DOI: 10.1111/fme.12263

ORIGINAL ARTICLE

WILEY Fisheries Management and Ecology

Catch-related fish injury and catch efficiency of stow-net-based fish recovery installations for fish-monitoring at hydropower plants

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Funding information
Bavarian State Ministry of the Environment and Consumer Protection, Grant/Award Number: OelB-0270-45821/2014

Abstract

Hydropower-related damage to fish remains a great challenge, making objective monitoring of turbine-related fish injury a necessity. The catch of fish at turbine outlets is currently realised by net fishing, but potential catch-related injuries are largely unknown. Catch efficiency and fish-friendliness in relation to fish handling, exposure time, floating debris and fish biomass of four fish recovery installations were assessed using seven species. Highly species-specific lethal and sublethal effects were observed. Exposure time had the strongest effects on catch-related damage, being up to 150-fold increase after 12 hr compared to 1 hr. Up to 84% mortality occurred in the most sensitive species *Thymallus thymallus* L. Besides exposure time, higher current speed and biomass within the net resulted in greater fish damage. To minimise catch-related effects, keeping emptying periods <1–2 hr and considering the effects of current speed, fish and debris biomass are crucial to increase data comparability among studies.

KEYWORDS
catch mortality, fish conservation, fish damage, fish population, turbine passage

1 | INTRODUCTION

Hydropower is the most rapidly increasing renewable energy source worldwide (Kaygusuz, 2016), but it can have severe impacts on aquatic communities, particularly on fishes (Brown et al., 2014; Hogan, Čada & Amaral, 2014). During downstream movement, fish can either pass through turbines, be diverted, or screened, depending on life history stages, behaviour and technical features of the facility. Possible impacts include mortality or severe injuries during power-plant passage or in spillways (Abernethy, Amidan & Čada, 2001; Baumgartner et al., 2014; Boys et al., 2016; Čada, Garrison & Fisher, 2007; Dedual, 2007; Killgore, Maynord, Chan & Morgan, 2001) and changes in habitat morphology (Mueller, Pander & Geist, 2011). As fish have become an important ecological quality element in the Water Framework Directive (European Parliament, 2000), the ecological consequences of hydropower use are increasingly being considered during licensing. To decide which hydropower technologies minimise fish damage, evidence-based knowledge on the effects of different techniques is mandatory. For monitoring of turbine-related fish injury and bypass efficiency, it is necessary to catch fish at turbine outlets, which is in small- to medium-sized rivers mostly done by placing nets downstream of the turbine outlets (e.g. Cramer & Donaldson, 1964; Dedual, 2007; Dubois & Gloss, 1993). However, the representative catch of fishes at hydrostructures for the purpose of injury and mortality investigations in rivers with a discharge of more than 1 m^3/s still remains a great challenge (DWA, 2005) and is currently surrogated by the use of autonomous sensors, such as the Sensor Fish (Deng, Carlson, Duncan & Richmond, 2007; Deng, Carlson, Duncan, Richmond & Dauble, 2010). Besides the technical challenge to run fish-catching devices at turbine outlets due to the extreme hydraulic conditions, fish injuries and mortality can not only caused by the hydropower turbines, but also by the catching procedure itself (Dedual, 2007; Dubois & Gloss, 1993). Net- and handling-related injuries, such as scale losses, bruises, dermal lesions or even mortality, mostly remain unconsidered in the current monitoring practice of hydropower-related fish damage (Ebel, 2013; Mueller, Pander & Geist, 2017). If catch-related injuries occur in high severity during the monitoring, it is possible that they disguise the results of injuries resulting from the turbine passage (Dubois & Gloss, 1993). This can in turn lead to an over interpretation of turbine effects and must be considered undesirable from an animal welfare perspective. Therefore, the usage of fish-friendly catching techniques is essential to keep catch-related injuries to a minimum or at least to test for catch-related injuries in the monitoring to allow a detailed differentiation (Mueller et al., 2017). In fisheries practice, a large variety of different fish-catching techniques, for example stow-nets, fyke-nets and fish-catching boxes (e.g. Craddock, 1961; Dedual, 2007), are widely applied and probably strongly differ in their severity of catch-related injuries and catch efficiency. In particular, hydraulic conditions dependent on size and shape of the catch device, the construction design and materials (e.g. flexible knotless nets vs metal boxes of fixed shape), the amount and composition of floating debris, fish biomass and exposure time are likely to determine the intensity of catch-related effects on fish. However, to date, comparisons of different methods to catch fish at hydropower structures and systematic studies that have quantified the effects of potentially confounding environmental factors, such as the amount of debris in the nets, are lacking.

In this study, the fish-friendliness and catch efficiency of four different fish recovery installations were compared in relation to the effects of fish handling, exposure time, floating debris and fish biomass. The study was carried out as a large animal experiment using seven different fish species. In particular, it was hypothesised that: (i) the catch of fish causes lethal and sublethal injuries, which differ among species and fish recovery installations in their type and intensity; (ii) increased exposure time, increasing amount of floating debris and fish biomass negatively affect the severity of fish injuries; and (iii) the catch efficiency differs between the investigated fish recovery installations.

2 | MATERIALS AND METHODS

Overall, 19,920 individuals (including 1,752 control fish) of seven fish species were used between May and November 2015 in accordance with national laws and regulations (animal care permit number 55.2-1-54-2532-24-2015). All protocols and methods were evaluated for appropriate animal care and use by the ethics commission of the Bavarian Government. Adequate measures to minimise pain or discomfort were taken following European guidelines (European Parliament, 2010) and national standards for the use of aquatic animals for experimental purposes (Adam, Schürmann & Schwevers, 2013).

2.1 | Study site

The comparison of catch-related injury and catch efficiency of the different fish recovery installations was carried out on the River Moosach (mean annual discharge = 2.64 m/s) at the turbine outlet (width = 2.27 m, average water depth = 85 cm) of an abandoned powerhouse (without turbine) of the Technical University of Munich, Germany (48°23′39.07″N, 11°43′25.06″E). For a more detailed description of the study site, see Mueller et al. (2011).

2.2 | Fish recovery installations

The term fish recovery installation refers to funnel-shaped stow-nets (full stow-net and partial stow-nets) fixed at a metal frame at the turbine outlet, combined with different fish-catching units (fyke-net and fish-catching box) at the end (Figure 1). This system is most commonly used to catch fish at hydropower turbine outlets (Dubois & Gloss, 1993) and considered best practice design (Ebel, 2013). In this study, four different types of fish recovery installations were used: full stow-net combined with fyke-net (FSN+FN), full stow-net combined with fish-catching box (FSN + FCB), medium stow-net combined with fyke-net (MSN + FN) and small stow-net combined with fyke-net (SSN + FN) (Figure 2). The different parts of the fish recovery installations are described below.

The full stow-net (FSN, Figure 1) had a rectangular opening of 208 × 108 cm to cover 100% of the study river's discharge and reduced to a circular opening of 60 cm diameter over a length of 8 m. The mesh size decreased from 30 to 20 mm, 15 and 10 mm at the cod end (Engel Netze, Bremerhaven, Germany). Following best practice

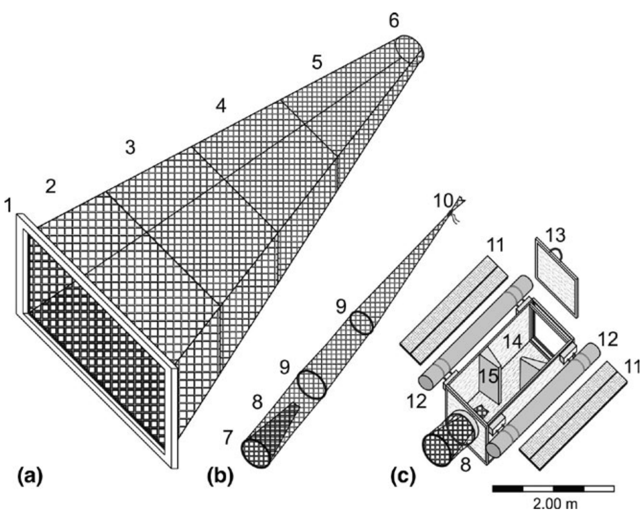

FIGURE 1 Schematic of the used fish recovery installations. (a) stow-net with 1 = rectangular net opening fixed on a steel frame with circumferential steel rail to which each mesh of the net is knotted; 2 = net field of mesh size 30 mm; 3 = net field of mesh size 20 mm; 4 = net field of mesh size 15 mm; 5 = net field of mesh size 10 mm; 6 = steel opening ring to which the fyke-net or the fish-catching box is attached. (b) fyke-net (mesh size 8 mm) with 7 = steel opening ring which can be attached to the stow-net, 8 = funnel-shaped net as trap to ensure that fish cannot escape, 9 = steel opening rings, 10 = rope to close the fyke-net. (c) fish-catching box with 11 = foldable lids, 12 = floating bodies, 13 = box closure plate for a quick release of floating debris (emergency release), 14 = main body of the box with 15 = current deflectors

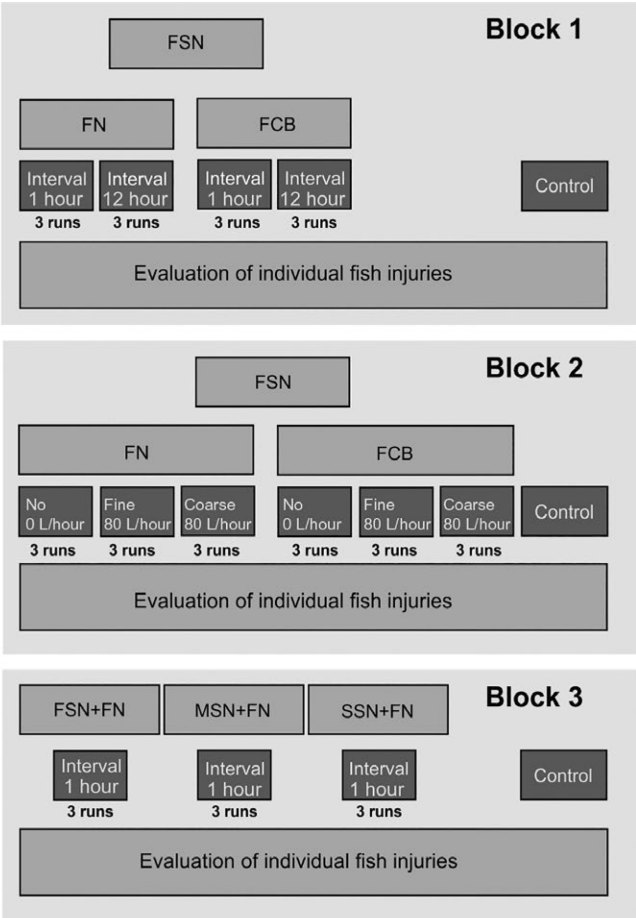

FIGURE 2 Schematic of the three experimental blocks. Block 1 addresses catch-related mortality and injury using a full stow-net (FSN) and two different fish recovery units, fyke-net (FN) and fish-catching box (FCB) considering two different exposure times (1 and 12 hr). Block 2 addresses the effects of coarse floating debris versus fine floating debris using the full stow-net combined with the fyke-net and the fish-catching box during 1 hr exposure time. Of each debris mixture, 80 L were added during 1 hr (80 L/hr). Block 3 addresses the effects of different sized stow-nets (SN) under 1-hr exposure, including a full stow-net covering 100% of the river cross-section, a medium-sized stow-net (MSN) covering 50% of the river cross-section and a small stow-net (SSN) covering 30% of the river cross-section. In each experimental block, a control with untreated test fish was carried out

design, the net consisted of a knotless polyamide material to reduce mucosal injuries and scale losses to a minimum. The rectangular opening of the stow-net was knotted with each mesh to a metal frame (220 × 120 cm), which allowed fixation in the u-profiles that were installed at the turbine outlet.

In large hydropower facilities, it may be not possible to cover the full width of the river discharge due to extreme hydraulic conditions. Therefore, partial stow-nets covering 50% (medium stow-net MSN, rectangular opening = 97 × 91 cm) and 30% (small stow-net SSN, rectangular opening = 97 × 60 cm) of the discharge were additionally tested. The length of the stow-net, the net material and the mesh sizes were identical to the 100% stow-net. The partial stow-nets were fixed to smaller metal frames (50%: 114 × 106 cm, 30%: 114 × 77 cm), which were mounted on the large metal frame of the 100% stow-net (220 × 120 cm).

The fyke-net (FN, Figure 1) had a circular opening of 60 cm diameter and was attached to the end of the stow-nets with strong zip ties. It had a funnel-shaped throat at the entrance, was 5.5 m long, had three metal rings to keep the net open throughout the length and had a mesh size of 8 mm. The net material was the same as for the stow-nets. The end of the fyke-net could be easily closed with a rope. To empty the fyke-net, it was lifted into a boat; the knot at the nets end was opened, and fish were directly transferred into a water-filled bin. The emptying of the stow-net took 2 minutes on average.

The fish-catching box (FCB) was a riveted cuboid box made of perforated (5 × 20 mm) aluminium plates and aluminium angle profiles (Figure 1). The outside of the box was equipped with two tube-shaped floating bodies to keep the box floating and to ensure a constant water level inside. The box was covered with two foldable lids on the top, which can be opened to recover the fish from the box using a dip-net. The inside of the box was equipped with two triangular current deflectors to create slow-flow sections for fish to recover (Figure 1). The FCB was crafted at the Aquatic Systems Biology Unit. A short fyke-net with only one ring, and a funnel-shaped throat (Engel Netze, Bremerhaven, Germany) was attached to the circular entrance of the box on one side and to the end of the stow-net on the other side with strong zip ties. To empty the FCB, the boat was tied to the box, and the foldable lids were opened and two persons using dip-nets caught the fish. The fish were transferred from the dip-nets to a water-filled bin. The emptying procedure of the FCB took on average 15 minutes for two persons.

2.3 | Study design

The experiment was carried out in three blocks (Figure 2). The first experimental block was carried out to examine the effects of the different fish-catching units fyke-net and FCB under two different exposure times (1 hr vs 12 hr) on catch efficiency and potential fish injury. In the second experimental block, the effects of standardised mixtures of floating debris on potential fish injury were investigated and compared with a treatment without standardised input of floating debris. The amount of naturally occurring debris in the reference treatment was 5–10 L, consisting out of leaves, parts of macrophytes and single small branches of trees. A fine and a coarse mixture of floating debris (80 L each) were tested using the 100% stow-net combined with fyke-net and FCB during 1-hr exposure time. The fine mixture represented floating debris that can pass bar screens with small spacing and contained three equal parts of shredded small tree branches, shredded leaves and macrophytes. The coarser mixture represented conditions at large spaced bar racks and contained five equal parts of 10–20-cm long and 5-cm thick tree branches, leaves, small tree branches, herbaceous plants and macrophytes. The third experimental block was intended to compare the catch efficiency and fish damage of different sized stow-nets, comprising 100%, 50% and 30% coverage of the discharge. The different sized stow-nets were used in combination with the fyke-net and during 1-hr exposure time.

In each experimental block, fish were acclimatised to Moosach water prior to the experiment and were released directly upstream of the powerhouse to move freely into the fish-catching unit. Each fish was evaluated immediately after recovery using a standardised and detailed fish injury assessment protocol. Four general health criteria necessary for animal care documentation, as well as 86 lethal and sub-lethal injury types assigned to distinctive body parts, were assessed following the protocol by Mueller et al. (2017). In addition to fish caught in the treatments, a minimum of 80 untreated fish was evaluated for their individual injuries in each experimental block as a control group following the same procedure as for the treated fish.

2.4 | Test fish species

As morphological characteristics of fishes may have a major impact on their susceptibility to external injuries and catch-related effects have not been tested sufficiently for species other than salmonids (Dubois & Gloss, 1993), seven fish species with different body shapes were tested. These included species with a streamlined fusiform body shape (brown trout, *Salmo trutta* L., Danube salmon, *Hucho hucho* L.), streamlined laterally compressed body form (common nase, *Chondrostoma nasus* (L.), European grayling, *Thymallus thymallus* L.), streamlined ventrally compressed body shape (barbel, *Barbus barbus* L.) and high-backed laterally compressed body shape (roach, *Rutilus rutilus* (L.), European perch, *Perca fluviatilis* L.). In addition to body shape, different fin shapes and types of fin rays, as well as different scale types, were represented by this set of test species (e.g. Kottelat & Freyhof, 2007). In this experiment, a size range of test fish that typically can pass hydropower turbines was chosen (Table 1). To ensure continuous high quality of test fishes throughout the experiment, fish were purchased from local authorised fish farms (Table 1). Viable fish were released in the study stream after the experiment; non-viable fish were killed using an overdose of MS 222 following national aquatic animal care standards (e.g. Adam et al., 2013).

2.5 | Measurement of physicochemical variables

During the experiment, discharge, current speed, water temperature, dissolved oxygen, pH value, electric conductivity, turbidity, the amount of naturally occurring debris and fish biomass were recorded for each run. Discharge was measured at the water gauge in the Moosach adjacent to the experimental site. The experiment was carried out within a discharge range of 1.8 m^3/s and 4.5 m^3/s. Current speed inside the fish recovery unit was positively correlated to discharge (linear model FN: $r^2 = .49$, $P \le .001$, linear model FCB: $r^2 = .51$, $P \le .001$). Current speed was measured in the headwater in three cross-sections at the point of fish release, in three cross-sections of the entrance of the stow-net, in three cross-sections along the stow-net and in three cross-sections inside the fish recovery unit using a hand-held electromagnetic water flow meter (Ott MF pro, Kempten, Germany). Water temperature, dissolved oxygen, pH value, electric conductivity and turbidity were measured in the study stream three times a day using a hand-held measuring device (Multi 3430 Set G, WTW, Weilheim, Germany). The volume of the naturally occurring floating debris was determined for each run individually. Fish biomass was calculated for each run using individual fish length and species-specific condition factors as described by Pander and Geist (2010).

TABLE 1 Origin, size, age, weight and numbers of the used test fish from seven species

	Origin	Size range	Medium size	Age	Weight	Number of individuals	Recaptured individuals
Barbus barbus	Bavarian Environment Agency, Wielenbach, Germany	4.0–11.0	7.4	0+	3.9	2,051	1,013
Chondrostoma nasus	State fish hatchery Lindbergmühle, Lindberg, Germany; State fish hatchery Maidbronn, Rimpar, Germany	4.0–12.0	8.2	0+, 1+	6.4	2,772	1,899
Hucho hucho	Bavarian Environment Agency, Wielenbach, Germany; Fish hatchery Michael Rösch, Bärnau, Germany	6.0–27.0	17.3	1+, 2+	70.9	2,772	2,163
Perca fluviatilis	Fish hatchery Michael Rösch, Bärnau, Germany	4.0–15.0	10.0	1+, 2+	14.0	2,154	1,684
Rutilus rutilus	Fish hatchery Michael Rösch, Bärnau, Germany	3.0–10.0	6.3	0+, 1+	2.7	2,772	2,383
Salmo trutta	Fisheries Association Hatchery Mauka, Neufahrn, Germany	10.0–23.0	17.7	1+, 2+	62.9	2,772	1,341
Thymallus thymallus	Bavarian Environment Agency, Wielenbach, Germany	8.0–23.0	15.2	1+, 2+	43.9	2,772	1,669

Size range = minimum − maximum total length in cm. Medium size = arithmetic mean value of the total length [cm] of all individuals. Age: 0+ = fish before the first summer after hatching, 1+ = fish between first and second summer after hatching, 2+ = fish between second and third summer after hatching. Weight = average individual fish weight in gram. Number of individuals = number of individuals released in the river, Recaptured individuals = number of recaptured individuals.

2.6 | Statistical analysis

To obtain the fish numbers necessary for the statistical evaluation of the results, power analyses based on the proportion test were carried out in the program R using the function: power.prop.test from the package stats (Blomberg, 2014). For catch-related mortality, low effect size following Cohen (1992) was assumed. The probability of type I error was set to 5% and the probability of type II error to 20%, resulting in a statistical power of 80%. Additionally, a safety coefficient of 5% was added and the recovery rate of fish was set at 77% following studies of Lagarrigue and Frey (2010) and Schneider, Hübner and Korte (2012). The calculation resulted in 309 fish per treatment and species. To avoid too high fish biomass in the recovery unit, the 309 fish were separated in three repeated runs of each treatment with 103 fish per species and run (Figure 2).

Mortality and recapture rates were compared between treatments using Bonferroni-corrected pairwise proportion tests. Observed recapture rates of the four different fish recovery installations were compared to expected values (100% for FSN + FN and FSN + FCB, 50% for MSN + FN and 30% for SSN + FN) using *Chi-square* tests. Vitality, number of injuries and injury intensity were compared between treatments using non-parametric Kruskal–Wallis Tests and Bonferroni-corrected post hoc pairwise Mann–Whitney U Tests, as all data were not normally distributed. All univariate analyses were carried out in the open-source software R (version 3.1.2, http://www.r-project.org).

To test for differences in fish injury patterns between treatments, a multivariate approach based on Bray–Curtis Similarities as in Mueller et al. (2017) was used, as it allows for a simultaneous inclusion of all injuries at each part of the body. Non-metric multidimensional scaling (NMDS) was used to visualise differences in fish injury patterns between treatments and test fish species. To test for significant differences between multivariate injury patterns of different treatments, one-way ANOSIMs were applied (Clarke, Somerfield & Chapman, 2006). Underlying patterns of injury types causing the differences identified via ANOSIM were examined using one-way Similarity Percentages analysis (SIMPER, Clarke & Warwick, 2014). SIMPER tested differences in constantly occurring injury types to be responsible for between-group dissimilarities.

Interactions between catch-related mortality (dependent variable) for each run and different categorical and continuous independent variables were tested using linear modelling. Mortality was calculated as a percentage of dead fish over all species per run. Continuous independent variables were averaged per run. The linear model considered interactions among the categorical variables fish recovery installation and exposure time, as well as each of the continuously measured variables fish condition (average vitality of control fish observed after 96 hr), average fish weight, biomass, amount of floating debris, water temperature, current speed at the entrance of the stow-net, current speed along stow-net, current speed fyke-net/FCB, current speed river at fish release and river discharge. The linear model was calculated using the function “lm” in R v3.3.1. The model to best explain catch-related mortality was constructed using the StepAIC function. For all statistical analyses, significance was accepted at $P \le .05$.

3 | RESULTS

3.1 | Catch-related mortality and sublethal injuries

Catches of fish in the fish recovery installations tested resulted in both lethal and sublethal effects. These effects were highly dependent on species, exposure time and the type of fish recovery installation. For all species, mortality rates were significantly lower during 1-hr exposure time in the fyke-net, with mortality after 12-hr exposure up to 150-fold higher (*P. fluviatilis*, Table 2), and reaching 84% for *T. thymallus*. Mortality rates were generally lower in the FCB than the fyke-net (1 hr: 1.8-fold, 12 hr: 2.9 fold, Table 2), except for *C. nasus* where mortality was significantly lower in the fyke-net during 1-hr exposure time. A similar trend of lower mortality in the fyke-net was observed for *P. fluviatilis* and *B. barbus* during 1-hr exposure, but this was not significant. Mortality in the 12-hr treatment was generally very high for *H. hucho*, with more than double the percentage of fish dying in the FCB (44% mortality) compared with the fyke-net (18% mortality). In partial stow-nets, mortality was only observed in *T. thymallus* (1.4%, Table 2).

The most frequently occurring injuries were scale loss (control fish: 80%, treated fish: 80%) and tears in the fins (control fish: 40%, treated fish: 40%). Change of pigmentation (control fish: 10%, treated fish: 10%), dermal lesions (control fish: 5%, treated fish: 5%), amputations (control fish: 3%, treated fish: 3%), haemorrhages (control fish: 2%, treated fish: 3%), bruises (control fish: 0%, treated fish: 1%) and gas bubbles (control fish: 0% = 1 fish, treated fish: 0% = 5 fish) were observed less frequently. All types of injury could also be detected in control fish, but the severity of the injuries strongly differed between the treated fish and the control (Table 3). The greatest change in intensity was for dermal lesions and haemorrhages (30% increase in intensity), followed by amputations of fin parts or gill covers (25% increase in intensity), scale loss (20% increase in intensity) and tears in the fins (8% increase in intensity).

Multivariate analyses revealed significant species-specific differences in fish injury patterns for all species except *C. nasus* and *R. rutilus* (Figure 3, ANOSIM: Global $R = 0.73$, $P \le .001$). Treatments generally differed significantly in injury patterns, but these differences were less pronounced than species-specific effects (ANOSIM: Global $R = 0.09$, $P \le .001$). Over all species, fish injury patterns of 1-hr treatments were significantly different from control fish, except for fyke-nets, which revealed similar injury patterns to control fish. The greatest differences in fish damage patterns of treatment fish compared to control fish were detected for 12-hr treatments, with the 12-hr fyke-net having the greatest dissimilarity (Figure 3, Table 4).

Exposure time had the strongest influence on sublethal effects, with increased intensity of injuries and decreased vitality during 12-hr exposure in the fyke-net and FCB (Figure 3, Table 4). Differences in injury patterns (SIMPER Analysis) between fyke-net and FCB were mainly attributed to more intense scale losses in the fyke-net (12% higher intensity, contribution to between-group dissimilarity = 26%,) and more intense tears in the caudal fin in the FCB (1% higher intensity, contribution to between-group dissimilarity = 9%), as well as

TABLE 2 Recapture rates and mortality rates for each species as well as over all species using different fish recovery installations and exposure times (1, 12 hr)

	Recapture rate %				Mortality rate %			
	SSN + FN	MSN + FN	FSN + FCB	FSN + FN	SSN + FN	MSN + FN	FSN + FCB	FSN + FN
Barbus barbus								
1 hr	26.0^{a}	44.7^{b}	47.4^{bA***}	43.5^{bA***}	0.0	0.0	1.4	0.0^{A}
12 hr			73.1^{aB}	57.8^{bB***}			3.1^{a}	35.3^{bB}
Chondrostoma nasus								
1 hr	30.0^{a***}	49.3^{b}	60.3^{bA***}	85.4^{cA***}			7.3^{aA}	1,0^{bA}
12 hr			95.8^{aB}	43.0^{***bB}			14.9^{aB}	54.9^{bB}
Hucho hucho								
1 hr	33.3^{a}	40.7^{a}	86.0^{bA**}	84.9^{bA**}	0.0	0.0	1.1^{A}	4.1^{A}
12 hr			92.9^{aB}	58.6^{*bB}			44.9^{aB}	18.8^{bB}
Perca fluviatilis								
1 hr	38.7^{a}	50.0^{a}	67.5^{bA***}	94.2^{cA}	0.0	0.0	1.0	0.2^{A}
12 hr			88.3^{B***}	90.3^{B}			3.3^{a}	30.1^{bB}
Rutilus rutilus								
1 hr	32.7^{a}	58.0^{b}	91.4^{c}	91.8^{cA***}			1.2^{A}	2.6^{A}
12 hr			92.9^{a}	84.8^{bB***}			16.7^{aB}	28.2^{bB}
Salmo trutta								
1 hr	35.3^{a}	42.0^{ab}	51.3^{bc***}	55.2^{cA***}	0.0	0.0	1.1	2.1^{A}
12 hr			50.5^{a***}	26.2^{bB**}			1.9^{a}	34.6^{bB}
Thymallus thymallus								
1 hr	30.0^{a}	48.0^{b}	60.8^{c***}	53.3^{dA***}	0.0^{a}	1.4^{a}	4.3^{aA}	23.3^{bA}
12 hr			66.3^{a}	93.5^{bB}			8.8^{aB}	84.4^{bB}
Over all species								
1 hr	32.3^{a}	47.5^{b}	67.3^{cA***}	73.0^{dA***}	0.0^{a}	0.2^{a}	2.5^{bA}	4.4^{cA}
12 hr			80.0^{aB***}	65.2^{bB***}			14.9^{aB}	43.1^{bB}

Fish recovery installations: FN = fyke-net; FCB = fish-catching box; FSN = full stow-net covering 100% of the river cross-section, MSN = medium-sized stow-net covering 50% of the river cross-section; SSN = small-sized stow-net covering 30% of the river cross-section. Superscript stars indicate significant differences compared to expected recapture rates according to *chi-square* tests, with the significance levels * = significance ($P \le .05$), ** = high significance ($P \le 0.01$) and *** = highest significance ($P \le .001$). Different superscript capital letters indicate significant differences between 1 and 12 hr exposure time within each species and fish recovery installation according to pairwise proportion tests. Different superscript small letters indicate significant differences between fish recovery installations within one species and exposure time according to pairwise proportion tests.

more intense change of pigmentation on the head in the FCB (9% higher intensity, contribution to between-group dissimilarity = 3%). During the 12-hr exposure time, reduced vitality in the fyke-net additionally contributed to the dissimilarity between fyke-net and FCB (57% higher vitality in FCB, contribution to between-group dissimilarity = 6%). Higher scale losses contributed most to the difference between full stow-net and the partial stow-nets, with 69% higher intensity in the full stow-net than the small stow-net (contribution to between-group dissimilarity = 23%) and 73% higher intensity in the full stow-net than the medium stow-net (contribution to between-group dissimilarity = 26%). The two partial stow-nets did not differ in the intensity of scale losses, but more severe tears in the fins were detected in the small stow-net than the medium stow-net (37% higher intensity in small stow-net than the medium stow-net, contribution to between-group dissimilarity = 40%).

3.2 | Effects of floating debris, fish biomass and current speed on mortality and injuries

Catch-related mortality was best explained by a linear model including all measured variables (r^2 = .98%, $P \le .001$, F-statistic = 86.56 on 55 and 64 *df*, residual standard error = 2.062 on 64 *df*). The model revealed a significant difference in mortality between fyke-net and FCB. Additionally, all discharge-related variables (current speed inside and outside of the fish recovery units, turbidity, electric conductivity, temperature and dissolved oxygen), as well as fish condition and the amount of floating debris, significantly explained mortality rates (Table 4). Significant interactions were found between exposure time and fish condition, amount of floating debris, current speed inside and outside of the fish recovery units, turbidity, conductivity, temperature and dissolved oxygen, as well

TABLE 3 Average vitality, average number of injuries and average injury intensity over all injury types for each species as well as over all species using different fish recovery installations and exposure times (1, 12 hr)

	Vitality				Number of injuries					Overall injury intensity				
	SSN + FN	MSN + FN	FSN + FCB	FSN + FN	SSN + FN	MSN + FN	FSN + FCB	FSN + FN	PD	SSN + FN	MSN + FN	FSN + FCB	FSN + FN	PD
Barbus barbus														
1 hr	4.00	4.00	3.94	4.00^{A}	1.9^{a}	1.9^{a}	2.2^{a}	2.2^{aA}	1.0^{b}	2.4^{a}	2.2^{a}	3.7^{a}	3.0^{aA}	1.2^{b}
12 hr			3.86^{a}	2.48^{bB***}			2.2^{a}	5.6^{bB}	1.0^{c}			3.7^{a}	12.5^{bB}	1.2^{c}
Chondrostoma nasus														
1 hr			3.72^{aA**}	3.95^{bA}			6.2^{aA}	7.0^{bA}	3.6^{c}			10.3^{aA}	10.6^{bA}	4.3^{c}
12 hr			3.40^{aB***}	1.80^{bB***}			6.9^{aB}	13.4^{bB}	3.6^{c}			14.0^{aB}	37.7^{bB}	4.3^{c}
Hucho hucho														
1 hr	4.00^{ab***}	4.00^{a***}	3.85^{bA***}	3.70^{cA***}	9.8^{a}	8.7^{a}	12.2^{bA}	14.0^{cA}	13.5^{b}	13.4^{a}	10.5^{a}	16.9^{bA}	20.6^{cA}	18.5^{b}
12 hr			1.80^{aB***}	2.44^{bB***}			21.3^{aB}	20.9^{aB}	13.5^{b}			36.9^{aB}	42.1^{bB}	18.5^{c}
Perca fluviatilis														
1 hr	3.98^{ab}	3.99^{ab}	3.91^{a}	3.99^{bA}	3.8^{a}	4.4^{a}	3.9^{a}	2.8^{bA}	2.6^{b}	6.9^{a}	6.9^{a}	6.6^{a}	4.3^{bA}	3.9^{b}
12 hr			3.83^{a}	2.63^{bB***}			4.0^{a}	6.5^{bB}	2.6^{c}			7.1^{a}	11.1^{bB}	3.9^{c}
Rutilus rutilus														
1 hr			3.95^{A}	3.89^{A*}			5.2^{aA}	6.1^{bA}	4.3^{c}			11.1^{aA}	13.3^{bA}	7.3^{c}
12 hr			3.31^{aB***}	2.87^{bB***}			6.9^{aB}	7.4^{aB}	4.3^{b}			16.9^{aB}	20.2^{aB}	7.3^{b}
Salmo trutta														
1 hr	4.00^{ab}	3.89^{ab}	3.96^{a}	3.88^{bA}	15.7^{a}	13.3^{b}	14.7^{cA}	15.4^{aA}	13.5^{b}	37.3^{ac}	28.7^{b}	36.5^{a}	39.3^{cA}	30.2^{b}
12 hr			3.92^{a}	2.56^{bB***}			15.9^{aB}	14.4^{bB}	13.5^{b}			37.3^{a}	41.3^{aB}	30.2^{b}
Thymallus thymallus														
1 hr	4.00^{a}	3.94^{a}	3.80^{a}	2.87^{bA***}	9.8^{ab}	8.3^{ac}	9.5^{aA}	10.4^{bA}	7.8^{c}	13.9^{ab}	11.5^{bc}	15.3^{abA}	16.1^{aA}	11.4^{c}
12 hr			3.62^{a**}	0.56^{bB***}			14.6^{aB}	18.3^{bB}	7.8^{c}			30.5^{aB}	40.0^{bB}	11.4^{c}
Over all species														
1 hr	4.00^{a***}	3.96^{a***}	3.87^{bA***}	3.77^{cA}	8.4^{abcd}	7.2^{c}	8.1^{aA}	8.6^{bA}	9.4^{d}	15.4^{abc}	11.7^{c}	14.8^{aA}	15.7^{bA}	15.8^{ab}
12 hr			3.32^{aB***}	2.11^{bB***}			10.0^{aB}	12.2^{bB}	9.4^{a}			19.9^{aB}	27.9^{bB}	15.8^{c}

Fish recovery installations: FN = fyke-net; FCB = fish-catching box; FSN = full stow-net covering 100% of the river cross-section, MSN = medium-sized stow-net covering 50% of the river cross-section; SSN = small-sized stow-net covering 30% of the river cross-section; PD = pre-damage (hatchery-reared fish without further treatment). Different superscript capital letters indicate significant differences between 1 hr and 12 hr exposure time within each species and fish recovery installation. Different superscript small letters indicate significant differences between fish recovery installations within one species and exposure time. In section Vitality, superscript stars indicate significant differences compared to treatment pre-damage, with the significance levels * = significance ($P \le .05$), ** = high significance ($P \le .01$) and *** = highest significance ($P \le .001$). Vitality in group pre-damage was always 4.

FIGURE 3 Non-metric multidimensional scaling (NMDS) of fish injuries in all experimental treatments and fish species. Analyses were based on pairwise Bray–Curtis Similarities between each pair of treatments calculated from average injury intensities and average vitality per treatment. Each symbol in the NMDS plots indicates one treatment. The different symbols represent the seven test species. 1, 12 hr = exposure time, PD = pre-damage (hatchery-reared fish without further treatment), FN = fyke-net used with a full stow-net, FCB = fish-catching box used with a full stow-net (100% coverage), MSN = fyke-net used with a medium stow-net (50% coverage), SSN = fyke-net used with a small stow-net (30% coverage). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Test results of ANOSIM comparisons of fish injury patterns between treatments

Comparison	*R* statistic	*P* value
FSN + FCB 1 hr, FSN + FN 1 hr	0.001	>.05
FSN + FCB 1 hr, PD	0.016	**<.001**
FSN + FCB 1 hr, FSN + FCB 12 hr	0.119	**<.001**
FSN + FN 1 hr, PD	−0.004	>.05
FSN + FN 1 hr, MSN + FN 1 hr	0.006	>.05
FSN + FN 1 hr, SSN + FN 1 hr	0.066	**<.001**
FSN + FN 1 hr, FSN + FN 12 hr	0.298	**<.001**
PD, MSN + FN 1 hr	0.025	**<.05**
PD, SSN + FN 1 hr	0.079	**<.001**
PD, FSN + FN 12 hr	0.209	**<.001**
PD, FSN + FCB 12 hr	0.040	**<.001**
MSN + FN 1 hr, SSN + FN 1 hr	0.035	**<.001**
FSN + FN 12 hr, FSN + FCB 12 hr	0.091	**<.001**

Exposure times: 1 hr, 12 hr. Fish recovery installations: FN = fyke-net; FCB = fish-catching box; FSN = full stow-net covering 100% of the river cross-section, MSN = medium-sized stow-net covering 50% of the river cross-section; SSN = small-sized stow-net covering 30% of the river cross-section; PD = pre-damage (hatchery-reared fish without further treatment). *R* statistic = ANOSIM test statistic, *P* value = level of significance. Bold *P* values indicate statistical significance ($P \le .05$).

as interactions between fish-catching unit and exposure time, fish condition, biomass, individual fish weight, amount of floating debris, temperature and current speed inside the fish-catching unit (Table 5). Furthermore, the model detected three-way interactions between fish-catching unit, exposure time as well as fish condition, individual fish weight, amount of floating debris and temperature (Table 5).

Linear regressions of single variables revealed the most pronounced effects on mortality were fish biomass and current speed inside the fish recovery unit. However, this trend of enhanced mortality at increased current speed and fish biomass was only detected for the fyke-net (Figure 4). Fish mortality occurred consistently if the fish biomass in the fyke-net increased over 3.5 kg. Mortality also always increased for current speeds inside the fyke-net of more than 0.5 m/s.

Surprisingly, there was no significant correlation between the amount of floating debris and mortality rates, but a weak trend towards higher mortality with increasing amount of floating debris was observed for the fyke-net and FCB (Figure 4). Fitting an exponential function ($r^2 = .28$, $P = .10$) or polynomial function ($r^2 = .46$, $P = .10$) resulted in higher coefficients of determination, but no significance was detected for these functions. No effects concerning the two different mixtures of floating debris were detected in all uni- and multivariate analyses of mortality and injury patterns.

3.3 | Catch efficiency

Over all treatments, 67% of all fish released into the Moosach River (18,168 individuals) were recaptured during the experiment. Recapture was highest in the full stow-net (71%), and lower in the medium stow-net (48%) and small stow-net (32%). For 1-hr exposure time, a significant difference between observed and expected recapture rates for the full stow-net in combination with the fyke-net was evident ($\chi^2 = 167.64$, $df = 23$, $P \le .001$) and the FCB ($\chi^2 = 150.75$, $df = 23$, $P \le .001$). By contrast, no significant differences were detected for the medium size ($\chi^2 = 1.66$, $df = 5$, $P = .89$) and the small stow-net ($\chi^2 = 1.68$, $df = 5$, $P = .89$). Significantly, higher recapture rates were detected in the FCB for all species for 12-hr exposure time and recapture rates in the fyke-net were significantly higher than in the FCB for 1-hr exposure time (Table 2).

Recapture rates differed between species and within species, and were highly variable for FCB and fyke-net, as well as for the different exposure times (Table 2). Highest recapture rates were found for *R. rutilus* (FSN + FCB for 12 hr = 92.2) and *P. fluviatilis* (FSN + FN for 1 hr = 94.2), while *S. trutta* and *B. barbus* were recaptured in the lowest numbers (e.g. *S. trutta* FSN + FN for 12-hr = 26.2 and *B. barbus* FSN + FN for 1-hr = 43.5; Table 2). Recapture rates for *S. trutta*, *C. nasus* and *H. hucho* were almost half using the fyke-net with 12-hr exposure time than 1-hr exposure time (Table 2). Recapture rate in the FCB after 12-hr exposure time for these three species was constant or even higher than 1-hr exposure time. This was similar for *B. barbus* and *R. rutilus*, but with a less pronounced difference between the FCB and fyke-net. By contrast, *T. thymallus* was caught in much larger numbers using the fyke-net and 12-hr exposure time (Table 2). Observed recapture rates for partial stow-nets during 1-hr exposure time did not differ from expected values for all species except *C. nasus*, where the catch efficiency in the small stow-net was significantly lower ($\chi^2 = 9.87$, $df = 2$, $P \le .01$). The processing time for emptying the fish recovery unit differed between the fyke-net and the FCB, being sevenfold higher for the FCB (fyke-net: 2 min, FCB: 15 min).

4 | DISCUSSION

Assessment of hydropower-related mortality rates and damage patterns of fish can be strongly biased if catch-related effects are not appropriately considered. Under field conditions, cumulative effects of current speed, fish biomass in the net and floating debris can lead to mortality rates of more than 80% for sensitive species, such as *T. thymallus*. Consequently, experimental conditions and catch-related injury should be determined and reported, which, to date, is the exception rather than the rule (see summary of studies for the same range of test species in Ebel, 2013).

4.1 | Effects of exposure time and design of fish-catching unit

Exposure time was the most influential factor determining catch-related mortality and sublethal injuries. This was expected as it is likely that fish exposed for longer to stressors can have both a higher frequency and more severe injuries (Dedual, 2007; Dubois & Gloss, 1993). For instance, in fish recovery units with high current speed, as observed for the fyke-net herein, fish can get exhausted over time and are pushed against the net material. Moreover, fish biomass and the amount of floating debris can accumulate during long exposure times and contribute to additional mortality, more intense injuries such as scale losses, tears in the fins, change of pigmentation and an overall reduced vitality.

The differences between the fish recovery units used on mortality and injury patterns (e.g. more scale loss in fyke-net and tears in the caudal fin in the FCB) indicated that the construction design and emptying procedure can have a large impact on fish health. It is likely that the two completely different handling procedures used for the fyke-nets and FCB lead to different injury patterns. The fyke-net is emptied by lifting up the net and quickly releasing the catch into the fish bin. Consequently, fish get in intense contact with the net material but emptying of the FCB requires fish to be chased with a dip-net during ≈15 min and they may accidently hit the box or the frame of the dip-net.

4.2 | Effects of physicochemical variables, bioenvironmental variables and species-specific behaviour

In this study, the FCB performed better than the fyke-net for some species, as effects of biomass and current speed inside the box were reduced by the more stable construction with current deflectors and greater water volume inside. In experiments where a defined number of test fish is released and probably recaptured in high numbers, it is preferable to release fish in several runs per treatment to avoid biomass-induced mortality, especially if a fyke-net is used. According to this study, fish biomass within the fyke-net should not exceed 3.5 kg for the net size used herein. To avoid current speed-induced mortality in the fyke-net, the construction of the fish recovery installation should be optimised so the current speed inside the fyke-net is <0.5 m/s. This can be achieved by adapting the length, diameter and mesh sizes of the fish recovery installation to the site-specific discharge conditions. If long exposure times are required due to monitoring reasons, the use of fish recovery units that provide shelter from current, sufficient room during the occurrence of high amounts of floating debris or fish biomass and are darkened to protect fish from daylight-related stress is recommended. However, during 1-hr exposure some species were harmed less in the fyke-net than in the FCB. Behaviour of benthic species such as *C. nasus* can cause difficulties during their recovery from the FCB with the dip-net, as they always tend to hide on the bottom and in the corners of the box. Consequently, these species are more prone to injuries from dip-netting than fish that inhabit the open water column and tend to school in the middle of the box (e.g. *R. rutilus*). The fish-friendliness of the fyke-net can be improved by combining this fish recovery unit with partial stow-nets because injury intensity was lowest in the medium stow-net compared with the small and full stow-nets. The medium-sized stow-net probably balances the effects of sufficient space to pass the stow-net and reduced current speed, floating debris and biomass in the fish recovery unit due to the smaller entrance diameter. However, the partial stow-nets may cause issues over sufficient sample size when evaluating the effects of hydropower turbines.

Besides the effects of current speed, floating debris and biomass, water temperature and individual fish condition can determine the severity of fish injuries. It is known that freshwater fish of pre-alpine regions are adapted to cold water and high oxygen supply (Brett, 1972; Farrell, 2002), thus catch-related stress can be enhanced for these species with increasing water temperature resulting in higher mortality. As expected, catch-related mortality was higher for fish that had a slightly reduced individual condition prior to the experiment, as

TABLE 5 Results from linear modelling after model selection (AIC). Mortality was used as dependent variable and different categorical variables as well as continuously measured variables were used as independent variables

	Estimate	*SE*	*t* value	*P* value		Estimate	*SE*	*t* value	*P* value
(Intercept)	1,400,000	9,249,00	1.5	>.05	FSN + FN*AFD	770	105	7.3	**≤.001**
MSN + FN	3,167	22,850	0.1	>.05	EI 1 hr*AFD	−1,993	284	−7.0	**≤.001**
SSN + FN	−8,925	35,370	−0.3	>.05	MSN + FN*WT	−2,395	1,883	−1.3	>.05
FSN + FN	3205,000	422,000	7.5	**≤.001**	SSN + FN*WT	−1,512	1,385	−1.1	>.05
EI 1 hr	−1E+06	924,300	−1.5	>.05	FSN + FN*WT	−322,800	43,920	−7.3	**≤.001**
FC	−618,600	72,440	−8.5	**≤.001**	EI 1 hr*WT	233,200	21,260	11.0	**≤.001**
AFW	−189	698	−0.3	>.05	EI 1 hr*V_{SN}	981,900	68,300	14.4	**≤.001**
AFD	1,981	283	7.0	**≤.001**	MSN + FN*$V_{FN/FCB}$	63,220	34,970	1.8	>.05
WT	−232,600	21,230	−11.0	**≤.001**	SSN + FN*$V_{FN/FCB}$	65,380	68,240	1.0	>.05
V_{SN}	−974,900	68,350	−14.3	**≤.001**	FSN + FN*$V_{FN/FCB}$	43,990	22,690	1.9	>.05
$V_{FN/FCB}$	3,279,000	388,900	8.4	**≤.001**	EI 1 hr*$V_{FN/FCB}$	−3E+06	386,900	−8.6	**≤.001**
V_{FR}	−576,800	65,740	−8.8	**≤.001**	FSN + FN*V_{FR}	−22,180	17,040	−1.3	>.05
V_{ESN}	−199,700	53,500	−3.7	**≤.001**	EI 1 hr*V_{FR}	598,500	65,810	9.1	**≤.001**
RD	−2E+06	285,900	−8.9	**≤.001**	FSN + FN*V_{ESN}	−17,750	10,010	−1.8	>.05
BM	0	0	−0.7	>.05	EI 1 hr*V_{ESN}	196,000	53,960	3.6	**≤.001**
TURB	125100	12140	10.3	**≤.001**	FSN + FN*RD	7,283	4,051	1.8	>.05
O_2	333,000	31,870	10.4	**≤.001**	EI 1 hr*RD	2,484,000	285,700	8.7	**≤.001**
pH	31,550	29,810	1.1	>.05	MSN + FN*BM	0	3	0.0	>.05
EC	6,549	2,273	2.9	**≤.01**	SSN + FN*BM	1	9	0.1	>.05
FSN + FN*EI 1 hr	−3E+06	418,700	−7.5	**≤.001**	FSN + FN*BM	1	0	2.5	**≤.05**
FSN + FN*FC	158,700	31,880	5.0	**≤.001**	EI 1 hr*TURB	−125,000	12,160	−10.3	**≤.001**
EI 1 hr*FC	618,500	72,420	8.5	**≤.001**	EI 1 hr*O2	−332,400	31,880	−10.4	**≤.001**
MSN + FN*AFW	10	35	0.3	>.05	EI 1 hr*pH	−34,460	29,860	−1.2	>.05
SSN + FN*AFW	10	37	0.3	>.05	EI 1 hr*EC	−6,564	2,274	−2.9	**≤.01**
FSN + FN*AFW	25,280	3,491	7.2	**≤.001**	FSN + FN*EI 1 hr*FC	−160,900	32,140	−5.0	**≤.001**
EI 1 hr*AFW	178	697	0.3	>.05	FSN + FN*EI 1 hr*AFW	−25,240	3,489	−7.2	**≤.001**
MSN + FN*AFD	6	200	0.0	>.05	FSN + FN*EI 1 hr*AFD	−756	109	−6.9	**≤.001**
SSN + FN*AFD	8	128	0.1	>.05	FSN + FN*EI 1 hr*WT	319,200	43,740	7.3	**≤.001**

Categorical variables: MSN = medium stow-net, SSN = small stow-net, FSN = full stow-net, FN = fyke-net, FCB = fish-catching box, EI = exposure time. Continuously measured variables: FC = fish condition, AFW = average individual fish weight, AFD = amount of floating debris [L/h], WT = water temperature [°C], V_{SN} = current speed along stow-net [m/s], $V_{FN/FCB}$ = current speed inside fish recovery unit (fyke-net or fish-catching box) [m/s], V_{FR} = current speed at fish release point [m/s], V_{ESN} = current speed at the entrance of the stow-net [m/s], RD = river discharge [m^3/s], BM = total fish biomass of the catch [g/h], TURB = turbidity of river water [NTU], O_2 = dissolved oxygen concentration in river water [mg/L], pH = pH value of river water, EC = electric conductivity of river water [µS/cm]. Estimate = slope, *SE* = standard error for the slope, *t* value = test statistic for estimate, *P* value = level of significance. Bold *P* values indicate statistical significance ($P \le .05$). * = interaction term.

they are less resistant to stress during the treatment. In this study, the highest available quality of farmed fish was used for each species. Nevertheless, the quality of the test fish differed greatly between species, as indicated by the number of injuries detected in the respective control fish. This is also an important aspect for studies using wild fish, where fish condition can strongly vary and should be evaluated initially. Consequently, it is important to carry out standardised experiments with fish of known condition to determine turbine-induced mortality in the field, in addition to consideration of the wild fish population condition status.

Precondition of the fish seems to play a major role in the evaluation of hydropower effects. All injury patterns detected herein also occurred in untreated control fish of all species and the main differences between treatment and control were attributed to changes in injury intensity. Fish production in the hatchery and the conditions during transportation can cause various injury types ranging from

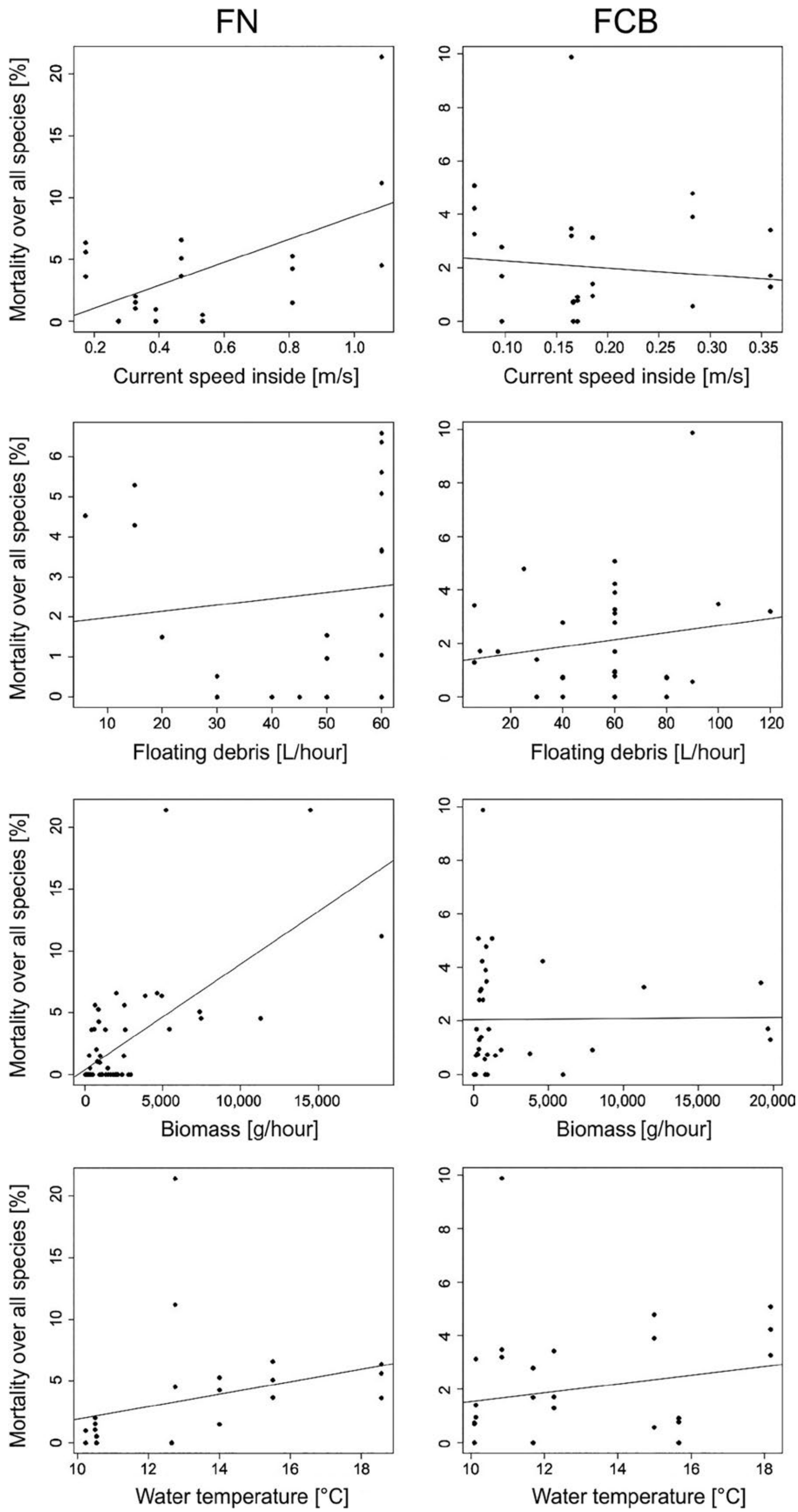

FIGURE 4 Linear regression plots of mortality rates over all species and current speed inside the fish recovery units, amount of floating debris accumulating during the exposure, total biomass of the catch accumulating during the exposure and water temperature in the fyke-net (FN) and fish-catching box (FCB) attached to a full stow-net (100% coverage) during 1-hr exposure time

scale losses, tears in the fins, bruises, dermal lesions or amputations of gill covers or fins. In principle, these injuries are very similar to injuries caused by the catching of fishes or by hydropower turbines. Consequently, hydropower- and catch-related injuries maybe over-estimated if damage to the test fish is not evaluated before the experiment.

4.3 | Catch efficiency

As the power of statistical analyses strongly depends on replication, that is a reasonable number of recaptured individuals, a high catch efficiency is desirable. This is particularly relevant in the context of animal experiments, where it is necessary to keep the number of test fish released to a minimum. Moreover, for an evaluation of the efficiency of bypass systems for wild fish, it is important to know the catch efficiency of the fish recovery installations. In this study, the full stow-net, which covered the complete water body, had a significantly reduced catch rate for all species compared with expected values, indicating that not all fish moved downstream from the release point or some of them escaped from the fish recovery installation. This effect was species-specific, with strong swimmers such as salmonids, *C. nasus* and *B. barbus* escaping in greater numbers than less current-adapted species. As *R. rutilus* and *P. fluviatilis*, which were among the smallest-sized individuals tested, were caught in highest numbers, the effect of individuals escaping through the larger meshes of the stow-net does not seem to be an explanation for this observation. Differences in catch efficiency between the three tested stow-nets with relatively higher proportions of fish in relation to the opening area of the stow-net can possibly be explained by the spatial positioning of the partial stow-nets. Most fish are known to prefer the main current for downstream movement (Northcote, 1984; Williams, Armstrong, Katapodis, Larinier & Travade, 2012). As the partial stow-nets were placed in the main current of the turbine outlet channel, the efficiency was higher for partial stow-nets in relation to the full stow-net. Besides the size of the stow-net and the species, the type of fish recovery unit and exposure time of the fish also had strong influences on catch efficiency. On the one hand, reduced recapture rates during the 12-hr exposure may be caused by the escapement of fish from the fish recovery unit, as found for *H. hucho*, *S. trutta* and *C. nasus* in the fyke-net. On the other hand, species that are more sensitive to catch-related mortality, for example *T. thymallus*, may die in the net due to stress or exhaustion during the long exposure time of 12 hr and not be able to escape anymore, resulting in higher catch efficiency. However, this effect can be overlain by a delayed downstream movement of the test fishes, which probably led to higher catch efficiency during 12-hr intervals than 1-hr intervals, particularly for *B. barbus*.

5 | CONCLUSIONS

Assessment of hydropower-induced fish mortalities and injuries following passage through the turbines, through diversion channels or past screening needs to account for pre-damage, catch-related mortality and injuries to fish during the capture procedures to be accurate. As long exposure times strongly increased mortality and fish injuries, it is crucial to keep emptying intervals of fish-catching units as short as possible. The construction design, materials and handling procedures of the fish recovery units tested had significantly different impacts on fish. These effects were species-specific, so the type of fish recovery unit to be used has to be selected according to the purpose of the monitoring. For instance, the fyke-net is much quicker and easier to empty and was advantageous for *C. nasus*, *B. barbus* and *P. fluviatilis*. However, mortality of *S. trutta* and *T. thymallus* was significantly lower in the FCB treatments, in particular during 12-hr treatments. Partial stow-nets can be alternatively used, for example if a representative evaluation of the spectrum of downstream moving fish is more important than a total census. This may be the only option in large rivers where the use of full stow-nets is technically impossible.

ACKNOWLEDGMENTS

We are grateful to the Bavarian State Ministry of the Environment and Consumer Protection for financial support, and to the Bavarian Environment Agency for administrative coordination of this study [grant number OelB-0270-45821/2014]. We are also grateful to Sibylle Zavala-Kugler Annemarie Kober and all other students for their help with the field experiment.

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How to cite this article: Pander J, Mueller M, Knott J, Geist J. Catch-related fish injury and catch efficiency of stow-net-based fish recovery installations for fish-monitoring at hydropower plants. *Fish Manag Ecol*. 2018;25:31–43. https://doi.org/10.1111/fme.12263