Fisheries and Oceans Canada | Pêches et Océans Canada
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Ontario and Prairie Region
Canadian Science Advisory Secretariat
Science Response 2024/035

RISK TO FISH FROM VERY LOW HEAD TURBINE INSTALLATIONS

Context

One of the most significant concerns with hydroelectric power production is injury and mortality of fish passing through turbines during intentional or unintentional downstream passage (Algera et al. 2020). There are several mechanisms by which fish can become injured or killed as a result of passage (entrainment) through turbines as summarized by Čada (2001), including rapid and extreme pressure changes, cavitation, sheer stress, collision, turbulence, and grinding. As a result, developers have been working for decades to create 'fish friendly' turbines that incorporate features to make them less hazardous to entrained fish (Fraser et al. 2007, Foust et al. 2011, Romero-Gomez et al. 2022, Watson et al. 2022). To determine whether a turbine is indeed 'fish friendly', not only does mortality rate need to be quantified, but sublethal effects must also be considered (Ferguson et al. 2006). Many current hydro entrainment mortality monitoring plans typically involve periodically walking downstream of the turbine to observe and record dead fish; this level of monitoring likely does not yield reliable information as to the risk to fish. Increasingly, other methods of monitoring entrainment mortality are being employed, including fish flushing trials and modelling to estimate the death of fish from entrainment, but to date there are no standard or consistent methods considered as 'best practices'.

Several novel turbine technologies (Quaranta et al. 2022) are being proposed at new and existing infrastructure (weirs, non-power dams), which still need to be assessed for their 'fish friendliness' (Cooke et al. 2011) and Canadian application (NRCan 2018). Low head (< 15 m) dams are being explored as viable hydropower options, which could add between 5-10 GW of power (Tung et al. 2007, or about 10% of Canada's 82.3 GW of installed capacity, IHA 2022) to Canada's total energy generation capacity. The Very Low Head (VLH) turbine, developed by MJ2 Technologies, is a unique, cost-effective class of turbines designed to address a head of 1.4-4.5 m, discharge of 10-30 m^3/s and up to 500 kW of capacity (Fraser et al. 2007, Quaranta et al. 2022). The standard configuration consists of 8 Kaplan-style adjustable runner blades and 18 fixed guide veins, with a diameter of 0.6-5.6 m. The VLH turbine design incorporates several features designed to minimize impact to fish including:

- using a large runner diameter (which allows for low velocity and negates the need for a draft tube),
- minimizing velocity and pressure gradients,
- minimizing the tip gap and the number of blades, and
- ensuring the shape of the Kaplan style runner blades is blunt (Fraser et al. 2007).

A VLH turbine that was installed in 2015 at Wasdell Falls on the Severn River, ON, provided a unique site for the first study of this new technology in Canada. The VLH installation on the Severn River was supported by NRCan as a demonstration site to represent a clean and reliable low-impact source of electricity. VLH technology allows for significant cost savings related to civil works due to its modularity concept, making the development of VLH hydro resources economically feasible, yet it is important that testing was conducted in Canada to determine if this technology can indeed be considered 'fish friendly' for Canadian taxa and systems.

Using acoustic telemetry, live fish passage, and sensors designed to record the conditions experienced by fish as they pass through turbines, this research aimed to provide a direct quantification of the risk of entrainment, injury, and immediate or delayed mortality to fish resulting from the VLH turbine installation at Wasdell Falls. Since the Wadell Falls installation was at the site of an existing dam, this research was designed to specifically quantify the increased risk to fish from the installation of the turbine at an existing barrier, not to assess the full impacts of the presence of the dam itself. The risk of entrainment to resident fish upstream of the VLH was estimated by measuring the rate of entrainment of tagged fish via acoustic telemetry. Live fish, representative of the local fish community, were flushed through a VLH turbine to estimate expected injury and mortality rates for resident fish that pass through the VLH turbines. Together, the likelihood of entrainment and risk of injury or mortality from turbine passage can be used to provide an estimate of the overall risk to the fish upstream of the VLH. In addition to live fish passage, electronic sensors were passed through the VLH turbine to provide quantitative information on the physical conditions experienced by fish during passage, some of which may not have presented as obvious injuries during the live fish trials. The results presented in this Science Response Report are intended to provide direct quantification of risk from VLH turbines to Fisheries and Oceans Canada (DFO)'s Fish and Fish Habitat Protection Program (FFHPP). Specifically, the objectives are as follows:

1. To determine the overall risk to the resident fish community from the VLH turbine installation at Wasdell Falls;
2. To determine the level and type of monitoring required at future installations; and,
3. Identify uncertainties and knowledge gaps, and if necessary, recommend additional information, research, monitoring, data collection, etc. that is required to further assess the potential impacts of VLH turbine installations on Canadian fish communities.

This Science Response Report results from the regional peer review of December 5-6, 2023, for the Risk to Fish from Very Low Head Turbine Installations.

Background

The 'fish friendliness' of turbines is only part of the equation regarding the fish population-level implications of a turbine installation. If the entrainment rate is low, a turbine's 'fish friendliness', or lack thereof, will have little influence at the population level (Lin et al. 2022). In the present study, acoustic telemetry was used to estimate entrainment rates of common resident fish species at the Wasdell Falls VLH turbines, injury and mortality rates of individuals were assessed, and physical conditions of turbine and crest gate passage were quantified. The focus was to quantify the increased risk to fish from the turbine installation at a long-term existing barrier.

Of concern regarding the risk of injury and mortality for fish during turbine passage are: changes in pressure, cavitation, shear stress, and mechanical injury such as collision, grinding, or impingement (Čada et al. 1997). Pressure forces acting on fish are perpendicular to the body and changes in pressure during turbine passage at hydro facilities can be severe enough to cause barotrauma in fish (Čada et al. 1997, Brown et al. 2014). Cavitation results when pressure decreases to critically low values, at which point the collapse of vapour bubbles or cavities can cause violent shock waves that result in damage to turbine infrastructure and injury in fish (Čada 2001, Long et al. 2019). Shear stress, in contrast to pressure, acts parallel to the body of fish and can cause injury and mortality from masses of water moving past each other in different directions or at different velocities, such as in areas adjacent to fixed objects like hydro infrastructure (Čada et al. 1997, 2006, Deng et al. 2005). Mechanical injury and mortality can result from situations where fish come into physical contact with infrastructure, such as directly striking turbines or grinding and impingement between moving parts of the machinery (Čada et al. 1997).

Sensors or ‘Sensor Fish’ have been developed that are small, plastic tubular devices, similar to the size of a salmon smolt, that have the ability to capture in situ measurements of pressure, temperature, and three-dimensional linear acceleration/rotational velocity/orientation at sampling frequencies of up to 2048 Hz (Advanced Telemetry Systems Sensor Fish [ATS, ARC800], Deng et al. 2014). They have been used successfully at a variety of infrastructure to quantify passage conditions experienced by fish and provide guidance for mitigation measures (Fu et al. 2016, Deng et al. 2017, Duncan et al. 2018). A typical pressure profile for conditions during turbine passage (Figure 1a) has been demonstrated through sensor deployment and computational fluid dynamics (CFD) modelling that generally shows increasing pressure when approaching the turbine (T1), followed by a sudden and often drastic decrease in pressure when passing through the turbine runner (T2), and by another small increase in pressure when encountering tail race conditions (T3) (Carlson et al. 2008, Richmond et al. 2014, Martinez et al. 2019a). The lowest (nadir) pressures during passage have been shown to occur on the downstream (suction) side of the turbine runner and along the tip of the runner opposite the hub (Richmond et al. 2014). A similar (typical) pressure profile was observed in the VLH at Wasdell Falls from this study (Figure 1a). However, the control deployments lacked the signature drastic decrease in pressure (i.e., there was no obvious lowest or ‘nadir’ pressure recorded for controls) as was observed in turbine treatments that are the major concern for fish (Figure 1b). We used these sensors, in addition to live fish trials and estimates of entrainment rate, to gain insight into the overall risk posed by the VLH turbine at Wasdell Falls to the Severn River fish community. Definitions of terms used through this report can be found in Appendix A.

Analysis and Response

Methods

Study Site

Experiments were conducted between June 2017 and October 2019, at Wasdell Falls Hydro Power Project on the Severn River near Washago, Ontario, Canada (44.780804, -79.293895). In 2015 Wasdell Falls became the first site in Canada to employ VLH turbines for hydro power generation (NRCan, 2018). Developed by MJ2 Technologies of France, these turbines are designed to operate with very little head (as low as 1.4-3.2 m) and overall conditions similar to run-of-the-river (Fraser et al., 2007). Each turbine consists of a Kaplan runner with eight adjustable blades, with features incorporated in the design to minimize negative effects on fish (Fraser et al., 2007). The site at Wasdell Falls, which has a normal operating head height of 3.8 m, contains three turbines that can be independently operated to discharge between 5.4 to 20 m^3/s each, with a portion of the flow continuously spilling over the top of the dam (crest gate) when in operation (Figure 2c,d). In addition to the VLH turbines, a spillway on an adjacent dam structure provides a supplementary means of water control and an alternative downstream passage route for fish (Figure 2a). Historic (1965-2020) mean annual flow at Wasdell Falls was 46.9 m^3/s. Mean annual flow in 2017 was 92.4 m^3/s, the highest on record, while in 2018 the mean annual flow was 60.7 m^3/s (Figure 3). The dam at Wasdell Falls was initially completed in 1914 as part of a power generation project and there have been no natural channel features available for passage since that time. A more detailed description of the study site can be found in Tuononen et al. (2022a).

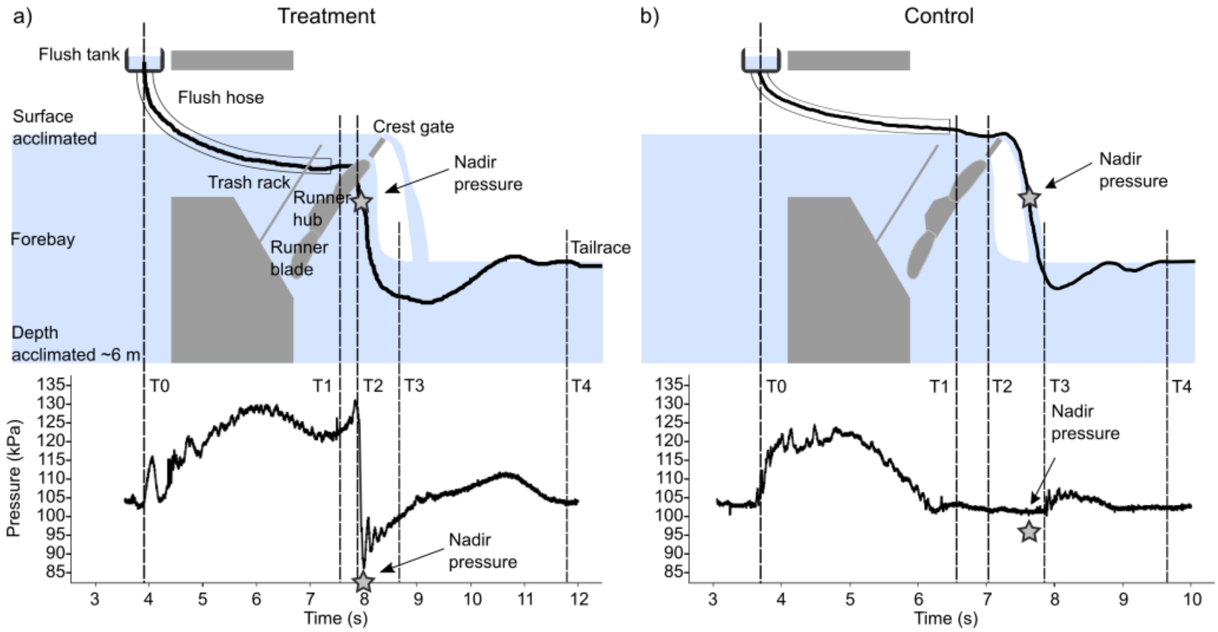

Figure 1. A schematic of the path that live fish and sensors in experimental and control groups experienced during trials. The solid black lines represent the path of a fish or sensor (upper) and corresponding pressure profile (lower) for a) the treatment group passing through the turbine, and (b) the control group passing over the crest gate. Examples of pressure profiles for treatment (a) and control groups (b), including time stamps identifying the start and end of each passage zone (vertical dashed lines), are included. Zones are defined as: T0-T1 = Fish/Sensor flush through trash rack, T1-T2 = Turbine approach, T2-T3 = Turbine passage and exit to tailrace, T3-T4 = Tailrace. Grey stars demonstrate where the nadir (lowest) pressure was experienced in each case.

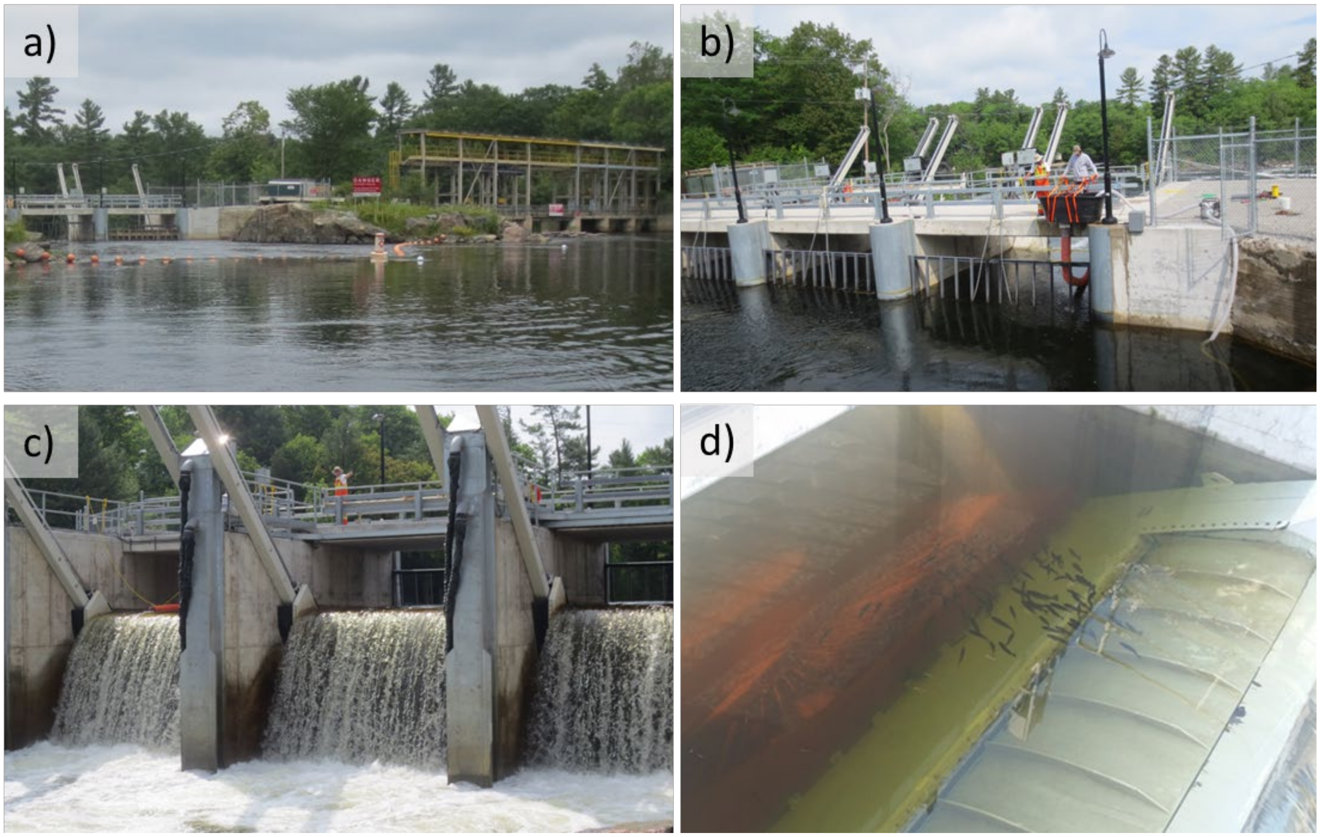

Figure 2. a) Water control dam on east side of island from the Very Low Head (VLH) turbines; b) VLH turbines at Wasdell Falls looking from upstream to downstream. Flushing tank and fish introduction hose visible at the third turbine; c) VLH turbines looking from downstream to upstream. Flow over crest gate is apparent as all three turbines are operating, and orange end of flushing hose is visible at the third turbine; d) Congregation of fish holding position in the water flowing over the crest gate, on the upstream side of the dam (photo credits: a-c - DFO; d - Glenn Hepinstall).

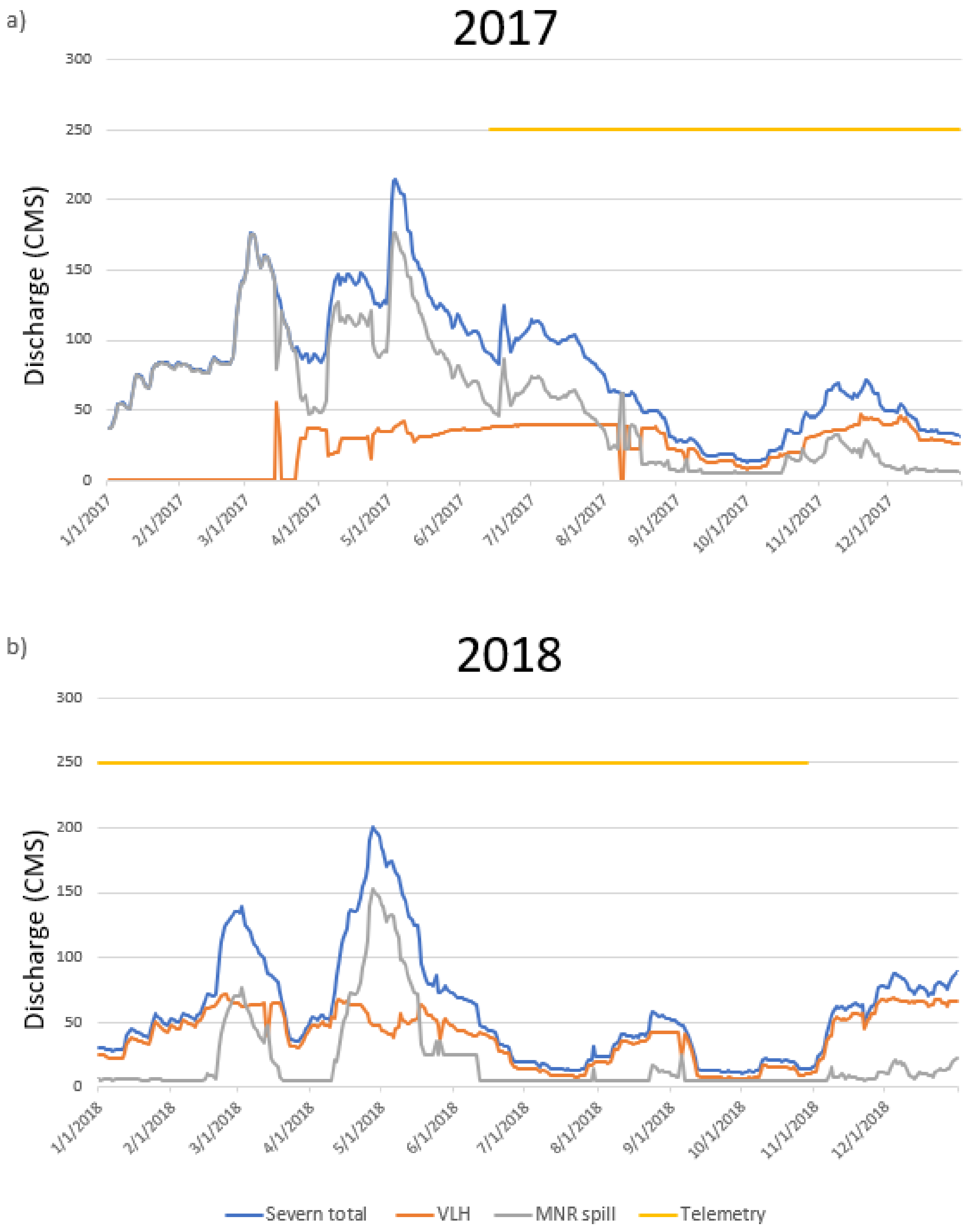

Figure 3. Daily mean discharge in cubic meters per second (m^3/s) on the Severn River at Wasdell Falls (blue line) in (a) 2017 and (b) 2018. The proportion of flow in the very low head turbine (VLH) channel and Ministry of Natural Resources (MNR) spillway are identified by the orange and grey lines, respectively. The yellow line denotes the period during which the volitional passage telemetry study was conducted. Mean annual flow was 92.4 m^3/s and 60.7 m^3/s in 2017 and 2018, respectively. Historic mean annual flow is 46.9 m^3/s.

Volitional Passage Behaviour

Acoustic telemetry was used to estimate the risk of entrainment to resident fishes by monitoring fish movement near Wasdell Falls between 14 June 2017 and 6 November 2018. A combination of boat electrofishing and angling were used to capture fish for acoustic telemetry tagging. All fish captured that were of adequate size to support an acoustic tag (~75 g; tag mass < 1.5% of fish mass as per Brown et al. 1999) were used and thus species proportions reflect what was captured and met these criteria. Fish that were too small to tag were not targeted or retained, and, therefore, movement behaviour analysis is not representative of the full fish community in the river. A total of 138 individuals across eight species (68 Smallmouth Bass (*Micropterus dolomieu*), 7 Largemouth Bass (*Micropterus salmoides*), 43 Rock Bass (Ambloplites rupestris), 3 Walleye (*Sander vitreus*), 4 Northern Pike (*Esox lucius*), 6 Channel Catfish (*Ictalurus punctatus*), 6 White Sucker (*Catostomus commersonii*), and 1 Pumpkinseed (*Lepomis gibbosus*)) were tagged with Juvenile Salmonid Acoustic Telemetry System tags (JSATS; Lotek Wireless, Newmarket, ON). While these tags allow for relatively small fish to be tagged the smallest individuals of this population (< 75 g) were not captured in this assessment of volitional passage. The JSATS tags were developed to be used in noisy environments and to avoid tag collisions when many tagged fish are present in a system and high ping rates are used. However, they do still generate false detections under some conditions, which need to be filtered out of the data prior to processing. All tagged fish were released near their capture locations within 3 km upstream of the VLH turbine. A total of 24 model WHS 4200 acoustic receivers (Lotek Wireless, Newmarket, ON) were deployed upstream and downstream of the VLH site, including nine concentrated in the forebay area, to track fish passage events through the VLH (Figure 4). Detection efficiencies were estimated using reference tags following the methods of Kessel et al. (2014). Residency time within each of the three forebay areas (VLH forebay, Water Control Dam Forebay, and Pre-forebay groups; Figure 4) was estimated for each species. Evidence of post-tagging mortality was not observed. The historic (1965-2020) mean annual flow at Wasdell Falls was 46.9 m3/s while mean discharge during the volitional passage monitoring was 56.4 m3/s (Median 48, lower quartile 24.8, upper quartile 72.6). Despite a surplus of water during 2017, discharge through the VLH turbines was generally only 50-75% of maximum turbinable flow due to ongoing maintenance of one of the turbines (Figure 3). The 2018 season saw extended periods with maximum turbinable flow. Additional details, including the tagging procedure, tag sizes, acoustic receiver array setup, telemetry data filtering, and statistical methods can be found in Tuononen et al. (2022b).

Live fish passage

To determine live fish injury and mortality rates during turbine passage, boat electrofishing and angling were used to capture fish for live fish entrainment trials. Live fish flushing trials occurred June 18-22, 2018 at an average total river discharge of 35.7 m^3/s. The total discharge through the turbine during live fish flushing was 10 m^3/s (i.e., blade opening at approximately 50% of potential). Total head elevation differential between the forebay and tailrace ranged from 4.0-4.4 m. A total of 141 individuals representing five species (Largemouth Bass (29), Smallmouth Bass (48), Rock Bass (36), Northern Pike (24) and Walleye (4)) were used (See Tables 1 and 2 in Tuononen et al. 2022a). All fish were implanted with a passive integrative transponder (PIT) tag for individual identification purposes to ensure pre- and post-injury assessment were performed on the correct fish. All fish were also outfitted with balloon tags to facilitate recovery (Salalila et al. 2023). A subset also received an acoustic tag to monitor for delayed mortality (1 week) or migratory behaviour (> 4 months) after passage. The experiment consisted of two treatments; a control group that was flushed over the crest gate, and an experimental group that was flushed through the VLH turbine. Note that this design allowed for testing of turbine passage but not for other environmental consequences of the dam and further added a potential confounding factor of the approximate 4 m drop to the plunge pool. As water velocities at the turbine approach are low, entrainment of live fish required the use of a flushing apparatus (Figure 1a and 2b), which did not replicate the behaviour and conditions that would occur with an entrained wild fish. Absolute risk of turbine passage mortality was calculated by dividing the number of mortalities in an experimental group by the total number of individuals in that experimental group. Binomial probability confidence intervals were calculated for absolute mortality rates using the Hmisc package in R-studio (R Core Team, 2019, Version 4.2.2). Relative risk of immediate and delayed mortality was calculated with the following formula:

$$RR = \left[\frac{T/n1}{C/n2} - 1\right]100 \qquad \text{Equation 1}$$

Where T is the number of mortalities in the treatment group, C is the number of mortalities in the control group and n1 and n2 are the total number of fish in the treatment and control groups, respectively. The control group was regarded as having a 100% baseline risk and the treatment group was expressed relative to the control group. When the control group had zero mortalities then a ‘1’ was added to both the treatment and control groups to calculate relative risk. Additional details on the live fish passage methods and statistics used can be found in Tuononen et al. (2022a).

Sensor Deployments

Advanced Telemetry Systems Sensor Fish (ATS, ARC800, USA; length x diameter 8.99 x 2.45 cm) were used in this experiment to measure the physical passage characteristics that would approximate those experienced by entrained fish passing through a VLH turbine. ATS Sensor Fish is a patented technology developed by the Pacific Northwest National Lab (PNNL), and measured pressure, 3D acceleration, and rotational velocity at a rate of 2048 Hz (Deng et al. 2014). Sensor Fish, with balloon tags attached (Salalila et al. 2023), were entrained via the same flush apparatus used for live fish (Figure 1a and b; and Tuononen et al. 2022a). Sensor Fish were flushed directly into the turbine (treatments) or the water surface to spill over the crest gate (controls). Sensor Fish were recovered downstream of the VLH turbine and data for each deployment were downloaded and saved while sensors were prepared for redeployment.

The sensor deployments occurred on October 2-3, 2019, with discharge through the turbine maintained at 10 m3/s. The turbine was operated with the blade angle open 50%, as was the case for the live fish trials. The total head elevation differential between the forebay and tailrace ranged from 4.15-4.18 m. In total, 34 treatment and 30 control deployments were performed with Sensor Fish.

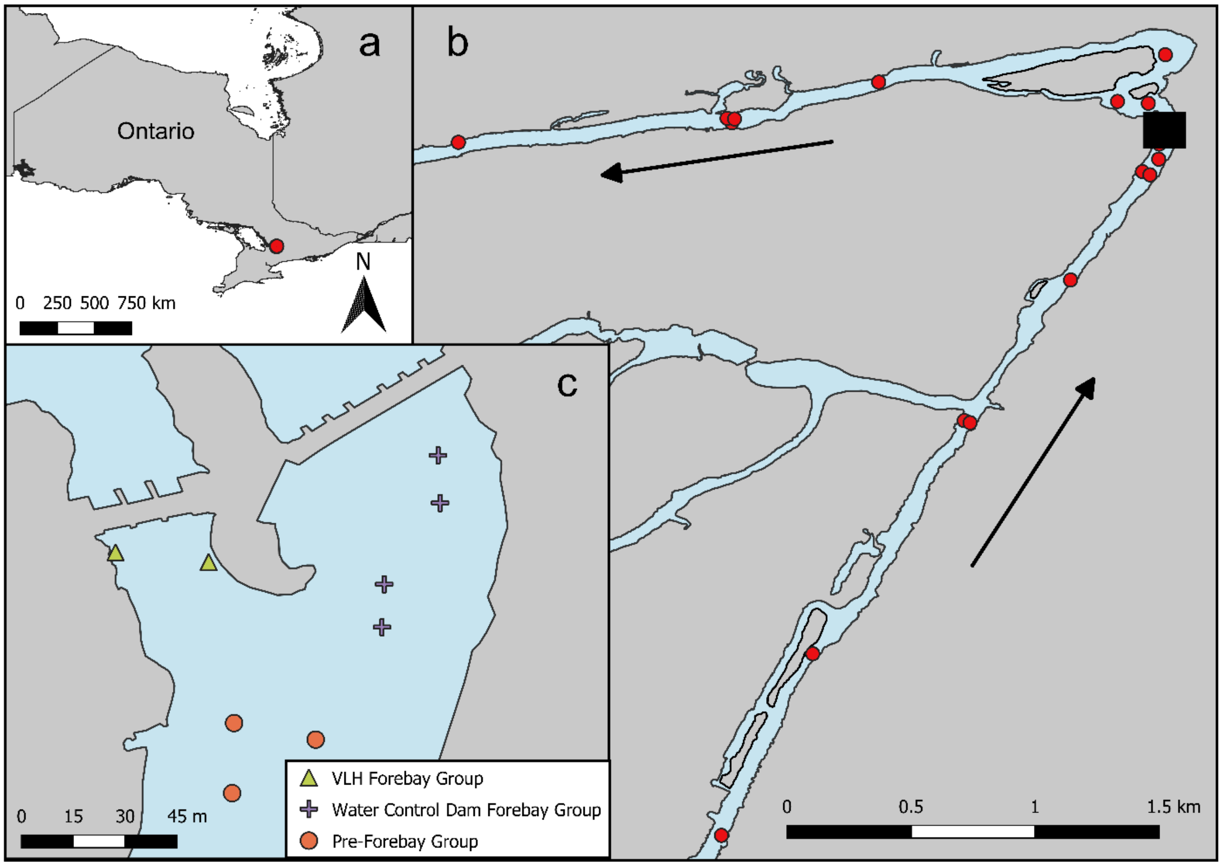

Figure 4. Adapted from Tuononen et al. (2022b). a) Location of the study site (Wasdell Falls) within Ontario, Canada - circle; b) Locations of stations in the entire acoustic telemetry receiver (red circles) array deployed from summer 2017 to fall 2018 on the Severn River with arrows showing flow direction and black square showing inset of c; and c) Closeup of receiver array and station groupings upstream of the very low head (VLH) turbines at Wasdell Falls. Note that these are stations of deployment and that not all receivers were deployed concurrently.

Sensor Fish Data Processing

Data from the ATS Sensor Fish were initially processed using the Hydropower Biological Evaluation Toolset (HBET), which was designed for analysis of Sensor Fish data (Hou et al. 2018). Data were uploaded, plotted as time series, and visually inspected in HBET. Time stamps were manually placed at specific times to define regions in the data associated with events that occurred during sensor deployments. Determination of time stamp placement for each plot was based on characteristic patterns evident in the pressure, acceleration, and velocity profiles. Time stamps were placed to filter data for each region of interest, specifically: the flush event (T0 and T1), turbine passage for treatments and spill over the crest gate for controls (T2 and T3), and tailrace region (T3 and T4) (Figure 1). Time stamps were essential for filtering data to determine directly, or to calculate, various parameters that capture passage conditions, and to evaluate the potential for conditions that may produce barotrauma in fish. Also, the time stamps allow HBET to identify potential severe events likely to cause injury, such as collision or shear.

Several parameters were determined or calculated to assess the likelihood of barotrauma injury based on changes in pressure, as well as the likelihood of injury associated with blade collision or shear (Brown et al. 2014). Nadir pressure after turbine passage was identified between time stamps T2 and T3. Acclimation pressures approximating pressure at both surface and 6 m were used to determine ratio of pressure change (RPC) for best- and worst-case scenarios, respectively. RPC was calculated by dividing the acclimated pressure by the nadir pressure measured during passage. The probability of mortal injury was estimated for both acclimation scenarios (surface and 6 m depth) using a formula presented in Brown et al. (2012a,b):

$$P\_mort = \frac{e^{\beta_0+\beta_1 \cdot \ln RPC}}{1+e^{\beta_0+\beta_1 \cdot \ln RPC}} \qquad \text{Equation 2}$$

Where *P_mort* is the probability of mortal injury, β_0 and β_1 are regression coefficients, and ln*RPC* is the natural log of the ratio of pressure change (Brown et al. 2012a,b). Coefficients were derived from dose-response experiments on rapid decompression for various species and were obtained from Pflugrath et al. (2021). Probability of mortal injury estimates were estimated for a variety of species present in the Trent-Severn system near the Wasdell site, as well as several other species not present near Wasdell to provide additional Canadian context. Barometric pressure must be recorded before each Sensor Fish deployment as these measurements are used to calibrate the pressure sensors prior to analyzing pressure data.

Collision and Shear Events

For each Sensor Fish dataset, events of interest, such as rapid pressure changes, collisions, and shear, were identified and quantified. Quantification of events included the time of occurrence, location (zone), severity, and the proportion of releases containing at least one severe acceleration event (Maximum Acceleration (Max Acc) where the acceleration magnitude > 95 G, established in laboratory using juvenile Chinook Salmon (*Oncorhynchus tshawytscha*); Deng et al. 2005), by zone, was calculated. In addition to the severity, the events were categorized as being attributed to collision or shear. A collision event was defined by an acceleration peak with a duration less than 0.0075 s (measured at 70% of peak value); otherwise, it was categorized as a shear event (Deng et al. 2007) (Figure 5).

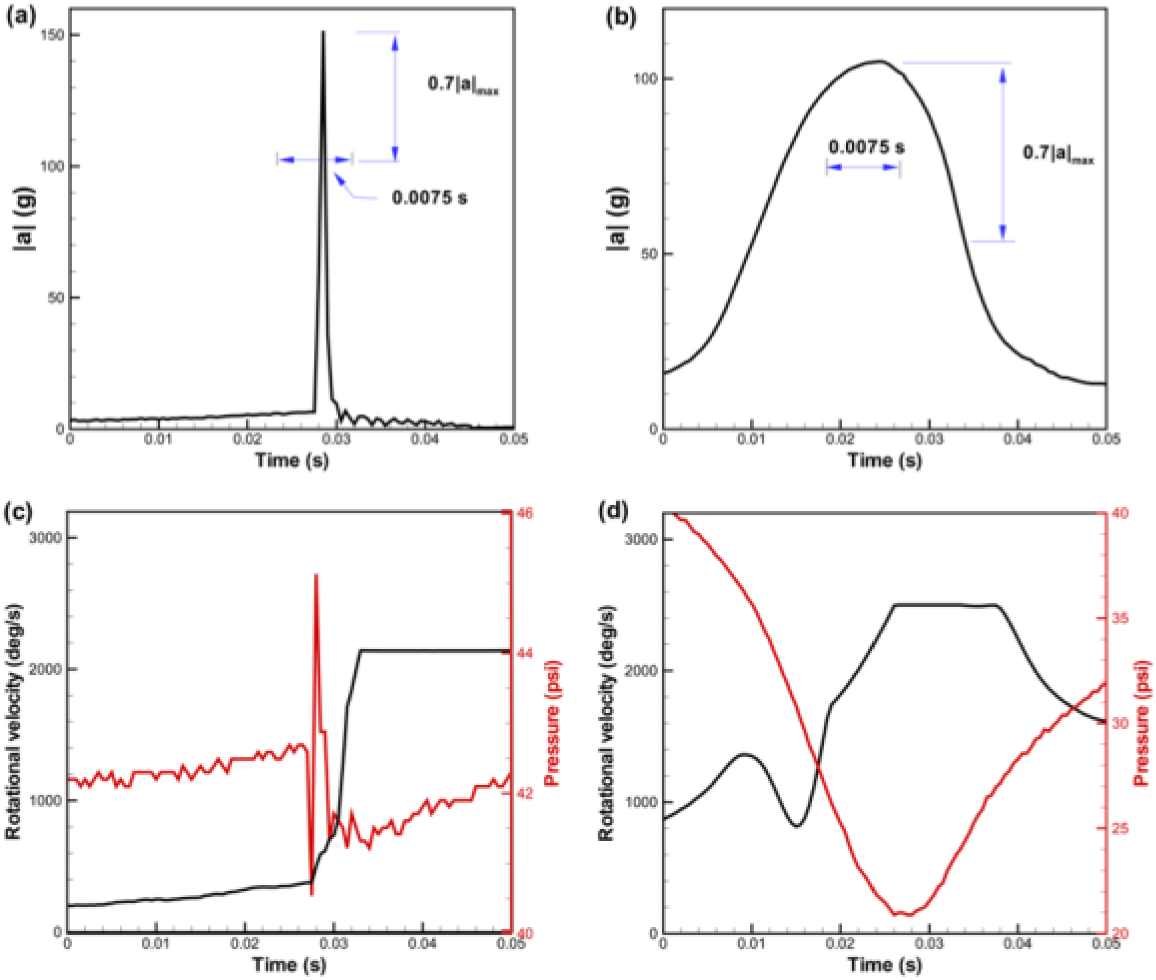

Figure 5. Duration of acceleration (|a|, where g = m/s^2) within 70% of the peak value is (a) less than 0.0075 second for a collision event; (b) > 0.0075 s for a shear event. Pressure (red lines) and rotation (black lines) increase more dramatically during (c) a collision event than during (d) a shear event.

To quantify the collision between Sensor Fish and rigid objects during passage through a hydraulic structure, two collision intensity (HIT) indices were developed using rates of change from 750 successful Sensor Fish datasets (reported in Martinez et al. 2019a): one HIT index was developed using pressure measurements (M_P), and the other using impact velocity estimates derived from acceleration measurements (M_V) (Daniel Deng, Pacific Northwest National Laboratory, pers. comm). While still in development, preliminary studies using juvenile Chinook Salmon have found that HIT indices can be used to quantify the potential live fish collision severity in field studies, however the metric thresholds are not intended to be predictive of fish injury (Daniel Deng, Pacific Northwest National Laboratory, pers. comm). Juvenile Pacific Salmon are more likely to get injured when M_V and M_P are above certain thresholds, and the probability of injury is much less when their values are less than the thresholds. The thresholds may vary for different turbine types and fish species, and at present few have been derived. The above thresholds were developed using 48-h survival data from 1030 juvenile Chinook Salmon passing through a large Kaplan turbine (Heisey et al. 2019), although similar thresholds could be derived for alternate scenarios (i.e., other turbine types and fish species) if survival data are available.

Statistical Analysis

Pressure data (nadir and RPC) were tested for normality and homogeneity of variance using Shapiro-Wilks test and Levene's test, respectively. Mann-Whitney U test was used to compare pressure parameters (nadir and RPC) between treatment and control deployments. The proportion of trials with severe events (collisions and shears) were compared between treatments and controls using a χ^2 test. All filtering of data, determination or calculation of parameters, and statistical comparison was conducted using R-studio (R Core Team 2019, Version 4.2.2). Collision and shear events were determined from HBET. Significance is considered at $\alpha < 0.05$.

Results

Volitional Passage Behaviour

The telemetry data did not provide evidence of fish passage through the VLH turbine (Tuononen et al. 2022b). No post tagging mortalities were detected. Detection efficiencies depended on distance of the tag from the receiver, and ranged from 70-72% at 7 m and from 13-66% at 19 m. Of the 138 tagged fish, five were detected downstream of the VLH, three of which were determined to have most likely passed via the spillway based on last receiver detection. The two remaining fish may have taken an alternative route downstream through a series of canals, or via live-well transfer. Rock Bass, Smallmouth Bass, Largemouth Bass and Northern Pike were detected in the forebay area (Figure 6), however, none of the tagged Channel Catfish (6), White Sucker (6), Walleye (3) or Pumpkinseed (1) were detected in the forebay, and generally fish stayed near their release site. For species that were detected within the three forebay areas (Figure 4), the cumulative average residency time was much lower in the VLH forebay area compared to the other forebay areas for all species except Smallmouth Bass (Figure 7). Most forebay fish detections occurred between June and November, however, there were isolated winter detections for Rock Bass and Smallmouth Bass. More detailed telemetry results are available in Tuononen et al. (2022b).

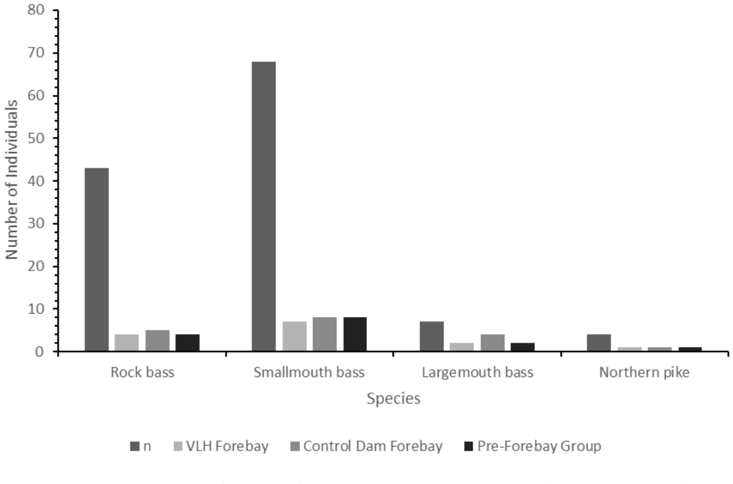

Figure 6. Adapted from Tuononen et al. (2022b). The total number of individual fishes of the species detected within the forebay areas at the Wasdell Falls generating complex on the Severn River (in Ontario, Canada) in each of the three forebay station groups (1-VLH Forebay, 2-Water Control Dam Forebay, and 3-Pre-Forebay; See Figure 4c), over the course of the study. n represents the overall number of individuals of each species tagged.

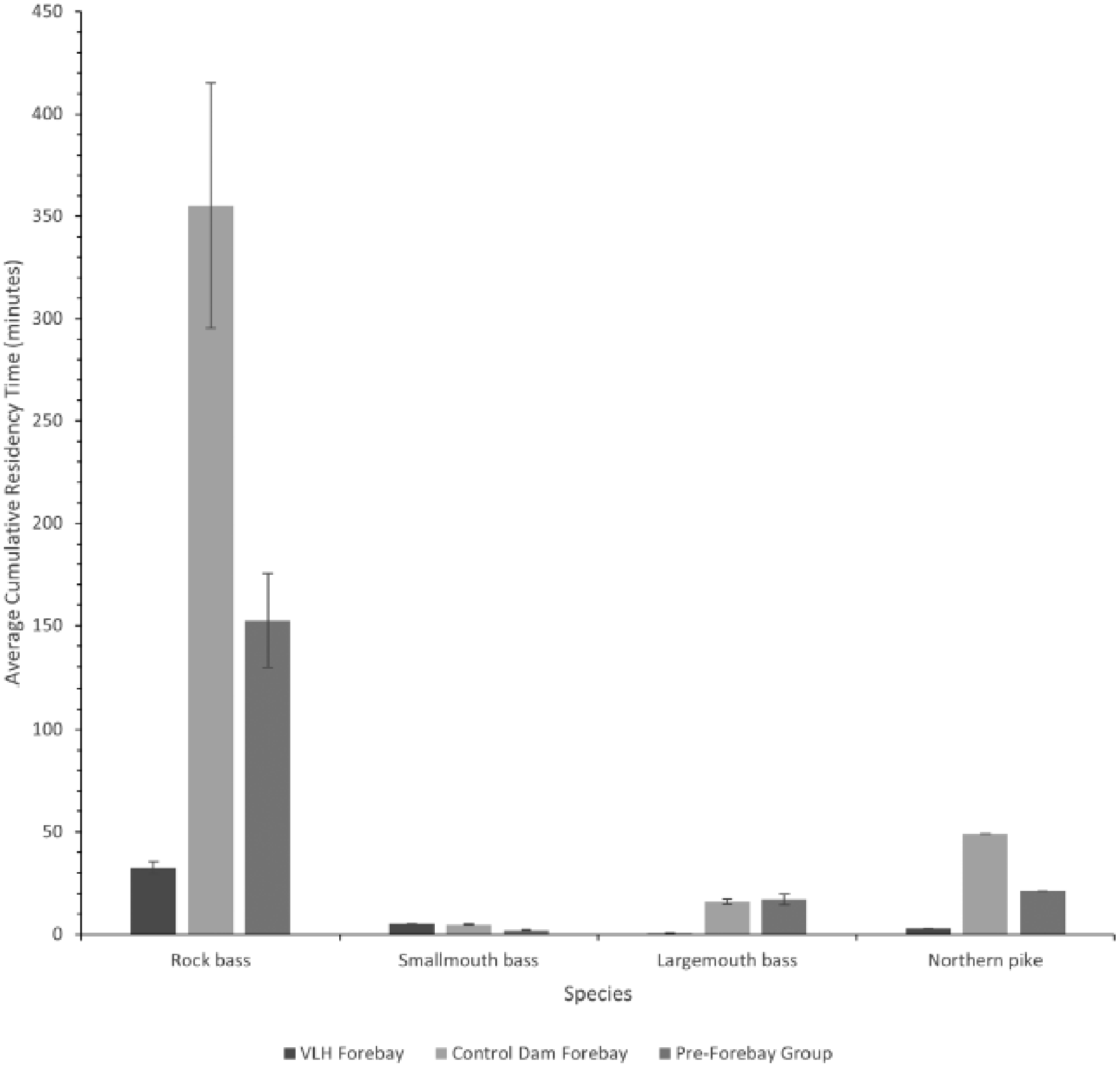

Figure 7. Adapted from Tuononen et al. (2022b). The average cumulative residency time (minutes with standard error) per species and location within the forebay areas upstream of infrastructure at Wasdell Falls on the Severn River, Canada.

Live Fish Passage

In total, 86 fish received the experimental passage treatment while 55 received the control treatment (Tuononen et al. 2022a). Both treatments included individuals representative of the captured taggable size range in the Severn River for the five species included. Injuries most commonly observed were dermal lesions, minor hemorrhaging, and cloudy eyes, and were prevalent in all fish both pre- and post-assessment, likely due to pre-existing injuries, or capture, handling, and holding in net pens. However, there were no significant differences in the frequency of these injuries between the control and treatment groups from pre- to post-passage (PERMANOVA - all interactions were not significant – Figure 8; see also Table 4 in Tuononen et al. 2022a). There was only a single instance of confirmed turbine-induced mortality, the result of a partial decapitation of a single Northern Pike. No injuries indicative of barotrauma were observed in either treatment. Immediate mortality rate in the treatment group was as high as 6.25% (1/16, 95% CI (0.32, 28.33)) for Northern Pike, while the treatment group immediate mortality rate was 1.16% across all species. Relative rate of immediate mortality was 30% higher in the treatment vs the control group (Table 1). Post-treatment delayed mortality, assessed via acoustic telemetry, identified a single post-passage mortality in each of the control (Smallmouth Bass (1/13)) and treatment (Largemouth Bass (1/7)) groups (Table 2). Delayed mortality rate in the treatment group was 2.6% and in the control group was 3.7% across all species, but 95% confidence intervals based on the binomial distribution for our small sample sizes suggested delayed mortality could be as high as 18%. The relative rate of delayed mortality was 29% lower in the treatment group given the larger sample size for the treatment group relative to control. Our power to detect a 10% rate of immediate and delayed mortality in the treatment groups was reasonable (0.98 and 0.54, respectively), however adequate power to detect lower mortality rates, like those observed, would have required sample sizes greater than 1000. More detailed results are available in Tuononen et al. (2022a).

Table 1. Sample sizes and results from live fish passage trials and estimates of percent absolute (± 95% confidence intervals) and relative risk of immediate mortality. To accommodate for no immediate mortalities in the control group, the total number of fish that died and survived were both increased by one in treatment and control groups. From equation 1 (RR): (T) = # of treatment fish killed, (C) = number control fish killed, (n1) = number of treatment fish released, and (n2) = number of control fish released.

Immediate Mortality	# Killed	# Survived	Total Fish Released	% Absolute Mortality (95% CI)	% Relative Risk of Delayed Mortality
Treatment	1	85	86	1.16 (0.06, 6.30)	-
Control	0	55	55	0 (0.00, 6.52)	-
Treatment +1	2 (T)	86	88 (n1)	-	30
Control +1	1 (C)	56	57 (n2)	-	

Table 2. Sample sizes and results from live fish passage trials and estimates of percent absolute (± 95% confidence intervals) and relative risk of delayed mortality. From equation 1 (RR): (T) = # of treatment fish killed, (C) = number control fish killed, (n1) = number of treatment fish released, and (n2) = number of control fish released.

Delayed Mortality	# Killed	# Survived	Total Fish Released	% Absolute Mortality (95% CI)	% Relative Risk of Delayed Mortality
Treatment	1 (T)	37	38 (n1)	2.63 (0.13, 13.49)	-29
Control	1 (C)	26	27 (n2)	3.70 (0.19, 18.28)	

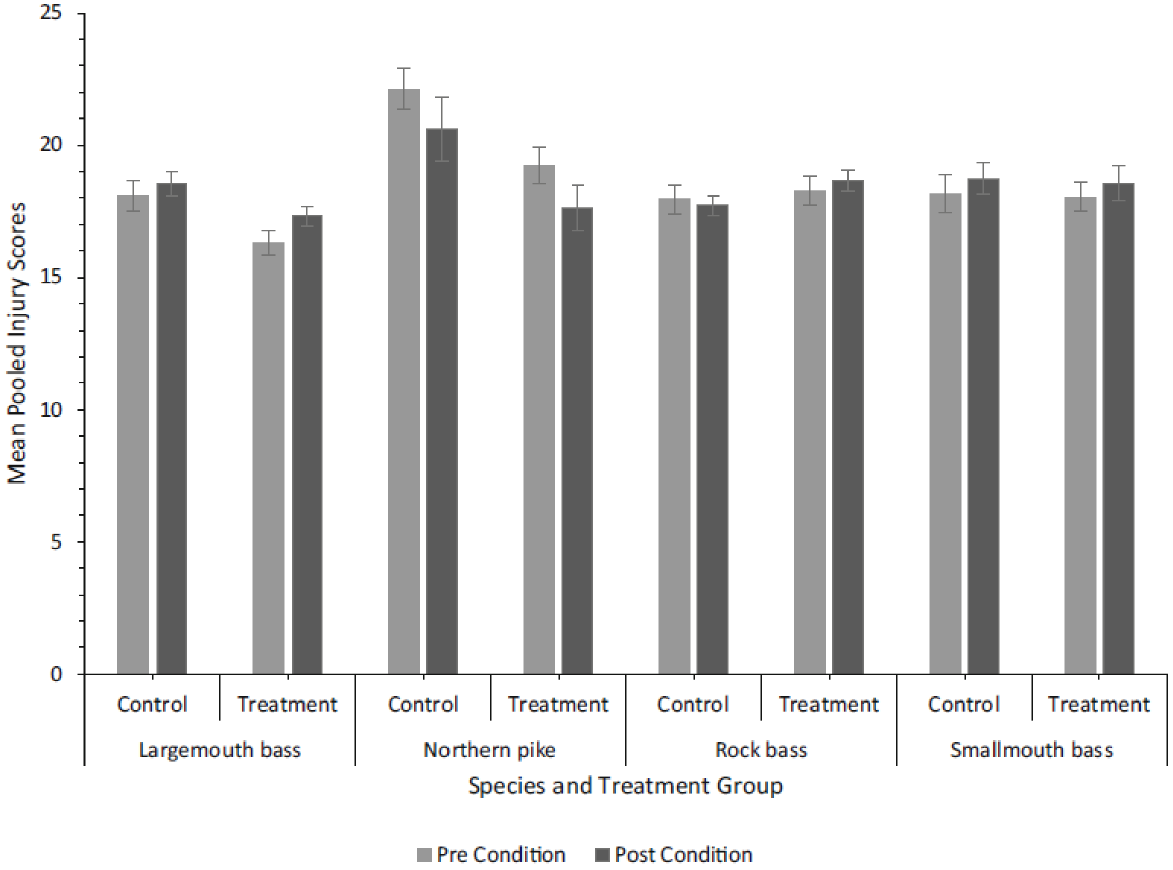

Figure 8. Mean pooled injury scores, by species, for fish flushed through the VLH turbine (treatment) and over the crest gate of the VLH turbine (control). Before and after scores are plotted with standard error.

Sensor Fish Deployments

Although we conducted 34 replicate deployments in both treatment and control runs, data for 13 treatment deployments were removed from pressure analysis because sensors either did not record properly (n = 5), appeared to become snagged during flush or passage, which reduced the ability to accurately capture specific regions in the data (n = 5, example in Figure 9a), or provided uncharacteristic traces making it too difficult to accurately place time stamps (n = 3, example in Figure 9b). No data for control deployments was removed (Table 3).

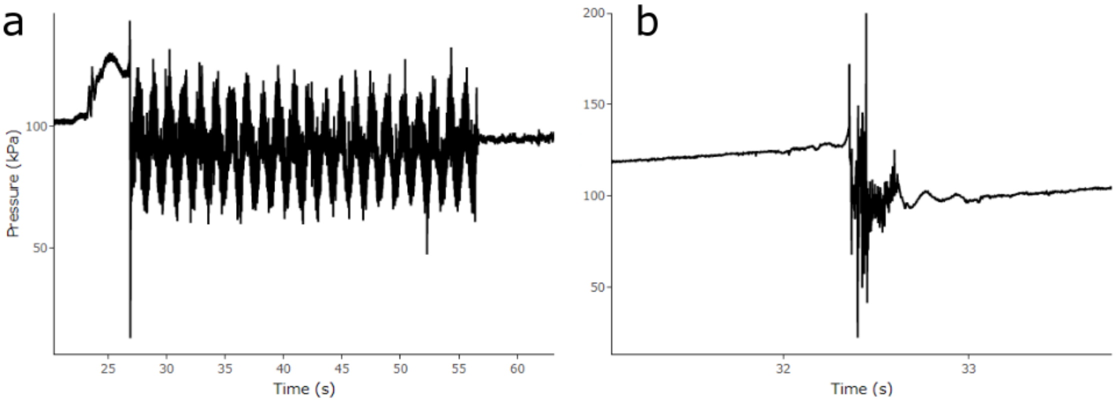

Figure 9. Examples of Sensor Fish treatment recordings that were not included in data analyses: a) Sensor Fish was 'snagged' on something, after going through the turbine, unclear of true nadir; b) Turbine passage region, unclear where to place time stamp to capture true nadir.

Nadir Pressure

Pressure data were non-normally distributed, and variances were non-homogeneous, although means and median values were similar (Tables 3-5). Significant differences were detected in nadir pressures between treatment and control groups (medians: U = 630, $p < 0.001$). As would be expected, median and mean nadir values were lower for treatments compared to controls (Table 3).

Table 3. Mean and median nadir pressure (kPa) for control and treatment groups for Sensor Fish.

Treatment	N	Mean	Median	Range
Control	30	99.80	99.39	93.77–101.49
Treatment	21	83.40	86.25	61.50–89.29

Ratio of Pressure Change – acclimated/nadir

Control and treatment group RPC medians were significantly different (U = 0, $p < 0.001$), regardless of acclimation depth. The median RPC was higher for the treatment group compared to the control group (Table 4). Using an acclimation pressure approximating surface pressure (101.3 kPa) median treatment RPC was 1.17 (Table 4). Median treatment RPC values increased to 1.86 when an acclimation pressure approximating pressure at a depth of 6 m (160.2 kPa) was used (Table 5). The estimates for mean and median probability of mortal injury due to decompression (Table 6) were lower for the surface acclimated RPC scenario (best-case) compared to depth acclimated scenario (6m – worst-case). Both lamprey species had 0% probability of mortality estimates in both surface and depth acclimated scenarios. For non-lamprey species, the mean probability of mortal injury in the surface acclimated scenario ranged from 0.43% to 12.70% (median – 0.32% to 9.01%), while estimates in the depth acclimated scenario ranged widely from 3.52% to 66.70% (median – 2.62% to 62.90%). For species relevant to the Wasdell VLH site, Bluegill (*Lepomis macrochirus*) and Largemouth Bass had the highest mean probability of mortal injury in both acclimation scenarios, while Tiger Muskie (*Esox masquinongy* × *lucius or Esox lucius* × *masquinongy*) and Walleye had the lowest probability (Table 6).

Table 4. Mean and median ratio of pressure change (RPC) for control and treatment groups for Sensor Fish acclimated to the surface.

Treatment	n	Mean RPC	Median RPC	Range
Control	30	1.03	1.02	1.00–1.08
Treatment	21	1.23	1.17	1.14–1.65

Table 5. Mean and median ratio of pressure change (RPC) for control and treatment groups for Sensor Fish acclimated to a depth of 6m.

Treatment	n	Mean RPC	Median RPC	Range
Control	30	1.62	1.61	1.58–1.71
Treatment	21	1.94	1.86	1.79–2.60

Table 6. Estimated probability of mortal injury due to rapid decompression for different fish species. Mean and median estimates are provided for scenarios where fish may be acclimated at surface pressure (0 m) and at depth (6 m).

Fish Species	Probability Estimated at Acclimation Depth of 0 m (%)		Probability Estimated at Acclimation Depth of 6 m (%)	
	Mean	Median	Mean	Median
*Bluegill (*Lepomis macrochirus*)	12.70	9.01	66.70	62.90
*Largemouth Bass (*Micropterus salmoides*)	6.74	4.67	45.4	40.30
*Tiger Muskellunge (*Esox lucius* X *E. masquinongy – surrogate for Northern Pike and Muskellunge*)	2.89	2.63	6.78	6.21
*Walleye (juvenile) (Sander vitreus)	1.28	1.10	4.52	3.92
American Shad (*Alosa sapidissima*)	1.48	1.07	11.60	9.00
Brook Lamprey (*Lampetra planeri*)	0.00	0.00	0.00	0.00
Chinook Salmon (*Oncorhynchus tshawytscha*)	0.90	0.71	4.97	4.01
Kokanee (*Oncorhynchus nerka)*	0.43	0.32	3.52	2.62
Pacific Lamprey (*Entosphenus tridentatus*)	0.00	0.00	0.00	0.00
Rainbow Trout (*Oncorhynchus mykiss*)	1.11	0.95	4.11	3.54

** species present at the Wasdell Falls VLH site.*

Collision and Shear Events – HIT Index

Of the 21 Sensor Fish treatment releases retained for analyses, 16 severe events were observed from 10 releases: 15 collisions and 1 shear (Table 7). Nine of these 15 collisions (60%) occurred in the flushing apparatus zone (T0–T1) during 7 of the 21 treatment releases (33%). For the turbine passage zones (T1–T3), 5 (24%) releases had severe collision events, of which 1 occurred in zone T1–T2 and 4 in zone T2–T3. Of these severe events, one (5%) had a M_V index value above the threshold of 3.45 (region T1–T2) and one (5%) had a M_P index value above the threshold of 8.46 m/s (region T2–T3) (Table 7). For the Sensor Fish control releases, 16 of 30 (53%) experienced severe events, all of which occurred in the flushing apparatus (T0–T1) zone. A single Sensor Fish control release had a M_V index value above the threshold of 3.45 m/s (3%). No control releases had a M_P index value above the threshold of 8.46 m/s.

Table 7. Detailed information of severe events observed during the Sensor Fish release where Max Acc is the maximum acceleration in G, and M_V and M_P are the collision intensity metric indices for velocity and pressure, respectively. M_V values above 3.45 m/s and M_P values above 8.46 m/s, both of which are considered to have a high probability to cause injury in live fish, are in bold text.

File Name	Max Acc	Zone	Event Type	M_V	M_P
SF 10	142.38	T0 - T1	Collision	1.78	1.34
	108.43	T0 - T1	Collision	0.81	2.83
SF 11	164.5	T1 - T2	Collision	**3.66**	2.68
	113.48	T2 - T3	Shear	N/A	N/A
SF 12	160.22	T2 - T3	Collision	0.96	4.01
SF 13	111.68	T0 - T1	Collision	1.81	1.70
SF 14	169.18	T0 - T1	Collision	1.23	3.07
SF 16	116.55	T0 - T1	Collision	1.40	2.76
	125.94	T0 - T1	Collision	1.12	3.24
SF 1	237.65	T2 - T3	Collision	0.74	**9.12**
	153.48	T2 - T3	Collision	0.99	4.02
SF 2	234.75	T0 - T1	Collision	1.52	4.34
	175.35	T2 - T3	Collision	0.95	2.32
SF 6	119.14	T0 - T1	Collision	1.48	1.78
SF 8	97.15	T0 - T1	Collision	0.77	3.45
	105.08	T2 - T3	Collision	0.62	2.17

Discussion

The potential exists for the widespread use of VLH turbines at water control structures across Canada that are presently lacking hydroelectric infrastructure (NRCan 2018). In the development of this turbine technology several 'fish friendly' considerations (as identified in US Department of Energy 1999) were incorporated, including minimizing velocity and pressure gradients, runner velocity, and the number and shape of runner blades (Fraser et al. 2007). However, few assessments of VLH turbines and their potential impact on wild fish have been completed, and in particular, data for North American fish species are lacking (Tuononen et al.

2022a). We have used acoustic telemetry to assess the risk of entrainment to resident fishes, live fish passage trials to determine injury and mortality rates for entrained fish, and Sensor Fish passage trials to better understand physical conditions experienced by fish during passage. The telemetry and live fish results together suggest the risk for this particular fish community is low (Tuononen et al. 2022b). While sensor passage trial pressure data largely supports that of live fish passage, it did identify a greater potential risk of injury from barotrauma than was suggested by the live fish trials. A greater number of Sensor Fish passages documented collision and shear events than suggested by live fish trials, although most were not considered severe enough to cause injury. Overall, the risk to this fish community from the VLH installation seems low, but limitations regarding widespread application of these results are discussed.

The risk of entrainment for the fish community on the Severn River, upstream of the VLH at Wasdell Falls, appears to be low. The fish community upstream of the VLH did not appear to have strong behavioural affinity to move downstream, however, we did observe some downstream passage (~1% of tagged fish) via the spillway adjacent to the VLH. Bypass channel discharge is a strong predictor of bypass channel use by fish (Knott et al. 2023), with a bypass discharge of 2-10% of turbine discharge commonly cited as the minimum for good bypass efficiency, but determining required discharge requires consideration of bypass location, hydraulic conditions and other aspects of the site that are known to influence bypass efficiency (Klopries et al. 2018, Larinier and Travade 2002). While not specifically designed for fish bypass, the spillway at Wasdell Falls always received discharge well in excess of 2% of the turbine discharge during 2017 and 2018, and thus may be an attractive bypass channel, even though its safety and efficacy are unknown. Mean annual flow at Wasdell Falls was higher than average during the telemetry portion of this study, with maximum turbinable flow reached for much of the spring of 2018. Turbine entrainment rates are often positively correlated to discharge (Ransom and Steig 1994, Knott et al. 2023, Yao et al. 2023), yet we found no evidence of turbine passage of tagged fish. The apparent overall lack of behavioural affinity to move downstream in the fish community upstream of the Wasdell Falls VLH should be acknowledged. Variation in affinity to move downstream through hydropower infrastructure is known to exist within non-migratory freshwater fish species (Knott et al. 2020) and thus overall community risk of entrainment will vary from one fish community to another based on community membership.

It is possible that the risk of entrainment may be elevated in systems lacking an alternative to the VLH for downstream passage (i.e., separate spillway). Yet, when VLH turbines are generating power, they operate with a proportion of water spilling over the crest gate (Figure 2c), which may provide a relatively safe downstream route as demonstrated by the control fish and sensors that went downstream via the crest gate flow. Depth at the base of the VLH dam ranges from 2.5 m (low flow) to 4 m (freshet flows; G. Hepinstall, Wasdell Falls Hydro Project/Bracebridge Generation Ltd., pers. comm.). Blueback Herring (*Alosa aestivalis*) exposed to similar plunge-pool conditions demonstrated a 96-h survival > 90% (Castro-Santos et al. 2021), supporting the notion that crest gate passage at this VLH site provides a viable downstream passage option for fish. Furthermore, while water velocities at the turbine intake were reported to be much lower than the known maximum critical swim speed for most fishes (i.e., intake velocity was reported as 3–21 cm·s-1 in Tuononen et al. 2022b), they are in fact higher than those reported due to an error in units (i.e., should have been 3-21 m3/s, which is a discharge unit of Cubic Meters per Second, often written as CMS). Intake velocities at the concrete structure behind the trash racks would have an estimated average velocity of 66.0 cm·s-1 at 20 m3/s (maximum turbinable discharge) and 16.7 cm·s-1 at 5 m3/s (J. Stasiuk, Bracebridge Generation, pers. comm.). The velocity experienced by fish, however, would range from being quite low at the runner hub and in the corners of the structure, to a maximum at the runner blades where there would be a ring shape of higher velocity. For the species reported in Tuononen et al. (2022b), a strong swimmer like Smallmouth Bass would likely still not have an issue avoiding entrainment, but a weaker swimmer like Rock Bass could get involuntarily entrained if they entered the trash rack and encountered a high velocity area. However, it is also important to consider that fish could pass through or over the turbine voluntarily and behaviour of fish at a given site should feed into any population level risk-assessment. It is notable that Smallmouth Bass are often observed congregating at the upstream end of the dam, above the turbine, holding steady in the flow without issue (G. Hepinstall, Wasdell Falls Hydro Project/Bracebridge Generation Ltd., pers. comm.; Figure 2d).

While many injuries were noted for fish used in the live fish passage trials, many of these injuries existed prior to passage. Acoustically tagged fish used in passage trials were held overnight in a calm area of the river in mesh pens to monitor their condition following surgery. For handling consistency, all fish used in the live fish passage trials were kept overnight in mesh pens before use. The most common injuries observed were the result of abrasion (Tuononen et al. 2022a). Previous studies on injuries resulting from net pen use have noted fraying of fins, mouth injuries and scale loss (Colotelo et al. 2013a,b), which is consistent with the most common injuries observed. Rates of abrasion injuries did not differ between experimental and control treatments suggesting capture and handling practices shared between the experimental and control groups, be it capture method (angling, electrofishing), time spent in the mesh pen, passage through the flushing apparatus, or handling related to physical condition assessments pre- and post-experimental passage, were responsible for these injuries, rather than turbine passage. The presence of abrasion induced injuries for fish in both treatment and control groups was high prior to treatments, suggesting time in the mesh pens was the primary cause of these injuries. However, abrasion injuries prior to live fish passage trials may have masked injuries that incurred during flushing and turbine passage. Most new injuries noted following experimental and control treatments were likely inflicted by the flushing apparatus. Indeed, sensor passage trials identified a high risk of collision (33-60%) during the flushing apparatus portion of both treatments and control. The low water velocities at the turbine entrance required the flushing apparatus to entrain (non-anesthetized) fish, but a resident fish would never experience this during a VLH turbine passage. It should be noted that our control group, which passed over the crest gate of the VLH turbine, might more appropriately be referred to as an alternative treatment. While we expect the drop from the crest gate into the spillway to be relatively benign, which is supported by the Sensor Fish data, we can’t exclude the possibility of injury resulting from this component of the control group passage. Care must be taken to ensure control groups aren’t exposed to potential sources of injury outside of those they share by design with the treatment group.

Despite the lack of greater injury of treatment fish relative to controls, VLH turbine passage was not without risk of injury. Fish length is positively related to blade collision during turbine passage (Ferguson et al. 2008) and, as a result, species with elongate body forms and/or individuals of species who are longer are generally at a higher risk of blade strike. Most of the fish used in the passage trials were fusiform (Smallmouth Bass, Largemouth Bass and Walleye) or compressiform (Rock Bass), body shape-types that should have a lower risk of injury. Northern Pike is the only species with an elongate body form and indeed, the single incidence of mortal injury was a partial decapitation in an adult of this species. While shear events can result in decapitation (Stokesbury and Dadswell 1991), it is unlikely that the reported maximum velocity gradient for VLH turbines (10 m·s-1·m-1, reported in Fraser et al. 2007) is capable of producing such an injury. The mortal Northern Pike injury was consistent with grinding or blade impingement (Cooke et al. 2011) between the turbine house or trash-rack and the turbine blade. Extrapolation of this result must be done with caution. Our sample size for Northern Pike was small (16 individuals in the experimental treatment) and much uncertainty remains about the expected mortality rate for Northern Pike at this VLH turbine. Data from Sensor Fish suggest the risk of collision events for fish passage within the turbine area may be as high as ~24%, with ~9.5% of passages expected to cause injury, but these sensors are not designed to identify grinding or impingement events. No definitive collisions were observed in the live fish trials and thus the estimate of collision induced injury provided by the Sensor Fish is higher than expected based on the live fish trials. Sensor Fish are inanimate and physically smaller than the fish used in live fish trials. How well collision data from sensors translates to risk of collision for live fish has yet to be determined (Pauwels et al. 2020). It is possible that some live fish experienced collision events that were not detected in the post-passage injury assessment, underestimating the actual risk of injury for live fish passage. Live fish were only assessed for external injuries, however internal injuries are not always detectable from external examination (Mueller et al. 2020) and internal injuries may have gone undetected. Furthermore, the injury thresholds used in the present study, which were developed for juvenile Pacific Salmon, were not intended to be predictive, and it is not known how well these thresholds translate to other species, including those found in the Severn River.

Overall mortality rates at the Wasdell Falls VLH turbine were similar to the most recent VLH entrainment mortality estimates reported in the literature (Lagarrigue 2013). Lagarrigue (2013) reported mortality rates of 1.1–4.4% at 50% blade opening and the periphery of the turbine, with delayed (48 h) mortality rates of 3.45% for small Common Carp (*Cyprinus carpio*) and 6.7% for large Rainbow Trout (*Oncorhynchus mykiss*). Our absolute values for immediate and delayed mortality closely mirror the results of Lagarrigue, despite differences in the species used, although our small sample sizes did result in wide 95% confidence intervals. A recent systematic review on the relative risks of mortality and injury for fish during downstream passage at hydroelectric dams found that passage through higher head turbines came with a significant increase in risk of injury (406%) and immediate mortality (283%) relative to controls (Algera et al. 2020). Turbine type was a significant moderator of these results, with Kaplan turbines having lower relative risk (144% increase in risk of immediate mortality) than Francis turbines (522% increase in risk of immediate mortality) relative to controls. Many ‘fish friendly’ characteristics were incorporated into the design of VLH turbines (e.g., blunt leading blade edges, low peripheral velocity, low pressure, and velocity gradients; Fraser et al. 2007) and the live fish passage results suggest the relative risk of immediate (30%) and delayed (-29%) mortality for fish species found upstream of this VLH turbine is low under the conditions tested. However, Lagarrigue (2013) found a greater risk of mortality as blade opening decreased, with 50% opening being the lowest tested and showing the highest risk. VLH blade position is rarely static and adjusts based on flow through the turbine and the net head, or difference between water levels upstream vs. downstream of the turbine (J.Stasiuk, Bracebridge Generation, pers. comm.). It was estimated that the maximum blade opening (100%) is 630 mm, at 50% the estimate is reduced to 315 mm (the conditions tested), at minimum power output it reduces to 31 mm, and when not generating at all the gap could be down to 4 mm. It was further estimated that the VLH turbines at Wasdell Falls are operated at < 50% open approximately 40% of the time in an average year (G. Hepinstall, Wasdell Falls Hydro Project/Bracebridge Generation Ltd., pers. comm.). Thus, while a smaller blade opening can result in higher rates of fish injury and mortality, at very low generation, intake velocities are reduced, and theoretically, larger fish would be excluded from turbine passage. Mortality events reported in Lagarrigue (2013) and in the present study appear to stem from blade collision and/or blade impingement, with larger individuals being more susceptible than smaller individuals. Regardless, conclusions only apply for the operating conditions tested, and could underestimate the potential risk of injury for fish under different conditions.

Nadir (i.e., lowest) pressures recorded from Sensor Fish were higher than reported values from large Kaplan and Francis turbines (Table 8), but lower than what has previously been reported for VLH Kaplan turbines (Boys et al. 2018). Brown et al. (2012a,b) found RPC to be the best predictor of barotrauma induced injury for Chinook Salmon smolts, and thus based their probability of mortal injury metric on the RPC. This ratio is a measure of expected gas volume expansion between a fish’s acclimated pressure and nadir pressure. The risk of barotrauma injury increases with decreasing nadir pressure and higher acclimation pressure (Becker et al. 2003). Fraser et al. (2007) reported a minimum simulated nadir pressure of 94 kPa for the VLH turbine, however we recorded median nadir pressure of 86.3 kPa from the Sensor Fish. It has been suggested that a nadir pressure of at least 40% of the upstream acclimated pressure (RPC of 2.5) is ‘fish friendly’ (Fraser et al. 2007). Using an acclimation pressure at 6 m (i.e., the highest acclimation pressure scenario possible via maximum depth upstream at the Wasdell VLH) the median pressure change at the VLH turbine meets this criterium for being ‘fish friendly’ (i.e., RPC 1.2-1.9; Table 8). However, similar to Boys et al. (2018), at least some fish at the VLH turbine could be expected to experience nadir pressures less than 40% of acclimation pressure (i.e., if a subset of those fish were acclimated to 6 m, and the nadir actually experienced was on the low end of the range, see Table 5). Since both the live fish trials presented here and in Lagarrigue (2013) used fish acclimated to surface (or near surface) pressure, the live fish trials may be underestimating the risk of injury or death, as depth acclimated fish would be more likely to experience barotrauma.

Table 8. Comparison of head height, acclimated pressure, nadir pressure and ratio of pressure change for a variety of turbine and dam configurations. Acclimation depth, when presented in the referenced paper, is included in parentheses.

Turbine	Head Height (m)	Acclimated pressure (kPa)	Nadir (kPa)	Ratio of Pressure Change	Source
Very Low Head[1]	4.2	-	86.3	-	Wasdell Falls (this study)
Surface	-	101.3	-	1.2	
Depth (6 m)	-	160.2	-	1.9	
Very Low Head[2]	1.5-2.35	-	106.7	-	Boys et al. 2018
Surface	-	101.3	-	0.95	
Depth	-	150	-	1.41	
Archimedes screw[2]	2.6	-	99.2	-	Boys et al. 2018
Surface	-	101.3	-	1.02	
Depth	-	116.7	-	1.08	
Horizontal Kaplan[2]	2.4	-	67.1	-	Boys et al. 2018
Surface	-	101.3	-	1.51	
Depth	-	154.6	-	2.32	
Kaplan (small)[1]	5	-	22.4	-	Martinez et al. 2019b
Surface	-	101.3	-	3.75	
Depth (1.9 m)	-	119.9	-	4.52	
Francis-Cougar Dam[1]	88.1	-	24	-	Fu et al. 2016
Depth (6.7 m)	-	167.0	-	6.95	

[1] *median Nadir and Ratio of Pressure Change values presented*

[2] *mean Nadir and Ratio of Pressure Change values presented*

Risk of mortality from pressure changes associated with turbine passage varies from species to species and between life stages, largely as a result of variation in swim bladder morphology (reviewed in Brown et al. 2014). For example, in a lab study Becker et al. (2003) found death rates for Chinook Salmon and Rainbow Trout exposed to nadir pressures as low as 2-10 kPa to be negligible, while Bluegill subjected to the same pressure change experienced a significant risk of death. Probability of mortal injury, as defined in Brown et al. (2012a,b), is estimated using the logarithm of pressure change (LPR), which is calculated by taking the natural logarithm of the RPC. Using the observed RPC values at the Wasdell Falls VLH and the dose-response for juvenile Walleye, Tiger Muskellunge, Largemouth Bass and Bluegill the mean probability of mortal injury at the 'best-case' surface acclimation depth was 1.28%, 2.89%, 6.74% and 12.70% respectively. These values are relatively low, and our surface acclimated live-fish flushing trials found no evidence of barotrauma. However, for the same species the 'worst-case' acclimation depth of 6 m was 4.52%, 6.78%, 45.40%, and 66.70%, respectively (Table 6). Bluegill and Largemouth Bass had high estimated risks of mortality, likely in part a result of both species being physoclists and lacking a pneumatic duct connection to the esophagus, meaning they do not have the ability to rapidly deflate the swim bladder upon decompression. Muskellunge and salmonids are species with the duct (physostomes) and have a greater ability to rapidly adjust their gas volume as needed. Walleye, however, are more like Bass physiologically yet the risk of mortality for this species was considerably lower. Other factors that come into play when it comes to mortality due to rapid decompression include gas bubbles (emboli) in the gills, hemorrhaging of other organs, and disruption of heart function (Brown et al. 2009). Furthermore, the rate at which physostomes can release gas varies between and within species, with barotrauma occurring when they are not able to release gas fast enough during rapid pressure change (Brown et al. 2014). Larval fish are often more sensitive than their adult conspecifics (Pflugrath et al. 2021), although many physoclistous species are physostomes as juveniles (Brown et al. 2014). Thus, it is important that species and life-stage specific dose-response data are collected to understand the estimated risks to the species of concern. Dose-response data is sparse in general though the community present in the Severn River appears to be representative of the dose-response variation present in Canadian species (Table 6). The sample sizes used for developing dose response data have been variable, with coefficients for some species being derived from lower than ideal sample sizes (Brown et al. 2016) while others have been derived from robust sample sizes (Daniel Deng, Pacific Northwest National Laboratory, pers. comm). Dose response relationships were developed in laboratories using small and/or juvenile individuals, so do not necessarily represent adults (Pflugrath et al. 2021). Furthermore, our RPC values were lower than those used to generate some of the dose-response relationships, meaning some of the probabilities presented in Table 6 were estimated by extrapolation, which is not ideal.

Monitoring Guidance

The second objective of this process was to provide science advice towards the level and type of monitoring required at future VLH turbine installations. Fundamentally there are two ways to estimate rates of entrainment, injury, and mortality of fishes at turbines: 1) to model the risks, and 2) to collect empirical evidence. These recommendations focus on the latter, given that little empirical evidence exists for VLH turbines to use in modelling, and that was the method employed to assess the Wasdell Falls VLH turbine.

Entrainment Rates

Rates of entrainment depend on a number of factors including the composition of the fish community, relative abundance of fishes, behavioural traits such as their propensity to inhabit the head pond and forebay of the facility and/or to migrate downstream, the season, and the physical characteristics of the site, including turbine discharge (Silva et al. 2018, Yao et al. 2023). When deciding on a monitoring strategy site history, the presence of especially sensitive species (e.g., American Eel (*Anguilla rostrata*)) and management objectives need to be considered. The ideal scenario would be to conduct a telemetry study (acoustic or radio) at the proposed site prior to construction and track movements of a representative sample of individuals. This type of data collection is impossible if the facility already exists but can still have utility at sites with pre-existing barriers as the addition of VLH turbines may result in changes to the time it takes to pass the barrier, regardless of the route used. Furthermore, where alternative passage routes exist, movement data are critical to fully understanding entrainment risk. Where the VLH has already been installed, post-installation telemetry tracking of representative individuals is the next recommended option, but can be time consuming and costly to implement, so may not be mandatory if adequate data exists. However, downstream migration of fish through hydropower facilities has been understudied historically and data are especially sparce for non-Pacific salmonids (reviewed in Algera et al. 2020). Migration in freshwater fish is a widespread phenomenon which shows much variation both between and within species (Lucas and Baras 2001, Chapman et al. 2012, Brönmark et al. 2014). The use of a PIT tag array to track passage could also be considered, both before and after the turbine installation. PIT tags are smaller and thus could be used in smaller fish, they allow for less handling and reduced holding time, and have an overall lower cost relative to acoustic or radio telemetry. Another alternative at sites where there is good visual clarity is to use video cameras and image recognition for tracking fish movements/entrainment, or to similarly use imaging sonar (hydroacoustics) where clarity is an issue (Hawkins et al. 2018, Helminen and Linnansaari 2021, Jones et al. 2021).

Mandatory data does include a detailed site history, description of the fish community (potentially sourced from existing data), and a literature review conducted to assess the species' propensity to migrate or occupy large home ranges or centers of activity. At sites where upstream migration connectivity currently exists, or existed historically, the construction plans should include a fishway to maintain or restore connectivity to provide access to upstream habitats for spawning and other life history requirements, and avoid potential population decline upstream of the dam site resulting from passage only in the downstream direction. If no data exists on the composition of the fish community, relative abundance sampling should be conducted. If literature evidence on movement behaviour of resident fish species is weak, collection of such empirical evidence via telemetry becomes increasingly important. Rates of entrainment also depend on the physical characteristics of the site (e.g., if there is a bypass or spillway), and of the intake itself, in particular the range of possible intake velocities, both of which should be relatively accessible or easily measured, and therefore should be considered mandatory. Intake velocities should be well captured for comparison to swim speeds of all life stages of resident fishes.

Injury and Mortality Rates

Very little evidence exists for Canadian fish communities at VLH turbines regarding the risk of injury, as well as immediate and delayed mortality for fish that are entrained. We therefore recommend that empirical data on injury and mortality continue to be collected until the evidence base is more robust. In order to maximize the utility of future efforts to assess the impact of new VLH turbines on Canadian fish communities, research and monitoring efforts should be designed to facilitate comparison to existing research and contribute to science advice. Following the design and techniques used in this study would allow direct comparison of results, thereby increasing the value of the additional data. Specifically, the use of control treatments as a comparator is extremely important in fish passage assessments; i.e., fish that undergo the exact same treatment as fish that pass through turbines with the exception that the control group bypasses turbines during downstream passage. Care must be taken to ensure control fish are not exposed to unintended sources of injury via the alternative passage route, outside of shared handling procedures between control and impact groups, which may confound interpretation of the data. Since wild fish may have pre-existing injuries, pre-passage assessments are required for both control and treatment (turbine passage) groups. Training observers in the fish assessment protocol is important for ensuring consistency. A second evaluation of a subset of fish can be used to capture variability in assessments within and among observers. Consideration should be given to how to quantify internal injuries at the site of live fish flushing trials. The sample size needs to be adequate to allow for a quantitative estimate of the rates (including an estimate of variance) of injury and mortality for both groups by species, recognizing that this is dependent on the relative abundance of available fish for capture. If or when appropriate, using fish sourced from a hatchery (i.e., species are available and already stocked in the system) is a viable option for increasing sample size. If enough fish are available, it would be important to include a broader range of operating conditions than was achieved in this study.

Care needs to be taken when designing the mechanism used to force non-volitional turbine passage since injuries to fish likely occurred in our flushing apparatus as was evidenced from Sensor Fish control trial strike data. Balloon tags, while not ideal due to the injury they can inflict on fish via attachment through the dorsal tissue, as well as impact they can have on natural swimming ability, are an effective means of recapturing fish downstream of the turbine. However, they are not foolproof, and some live fish and sensors were never retrieved, despite extensive searching after flushing. The inclusion of a 5-10 cm tether between the fish and the balloons provided a mechanism for the fish to become snagged during passage, as was apparent from some of the Sensor Fish traces. The likelihood of this occurrence would depend on the flushing mechanism and the physical characteristics of the dam. At the base of Wasdell Falls there were rubber flaps held together at the bottom by large chains. On a few occasions both live fish and sensors were not observed in the tailrace of the dam after the flush. It is difficult to know if the failure to find the fish in the tailrace was due to the balloons not inflating adequately by the time they entered the tailrace (thereby the fish or sensor passing netters sub-surface unobserved or allowing the fish to shelter in the boulders or swim by undetected), or the fish not exiting the dam. On such occasions a long hook was used to lift the flaps to see if either a live fish or sensor could be dislodged, and on a few occasions the fish or sensor was dislodged from these flaps and recaptured. A live fish without such a tether would not similarly be snagged on dam infrastructure. If the physical conditions of the facility permit, attaching a net to infrastructure downstream can increase the probability of recapture (including parts of fish should injuries be severe) and should be considered. Nets could also be used to capture information on natural entrainment, potentially increasing information on entrainment of smaller fish or life stages than used in experimental trials. Injury due to the flushing apparatus and balloon tag attachment were apparent on both treatment and control fish, highlighting the importance of using such a comparator. Our study focused on adult fish, however, it would be valuable to include other life stages in future fish passage evaluations.

Use of Sensor Technology

The use of existing and emerging sensor technologies to evaluate the conditions experienced during turbine passage should be considered. If live fish trials are conducted at a site, we are not recommending that the use of Sensor Fish is mandatory. However, the collection of additional Sensor Fish data in conjunction with live fish data would more rapidly improve the evidence base that could allow for the robust use of modelling assessments at new VLH facilities. These sensors are continually evolving to be more realistic to fish passage. For example, fish behaviour is known to modify the probability of strike during turbine passage (Coutant and Whitney 2000, Vowles et al. 2014). Thus, the option to add a sensor to a live fish passage is particularly promising for the collection of more realistic data on conditions actually experienced, with sensors mounted on the dorsal fins of live fish to compare the physical conditions during downstream passage (Wagner et al. 2022). Other emerging technology combines biotelemetry with in vivo physiology, behaviour, and ambient environment, and could have promising applications in fish passage research (Yang et al. 2022). Increasing the use of sensors can ultimately reduce the number of live fish used in passage trials, which is an important ethics and animal welfare consideration.

Uncertainties

- JSATS technology was designed to be used in noisy environments but can still generate a large number of detections that are not true tag codes, and it is important to use the recommended filtering algorithm (Deng et al. 2017) to avoid including false positives in data remaining for analysis. Other telemetry technologies (e.g., other acoustic, radio) may have produced different results.
- It is important to be aware of potential issues with acoustic telemetry and factors that influence detection efficiency (e.g., Long et al. 2023).
- While no post tagging mortalities were detected, it is possible that some tagged fish died during the telemetry study period, which would result in underestimated fish passage rates. 80% of telemetry tagged fish were limited to two species (Smallmouth Bass and Rock Bass) and thus conclusions for remaining species remain highly uncertain due to low sample sizes. The fish used in this study were reflective of the relative abundance of taggable species at the site, an issue typical of tagging studies due to minimum size limits dependent on size of the tag. Consequently, entrainment of small-bodied and juvenile fish has not been assessed.
- The risk of entrainment could vary depending on how much flow is running through the turbines, and how many they are operating at a given time. However, the VLH turbines at Wasdell covered a wide range of operating conditions during our telemetry tracking period, including a considerable amount of time at or near maximum turbinable flow, and we still detected no passage of tagged fish via the VLH route.
- The risk of entrainment could be more of a factor at sites where there is no alternative downstream passage route. Although the crest gate flow is always an alternative potential to turbine passage, there is uncertainty as to which path a fish would take should it pass downstream via the VLH turbine.
- Uncertainty remains regarding VLH entrainment impacts on life stages other than adults, and on non-salmonid resident fish (e.g., those in this study), especially those that are not targeted for sport fishing (e.g., Brook Silverside [*Labidesthes sicculus*]).
- Given the high rate of potential injury revealed from Sensor Fish data within the flushing apparatus, the injury rate of unobserved fish would likely be lower than the observed rate in this study.

- Potential differences exist between fish introduced by the flushing mechanism vs. volitional or non-volitional entrainment of wild fish (e.g., fish orientation or other compensatory behaviour related to the flushing mechanism used).
- While a single observer assessed all fish for pre- and post-passage injuries, variability in injury assessments is unknown. Potential variability or uncertainty in injury assessments within and among assessors should be minimized via training and/or QAQC tests.
- Acclimation depth for fish entrained in any turbine is critical to accurately estimating, with Sensor Fish, the risk of barotrauma and probability of mortal injury resulting from it, yet actual acclimation depth of fish is unknown. Our live fish trials were performed on surface acclimated fish and thus represent the best-case scenario regarding risk of barotrauma.
- More research is required on determining injury thresholds for different species as injury threshold values considered were derived from juvenile Pacific salmon at large Kaplan turbines. This is ongoing work at the PNNL. Future work in this area should also assess delayed mortality beyond 48 hours.
- The single operating condition (50% blade opening) that was used for both the live fish and Sensor Fish deployments limits some of the conclusions around survival at this site and the transferability of results elsewhere. With 40% of operations typically being lower than 50% opening, the risk of injury and mortality to fish is unknown for a large proportion of the time.
- Sensor Fish used in this study were designed to be similar to salmon smolts, and therefore were smaller than the live fish used in this study, which could have influenced results, particularly related to probability of an injurious strike. Other sizes and shapes of Sensor Fish are currently available for research purposes and development is ongoing.
- Sensor Fish are neutrally buoyant and thus not representative of live fish behaviour – future work should consider how to resolve the potential differences (e.g., backpack or implanted sensors on live fish are in development). Currently sensors are designed to understand relative differences in physical conditions of dam passage, not to be predictive of injury.
- Uncertainty remains regarding how well sensors approximate the risk of collision and shear events for live fish, or how these events translate into actual injury, particularly those found in the Severn River.
- There is uncertainty related to impingement or collision rates on trash racks since our flushing mechanism bypassed this hazard, injecting fish directly into the turbine.

Other Considerations

- At future sites where alternative routes are available (i.e., the control dam spillway at this site), consideration should be given to using this as an additional control/alternative treatment, particularly for the live fish portion of the work.
- At sites where migrant fish species are present it would be important to consider the timing and location of tagging to capture peaks in downstream movement.
- Time–to-event analysis (Castro-Santos and Perry 2012) or similar (movement analysis) is very important to understand passage route selection at a given site. Such analyses can examine the movement behaviours of fish in the area and factors that influence passage routes, potentially informing management decisions to either facilitate or discourage passage at a given route.

- Telemetry data processing techniques, including those used for filtering out false positives, have improved in recent years (see Nebiolo and Meyer 2021 and Nebiolo and Castro-Santos 2022). Future research involving telemetry data must be sure to use the most appropriate processing tools and techniques available.
- VLH turbines could either be installed at sites with an existing barrier (that would not otherwise be removed) or would require the construction of a new low-head dam. Significantly more work would need to be conducted if a new barrier was installed along with a VLH turbine (including scaling to a population level (Lin et al. 2022, DFO 2022a) and assessment of cumulative effects (DFO 2022b) of additional barriers). The addition of turbines to existing sites is often accompanied by physical changes upstream, including increased head height, that should be documented and evaluated.
- It is important to carefully consider the effect of the entire structure on habitat both upstream and downstream, on fish behaviour, and on the risk of mortality. Sites with both upstream and downstream passage may increase risk of exposure (as fish potentially reencounter the structure multiple times).
- Even at existing structures the installation of a turbine could have implications for either delaying or facilitating passage that should be considered. Dams can result in delayed downstream migration (Ohms et al. 2022), which has the potential to concentrate fish in the forebay area and thus increase the probability of mortality via predation. In some cases, fish friendly turbines may provide a safer passage route than had previously existed.
- The VLH is a class of turbines that can have a range of design specifics within certain parameters. The VLH installed at Wasdell is at the larger end of the design spectrum (i.e., at the high end of the head height and diameter ranges), and thus smaller models with lower head height may produce different results.
- There is a need to consider long-term cumulative effects on the system by indexing the fish community upstream and downstream prior to installation and then periodically after installation to provide relative comparisons over time.

Conclusions

As outlined above, many uncertainties remain regarding the interpretation and transferability of our results and need to be carefully assessed when considering more widespread use of VLH turbines. It is critical to recognize that these results apply only in the context of installing a VLH turbine at an existing impassible barrier at a location with fish with a low propensity to move large distances (i.e., have smaller home ranges). As noted in the ‘Other Considerations’ section, the broader implications of constructing a new barrier to the fish community would need to be fully assessed (including more fulsome behavioural analysis, time-to-event analysis, scaling results to the population level, and assessment of cumulative effects) if a new barrier is proposed to allow the installation of VLH turbines.

Entrainment risk at this VLH turbine site appears to be low for the species and size ranges tagged, over the range of operational conditions evaluated. From telemetry monitoring of individuals representative of the fish community for 1.5 years, it appears that none moved downstream via the VLH turbine, and only 3.6% (5/138) ended up downstream of the dam at all. Caution must be exercised when extrapolating the results presented here to other VLH sites and fish communities, as much variation in the behavioural affinity to move through hydropower structures exists among fish species (Knott et al. 2020). Behaviour is likely the primary determinant of movement through these turbines given that the low intake velocity would likely involuntarily entrain only weaker swimmers who ventured immediately in front of the turbine, particularly when operating at maximum generation. The presence of an alternative passage route is likely another factor contributing to the apparent lack of use of the VLH turbines for downstream passage.

The live and Sensor Fish flushing trials indicate that risk of barotrauma injury and mortality is low for VLH turbine entrainment under the limited operating ranges tested, although acclimation depth is an important factor that would be unknown for wild entrained fish and would be site specific. Other sizes of VLH turbine could also produce different results. Large variation in susceptibility to barotrauma (Crew et al. 2017) exists in riverine fish species. Additional variation in susceptibility to barotrauma injury exists among life stages within species (Brown et al. 2014), which have not been captured in this work. Our live fish results suggest the overall risk of collision and shear related injuries is low for this fish community under the limited operating ranges tested. Consistent with previous studies, fish with elongate body forms are likely at greatest risk of injury due to blade collision. Unfortunately, our sample size for Northern Pike, a fish with an elongate body form, was too small to draw meaningful conclusions. Sensor Fish results for shear and collision suggest a higher risk than the live fish results, although most of these collisions were not over the threshold suggested to be a risk of severe injury and the estimate is lower than larger, conventional turbines. Further refinement of critical injury thresholds are needed for a broader range of species.

While uncertainties remain, overall, it appears from this one-site study that the VLH turbine presents a low risk of entrainment, injury, and mortality to resident fishes without a propensity to migrate. However, VLH turbines would still fragment a system if one was placed at a location that did not already have an impassable barrier. VLH turbines do provide a relatively low risk option for producing power at sites that already have an impassable barrier (existing dam or weir) and a fish community with low movement rates. At sites where there is no such existing barrier, the connectivity issue needs to be taken into account, and fish passage options (both upstream and downstream) should be considered. Additional testing of VLH turbine sites and a variety of fish communities is needed to confirm the transferability of results presented here.

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(July 29, 2024)

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Appendix A. Definition of Terms

Table A1. The following terms, which are used throughout this document, are defined below.

Term	Definition
Nadir pressure	Lowest pressure during passage.
Acclimated pressure	Assumed pressure that fish would be acclimated (neutrally buoyant) to prior to passing through or over the dam.
Ratio of Pressure Change (RPC)	Acclimated pressure divided by the nadir pressure.
Sensor Collision	An acceleration spike with an amplitude greater than 95 G, where the duration of time at 70% of the peak spike amplitude is less than 0.0075 s. Based on acceleration data from the sensor as interpreted by HBET (Hou et al. 2018).
Sensor Shear	An acceleration spike with an amplitude greater than 95 G, where the duration of time at 70 % of the peak spike amplitude is greater than 0.0075 s. Based on acceleration data from the sensor as interpreted by HBET (Hou et al. 2018).

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ISSN 1919-3769
ISBN 978-0-660-74024-9 Cat. No. Fs70-7/2024-035E-PDF

Correct Citation for this Publication:

DFO. 2024. Risk to Fish from Very Low Head Turbine Installations. DFO Can. Sci. Advis. Sec. Sci. Resp. 2024/035.

Aussi disponible en français :

MPO. 2024. Risques pour les poissons liés aux installations de turbines à très faible hauteur de chute. Secr. can. des avis sci. du MPO. Rép. des Sci. 2024/035.