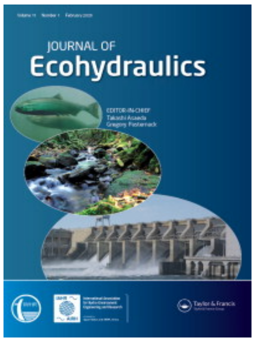

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Comparison of juvenile white sturgeon blade strike survival through a conventional and a novel hydropower turbine

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ABSTRACT

Hydropower is a globally important renewable energy source with profound impacts on aquatic organisms, including direct injury and mortality to fish that move through hydropower facilities. While it is expected that the characteristics of turbine design and operation influence the type, frequency, and magnitude of injuries suffered by entrained fish, few direct comparisons exist to illustrate differences in fish survival outcomes for conventional and novel turbine designs. This study evaluated blade strike-associated injury and mortality rates for juvenile white sturgeon (*Acipenser transmontanus*) passed through a model-scale turbine equipped with a runner having conventional blade profiles (thin, straight leading edges) and the same turbine equipped with a runner designed for improved fish survival (thick, slanted leading edges). In both trials, head and turbine runner rotational speeds were matched to produce five blade peripheral speeds between 15.0 and 27.6 m/s. High-speed video was captured for all turbine passage events. Fish were assessed for injuries following passage, and mortalities were assessed immediately after passage and after 48 h. Conventional runner passage resulted in 42% to 78% survival after 48 h, with approximately one-third of all tested fish killed by severing. Under the same test conditions, immediate and 48 h survival rates through the novel runner were 100% except at the highest speed condition (95.6% survival at 48 h). These results clearly indicate that turbine design has a profound effect on fish survival, and suggest that thoughtful redesign of hydropower equipment could significantly ameliorate the risks of blade strike mortality.

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Fish passage; downstream passage; innovative hydropower; renewable energy; restoration hydro turbine; river connectivity; turbine passage

1. Introduction

Hydropower is the largest source of renewable energy globally and is expected to play a vital role in the transition to net-zero carbon emissions (Bilgili et al. 2018; IEA 2021). Hydropower offers substantial environmental benefits, such as low CO_2 emissions and flexibility to balance intermittent renewables, yet it also presents challenges due to its impact on river structures, flow patterns, and habitat connectivity (Liermann et al. 2012). Turbine passage represents a persistent point-source of fish mortality which can effectively fragment populations and erode population numbers. These impacts may be most prominent on long-lived, migratory fish species such as sturgeons where the risks associated with passage can compound *via* repeated interactions over time (Zhang et al. 2023).

Acipenseriformes (sturgeons and paddlefishes) are an order of ancient (>200 myo) fishes found throughout the Northern Hemisphere and are considered to be the most imperiled vertebrate taxon in the world (Pikitch et al. 2005). Of the 27 species, two are extinct, and 17 of the remaining 25 (68%) are classified as critically endangered, where critically endangered is defined as facing an extremely high risk of extinction in the wild (IUCN 2024). Conservation of sturgeon species is a global effort and primary causes of population decline include overharvest, habitat degradation, and barriers to migration (Rochard et al. 1990). Sturgeons are late to mature (some species requiring up to 30 years), long-lived (capable of exceeding 100 years of age), iteroparous, and migratory, with all species spawning in freshwater and engaging in anadromous or potamodromous migrations (Billard and Lecointre 2000).

North American sturgeon species affected by anthropogenic river modifications include white sturgeon (*A. transmontanus*) and green sturgeon (*A. medirostris*) in the western part of the continent,

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pallid sturgeon (*Scaphirhynchus albus*) and shovelnose sturgeon (*S. platorynchus*) in the Mississippi and Missouri Rivers, lake sturgeon (*A. fulvescens*) in the Great Lakes drainage, and Atlantic sturgeon (*A. oxyrinchus*) and shortnose sturgeon (*A. brevirostrum*) which occupy rivers along the East Coast. All of these sturgeon species exhibit migratory behaviour and have populations that are listed as endangered or threatened by state or federal agencies. Among North American sturgeons, only the Hudson Bay drainage subpopulation of lake sturgeon is classified as "least concern" on the International Union for Conservation of Nature (IUCN) Red List. All other subpopulations are listed as vulnerable, endangered, or critically endangered, with many of these declining populations inhabiting rivers fragmented by hydropower dams (Figure 1). The most widespread and persistent threat to sturgeon populations are hydropower developments and operations (Rochard et al. 1990; Huang and Li 2024).

Sturgeon are likely to encounter hydropower development during downstream movements and passage through conventional turbines can result in severe injury or mortality. The distribution of sturgeons substantially overlap with hydropower development (Figure 1) and they are capable of traveling thousands of kilometers between adult feeding grounds and spawning habitats (Auer 1996). Typical physical barriers installed at turbine intakes, such as bar racks, may prevent adults from entering the turbines, yet developing larvae and juveniles are typically not protected (Parsley et al. 2007; Poletto et al. 2014). These larval and juvenile sturgeon are most likely to follow the bulk river flow, which often passes through turbines (Cooke et al. 2020). Within a turbine, fish are exposed to physical stressors such as rapid decompression, cavitation, fluid shear, turbulence, and blade strike (Čada 2001; Pracheil et al. 2016), which can result in injury, reduced fitness, or mortality. The impact of these stressors varies by species, age, and size (Coutant and Whitney 2000; Brown et al. 2014). In general, larger fish face a higher risk of blade strike and more severe injuries from strikes (Coutant and Whitney 2000). If

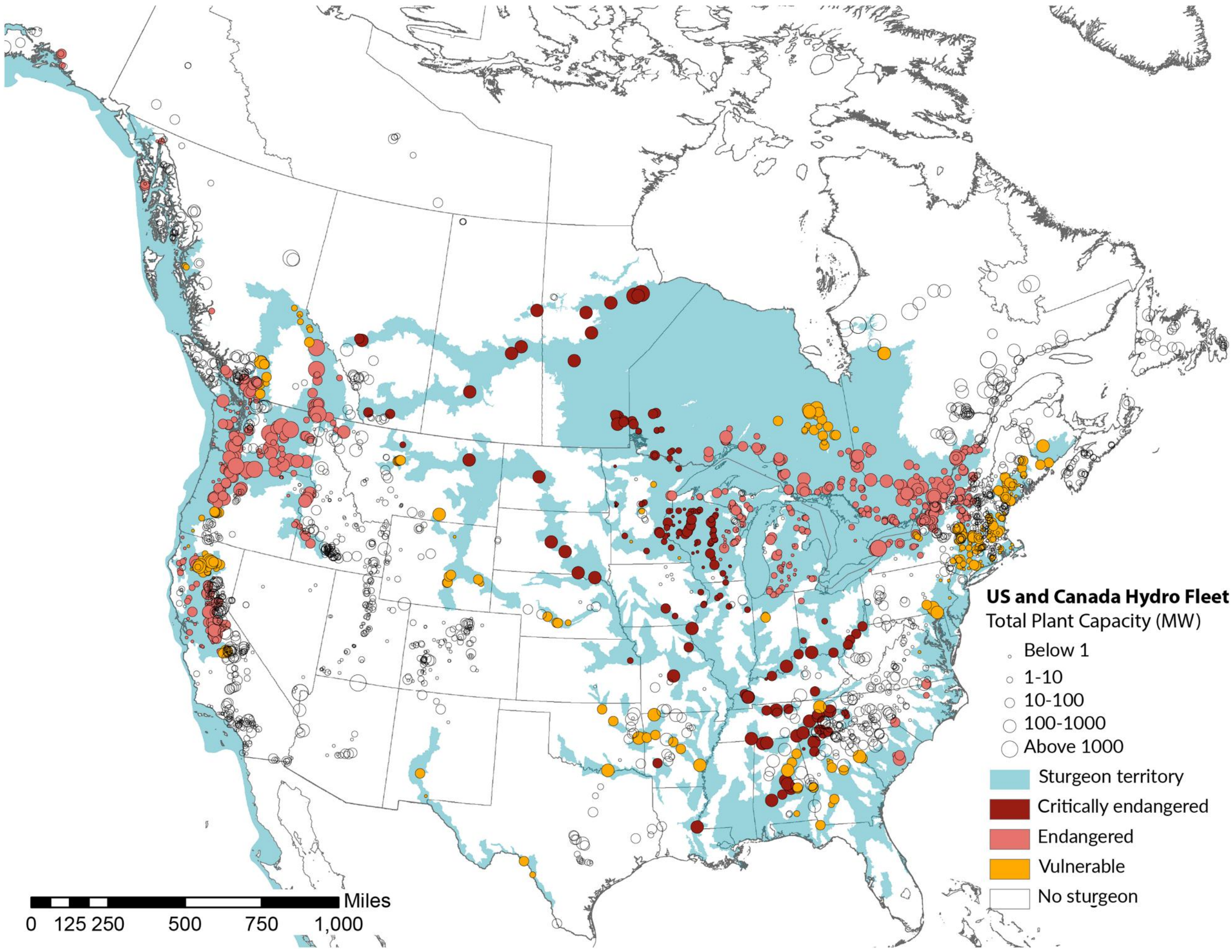

Figure 1. North American Sturgeon (white sturgeon, shortnose sturgeon, lake sturgeon, green sturgeon, Atlantic sturgeon, pallid sturgeon, shovelnose sturgeon, and Alabama sturgeon) combined ranges overlaid with existing hydropower sites. Conservation data is based on the status of subpopulations of species, with the most endangered population determining the dot color. Sturgeon range data comes from NatureServe (2024) and IUCN Red List (IUCN 2024), conservation status comes from IUCN Red List (IUCN 2024). US Hydropower capacity data comes from Oak Ridge National Lab (Johnson et al. 2022). Canadian hydropower data comes from the Government of Canada (Natural Resources Canada 2017).

entrained in turbines, adult sturgeon are especially vulnerable to severe injury and mortality from blade strike due to their large size. Finally, the long lives and migrations of sturgeon mean that individual fish may pass multiple turbines throughout their lives. As efforts to facilitate upstream passage expand (Cooke et al. 2020; Zhang et al. 2023), the compounding risks of repeated downstream passage will require greater efforts to prevent injury and mortality associated with turbine passage.

Methods exist to prevent fish entrainment into turbine intakes, but are limited in applicability. Bar racks designed to keep large debris out of turbines may also prevent large fish from entrainment, but their use is not universal. At larger facilities, constructing and maintaining screens that can withstand high hydraulic loads is challenging, and keeping them free of debris requires significant effort. Additionally, large, powerful turbines are less vulnerable to damage or jamming from debris, so they are often operated without bar racks. Similarly, fine screens (15-20 mm bar spacing), which are specifically designed to exclude fish from turbine entrainment, cannot be installed at all hydropower facilities. For turbines with increasingly large flow capacity, the installation, operation, and maintenance of exclusion screens becomes prohibitive due to the greater amounts and size of excluded debris. Furthermore, exclusion screens are not fully effective at preventing the entrainment of small- and medium-sized fish. For instance, (Knott et al. 2023) found that 9% of fish (*Barbus barbus, Salmo trutta, Perca fluviatilis, and Hucho hucho*) $\geq$15 cm in length were able to pass through 15 mm exclusion screens, while 18% were able to pass through 20 mm screens; additionally, they found that screens with 15 to 20 mm bar spacing were completely ineffective at excluding small-bodied species (*Cottus gobio, Gobio gobio*) with maximum total lengths below 20 cm. If designed incorrectly, fine exclusion screens have been observed to directly injure or kill fish that are impinged on or forced through the screen when flow velocities exceed their swimming ability (Calles et al. 2010; Rytwinski et al. 2017). On the USA's west coast, screening criteria at hydropower facilities are designed to protect salmonids (NMFS 2023), yet their effects on other species, including threatened and endangered ones, remains limited. Species with reduced swimming capabilities compared to salmonids, such as sturgeon (Peake et al. 1997), may be at greater risk of injury from screens designed primarily for salmonids. For instance, green sturgeon have been shown to be particularly prone to contact and impingement on screens (Poletto et al. 2014). Given the difficulty of effectively preventing fish from entering turbine intakes, it is important to adapt turbines to minimize harm to entrained fish.

Various aspects of hydropower plant and turbine design affect fish survival outcomes. Strike speed is a key determiner of blade strike severity, with typical blade peripheral speeds (speed at a blade's outermost radius) ranging from 20 to 35 m/s. Turbines designed specifically for high fish survival have historically been designed to operate at reduced peripheral speeds (5.8-22.0 m/s) to minimize the blade strike severity (Cook et al. 2003; Mueller et al. 2022). However, low-speed turbines can be difficult to implement within existing hydropower infrastructure due to higher torque requirements on the generator, which can increase generator size and cost, as well as a larger runner diameter and overall turbine footprint. These costs and complexities make turbine replacement with lower-speed units at existing hydropower facilities exceptionally challenging. Consequently, most "fish-friendly" turbines have been installed at new hydropower developments or for niche applications. Turbines capable of passing fish safely while operating at high speeds would offer an option for in-situ runner replacement at existing hydropower sites where fish survival is a concern.

Another important determinant of blade strike severity is the shape of the blade's leading edge. In conventional hydropower turbine blade designs, it is thin and emerges radially, directly outward from the hub. Evaluations of the effect of blade leading edge shape on strike survival in the laboratory have shown that at the same speeds, survival rates are higher for fish struck by blades with thick and slanted leading edges compared to conventional blades (EPRI 2008; 2011; Amaral et al. 2020). The Restoration Hydro Turbine (RHT) design concept, introduced by Natel Energy, incorporates these thick and slanted turbine blade geometries and has been evaluated in a turbine passage context for juvenile alewife (*Alosa pseudoharengus*) and American eel (*Anguilla rostrata*) at peripheral speeds of 15.6 and 19.2 m/s, respectively, with 100% survival (Watson et al. 2022; 2023 Mar 3).

In this study, we evaluated the effect of runner design on turbine passage survival of juvenile white sturgeon. Two runners were tested: one with conventional blade profiles, and an RHT design with thick and slanted blade leading edges. Footage of fish passage through both runners was recorded with high speed video cameras. A control group was subjected to identical handling and passage procedures, but did not pass through a turbine. To the best of our knowledge, this study represents the first controlled comparison of two runner designs tested within the same turbine, evaluating injury and mortality outcomes for fish. We predicted that the design of the RHT-type runner would yield reduced blade strike mortalities and lower rates of injury relative to the conventional turbine runner across a range of operationally relevant peripheral speeds. Finally, we used the results of this study to conduct a simulation of how the compounding threats of repeated passage may be influenced by RHT-type turbine runners.

2. Material and methods

2.1. Turbine testing facility

Turbine passage testing occurred at the Natel Energy hydraulic turbine and fish passage testing facility in Alameda, California (Figure 2). The testing facility consisted of a closed-loop recirculating system with a 76,000 L sump tank, pipeline, 336 kW pump, and 55 cm diameter turbine. The turbine generator was connected to a variable frequency drive allowing for variable speed control. Net head across the turbine was measured with a Rosemount 3051 C differential pressure sensor (−25.4 to +25.4 mH_2O ± 0.04%) and flow rate was measured with a Krohne Enviromag 2000 electromagnetic flow meter (−12 to 12 $m/s \pm 0.2\%$).

Groups of five fish were released into the pipeline *via* an injector, which consisted of a pressure canister connected to an air compressor line and a 10 cm diameter transparent pipe with a knife gate valve (Figure 2c) (Watson et al. 2022). After increasing the pressure in the injector canister to match that of the turbine testing pipeline, the valve was opened and fish were released into the pipeline. For treatment releases, the injector was inserted into the pipeline 8.7 m upstream of the turbine, and for control releases, it was inserted 5.5 m downstream of the turbine. The inner diameter of the pipeline upstream of the turbine was 0.56 m, increasing to 0.71 m just downstream of the turbine. When assembled, the transparent injector outlet pipe extended into the center of the flow cross section. The control injector was removed from the pipeline during treatment releases, to eliminate the risk of

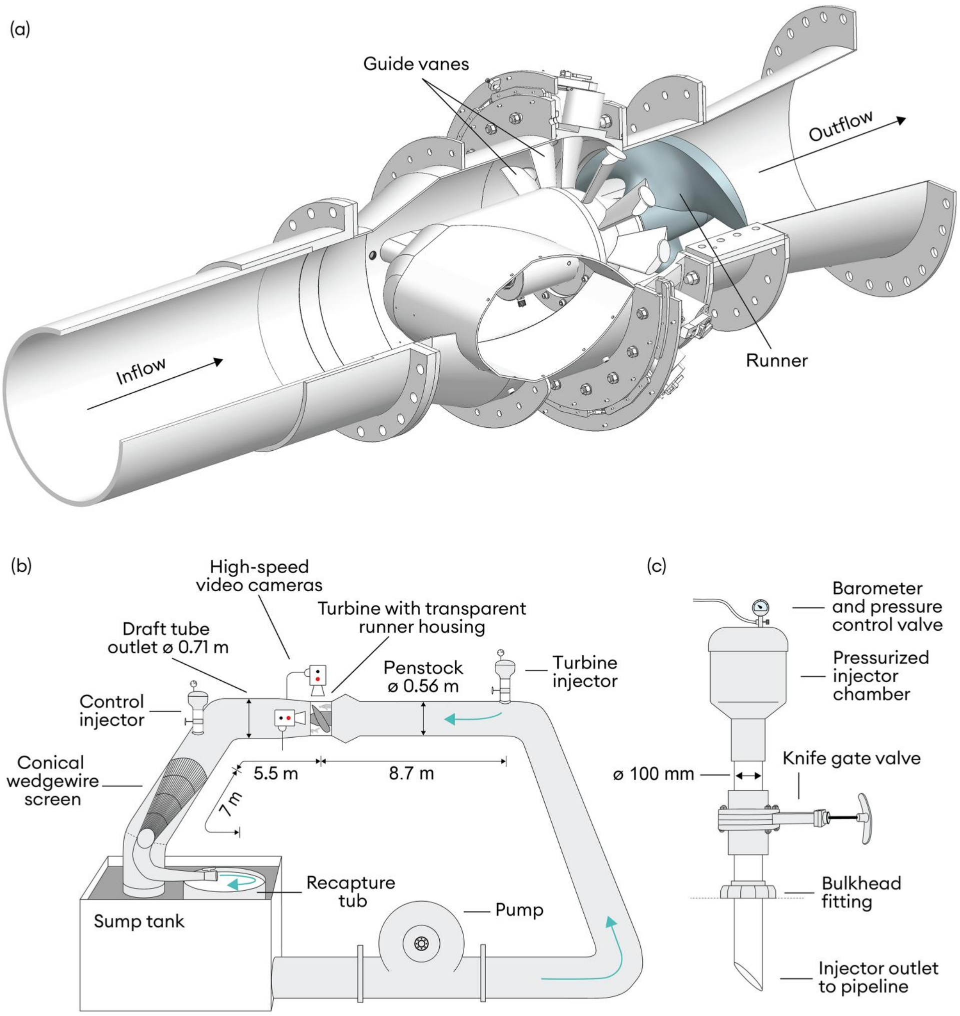

Figure 2. (a) Partial cutaway trimetric view of the test facility turbine with a Restoration Hydro Turbine (RHT) type runner installed; (b) diagram of the hydraulic turbine and fish passage testing facility; and (c) injector used to release groups of sturgeon into the pipeline for treatment and control releases.

treatment fish colliding with it. The average flow velocity in the pipeline increased proportionally with flow according to the operating condition, ranging from 2.4 m/s to 4.7 m/s.

The runner was encased in a transparent acrylic housing to allow for observation of the fish passage through the runner during turbine operation. Two high-speed video cameras, one monochrome (Chronos 1.4, 16 GB, with Canon EF 8–15-mm f/4L Fisheye lens) and one colour (Chronos 1.4, 32 GB, with Computar 8-mm f/1.4 prime lens), were placed on opposite sides of the housing and captured footage at 1280 × 1024 pixel resolution and 1069 fps. The region was illuminated externally through the transparent housing with two Godox SL150W II LED Video lights (150 watts).

To enable extraction of the fish from the pipeline, a conical wedgewire screen was installed downstream of the turbine and control injectors (Figure 2). The included half-angle of this conical screen was approximately 7.9° to the flow and was constructed of 2 mm stainless steel wedgewire. The downstream end of the screen led to a 150 mm inner diameter, 3 m long flexible hose terminating in a 200 mm diameter diffuser, which released the fish into a circular, 1.83 m diameter galvanized steel recapture tub. Water and fish were released tangentially along the wall of the cylindrical recapture tub. An elongated rectangular cutout screened with soft fabric mesh (3 mm hole size) allowed flow to exit the recapture tub into the sump tank.

Table 1. RHT-type and conventional runner dimensional and operational specifications.

	RHT-type	Conventional
Runner outer diameter (cm)	55.0	55.0
Hub diameter (cm)	19.4	19.3
Number of blades	2	3
Approximate blade leading edge thickness (mm)	100	6
Head (m)	2.65–8.94	2.65–8.94
Shaft speed (rpm)	521–976	521–976
Peripheral speed (m/s)	15–27.6	15–27.6

2.2. Runner specifications

Two 55 cm diameter runners were designed and manufactured for the turbine passage trials (Table 1). The first runner was an innovative design, with two blades of approximately 100 mm leading edge thickness emerging from the hub with a forward-sweeping slant toward the maximum radius (Figure 3a). These geometric characteristics are representative of the RHT design concept. The second runner was a conventional design, consisting of three fixed blades with a leading edge thickness of approximately 6 mm (Figure 3b). The blade profile and axial outline of the conventional blades were derived from traditional Göttingen airfoil geometries (Adolph 1965). In contrast to the RHT-type runner, the conventional blade's leading edge curved slightly backward at the maximum radius, which is typical of most fixed- and variable-pitch Kaplan runners.

For both trials, tests were conducted at five speeds—521, 625, 729, 833, and 957 rpm—corresponding to 15.0, 18.0, 21.0, 24.0, and 27.6 m/s peripheral speed. These speeds were selected to cover

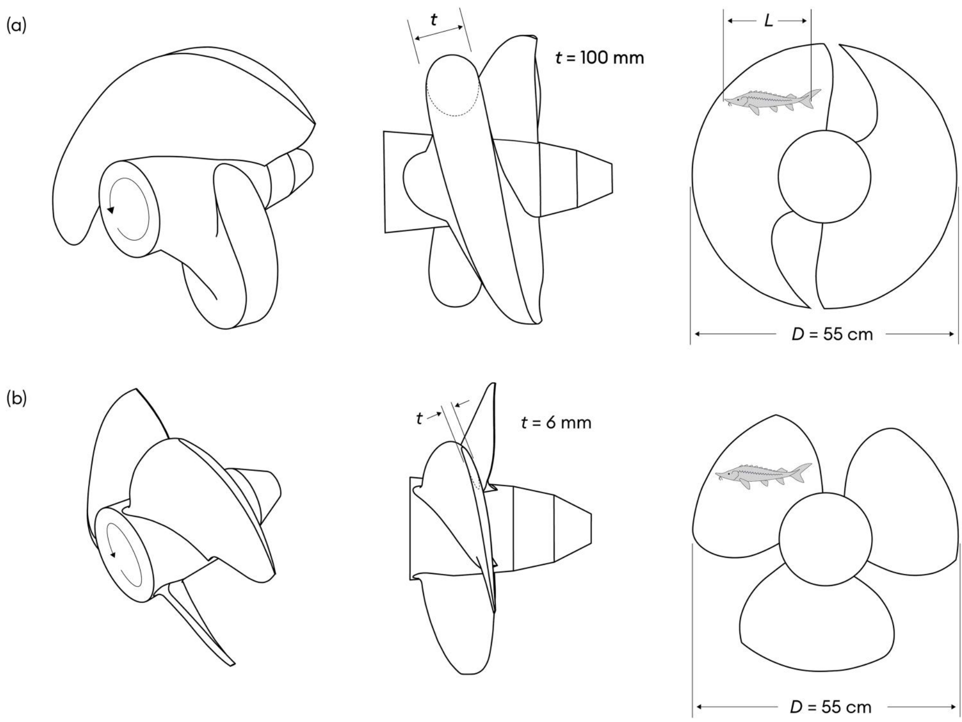

Figure 3. Illustration of (a) the RHT-type runner tested and (b) the conventional runner tested, showing blade leading edge thickness (t), and fish fork length (L).

Table 2. Turbine operating conditions. Peripheral speed refers to the speed of the blade at its outermost radius and RPM refers to revolutions per minute.

Peripheral speed (m/s)	RPM	Head (m)	Runner type	Flow rate (m^3/s)	Shaft Power (kW)
15.0	521	2.65	RHT-type	0.63	13.8
			Conventional	0.60	13.9
18.0	625	3.82	RHT-type	0.75	23.5
			Conventional	0.73	23.9
21.0	729	5.19	RHT-type	0.88	37.3
			Conventional	0.84	38.1
24.0	833	6.78	RHT-type	1.01	56.1
			Conventional	0.96	56.8
27.6	957	8.94	RHT-type	1.16	83.6
			Conventional	1.11	86.1

the peripheral speed range of most conventional hydropower turbines. Flow rate and power were closely matched for both runners across all tested speeds (Table 2). The five operating points were selected to preserve kinematic similitude; i.e. the shaft speed increased with the square root of net head such that the fluid streamlines were identical, with velocities proportional by a constant scale factor, maintaining the shape and direction of the flow.

2.3. Fish holding and handling

White sturgeon were sourced from The Fishery, Inc. aquaculture facility located in Galt, California and were transported (42 miles) as one day post-hatch larvae to UC Davis' Center for Aquatic Biology and Aquaculture (CABA) in Davis, California on April 11, 2024. At CABA, the sturgeon were reared in 850 L round fiberglass tanks equipped with air-equilibrated water (18 ± 0.5 °C) from a designated well and fed *ad libitum* of a commercial pellet diet (Rangen, Skretting) before being transported to Natel Energy hydraulic turbine testing and aquaculture facility. The two sets of trials occurred over two separate days, two weeks apart: July 29, 2024, for the RHT-type runner and August 13, 2024, for the conventional runner. Individuals were selected such that the fork length distribution of the fish passed through both runners would be similar. All work with live organisms was reviewed and approved by the University of California, Davis IACUC committee (Protocol No. 23871).

Two days prior to testing, fish ($N = 352$ total; $n = 112$ for RHT, $n = 115$ for conventional, and $n = 125$ for control; fork length 15.8 ± 1.2 cm) were transported from CABA to the testing facility (72 miles) in a transport truck equipped with an 765 L insulated metal tank. No injury or mortality resulted from transport. Once at the facility, fish were transferred into one of six 1136 L round, circular tanks. Each tank held approximately 3,800 L of recirculating water and was equipped with a bioreactor, chiller, and air bubbler. Fish were held undisturbed for two days prior to testing to minimize the effects of transport and allow time for acclimation to the new environmental conditions.

To maintain holding tank water quality, municipal water was filtered *via* three filtration columns (BRS Universal Carbon Block Filters – 1 Micron) in series to remove chlorine and chloramines, and the water was then continuously added to each recirculating system at a rate of 19 L per hour. Every 24 h, approximately 460 L were removed from each tank system.

Temperature, pH, ammonia, nitrite, and nitrate levels in the holding tanks were measured daily. Over the course of the experiments, ammonia and nitrite measured 0 ppm, nitrate remained below 5 ppm, pH ranged from 7 to 7.7, and water temperatures ranged from 15.9 to 22.3 °C. During testing, water temperatures in the hydraulic turbine test facility ranged from 16.3 to 20.4 °C. Food was withheld while fish were at the turbine test facility for the entire duration of the experiments.

2.4. Experimental procedure

Experimental procedures were identical for RHT and conventional turbine trials. Control groups were utilized to account for handling, release, and recapture effects. The control groups underwent identical handling to treatment groups, but were released downstream of the operating turbine. The RHT trial consisted of 36 passage events ($N = 172$ fish): 12 control passages ($n = 60$) and 24 treatment passages ($n = 112$). The conventional trial also consisted of 36 passage events ($N = 180$ fish): 13 control passages ($n = 65$) and 23 treatment passages ($n = 115$). Each passage event consisted of a group of five fish, except for one RHT treatment passage with only two fish. All groups underwent preexposure evaluations, release and recapture, postexposure evaluations, and a 48 h post-passage holding period.

Prior to each passage event, a group of fish was gently transferred using a dip net from the holding tank into a 19 L bucket. Each fish was briefly removed from the bucket and individually examined for injuries. Preexisting injuries included frayed fins, small fin tears, and abrasions. Since individual fish were not tagged, any preexisting injuries were recorded for the entire group.

Due to the possibility of severe injury associated with turbine passage, all fish (treatments and control) were anesthetized prior to being placed in the injector chamber. Each group of fish was anesthetized in a 350 mg/L MS-222 solution buffered with 420 mg/L $NaHCO_3$ and 6.0 g/L NaCl (InstantOcean^{TM}). Fish remained in the anesthetic until loss of equilibrium and unresponsiveness to light physical stimulus indicated that they had reached stage IV surgical anesthesia (Summerfelt and Smith 1990).

Once anesthetized, fish were placed into the water-filled injector chamber, and chamber pressure was increased *via* air compressor slowly (over a period of 15 to 30 s) to approximately 103 kPa (10.5 m of head) above atmospheric pressure. The injector valve was then opened quickly (<1 s), allowing the pressurized air to push the water and fish into the pipeline, and closed after all fish were observed entering the pipeline (Watson et al. 2022). After passing through the pipeline (including the turbine, for treatment groups) the fish were extracted from the outlet pipe flow *via* the conical screen and recovered from the recapture tub with a dip net. The duration between removal from anesthetic to recapture at the outlet was kept below one minute to ensure that the fish would remain anesthetized during turbine passage.

After recapture at the outlet, the fish were returned to a buffered MS-222 solution (350 mg/L MS-222) to re-anesthetize. Immediately upon losing equilibrium, each fish was transferred to a lower concentration of buffered MS-222 (100 mg/L) to maintain their anesthetized state while they were inspected for injury. Fish that presented with mortal injuries were immediately euthanized with an overdose of buffered MS-222 solution (500 mg/L).

Once anesthetized or euthanized, each fish was imaged, weighed, measured, and evaluated for injuries. Photographs were taken using a Canon Rebel Ti (EOS Rebel T2i) camera with 35 mm lens. The camera was mounted on a tripod above the fish, which was laid on a flat surface. Each fish was imaged dorsally, then inverted and placed on supports for a ventral image. A visual inspection was conducted to identify and note injuries across all external body parts (Table 3). Injuries were not rated for severity. No internal injury assessments were conducted post passage. Postexposure injury evaluations were performed by a single evaluator experienced in white sturgeon injury identification. Injuries were classified as amputations, hemorrhages, scale/scute loss, fin tears and gouges, or dermal lesions as described in Mueller et al. (2017).

After injury assessment, all live fish remaining from each group were placed into a 19 L bucket placed inside one of two partially filled 1136 L circular holding tanks. Each bucket was equipped with a secure lid and an air and water supply (8 L/hr), as well as holes in the sides to allow water to exit. Each group of fish was assigned to its own bucket (36 buckets total). Any mortalities occurring within the 48 h hold period were recorded and removed. Since fish were not tagged, 48 h mortalities were identified within their group and matched with their post-passage injury assessment based on fork length and other distinguishing features. After the 48 h holding period, all fish were euthanized with an overdose of buffered MS-222 (500 mg/L).

Table 3. Injuries observed across categories across the body for each trial type.

Category	Specific injuries included within injury category	Control ($n = 119$)	RHT ($n = 106$)	Conventional ($n = 110$)
Severing (mortal injury)	Fish severed*	0% (0)	0% (0)	27% (30)
Severe eye injury (mortal injury)	Ruptured eyes*, eye missing from sockets*	0% (0)	0% (0)	2% (2)
Severe laceration (mortal injury)	Severe laceration through skin*	0% (0)	0% (0)	1% (1)
Body	Scraped or hemorrhaging scutes, lacerations, abrasions*, crushed caudal peduncle*, detached scutes*	5% (6)	9% (10)	9% (10)
Head	Abrasions on head	5% (6)	10% (11)	5% (6)
Rostrum	Abrasions, hemorrhaging on dorsal surface or tip of rostrum, laceration to ventral surface*	5% (6)	8% (8)	5% (5)
Mouth	Hemorrhaging lips	2% (2)	2% (2)	0% (0)
Nares	Gouge of skin missing from nare*	0% (0)	0% (0)	1% (1)
Gills/Operculum	Abrasion behind operculum*	0% (0)	0% (0)	1% (1)
Pectoral Fins	Hemorrhaging in fin, split fin, missing piece of fin, abrasion on leading edge of fin, fin ripped from base*	5% (6)	13% (14)	9% (11)
Dorsal Fin	Hemorrhaging in fin, split fin, fin ripped from base*	1% (1)	3% (3)	3% (3)
Anal Fins	Hemorrhaging in fin, hemorrhage at the base of fin*	2% (2)	1% (1)	5% (5)
Caudal Fin	Hemorrhaging in fin, split fin, crimped top of fin*	3% (4)	6% (6)	5% (5)
Pelvic Fins	Hemorrhaging in fin, split fins, hemorrhage at base of fin	11% (13)	8% (9)	8% (9)
Barbels	Hemorrhaging on barbels	0% (0)	2% (2)	5% (6)
Cloaca	Bleeding from cloaca (internal hemorrhage)*	0% (0)	0% (0)	2% (2)

Only non-impinged fish were included in injury analyses. An asterisk (*) indicates injuries observed only in the conventional trial, no injuries were observed only in the RHT or control trial.

2.5. Data analysis

Conditions for controls were nearly identical between RHT and conventional trials, with the only difference being a slightly higher flow rate during the RHT trial (see Table 2). As no mortalities were observed from any control passage we combined control trials from the RHT and conventional testing and analyzed them as a single group, referred to hereafter as “controls.” Similarly, for injury analysis a preliminary analysis estimated the ratio of injury rates between the two control varieties (RHT vs. conventional) as 0.81 (95% CI $0.35 - 1.46$). This interval includes 1, therefore the rates of injuries between these two control type is considered non-significant and further analysis considered them a single control group.

2.5.1. Survival modeling

Fish survival rates (both immediate and after 48 h) were assessed using a generalized linear mixed-effect model assuming a Bernoulli distribution with a logit link function implemented in a Bayesian framework. Models were constructed using R (v 4.3.2) and the packages brms (Bürkner 2017; 2018) and emmeans (Lenth 2020) and visualized using ggplot2 (Wickham 2016). Fish survival was the response variable and the predictor variables included turbine runner type (categorical), runner peripheral speed (continuous), fish length (continuous), and a random intercept attributed to passage group. Priors used were weakly regularizing but uninformed. Fish that were immediately euthanized post-passage due to serious injury, such as complete or partial severing, were classified as immediate mortalities. Any mortalities that occurred within the 48 h postexposure hold period were classified as 48 h mortalities. Model-fit was evaluated using leave-one-out criterion (LOO scores) and the model which exhibited the lowest LOO score was selected (model summaries in Supplemental Tables 1 and 2). Significance was assigned when the 95% credible interval (95% CI) of the posterior distribution did not include 0.

2.5.2. Injury rates

Recorded injuries were scored with each occurrence of an injury increasing the score by one unit. For example, a fish with a torn pelvic fin, a torn pectoral fin, and a scrape on its rostrum would receive an injury count of 3. Injuries were not scored differently based on severity due to inherent subjectivity; all injuries including mortal injuries like severing received an injury value of 1. Injuries recorded pre-passage were attempted to be matched with injuries recorded post-passage within the 5-fish group. For example, if one fish in a group was recorded with a split pectoral fin prior to passage, and one fish was recorded with the same injury after passage, then it was assumed those were the same fish and the pre-passage injury count was subtracted from the post-passage count. If a pre-passage injury was not recorded on any of the fish following passage, then the pre-passage injury was disregarded.

The injury rate analysis focused on identifying differences among the trial types (control, RHT, or conventional) as well as any differences across turbine peripheral speeds. The analysis was performed with generalized linear mixed-effects models using a Poisson distribution including fixed effects of fish length, turbine runner type, and turbine peripheral speed as both a linear and quadratic predictor. A random intercept passage group was also included in the analysis.

2.5.3. High-speed video analysis

Each group that passed through the RHT-type or conventional runner was recorded from two synchronized high-speed camera angles, one on each side of the runner, to maximize coverage. Videos were manually reviewed to identify individual fish, which were then matched across both views. In some cases, if a fish moved out of one camera’s field of view, the other camera could be used to complete its passage record. Fish were categorized as “struck” if visible contact with a runner blade was observed. In the RHT trials only, it was sometimes difficult to determine whether a fish made contact or simply passed very close to a blade. Some fish passages through the RHT-type runner were classified as “deflected around the blade” if they appeared to be directly in the path of the blade but were visibly deflected without contact. Due to the subtlety of these interactions, and the limitations of the camera angles, some deflections may have gone unrecorded, meaning the reported number of “deflections around the blade” likely underestimates the true value.

2.5.4. Simulation of repeated passages

To estimate the effect of repeated turbine passages on survival we used our lowest LOO-scoring 48h survival model to simulate passing through one of four different passage conditions: control passage with no turbine exposure, RHT-type runner passage, conventional runner passage, and an optimized conventional runner passage. This ‘optimized conventional turbine’ condition was added to represent the survival of repeated passage under theoretical conditions optimized for fish survival. For each passage event, each simulated fish was assigned a randomly generated runner peripheral speed between 15 m/s and 27.6 m/s. For the ‘optimized conventional turbine’ condition, the randomized runner peripheral speed was limited to between 19.0 m/s and 22 m/s, velocities which yield mean survival probability greater than 0.80 based upon the best fitting model. We used a simulated fish's assigned velocity and passage treatment to predict its likelihood of survival. Then, if a randomly generated number was smaller than a given fish's predicted survival likelihood, the simulated fish was marked as surviving passage; otherwise, it was deemed to have died during passage. To assess the impact of repeated passage, the simulation was rerun on the dataset of all simulated fish that survived passage to represent a second passage event. This process was iterated to simulate a total of five sequential passage events. Each iteration of the simulation modeled 100 fish per passage condition. We conducted 10,000 interactions for a total of 4,000,000 simulated fish (1,000,000 per passage treatment).

2.6. Impingements

Fish were occasionally impinged on the conical screen downstream of the turbine. This screen was designed to reduce impingement risk by minimizing the ratio of the normal component of flow velocity to the screen to the parallel component; however, approximately 4.8% (17 out of 352; RHT: $n = 6$, control: $n = 6$, conventional: $n = 5$) of the fish across all trials were impinged. Since all fish were anesthetized, impingement likelihood was assumed to be unrelated to swimming ability or injury status. Impinged fish, identified by their failure to exit the pipeline until turbine shutdown, experienced being pinned against the conical screen (an injury mechanism distinct from turbine passage). They were therefore excluded from the injury and survival rate analyses. These impinged fish were immediately euthanized with an overdose of buffered MS-222 (500 mg/L).

3. Results

Fish fork length was closely matched among the RHT, conventional, and control trials. It ranged from 129 to 199 mm (average 156 ± 12 mm) in the RHT trial; in the conventional trial, from 132 to 182 mm (average 161 ± 11 mm); and in the control group, from 130 to 188 mm (average 157 ± 12 mm) (Table 4). The fish length to blade thickness ratio *(L/t)* of the RHT trial was much lower than that of the conventional trial, because of the RHT-type runner's comparatively thick blades. The average *L/t* ratio for the RHT trial was 1.5, compared to 25.2 in the conventional trial.

Runner type had a pronounced effect on survival. For the RHT trial, immediate survival was 100%, and 48 h survival was 99.1% (105 of 106 fish). For the conventional runner trial, immediate survival was 70.0% (77 of 110 fish), and 48 h survival was 64.5% (71 of 110 fish). Control survival was 100% (119 of 119 fish) for both immediate and 48 h survival. Moralities occurring within the 48 h postexposure hold period were highest at the highest peripheral speed tested (27.6 m/s), with one 48 h mortality occurring from the RHT and three 48 h mortalities occurring from the conventional runner. For the conventional runner trial, survival after 48 h was highest (78%, 18 of 23) at the middle speed (21 m/s), and 3 of the 5 mortalities at this speed occurred within 48 h of passage (Table 4).

3.1. Survival modeling

A linear model using a Bernoulli distribution (logit link) was fit to assess the influence of runner

Table 4. Fork length, mortality, and immediate and 48 h survival results for control, RHT, and conventional trials.

	RPM	m/s	Average Fork Length (mm) μ ± S.D.	N fish	Impinged fish (n =)	Non -impinged fish (n =)	Immediate mortalities (n =)	48 h mortalities (n =)	Total mortalities (n =)	Immediate survival rate	48 h survival rate
Control	521	15	157 ± 12	25	2	23	0	0	0	100%	100%
	625	18	157 ± 12	30	2	28	0	0	0	100%	100%
	729	21	159 ± 11	25	1	24	0	0	0	100%	100%
	833	24	158 ± 12	25	1	24	0	0	0	100%	100%
	957	27.6	157 ± 12	20	0	20	0	0	0	100%	100%
Total	-	-	**157 ± 12**	**125**	**6**	**119**	**0**	**0**	**0**	**100%**	**100%**
RHT	521	15	158 ± 12	25	3	22	0	0	0	100%	100%
	625	18	154 ± 9	20	0	20	0	0	0	100%	100%
	729	21	152 ± 12	20	0	20	0	0	0	100%	100%
	833	24	154 ± 11	22	1	21	0	0	0	100%	100%
	957	27.6	160 ± 15	25	2	23	0	1	1	100%	96%
Total	-	-	**156 ± 12**	**112**	**6**	**106**	**0**	**1**	**1**	**100%**	**99%**
Conven-tional	521	15	161 ± 13	20	0	20	9	0	9	55%	55%
	625	18	162 ± 11	20	0	20	5	0	5	75%	75%
	729	21	164 ± 9	25	2	23	2	3	5	91%	78%
	833	24	161 ± 13	25	2	23	6	0	6	74%	74%
	957	27.6	159 ± 9	25	1	24	11	3	14	54%	42%
Total	-	-	**161 ± 11**	**115**	**5**	**110**	**33**	**6**	**39**	**70%**	**65%**

Impinged fish were not included in the calculation of survival rate. Both turbine rotations per minute (RPM) and peripheral tips speed (m/s) are reported.

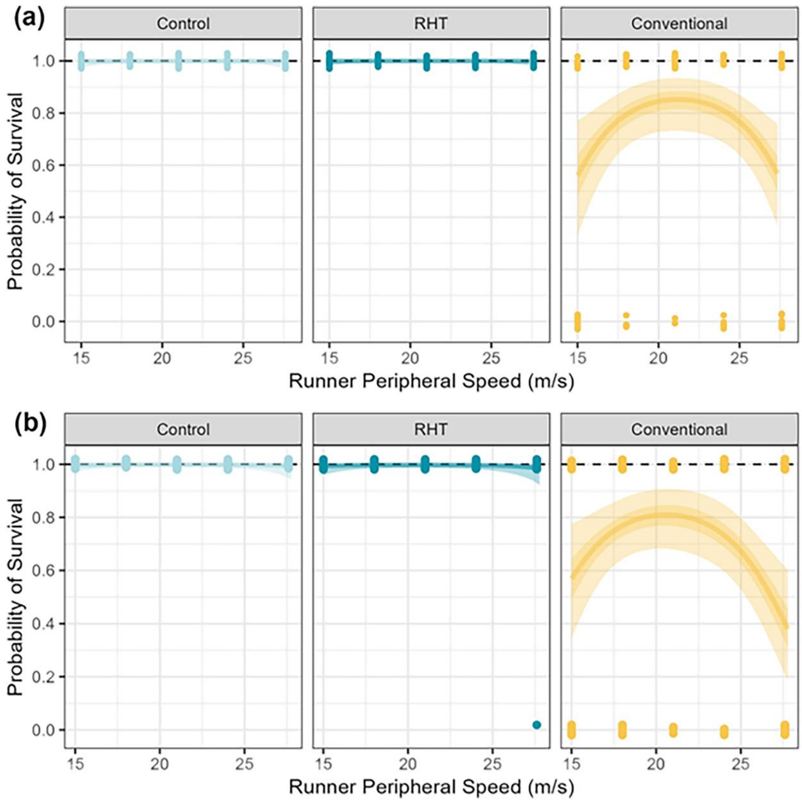

Figure 4. Immediate (a) and 48 h (b) survival for each trial by runner peripheral speed. Points represent individual fish which could either have a value of 1 (survived) or 0 (mortality). Curves represent the model estimate of the best-fitting model with the 50% and 95% credible intervals represented by the dark and light shading,.

peripheral speed on immediate survival rate. The best-fitting model, using a leave-one-out (LOO) approach, included a categorical predictor for passage type (RHT, conventional, or control) and a continuous quadratic predictor for speed as well as the random effect for passage group. Passage type and peripheral speed did not interact. Two other models exhibited non-significantly different LOO scores, one included an additional predictor of fish length and the other included an interaction between peripheral speed and runner type. In both cases, the additional terms were not found to be significant. Runner peripheral speed was found to have a significant effect on immediate survival for the conventional runner (Figure 4a). Survival rates were lowest at the extreme velocities tested: 55.8%, [95% CI: 33.3, 77.3] at 15.0 m/s and 53.5% [32.6, 74.6] at 27.6 m/s. In contrast, survival peaked at 84.7% [74.6, 94.4] when the runner operated at 21.0 m/s. Immediate survival was 100% in both the RHT and control trials, so there was no predicted relationship between survival and runner peripheral speed.

Similar models were constructed to estimate the impact of peripheral speed on 48 h mortality. The lowest LOO-score 48 h mortality model had the same structure as the lowest LOO-score immediate mortality model: a categorical predictor for passage type and a continuous quadratic term for peripheral speed. Alternate, low-scoring models included fish length or an interaction between velocity and passage type. In both cases, these predictors did not have a significant effect on model estimates. Control fish exhibited no mortality and thus there was no predicted relationship with peripheral speed. The model found that probabilities of survival were not significantly different between the RHT and control trials, with the lowest rates of survival for either treatment at a velocity of 27.6 m/s (98.1% [95% CI: 94.4, 100] and 98.9% [96.2, 100] respectively), while the conventional runner elicited reduced survival ranging from 40.5% [20.4, 60.8] at 27.6 m/s to 80.5% [69.0, 91.4] at 21 m/s (Figure 4b).

3.2. Injury rates

The injuries observed in this study were primarily associated with blade strike. The dominant injury associated with the conventional runner was severing (27%, 30 of 110 passed fish). No severing was observed in the RHT trial or during control passage events.

Injury likelihood, as with mortality, was highest for the conventional turbine. The best-fitting model (lowest LOO-score) included fish passage treatment (RHT, conventional, or control) and peripheral velocity predictor modelled quadratically. Comparably well-fitting models included an interaction of passage treatment and velocity, or as velocity modeled

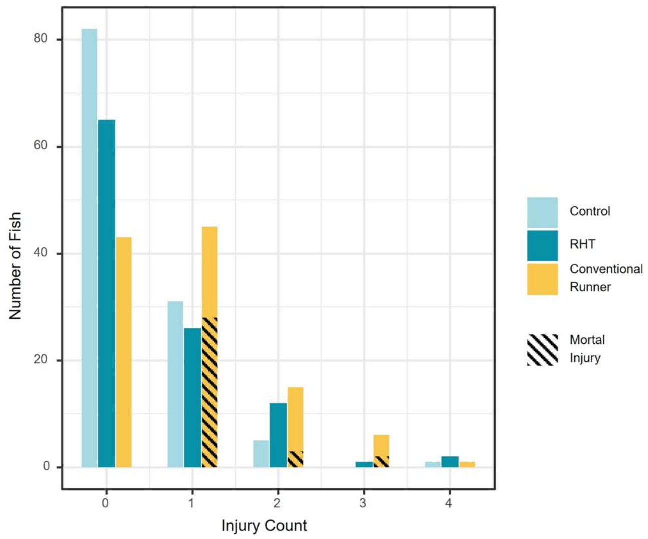

Figure 5. Number of injuries sustained by fish undergoing three different passage treatments. Fish which suffered a mortal injury (See Table 3 for description) are shaded with black striping.

linearly. In these alternate models, velocity was always a significant predictor, although the interaction terms were not.

Fish which passed the conventional runner had greater total rates of injury than either the control or RHT passages, and only the conventional runner produced mortal injuries (Figure 5). In the conventional trial, 30% (33 of 110) of fish suffered an immediate mortal injury. Based upon the counting system, fish undergoing the control passage received a modeled estimated 0.30 [95% CI: 0.19, 0.43] injuries per fish which are attributable to handling or non-turbine related passage injuries (e.g. interaction with the wedge wire screen). Fish that passed through the conventional runner had an average of 0.68 [0.48, 0.91] injuries per fish and of the fish which suffered any injury, 54% (36 of 67 injured fish) led to immediate mortality. Fish which passed the RHT had an average of 0.45 [0.30, 0.62] injuries per fish and none led to immediate mortality or required subsequent euthanasia. Across trials, pre-passage injury rates were low averaging 0.01, 0.04, and 0.02 injuries per fish for control, RHT, and conventional trials, respectively. Pre-passage injuries consisted of small splits or fraying in the caudal, pectoral, or pelvic fins.

Turbine velocity was associated with the count of injuries, with a significantly positive first-order term and a non-significant but positive second order term, indicating that injuries became more common as turbine velocity increased. At the lowest peripheral speeds (15.0 m/s) mean injuries per fish were estimated to be 0.46 [95% CI: 0.29, 0.64] and at the highest peripheral speed (27.6 m/s) injuries per fish were estimated at 0.84 [0.57-1.10].

Fish that experienced mortality within 48 h had a range of injuries and injury counts immediately post-passage. The one 48 h mortality from the RHT trial received an injury count of 4, which included several injuries to fins, including a split dorsal fin, split caudal fin, hemorrhaging at the base of pelvic fins, and a split pelvic fin. In the conventional trial, there were six total 48 h mortalities split evenly between the 21.0 m/s and 27.6 m/s velocity tests. One of these fish received an injury count of 3 (hemorrhaging in both pelvic fins, detached scutes), two received counts of 1 (hemorrhaging ventral scutes and hemorrhaging at the base of anal fins), and two received injury counts of 0.

3.3. High-speed video analysis

High-speed video footage of turbine passage was captured for all treatment trials. The duration of time that each fish spent passing through the runner region was approximately 0.2 s. Because of blind spots in the field of view of the two cameras, some fish were able to pass through the runner unobserved. The proportion of fish that were visible in the video footage was similar for both trials: 82.1% (92 of 112 fish) and 82.6% (95 of 115 fish) for the RHT and conventional trials, respectively. Of the fish visible, a smaller proportion were observed being struck by a blade of the RHT-type runner (21.7%, 20 of 92 fish) than the conventional runner (57.9%, 55 of 95 fish). An additional 8.7% of visible fish (8 of 92 fish) in the RHT trial were observed entering the runner in the direct path of a blade, but were deflected away without contacting the blade (see Table 5). In contrast, all fish observed in the direct path of a conventional runner blade were subsequently struck.

Approximately half of the strikes observed in the conventional runner footage were obviously lethal, with 51% (28 of 55) of visible strikes resulting in immediate mortality. These “clearly mortal” strikes were categorized as either immediate severing

Table 5. Results of high-speed video review and analysis for conventional and RHT passed fish.

Treatment	Velocity (RPM)	Velocity (m/s)	Fish passed	Observed on camera (n=)	Observed strike occurrence (n=)	Observed deflected around blade (n=)
RHT	521	15.0	25	25	7	2
RHT	625	18.0	20	15	3	1
RHT	729	21.0	20	18	5	1
RHT	833	24.0	22	17	1	1
RHT	957	27.6	25	17	4	3
Conventional	521	15.0	20	19	15	0
Conventional	625	18.0	20	14	8	0
Conventional	729	21.0	25	20	6	0
Conventional	833	24.0	25	21	12	0
Conventional	957	27.6	25	21	14	0

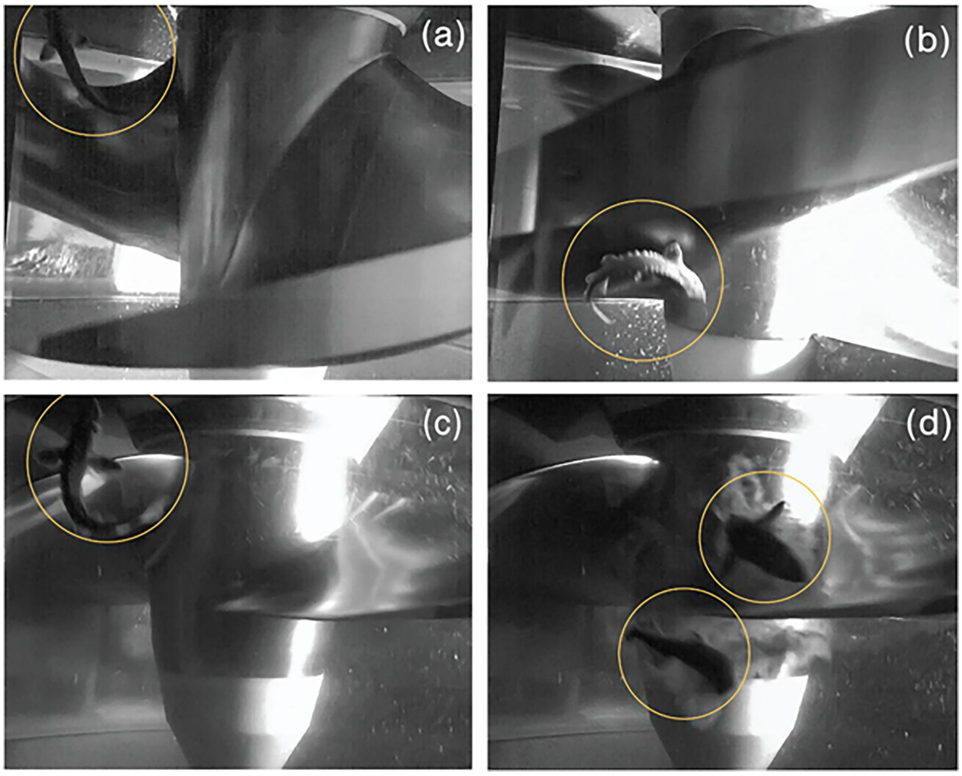

Figure 6. High speed video stills comparing blade strikes between the RHT-type and conventional runners. Panels (a) and (b) show a fish before and after being struck by the RHT-type runner, while panels (c) and (d) show a fish before and after being struck by the conventional runner. The fish in (d) was severed by the strike. All fish were under Stage IV anesthesia prior to turbine passage.

(as illustrated in Figure 6) or "dragging", in which the fish was caught on the leading edge of the blade and dragged at high speed for numerous runner rotations. Of the 28 clearly mortal visible strikes, 25 were the immediate severing type, and 3 were the dragging type. All dragging type strikes occurred close to the hub and resulted in axial disruption of the notochord, although the fish remained intact., due to the high velocities the fish experienced while being dragged by the blade. Strikes that resulted in severing more commonly occurred closer to the blade tip. Strikes that occurred closer to the tail region of the fish were less likely to be mortal.

3.4. Simulation of repeated passages

It is possible that a fish may pass hydropower turbines repeatedly throughout their life (e.g. one dam passed annually during migration, several dams passed in sequence, or frequent exposure during tidal hydropower). We conducted a simple mathematical simulation to estimate the probability of survival that could be expected after repeated passage events. We found that the RHT-type turbine runner exhibited simulated single-passage survival (99.4% [95% CI: 98, 100]) very similar to the control passage survival (99.7% [99, 100]. For both the Conventional Runner and Optimized Conventional Runner (where turbine velocity was constricted to a range which yielded survival $\geq$ 80%) treatments, survival was significantly lower after a single passage (70.0% [62, 80] and 79.3% [72, 87] respectively) as compared to the RHT-type turbine. After five simulated passage events survival of the conventional turbine was 16.8% [10, 24] and 31.4% [23, 41] for the conventional turbine operated at 'optimized'

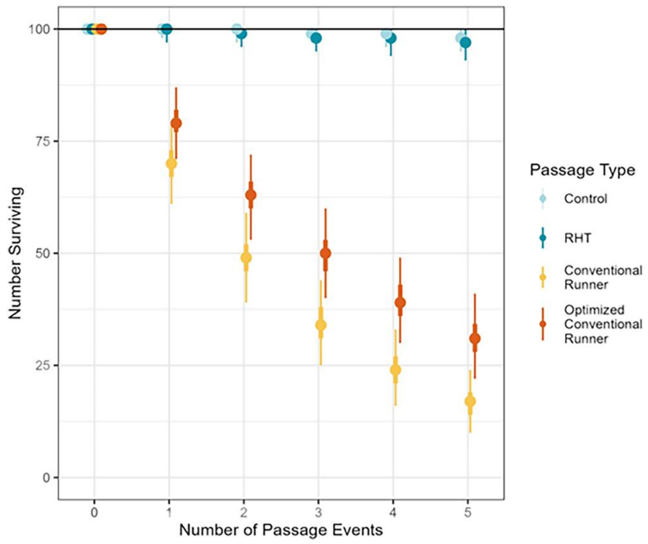

Figure 7. Survival rates of simulated fish undergoing repeated passages past different turbine types. Points represent the mean number of fish surviving whereas the whiskers represent the 50% (thick) and 95% (thin) credible intervals.

velocities, whereas survival among simulated fish which passed the RHT or control passage was 96.9% [94, 100] or 98.3% [96, 100] respectively (Figure 7).

4. Discussion and conclusions

Hydropower can provide reliable, low-carbon energy, but with manifold negative impacts on aquatic ecosystems. Improved downstream migration success for aquatic fauna through hydropower facilities is essential to reconcile the life-history needs of aquatic fauna with the energy demands of human society. To date, research efforts have focused both on documenting and understanding the impacts of hydropower turbines on wildlife (Pracheil et al. 2016; Dadswell et al. 2018; Algera et al. 2020; Mueller et al. 2022; Huang and Li 2024) as well as designing turbines to reduce injury and mortality risk for entrained fish (Cook et al. 2003; Lagarrigue and Frey 2011; Watson et al. 2022; 2023 Mar 3). The objective of this study was to understand the effect of turbine runner design on blade strike injury and mortality outcomes for white sturgeon across a range of operationally relevant peripheral speeds, flow rates and head pressures. Two representative runner designs were directly compared for their fish passage performance: the RHT-type runner, which was deliberately designed to minimize fish mortality associated with blade strike (Amaral et al. 2020), and a conventional runner, which was designed to match typical blade profiles of the existing hydropower fleet. Analysis of immediate and 48 h survival rates, as well as qualitative and quantitative assessment of high-speed video revealed substantial differences in survival outcomes for fish subjected to turbine passage through the two runners.

4.1. Survival results

The rates of survival observed through the conventional runner in the present study is consistent with work on turbines around the world. Across our test velocities, passage past a conventional turbine yielded 48 h survival rates between 42% to 78%. Dadswell and Rulifson (1994) reviewed rates of survival for several anadromous fishes passing a low-head tidal turbine and found the results to be species specific, but with an overall mean of 62.3 ± 25.9%. These results are supported by a systematic review of 206 datasets on hydropower induced fish mortality and injury (Algera et al. 2020). Notably, their results indicate that turbines are the dominant source of immediate mortality among fishes, with Francis-style turbines being more dangerous than Kaplan-style turbines.

Among passage trials using the conventional runner, survival was low across all speeds but was significantly higher at the middle speed (21 m/s). High-speed video analysis also showed a lower strike occurrence at this middle speed than the other speeds tested. As that all combinations of turbine speed and head were kinematically similar (i.e. the ratio of speed at which the flow moves axially downstream to the speed at which the blades move circumferentially is constant), it is not immediately clear why the middle speed resulted in a lower strike probability and corresponding higher survival rate than other speeds for the conventional runner trials. Kinematic similarity would indicate an equal geometric probability of blade strike across all tested speed conditions, and increasing strike speed would indicate an increased likelihood of strike mortality at the highest speed tested. Further research is needed to understand the effect of absolute speed on strike probability and survival under kinematically similar operating conditions.

4.2. High-speed video

Quantitative analysis of high-speed video footage showed that the RHT-type runner produced both fewer and less severe strikes compared to the conventional runner. While the conventional runner had 50% more blades than the RHT-type runner (3 blades versus 2), 167% more blade strikes were observed in the conventional trial (57.9% of fish struck) than the RHT trial (21.7% of fish struck). This result directly contradicts the hypothesis that increased blade thickness necessarily results in higher strike probability for fish, which has been proposed in some analyses of blade strike risk for turbine and pump design (Yang et al. 2023). Instead, there appears to be a deflection effect near the leading edge of the thick blades that reduces strike probability under the tested conditions, as hypothesized in several prior works (Solomon 1988; Franke et al. 1997; Turnpenny 1998). Approximately one third of fish (8 of 28) that were observed entering the RHT-type runner in the direct path of the blade were visibly deflected away from it without contacting the blade at all. In contrast, all fish that were observed entering the runner in the direct path of the conventional runner blades were clearly struck. Not only were strikes less frequent in the RHT trial, but the strikes that did occur were also less severe than those that occurred in the conventional runner. Nearly half (25 of 55) of all fish that were observed being struck by the conventional runner blades were immediately severed, even at the lowest peripheral speed tested (15.0 m/s).

Sturgeon in this study were fully anaesthetized due to risk of injury, preventing any ability for fish to orient to the water flow or turbine. It is possible that un-anesthetized fish, oriented to the flow of the water may have different rates of injury or mortality, however anesthetized fish are likely an effective proxy given the speed of the water (≥2.5 m/s) and turbine (≥571 rpm). At our slowest velocity, a fish would have ≲50 ms between passing runner blades, approaching the limits of sturgeon reaction time (Izvekov et al. 2014). Rheotaxic swimming by the sturgeon could extend the time that a sturgeon is vulnerable to a passing blade, subsequently increasing the risk of blade strike. However, prior research on the RHT runner using un-anesthetized alewives (Watson et al. 2023), and eels (Watson et al. 2022) resulted in very low mortality (97.4% and 100.0% respectively), indicating that for the RHT treatment, anesthetization was not likely a cause of high survival for that treatment.

4.2. Relevancy to full scale turbine passage

This study investigated the effects of turbine passage on small juvenile sturgeon passing through a small, model-scale turbine. Provided the assumption that the impact of a blade-strike is a function of the ratio of fish length to blade thickness (EPRI 2008; 2011; Amaral et al. 2020), similar conclusions may be drawn for large sturgeon individuals passing through proportionally large turbines. We used fork length to turbine diameter as a proxy for fork length to blade thickness, because blade thickness will scale proportionally with turbine diameter for a given runner design. The ratio of sturgeon fork length to turbine diameter in this study was 0.23 to 0.36. While limited knowledge exists of large sturgeon passage through hydropower turbines, one published example is the Annapolis Royal Generating Station, a tidal power hydropower facility in Nova Scotia with a single 7.6 m diameter Straflo turbine (Dadswell et al. 2018). Since the project's commissioning in 1985, a total of 21 dead adult Atlantic sturgeon (ranging from 146 to 203 cm fork length) with clear turbine-related injuries have been observed floating or on shorelines seaward of the hydropower project, which is likely an underestimate since dead sturgeon tend to sink. The ratio of fork length to turbine diameter for the fatally injured sturgeon at this site is 0.19 to 0.27, similar to the present study. The peripheral speed of the Annapolis turbine runner is 19.9 m/s, which is also within the operating conditions tested in this study. Crucially, many of these large individuals exhibited similar severing injuries to the juvenile sturgeon described here (see Supplemental Figure 1). The present laboratory-based results indicate that blade strike can pose a high risk to passing sturgeon, and furthermore that it can be effectively ameliorated through alterations to blade design.

Full scale turbines at hydropower facilities differ in size (<1 m to 12 m), speed (∼10 to 40 m/s [Ma et al. 2021, Odeh 1999]), and design (*e.g.* Kaplan turbine, Francis turbine), and the risk they pose to passing fish varies accordingly. The hydraulic conditions tested in this study (Table 1) are not identical to any particular full-scale hydropower facility, and the survival rates reported here should not be interpreted as representative of passage outcomes for all hydropower installations. However, the blade strike phenomena observable at small scale in this study and the difference in survival outcomes of passing fish provide valuable insights into the type and severity of blade strike traumas that can occur for larger fish passing through proportionally larger turbines operating at similar speeds to those evaluated here (15.0 – 27.9 m/s peripheral speed).

In addition to blade strike, barotrauma, fluid shear, and turbulence can also contribute to turbine passage mortality (Čada et al. 2001) and were not tested in the present study. All of these factors are necessary to consider when evaluating the risk that a turbine at any given operating point poses to passing fish. Furthermore, other components of hydropower turbines beyond the runner (stay vanes, guide vanes, etc.) should be considered for the risk they pose to entrained fish, and may benefit from morphological alternations that improve fish passage survival outcomes.

4.3. Comparison to other turbines and pumps designed for improved fish survival

Compared to other evaluations of turbines designed for improved fish survival, the speeds tested in this study were relatively high, up to 27.6 m/s at the blade periphery. Among similar turbine passage evaluations (Table 6), only the minimum gap runner (MGR) has been evaluated at comparable or higher speeds, up to 34.8 m/s peripheral speed (Dauble et al. 2007). These high-speed units also stand out as retrofits for existing hydropower turbines, as opposed to construction with highly different civil works and generator requirements compared to conventional hydropower. It is notable that the survival rate of juvenile white sturgeon through the model-scale RHT-type runner exceeds that of the 7.1 and 7.7 m diameter MGR units, with comparably sized fish (juvenile chinook salmon, mean fork length 16.6 cm at Bonneville Dam [Normandeau Associates Inc., Skalski JR, Mid Columbia Consulting, Inc 2000], 16.9 cm at Wanapum [Dauble et al. 2007], 13.0 cm at Ice Harbor Dam [Heisey et al. 2019)]). This suggests that RHT-type runners could be a viable retrofit option for enabling very high fish survival rates at similar high-speed large hydropower facilities.

When turbines and pumps are operated at peripheral speeds above those tested for fish impacts, survival rates tend to be lower than expected. Research on the Fairbank Nijhuis Axial Flow Pump (FNAFP) demonstrated much lower than expected survival rates for common bream (*Abramis brama,* 24%) and common roach (*Rutilus rutilus,* 70%) in field testing (Bruneel et al. 2024). Expectations for survival were based on a smaller-scale study conducted at a single peripheral speed of 13.9 m/s (Vriese 2009), whereas the field tests operated at higher speeds of 14.7 and 17.3 m/s. Turbines and pumps designed for high fish survival should be evaluated at the highest peripheral speeds present in real-world operations. In the present study, the RHT-type runner maintained a high rate of survival across the range of peripheral speeds (15.0 to 27.6 m/s) providing a broad range of deployment speeds over which fish survival is expected to be high.

4.4. Additional considerations for sturgeon passage

This study focused on effects of downstream passage through turbines, but there are other negative impacts of hydropower on sturgeon populations. The design of upstream fish passage facilities is a complex biological and engineering challenge, especially when aiming to accommodate a diverse range of migratory fish species and life stages. Upstream passage facilities have been shown to be highly effective at passing adult salmonids (Keefer et al. 2021), so many early attempts to pass other species relied on, unsuccessfully, adapting designs of facilities that worked for salmonid passage (Parsley et al. 2007). More recently, studies have focused on identifying characteristics of effective sturgeon upstream passage facilities. Cooke et al. (2020) describe a variety of upstream fish passage facilities that have been studied with regards to passing sturgeon with varying levels of success. Equal upstream and downstream migration rates are highly important. Jager et al. (2001) simulated white sturgeon populations in fragmented rivers and found that extinction risk remained high for populations linked by high downstream but low upstream migration rates. Thus, as the technology around downstream passage develops, there is continued need for research to improve upstream passage.

Sublethal effects of turbine passage on sturgeon are poorly understood (e.g. effects on feeding and growth, changes in fish behaviour, or stress responses). This study looked at acute rates of injury and mortality of turbine passage, but we posit that sublethal effects of turbine passage are correlated to lethal effects, at least directionally if not in magnitude or frequency. Under this assumption, the high rates of injury and mortality caused by passage past the conventional runner would be expected to yield greater sublethal effects than RHT passage. Sublethal stressors in fish can have a range of negative consequences, including reduced fitness, increased energy expenditure, and impaired immune function (Baktoft et al. 2020; Ben Ammar et al. 2020; Watson et al. 2020). The combined effects of sublethal stressors may be greater than the sum of individual impacts due to synergistic interactions between stressors (Crain et al. 2008). The sublethal impacts of RHT passage remain unstudied. Additional research is needed to draw conclusions on the long-term effects that downstream passage through an RHT-type runner may have on sturgeon.

Sturgeon are iteroparous, and thus their life histories require repeated spawning migrations over years (Rochard et al. 1990), typically necessitating movement into large river systems. The sympatry of sturgeon species with hydropower (Figure 1), and

Table 6. Field or lab test survival results for turbines and pumps designed for improved fish survival.

Turbine or pump designed for improved fish survival	Design characteristics	Study type and site	Peripheral speeds tested (m/s)	Diameter (m)	Species studied	Total survival (%)	Reference
RHT-type	Very thick, rounded, and swept leading edges, minimum gaps.	Laboratory test	15.0-27.6	0.55	Juvenile white sturgeon (*Acipenser transmontanus*)	99.1	Current paper
		Laboratory test	19.2	0.55	Adult American eel (*Anguilla rostrata*)	100	Watson et al. 2022
		Field test. Freedom, Maine hydropower plant, USA.	15.6	0.55	Juvenile alewife (*Alosa pseudoharengus*)	100	Watson et al. 2023
Alden turbine	Limited peripheral speeds, reduced blade number, rounded leading edges, minimum gaps, minimal pressure changes and shear stresses.	Laboratory tests	15.3, 22.0	1.2	Rainbow trout (*Oncorhynchus mykiss*), smallmouth bass (*Micropterus dolomieu*), American eel, white sturgeon, alewife, coho salmon (*O. kisutch*)	80.7-96.2 (rainbow trout) 89.5-97.4 (smallmouth bass) 98.3-99.6 (American eel) 97.0 (white sturgeon) 93.7 (alewife) 93.1 (coho salmon)	Cook et al. 2003
Fairbanks Nijhuis axial flow pump	Rounded and swept leading edges, and increased opening between blades.	Field test. Devil's Hole pumping station, Belgium.	14.7, 17.3	0.6	European eel (*A. anguilla*), common roach (*Rutilus rutilus*), common bream (*Abramis brama*)	100 (European eel) 70 (common roach) 24 (common bream)	Bruneel et al. 2024
		Field test. Saubach pumping station, Germany.	15.6	0.6	European perch (*Perca fluviatilis*), various wild fish	63.6 (European perch) 61.5 (wild fish)	Bierschenk et al. 2019
Very low head turbine	Low peripheral speed, large runner diameter.	Field test. Frouard hydropower plant, France.	9	4.5	Adult European eel	100	Lagarrigue et al. 2011
		Field test. La Glacière hydropower plant, France.	7.1-7.9	5	Adult and juvenile rainbow trout and common carp (*Cyprinus carpio*)	95.6-100 (rainbow trout) 98.9-100 (common carp)	Lagarrigue et al. 2013
		Field tests. Sites in Bavaria, Germany.	5.8-10.4	3.6-5.0	European eel, common nase (*Chondrostoma nasus*), brown trout (*Salmo trutta*), European perch, common barbel (*Barbus barbus*), common roach, European grayling (*Thymallus thymallus*), Huchen (*Hucho hucho*)	98.9-99.5 (European eel) 90.8-100 (common nase) 80.4-99.6 (brown trout) 91.5-100 (European perch) 72.7-96.2 (common barbel) 35.6-99.8 (common roach) 69.8-95.2 (European grayling) 69.7-97.1 (Huchen)	Mueller et al. 2022
Archimedes screw	Low peripheral speed, large runner diameter, minimal pressure changes and shear stresses.	Field tests. Sites in Bavaria, Germany.	0.5-4.4	3.2-4.3	European eel, common nase, brown trout, European perch, common barbel, common roach, European grayling, huchen	98.1-100 (European eel) 74-89.6 (common nase) 99.2-100 (brown trout) 50.3-100 (European perch) 98.7-100 (common barbel) 78.9-98.9 (common roach) 88.2-100 (European grayling) 100-100 (huchen)	Mueller et al. 2022
		Field test. Screw in the bypass channel of the Albert canal, Belgium.	2.2-3.2	3.1	European eel, common roach, common bream	97 (European eel) 81 (common roach) 63 (common bream)	Pauwels et al. 2020
		Field test. Screw on the River Dart, UK.	2.3-3.6	2.2	Brown trout (*Salmo trutta*), rainbow trout, European eel, sea trout kelts (*Salmo trutta*), Atlantic salmon kelts (*Salmo salar*).	100 (all species)	Fishtek Consulting 2007 and 2008

(*continued*)

Table 6. Continued.

Turbine or pump designed for improved fish survival	Design characteristics	Study type and site	Peripheral speeds tested (m/s)	Diameter (m)	Species studied	Total survival (%)	Reference
Minimum gap runner	Minimized the gap between the runner blade root and tip regions and the hub and outer wall.	Field test. Bonneville Dam Unit 6, USA.	27.9	7.1	Juvenile chinook salmon (*O. tshawytscha*)	95.7-97.0	Normandeau Associates et al. 2000 in Ploskey et al. 2007
		Field test. Wanapum Dam Unit 8, USA.	34.8	7.7	Juvenile chinook salmon	96.9	Dauble et al. 2007
	Minimum gaps and higher nadir pressures.	Field test. Ice Harbor Dam Unit 2, USA.	33.4	7.1	None - sensor fish used	N/A	Martinez et al. 2025
					Juvenile chinook salmon	98.2 – 98.6	Quaranta et al. 2020

Diameter refers to that of the turbine or pump runner/impeller. Peripheral speeds are those reported for speed at the outermost radius of the turbine or pump runner.

their life-history reliance on repeated, directional movement within the river system ensures repeated interaction with hydropower installments. As we have demonstrated, these interactions can prove acutely lethal. We simulated the impact of repeated passage to explore how a population of fish can rapidly be winnowed *via* repeated or sequential passage events. As an extant example, the Annapolis Royal Generating Station in Nova Scotia captures the large tidal flux of the Bay of Fundy twice per day. Each time the tide rises, there is the opportunity for an Atlantic sturgeon to become trapped above the dam and subsequently pass through the turbine as the tide recedes. In this case, a fish could conceivably pass through a given turbine twice a day. Our simulation results indicate that when using a conventional runner only two to three passages are required to reduce the passed population to 50% of its original number. Work by Dadswell et al. (2018) studying the Annapolis Royal Generating Station demonstrated its impact on American shad (*A. sapidissima*), striped bass (*Morone saxatilis*), and Atlantic sturgeon population size and structure. After hydropower operations commenced, populations of these fish became younger, smaller and with fewer repeating spawners. These population-level impacts are consistent with strong, size-dependent selective pressure, such as repeated passage past conventional hydropower turbines. Given the long lives of sturgeon (>40 years) the default expectation should be that if upstream movement is facilitated (e.g. tidally, sturgeon passage structures, etc.), then repeated downstream passage will occur. If safe downstream passage is not facilitated, then the high rates of injury and mortality will serve as lethal barriers to migration, thereby decimating populations and fragmenting habitats.

The effects of habitat fragmentation on sturgeon populations have been documented globally (Haxton and Cano 2016; Friedrich et al. 2019; Steel et al. 2019; Wang et al. 2025) with consequences to genetic diversity and overall population abundance. Research on lake sturgeon from the Black Sturgeon River highlights the impact of dams on habitat quality. Prior to the installation of the Camp 43 Dam, this population had access to both the natural spawning habitat in the upper watershed of the Black Sturgeon River as well as a highly productive habitat in Black Bay, Lake Superior for rearing and growth. Post installation, the now-bifurcated lake sturgeon population does not have access to both habitat types. This has resulted in the decline of the upper river population and indicators of detrimental genetic impacts on both the upper and lower river populations (Wilson et al. 2022). Facilitating fish movement can alleviate these impacts as fish gain access to historical habitat types and expanded genetic diversity.

Novel runner designs that improve fish survival and thereby reduce habitat fragmentation represent an important reconciliation between the needs of society for power and water management, and the use of the riverscape by resident species. In this context, hydropower runners, like RHT-types, can be designed to provide an effective additional pathway for sturgeon to safely migrate downstream through hydropower facilities. Improving the survivability of fish through hydropower turbines will remove an important barrier to downstream migration. To fully reconnect populations and habitats, improving upstream passage of hydropower barriers is necessary as well (Cooke et al. 2020). The deployment of technologies capable of achieving high fish survival across a variety of species and life stages for downstream passage will hopefully motivate the development of methods for effective upstream passage as well.

Research by Mueller et al. (2020) documented that turbine (Kaplan turbine) passage can have distinct rates of injury and mortality among different species of fish. While the RHT has been found to be generally protective of juvenile salmonids (Amaral et al. 2020), alewife (Watson et al. 2023), American eel (Watson et al. 2022) and presently white sturgeon, it is possible that the impacts of a conventional turbine on rates of fish injury and survival may differ from those observed for the juvenile sturgeon in this study. Additional research is needed to investigate whether other species experience similar risks associated with passage past a conventional turbine.

5. Conclusion

This study reinforces the strong effect of blade shape and runner design on fish survival during turbine passage. In this study, an RHT-type runner, with extremely thick and swept leading edges and minimum gaps, led to high survival and low injury rates for juvenile white sturgeon passage compared to a conventional thin-bladed runner when operated under similar hydraulic conditions. While many turbines are marketed as “fish friendly,” their true effectiveness depends on whether they can operate safely at conditions relevant to the hydropower fleet. RHT-type runners stand out in this regard, demonstrating high survival even at elevated peripheral speeds, conditions where other designs often fall short. As sturgeon and other freshwater species continue to decline globally, it is critical that hydropower turbine runner designs not only reduce immediate mortality but also address sublethal effects that can impact long-term health and behaviour. We are unable to address these concerns presently and future research is needed to evaluate the potential for delayed and sublethal impacts. Designing turbine runners that can truly offer safe downstream passage for sturgeon and other fish species requires a holistic understanding of both biological and operational factors.

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Ethics statement

Fish care and use for this study were approved by the University of California, Davis Institutional Animal Care and Use Committee (Protocol No. 23871).

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Data availability statement

Data will be made available on request.

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