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Safe passage for fish: The case for in-stream turbines[☆]

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ABSTRACT

Current hydro power turbine technology is reviewed regarding safe fish passage. Much of the literature has focused on dam turbine configurations, while some have recommended to develop in-stream turbines as an alternative and potentially more environmentally- and ecologically-friendly option. Throughout the literature, several key design parameters and considerations appear consistently, with which future turbines are recommended to be designed if installed near fish habitats or migratory routes. Design parameters and recommendations are compiled and examined here, and conclusions about future developments of hydro turbines are provided. Additionally, the criteria and considerations are applied to an in-stream turbine design, which is shown to exhibit fish-friendly operation over a wide range of riverine velocities with mitigated fish access to the tip region. It is shown that in-stream turbines are a future-friendly (environmentally, ecologically and socially) technology that can provide sustainable energy generation to people throughout the world as an alternative to dams, including those in off-grid communities with little-to-no access to electricity.

1. Introduction

Globally, only 23% of large rivers flow uninterrupted to their destined oceans, disconnected mainly by dams and reservoirs [1]. The traditional dam configuration blocks a body of water to create a reservoir providing an increased head for the turbine in the dam, where head directly relates to the difference of the total pressure that is theoretically available across the turbine. Dams and many real world run-of-river plants (ROR, such as Belo Monte, Santo Antonio, and Jirau in Brazil), unlike in-stream turbines (ISTs), are built across the entire span of the body of water and develop increased residence times, blocking fish from being able to migrate naturally [2,3]. Regardless of the installation configuration (dam, run-of-river or in-stream), the fundamental physics that govern the flow through the rotors are the same, however, the scale of energy produced and level of social, environmental, ecological, and financial (SEEF) effects will vary within a continuum. Namely, dams will produce the highest and most weather event independent energy density due to their large reservoirs and heads, but will produce the highest SEEF risk. On the opposite end of the spectrum are ISTs that will have the least individual SEEF risk of any of the configurations, traded off for the lower power density and more seasonal variability of energy generation. ROR will operate somewhere between those two configurations, balancing energy density and SEEF factors. To examine the balance of energy density and risk, the focus of this work is to examine the ecological risk of the devices, and to briefly cover the social, environmental, and financial factors for completeness.

While there are concepts like fish ladders and bypasses meant to mitigate the blockage of migrating riverine life by a dam, these often are found to be insufficient or ineffective in configuration, number, and size, leaving many a number of fish to retreat or attempt to pass through the turbine [4–7], depending on the time of day, preferred acclimation depth, among other variables [8,9]. This blockage or river disconnection, as well as other direct and indirect effects reduce the local fish biodiversity and stock, in all riverine locations: upstream of the reservoir, in the reservoir, and downstream of the dam [10,11], adding to other cumulative effects that will likely lead to more severe damage than the individual factors, such as habitat health degradation and modification [12]. For the fish that choose not to retreat, passing through a traditional turbine configuration encounter several canonical key mechanisms for injury or mortality: physical strike, pressure change, shear, and turbulence [13]; another mechanism that can have a negative impact on fish, but may not directly lead to injury or mortality, is the sound emitted from the device.

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Table 1
Fish safety criteria and considerations.

Phenomena	Risks	Sections	Configurations
physical strike	physical damage	2.1, 3.1	Dam, ROR and IST
Pressure change	Organ rupture, Organ malfunction	2.2, 3.2	Dam, ROR and IST
Shear	Physical damage	2.3, 3.2	Dam, ROR and IST
Turbulence	Disorientation	2.4, 3.2	Dam, ROR and IST
Sound	Behavior change	3.3	Dam, ROR and IST
Blockage	Behavior, habitat, and fitness impact	3.4	Dam and ROR

As an alternative to dams, an in-stream turbine is placed directly into the flowing body of water without significantly increasing the water level in front of the turbine and not blocking the passage as typically results from a dam. The bypassing flow that is inherent to (the design of) an in-stream turbine allows rivers to maintain high connectivity. Still, the risks involved with the device itself still need to be examined, and the acceptable operating range to meet the criteria needs to be investigated to ensure ecological safety. In this work, existing hydro turbine technology is reviewed in regards to effects on fish. Key design parameters and recommendations are compiled and examined from literature, and applied to an in-stream turbine. The model is simulated in a full-wheel 3D Computational Fluid Dynamics (CFD) environment to examine the breadth of fish-friendly operation over a wide range of river velocities. Finally, based on the review of critical safety criteria and the simulation results, conclusions about the design of in-stream turbines and future developments are provided. This study addresses critical aspects of the design of in-stream turbines as an alternative to dams to conserve the survival, health, and connectedness of riverine life and ecosystems.

2. Literature review of fish injury mechanisms

Table 1 covers the critical phenomena and the associated risks that will be examined in Sections 2 and 3 as they apply to turbine design. Note that in the turbine configurations column, there exist three main options: dam, run-of-river (ROR) and in-stream turbines (IST). The most common externally visible physical damages include, but are not limited to: fin tearing, scale loss, hemorrhages, dermal lesions, and partial fin amputations [14]. Additionally, internal damage may occur, including: injury to the swim bladder, and compressions, deformations and fractures of the spine, which can all lead to delayed mortality [15].

2.1. Physical strike

An injury from physical strike is considered to be when contact is made (either sliding or impact) with walls or structures that are associated with the turbine rotor, support piers or stator vanes. Injury from physical strike occurs when the relative velocity between the fish and a physical barrier induces a shear or pressure that is greater than the material moduli in question, where the scales, skin or organs are sheared or ruptured. There are several important factors involved in risk of physical strike: fluid velocity, fish velocity (which may be different than fluid velocity), wall velocity (nonzero for rotor blades), wall geometry, fish geometry, and gaps between moving and stationary walls or structures. These factors together determine the strike risk and possible extent of damage for a fish. One recommendation in the literature is to keep the peripheral blade speed below 6–12 m/s for minimal fish strike risk [16]. This range could have higher risk than originally thought at the higher velocities, based on experiments that have been performed to examine fish behavior and strike risk, in an attempt to quantify the effect of some of these variables [13,17,18].

Namely, new data on rainbow trout of lengths 110 to 163 and 182 to 236 mm (a fish length to blade thickness ratio (L/t) of approximately 1.14 to 2), showed that if a fish impacts the blades at an angle of 60 degrees between the fish direction of travel and the blade surface, the survivability of fish drops to and below 67% and 4.2% at strike speeds of 10 and 12 m/s, respectively [18]. Further, at 7 m/s, the tested fish survived at 98% or more through all of the degrees of impact with the blade surface tested (30, 60, and 90 degrees), and similar survivability at 10 m/s if the strike angle is at or below 45 degrees [18]. Comparatively, the 5 m/s criteria is used here as a conservative measure, allowing for larger than a 2 L/t ratio between the fish length and the blade thickness (longer fish and/or thinner blades), however, the strike speed could approach 10 m/s depending on the fish present and blade design developed. To minimize the risk of fish injury, it is concluded that blade strike velocities should be kept below 5 m/s, assuming that the fish in question are much longer than the blades are thick ($L/t > 2$). Additionally, it can be concluded from the literature that blade leading edges should be kept as thick and rounded as possible, blade spacing should be kept high, gaps between rotor blades and outer walls should be minimized, and gaps between rotor blades and gates or vanes should be maximized.

2.2. Pressure changes

Traditional dam-turbine configurations rely on small to large head differences, which is converted into extractable energy through a pressure drop across the turbine at a designed flow rate. As fish enter the turbine intake leading to the turbine, they experience an increasing pressure above atmospheric (depending on the depth of the intake below the surface of the reservoir), and then they experience a rapid decrease in fluid pressure as they move through the turbine section, that can approach a ratio of four [19,20] to over ten [16] from the gates to after the runner blades for typical turbines. A low minimum pressure relative to the pressure that the fish is acclimated to (the pressure at which the fish was in gaseous equilibrium, or neutrally buoyant before passing through the minimum pressure region) gives rise to several issues: rupture of organs, such as swim bladders and eyes, disruption of the function of the swim bladder (allowing for easy predation), and cavitation if pressures fall below the vapor pressure of the fluid, which can cause physical damage to fish.

The work done in [21] showed that the most important factor for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) is the ratio of acclimation pressure to minimum pressure, when compared to rate of pressure change, condition factor of the fish (a measure of the physiological characteristics of the fish, such as a weight to volume ratio), and total dissolved gas content of the water (the available amount of soluble gas that could be absorbed by the fish). It can be seen from the same work that if the minimum pressure does not fall below around half of the acclimation pressure for a given fish (an acclimation to minimum pressure ratio of 2), there is a low probability of injury or death. It was also concluded in [21] that the juvenile Chinook salmon that were studied responded well to slow decompression, though it has been commented in literature that other fish species might not respond well to even slow decompression [22].

A lower minimum pressure criteria in the literature allows the minimum pressure to drop to 30% of the acclimation pressure (a pressure ratio of 3.33) [16]. The author of [16] cites a figure from [23], justifying the criteria by shifting focus away from non-anadromous (bass and crappie) data points. The original cited work recommends a criteria of not allowing a minimum pressure below 60% of adjusted pressure (a pressure ratio of 1.67). The studies performed to gather the data for these two recommendations is commented by the original author as being "...old, poorly documented, have inadequate or no controls, and used only small numbers of fish" [23], and as such, newer, well-explored and well-documented data is considered here. Thus, the more restrictive criteria of not allowing a pressure ratio of greater than 2 is adopted here.

2.3. Shear

Similar to physical strike, damage from shear is due to relative velocity, but the velocity in question is of the fluid instead of a physical wall. According to experiments and simulations, around 1%–2% of a typical conventional turbine dam configuration will have shear rate (often referred to as strain rate) greater than 495 1/s, which is reported as the point where injuries to fish will tend to increase [17,24]. These regions are mostly areas associated with wakes behind structures, such as support piers or stationary gates or vanes, though the turbine rotor can also produce high shear rates near the tips, depending on the design and loads. The strain limit can be converted to a corresponding shear stress of slightly less than 1600 Pa (where 1600 Pa is calculated from 517 1/s) [17].

An additional criteria in the literature that could be used to evaluate a design is a lower strain rate level of 180 1/s [16]. This lower value is used for examining the "bulk" flow through a turbine passage, and not the entirety of the turbine rotating region. Most of the flow through a passage should be well-behaved and will not have as high of strain rates as would be found in the boundary layer near to solid surfaces, and so a lower criteria can be used to evaluate this region. It is additionally commented in [16] that in the boundary layer, where the strain rate is highest, the probability of physical strike is also at its highest, and so assumes that in the near-wall region, if physical strike risk is mitigated (through design blade velocity), then that region could be considered 'safe'. These two criteria can be used in conjunction, however, the 495 1/s criteria is cited here as the more robust measurement, as it theoretically is valid for the entire turbine passage, not just near-wall flow.

2.4. Turbulence

Driven by shear, the velocity gradients associated with turbulence can have two main effects on fish: physical shear damage of the fish body and disorientation by large scale vortical structures (eddies). Experiments with a controlled level of turbulence induced by generated shear stress can be performed, an example of which attempted to estimate the risk of mortality of small fish and larvae by a ship's propeller [25,26]. The study concluded that a linear relationship between shear developed by a boat's propeller and larval, egg, and juvenile fish mortality can be predicted, with larval fish being the most sensitive to shear. It is postulated that turbulence can also enhance predation by inducing disorientation if the turbulence intensity is high enough, but quantifying 'disorientation' is not simple, so no explicit criteria has been found as to an acceptable level of turbulence. It has also been noted that turbulence and disorientation can also affect the fish's ability to eat, swim, as well as where they choose to make a habitat [27]. Though no singular criteria was found in the literature to determine a turbine design's safety with regards to turbulence, it is likely that any risk of physical damage to the fish will be minimized as long as the shear criteria from Section 2.3 is met.

2.5. Existing traditional configuration rotor designs for risk reduction

With the aforementioned parameters, a few novel designs for traditional turbine configuration rotors have been developed to reduce risk to fish; the most prominent of these designs is the Alden turbine. The Alden turbine's main features are a runner that rotates with its outer shroud, eliminating relative velocity between the blade tip and the outer wall, and also has only three blades to reduce the probability of strike. Another design is the Minimized Gap Runner (MGR), which alleviates some of the issues associated with blade strike risk to fish, namely, minimizing the gap between the runner blade root and tip regions and the hub and outer wall, lowering the risk of fish becoming trapped and injured [28,29]. The company MJ2 set out to develop a very low head (VLH) turbine that can minimize civil works costs, as well as having higher survival rates than typical high head devices [30]. Other companies have also developed their own fish friendly concepts, working to increase the ease for fish to pass through the gate and runner sections without harm, such as GE and Natel [31,32]. Of the designs that have been tested, an over 90% survival rate is often quoted, however, full-scale, in-situ operational survival studies indicate that the performed studies may not accurately represent the total survival probabilities when considering all native species that may attempt to pass through the rotor: mortality rates were found to vary between 3 and 83% depending on the turbine configuration and local species present [33]. One specific example of why these previous studies have been shown to be inaccurate is the VLH turbine: it has been noted that only surface-acclimated fish were examined in the original study, which will experience the lowest pressure drop possible through the rotor, increasing the chance of survival [8]. Measuring both the instantaneous and average survival over various seasons and times of day would be beneficial to evaluate the probability of riverine life survival, with varying diurnal behaviors and water column depth preferences affecting survivability [34,35] when passing through the rotor as well as potential delayed conditions after the passage.

3. Fish safe design considerations for an individual rotor

It has been noted that in-stream turbines have a relatively small environmental impact, and can be considered to be very low risk devices, even when in small array configurations [36–38]. The fish-safe design considerations of an individual rotor are examined here.

3.1. Physical strike

For low-head turbines in a traditional dam configuration, it has been reported that blade strike is the most critical issue for fish safety [39]; the issue of impact with the rotor blades themselves exists for any turbine configuration. However, in-stream turbines allow the fish to pass around the turbine or retreat at any point up until the fish reaches the rotor blades themselves, giving the fish more time and space to react to the turbine. For fish passing through the turbine rotating section, in-stream turbines have the advantage of generally being lower solidity than their traditional counterparts, allowing for more space between the blades for fish to pass through [40].

For in-stream turbines, there could exist a critical rotation-per-minute (RPM) of the rotor that can increase the chance of fish survival; the common design for "low-speed" devices is around 15–40 RPM [13,41–44]. There is a design choice, however, to design the turbine at one end or the other of the aforementioned range, due to the different ecological phenomena or design constraints. At the low end of the range, rotating at very low RPM can be seen as safer than higher RPM in the case of fish impact with the rotating blades (physical strike), due to low RPM designs being associated with large turbine diameters, such as the Cape Sharp turbine (6–8 RPM) [45]. These large diameter, slow rotating turbines can allow for large gaps between the blades and also provide the fish with more time to maneuver around the blades, facilitating more effective fish passage. Towards the higher end of the range, rotating above 20 RPM has been noted as being the point where fish tend to avoid the local area around the turbine, and thus would not attempt to pass through the turbine [46] which could also reduce the risk for strike, though this may introduce migration route and habitat choice changes. A study in [41] showed that of all of the observations of fish encountering a vertical axis in-stream turbine in a real river channel, while the rotor was spinning only two individual fish entered the rotor (out of approximately 150 measurable fish passings with the rotor present), and only when the current speed (approximately 0.25 m/s) and rotor speed were low (17 RPM).

This RPM phenomena could have varying importance to the fish attempting to pass through depending on the species, channel geometry, time of day, number of fish in the group, among other variables, as was shown by work from various authors. For example, [47] noted an approximately 0.477 probability of fish entering an Ocean Renewable Power Company (ORPC) Turbine Generating Unit (TGU) in a tidal channel during the combined night and day, when it was rotating at an average of 21.4 RPM. It was also shown that the probability of fish entering during the day was much lower than at night, as has been indicated throughout the literature in regards to fish response to light stimuli [48,49], particularly, only approximately 4% of the observed fish passed through the turbine during the day while it was rotating. [50] also showed that certain species of fish may still choose to pass through a runner that is rotating above 20 RPM, as was shown by the avoidance of only 33% for hybrid striped bass (*Morone saxatilis* x *Morone chrysops*), while much closer to 100% for the other tested species (86%–100%). Much like the way light affects the behavioral response of fish via the visual sensory system, the reason for the critical speed being around 20 RPM is presumably due to the nature of the interaction between the turbine emitted sound waves and the fish auditory sensory systems: the inner ear (similar to a human's ear), and the lateral line (a network of pores and nerves under the scales). [51] commented that the low frequency stimuli results in an elongated 'near field radius', allowing the fish to sense the flow disturbance from much farther away, which could lead to increased likelihood of attempting avoidance maneuvers. The influence of turbine sound on fish will be examined further in Section 3.3.

3.2. Pressure change, shear, and turbulence

Based on a study in [52] where computational simulations of a 5-m radius turbine rotating at 21.5 RPM (2.25 rad/s) were performed, it has been shown that in-stream turbines can have pressure drops of one order of magnitude or more less than a typical high-head dam-turbine configurations: the maximum ratio of total pressure change (dynamic and static) was shown to be approximately 1.1 near the blade tip. The relatively high minimum pressure corresponds to a high survival rate of fish in regards to pressure effects, as well as a low risk of cavitation damage. The time of decompression is also noted as an important factor, which is shown to be approximately of the same order for in-stream turbines as traditional dam-turbine configurations when considering a full blade resolved geometry (BRG) CFD model, however the author notes that the time for decompression is longer based on the results of Blade Element Momentum (BEM) CFD simulation [52].

Similarly, shear and turbulence produced by a typical in-stream turbine have been shown to be low in most of the turbine. The shear rate is shown to peak around 300 1/s (from blade resolved geometry CFD simulation), which is less than the 495 1/s criteria for fish safety [52]. The numerical investigation concluded that the only region of issue for shear is very near to the tip (within 0.01 m), where access can be mitigated with the introduction of a shroud or nozzle/diffuser around the periphery of the rotor, as it would be more difficult for fish to encounter this region. The turbulence length scale was shown to reach the peak of 1.7 m at the end of the domain (approximately 300 to 400 m after the turbine), and the largest turbulent kinetic energy eddies behind the blade tips have a length scale of approximately 10 cm. For small fish with swim bladders, this could cause disorientation, and thus mitigating the ability of fish to reach near to the blade tips would be beneficial in design.

3.3. Sound

Though not necessarily a direct injury mechanism, the emitted sound from a turbine can still have an effect on fish. It has been known since at least the 1980's that sound can affect how fish will interact with regions around dam turbines [53]. Fish have two main acoustic sensing systems: the inner ear and the lateral line [54]. The two systems work in concert to produce a complete flow disturbance image (direction and magnitude) in the fish's brain, by analyzing near-field (approximately 1 to 2 fish body lengths away) and far-field (greater than 2 body lengths; the maximum range varies with the fish species) disturbances. These auditory sensors detect both water-convected sound pressure waves and lower frequency particle motion (the near-field motion of particles) [55]. If a swim bladder is present, the bladder acts as a third auditory sensor, converting acoustic pressure into particle motion for the inner ear to detect [56].

According to [57], producing external interference to the natural frequencies emitted and heard by fish can affect: fisheries distribution and density, fish growth and reproduction (or 'fitness'), predator–prey relationships, and fish communication. Any external noise source could affect these natural interactions of fish, to a degree that depends on the frequency spectrum emitted by the source. Manmade disturbances can emit loud acoustic disturbances, from boats, barges, and underwater machines. Underwater noise emitted from a dam-turbine configuration has been of little focus in the literature, though it can be an important study in an attempt to understand fish behavior proximal to dams and to minimize fish entrainment through hydropower plants [58–61]. With minds geared towards fish safety and gaining an insight into fish behavior relative to underwater machinery, investigations have been conducted to quantify sound produced from in-stream turbines. [62] in particular concluded that the sound level produced by a TidGen turbine is about the same as the natural environment at high water velocity (by utilizing a cylindrical sound spreading model), and slightly higher. The author also states that at a distance of 21 m away, it is likely that some species of fish cannot hear the turbine. This means that the turbine will not interfere with fish interactions except possibly close to the turbine itself, where the fish could likely avoid due to the pressure sound level produced by the turbine rotation. It has been noted, however, that using the individual classic spreading models (spherical or cylindrical) can lead to an underestimate of the sound levels from the source [63]. In another investigation, [64] concluded that there is a measurable change to fish behavior from short- and long-term playback of a pre-recorded turbine soundtrack, but for the fish species studied, the behavioral changes in an experimental setup were not statistically significant enough to determine behavior in the case of an actual in-stream turbine in nature.

3.4. Bypasses and ladders

Traditional dam configurations should have systems in place that attempt to allow fish to bypass the turbine intake and safely continue swimming up or downstream. However, these systems can be ineffective, not allowing all fish to pass through, due to their geometric setup and location [4–7], and often go over budget, averaging around twice their projected per meter costs [65]. Unless the specific species is particularly adept at jumping over obstacles, or laterally altering their path of motion to seek open routes, many of the fish bypasses or ladders can block migration and normal fish behavior. Several authors have investigated alternatives to current fish bypass configurations to increase their effectiveness [66–69]. Unfortunately, most of these efforts have been made after large dams have been constructed in major waterways, and may not be implemented due to the costs of renovating the existing structures. Utilizing ineffective fish bypass systems, modern dams provide only two main options to migrating fish: retreat or attempt to pass through the turbine.

A ladder is defined here as a structure designed to allow fish to pass upstream across the dam. In contrast, a bypass is defined as a structure designed to allow fish to choose to avoid to enter the turbine penstock and can continue swimming downstream past the dam. These two categories will be referred to in general and called "fish passage" systems. There are five main types of fish passage systems: pool/weir ladders, vertical slot ladders, chute fishway ladders (also called "baffle" ladders), culverts, and fish locks and elevators [70]. The pool/weir type is the oldest of the ladder technologies, made up of a long ramp with "buckets" or "boxes" for the fish to jump in and out of (or through,

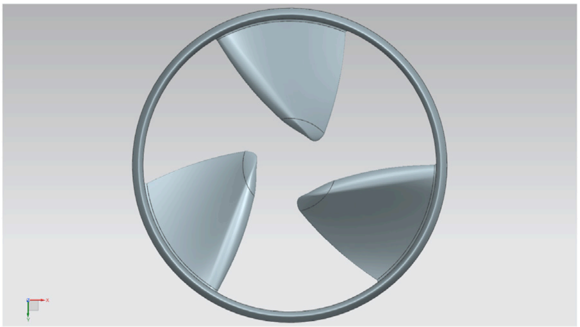

Fig. 1. Ducted rotor model flow-direction view.

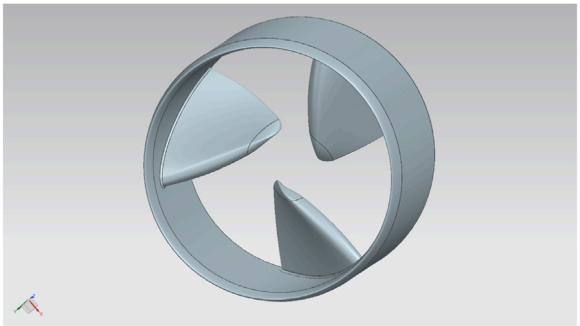

Fig. 2. Ducted rotor model oblique view.

for an orifice/port type) to move up and down the ramp, similar to a lock for a boat. The chute or "baffle" ladder is similar to the vertical slot ladder, in that they both include structural protrusions that are designed to produce a flow behavior that is advantageous for the fish to travel through with respect to flow speed, orifice sizes, areas for rest, etc. The culvert-type ladder is a duct of some sorts that allow natural flow through it (such as through a road or dam), and can include internal baffles to keep the flow velocity from becoming too high for fish passage. Lastly, the fish elevators are the most unique of the aforementioned passage technologies, in that the fish are collected in a holding area, and are transported via an elevator over the dam. Other types of passage systems exist, such as removing the barrier to flow (dam removal), as well as the newer-coined "nature-like" or biomimetic bypasses, which attempt to mimic natural rapids or river sections [71]. The last method is to collect the fish and transport them in barges or trucks to move them to the other side of the dam, or transporting them in helicopters, giving them the name "flying fish" [72]. The question arises whether these are implemented sufficiently in number, location, and scale for current dam systems.

For in-stream devices, the creation of bypasses or ladders is not necessary, due to the natural bypass around the devices themselves. The bypass is created by the hydraulic nature of flow to diverge around a body, as opposed to the converging nature of reservoir flow towards an inlet, such as at a dam intake. This would also hold true for farms of in-stream turbines, if designed effectively, see Section 3.5.

3.5. In-stream turbines in farms

Another difference between in-stream and dam-turbine configurations is that in-stream turbines generally need to be designed in larger numbers of units to develop large power potentials. This is due to the fact that in-stream turbines are extremely low head turbines, and thus rely heavily on flow kinetic energy (which is partially converted into a potential energy due to flow resistance) to convert to mechanical shaft energy. Placing turbines in high blockage ratio farms, however, could possibly lead to issues with the natural aquatic environment, if the spacing between turbines is made too small (in both the streamwise and the crossflow directions). If the cross-stream spacing between turbines is too small, aquatic life might have a more difficult time maneuvering around the turbines, and the blockage effect could become too great, reducing the total power output of the turbine array [73] and the ability of the river to recover a natural flow steady-state [74]. The optimum number of turbines and their spacing will depend on the channel geometry, flow characteristics, individual turbine design, and the type and quantity of aquatic life present.

3.6. Riverine health

Along with the life supported by the riverine environment, the organic and inorganic materials transported by the flow also play an important role in the ecosystem. The sediments, comprised of organic and inorganic components of soils, silts, sands, and solids, as well as trapped gases and un-dissolved compounds are needed by plankton, farmland, and riverine life throughout the river. The sediments provide nutrients, a balance of water quality, and habitat for aquatic life. It has been shown that in-stream turbines can have a local effect on the sediment dynamics of a river by scouring below the turbine and depositing sediment towards the outside of the channel and downstream [75,76] depending on the shape of the river and the flow velocity. The severity of the influence of the turbine on the sediment dynamics is likely related to the blockage ratio of the turbine device(s), though no existing literature was found to provide a functional relationship between them; the advantage of in-stream devices being that unlike with a dam, the sediment will still transport downstream through the natural bypass and not be blocked from reaching its ultimate destination.

4. Investigation of range of fish-friendly behavior

Based on the aforementioned injury risk considerations from Sections 2 and 3, a hubless rotor (see Figs. 1 and 2) was designed to investigate the range of fish-friendly behavior of an in-stream device when deployed in a configuration such as that shown in Fig. 3 where the natural riverine bypass region can be seen, through which fish, debris, and nutrients are free to travel past the turbine in either direction. The design parameters and considerations are described in the following sections.

4.1. Model and mesh

To design the rotor blades, a spanwise-sectional velocity triangle design method was utilized to determine blade angles. The rotor orientation is chosen to be axial, due to the high power density over a wide range of tip speed ratio (TSR, shown in Eq. (1)), with a configuration similar to a Kaplan or propeller turbine (a specific speed of 0.73, based on Eq. (2)). The camberline and 3D point cloud were developed in BladeGen and modeled in Siemens NX, and then imported into ANSYS for meshing and Computational Fluid Dynamics (CFD) simulation. The mesh comprised of a mixture of 12.5 million tetrahedral and hexahedral elements for the turbine, shroud, and flow domain as shown in Figures 4 and 5, with domain spacing shown in Figure 4. The mesh quality was measured in terms of the skewness and the orthogonal quality: the maximum element skewness was 0.851 and the minimum orthogonal quality was 0.182.

$$TSR = C_m/U \tag{1}$$

$$\sigma = \sqrt{\phi^*}/\Psi^{3/4} = 2.108 * n * \sqrt{\dot{V}}/e^{3/4} \tag{2}$$

where $C_m = \sqrt{C_{ax}^2 + C_r^2}$ is the meridional velocity, $U = \omega * R$ is the tip speed, $\phi^* = \dot{V}/pi * R^2 * U$ is the capacity coefficient, $\Psi = 2 * e/U^2$

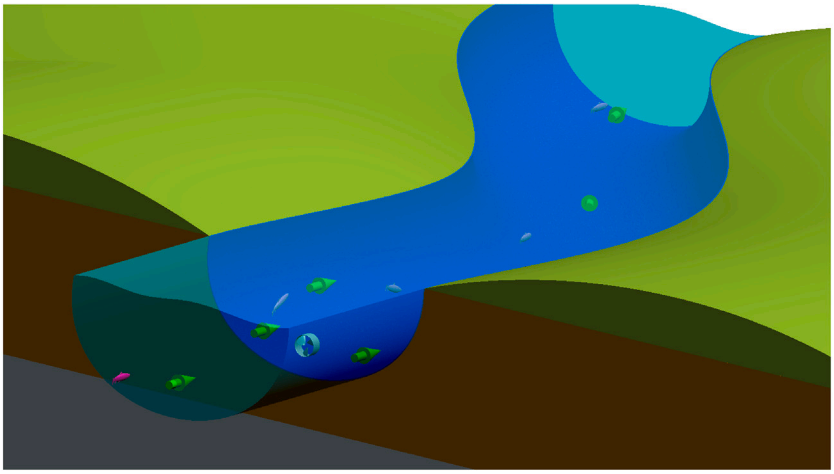

Fig. 3. In-stream turbine in a river channel.

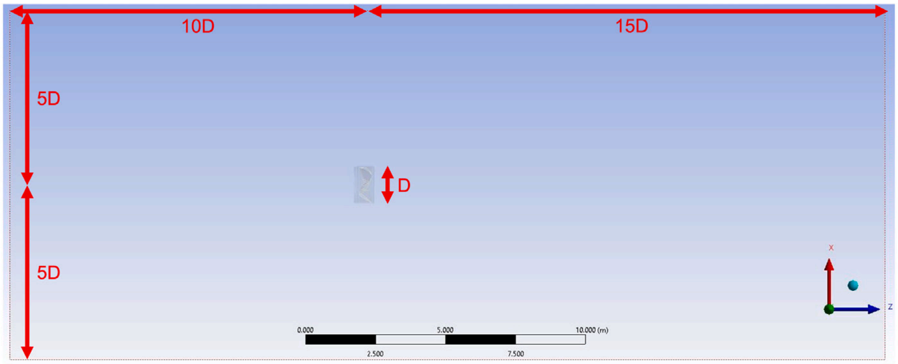

Fig. 4. Computational domain.

is the pressure rise (or fall) coefficient, $\dot{V}$ is the volume flow rate, and $e = \tilde{e} * \eta = \eta * U * (C_{u1} - C_{u2})$ is the massflow specific shaft work. It is noted that C_{ax}, C_r and C_u are the axial, radial, and tangential components of absolute velocity, respectively. The rotor is designed to be hubless, and thus instead drives a generator at the rim of the blades instead of in the hub, such as the simplified model in Fig. 6. The hubless design is chosen due to the benefit of any fish or debris manage to resist the natural bypass flow and make it past the trashrack (not shown) can travel through the open center. Additionally, backward-leaned blades can help to pass the fish or debris through without contacting the blades, making the design "self-cleaning" (see Fig. 4).

4.2. Computational domain setup

The turbine was simulated in a transient, full-wheel 3D flow environment in ANSYS Fluent for two main reasons: simulating the bypass region around the device, and to evaluate the turbine inlet speed from the channel inlet conditions, with the interaction of the turbine and duct included. The turbulence closure problem was handled with the $k - \omega$ Shear Stress Transport (SST) model, in order to enhance the accuracy of the turbulence modeling near to the blade walls as well as far out into the fluid. This is done by combining the standard $k - \epsilon$ and $k - \omega$ closure models, and blending them between wall and free-stream regions. Eqs. (3) through (6) show the set of equations that are solved in ANSYS Fluent, with the k–ω SST closure model. The difference between the standard $k - \omega$ and the SST model is in the functional form of the turbulent viscosity μ_t and the turbulent Prandtl numbers σ_k and σ_ω that are used to calculate Γ_k and Γ_ω in Eqs. (5) and (6). The SST model used a hyperbolic tangent function to blend $k - \omega$ and $k - \epsilon$, instead of purely using $k - \omega$. The production (G), dissipation (-Y), and user source terms (S) for both k and ω are similar among the standard and SST $k - \omega$ models, with a few constants and calculation logic components that set them apart.

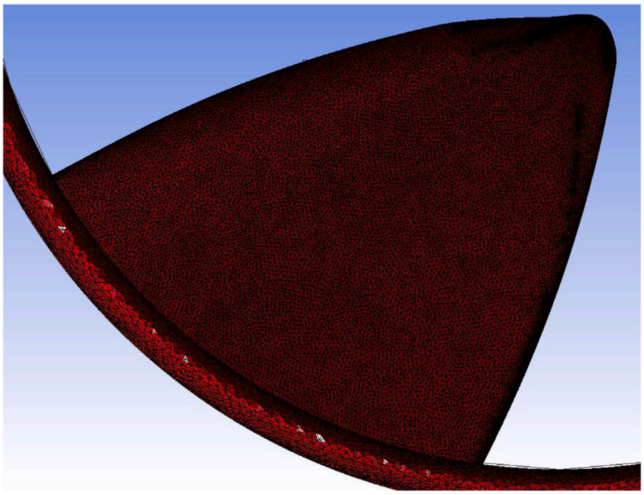

Fig. 5. Ducted rotor blade surface mesh.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{4}$$

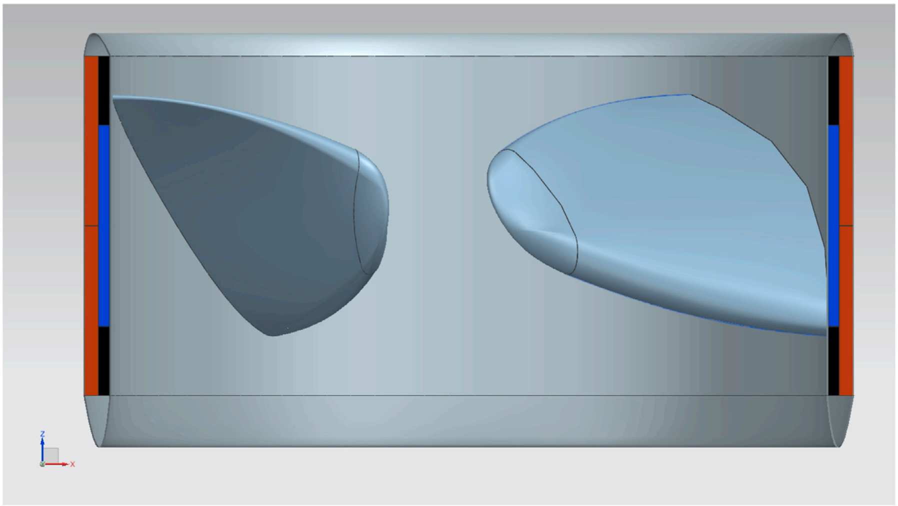

Fig. 6. Cross-section of the in-stream turbine, with a simplified rim-drive generator. The black blocks are bearings, the dark blue blocks are magnets (rotating with the blades), and the red blocks are the stator windings and core (stationary with shroud).

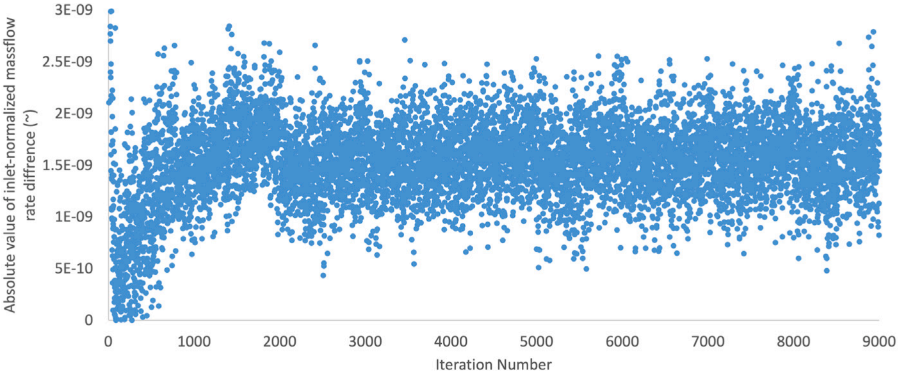

Fig. 7. Absolute value of the massflow rate difference between the inlet and outlet normalized by inlet massflow rate versus iteration count.

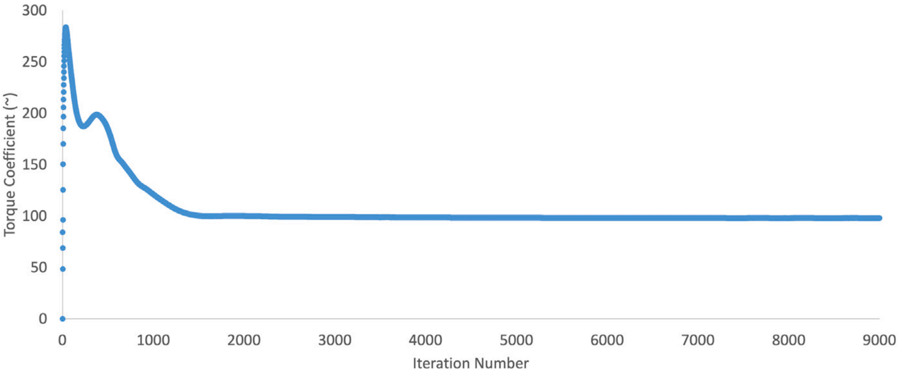

Fig. 8. Torque coefficient versus iteration count.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}(\Gamma_k\frac{\partial k}{\partial x_j})+\widetilde{G}_k-Y_k+S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)=\frac{\partial}{\partial x_j}(\Gamma_\omega\frac{\partial\omega}{\partial x_j})+G_\omega-Y_\omega+D_\omega+S_\omega \tag{6}$$

The boundary conditions were set as: velocity inlet (at 1 m/s), a pressure-outlet (at zero gauge), and the other outer domain surfaces were set to symmetry conditions, to simulate a turbine far away from the free surface or river walls. The spatial and temporal finite difference schemes were all evaluated at second order, and the pressure-velocity variables were coupled, with a Courant number of 2. To model the motion of the rotor, a sliding mesh technique was implemented. The rotating reference frame, consisting of a cylinder of fluid that represented the turbine-turned flow was given a rotational mesh motion at 2.09 rad/s, and the same treatment was given to the walls associated with that fluid zone. The flow domain was initialized with the inlet conditions, and was solved implicitly with a time step of one millisecond. The solution was allowed to time-step for at least two full blade rotations

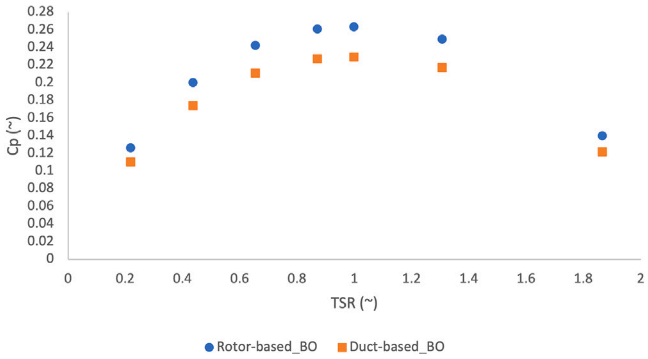

Fig. 9. Plot of power coefficient over tip speed ratio, based on the rotor and duct areas.

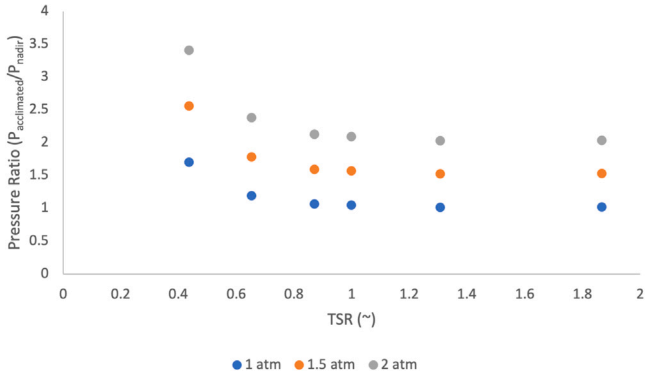

Fig. 10. Plot of pressure ratio over tip speed ratio, at three acclimation pressures: 1 atm, 1.5 atm, and 2 atm.

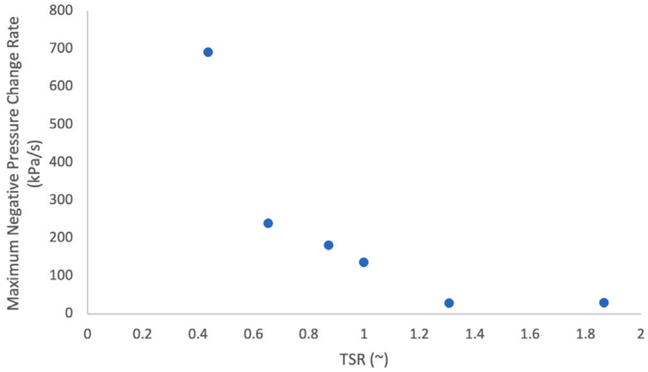

Fig. 11. Plot of maximum negative pressure rate of change over tip speed ratio.

(6000 time steps, or 6 s), and was allowed 100 iterations at each time step to converge the tracked variables to a residual of $1 * 10^{-5}$. The simulation is considered converged once the inlet-normalized massflow rate difference between inlet and outlet reached a semi-steady low level, and the torque coefficient on the blades reaches a quasi-steady level (fluctuations are about a constant mean value), as is shown in Figs. 7 and 8.

4.3. *Simulation results*

The initial design case was simulated at a TSR of approximately unity. The TSR was varied from 1.87 to 0.22 by varying the inflow velocity, mimicking large changes in seasonal river flow rates, while the generator maintains constant RPM. The performance of the turbine design was measured in terms of its ability to meet the aforementioned criteria as well as its ability to produce power. The shaft power is reported in terms of the power coefficient, and the 'fish-friendliness' of the design is measured in terms of the maximum strain rate and the minimum pressure encountered in the flow. The results calculated from Fluent are shown in Figs. 9–13.

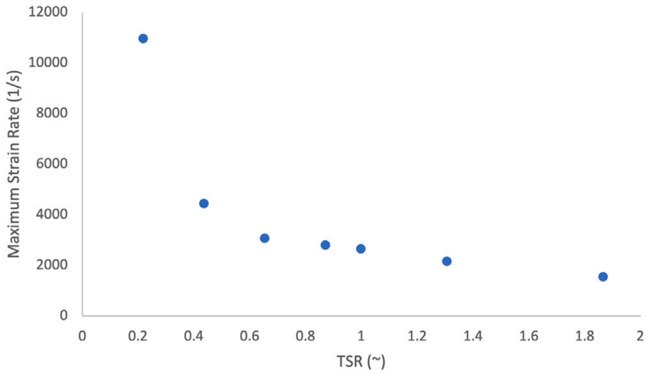

Fig. 12. Plot of maximum domain strain rate over tip speed ratio.

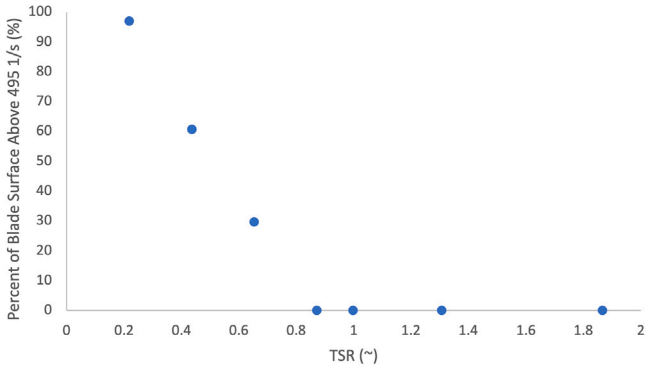

Fig. 13. Plot of percent of blade surrounding volume above criteria of 495 1/s over tip speed ratio.

4.3.1. *Power coefficient*

The primary metric to evaluate the performance of a turbomachine is the efficiency or power coefficient, where the maximum power coefficient was found for the simulated design to be just over 0.26 using the rotor diameter as the basis for maximum kinetic flux, or 0.22 when considering the duct outermost diameter, as can be seen in Fig. 9. Comparing this peak power coefficient to the so-called Betz limit yields a relative efficiency of 39%–44%, comparing to a bare rotor on a 1-D momentum calculation basis. However, the maximum power of free-flowing devices has been investigated in the literature for various device-environment configurations, with no clear answer yet as to the true upper limit, or equations relative to the most accurate basis for calculation (the turbine inlet streamtube, or the outlet streamtube where mixing is complete downstream). Taking the analysis of Betz one step further, using the results of the rotor disk model (adding wake rotation), Eqs. (7) and (8) can be used to evaluate a somewhat more realistic value for maximum power coefficient than Betz [77]:

$$\lambda^2 = \frac{(1-a_2)(4a_2-1)^2}{(1-3a_2)} \tag{7}$$

$$C_{p,max} = \frac{8}{729\lambda}\left[\frac{64}{5}x^5+72x^4+124x^3+38x^2-63x-12ln(x)-4x^{-1}\right]\Big|_{x=(1-3a_2)}^{x=0.25} \tag{8}$$

Using these two equations allows for the calculation of a maximum power coefficient equal to 0.39 at the design point. This increases the

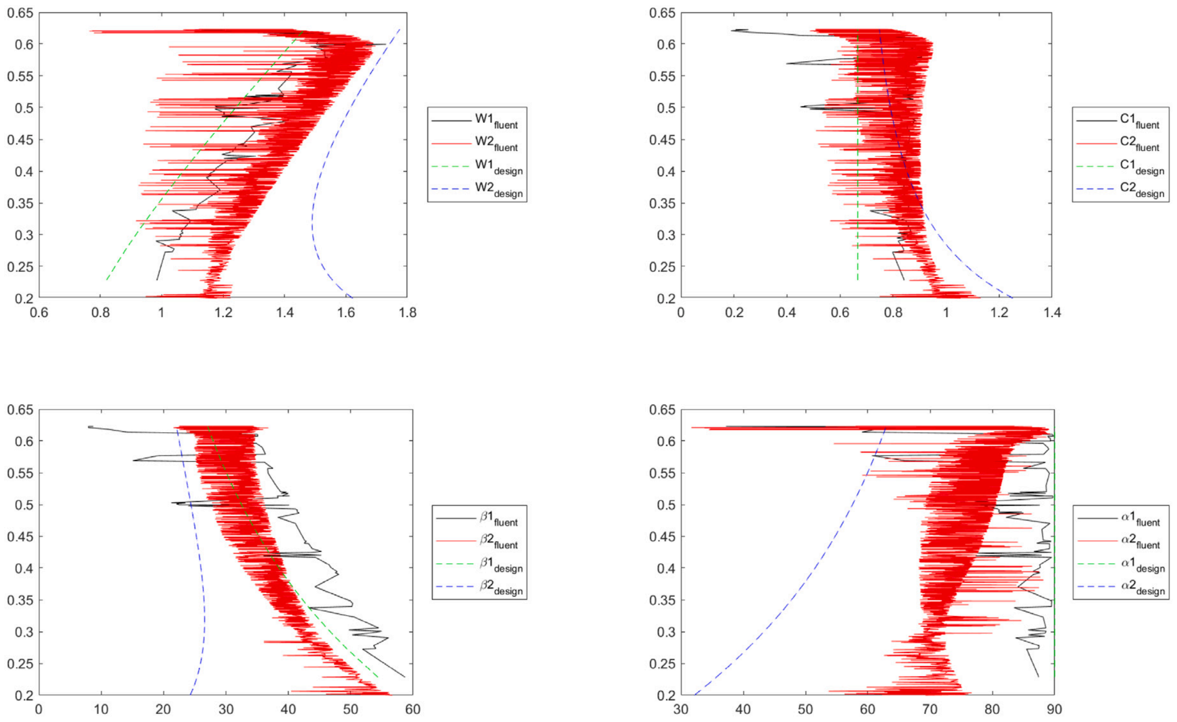

Fig. 14. Comparison of designed blade triangle velocities with CFD output.

efficiency of the design to around 55%–63% when utilizing rotor disk theory over pure actuator disk theory.

4.3.2. Pressure

The goal for the change of pressure experienced by a fish is to maintain pressure ratio lower than a value of two, which is shown to be true over the range of acclimation pressures in Fig. 10 for most of the design points considered. At acclimation pressures higher than two atmospheres, the peak performance point and higher velocities would present too high of a pressure ratio to keep injury probabilities at a minimum. This may not be a problem, however, depending on the placement of the turbine within a river channel, because a bottom-dwelling fish may not move quickly or close enough towards the surface to swim through the turbine-affected flow if the turbine was not placed on/very near to the bottom. Similarly, the maximum negative rate of pressure change is shown to be acceptable when compared with the industry-used 550 kPa/s criteria [16], down to a TSR of approximately 0.65.

4.3.3. Strain rate

The criteria for strain rate is to not exceed 495 1/s in flow regions that fish will likely pass. This results are examined in two ways relative to this criteria, based on the maximum strain of all mesh elements (Fig. 12) and the percent of the blade surface above the criteria 13. Fig. 12 shows that on a hyper-local maximum strain basis, none of the examined design conditions have an acceptably low level of shear; in other words, even if one mesh element experiences over-criteria strain rate, then the design fails. However, Fig. 13 tells a different story by examining the entire high-strain region, namely, near to the blade surface, and the percent of the blade surface that is above the criteria. It is found that at a tip speed ratio of 0.871 and above, the percent of the blade surface (calculated by element volume) that is above the criteria is nearly null; only a very small number of elements near the blade "tip" (the blade root for the hubless design considered here) could present risk. To further avoid risk, the presence of the duct mitigates riverine access to the tip, and the hubless open center can encourage (by lower pressure change and flow resistance) fish to swim through without needing to swim past the blades.

4.4. Postprocessing

To better visualize and analyze the performance of the simulated machine, it was desired to examine the flow and turbomachine variables qualitatively and quantitatively. The ANSYS solver package CFX does not easily allow full-wheel 3D environment simulation within the turbomachinery toolset (only a repeated flow passage with a traditional hub and case). Therefore, analysis needs to be done with general visualization/evaluation tools (simple geometry-bound plotting, post-processing of elemental flow values, etc.), or needs to be developed externally with the simulation data. In this case, an "unwrapped" view of the flow passages was desired (visualization on a 2D axial–tangential directional plane), thus MATLAB was chosen as the best environment for analysis for its strong visualization toolset. Figs. 14–17 show the output from the MATLAB script. Fig. 14 shows the comparison of the free-vortex design with the near-blade data output from Fluent. Figs. 15–17 focus on the 2D visualization of a flow passage on either side of one blade, in terms of the relative flow velocity vectors and contours at three root-of-the-sum-of-the-square (RSS) radial span locations: 10%, 50% and 90%.

It can be seen from Figs. 15–17 that the relative velocity vectors align well with the blade shapes through the flow passages. Fig. 14 indicates that, when calculated using the cell-centered values, the mass-average span difference between the designed relative velocity angles (β) and the CFD calculated angles are approximately 4 and 11 degrees, at the leading and trailing edges, respectively. For the absolute velocity angles (α), the calculated mass-averaged differences are approximately 5 and 22 degrees, at the leading and tailing edges. The relative angle difference can be qualitatively seen in Figs. 15–17 in that the relative flow is well-aligned with the blade surfaces, with a difference of a few degrees at the leading and trailing edges, leading to reduced power extraction via less swirl difference ("unswirling") than designed.

5. Recommendations and concluding remarks

The canonical injury mechanisms of dam-turbine configurations have been reviewed, and applied to fish safe turbine design with the addition of RPM and sound considerations. In this work, it has been shown

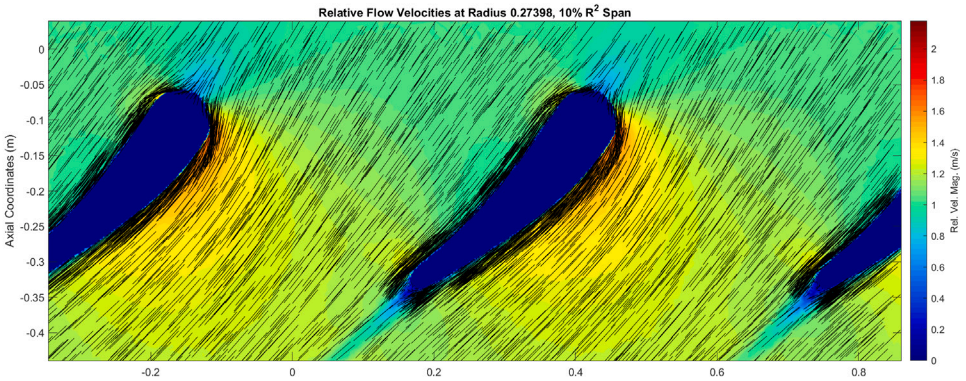

Fig. 15. Relative flow velocity vectors and contours at 10% square radial span, using nodal values.

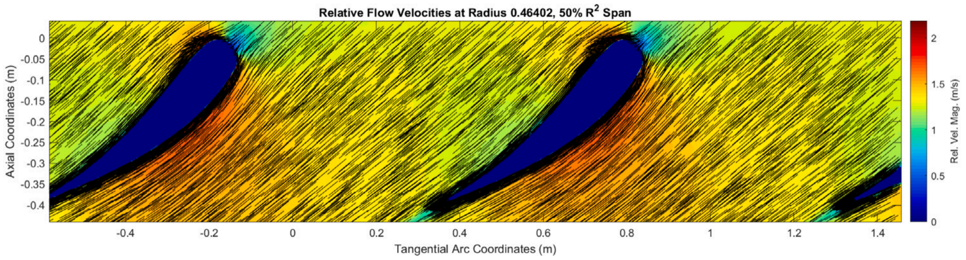

Fig. 16. Relative flow velocity vectors and contours at 50% square radial span, using nodal values.

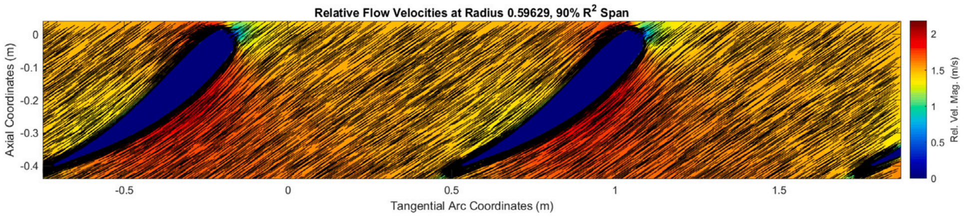

Fig. 17. Relative flow velocity vectors and contours at 90% square radial span, using nodal values.

that in-stream turbines can operate with low risk to the surrounding aquatic environment in regards to physical strike, pressure, shear, and turbulence if the following are included in the design process:

- Keep tip strike velocity below 5 m/s (balance of RPM, free stream velocity, and rotor radius)
- Keep maximum strain rate less than 495 1/s
- Keep maximum pressure ratio less than 2
- Operate at low RPM (around 20 RPM)
- Long blade chord and gaps between blades large (depending on size of largest fish present in waterway and trashrack design)
- Eliminate or minimize gap distances between stationary and moving parts
- Keep distance between turbines as large as possible, if placed in farms
- Mitigate fish access to blade tip region

It is to be noted that these design criteria are from the available data in the literature, corresponding to the studied species in question: future experiments will show how well these parameters will hold for other fish species. It is recommended that in-stream technology be further investigated, particularly in regards to in-situ riverine interaction with the turbine. One of the main gaps in the current knowledge is the effect of the sound produced by a single real installed turbine and by a farm of turbines. It is thus recommended to perform short- and long-term experiments before and after the installation of real turbine unit(s) to fully understand the local temporal effects on aquatic life as well as to monitor the behavior change in native riverine species. Acceptable criteria for safe sound levels (consequently, RPM and flow velocity) should then be established to minimize the interference with the local aquatic life and should be included in the suggested list of design criteria for fish-friendly design. Thus, it is recommended that hyperlocal environmental and ecological evaluations be done to understand the species of animals, plants, and people present, and the specific needs and risks associated with them. Utilizing in-stream turbines will allow for an increase in future hydraulic base load for both centralized on-grid and distributed off-grid applications in an environmentally- and ecologically-friendly manner, being designable with fish-friendliness in mind, and having a natural bypass to allow riverine ecosystems to remain continuous. In-stream turbines have the potential to be applied as an energy alternative to dams that also allow for natural transport of riverine life as well as nutrients and riverine materials; in-stream turbines are a future-friendly energy source that can help to maintain the connectivity and health of waterways for future generations.

CRediT authorship contribution statement

Erik Brown: Conceptualization, Methodology, Writing – original draft. **Samer Sulaeman:** Writing – review & editing. **Raul Quispe-Abad:** Writing – review & editing. **Norbert Müller:** Writing – review & editing, Supervision. **Emilio Moran:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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