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ARTICLE

Evaluation of Behavior and Survival of Fish Exposed to an Axial-Flow Hydrokinetic Turbine

Stephen V. Amaral
Alden Research Laboratory, Inc., 30 Shrewsbury Street, Holden, Massachusetts 01520-1843, USA

Mark S. Bevelhimer and Glenn F. Čada[1]
Oak Ridge National Laboratory, Environmental Sciences Division, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831, USA

Daniel J. Giza
Alden Research Laboratory, Inc., 30 Shrewsbury Street, Holden, Massachusetts 01520-1843, USA

Paul T. Jacobson
Electric Power Research Institute, 5637 Gulfstream Row, Columbia, Maryland 21044, USA

Brian J. McMahon
Alden Research Laboratory, Inc., 30 Shrewsbury Street, Holden, Massachusetts 01520-1843, USA

Brenda M. Pracheil*
Oak Ridge National Laboratory, Environmental Sciences Division, 1 Bethel Valley Road, Oak Ridge, Tennessee 37831, USA

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Abstract

Previous studies have evaluated fish injury and mortality at hydrokinetic (HK) turbines, but because these studies focused on the impacts of these turbines in situ they were unable to evaluate fish responses to controlled environmental characteristics (e.g., current velocity and light or dark conditions). In this study, we used juvenile hybrid Striped Bass (HSB; Striped Bass *Morone saxatilis* × White Bass *M. chrysops*; $N = 620$), Rainbow Trout *Oncorhynchus mykiss* ($N = 3{,}719$), and White Sturgeon *Acipenser transmontanus* ($N = 294$) in a series of laboratory experiments to (1) evaluate the ability of fish to avoid entrainment through an axial-flow HK turbine, (2) evaluate fish injury and survival associated with turbine entrainment, and (3) compare the effects of different HK turbines on fish. We found that the probability of turbine entrainment was species dependent and highest for HSB. Across species, current velocity influenced entrainment probability. Among entrained fish, observed survival rates were generally >0.95. The probability of injury for surviving entrained fish only differed from that for nonentrained fish for Rainbow Trout and in general was not >0.20. The probability of injury following entrainment was greater only for HSB, although there were no differences in injury rates between fish that were turbine entrained and those that were not, suggesting that injuries were not turbine related. Taking turbine entrainment, survival, and injury estimates together allowed us to estimate the probability of a randomly selected fish in a population proximate to an HK turbine surviving passage or remaining uninjured after passage. For species and current velocities for which there was a significant effect due to entrainment, we estimated, for instance, that HSB had a survival probability of 0.95 and that Rainbow Trout and White Sturgeon had a >0.99 probability of survival. Similarly, by combining these estimates with those from previous studies, we derived total passage survival probabilities >0.90 but generally approaching 1.00 across different HK turbine types, fish species, and fish lengths.

*Corresponding author: pracheilbm@ornl.gov
[1]Retired.
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There is considerable interest in the development of marine and hydrokinetic (HK) energy projects in rivers, estuaries, and coastal ocean waters around the world. Hydrokinetic technologies convert the energy of water currents into electricity without the adverse impacts of the dams and impoundments associated with conventional hydropower (which relies on the flow of water from a higher elevation to generate electricity) or the extraction and combustion of fossil fuels. In particular, the renewable energy potential in U.S. river and ocean currents is very large. For instance, the Electric Power Research Institute (EPRI 2011a, 2012) has estimated that approximately one-third of all U.S. electricity needs could be met by harnessing energy from river and ocean currents and waves. At present, however, only a small number of HK turbines have been deployed in U.S. waters, in part because the environmental impacts of these turbines are not known.

Although numerous HK designs are under development (see DOE 2009 for a description of the technologies and their potential environmental effects), the most commonly proposed projects entail arrays of rotating devices, much like submerged wind turbines, that are positioned in high-velocity (high-energy) areas such as tidal and river channels. The diversity of HK designs implies a diversity of environmental impacts (Čada et al. 2007, 2011), but a potential impact common to most designs is the risk of blade strike to aquatic organisms (Wilson et al. 2007). Only a limited number of studies have examined the risk of blade strike that HK technologies pose to freshwater fish (Turnpenny et al. 1992; NAI 2009; Amaral et al. 2011; Seitz et al. 2011; Castro-Santos and Haro 2015), and the probabilities of blade encounter and turbine rotor passage survival are unknown for most species of fish. One study (EPRI 2011b) suggested that HK turbines present less harsh physical conditions to entrained fish than conventional hydropower turbines. For example, HK turbine runners typically cause smaller changes in shear stress, turbulence, and water pressure than do conventional turbines. Specifically, the relatively open configuration of HK turbines allows fish to avoid turbine passage and, if they are unable to avoid entrainment, the slow blade rotation rate should result in less damaging strikes and better fish survival than with conventional turbines (EPRI 2011b).

An important consideration for fish and HK turbine interactions is whether fish residing in or moving through an area with turbines will ever encounter a rotor. To be killed by HK turbine passage, a fish must (1) inhabit or pass through the water body in the vicinity of the HK turbine, (2) become unavoidably entrained in the "cylinder" of water that is destined to pass through the HK turbine, (3) be struck by a rotor blade (strike probability will primarily depend on fish behavior and length, the number of blades and their rotational speed, and the angle of the flow entering the blade-swept area), and (4) receive lethal injuries if struck by a blade (a function of leading-edge blade thickness, fish length, and relative velocity of the fish to that of the blade). With regard to the first condition, the probability of encountering a midwater turbine will be low for particular species or life stages that typically move downstream near shore, on the bottom, or near the surface of a river or tidal area (Čada and Bevelhimer 2011; Schweizer et al. 2011). Incorporation of habitat preference–based encounter probabilities into the analysis may lead to higher total passage survival than would be obtained using only turbine survival and avoidance probabilities. Encounter probabilities can be derived from information on species habitat preferences and migratory patterns. Tracking tagged fish approaching and passing turbines in field situations using radio- or acoustic telemetry techniques or bottom-mounted sonar can provide this information if it does not already exist.

Most of the elements that influence HK turbine survival (i.e., HK encounter and entrainment probabilities, HK rotor avoidance by entrained fish, and rotor blade strike mortality) are difficult to quantify in a field setting. To better understand the probabilities of HK turbine passage survival, we conducted a series of tests in a large laboratory flume that quantified (1) the ability of fish to avoid HK rotor passage and (2) blade strike injuries and mortalities that occurred when fish were forced to pass through the HK rotor. We then used this information to (3) calculate the probability of entrainment and survival given avoidance behaviors and (4) compare estimates of passage survival among HK turbine types from our own and previous studies. The tests were carried out using a ducted axial-flow HK turbine and three fish species with differing morphologies and behaviors. The ability of these fish to avoid HK turbine passage was evaluated under both light and dark conditions.

METHODS

Biological testing was conducted with a ducted, axial-flow HK turbine developed by Free Flow Power (FFP; Boston, Massachusetts). The turbine is 1.5 m in diameter and has seven blades (Figure 1). The expected rotational speeds for this unit range from 40 to 125 rpm at stream flow velocities of 1–3 m/s. This rotational speed is slower than those of many similarly sized conventional (i.e., Francis and Kaplan) turbines (EPRI 2011c). Biological evaluations included two types of tests, one designed to assess behavioral interactions and avoidance as fish moved downstream and encountered the turbine and another designed to estimate turbine passage survival. Our experimental protocols and pre- and posttest holding conditions and observations are summarized here and provided in detail in Amaral et al. (2014).

Study Species

Interactions of fish with the FFP turbine were evaluated for three species: hybrid Striped Bass (HSB; Striped Bass *Morone*

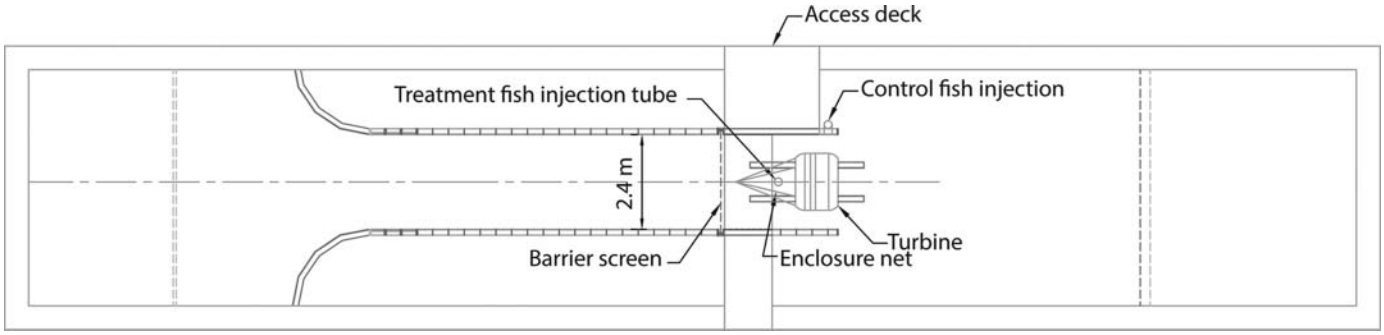

FIGURE 1. Schematic in-plan view of the test flume showing the locations of the FFP turbine, the enclosure net, and the fish injection pipes used for the turbine passage survival trials. Water flow is from left to right.

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saxatilis × White Bass *M. chrysops*), Rainbow Trout *Oncorhynchus mykiss*, and White Sturgeon *Acipenser transmontanus* (Table 1). These species represent different families of fish that will be susceptible to HK turbine entrainment in large rivers but that have different morphologies and that were expected to exhibit different avoidance behaviors and sensitivities to blade strike injuries. Rainbow Trout are a widely distributed sport fish that are considered representative of other trout and salmon species in terms of swimming behavior and, with respect to blade strike injury and survival, are similar to many other teleost species (i.e., bony fishes common to riverine and estuarine environments). White Sturgeon are considered representative of other sturgeon species that are likely to encounter HK turbines in rivers and the nearshore ocean. Also, evidence from blade-strike and turbine passage studies indicates that sturgeons are less susceptible to injury from blade strikes than are teleost species. There may also be behavioral differences that lead sturgeons to react differently to HK turbines than trouts and other common teleost fishes. Hybrid Striped Bass have a different body shape and are typically considered to be weaker swimmers at higher velocities than Rainbow Trout and White Sturgeon (Mellas and Haynes 1985).

Striped Bass are an anadromous species that could be expected to encounter HK turbines in both rivers and tidal streams. We expected HSB and White Sturgeon to have the

TABLE 1. Summary of release, recovery, and mortality data for three fish species tested during the survival evaluation with the FFP turbine. Test group abbreviations denote whether a fish was assigned to the turbine passage treatment group (T) or the control group (C). The number of fish used in the analyses can be obtained by summing the live and dead recoveries; fish censored from the study are not included in these totals. The size-classes of Rainbow Trout are as follows: small, ≤200 mm FL; large, >200 mm FL.

Species	Water velocity (m/s)	Mean FL (mm) (SD)	No. of trials	Test group	Live recoveries (1 h)	Dead recoveries[a] (1 h)	Dead recoveries[a] (48 h)
Hybrid Striped Bass	1.5	131 (30.1)	3	T	145	3	12
				C	148	0	2
	2.0	118 (25.7)	3	T	146	0	6
				C	151	1	6
Rainbow Trout	1.5 (small)	172 (12.8)	5	T	404	0	0
				C	500	0	0
	2.0 (small)	168 (15.5)	5	T	477	3	3
				C	477	1	0
	1.5 (large)	271 (21.6)	5	T	392	0	0
				C	471	0	0
	2.0 (large)	246 (16.5)	5	T	478	11	1
				C	501	0	0
White Sturgeon	1.5	123 (14.7)	1	T	69	0	1
				C	74	0	1
	2.0	126 (14.6)	1	T	74	0	0
				C	76	0	0

[a]All treatment fish recovered dead downstream of the turbine at the end of a trial were assumed to be turbine-passed fish.

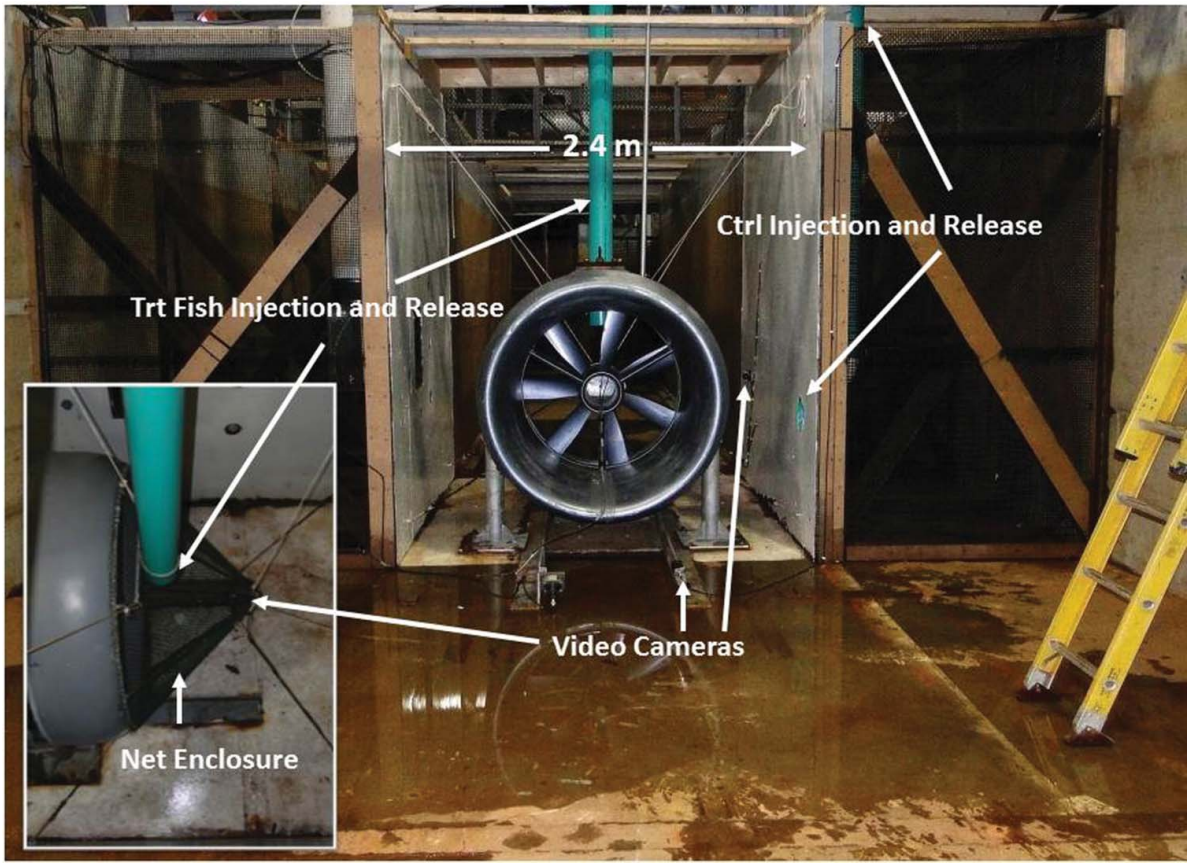

FIGURE 2. Photograph of the large-flume fish testing facility as it would appear from downstream (facing into the direction of flow) showing the locations of the treatment and control injection and release points, the video cameras, and the net enclosure (insert).

highest probabilities of entrainment due to their lesser burst swimming capabilities compared with Rainbow Trout (Mellas and Haynes 1985). We also expected that due to their tough body armoring White Sturgeon would have a lower probability of injury and mortality than HSB and Rainbow Trout.

Test Turbine and Flume Design

The FFP turbine was installed in a large, recirculating laboratory flume at the Alden Research Laboratory in Holden, Massachusetts (Figure 1). The test flume has a concrete floor 3.05 m below the top of the side walls. To create a water current in the flume, beneath this floor at the downstream end of the flume are two 1.7-m-diameter bow thrusters (400 hp each [1 hp = 746 W]) capable of pumping up to 14.2 m^3 of filtered water per second through the test channel with the assistance of turning vanes at both ends (i.e., flume water is circulated vertically at either end). The section of flume available for testing was 24.4 m long, 6.1 m wide, and up to 2.4 m deep. In this configuration, the maximum channel velocity for the full width of the flume is 0.91 m/s. Higher flow velocities for testing the FFP turbine were achieved with temporary walls that narrowed the flume width to 2.4 m while maintaining the water depth at 2.4 m (Figure 2). With a narrower channel, the maximum current velocity that could be achieved was about 2 m/s. To minimize flow separation and turbulence, the entrance to the narrowed section had rounded walls.

The flume was equipped with a side-mounted Acoustic Doppler Current Profiler to measure current velocities and determine flow rates. Velocity measurements were recorded to verify that the flume operating conditions produced the desired current velocities with a relatively uniform distribution upstream of the test turbine. These measurements were used to develop a predicted bow thruster output curve (a rating curve that relates the flow velocity to bow thruster rpm), so that bow thruster rpm could be used to set the current velocity for each test. Once the appropriate rpm for each velocity condition was determined, a complete velocity profile was developed for each velocity condition. Velocities in the flume were measured for each test type (survival and behavioral) and velocity condition in a 3 × 3 grid to determine the average velocity profile for a given condition across the flume channel (Amaral et al. 2014). Velocity measurements were recorded with a Swoffer propeller-style velocity meter. Velocity profile measurements were recorded 6.9 m upstream of the turbine for both test types. An additional velocity profile was recorded 0.46 m in

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front of the turbine for the behavioral velocity conditions. The velocity measurements recorded during the survival conditions were taken with the containment net in place (see the Survival Evaluation subsection below). Additionally, velocity measurements were recorded 0.33 m upstream of the HK turbine rotor hub (center) and at a location half way between the hub and the turbine shroud that surrounds the rotor (off center) approximately 0.66 m upstream of the blades for each velocity condition. These velocity measurements were recorded in front of the turbine within the containment net enclosure to document the current velocities experienced by turbine-entrained fish during the survival trials (Figure 2).

The underwater video cameras (resolution: 640 × 480 pixels; frame rate: 29 frames/s) used to record fish movements during the survival and lighted behavioral trials were located (1) upstream of and on either side of the turbine and (2) on the flume floor downstream of the turbine. For survival testing, an additional camera was mounted inside the net enclosure at the upstream end with a partial view of the turbine blade rotational area. A dual-frequency identification sonar (DIDSON; Sound Metrics Corp., Bellevue, Washington) unit recorded the movements of fish under both light and dark test conditions at a velocity of 1.1 m/s during the behavioral trials. The DIDSON was positioned 6.9 m upstream of the turbine at a depth of 0.45 m. We also used the DIDSON during lighted trials to enable us to calculate a correction factor for entrainment counts recorded from DIDSON images under dark conditions by comparing the underwater video entrainment counts with the DIDSON counts from the lighted trials (see the next subsection).

Behavioral Testing

The behavioral trials evaluated the ability of fish to actively avoid passing through the turbine after they were released into the flume and moved downstream. In this study, fish were released from a vertical 20.3-cm-diameter tube positioned 1.45 m upstream of the FFP turbine and 40.6 cm above the centerline of the unit at the hub. The containment net was not used in these experiments, so this design allowed fish the opportunity to avoid entrainment into the HK duct (e.g., the circular cover, or shroud surrounding the turbine rotor) and through the rotor.

We estimated entrainment probability under simulated daytime (hereafter, light) and nighttime (hereafter, dark) lighting conditions and three current velocities. Although we only used two current velocities in the survival evaluation, the behavioral testing included an additional, slower current velocity (1.1 m/s) because images from the DIDSON unit used to record fish movements in the dark were obscured by air bubbles at the 1.5 and 2.0 m/s velocities. Consequently, we were only able to evaluate avoidance of the FFP turbine in the light at the two higher velocities by means of the underwater video cameras. To evaluate the influence of visual cues on a fish's avoidance of the FFP turbine, trials were added at the 1.1-m/s current velocity under both light and dark conditions using video and DIDSON cameras. Because the counts obtained from the video cameras were higher than those obtained from the DIDSON unit, we created a correction factor for the DIDSON-based entrainment counts at the two higher velocities. Two independent observers made fish entrainment counts using both the DIDSON and underwater video camera images from the 1.1-m/s velocity light trials. We calculated this correction factor using the equation

$$R = \frac{\sum_{i=3}^{n} U}{\sum_{i=3}^{n} D}, \tag{1}$$

where R is the ratio of underwater video camera entrainment counts (U) to DIDSON entrainment counts (D) in the various trials. Values of R were calculated independently for each observer and then averaged between the two observers; this average was then used as a correction factor for the corresponding pooled-replicate DIDSON counts from dark condition tests at the two higher flume velocities.

For the behavioral testing, three replicate trials were conducted for each set of test conditions (species, size-group [for Rainbow Trout], and current velocity; Table 1). The numbers of fish released in the trials were as follows: HSB = 50 per trial (150 per test condition), large Rainbow Trout (>200 mm FL) = 100 per trial (300 per test condition), small Rainbow Trout (≤200 mm FL) = 50 per trial (150 per test condition), and White Sturgeon = 23 per trial (69 per test condition). It was our original goal to use 100 fish per trial for all species, but our sample sizes were limited by fish availability. We obtained fish from the following sources: Osage Catfisheries, Osage Beach, Missouri (HSB); Hy-On-A-Hill Trout Farm, Plainsfield, New Hampshire (Rainbow Trout); and Professional Aquaculture Services Farm, Chico, California (White Sturgeon). We introduced fish into the flume and monitored and recorded their movements through or around the turbine with the underwater video system and/or DIDSON unit, as described previously. Each trial ended after all fish had moved downstream of the turbine, which took approximately 5 min. After completion of a trial with each species/size-group at a given current velocity, a barrier screen was lowered immediately to prevent fish from moving up or downstream of the turbine (Figures 1, 2). At the end of each trial, fish were recovered with a seine and transferred to the holding facility.

Survival Evaluation

Survival tests were conducted to estimate the fish survival, injury, and descaling rates associated with passage through the FFP turbine at two current velocities (1.5 and 2.0 m/s). Turbine passage survival was then evaluated for the three fish species 1 and 48 h poststudy. Our study evaluated the passage

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survival of treatment groups that were subjected to turbine entrainment (hereafter, treatment) and control groups that were not subjected to turbine entrainment (hereafter, control). In this experiment, the control group allowed for injury and mortality associated with handling and test procedures (e.g., marking, release, and collection) to be distinguished from turbine-induced injury and mortality. Initial sample sizes were determined based on an analysis of desired precision levels (±5% over 95% of the time) for survival estimates, fish costs, and availability. For Rainbow Trout tests, the goal was to use 1,000 fish for five replicate trials (100 treatment fish and 100 control fish per trial) conducted with each set of test conditions (fish size-class, approach velocity, and light condition). The target sample sizes per trial for HSB and White Sturgeon were 50 and 25, respectively, and three replicates were conducted with each species.

We marked fish with biologically inert, encapsulated photonic dyes 24 h or more prior to testing using a POW'R-Ject marking gun (New West Technology, Arcata, California). This marking system uses compressed CO_2 to inject the photonic dye at the base of or into individual fins. Four dye colors and four fin location combinations were used to create 16 unique marks to distinguish treatment and control fish for each trial. Mark retention was very high; of the 4,899 treatment and control fish recovered during survival testing, only 61 (1.3%) did not have a discernible mark when recovered and were censored from the analyses. Prior to testing, we removed any fish with visible injuries or abnormal swimming behavior.

Treatment fish were released into a 2.2-cm knotless mesh containment net attached to the upstream side of the turbine through a vertical 20.3-cm-diameter release tube with an exit located 12.7 cm upstream of the turbine duct and 40.6 cm above the centerline of the unit at the hub (Figures 1, 2). The containment net prevented escape and forced downstream-moving treatment fish to pass through the turbine. Control fish were released into the flume at approximately the same time as the treatment fish. The control fish introduction system was similar to that for treatment fish, but with the exit located at the downstream end and to the side of the turbine duct.

Each group was released into the flume after the channel velocity and turbine rotational speed stabilized. Each trial was terminated after all treatment fish had passed the turbine or 10 min postintroduction, whichever came first. At the completion of each trial, fish were recovered with a seine, counted, and transferred to a holding tank where live fish were held for a 48-h observation period. Fish that died during the observation period were immediately removed from the tank.

Survival, injury, and scale loss evaluations were conducted on all recovered fish to enumerate immediate and delayed mortalities, external injuries, and percent scale loss (Table 2). Immediate mortalities were classified as any fish that died within 1 h of the completion of a test. This included any fish that were euthanized at the 1-h posttest observation due to abnormal swimming behavior (e.g., lying on tank bottom) or extensive injuries (e.g., large lacerations). We classified any fish that died between 1 and 48 h posttest as a 48-h mortality. We conducted injury and scale loss evaluations at 1 and 48 h posttest for live fish and at the time of recovery for mortalities. External injuries were recorded as bruising/hemorrhaging, lacerations, severed body, and eye damage. Using methods similar to those reported by Neitzel et al. (1985) and Basham et al. (1982), percent scale loss (<3%, 3–20%, >20–40%, and >40%) was recorded for each of three locations along the length of both sides of the body. If >20% scale loss was recorded at two or more locations, a fish was classified as descaled. During the injury evaluation, each fish was also inspected for fin mark location and color to determine its

TABLE 2. Frequency of injury type by species, size of fish (for Rainbow Trout), and current velocity from the survival experiment. Evaluations of injuries aggregated bruising, eye injury, and lacerations into a general injury category but tallied descaling separately.

	No injury		Bruising		Eye injury		Lacerations		Descaling	
Velocity (m/s)	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control
Hybrid Striped Bass										
1.5	110	148	38	18	0	0	1	0	39	40
2.0	117	152	29	49	0	1	0	0	58	74
Rainbow Trout										
Small 1.5	443	501	44	6	3	0	0	0	230	280
2.0	399	477	86	29	3	1	0	0	220	191
Large 1.5	424	471	66	14	4	6	2	2	270	182
2.0	386	501	109	18	2	1	0	0	194	125
White Sturgeon										
1.5	72	74	0	0	0	0	0	0	0	0
2.0	67	76	6	2	0	0	0	0	0	0

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release group and test number and measured to the nearest millimeter (fork length).

Data Analysis

Behavioral studies.—Our behavioral data analysis was based on both qualitative observations of fish behavior as the fish moved downstream past the turbine and quantitative estimates of entrainment and avoidance rates. Video from the underwater cameras and/or the DIDSON unit were used to count the number of fish that were entrained through the FFP turbine during each behavioral trial. Counts of entrained fish were subtracted from the total number of fish collected downstream of the turbine at the end of a test to determine the number of fish that avoided entrainment during each trial.

We used a recapture-only multistate model (Hestbeck et al. 1991; Brownie et al. 1993) in Program MARK (White and Burnham 1999) with covariates (trial, velocity, and size [the last for Rainbow Trout only]) to estimate entrainment probability (ψ), that is, the probability of moving from a nonentrained (noent) to an entrained state (ent). For instance, the probability of a fish's being entrained would be represented by $\psi_{\text{noent–ent}}$. We were only interested in ψ, which was calculated from the initial release and one encounter period. We manually fixed some of the parameters in the model to 0 (e.g., $\psi_{\text{ent–noent}}$, as it is unlikely that a fish would swim back out of the turbine once it was entrained) and others to 1 (e.g., S_0 [survival at the beginning of the experiment] and ρ [the recapture probability, which was assumed to be constant throughout the study]). Because light was manipulated only in the slowest velocity, we ran separate models for each species to account for potential differences in light treatments that included only trial and size (for Rainbow Trout) as covariates. All of the differences in this study, such as those between treatment and control, flume velocities, and light conditions, were compared by means of 95% CIs, that is, we determined differences to be significant when the 95% CIs of two groups did not overlap.

Turbine passage survival.—We assessed turbine passage survival (S) using a known-fate mark–recapture model (Program MARK; White and Burnham 1999). Known-fate models allow for high-precision estimation of S probabilities and their associated confidence intervals because the status of every fish (alive or dead) can be determined with certainty at each time period. This model type allowed estimation of S both at 1 h postexperiment and over the entire 48-h study period. For this analysis, we made encounter histories using Microsoft Excel. We included the initial release (t_0) plus two encounter periods (t_1 and t_{48}) and three or four covariates (trial, treatment, velocity [1.5 or 2.0 m/s], and, for Rainbow Trout only, fish size) in our encounter histories. We tested models that included no covariates, all of the covariates jointly, and each covariate separately and that allowed S to vary by time period (S_t) as well as remain constant in all combinations and then used a corrected Akaike's information criterion (AIC_c) for model selection. We chose to use AIC_c-based model selection to increase the accuracy of our parameter estimates and understand what factors most influenced fish injury and mortality in relation to HK turbines. The model(s) with the lowest AIC_c value was/were considered the best model(s), and all models with a ΔAIC_c value of <2 were considered to be equally parsimonious. In cases in which more than one model had a ΔAIC_c of <2, we obtained model-averaged parameter estimates by multiplying the estimate by the model weight for each model and summing these products. Only models with a ΔAIC_c of <2 were used in calculating model weights. Of the 4,899 fish that were used in this portion of the study, 62 were censored either because they could not be recovered during the trial in which they were used ($N = 1$) or they did not have discernable marks ($N = 61$, all of which were still alive at t_{48}).

Injury and descaling attributable to turbine passage.—We used a multistate mark–recapture model with live and dead encounters (Hestbeck et al. 1991; Brownie et al. 1993) to assess the probability of fish injury (i.e., bruising, lacerations, or eye injury) during turbine passage (Program MARK; White and Burnham 1999). We estimated the transition from the uninjured state to the injured state (inj) whether fish were subjected to the turbine passage treatment (trt)or not (ctrl). We also included 4 covariates: trial, velocity (1.5 or 2.0 m/s), fork length (mm), and whether or not a fish was descaled. We included descaling as a covariate because this was a fairly common injury among the fish and it has been linked to mortality (Bouck and Smith 1979). For the purposes of this study, descaling was assessed separately from other forms of injury; thus, descaling was not captured by the injury covariate. Owing to logistical constraints with the holding tanks and the high cost associated with obtaining individual marks for such a large number of fish, individual injury data were only recorded at t_1, thus leaving us with only one encounter occasion (in addition to the injury assessment prior to releasing the fish).

In general, mark–recapture models require two or more reencounter (injury assessment) occasions because estimating S_t requires knowing an individual's fate at S_{t+1}. Although our data do not meet this requirement, this is not problematic in our case. We were interested in comparing the maximum likelihood estimates of transitioning from an uninjured state to an injured state (ψ) for treatment and control fish, as expressed by the ratio

$$\psi_{\text{uninj}-\text{inj}} = \phi_{\text{uninj}-\text{inj}}/\phi_{\text{inj}}, \tag{2}$$

where $\psi_{\text{uninj–inj}}$ represents the probability of transitioning from an uninjured state to an injured state, $\phi_{\text{uninj–inj}}$ is the probability of being in an injured state at $t + 1$ for fish that were found in an uninjured state at time t and survived to $t + 1$ (Hestbeck et al. 1991; Brownie et al. 1993), and ϕ_{inj} is the probability of being injured at $t + 1$. For example, $\psi_{\text{trt–inj}}$ is the probability

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that an uninjured fish subjected to the turbine passage treatment will be injured over the course of the study. In our case, the estimate of $\phi_{\text{uninj–inj}}$ would be 1 because all fish were alive at the start of the study. Thus, $\psi_{\text{trt–inj}}$ represents the maximum likelihood estimate of being injured over the course of the study, discounted for fish that do not survive to t_1. We attempted to increase the accuracy of the estimates of ψ by manually setting to 0 the probabilities for transitions that could not occur, such as $\psi_{\text{trt–ctrl}}$ and $\psi_{\text{inj–ctrl}}$ (because all state transitions are permanent) and manually setting to 1 S_0 and all recapture probabilities (ρ) because the fate of all fish was known. As the data for this portion of the study were from the same trials as for the FFP turbine survival study, the same numbers of individuals were censored.

We used this same approach to measure the probability of descaling, that is, the probability $\psi_{\text{uninj–descaled}}$ (from equation 2) of transitioning from a scaled state (uninj; both treatment and control fish) to a descaled state. We again included four covariates: trial, velocity, length (a continuous variable), and whether a fish was injured or not. Corrected AIC (AIC_c) values were used for model selection. We again made statistical comparisons between groups by examining the overlaps between 95% CIs; groups were considered to differ if there was no overlap.

Estimation of total passage survival.—The passage survival associated with an HK turbine is a function of (1) the ability of fish to avoid entrainment into the rotor-swept area and (2) the survival of those fish that are entrained through the rotor. To provide a more representative estimate of the probability that a randomly selected fish will be entrained and survive that entrainment, we calculated total passage survival (S_P), that is, the joint probability of these events, as

$$S_P = A + (\psi_{\text{ent}} \cdot S_{\text{total}}), \tag{3}$$

where A is the probability of avoiding turbine entrainment and is calculated as

$$A = 1 - \psi_{\text{ent}}, \tag{4}$$

ψ_{ent} is the probability of entrainment, and S_{total} is turbine passage survival over the entire study period. This approximation was only used when S_{total} differed between the treatment and control groups. The survival of fish that avoided turbine entrainment was assumed to be 100%. We used the delta method (Seber 1982; Powell 2007) to approximate the variance for our extrapolated estimate of S_p as

$$\hat{\text{var}}(S_p) = \hat{\text{var}}(A) + (\hat{\text{var}}(\psi_{\text{ent}}) \cdot S_{\text{total}}^2) + (\hat{\text{var}}(S_{\text{total}}) \cdot \psi_{\text{ent}}^2). \tag{5}$$

Total passage survival, injury, and descaling probability.—Based on our results, we estimated the probability of a fish near an FFP turbine in a natural setting not being injured, descaled, or killed by a turbine. To do this, we calculated the total passage noninjury (I_p) and nondescaling (D_p) probabilities, that is, the joint probability of either (1) not being entrained or (2) being entrained but surviving that entrainment and not being injured or descaled during it as follows:

$$I_p = A + (\psi_{\text{ent}} \cdot S_{\text{total}} \cdot (1 - \psi_{\text{inj}})) \tag{6}$$

for total noninjury probability or

$$D_p = A + (\psi_{\text{ent}} \cdot S_{\text{total}} \cdot (1 - \psi_{\text{descaled}})) \tag{7}$$

for total nondescaling probability.

The survival of fish that avoided entrainment was assumed to be 100%. The variance approximation for I_p was also made according to the delta method and calculated as

$$\begin{aligned} \hat{\text{var}}(I_p) = {} & \hat{\text{var}}(A) + (\hat{\text{var}}(\psi_{\text{ent}}) \cdot (S_{\text{total}} \cdot (1 - \psi_{\text{inj}}))^2) \\ & + (\hat{\text{var}}(S_{\text{total}}) \cdot (\psi_{\text{ent}} \cdot (1 - \psi_{\text{inj}}))^2) \\ & + (\hat{\text{var}}(1 - \psi_{\text{inj}}) \cdot (S_{\text{total}} \cdot \psi_{\text{ent}})^2) \end{aligned} \tag{8}$$

while the variance for D_p was calculated as

$$\begin{aligned} \hat{\text{var}}(D_p) = {} & \hat{\text{var}}(A) + (\hat{\text{var}}(\psi_{\text{ent}}) \cdot (S_{\text{total}} \cdot (1 - \psi_{\text{descaled}}))^2) \\ & + (\hat{\text{var}}(S_{\text{total}}) \cdot (\psi_{\text{ent}} \cdot (1 - \psi_{\text{descaled}}))^2) \\ & + (\hat{\text{var}}(\psi_{\text{descaled}}) \cdot (S_{\text{total}} \cdot (1 - \psi_{\text{ent}}))^2) \end{aligned} \tag{9}$$

In these equations, $\hat{\text{var}}(1 - \psi_{\text{inj}})$ and $\hat{\text{var}}(1 - \psi_{\text{descaled}})$ are equal to $\hat{\text{var}}(\psi_{\text{inj}})$ and $\hat{\text{var}}(\psi_{\text{descaled}})$, as shown in Powell (2007).

Comparisons among hydrokinetic turbine types.—Turbine passage survival data have now been collected for fish entrained through four different pilot-scale HK turbines evaluated in a laboratory flume, two of which are ducted axial-flow designs and two of which are cross-flow units (EPRI 2011b; Castro-Santos and Haro 2015). In addition to these laboratory studies, there has also been one field study that evaluated the turbine survival of several fish species passed through a full-scale ducted axial-flow turbine (NAI 2009). The FFP, Welka UPG, and Lucid turbines evaluated in the Alden laboratory flume were all tested at approach velocities of 1.5 and 2.0 m/s, and we used these common conditions to make explicit comparisons among turbine types.

RESULTS

Behavioral Testing

Hybrid Striped Bass.—When released above the turbine, HSB actively resisted entrainment by swimming away from the turbine. Probabilities of entrainment ($\psi_{\text{noent–ent}}$) were best estimated using a single model containing trial, light, and velocity as covariates (Table 3) that showed HSB having the

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TABLE 3. Corrected Akaike information criterion values (AIC_c), ΔAIC_c values, and AIC_c weights for the best behavioral models ($\Delta AIC_c < 2$), by species.

Species and covariate(s)	AIC_c	ΔAIC_c	AIC_c weight
Behavior experiment			
Hybrid Striped Bass			
Trial + light + velocity	777.29	0.00	1.00
Rainbow Trout			
Trial	440.60	0.00	0.35
Size + velocity	440.93	0.33	0.21
Trial + velocity	441.29	0.68	0.18
Trial + size	442.24	1.64	0.13
White Sturgeon			
Trial + velocity	159.85	0.00	0.59
Trial + light + velocity	160.54	0.69	0.41
Light and behavior experiment			
Hybrid Striped Bass			
Trial	396.86	0.00	0.64
Trial + light	396.86	1.13	0.36
Rainbow Trout			
Trial	172.48	0.00	0.27
Size	172.57	0.10	0.25
Size + light	174.04	1.56	0.12
Trial + light	174.04	1.56	0.12
Light	174.07	1.59	0.12
Trial + size	174.16	1.69	0.11
White Sturgeon			
Trial	106.40	0.00	0.43
Light	106.49	0.09	0.41
Trial + light	108.48	2.08	0.15

highest probability among the tested species of being entrained through the rotor (Table 4). Model AIC_c values highlighted two best models of entrainment probabilities at different light levels (at the 1.1-m/s velocity; Table 4). Interestingly, the averaged estimates from these two models showed that the daytime light treatment—which also had the lowest velocities— yielded the highest entrainment probabilities (0.55), although the light and dark entrainment estimates were not significantly different (Table 4).

Rainbow Trout.—After leaving the introduction pipe and entering the channel flow, Rainbow Trout typically exhibited positive rheotaxis and proceeded downstream in a controlled manner (head upstream and tail beating with some control of speed and directional movement). Anecdotally, of the species tested Rainbow Trout was the most active in avoiding entrainment by means of lateral and/or vertical movements. Velocity and trial were the most important covariates influencing entrainment probability and some combination of these covariates was included in all of the best models, thus suggesting that variation among trials and current velocity were important factors in whether or not a fish was entrained (Table 3). Size was included in two of the four best models and was also an important covariate influencing Rainbow Trout entrainment probability (Table 3). Interestingly, Rainbow Trout was the only species that exhibited a positive relationship between current velocity and entrainment probability. It was also the only species for which size was noted (although length was recorded for all fish in the survival trials), and although it was included in the best models there was no difference in entrainment probability between sizes (Table 4). Trial, size, and light were equally important covariates, each being found in three of the six best models examining the influence of the light treatment on Rainbow Trout entrainment (Table 3). Overall, entrainment probabilities were low, with the highest probability (0.06) being found at the 2-m/s velocity (Table 4).

White Sturgeon.—Unlike the HSB and Rainbow Trout, most White Sturgeon appeared to drift passively downstream with minimal active swimming and directional movement once entering the channel flow. White Sturgeon typically rose slightly in the water column after exiting the release pipe and followed the flow streamlines, accelerating around the outside of the turbine duct. Trial and velocity were important covariates in determining White Sturgeon entrainment probabilities and were included in both of the best models. Although it may be counterintuitive, the probability of White Sturgeon being entrained decreased with increasing velocity, and the 1.1-m/s velocity had significantly higher entrainment probabilities than either of the faster treatments (Table 4). In models that examined the impact of light on $\psi_{noent-ent}$, light was included as a covariate in two of the three best models for White Sturgeon—a finding similar to those for the other species. For White Sturgeon, there was no significant difference between tests conducted under light and dark conditions (Table 4).

Survival, Injury, and Descaling Tests

Hybrid Striped Bass.—There was one best model for HSB survival, and it contained all covariates (trial, velocity, and treatment; Table 5). Compared with control fish, treatment HSB had significantly lower values of S at both t_1 (treatment: 0.96 [0.91–0.98]; control: 1.00 [1.00–1.00]) and t_{48} (treatment: 0.91 [0.84–0.95]; control: 1.00 [1.00–1.00]). In fact, treatment HSB subjected to low-velocity conditions had significantly lower S_{t1} estimates than treatment HSB subjected to the high velocity (slow: 0.96 [0.91–0.98]); fast: 1.00 [1.00–1.00]). The relatively low total survival estimated for HSB tested at the 1.5-m/s velocity was primarily due to the large number of delayed mortalities among treatment fish that occurred during one of the three trials. This appears to be an outlier, especially since the turbine passage survival of HSB was much higher at the higher approach velocity. We suspect that the high delayed mortality of treatment fish at the lower velocity was related to increased impingement on the enclosure net

TABLE 4. Model-averaged $\psi_{noent-ent}$ estimates (95% confidence intervals in parentheses) of the probability that a fish released upstream of the turbine would be entrained through it for measured levels of covariates for each species of fish tested in the behavior study. Only models with a $\Delta AIC_c < 2$ were included in the averaged estimates, and model weights were rescaled to 1.00 for calculating the average estimates for each species–covariate pairing.

Model	$\psi_{noent-ent}$ Overall	Light	Dark
Hybrid Striped Bass			
Velocity (m/s)			
1.1	0.59 (0.48–0.68)	0.55 (0.33–0.71)	0.24 (0.14–0.42)
1.5	0.43 (0.40–0.48)		
2.0	0.19 (0.09–0.34)		
Rainbow Trout			
Size			
Large	0.01 (0.01–0.06)	0.01 (0.01–0.03)	0.02 (0.01–0.05)
Small	0.01 (0.01–0.06)	0.02 (0.01–0.06)	0.02 (0.01–0.06)
Velocity (m/s)			
1.1	0.02 (0.01–0.03)		
1.5	0.03 (0.02–0.04)		
2.0	0.06 (0.04–0.08)		
White Sturgeon			
Velocity (m/s)			
1.1	0.23 (0.10–0.41)	0.11 (0.05–0.23)	0.14 (0.07–0.27)
1.5	0.05 (0.03–0.09)		
2.0	<0.01 (<0.01–0.04)		

before the fish passed through the turbine and/or on the downstream barrier screen after turbine passage.

Bruising was the most prevalent injury type in treatment and control HSB (23% of all fish; Table 2), with very few incidences of eye damage or lacerations. The relatively high incidence of bruising in both treatment and control fish likely resulted from impingement on the containment net before turbine passage or on the downstream isolation screen after passage in the trial with uncharacteristically high mortality. Although this higher injury rate may be attributable to impingement at either of these two locations, it is unknown what factors contributed to excessive impingement during the one trial in which many of these injuries were observed.

TABLE 5. Corrected Akaike information criterion values for the best survival models ($\Delta AIC_c < 2$), by species. All of the best models included time-specific survival (S_t) as a parameter.

Model	AIC_c	ΔAIC_c	AIC_c weight
Hybrid Striped Bass			
S_t + trial + velocity + treatment	233.51	0.00	1.00
Rainbow Trout			
S_t + velocity + treatment	235.29	0.00	0.47
S_t + size + treatment	236.52	1.24	0.25
S_t + trial+ velocity + treatment	237.26	1.97	0.18
White Sturgeon			
S_t	35.48	0.00	0.19
S_t + trial	35.48	0.00	0.19
S_t + velocity	35.48	0.00	0.19
S_t + treatment	35.48	0.00	0.19
S_t + trial + treatment	35.94	0.45	0.15
S_t + velocity + treatment	37.21	1.73	0.08

The best injury models for HSB only contained trial, length, and whether a fish was descaled; velocity was not included in these models (Table 6). Model-averaged estimates of the probability of injury indicated that there were no differences between treatment and control at any length (Figure 3), and these did not change based on whether a fish was descaled or not. The probability of injury did, however, increase with fish length (Figure 4). Fish that were descaled had a much higher rate of injury than fish that were not; descaling was associated with a 0.34 (0.27–0.43) probability of visible injury in fish, compared with a 0.15 (0.11–0.20) probability of visible injury in fish with intact scales (Table 7). This high rate of injury reflected the large number of mortalities that occurred during the single trial with uncharacteristically high mortality rates (in which nearly all of the dead fish sustained bruising and/or lacerations).

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TABLE 6. Best models of the probability of injury and descaling from survival experiments.

Model	AIC_c	ΔAIC_c	AIC_c weight
Probability of injury			
Hybrid Striped Bass			
Length + descaled	767.52	0.00	0.64
Trial + length + descaled	768.69	1.17	0.36
Rainbow Trout			
Trial + velocity	2,582.73	0.00	1.0
White Sturgeon			
Trial + velocity	209.22	0.00	0.71
Trial + velocity + length	210.98	1.76	0.29
Probability of descaling			
Hybrid Striped Bass			
Trial + velocity + length + injury	6,596.95	0.00	1.00
Rainbow Trout			
Trial + velocity + length + injury	5,268.06	0.00	1.00

The best model for estimating the probability of descaling in HSB also included all four covariates (Table 6). Both treatment and control fish had high probabilities of descaling and were more likely to be descaled at the lower velocity if they had an additional injury (Table 8). Like the injury rates, the higher descaling at the lower velocity was linked to the one trial with high mortality and injury rates. The probability of being descaled decreased as fish length increased, although there was no difference between treatment and control fish, suggesting that substantial differences in descaling were not caused by turbine passage (Figure 4).

Rainbow Trout.—There were three best survival models for Rainbow Trout; all of these contained treatment as a covariate, two contained velocity, and one each separately contained size and trial (Table 5). With the exception of small Rainbow Trout in the high-velocity treatment, which had a 48-h survival rate of 0.99 (0.97–0.99), no estimates of S_{t1} and S_{t48} differed from 1.00.

As with HSB, bruising was the most prevalent injury type observed for each test group, size-group, and velocity evaluated. Irrespective of species, bruising accounted for 138 of 149 (93%) recorded injuries for control fish and 382 of 398 (96%) for treatment fish (Table 2). The best model examining the probability of being injured only contained trial and velocity as covariates, suggesting that length and whether or not a Rainbow Trout was descaled were not associated with the probability of injury (Table 6; Figure 3). The numbers of Rainbow Trout recovered with visible external injuries were higher overall for treatment fish than for control fish and higher for the higher test velocity for both treatment and control fish.

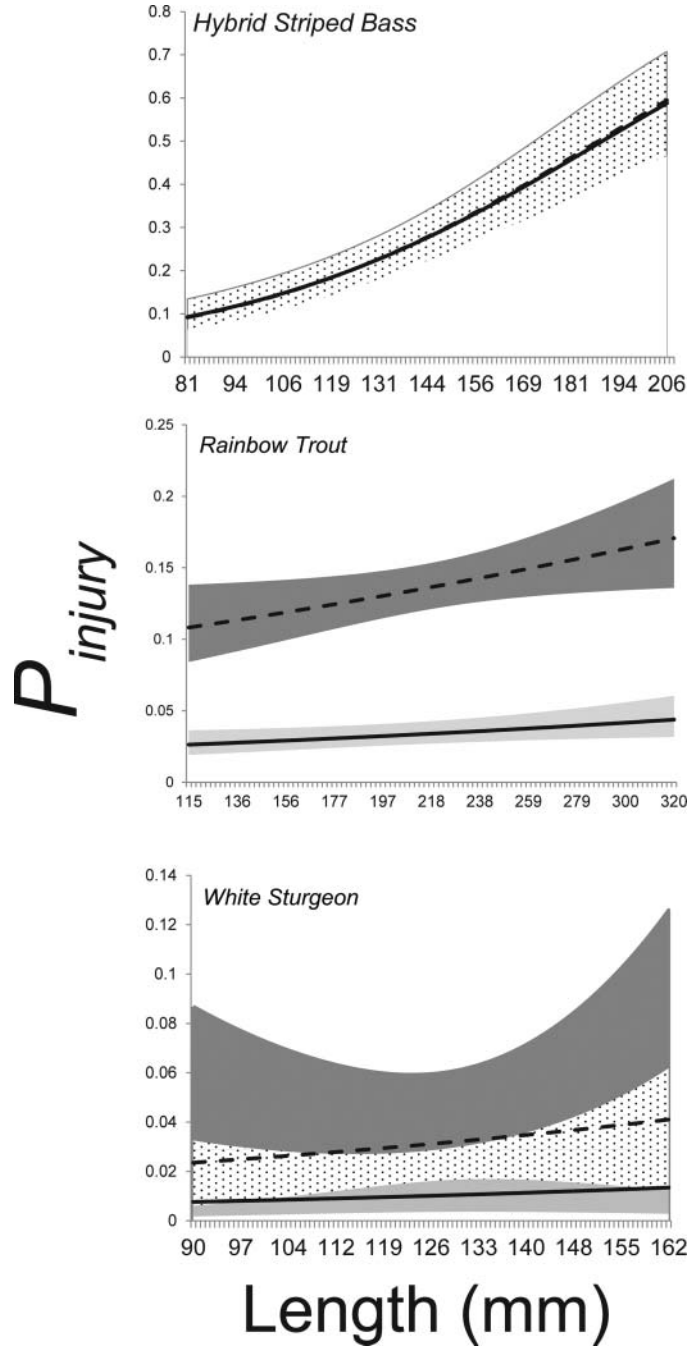

FIGURE 3. Probability of fish injury during the entrainment survival experiment with respect to fish length for control (dashed lines) and treatment (solid lines) hybrid Striped Bass, Rainbow Trout, and White Sturgeon. The shaded areas represent the 95% confidence intervals (control = dark gray, treatment = light gray) about the injury estimates. The stippled areas represent overlap between control and treatment fish, thus indicating no difference between them.

The model describing the probability of being descaled that contained all four covariates was ranked as the single best model by AIC_c value and showed that the probability of being descaled was higher for fish with other visible injuries (Table 8). In brief, this means that while injured fish

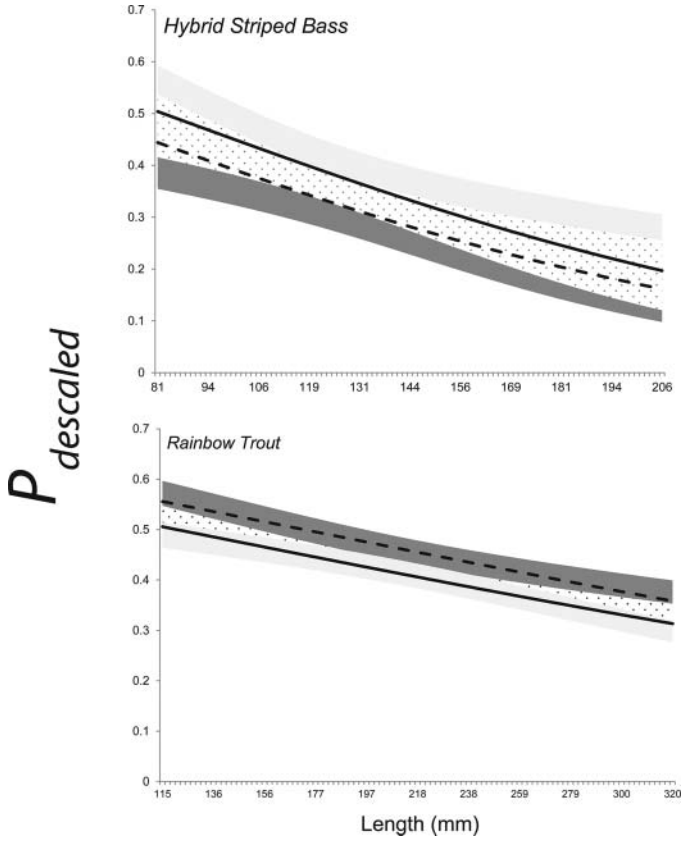

FIGURE 4. Probability of fish being descaled during the entrainment survival experiment with respect to fish length for control and treatment hybrid Striped Bass and Rainbow Trout.

were not more likely to be descaled, descaled fish were more likely to be injured. Also, descaling probabilities were higher for treatment than control fish and for both treatment and control fish at higher velocities. Descaling probability also increased with length for both treatment and control fish (Figure 4).

White Sturgeon.—Model selection procedures identified six best models, one of which was the no-covariate, time-specific S_t model and three of which were single-covariate models, suggesting that covariates were unimportant to model fit for White Sturgeon survival (Table 5). The survival of White Sturgeon in our study did not differ from 1.00 under any test conditions or time period evaluated. There were no statistically significant differences in survival rates between the two test velocities. The immediate and total survival rates of the control and treatment groups were not significantly different at either current velocity.

There were two best models describing White Sturgeon injury, which included trial, velocity, and length were averaged to provide parameter estimates of injury. No descaling occurred in White Sturgeon owing to their lack of true scales, and the only injury recorded was bruising at the higher test velocity (Table 2). Whereas there were virtually no injuries at 1.5 m/s, the probabilities of injury at the higher velocity were 0.04 (0.01–0.14) for control fish and 0.14 (0.06–0.28) for treatment fish (Table 7). However, the wide confidence intervals and resulting low statistical power for the treatment $\psi_{noinj-inj}$ estimates limited our ability to detect significant differences between the treatment and control groups. Injuries increased with length for both treatment and control fish; however, the confidence intervals for these two groups overlapped (Figure 3), indicating no statistical difference in the estimates.

Total Passage Survival, Noninjury, and Nondescaling Probability

All species had a high probability of surviving entrainment and being uninjured following passage through the FFP turbine (Table 9). For instance, the probabilities of surviving entrainment without injury were indistinguishable from 1.00 for both Rainbow Trout and White Sturgeon. As there were no significant differences in descaling probabilities between treatment and control fish, we did not calculate total descaling probabilities. The HSB had the lowest probability of surviving entrainment ($\geq$0.92).

Comparisons among Hydrokinetic Turbine Types

The collective data from all of the HK turbine passage survival evaluations (laboratory and field) demonstrate the effects of certain turbine design and operational features on entrainment mortality (Table 10). The FFP turbine, which has the most blades (seven) and the highest strike velocities at the blade tips, typically had the lowest survival rates, particularly in tests with Rainbow Trout (the low survival of HSB at 1.5 m/s was likely an experimental effect unrelated to turbine passage). Turbine survival was highest for the Welka UPG and Hydro Green units, which had the lowest strike velocities and fewest blades, respectively. Although there is some uncertainty in the strike velocity estimate for the Hydro Green turbine due to the assumptions made about operational parameters in the absence of actual data, high survival rates (0.99) were observed for relatively large fish (Table 10). These likely resulted from blade strike velocities that are low enough not to cause mortality (i.e., less than 5 m/s).

DISCUSSION

Entrainment Probability

Our study suggests that most fish will be able to escape or evade turbine entrainment, even when in close proximity to a turbine. For example, many Rainbow Trout and HSB were able to actively avoid turbine entrainment despite the relatively short distance between the release point and the turbine (1.5 m; Table 4). White Sturgeon also had high turbine

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TABLE 7. Estimates of the probability of an uninjured fish being injured ($\psi_{noinj-inj}$) for control and treatment fish from a multistate mark–recapture model, by species and covariate (95% confidence intervals in parentheses). The covariates included are those from the best models ($\Delta AIC_c < 2$). Model-averaged estimates are reported for species for which there was a set of best models.

Model	$\psi_{noinj-inj}$ Control	Treatment
Hybrid Striped Bass		
Injury		
Intact scales	0.15 (0.11–0.20)	0.15 (0.11–0.20)
Descaled	0.34 (0.27–0.42)	0.34 (0.27–0.43)
Overall	0.20 (0.16–0.26)	0.20 (0.16–0.26)
Rainbow Trout		
Velocity		
1.5	0.03 (0.02–0.04)	0.12 (0.10–0.14)
2.0	0.05 (0.04–0.06)	0.19 (0.17–0.22)
Overall	0.04 (0.03–0.05)	0.15 (0.14–0.17)
White Sturgeon		
Velocity		
1.5	<0.01 (<0.01–0.01)	0.01 (< 0.01–0.03)
2.0	0.04 (0.01–0.14)	0.14 (0.06–0.28)
Overall	0.01 (<0.01–0.02)	0.03 (0.02–0.06)

TABLE 8. Estimates of the probability of a fish being descaled ($\psi_{nodescale-descale}$) for control and treatment fish, by species and covariate (95% confidence intervals in parentheses). The covariates included are those from the best models ($\Delta AIC_c < 2$). Model-averaged estimates are reported for species for which there was a set of best models.

Model	$\psi_{nodescale-descale}$ Control	Treatment
Hybrid Striped Bass		
Velocity (m/s)		
1.5	0.45 (0.35–0.55)	0.39 (0.29–0.49)
2.0	0.32 (0.24–0.42)	0.27 (0.19–0.36)
Injury		
Uninjured	0.32 (0.26–0.38)	0.26 (0.22–0.33)
Injury	0.63 (0.53–0.72)	0.57 (0.47–0.67)
Overall	0.38 (0.33–0.44)	0.33 (0.27–0.39)
Rainbow Trout		
Velocity (m/s)		
1.5	0.45 (0.42–0.48)	0.50 (0.47–0.53)
2.0	0.38 (0.35–0.41)	0.43 (0.40–0.46)
Injury		
Uninjured	0.37 (0.35–0.40)	0.76 (0.71–0.79)
Injured	0.72 (0.67–0.76)	0.42 (0.40–0.44)
Overall	0.41 (0.39–0.43)	0.45 (0.44–0.48)

avoidance rates (similar to those of Rainbow Trout), but avoidance may have been an artifact of their release position in the water column given that they did not appear to use swimming as an active turbine avoidance technique. Rather, they typically drifted upward when entering the flume flow and followed the streamlines accelerating around the FFP turbine duct without apparent directional swimming.

Behavioral tests found that turbine avoidance was similar under light and dark test conditions for all three of the species tested, demonstrating the importance of nonvisual cues in promoting positive rheotaxis in HK turbine avoidance in this study. Although vison generally provides important cues, rheotaxis is a multisensory behavior with mechanisms that vary among species as a function of the combination of the stimuli and ambient conditions (Haro et al. 1997; Bak-Coleman et al. 2013); thus, for the species we tested the acoustic noise and hydrodynamic stimuli produced by HK turbines may play roles in the positive rheotaxis responsible for avoidance, especially under low-visibility conditions. Unfortunately, the DIDSON camera could not be used effectively to observe fish during behavioral tests at 1.5 and 2.0 m/s (due to air entrainment), and we were not able to determine whether the absence of visual cues is an important factor in hindering fish from avoiding turbine entrainment at higher approach velocities.

TABLE 9. Probability of surviving and not being injured for fish in the vicinity of an FFP turbine. These estimates incorporate the probability of survival given entrainment (for the HSB survival estimates) as well as the probability of injury given survival (for the Rainbow Trout and White Sturgeon estimates) for each velocity tested where there was a significant effect of treatment for the species in question.

Species	Velocity	FL (mean ± SE)	$P_{survival}$	$P_{noinjury}$
Hybrid Striped Bass	1.5	133.10 ± 2.68	0.96 (0.92–1.00)	[a]
	2.0	119.59 ± 2.21	1.00 (1.00–1.00)	[a]
Rainbow Trout	1.5	211.68 ± 1.67	1.00 (1.00–1.00)	0.99 (0.99–1.00)
	2.0	208.75 ± 1.40	1.00 (1.00–1.00)	0.99 (0.99–1.00)
White Sturgeon	1.5	125.97 ± 1.70	1.00 (1.00–1.00)	[a]
	2.0	128.38 ± 0.44	1.00 (1.00–1.00)	0.99 (0.99–1.00)

[a]As there was no difference between treatment and control, the effect of turbine entrainment on P_{injury} was assumed to be negligible.

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TABLE 10. Summary of turbine design and survival data for fish passed through five different hydrokinetic turbines during laboratory and field tests. Tip strike speeds were estimated based on actual parameters for the FFP (this study), Welka UPG (EPRI 2011b), Hydro Green (NAI 2009), Lucid Spherical (EPRI 2011b), and EnCurrent (Castro-Santos and Haro 2015) turbines. Species abbreviations are as follows: hybrid Striped Bass (HSB), Largemouth Bass *Micropterus salmoides* (LMB), Yellow Perch *Perca flavescens* (YLP), Bluegill *Lepomis macrochirus* (BLG), Channel Catfish *Ictalurus punctatus* (CCF), Smallmouth Buffalo *Ictiobus bubalus* (SBF), Bigmouth Buffalo *Ictiobus cyprinellus* (BBF), Atlantic Salmon *Salmo salar* (smolts only; ATS), and American Shad *Alosa sapidissima* (AMS).

Turbine	Design	Number of blades	Blade leading edge thickness (mm)	Rotor diameter (m)	Rotational speed (rpm)	Tip speed (m/s)	Tip strike speed (m/s)	Species	Fish length (mean or range; mm)	Total turbine passage survival probability
FFP	Ducted axial flow	7	15.2	1.5	64–84	5.1–6.7	5.3–7.0	Rainbow Trout	170	0.99–1.00
								Rainbow Trout	258	0.98–1.00
								White Sturgeon	125	1.00
								HSB	125	0.91–1.00
Welka UPG	Ducted axial flow	4	12.7	1.5	15–35	1.2–2.8	1.9–3.4	Rainbow Trout	125	1.00
								Rainbow Trout	239	0.99–1.00
								LMB	125	0.99–1.00
								LMB	242	0.99–1.00
Hydro Green	Ducted axial flow	3		3.7	21	4.0	4.7	YLP	118–235	0.99
								BLG	115–208	0.99
								CCF	451–627	0.99
								SBF	388–482	0.98
								BBF	415–710	0.99
Lucid Spherical	Cross flow	4	19.1	1.1	64–83	3.8–5.0	4.1–5.4	Rainbow Trout	150	0.99–1.00
								Rainbow Trout	256	0.99–1.00
EnCurrent	Vertical axis, cross flow	4		1.5	60			ATS	183	0.98[a]
								AMS	411	0.88[a]

[a]Not significantly different from control.

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Survival and Injury

The results of our study suggest that water velocity and fish length are important in determining whether fish become injured during or survive turbine entrainment (Tables 3, 5, 6), but because there was no significant difference between the treatment and control groups, it is not clear whether injury rates increased as a result of turbine passage (Figure 3). Still, some mortality did occur in both size-groups of Rainbow Trout at the higher velocity and velocity was included in the best subset of models (Tables 5, 6), suggesting that injury and mortality were velocity dependent in our study.

In our study, fish injuries increased with velocity, although there was no difference between the survival rates of the two size-groups of Rainbow Trout at either test velocity. The probability of injury increased with length for all three species, but only Rainbow Trout showed a significant difference between treatment and control groups. While we found no significant relationships between length and the probabilities of blade strike injury and mortality, these relationships may not have been detectable within the narrow range of fish lengths that we tested. Also, although the test flume water velocities of 1.5 and 2.0 m/s are within the range within which the FFP turbine is designed to operate (1.0–3.0 m/s), it is possible that higher fish passage mortalities would have been observed if we had been able to conduct tests at the highest FFP operating velocity.

Prior modeling studies of HK turbines have reported a positive relationship between fish length and the incidence of blade strike injury, similar to the relationship found for conventional hydropower turbines (Hecker and Allen 2005). For instance, Romero-Gomez and Richmond (2014) used a particle-tracking model to estimate the probability of blade strike injury as a function of length for a hypothetical, nonducted, 2.44-m-blade-height HK turbine. Their results suggest that greater fish lengths were associated with higher probabilities of blade strike and associated mortality (although they reported lower probabilities of strikes with increasing water velocity). There were differences in mortality and injury rates between the present study and Romero-Gomez and Richmond (2014), but differences in turbine design between the two studies (ducted in the present study versus nonducted in Romero-Gomez and Richmond 2014) preclude direct comparisons of the estimates. Moreover, the Romero-Gomez and Richmond (2014) study does not rely on empirical demonstration of the strike-to-fish-length relationship for HK turbines, so we urge caution in comparing their estimates with ours. Strike mortality has been shown to increase with the ratio of fish length to blade thickness with conventional hydropower turbines (i.e., for a given blade thickness, larger fish will have a higher probability of mortality) when strike speeds are sufficiently high to cause lethal injuries (Amaral et al. 2008; EPRI 2008, 2011c). Because the velocity vectors and hydrodynamic relationships between inflowing water and rotor blades are similar for conventional and HK turbines, we would expect a similar relationship between fish length and strike probability and mortality to hold true for HK turbines. Because validation of predictions is an essential component of robust science, testing the effects of HK turbines on a much wider range of fish lengths is a necessary next step in more fully understanding the potential impacts of these turbines on fish populations and communities.

Comparison of HK Turbine Types

The results of our study, in combination with those of past studies, suggest that fish are infrequently entrained through HK turbines and that those that are entrained pass with low incidence of injury. For example, video monitoring has indicated that benthic reef fish were able to avoid a vertical-axis, cross-flow HK turbine even when in close proximity to it (Hammar et al. 2013). In fact, no turbine blade collisions were observed by Hammar et al. (2013).

Taken together, the survival data collected during our study and prior studies indicate that the probability of survival for fish passing through a variety of HK turbine designs will be high (approaching or indistinguishable from 1.00 in many cases; Table 10) but that certain design features (e.g., the number of blades, rotational speed, and blade leading-edge thickness) can lead to slightly lower survival if they cause increases in blade strike and/or mortality from a strike. Prior flume studies have shown that fish length can influence survival rates if blade strike velocities (i.e., the speed of the turbine's blade tip) exceed 5 m/s. Even for the FFP turbine, which had a large number of blades and strike velocities at the blade tips greater than 5 m/s at the highest approach velocity tested, the estimated turbine survival probability was not distinguishable from 1.00 for the larger Rainbow Trout (mean length, 258 mm).

The turbine passage survival estimates reported for HK turbines are higher than those typically reported in field evaluations of conventional hydropower turbines (e.g., radial-flow Francis turbines and axial-flow Kaplan and other propeller-type turbines; Franke et al. 1997; EPRI 1997). We attribute the higher survival rates for HK turbines to their slower rotational speeds and strike velocities, which should lead to lower strike probabilities and mortality rates. The potential for entrained fish to be injured or killed by high shear stresses, severe turbulence, or rapid changes from high to very low pressure will be considerably less for HK turbines as well (EPRI 2011b).

CONCLUSIONS

Many of the fish in our study were able to avoid HK turbine entrainment despite features of the testing facility that may have inflated entrainment rates, such as smaller areas of safe passage around the turbine than would be the case in situ and hydrodynamic flow patterns and turbulence resulting from constrained spaces near the flume walls. On the other hand,

the water velocities and blade speeds in the laboratory studies were less than those that would occur under actual deployment. A number of investigators have cautioned that migratory fish passing through an entire HK power project with large numbers of closely spaced turbines may not be able to completely avoid turbine interactions (Wilson et al. 2007; Schweizer et al. 2011; Hammar et al. 2013). Further investigations examining entrainment avoidance by more species and lengths of fish as well as the probability of escaping entrainment and subsequent injury and mortality in an array of HK turbines are warranted to more fully understand the potential impacts of these turbines on riverine and tidal fishes.

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