north (alternative fishway, without barrier) side of the island, (b) river discharge, and (c) temperature, for tagged kelts ($n = 38$) and smolts ($n = 34$), for control (grey) and bubble treatment (red). Error bars showing ±1 SE and significant difference ($p < 0.05$) is indicated with *. [Color figure can be viewed at wileyonlinelibrary.com]

increasing the tendency of kelts to migrate on the south side of the island when discharge was higher.

4 | DISCUSSION

4.1 | Bubble barrier's ability to guide salmon and trout kelts

Our main hypothesis stating that bubble barriers can guide downstream migrating salmonid kelts was evaluated using two independent techniques (sonar and acoustic telemetry). Both methods confirm our hypothesis that bubble barriers can significantly increase kelt and smolt passages in an alternative fishway by diverting them away from the main migration channel. These findings expand on results from earlier studies of non-physical guidance structures targeting smolts (Leander et al., 2021; Perry et al., 2014; Welton et al., 2002), and are the first results showing the generality of these barriers for different life stages (smolts and kelts) and species (Atlantic salmon and brown trout).

Increased water velocities may have a negative effect on the guiding effect of bubble barriers (Noatch & Suski, 2012), considering that higher water flow will increase the downstream tilt of the barrier, increase dispersion of the bubbles, and reduce reaction time for the fish encountering the barrier. Indeed, the somewhat higher fish guidance efficiency reported in earlier studies (90%–95%: Leander et al., 2021; 20%–74%: Welton et al., 2002) compared to our study (40% and 57% for kelts and smolts, respectively), could result from the higher water velocity in our study system. Furthermore, the gradient in water velocity with slow-moving water close to land and fast-moving water in the mid-section created a non-linear displacement of the bubble barrier as seen in Figure 1. Fine-tuning the barrier by deployment in a convex shape could mitigate the concave shape in this study and possibly increase the efficiency. Nevertheless, our barrier still functioned even at considerable water flow rates up to 600 $m^3 s^{-1}$, indicating that bubble barriers could be successfully used in large-sized rivers, such as Ume River, where physical guidance structures are very expensive to install (Emanuelsson et al., 2017).

4.2 | Bubble barriers and their potential role for management of migratory salmonids

Considerable resources are spent on managing migratory fish populations in regulated rivers, by constructing fishways with various success (Noonan et al., 2012). Mitigation efforts are often focusing on upstream migration, while downstream migration historically has been neglected. Consequently, downstream migrating post-spawned individuals of iteroparous salmonids have received little attention compared to upstream adult spawners. Nevertheless, up to a quarter of Atlantic salmon egg production can be lost when repeat spawners are removed from a river (Bordeleau et al., 2020; Halttunen, 2011), making successful downstream migration of post-spawned individuals of high importance. Further, the positive correlations between female size, which generally is higher in repeat spawners (Bordeleau et al., 2020; Welton et al., 1999), egg size, and fry survival (Fleming, 1996; Jonsson & Jonsson, 2011) emphasize the substantial contribution from kelts to total recruitment. Moreover, survival at sea is higher for post-spawned fish compared to smolts with an average return rate of 39% and 19% for females and males, respectively (Halttunen, 2011), making this life-stage increasingly important in the light of high post-smolts mortality that has been observed for multiple Atlantic salmon populations over its distribution range (Thorstad et al., 2012). With this profound ecological role in mind, in combination with the socio-economical role played by large salmonids in recreational fishing (Curtis, 2002; Pokki et al., 2018), where repeat spawners are typically larger than their maiden counterpart (Bordeleau et al., 2020; Welton et al., 1999), it seems urgent to facilitate kelt migration and, thus, survival of post-spawn salmonids. Indeed, it also seems rational to expect that the ongoing revision of water management policies in European countries (European Commission, 2018) will emphasize more direct on management of kelts.

The 100 m long barrier used in this study that proved functional for one of the major rivers in Fennoscandia came with a cost of under 10,000 Euros, which can be compared to a calculated cost of between 28 and 35 million Euros for installing a 165 m long guiding structures (racks) implemented for a similar-sized river (Emanuelsson et al., 2017). Moreover, our installation took a less than 2 weeks, while installation of physical structures can take years. While physical barriers may be expected to have a higher efficiency if they cover the full width and depth of a river, these structures come with a high cost, and we argue that it is not economically realistic to implement and maintain physical structures around all hydropower dams within the short timescale needed for swift action. Furthermore, any physical structures upstream turbine intakes are associated with head loss that consequently leads to decreased electricity production. This is exaggerated by clogging debris, which also leads to higher safety risks and potentially failing equipment (Clay, 1995). As long as there are no functional and cost-effective solutions to the downstream migration of adult fish, wild populations of anadromous species with an iteroparous life cycle, such as Atlantic salmon and sea-running brown trout, will struggle. Here, we see bubble barriers as one of a few realistic options that can be rapidly implemented to facilitate efficient guiding of kelts to reduce mortality and, thus, promote populations by increasing the number of returning spawners. For many rivers, where repeat-spawning salmonids currently are rare (Baktoft et al., 2020; Karlsson & Karlström, 1994; Nyqvist et al., 2015), such successful diversion of only a few individuals to safe downstream passages would likely have large ecological and socio-economic impacts.

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DATA AVAILABILITY STATEMENT

All data used in this manuscript are available through the Figshare database: 10.6084/m9.figshare.24099726 and 10.6084/m9.figshare.24099750.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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