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Fish behavior at the horizontal screen of a novel shaft hydropower plant

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Abstract

Preventing fish entrainment during their downstream passage at hydropower plants remains a major challenge in reducing the ecological impacts of hydropower production. We investigated fish behavior at the world's first innovative shaft hydropower plant with its novel screen concept, aiming at reducing fish entrainment due to the fully horizontal arrangement of the screen and low vertical suction effects toward the turbine. Based on ARIS sonar recordings, we assessed whether fish could move unhindered across the turbine intake area toward the bypass corridors at the sluice gate for safe downstream passage. For a range of species (*Anguilla anguilla*, *Barbus barbus*, *Thymallus thymallus*, *Salmo trutta*, and *Hucho hucho*) and operation modes (high/low turbine load), we assessed behavioral patterns such as screen avoidance, dwelling behavior, and search behavior at the screen. Contrary to the engineers' expectations, the innovative screen arrangement neither guided the fish away from the turbine intake to the bypass corridors nor prevented them from swimming vertically into the turbine shaft. Rather, fish freely moved near the screen and avoidance behavior was only rarely observed. Both the dwelling and active search behavior, which was particularly evident in eel, are directly linked to an increased risk of screen passage and subsequent turbine-related death or injuries. Our findings illustrate that consideration of fish behavior at turbine inlet structures is a crucial component which needs to be integrated with other variables such as fish mortality and injury patterns for a comprehensive evaluation and improvement of fish passage at hydropower plants.

KEYWORDS
ARIS imaging sonar, fish behavior, fish passage, fish protection, horizontal screen, innovative hydropower, shaft power plant, turbine entrainment

1 | INTRODUCTION

Given the increasing need for sustainable yet efficient "green energy", hydropower technologies are constantly evolving (Kougias et al., 2019; Manzano-Agugliaro et al., 2017). Besides improving efficiency, innovative hydropower designs aim to minimize the ecological footprint, with particular emphasis on river connectivity and fish friendliness (Geist, 2021). The latter is also highlighted in European and German legislation, which demands that measures to protect fish populations against the effects of hydraulic engineering installations must be taken (BMUV, 2023; EC, 2018; EC, 2020). However, enabling a less harmful (i.e., reduced fish mortality) fish downstream passage remains the greatest challenge. Turbine passage is often the main downstream migration corridor for fish (Knott et al., 2023a), while at the same time posing the highest injury and mortality risk for them (Fjeldstad et al., 2018; Mueller et al., 2022). The most common measure to prevent fish from entering or being drawn into a turbine shaft is to install a fish protection screen (FPS) upstream of the turbine inlet (for review see Schwevers & Adam, 2020). Recent empirical work has shown that some fish species are capable of passing through much narrower openings than expected from their body dimensions (Knott et al., 2023b) which is in contrast to the assumption that body widths greater than the bar spacing should physically not be able to pass (Ebel, 2013; Schwevers & Adam, 2020). Ideally, such screens should be capable of protecting different species and life stages.

In addition to physical exclusion, some physical barriers are designed to guide fish toward alternative corridors such as bypass channels (Larinier & Travade, 2002; Meister et al., 2022). To achieve such a guiding effect, different shapes of FPSs (e.g., plane or semi-circular), different inclinations to the riverbed, or different arrangements of the screen bars (horizontal vs. vertical) are used, and many laboratory studies assessed their effectiveness with variable outcomes (e.g., Albayrak et al., 2020; Meister et al., 2022; Russon et al., 2010). However, there is still limited understanding of how species-specific behavior influences corridor choice in real-world scenarios at hydropower facilities (Egg et al., 2017; Knott et al., 2020; Noonan et al., 2012).

In addition to ecological considerations, the installation of FPSs to date is often associated with high costs and—depending on the screen type—some loss of operational efficiency of the hydropower plant. The main obstacles include construction problems, screen-cleaning issues, and increased hydraulic loss due to narrower bar spacing causing lower clearance (Schwevers & Adam, 2020). Moreover, the approach velocity or suction effect in front of the FPS needs to be held low to prevent damage to fish by impingement, usually resulting in larger and more costly screens (Calles et al., 2010; Larinier & Travade, 2002; Schwevers & Adam, 2020). Especially smaller fish and fish larvae have difficulties to escape enduring flow velocities >0.5 m s^{-1} that are postulated as a threshold for maximum flow velocities in front of the screen by Ebel (2013).

An alternative screen concept at the novel shaft hydropower plant (SHPP) was invented, claiming to improve interrupted matter fluxes and minimize habitat quality deterioration due to the damming effect, and to reduce turbine entrainment and simultaneously improve fish guidance to a safe downstream passage (Sepp & Rutschmann, 2014).

The SHPP at the world's first construction site in Großweil, Germany has been in operation since February 2020. While in this concept, the turbine is submerged and embedded in a shaft below the riverbed, the shaft is covered with a horizontal screen, which was intended to be plane with the river bottom. In theory, this FPS concept should allow fish to move freely across the screen/intake area and to get guided to safe downstream corridors at the sluice gate. It was assumed by the developers that approaching fish would perceive the FPS as an impassable barrier. Consequently, it was supposed that it would be unnatural for them to orient downwards toward the shaft and to try to swim through. In the United States, a similar screen concept of a self-cleaning flat-plate horizontal irrigation screen ("the farmers screen") showed promising results during field assessments concerning safe fish guidance. All fish were safely transported through the bypass channel along the screen with minimal screen and wall contacts resulting in low injuries and >98% survival (Mesa et al., 2012; Salalila et al., 2019).

So far, the potential protection effectiveness of this SHPP screen concept has only been tested under laboratory conditions at a small-scale prototype of the SHPP by the inventors themselves (Cuchet et al., 2012; Geiger et al., 2016). Since data on fish behavior and fish passage from small-scale flume experiments can strongly differ from actual field observations (Egg et al., 2017), an evaluation of the suitability of this screening concept requires an assessment of fish approaching the screen in a realistic field situation. Consequently, the installation of the SHPP provided an ideal opportunity for such a validation under realistic conditions.

The core objective of this study was to validate whether the innovative horizontal screen at the SHPP allows fish to move unhindered across the screen/intake area to reach the corridors at the sluice gate for safe downstream passage. This was achieved by recording the behavior of fish with an ARIS sonar system at the screen under different operational scenarios. Specifically, we hypothesized that (i) species-specific differences in behavior of fish approaching the screen exist which need to be considered to effectively bypass fish toward safe downstream corridors, and (ii) the innovative screen concept effectively prevents fish from entrainment into the turbine corridor.

2 | METHODS

The behavioral study described in this paper was performed simultaneously to an extensive ecological monitoring, which assessed ecological effects, turbine-related fish injuries and mortality, and physical conditions during turbine and bypass passage at the novel SHPP (for details see Knott et al., 2023c, 2024). Hence, this study took advantage of the logistics, permissions, and work power on site.

The study was conducted within the framework of an animal experiment, approved by the animal welfare officer of the Technical University of Munich and the Ethical Commission of the Bavarian Government (permit number ROB-55.2-2532.Vet_02–19-160). Fish handling in the experiments followed the guidelines by Adam et al. (2013), national laws and European guidelines for the use of aquatic animals for experimental purposes to prevent unnecessary stress and harm of fish (European Parliament, 2010). Additional permissions were obtained from the rural district office Garmisch-Partenkirchen for motorboat usage (permit numbers 32-6416/1, 32-8502.2) and for keeping test fish in on-site tanks (permit number 53-5682-Ho) during fieldwork.

2.1 | Study site

The study was conducted in fall 2020 and spring 2021 at the world's first SHPP situated near Großweil at the River Loisach in southern

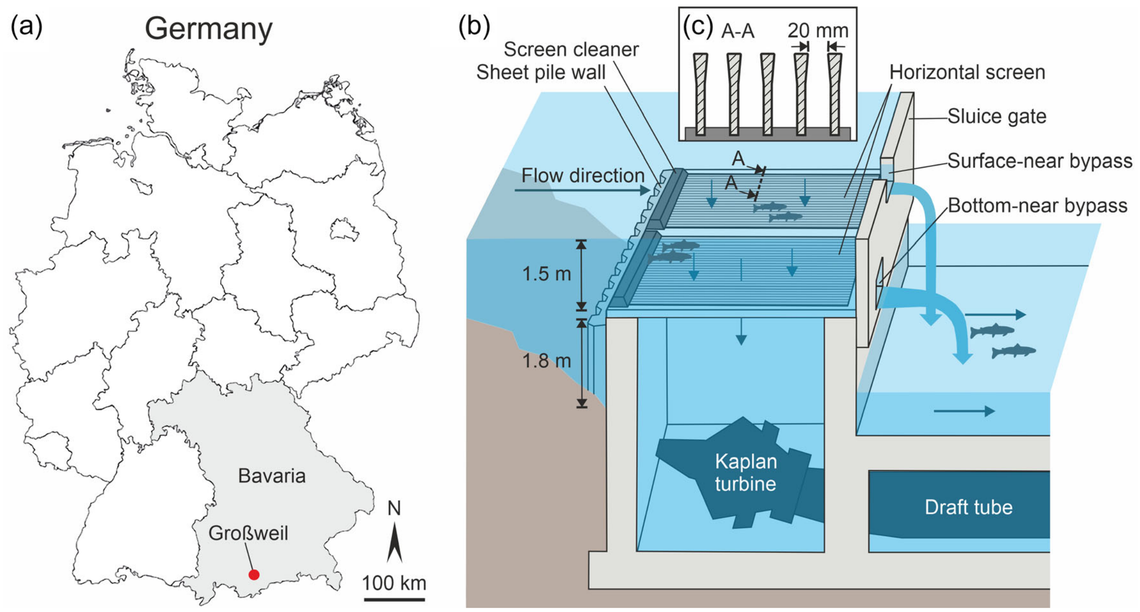

FIGURE 1 (a) Location of the study site near Großweil in Bavaria, Germany. (b) Schematic cross-section of the shaft hydropower plant with horizontal screen. The novel screen concept design is intended to enable unhindered fish passage across the intake area and to guide the fish to the bypass systems at the sluice gate. Arrows indicate directions of water flow. (c) Cross-section A–A (position indicated in b) of the Y-shaped screen bars with specification of the nominal bar spacing. [Color figure can be viewed at wileyonlinelibrary.com]

Germany (N 47.6819, E 11.3002). During the experiments, a mean discharge of 19.5 $m^3 s^{-1} \pm 4.1 m^3 s^{-1}$ was measured in fall and 14.7 $m^3 s^{-1} \pm 2.5 m^3 s^{-1}$ in spring at the test site (taken from the nearest water gauge Schlehdorf). The water parameters were constant throughout the study period (Table A1).

The SHPP is equipped with two 4-bladed horizontal Kaplan bulb turbines (diameter 1.75 m, runner speed 156 rpm). At a head of 2.5 m and a maximum discharge of 11 $m^3 s^{-1}$ per turbine, the maximum power capacity is 420 kW (annual output 2.4 million kWh). Both turbines are installed in a vertical shaft below the riverbed. The two shafts are each covered by two rectangular FPSs (6.0 m × 2.6 m area per screen) (Figure 1). Contrary to what was originally planned in the SHPP concept, the FPS was not level with the riverbed, but on average 1.8 m higher than the river bottom (Knott et al., 2023c). The screen bars are arranged in flow direction. They have a nominal bar spacing of 20 mm and a y-shaped profile that becomes narrower toward the bottom (Figure 1). A screen cleaner is installed on top of each screen. To prevent a possible suction effect toward the screen bars and the shaft, the intake area was designed so that flow velocities do not exceed 0.5 $m s^{-1}$, which should minimize the suction of fish vertically into the shaft and toward the turbine (Sepp et al., 2016). The water depth above the screens reaches on average 1.5 m. During the study, average flow velocity rates of 0.3 $m s^{-1} \pm 0.2 m s^{-1}$ (min–max: 0.01–0.87 $m s^{-1}$) were measured 10 cm above the screen area (Table A1). Measurements were taken three times a day at 12 different positions using a magnetic-inductive flow velocity meter (MFpro, OTT Hydromet, Kempten, Germany). A sheet pile wall borders the upper end of the screen area, while at the lower part it is directly adjacent to the sluice gates. Three bypass windows—one centrally located surface bypass in each sluice gate and one bottom bypass in the orographic right sluice gate—were built to enable fish downstream passage.

2.2 | Sonar-based monitoring

To observe fish behavior at the SHPP, we used the high-frequency multibeam sonar ARIS Explorer 3000 (Sound Metrics, Bellevue, WA, USA) with a rotator arm (ARIS Rotator AR2). The device was attached to a steel holder mounted to a floating pontoon (for detailed description see Egg et al., 2017) to allow placing the sonar at different angles, positions, and water depths. The ARIS sonar was placed about four meters away from the screen and was mounted 0.5 m below the water surface, looking toward the screen at an angle of ca. 15°. The sonar position was switched (position 1 and position 2 in Figure 2) once per test period to assess different operation modes (high/low turbine load) according to the prevailing discharge conditions (Table A2). It was operated at a frequency of 1.8 MHz with a resolution of 7.3 mm. The image contrast decreased with distance, increasing the chance to overlook smaller fish in the more distant areas. With a maximum view range of 15 m, it was possible to cover ca. 60% of each SHPP screen area. Figure 2 shows schematically the monitored screen areas from a bird's eye view. In total 60 h sonar material were recorded (fall: 41 h, spring: 19 h). The recordings were saved in 10-min intervals. All calculations and observations refer to sightings made in the sonar field of view.

Fish behavior at the screen intake of the SHPP was studied throughout the day during high (70%–100% turbine discharge) and low (34%–56% turbine discharge) turbine operation modes (for more

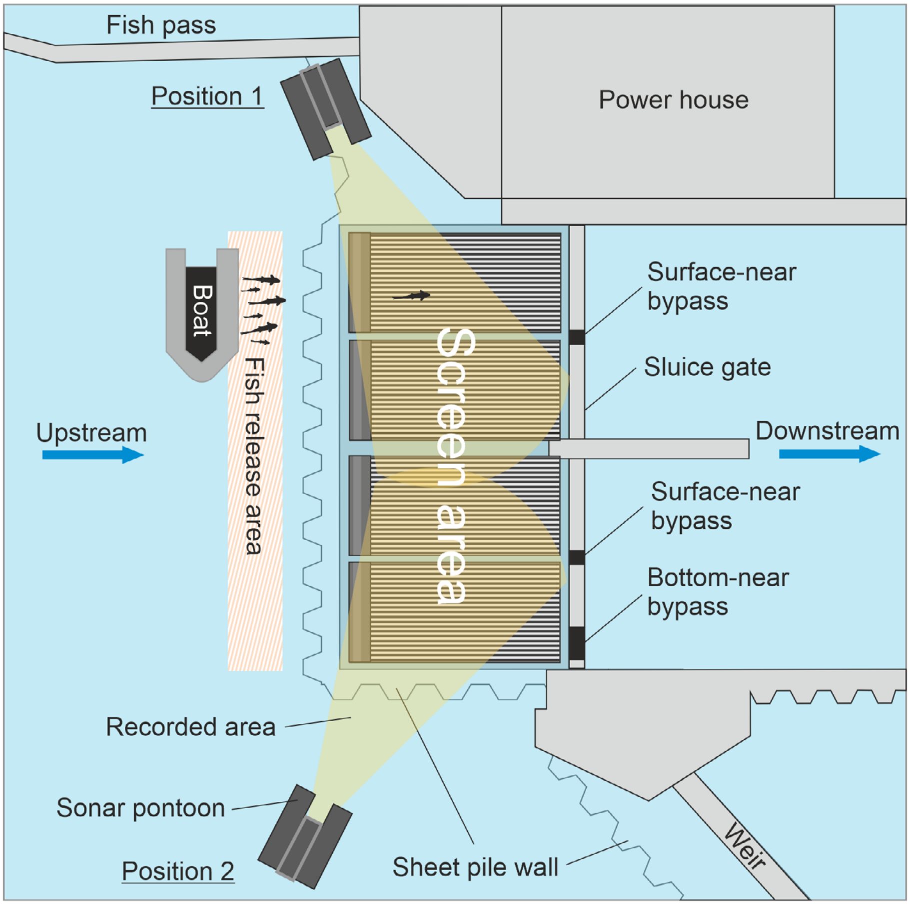

FIGURE 2 Schematic top view of the study set up at the shaft hydropower plant. Sonar coverage is indicated by yellow cones. Blue arrows indicate the flow direction. The same ARIS sonar was placed consecutively at two different positions (Position 1 and Position 2). [Color figure can be viewed at wileyonlinelibrary.com]

details see Table A2). Test fish were released several times during the day upstream of the SHPP ca. 2 m in front of the horizontal screen from an inflatable boat (Figure 2).

2.3 | Stow-fyke-net recaptures

Fish passing the FPS and the turbine were caught with stow-fyke nets at the downstream end of the hydropower shaft to assess species and fish size passing through the 20 mm bar spacing of the FPS. The nets were attached to metal frames and inserted into U-profiles at the turbine outlets (for detailed description from other test sites see Knott et al., 2020 or Smialek et al., 2021). The stow-fyke nets had decreasing mesh sizes, getting smaller toward the back (mesh sizes ranging from 30 to 8 mm). The nets were emptied every 1–2 h. Each individual fish caught in the nets was measured (total length = TL, to the closest mm), determined to species level and distinguished into wild or test fish based on the presence of a fin clip.

2.4 | Test fish

To investigate the behavior of fish approaching the FPS of the SHPP, standardized fish experiments with five species of hatchery reared test fish were performed. The test fish species used were European eel (*Anguilla anguilla* L.), barbel (*Barbus barbus* L.), brown trout (*Salmo trutta* L.), European grayling (*Thymallus thymallus* L.), and Danube salmon (*Hucho hucho* L.). These species were selected because they show different behavior (e.g., bottom- vs. open water-oriented) and differ in their morphological characteristics. TL of the test fish across all species ranged from 2.9 to 66.7 cm (Table 1). European eel and barbel were tested in fall 2020. European grayling, brown trout, and Danube salmon were tested in spring 2021. Since it was not possible to distinguish between the salmonid species on the sonar recordings, they were combined into a single group in the analysis further referred to as "SAL." Generally, it is hard to distinguish fish of similar shape on sonar recordings (e.g., besides our "SAL" species also barbel and brown tout; cf. Egg et al., 2018). Herby the separation of our test species in time (tested in different seasons) ensured an almost unambiguous identification of barbel and SAL fish. Since eel has a very characteristic body shape as well as swimming behavior (i.e., snake-like) it is considered easy identifiable and distinguishable from other species on the ARIS sonar (Egg et al., 2018). Hence, species registered other than eels in the eel test period were excluded from later analysis ($n = 482$). During the other test periods, only few wild fish (= naturally occurring fish) were present on the test site. Since test fish were all fin-clipped before release, a clear differentiation of test fish and wild fish was possible in the stow-net catches downstream of the installation. Control catches via stow-fyke net in the turbine tailrace throughout the sonar survey revealed that 94–100% of the

TABLE 1 Summary of information on species used, test period, and total length (TL) of released (Rel. fish) and recaptured (Recap. fish) test fish species during the ARIS sonar experiments.

Fish species	Test period	Rel. fish	TL (cm) a.m. ± SD (min–max)	Recap. fish	TL (cm) a.m. ± SD (min–max)
European eel (*Anguilla anguilla*)	September 22nd to September 25th, 2020	208	41.4 ± 7.8 (23.1–66.7)	74	41.6 ± 6.4 (31.4–57.7)
Barbel (*Barbus barbus*)	September 29th to October 2nd, 2020	412	12.7 ± 6.0 (6.2–37.4)	151	10.3 ± 2.2 (6.5–17.4)
Brown trout (*Salmo trutta*)	March 17th to March 19th, 2021	618	13.4 ± 8.4 (2.9–38.8)	133	10.8 ± 4.2 (3.4–17.8)
European grayling (*Thymallus thymallus*)	March 17th to March 19th, 2021	412	11.5 ± 3.2 (4.8–20.3)	241	10.8 ± 2.8 (6.5–16.5)
Danube salmon (*Hucho hucho*)	March 23rd to March 26th, 2021	824	20.1 ± 8.4 (9.2–59.3)	129	15.6 ± 4.0 (9.6–25.3)

recaptured fish consisted of the released test fish in the corresponding test period. The classification as barbel in the test period of barbel was 94% accurate, during the SAL test weeks >99% of the fish recaptured in the stow-fyke-net control catches were our test fish SAL.

2.5 | Viewing of sonar recordings and categorization of fish behavior

Sonar data were viewed with the Software ARIScope (Sound Metrics, Bellevue, WA, USA). Two different persons independently watched each video sequence, producing highly consistent results. For the best possible image quality, the zoom, playback speed, and signal intensity were changed as desired in ARIScope. To assess fish movements and specific behavioral patterns recorded, a standardized evaluation category table was used (Table 2). Regarding the category "behavioral pattern," five types of behavior were observed and thus distinguished: dwelling, drifting, avoiding, searching, and screen passage (Table 2). The relative vertical position of the fish in the water column was estimated from the size of the acoustic shadow.

2.6 | Data analysis

In order to answer the hypotheses and associated questions, different subsets of the obtained data were analyzed (see Table 3 for details). Under hypotheses (i) we analyzed: (a) the general behavior to assess if there is a relationship between species (eel, barbel, SAL) and the behavior shown; (b) the dwelling behavior at structures to investigate if there is a relationship between species (eel, barbel, SAL) and the structure it dwells at. Under hypotheses (ii) we analyzed: (c) if screen passage is linked to specific behavioral patterns; (d) if there is a relationship between species and their behavior shortly before screen passage; and (e) if there is a relationship between species and the way they pass the screen (active vs. passive).

All analyses on fish behavior were carried out using Fisher's exact test with Monte Carlo simulation (number of replicates = 2000). The expected values were calculated using Pearson's Chi-squared test. Since some expected cell counts were <2 and in >80% of cases ≤5, Fisher's exact test was favored over Pearson's Chi-squared test to compare species. The Wilcoxon test was used to compare the normalized number of test fish (individuals per hour) showing a specific behavioral pattern between high and low turbine load. Statistical test results were classified as significant at an error probability of $p \leq 0.05$. The analyses were computed using the statistical and graphical open-source software R (version 4.3.1; R Core Team, 2023). The results were plotted using the R-package ggplot2 (version 3.4.2; Wickham, 2016).

3 | RESULTS

3.1 | General behavior

The highest numbers of fish were observed shortly after fish releases. A total of 1600 fish sightings were registered. Of these, 1118 could be used for the further investigation, and 482 sightings were excluded from analysis (wild fish during eel test period). We observed 113 eels, 248 SAL, and 757 barbels. Four main behavioral patterns were observed among the 1118 test fishes recorded with the sonar, namely: dwelling, drifting (active and passive), searching, and avoidance (for definitions see Table 2). Only few fish displayed more than one behavioral pattern (29 of 1118). For those, only the dominant behavior (i.e., behavior displayed for the majority of time on the recording) was taken into account for the analyses. During the two tested operational modes (different turbine loads, Table A2), no significant differences in behavioral patterns of test fish were evident ($n = 1118$; Wilcoxon test, $p > 0.05$). The most frequently displayed behavioral patterns are summarized in Figure 3.

We found that behavior differed significantly among species ($n = 1118$; Fisher's exact test, $p < 0.05$; Figure 4). The largest differences were observed for eel in comparison to SAL and barbel. The dominant behavioral patterns in SAL and barbel were dwelling (71% of SAL, 92% of barbel) and active drift behavior (27% of SAL, 7% of barbel), while little other behavior was observed. In contrast, eels displayed all behavioral patterns. Interestingly, dwelling behavior was observed least (<1%) but instead, eel showed a pronounced drift (active and passive) and search behavior. A smaller proportion of eels (5%) displayed avoidance behavior.

TABLE 2 Fish behavior evaluation category table with definitions.

Theme	Category	Definition
Position in the water column	Near-bottom	Immediately at the sheet pile wall or just above the screen (no river bottom visible on the sonar recordings)
	Middle	Open water, between bottom structure and surface
	Near-surface	Near the surface, max. 10 cm below
Main area of residence	At sheet pile wall	At the sheet pile wall, laterally or at the top edge
	On screen area	On top of or just above the screen area
	Behind screen cleaner	In the flow shadow of the screen cleaner
	Free water column	Clearly above the screen or in the open water at a visible distance from the sheet pile wall
Fish activity	Active	Distinct swimming movement or other type of active behavior
	Passive	Steady drifting with the current, only slight counter-movements if any
Direction of movement	With flow direction	Fish moves with the flow direction, snout pointing into flow direction
	Against flow direction	Fish moves against the flow direction with active tail beats
	Left to right	Fish swims from orographic left side to the orographic right side of the river
	Right to left	Fish swims from orographic right side to the orographic left side of the river
	Static	After appearing, fish stays in one place most of the time or swims calmly back and forth in the same spot
Behavioral pattern	Screen passage	Fish shows one of the below mentioned behavioral patterns and then passes through the screen or suddenly disappears on the screen
	Searching	Fish changes from horizontal to vertical position at least three times, thus tapping the screen with the snout, or fish is already swimming vertically and stops at least three times with contact to a bottom structure
	Drifting	Fish moves continuously along the screen area, the sheet pile wall, or the deeper area next to the sheet pile wall without stopping or showing active searching behavior
	Dwelling	After appearing, fish stays in one place most of the time or swims calmly back and forth in the same spot
	Avoiding	Fish turns away from the screen area or sheet pile wall and quickly swims away

TABLE 3 Overview of data subsets used for the analyses.

Subset	Categorical variables 1	Categorical variables 2	Test
(a) $n = 1118$	Eel, barbel, SAL	Dwelling, drifting (active and passive), searching and avoidance	Fisher's exact test
(b) $n = 877$	Eel, barbel, SAL (only dwelling individuals considered)	Sheet pile wall, screen cleaner, screen area, open water	Fisher's exact test
(c) $n = 1118$	Passage, no passage	Dwelling, drifting (active and passive), searching and avoidance	Fisher's exact test
(d) $n = 106$	Eel, barbel, SAL	Dwelling, drifting (active and passive), searching	Fisher's exact test
(e) $n = 106$	Eel, barbel, SAL	Active, passive	Fisher's exact test

Note: All analyses were carried out using Fisher's exact test with Monte Carlo simulation (number of replicates = 2000).

3.2 | Dwelling at structures

We found significant differences among species in their preference to dwell at certain spots at the hydropower structures ($n = 877$; Fisher's exact test, $p < 0.05$). Barbel and SAL actively used physical structures to dwell. These structures included the sheet pile wall, the screen cleaner, and the screen (Figure 5). The screen area was the favored spot by both, barbel (47% of all barbel) and SAL (89% of all SAL), followed by the open water (27% of all barbel, 8% of all SAL). At the screen cleaner, only barbel were observed dwelling (16% of all barbel). Least fish were found dwelling at the sheet pile wall (10% of all barbel, 3% of all SAL). Only one eel (of 113) displayed dwelling behavior and was sighted at the screen area. On average, fishes dwelled at the sheet pile wall and screen cleaner 5:57 min:s ± SD 6:13 min:s in the flow shadow before they would swim away. On the screen area fishes stayed on average 6:26 min:s ± SD 10:43 min:s.

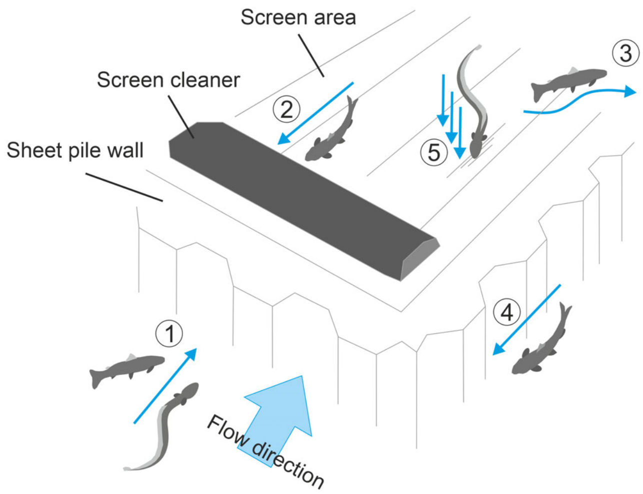

FIGURE 3 Schematic summary of the most frequent behavioral patterns (cf. Table 2) observed during the ARIS sonar recordings at the screen area of the investigated shaft hydropower plant. (1) fish released, (2) dwelling behind the screen cleaner, (3) fish drift through the observation area, (4) dwelling at the sheet pile wall, (5) active search behavior—body vertically above the screen (eel only). [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Screen passage

In total, 106 fish (9.5% of all fishes) were observed passing through the screen. A significant relationship was found between the general behavior displayed and the screen passages observed ($n = 1118$; Fisher's exact test, $p < 0.05$). Hereby, 76% of passive drifting and 30% of search behavior eventually resulted in screen passage. In 27% of cases, active drifting resulted in screen passage, whereas only 7% of "dwellers" passed the screen. When comparing observed with expected values, dwelling resulted less frequently in screen passage, while all other behaviors (except avoidance) resulted more often in screen passage than expected under the assumption of independence.

In a second step, the different behaviors prior to screen passage (i.e., the behavior displayed by fish shortly before they pass the screen, including only the fish that have passed the screen) were investigated to examine whether a specific behavior may have led to a higher probability of screen passage for the individual species or group (Figure 6). The observed behaviors prior to screen passage included (i) active drifting, (ii) passive drifting, (iii) dwelling, and (iv) search behavior. We found that species differed significantly in their behavior before screen passage ($n = 106$; Fisher's exact test, $p < 0.05$). For barbel, dwelling was the only observed behavior prior to screen passage. SAL displayed active drift (i.e., distinct swimming behavior where the fish moved continuously along the screen area; 74%) and dwelling (26%) behavior before passing the screen. Interestingly, only eel showed pronounced searching behavior prior to screen passage (Figure 6). Of all 113 eels sighted during the study, 35 (31%) systematically searched the screen area for loopholes by positioning themselves vertically in the water and repeatedly pressing their snouts between the bars of the screen. They either drifted with the flow or actively swam toward the screen to test for a potential passage. For 11 of 35 eels displaying this specific behavior, searching eventually resulted in screen passage. In direct comparison with the other behaviors displayed by the eel before screen passage, search behavior thus led to a passage in 21% of cases (Figure 6). Generally, search behavior was also observed sporadically in one barbel and two SAL individuals. However, unlike the eel, this did not result in screen passage.

We furthermore tested if species went active or passive through the screen. All SAL and barbel were observed to pass the screen actively, while eel showed in 44% of cases active ($n = 23$) and in 56% of cases passive screen passage ($n = 29$). The observed differences for species and species groups and their distinctive behavior were significant ($n = 106$; Fisher's exact test, $p < 0.05$).

4 | DISCUSSION

This study provides novel insights into fish behavior at the FPS of the world's first SHPP under realistic field conditions considering behavioral intra- and interspecific differences of different test fish. In contrast to hypothesis (ii), the innovative FPS did not effectively prevent fish from entering the turbine corridor, which contains a conventional Kaplan turbine that was found to cause substantial mortality and injuries to fish of various species (Knott et al., 2023c). This was partly attributed to active search behavior of eel for gaps to pass the FPS, and an absent avoidance behavior in other species. Instead, the FPS area seems to be recognized as a non-threatening physical structure. Analogously to fish species-specific patterns of mortality and injuries (Mueller et al., 2022), orientation in the water column (Knott et al., 2019) and corridor choices (Knott et al., 2023a), differing behavior types among different species were also found to strongly influence screen passage and subsequent turbine passage, which confirms hypothesis (i). Consequently, knowledge on the behavior of fish approaching the FPS can help improve safe fish passage and reduce negative ecological impacts of hydropower operations.

The results herein clearly indicate that fish perceived the screen and adjacent hydropower plant structures (e.g., sheet pile wall, screen cleaner) as nonthreatening. Most barbel and SAL tended to dwell at these structures probably to find shelter (e.g., at the sheet pile wall), search for food aggregations (due to flow field boundaries), or as resting spot (e.g., in the flow shadow of the screen cleaner). This preference of fish to stay at flow field boundaries at hydropower structures has also been observed in another study (Schmidt et al., 2018) where most fish were found in the border area between turbulent and recirculating flow. Such knowledge on areas preferred by fish can be very helpful to identify suitable entry pathways for safe downstream passage. Functional connectivity or guidance along structures is essential to enable safe fish passage (Schmidt et al., 2018). In contrast to barbel and SAL, eel displayed a wider range of different behavioral patterns after approaching the hydropower structures, of which dwelling was displayed least. Instead, eel showed pronounced search behavior for loopholes on the screen area, or avoidance where they turned around after contact with a structure and swam back

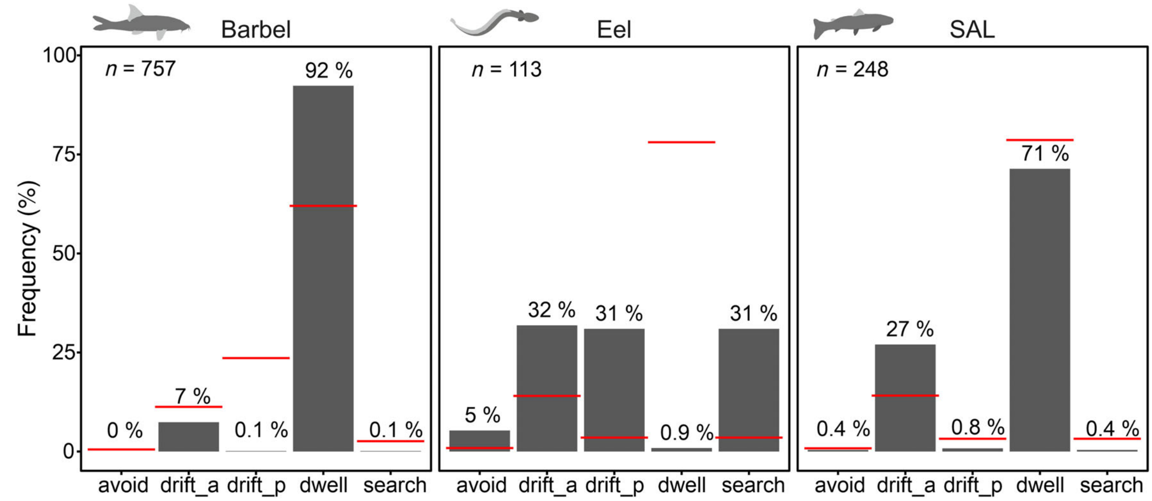

FIGURE 4 Frequency of behavioral patterns displayed by fishes during sonar recordings. drift_a = active drift, drift_p = passive drift. Grey bars = observed values, red line = expected values (Chi^2-calculation). [Color figure can be viewed at wileyonlinelibrary.com]

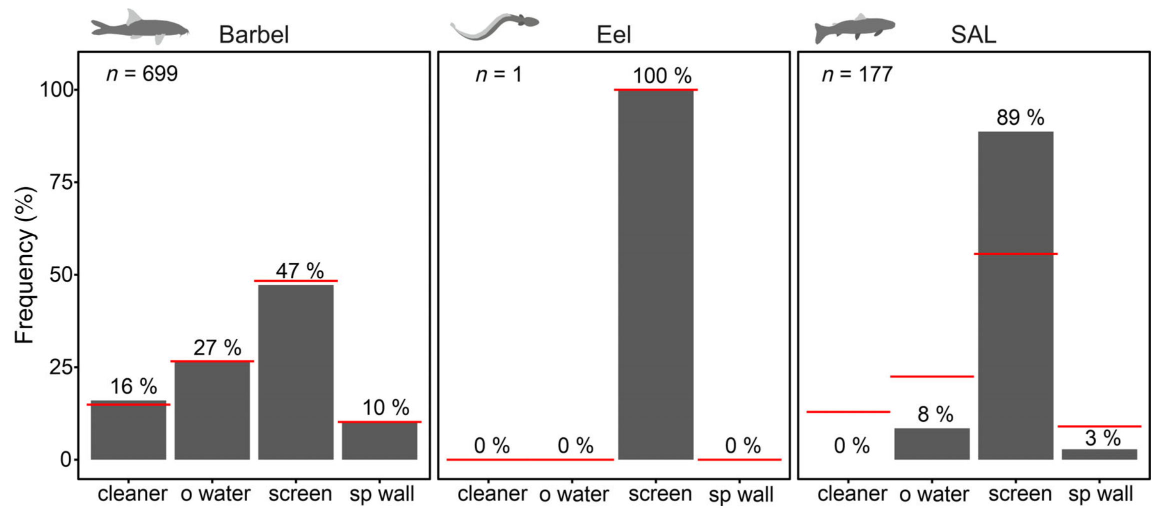

FIGURE 5 Frequency of fishes using the different localities at the hydropower structure. Cleaner = screen cleaner, o water = open water, screen = screen area, sp wall = sheet pile wall. Grey bars = observed values, red line = expected values (Chi^2-calculation). [Color figure can be viewed at wileyonlinelibrary.com]

upstream. This is also in line with previous studies that have investigated eel behavior at screen intakes of hydropower stations (Brown et al., 2009; Haro et al., 2000; Trancart et al., 2022; Travade et al., 2010). These studies all describe that when eel encounter a new structure, they tend to first actively approach it (often with contact) and then either pass directly through the screen bars (sometimes with previous pronounced search behavior) or turn around and swim away in the opposite direction back upstream (= avoidance behavior). The search behavior at the screen can include vertical excursions (Brown et al., 2009; Haro et al., 2000), a behavior that eel also displayed extensively in our experiment. Since eel are known to be rather nocturnal and photophobic, their search behavior probably was to escape light conditions by searching for hiding places (Bruijs & Durif, 2009). In addition, due to their elongated shape and small diameter compared to the other test fish, eels can more easily fit through the bar spacing. Hence, the combination of search behavior and slimmer body shape may considerably increase the risk of screen passage for eel at any FPS. However, extensive dwelling behavior on the screen, as displayed by barbel and SAL, may also increase the risk of screen passage. The longer the fish stay on the screen, the greater becomes the chance of finding a spot they can pass through, which ultimately will result in turbine passage.

The results clearly show that even larger fish can and (actively) did pass through the novel FPS concept. The bar spacing of 20 mm was not sufficient to prevent salmonids and barbel between 15 and 30 cm and eels of >50 cm from entering the turbine corridor. These observations are in line with findings from Knott et al. (2023c) which also found considerably larger fish passing FPSs (e.g., Danube salmon

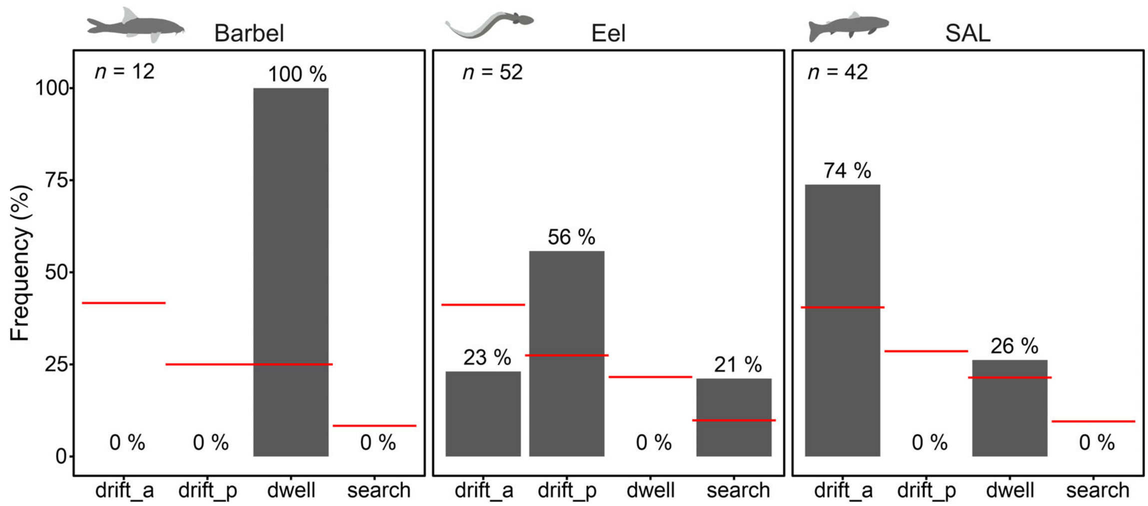

FIGURE 6 Frequency of the four behavioral patterns displayed by fishes prior to screen passage. drift_a = active drift, drift_p = passive drift. Grey bars = observed values, red line = expected values (Chi^2-calculation). [Color figure can be viewed at wileyonlinelibrary.com]

up to 36 cm, barbel up to 30 cm) during standardized fish recapture experiments at the same and other sites. Hence, both behavioral patterns, dwelling and searching, may have increased the risk of screen passage.

The so called "farmers screen" applies a similar screen concept (flat-plate oriented parallel to the bottom) as the herein studied FPS, where fish, debris, and water pass above a horizontal screen and are returned to the river. The main difference to the SHPP screen is that it consists of perforated, stainless steel flat plates instead of bars. The concept has shown a high level of fish protection and fish passed over the screen without hesitation or delay (Mesa et al., 2012; Salalila et al., 2019). However, it remains unclear if such a concept would also be suitable for the herein studied SHPP, especially with regard to a sufficient water supply for profitable turbine operation in such a setup.

Although fish passed through the SHPP screen, a possible suction effect could be excluded since fish were observed to dwell for an extended amount of time on the screen area (6:26 min:s ± SD 10:43 min:s) during both operational modes (high and low turbine load as well), with no signs of being drawn onto the bars. In addition, flow velocities at the water intake remained mainly below the critical threshold ($V_{max} = 0.50$ m·s^{-1}) for avoiding impingement (DWA, 2005; Ebel, 2013) which may also explain that no significant differences in fish behavior were observed between the two investigated operational modes. Previous tests by the developers at a smaller-scale laboratory test facility indicated a behavioral barrier effect of the novel screen concept. Fish could freely move above the screen area but would avoid any contact with it. They swam tilted, positioned against the downward flow. Furthermore, the flow at the intake area was interpreted as guiding the fish toward the bypass in the sluice gate (Cuchet et al., 2012; Geiger et al., 2016). Under field conditions, however, the test fish showed neither avoidance due to a barrier effect, nor direct guidance to reach the bypass systems for safe downstream passage. In contrast to the assumption that it would be unnatural for fish to orient themselves toward the shaft and rather avoid staying at the screen area for too long (e.g., to escape the unnatural loud noise, vibrations), fish did not avoid contact to the screen, but even actively sought it out.

Although it was not possible to monitor the whole screen area simultaneously, we assume that our recordings (covering ca. 60% of the screen) are representative for the entire FPS area. As the flow velocities on the screen were homogeneous, it is unlikely that the fish behaved differently in the areas that were not recorded by the sonar. Since it is not possible with imaging sonar to distinguish individual fish that may appear for several times in the sonar, the samples may not be truly independent. However, this would only apply to fish, which did not pass the screen or were not successfully guided toward the alternative downstream corridors.

5 | CONCLUSION

Contrary to expectations, we found that the new design of the FPS at the SHPP does not prevent fish from entering the turbine corridor, suggesting that improvements are mandatory. This includes consideration of fish behavior in the phase of approaching the screen (e.g., flow fields), the design of the screen area itself (e.g., bar spacing, inclination) as well as the guidance toward alternative corridors other than the turbine passage. The results also indicate that expectations and promises of innovative screen designs and hydropower concepts require a critical evaluation against pre-defined criteria under realistic field conditions. This may prevent decision-making toward "fish-friendly concepts" which eventually do not fulfill the promises made.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A

TABLE A1 Abiotic parameters at the shaft hydropower plant screen intake during the ARIS sonar observation periods.

Fish released	Fall 2020 Anguilla anguilla/Barbus barbus	Spring 2021 Salmo trutta/Thymallus thymallus/Hucho hucho
Temperature (°C)	10.8 ± 1.2	5.3 ± 0.9
Dissolved oxygen (mg L^{-1})	10.2 ± 0.3	11.8 ± 0.3
Flow velocity screen (m s^{-1})	0.32 ± 0.19	0.28 ± 0.20
Flow velocity screen (upstream section) (m s^{-1})	0.35 ± 0.17	0.27 ± 0.16
Flow velocity screen (midsection) (m s^{-1})	0.36 ± 0.19	0.29 ± 0.21
Flow velocity screen (downstream section) (m s^{-1})	0.25 ± 0.18	0.30 ± 0.21
Turbidity (NTU)	9.2 ± 5.0	6.1 ± 5.1
pH value	8.5 ± 0.2	8.3 ± 0.3
Electric conductivity (µS cm^{-1})	421.6 ± 13.7	458.1 ± 25.9
Discharge (m^3 s^{-1})	19.5 ± 4.1	14.7 ± 2.5

Note: All values are given as arithmetic means ± standard deviation.

TABLE A2 Flow rates and turbine load in the individual test blocks in fall 2020 and spring 2021.

		Orographic left turbine		Orographic right turbine	
Species	Date	Flow rate (m^3 s^{-1})	Turbine load (%)	Flow rate (m^3 s^{-1})	Turbine load (%)
Anguilla anguilla	September 22nd to September 25th, 2020	5.0–6.1	45.1–55.7	9.1–11.0	82.8–100
Barbus barbus	September 29th to October 2nd, 2020	3.7–5.5	33.9–50.0	11.0	100
Salmo trutta/Thymallus thymallus	March 17th to March 19th, 2021	5.5–5.8	49.6–52.8	8.0–8.8	72.7–79.6
Hucho hucho	March 23rd to March 26th, 2021	8.1	74.0	5.5–11.0	50.0–100

Note: Turbine discharge between 70% and 100% is considered as "high" turbine load, and turbine discharge between 34% and 56% is considered as "low" turbine load.