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OAK RIDGE NATIONAL LABORATORY
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Environmental Sciences Division

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ABSTRACT

Even dams lacking passage structures are passable by fish in a downstream direction and this passage may be important to population dynamics in fragmented rivers. However, in the case of hydropower dams, one-way connectivity provided via downstream turbine passage can introduce a new and significant source of mortality. Fish may be injured or killed during turbine passage owing to forces such as blade strike, shear and/ or turbulence, cavitation, and rapid pressure decreases. Determining contributions of individual forces is important for designing more environmentally friendly turbines and mitigations that minimize the effects of hydropower on fish populations. In this study, we use existing data from studies of fish turbine passage injury and survival to provide insight into what dam/ turbine characteristics and injuries are related to fish survival. Most turbine passage included in our analyses were salmonid species, so while our analyses are statistically robust, they are taxa-biased. Like previous studies, we found that Francis turbines, the most commonly deployed hydropower turbine in the US, have the lowest associated fish survival of any turbine type. We also found that injuries, relationships between injury and survival and factors affecting survival varied by turbine type. We conclude that analyses based on individual fish data is a needed next step to test hypotheses generated in this study.

1. INTRODUCTION

Hydropower dams are associated with declines of fish populations caused by blocked migration routes, habitat loss, changes in hydrological regimes, and mortality associated with turbine passage (Pracheil et al. 2016). In the United States, the Federal Energy Regulatory Commission (FERC) issues licenses to non-federal hydropower dams that require facilities to meet certain environmental requirements and in some cases, mitigate environmental losses resulting from construction and operation of the facility. Mitigations aimed at reducing hydrologic changes such as minimum and maximum flow requirements, are the most common FERC-ordered environmental mitigation (Figure 1a) although fish passage is probably the most iconic. Of the five most common non-social/ cultural categories of FERC mitigation per Schramm et al. (2016), fish passage is the third most commonly ordered mitigation after hydrologic and aquatic biodiversity mitigations (Figure 1a).

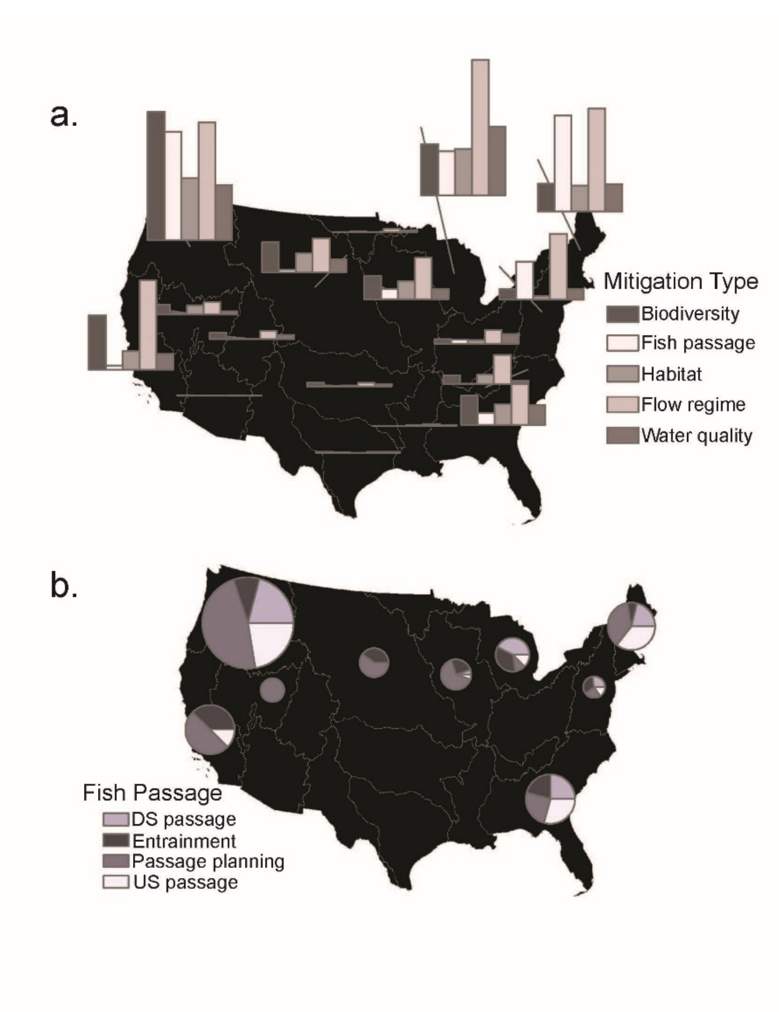

Figure 1. Frequency and location of mitigation types (upper map) and types of fish passage mitigations (lower map) ordered on Federal Energy Regulatory Commission (FERC) hydropower project licenses. Size of bar graphs and pie charts are relative to the number of FERC licenses ordering those mitigations in a United States Geologic Survey hydrologic region.

Interestingly, downstream fish passage at hydropower dams receives the bulk of passage-related regulatory attention (Figure 1b; Table 1) although upstream passage is more conspicuous to the public. For example, in all regions of the contiguous USA from 1997-2013, mitigations directed at constructing, monitoring or planning downstream passage and entrainment (N=354; totals of Downstream Fish Passage + Entrainment + First three rows of Passage Planning category) are ordered in FERC licensing agreements more frequently than upstream passage (Table 1). The focus of mitigation requirements on downstream passage is somewhat unsurprising, however, for two primary reasons. One reason is that downstream passage results in direct injury and mortality of fishes through blade strike, pressure, and shear forces that fish encounter during unmitigated passage through turbines (Schilt 2007; Pracheil et al. 2016). Upstream passage, in comparison, results in species declines indirectly through blocked and delayed spawning migrations and changes in downstream geomorphology/ habitat inherent in dam construction (Hall et al. 2011; Reidy-Liermann et al. 2012). A second reason that there is a regulatory focus on downstream passage mitigations is that downstream fish passage mitigations are often focused on preventing fish injury and increasing fish survival through entrainment reduction via bars, nets, screens, plates or even lights that prevent or deter fish from passing through turbines—a cost-effective alternative to constructing a large bypass facility. This cost-efficacy is demonstrated in frequency of downstream passage/ entrainment mitigations: of the 354 downstream fish passage mitigations, there are only 27 instances of newly constructed mitigation devices being ordered (i.e., bypass facility, conduit, fish friendly turbine, sluiceway, surface collector; Table 1).

Also noteworthy is that downstream passage mitigations vary by region potentially due to species-specific vulnerability to downstream passage. Factors related to survival and injury of downstream passage in fish leading to mitigations have been described by several authors (*sensu* Coutant and Whitney 2000; Cada 2001; Schilt 2007; Brown et al. 2014; Pracheil et al. 2016), although explicit relationships between injury and survival during turbine passage have only been explored for a small number of species, mostly salmonids. Furthermore, while we do have some understanding of broad-scale dam and turbine characteristics related to fish injury or survival, increases in sample sizes and species are needed to improve this understanding. In this study, we use a database of fish turbine passage injury and survival to explore relationships between physical characteristics (e.g., dam head, turbine type) and fish injury or survival to improve our understanding of effects of downstream turbine passage on fishes for an expanded number of species.

Table 1. Upstream and downstream fish passage mitigations listed on Federal Energy Regulatory Commission hydropower licenses issued from 1998-2013 by United States Geological Survey hydrologic regions. Please note that these are mitigations that were ordered on FERC licenses and are not necessarily mitigations that were installed. Hydrologic regions are identified by 2-digit number and correspond with regions shown in Figure 4. All hydrologic regions from 1-18 were surveyed and hydrologic regions without relevant mitigations were excluded from this table.

Mitigation Type	01	02	03	04	05	06	07	09	10	11	12	16	17	18	Total
Downstream Fish Passage	41	21	6	38	2		1						46		155
Bypass facility	3	2	3										2		10
Conduit		6													6
Downstream passage plan study design	29	5	3	18	2								14		71
Fish friendly turbine													1		1
Flashboard removal or modification													1		1
Generation shut down	6	2		2											10
Spill or gate operation modification	2	1		5			1						7		16
Modify bypass facility													1		1
Modify intake													1		1
Modify sluiceway		3		5											8
Modify spill or gate design	1	1		8									3		13
Sluiceway		1											1		2
Surface collector													8		8
Trap and transport													7		7
Entrainment	13	25	5	31	2	1	5		2	1	1		20	3	109
Barrier or guidance net		1					2		1				4		8
Fish screen		1	2				1						9	3	16
Gatewell exclusion screen													2		2
Perforated plate	1														1
Solid panel and bar rack		2													2
Strobe light													1		1
															79
Trash or bar rack	12	21	3	31	2	1	2		1	1	1		4		

Table 1. Continued

Passage Planning	**71**	**19**	**6**	**9**	**4**		**13**		**3**			**3**	**104**	**4**	**236**
Design entrainment avoidance system				**6**			**1**							**1**	**8**
Downstream fish passage monitoring	**28**	**10**	**3**				**1**						**23**		**65**
Entrainment mortality monitoring							**2**		**3**				**11**	**1**	**17**
Fish passage and operations plan	**11**	**3**			**2**		**1**						**17**		**34**
Fish passage feasibility assessment	**3**						**1**						**9**	**1**	**14**
Fish stranding plan monitoring evaluation	**5**	**3**		**2**	**2**		**6**					**3**	**12**	**1**	**34**
Fisheries disease management													**3**		**3**
Hatchery operations and management													**9**		**9**
Upstream fish passage monitoring sampling	**24**	**3**	**3**	**1**			**1**						**20**		**52**
Upstream Fish Passage	**69**	**12**	**7**	**11**			**1**	**1**					**49**	**1**	**151**
Adult fishway				**1**									**1**		**2**
Conduit		**1**													**1**
Eelway	**21**	**5**	**2**	**4**											**32**
Fish ladder	**6**	**1**	**1**										**6**		**14**
Lock or elevator	**10**												**1**		**11**
Modify adult fishway													**1**		**1**
Modify fish ladder	**1**												**2**		**3**
Modify lock or lift	**1**														**1**
Modify spill or gate operation							**1**								**1**
Modify trap and transport													**3**		**3**
Tailrace exclusion device	**2**	**1**						**1**					**3**		**7**
Trap and transport	**4**		**2**										**14**		**20**
Upstream passage study plan design	**24**	**4**	**2**	**6**									**18**	**1**	**55**
Total passage mitigations	**194**	**77**	**24**	**89**	**8**	**1**	**20**	**1**	**5**	**1**	**1**	**3**	**219**	**8**	**651**

2. METHODS

2.1 DATA

We used a database of fish turbine passage studies maintained by Normandeau and Associates, Inc. environmental consultants. This database contained information on turbine test conditions (e.g., turbine runner velocity, discharge, dam head) and dominant fish injuries or survival outcomes following turbine passage collected from 1990-2015 during 74 studies conducted at hydropower plants in the U.S. (62 studies at 59 projects), Canada (2 projects), France (3 projects), Ireland (3 projects), Russia (1 project) and U.K. (3 projects; Figure 2). While there were many turbine types included in tests listed in this database, we focused on Kaplan (N=203 turbine test conditions) and Francis (N=30 turbine test conditions) for analyses due to limited sample sizes for other turbine types.

A total of 20 fish species (not including varieties of a species) were included in studies in this database (N=number of turbine test conditions): American Eel (Anguilla rostrata, N=3), European Eel (Anguilla anguilla, N=8), Lake Sturgeon (Acipenser fulvescens, N=2), American Shad (Alosa sapidissima, N=12), Blueback Herring (Alosa aestivalis, N=3), Atlantic Salmon (Salmo salar, N=23), Chinook Salmon (Oncorhynchus tshawytscha, N=99), Coho Salmon (Oncorhynchus kisutch, N=12), four varieties of Rainbow Trout: wild-type (N=10), Steelhead (N=13), Triploid Rainbow Trout (N=10), and Triploid Steelhead (Oncorhynchus mykiss, N=1), Lake Whitefish (Coregonus clupeaformis, N=10), Northern Pike (Esox lucius, N=5), White Sucker (Catostomus commersoni, N=2), Channel Catfish (Ictalurus punctatus, N=5), Centrarchid Bass (Micropterus spp., N=6), Bluegill (Lepomis macrochirus, N=7), Redbreast Sunfish (Lepomis auritus, N=1), and Walleye (Sander vitreus, N=9).

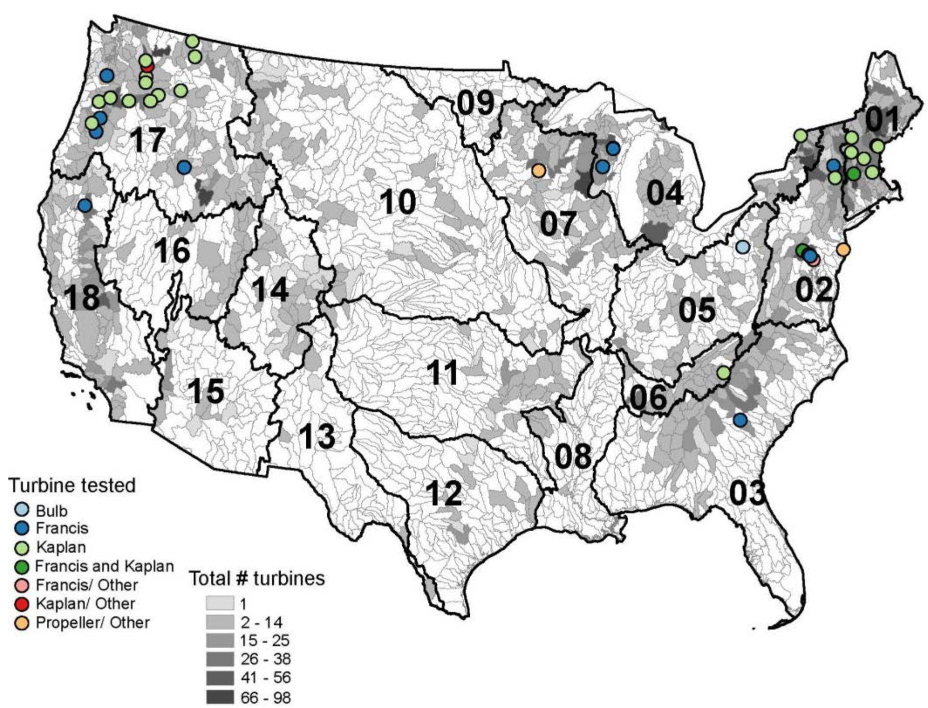

Figure 2. Map showing locations of U.S. turbine testing studies by turbine type and number of turbines found in each watershed (United States Geologic Survey 8-digit hydrologic unit). Hydrologic units (2-digit USGS hydrologic units) are outlined in bold black lines with the corresponding region number shown.

All fish tested and included in this database were fitted with HI-Z balloon tags (Heisey et al. 1992; Figure 3) that were activated just before fish were released into the turbine so that balloons would inflate and float fish to the water's surface approximately 3-5 minutes later when entrained fish could be recaptured and evaluated for injury/ survival (Figure 3) using evaluation points provided in Appendix A. These studies were designed to measure the direct effects of turbine entrainment, that is, injury, survival (both 1-hr and 48-hr) and/or change of behavior due to conditions encountered in the turbine environment. Data from this database were at the population-level for a turbine test condition. For example, if 100 American Shad were included in a turbine passage study, 95 of which survived and 5 of which died within 1-hr of passage, this study was reported in the database as having 95% survival without individual-level data reported. As such, our analyses only include this turbine test condition population–level data.

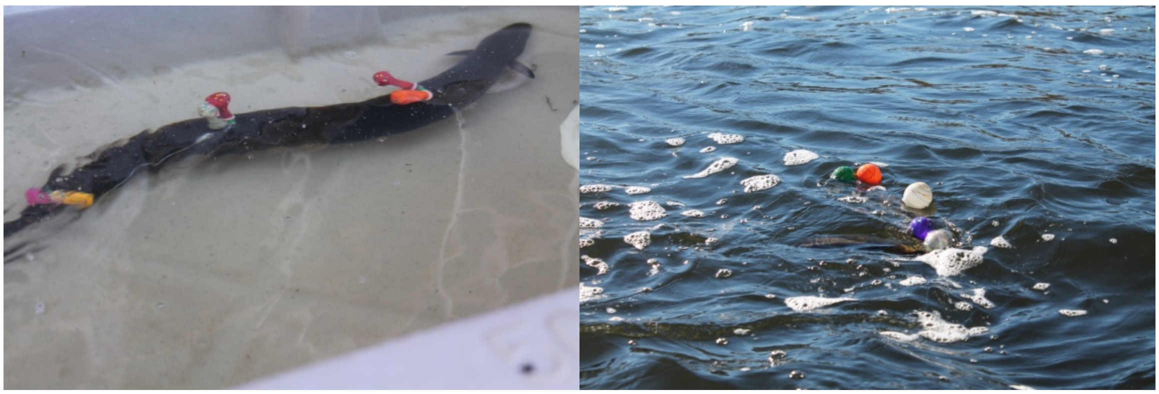

Figure 3. American eel fitted with HI-Z balloon tags. The left panel shows an eel with deflated balloon tags prior to release into the turbine and the right panel shows an eel that is about to be retrieved after turbine passage with inflated balloon tags.

2.1.1 DATA ANALYSIS

We summarized injury data by turbine type and 1-hr survival data by fish species and turbine type. Injury was considered in two ways: injury prevalence, which was the percentage of turbine-passed fish in a study that were injured minus the percentage of control fish in a study that were injured, and percentage of studies for which a particular injury was noted as the dominant injury type. We reported mean species survival± SE weighted by study sample size for each turbine type.

We used all-subsets selection to generate logistic regression models that examined the roles of dam/ turbine and injuries (Table 2) on unweighted 1-hr survival for Kaplan and Francis turbines (R-base package) irrespective of fish species. Due to occurrence of computational errors during model runs, injury types that were not reported for a turbine were necessarily excluded from the full-model. We conducted model selection using Akaike's Information Criteria (AIC) and we tallied the number of times each variable was included in the best 1 to n_v-1 variables model where n_v was the number of variables in the full model. Full models were first examined for multicollinearity using variance inflation factor (VIF) where a VIF >10 for a variable indicated a significant multicollinearity (Pracheil et al. 2009). We then calculated the ΔAIC between each of the n-variable best models and the best model (i.e., model with the lowest AIC value).

Table 2. Dam characteristic and injury variables included in general linear models with survival (dam and injury variables) or overall injury prevalence (dam variables only).

Variables	Kaplan	Francis
Dam		
Discharge	X	X
Number of blades	X	X
Head	X	X
Runner diameter	X	X
Runner speed	X	X
Injury		
Abrasion	X	
Broken bones		X
Bruise	X	X
Decapitation	X	X
Exopthalmia	X	
Eye injury	X	X
Gill injury	X	X
Hemorrhage	X	
Internal injury	X	
Laceration	X	X
Major scale loss		X
Multiple minor injuries	X	

3. RESULTS

Turbine Comparison - Irrespective of fish species, Francis turbines had lower survival rates than Kaplan turbines; Francis turbines had 1-hr survival rates of 0.82 and Kaplan turbines had 1-hr survival rates of 0.92. Francis turbines generally had higher prevalence of studies with injuries than Kaplan turbines, although Kaplan turbines had a higher prevalence of studies with decapitation than Francis turbines—36% of studies for Kaplan turbines versus 14% of studies for Francis turbines (Table 3).

Table 3. Prevalence of dominant injury types of turbine passed fish among turbine tests by turbine type irrespective of fish species or test conditions. Injury prevalence of control fish was subtracted from reported values.

Injury	Kaplan	Francis
Abrasion	<0.01	0
Amputation	<0.01	0
Broken bones	0	0.02
Bruise	0.06	0.16
Decapitation	0.36	0.14
Exopthalmia	0.01	0
Eye bleed	0.02	0.09
Eye injury	0.08	0
Gill bleed	0.03	0
Gill injury	0.04	0.12
Hemorrhage	0.01	0
Internal injury	0.03	0
Laceration	0.11	0.07
Major scale loss	0	0.05
Multiple minor injuries	0.03	0

Species Comparison - Salmonids including Chinook Salmon, Rainbow Trout, Atlantic Salmon, Coho Salmon, Steelhead, Lake Whitefish, and Triploid Rainbow were the most commonly studied fish species by an order of magnitude (N=213; Figure 4). Irrespective of turbine type, several fish species had weighted mean survival ≥95% in at least one turbine including Blueback Herring, Bluegill, White Sucker, Chinook Salmon and Coho Salmon (Table 4). Also irrespective of turbine type, three species had weighted mean survival ≤70% including Chinook Salmon and Rainbow Trout. In general, Francis turbines had lower survival rates than Kaplan turbines for many species such as Chinook Salmon (62% survival in Francis vs. 96% survival in Kaplan), although this was not true for Steelhead (92% survival in Francis vs. 84% survival in Kaplan).

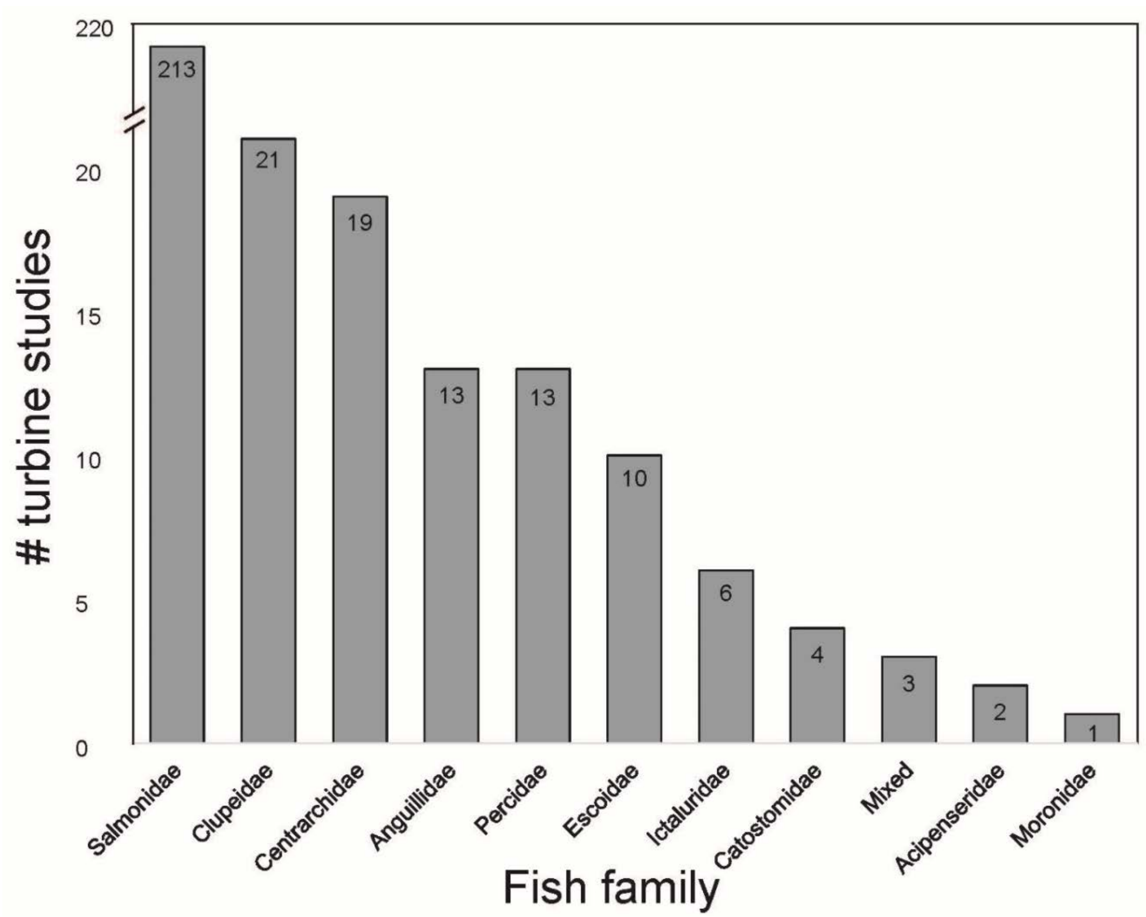

Figure 4. Number of sets of turbine test conditions in dataset focusing on fish families. Please note that left y-axis is only for Salmonidae and that its maximum value is an order of magnitude higher than that of the right y-axis. The number of studies is also shown on each bar.

Table 4. Sample size-weighted means for 1-hr fish survival of after experimental turbine passage studies by fish species and turbine type. Weighted standard error was calculated for all species, but was <0.01 in all cases and was, therefore, not reported. Fish in these studies were fitted with HI-Z balloon tags to allow for recovery. The "N turbine tests" column denotes the number of test conditions for each species. An individual test condition includes both differences in test conditions (e.g., different release depths, different turbine discharges) and differences in hydropower facilities.

Turbine type	Species	N turbine tests	Survival
Francis			
	American shad	7	0.89
	Atlantic salmon	4	0.92
	Blueback herring	2	0.95
	Bluegill	3	0.96
	Channel catfish	4	0.90
	Chinook salmon	4	0.62
	Coho salmon	2	0.92
	Lake sturgeon	2	0.92
	Micropterus spp. bass	6	0.88
	Rainbow trout	6	0.55
	Steelhead	2	0.92
	White sucker	2	0.97
Kaplan			
	American eel	3	0.85
	American shad	2	0.89
	Atlantic salmon	13	0.92
	Chinook salmon	121	0.96
	Coho salmon	10	0.96
	European eel	8	0.87
	Lake whitefish	4	0.92
	Northern pike	5	0.81
	Rainbow trout	3	0.56
	Steelhead	11	0.84
	Triploid Rainbow trout	10	0.79
	Walleye	9	0.83

Model Results - Regression models show differences in dam/ turbine factors related to fish survival outcomes between turbine types. The best model (i.e., model with lowest AIC) for both Kaplan and Francis turbines contained one variable—runner speed, both of which were different from the full model for each turbine type which contained five variables (Table 5). Other variables varied in importance with respect to turbine type: in models with ΔAIC <2 (the threshold at which models are considered equivalent, Burnham and Anderson 2004) Kaplan turbine models also included number of blades and Francis turbine models included runner diameter. Interestingly, Francis models other than the full model, did not suggest that number of blades was relatively an important dam/ turbine predictor of fish survival even though it is common among blade strike probability models.

Full models using dominant injury presence in a turbine test to predict population 1-hr survival for Kaplan turbines contained 10 injury variables and that for Francis turbines contained 6 injury variables (Table 5). Both Kaplan and Francis turbines showed presence of decapitation in a turbine test condition to be an important predictor of population survival probabilities. However, there were many differences in the injuries that predicted survival between turbine types. In Kaplan turbines, presence of lacerations, decapitation, and multiple minor injuries were the best predictors of population survival whereas in Francis turbines, broken bones, decapitation, and gill injury were the best predictors of population survival. In fact, some injury variables in models with ΔAIC <2 in one turbine type were reported only from the full model in the other turbine type. Multiple minor injuries were in the largest number of Kaplan turbine models but these were not reported from Francis turbines. Similarly, gill injuries were found to be a key predictor of survival in Francis turbines, but were not in Kaplan turbines, even though this injury type was reported in several turbine test conditions.

Table 5. All variables used in the full model and candidates for best subsets logistic regressions relating dam/ turbine or fish injuries to 1-hr survival for Kaplan and Francis turbines. For both turbine types, the number of times each variable appeared in the best subset of models (not including the full model containing all variables) is given in the Kaplan and Francis columns along with the ΔAIC for the best model in which a variable was contained and the overall best model (i.e., the model with lowest AIC value). Injury rows where there is no information indicates that was not a major injury observed for that turbine.

Model	Variable	Kaplan	$\Delta AIC_{bestKap}$	Francis	$\Delta AIC_{bestFra}$
Dam/ Turbine					
	Discharge	0	7.11	2	3.17
	# blades	3	0.86	0	6.92
	Head	2	2.16	1	5.08
	Runner diameter	1	5.06	3	1.88
	Runner speed	4	0	4	0
Injury					
	Abrasion	0	17.59		
	Broken bones			4	2.01
	Bruise	6	5.59	3	4.02
	Decapitation	8	1.56	5	0
	Exopthalmia	5	7.59		
	Eye injury	3	11.59		10.03
	Gill injury	4	9.59	5	0
	Hemorrhage	2	13.59		
	Internal injury	1	15.59		
	Laceration	2	0.58	1	8.03
	Major scale loss			2	6.02
	Multiple minor injuries	9	0		

4. DISCUSSION

The meta-analysis like approach taken with this database provides for robust conclusions due to the large number of fish that have been used in generating a single data point; in many cases, several hundred fish were used to create one data point. For example, the number of fish used in each test-condition ranged from 10-820 with a mean ± SD of 161 ± 132. As well, while this population-level survival information cannot provide dose-response information, it is important for generating specific hypotheses to test field and laboratory studies. The bulk of the data points from most of the species in this database are salmonids, so while conclusions are robust given the data used, interpretations of these data should be made with the knowledge that a majority of the points come from one family of fishes.

We were surprised that number of blades was not included in the top models relating dam/ turbine characteristics to 1-hr survival for Kaplan turbines. This was particularly surprising because fish blade strike probability models generally contain the number of turbine blades as a variable where the probability of blade strike and, hence, probability of injury and mortality, increase with the number of blades for both Kaplan and Francis turbines (Von Raben 1957; Deng et al. 2007; Ferguson et al. 2008). The nature of these data may partially explain our finding here. One data limitation we have is that on an individual study basis (i.e., a set of turbine test conditions at a hydropower plant), specific injuries were not reported as prevalence but as presence of dominant injuries only. It is possible that having data recorded in this way limits the sensitivity of models to detect trends and patterns with the injury data, although when looking at prevalence among all studies by turbine type, we find the prevalence of injuries generally higher for Francis than for Kaplan turbines. We will further explore these relationships with individual fish injury and survival data. Due to field-study limitations, our data also did not use depth-acclimated fish. Previous studies have found that fish that have not been depth-acclimated may have higher survival rates than depth-acclimated fish (Brown et al. 2009).

We did not expect to find different relationships between injuries and survival between turbines. That is, we expected the same injury to result in the same level of mortality regardless of how it was caused. This finding suggests that either the population-level data summary does not lend itself to this type of interpretation or that injuries may need to be interpreted differently depending on the turbine type, which seems possible considering different turbines produce different physical forces. Specifically, our finding that presence of gill injury in a study was one of the key predictors of survival for Francis but not for Kaplan turbines was interesting. A recent lab study on the effects of simulated turbine blade strike on fish injury and mortality also showed gill injury to be one of the most important predictors of mortality (Bevelhimer et al in review). However, that study used individual data which may have provided for greater sensitivity of the model to detect links between injury and survival. Moreover, it may be that gill injury was found to be a key predictor of survival outcomes in Francis but not in Kaplan turbines because Francis turbines are linked to lower survival rates than Kaplan turbines (this study; Pracheil et al. 2016). Similarly, turbine operating conditions have also been shown to affect injury and mortality rates (Mathur et al. 2000; Čada 2001).

As we gather more detailed study data, future analyses will include analyses of the relationships among turbine operating conditions, injury rates, and survival with individual fish turbine test data. Even though our initial modelling efforts in this study did not include turbine discharge in the top models (i.e., ΔAIC <2) for either Kaplan or Francis turbines, we believe that with individual fish data we will be able to better evaluate the effects of turbine discharge and other operational and turbine characteristics.

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6. APPENDIX A. LIST OF FISH INJURIES ASSESSED IN TURBINE-PASSAGE STUDIES

Table A-1. Injuries assigned to turbine-passed fish from NAI (2000). This list of injuries was used to create the list of dominant injuries.

No visible marks on fish
Flesh tear at tag site(s)
Minor scale loss, 3 to 20%
Major scale loss, >20%
Laceration(s); tear(s) on body
Severed body parts
Hemorrhaging, bruised
Stressed (lethargic, swimming poorly or sporadically)
Spasmodic movement of body
Very weak, barely gilling, died within 60 minutes of recovery
Fish likely preyed on based on telemetry, and/or circumstances relative to Turb'N recapture
Substantial bleeding at tag site
Bulging or missing eye(s)
Observed predator attack or marks indicative of predator
Other information
Necropsied, no obvious injuries
Necropsied, internal injuries observed
Trapped inside tunnel/gate well
Fins damaged (ripped, split, torn) or pulled from origin
Abrasion/scrape
No recovery information at all; fish remains unrecovered
Radio telemetry or other information; fish remains unrecovered
Swim bladder ruptured or expanded
Kidneys damaged (hemorrhaging)
Broken bones obvious
Hemorrhaging internally
Organ displacement
Heart damage, ruptured, hemorrhaging, etc.
Liver damage, ruptured, hemorrhaging, etc.