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Extent of injury and mortality arising from entrainment of fish through a Very Low Head hydropower turbine in central Ontario, Canada

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Abstract Because of growing interest in deploying newer very low head (VLH) turbine technology to generate electricity in rivers, there is a need to assess how fish fare in interactions with VLH turbines. We assessed injury and mortality rates from experimental VLH turbine entrainment of fish species local to the study site at Wasdell Falls on the Severn River, Ontario, which is one of the first such VLH installations in North America. Using balloon tags to recapture fish and before/after entrainment assessments, we found minimal injury and mortality differences between control (no entrainment) and treatment (entrainment) groups. One adult northern pike (*Esox lucius* Linnaeus, 1758; 1.16% of total entrained fish) was killed by turbine strike. Abrasion-related injuries (i.e., scale loss, torn fins) were the most common form of injury in both control and treatment fish, which was likely attributed to handling and not turbine passage per se. Telemetry monitoring of a subset of fish revealed that post-passage mortality was low. These results suggest that VLH turbine entrainment has negligible effects on the fish species studied here, and thus, VLH turbines may be suitable for increasing generating capacity at low head dam sites with minimal risk to fish.

Keywords Hydropower · Very low head · VLH · Entrainment · Balloon tag · Injury

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Introduction

Hydroelectric generation is one of the oldest and most widespread methods of electricity generation (Sahin et al., 2017). Most countries with fluvial systems (i.e., rivers) have some form of hydroelectric generating capacity. Harnessing electricity without the need to build mega-dams is regarded as a priority for the hydropower industry with great efforts to develop efficient facilities that can generate electricity on smaller waterways and do so using existing low head dams or requiring lower infrastructure investments (Inoue & Shiraishi, 2010). Head height is the difference in distance between intake and outflow at a site. High head is generally defined as being upwards of 100 m while low head is under 30 m (Loots et al., 2015). Smaller waterways in lowland areas that have

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low heads have historically been overlooked due to efficiency issues with older, conventional turbine designs that require relatively high pressure to operate. Recent developments in hydroelectric turbine technology have yielded more efficient turbines capable of operating on a lower head. These low head turbines could provide additional power, making use of the underutilized portion of a country's generating potential, with the benefits in the developing world possibly greater than in developed regions (Paish, 2002; Elbatran et al., 2015).

A relatively recent addition to the current limited number of low head turbine technologies is that of the Very Low Head or VLH turbine. This type of turbine was developed by MJ2 Technologies of France to operate efficiently at very low head (1.4 m–3.2 m) sites (Fraser & Deschênes, 2007) with periphery velocities of 4.5 m s^{-1} to 9.3 m s^{-1}, and overall conditions approaching run of the river (Fraser & Deschênes, 2007). There are multiple aspects of this low head turbine design which have drawn considerable interest from both utilities and regulators. Specifically, the ability for this type of turbine to make more efficient use of very low head sites and the capability of this turbine to be set up on existing infrastructure are two features that allow for reduced installation material quantity and costs in comparison to conventional turbines (Fraser & Deschênes, 2007). Retrofitting infrastructure at existing low head dam sites also has the benefit of not increasing habitat fragmentation, as it avoids the creation of new dams. VLH turbines have been installed at multiple sites in Europe (Kemp et al., 2014). The features of this type of turbine, coupled with the 80,000 prospective low head sites in North America, create much potential for this turbine technology (Kemp et al., 2014). Yet, questions remain regarding the environmental impacts of these facilities—particularly the consequences of entrainment, or the non-volitional passage of fish through the turbine.

Entrainment through conventional turbines can result in different injury types ranging from barotrauma and amputations to scale loss (reviewed Algera et al., 2020). The causes of these injuries vary and can be driven by large pressure changes associated with high head (conventional) turbines causing barotrauma, and/or contact with blades that can cause amputations and spinal deflections (Mueller et al., 2017). Otherwise, entrainment in conventional turbines can result in bruising, fin tearing, hemorrhaging, and numerous other injuries (Hogan et al., 2014). These injuries may not immediately have severe impacts on the overall condition of the fish, but may make the fish more vulnerable to disease, fungal infections, parasites, or predation (Cooke et al., 2011). Conventional hydropower differs from the VLH turbine in a number of ways, and as a result, the VLH turbines operate within parameters that may have less impact on entrained organisms (Fraser & Deschênes, 2007). The blades of the VLH turbine are much more blunt, and in operation, the turbine creates lower pressures of 80 kPa/s, while the maximum allotted pressure changes to meet fish friendliness guidelines is 550 kPa/s (Fraser & Deschênes, 2007). The VLH turbine uses Kaplan style blades mounted on an angle near the surface of the water, generating electricity through a direct drive system (Lautier et al., 2007). The VLH turbine contains eight blades that can be opened or closed to control the speed of the turbine or completely stop it (Fraser & Deschênes, 2007).

A number of studies have examined the direct impacts of VLH turbine passage on several fish species in Europe with encouraging results. Testing of these direct effects of passage was carried out in France on three separate occasions, in 2008, 2010 and in 2013. During testing in 2008, juvenile Atlantic salmon (*Salmo salar* Linnaeus, 1758) and European eel (*Anguilla anguilla* Linnaeus, 1758) were entrained in a VLH turbine and found a mortality rate of 3.1% with variations depending on the point of introduction into the turbine (i.e., near the periphery, near the hub, or mid-blade) (Lagarrigue et al., 2008). A further study on a newer generation of VLH turbines found no mortality and few injuries among test subjects (Lagarrigue & Frey, 2010). The anguilliform fishes suffered no fatal injuries and very few (2%) individuals suffered any injury. The most recent study out of France involved the use of rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792) to mimic native Salmonids and Cyprinids (tench (*Tinca tinca* Linnaeus, 1758) and common carp (*Cyprinus carpio* Linnaeus, 1758) (Lagarrigue, 2013), revealing that survival rates varied from 95.6 to 100% (Lagarrigue, 2013). All three studies found low mortality and injury rates; however, many of the species used were not representative of body characteristics seen in North American north temperate fish communities. Factors like different scale type/configuration and body shape presumably play a role in resilience of fish to entrainment-related injury. As a result of the studies in France, the VLH turbines are purported to have minimal entrainment impacts upon fish; however, this has never been verified on other North American ichthyofauna with differing traits.

Recently, the first VLH turbines in North America were installed at Wasdell Falls on the Severn River in Ontario, Canada. The use of VLH turbines at this site, and the large number of potential sites, are driving interest into wider use of these turbines in North America. This provides the impetus to rectify the lack of knowledge regarding the outcomes of fish entrainment prior to expansion in the number of VLH turbine sites. Our primary goal was to characterize mortality rates and the types and severity of injuries resulting from entrainment. In addition, we wanted to test for differences in impact on a representative north temperate community of North American fish species and observe which body form or species might be most at risk for injury resulting from entrainment within the VLH turbines. We used five different fish species with body shapes representative of a variety of north temperate fishes. With these species, we used a pre-entrainment and post-entrainment assessment of injury combined with balloon tags to determine injury and direct mortality rates and used acoustic telemetry to assess delayed mortality. This information will further inform North American utilities and regulators of the relative risks of VLH installations to a subsample of our local fish species.

Methods

Study site

This experiment was carried out at Wasdell Falls, Ontario (44.780804, − 79.293895), located on the Severn River. This site supports three VLH turbines that were installed making use of pre-existing infrastructure to provide sufficient water storage. This site previously supported two other hydroelectric generating ventures over the past century, leaving behind a dam that is currently used to regulate water levels. The three turbines (3rd generation, model 4000) can be independently operated, having a normal operating head height of 3.8 m. The river both upstream and downstream has many cottages and thus receives increased recreational activity (e.g., boating, fishing) during the summer. The fish community surrounding the site is typical of warm/coolwater fish communities of the area, dominated by centrarchids, esocids, and percids.

Experimental design

We used controlled entrainment and recapture to determine specific injury and mortality levels across five different fish species representing a wide variety of body shapes. These species listed from gibbous to elongate body forms were rock bass (*Ambloplites rupestris* Rafinesque, 1817), smallmouth bass (*Micropterus dolomieu* Lacépède, 1802), largemouth bass (*Micropterus salmoides* Lacépède, 1802), walleye (*Sander vitreus* Mitchill, 1818), and northern pike. Fish were captured for this study through a combination of boat electrofishing and angling. Upon capture, the mass, total length, and species were recorded. Fish that failed to recover from the capture event were omitted from the study.

All 141 fish (Table 1) in the study received an 11 mm Passive Integrated Transponder (PIT) tag (134.2 kHZ FDX-B) which was implanted in the dorsal tissue using a small gauge needle, to enable individual identification. A subset of 66 fish (38 treatment, 28 control) were also tagged with acoustic telemetry tags (JSATS Models SR626 and SR48, Lotek Wireless Inc; Table 2), to allow determination of post-entrainment survival rates by observing movements (or lack thereof). These tags worked in conjunction with an acoustic telemetry array of 24 Lotek WHS 4200 acoustic receivers located in the river 3 km downstream and 3 km upstream from the study site. The acoustic tags sent out acoustically transmitted signals every 10 s that were received and recorded by the receivers. The acoustic tags were surgically implanted in the abdominal cavity of the fish via a small incision which was closed using Ethicon© PDS® II sutures (Veilleux et al., 2018). During this procedure the fish were immobilized with electro-immobilization gloves (Reid et al., 2019). After the acoustic tags and/or PIT tags were implanted, the fish were held in a net pen in the river overnight to recover from the procedures. We monitored fish for recovery post-procedures and removed any subjects which did not recover or were in poor condition. Acoustically tagged fish experienced the

Table 1 Numbers of each species used in the exploration of injury and mortality resulting from entrainment through the VLH turbines at Wasdell Falls, Ontario

Species	# of fish (treatment)	# of fish (control)	Total # fish by species	Size range (mm)	Mass range (kg)
Rock bass	21	15	36	166–263	0.06–0.78
Smallmouth bass	30	18	48	160–481	0.11–1.62
Largemouth bass	16	13	29	183–429	0.09–1.19
Walleye	3	1	4	303–451	0.31–0.78
Northern pike	16	8	24	353–687	0.23–2.96
Total fish	86	55	141		

Also listed with size and mass ranges and control/treatment breakdown. Control fish were flushed over top of the crest gate of the turbine while treatment fish were flushed through the turbine

Table 2 Numbers of each species used in the subset of 66 fish tagged with acoustic tags during testing of injury and mortality resulting from entrainment through the VLH turbines at Wasdell Falls, Ontario

Species	# of fish (treatment)	# of fish (control)	Total # fish by species	Size range (mm)	Mass range (kg)
Rock bass	9	4	13	180–263	0.13–0.78
Smallmouth bass	16	13	29	212–481	0.11–1.62
Largemouth bass	7	9	16	183–429	0.09–1.19
Walleye	3	0	3	303–451	0.31–0.78
Northern pike	3	2	5	513–687	0.69–2.96
Total Fish	38	28	66		

same treatment as the other fish except for the surgical procedure to implant the tag. The effects of this procedure nevertheless should be considered as a potential contributor to mortality differences between acoustically tagged fish, and untagged fish.

Balloon tagging

Balloon tags were used for recapture as a less damaging alternative to other methods (like netting) as they cause minimal external damage to the fish (Heisey et al., 1993; Skalski et al., 2002; Boys et al., 2013). The fish for our study were kept in an aerated holding tank at the VLH site prior to entrainment. Before the application of balloon tags, fish were immobilized using electro-immobilization gloves (Reid et al., 2019). The balloon tags are applied following the methods of (Mathur & Heisey, 1992; Heisey et al., 1993). The balloon tags were affixed to the fish by inserting a length of 36 kg monofilament fishing line through a large-gauge needle which was itself fed through the dorsal tissue of the fish twice per anchor site to create a loop through the dorsal tissue. The number of balloons varied depending on the size of the fish (with each fully inflated balloon reaching a diameter of approximately 10 cm). Each balloon contained six capsules, composed of two anhydrous oxalic acid ($C_2H_2O_4$) capsules and four sodium bicarbonate ($NaHCO_3$) maintaining a 2:1 acid to base ratio. Immediately prior to use, 7 ml of water were added to the balloons using a syringe, after which the activated balloon tag was tied to the anchor loop of monofilament using an overhand knot. The capsules holding the reactants would be softened by the water and agitation of passing over or through the turbine which would break open the capsules mixing the reactants, inflating the balloons and thus pulling the fish to the surface for recapture.

Experimental entrainment device

The device (Fig. 1) used to experimentally entrain the fish through the VLH turbine was composed of a reinforced flexible 0.2 m diameter by 7.6 m PVC hose attached at one end to a 681L reservoir (stock tank), and the other end being the exit point. The entire interior of the apparatus was constructed with smooth edges to prevent fish from being injured in the apparatus. The entrainment device operated by having the reservoir full of water with the prepared fish and activated balloon tags held in a mesh positioning cylinder to ensure proper placement upon flushing, sending the entire contents of the reservoir (including the fish) down the hose. The fish was prevented from being entrained at excessive speed by the presence of standing water in the lower end of the hose, which absorbed much of the kinetic energy of the moving water and fish.

The fish in the treatment group were flushed through the turbine at the periphery (opposite to the hub). This treatment was chosen as previous testing found that entrainment at the periphery had the highest occurrences of mortality and injury in comparison to mid-blade or near-hub introductions (Lagarrigue & Frey, 2010; Lagarrigue, 2013). We also entrained the fish in the treatment group at 50% blade opening as this was also found to have a higher incidence of injury and mortality in comparison to 75% and 100% blade openings (Lagarrigue, 2013).

Recapture and injury assessment

Upon exiting the entrainment apparatus, the balloon tags began to inflate (from 9 to 20 min depending on water temperature), pulling the fish to the surface to be recovered via a crew waiting on a boat using dip nets. Fish within the control group received the same treatment and tagging procedures as above, but were instead flushed with the hose nozzle at the water surface about 1 m away from the edge of the crest gate (located at the top of the turbine). Therefore, these control fish experienced the same drop height into the tailrace post-flushing, but did not encounter the blades of the VLH.

Injuries by class (e.g., cloudiness of eyes, spinal deflections, bruises, dermal lesions, hemorrhages, scale loss, tears in fins, amputations, and emboli) were visually assessed both pre- and post-passage while the fish were held in an aquarium. The types of injuries were assessed in standardized body sections, and were assigned a score of 0 (lack of injury) to 5 (high intensity of injury type) following the protocol used by Mueller et al. (2017). For the purposes of cataloging injuries and for injury assessment backup, a digital photograph was taken of both sides of the fish during the pre- and post-passage assessment. A ruler and gridded background were included in each photo as a reference for scale. Immediately after post-

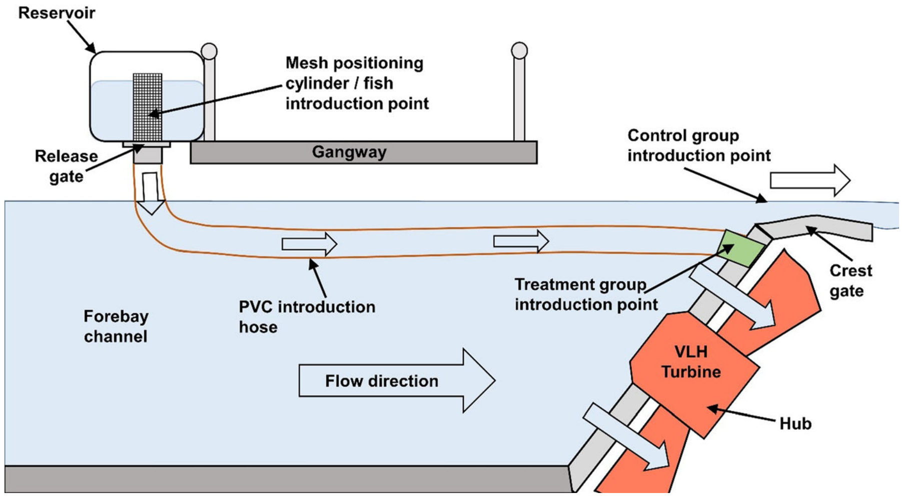


Fig. 1 Schematic of the experimental entrainment apparatus used to experimentally entrain fish through the VLH turbines at Wasdell Falls, on the Severn River in Canada. The fish rested within the mesh positioning cylinder within the filled stock tank. A pull of the release gate below the stock tank sent the fish and the water down through the hose and through the treatment introduction point (in green) or the control group introduction point above the crest gate

entrainment assessment was completed, the fish were released below the dam.

Data analysis

Analyses involving permutational multivariate analysis of variance (PERMANOVA)s and non-metric multidimensional scaling (NMDS) were run using R version 3.6.0 (R Core Team, 2019). The injury class score dataset (un-pooled injury scores) was used to make a fish by fish matrix of Bray–Curtis dissimilarities. From here one-way PERMANOVAs were run on within species groups looking at time (pre-entrainment and post-entrainment) and treatment (entrained vs control) effects. This test was chosen as it is nonparametric and robust, which was needed to function effectively on this dataset. From here, NMDS ordinations were run using the "vegdist" function from the Vegan package for R (Oksanen et al., 2019). NMDS plots were created within control and treatment groups on pre- and post-retrieval injury scores. The treatment group NMDS had a stress level of 21.0 at two dimensions and the control group had a stress level of 19.5 at two dimensions.

For the Wilcoxon signed-rank tests, the injury score for each fish were pooled by summation into a single pre-retrieval and a single post-retrieval pooled injury score. Wilcoxon signed-rank tests were run using SPSS version 26.0 (IBM Corp, 2019) within species and treatment groups between pre- and post-retrieval pooled injury scores. This test was used as the data (ordinal)-violated assumptions of many parametric statistical tests.

The data from the fish tagged with acoustic transmitters were imported into R and filtered using the min lag filter from the GLATOS package (Holbrook et al., 2019). The data were also filtered by tag signal rate and a conditional filter to remove other false detections. These false detections are inherent to the noisy environment of the system. From here fish movements were examined to identify potential mortalities during the 7-day period post-treatment (after balloon tags were removed and the fish were released). Individual maps were generated to explore movements of fish. Fish that failed to move throughout the 7-day monitoring period or those that only moved downstream were subjected to more detailed longer-term examination to determine if there was evidence of any upstream–downstream movements or lateral movements that would indicate that fish were alive.

Results

Generally, patterns of decreasing fish condition post-entrainment were seen in both treatment and control fish. Across all fish species and treatment groups, the most common injuries seen in both the pre-(pre-existing injuries) and post-assessments were abrasion related, including cloudiness of eyes (65% of fish), dermal lesions (82.3%), and minor hemorrhaging (79.4%). These injuries affected similar percentages of fish in both treatment and control groups (Table 3), suggesting they were related to capture and handling rather than turbine passage per se. Throughout this study there were no instances of visible barotrauma on any of the fish (e.g., emboli, bulging of the eyes, etc.). Rates of other more serious injuries, including spinal deflections and minor body amputations, were low (Table 3).

Severe amputation events were even more rare with only one mortality occurrence definitively caused by entrainment, in which a single northern pike that was passed through the turbine was recaptured with a partial decapitation (Fig. 2). This accounts for a direct mortality rate in the overall treatment group across (all species) of 1.16% and of the treatment group of northern pike (16 fish) (Table 1) of 6.25%. Walleye were used in this study but, due to the low sample size, were excluded from further analysis.

The results from one-way PERMANOVAs within species, pre/post-passage, between treatment groups, and their interaction (Table 4) show that the difference between injury rates in the control group and treatment group were not significantly different for rock bass, smallmouth bass and northern pike. NMDS for the control group (Fig. 3) showed that rock bass, smallmouth bass, and northern pike had injury patterns that overlapped considerably, while largemouth bass appeared to have injury patterns that differed from the other three species. Regardless, there are no major spatial changes in these injury patterns between pre- and post-passage. In the treatment group NMDS (Fig. 4), even greater overlapping injury patterns across all species in the pre-passage group was evident. In the post-passage group, the spread in the largemouth bass injuries post-passage deviate from

Table 3 Percentage of fishes affected by injury type, species, and time within treatment groups and pre- or post-flushing

Species	Rock bass		Smallmouth bass		Largemouth bass		Walleye		Northern pike	
Time	Pre (%)	Post (%)	Pre (%)	Post (%)	Pre (%)	Post (%)	Pre (%)	Post (%)	Pre (%)	Post (%)
Control										
Cloudiness of eyes	60	93	67	89	46	54	100	100	0	13
Spinal deflection	0	0	0	0	0	0	0	0	0	0
Bruises	27	47	28	44	15	62	100	100	100	88
Dermal lesions	67	60	89	78	92	92	0	0	100	100
Hemorrhage	93	53	83	89	92	100	0	100	100	100
Tears in fins	100	100	100	100	100	100	100	100	100	100
Scale loss	60	60	44	44	46	62	0	0	88	100
Amputations	7	0	6	11	15	8	0	0	25	38
Emboli	0	0	0	0	0	0	0	0	0	0
Treatment										
Cloudiness of eyes	76	90	*50*	*77*	*19*	*50*	33	33	19	19
Spinal deflection	0	0	*0*	*3*	0	0	0	0	0	6
Bruises	5	10	*30*	*47*	13	38	33	33	*56*	*88*
Dermal lesions	81	81	*73*	*83*	*88*	*100*	0	0	*81*	*94*
Hemorrhage	86	76	90	83	75	81	67	33	94	69
Tears in fins	100	100	100	100	100	100	100	100	100	100
Scale loss	67	67	*50*	*63*	50	63	*67*	*100*	*69*	*100*
Amputations	0	0	10	3	*6*	*13*	0	0	13	25
Emboli	0	0	0	0	0	0	0	0	0	0

Control fish were flushed over top of the crest gate of the turbine while treatment fish were flushed through the turbine. Percentages of fish within the treatment group, with increases in injury occurrences (relative to the control group) indicated in italics

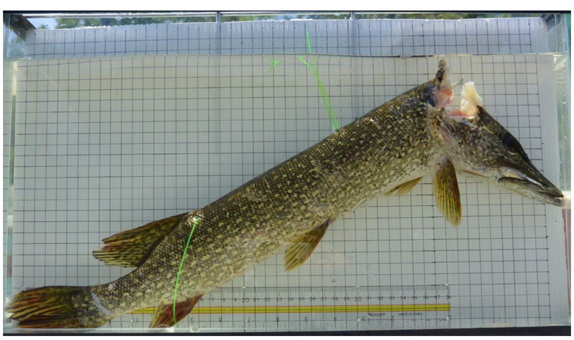


Fig. 2 The single direct mortality observed in this study of the effects of entrainment on fishes through the VLH turbines at Wasdell Falls on the Severn River, Canada. This northern pike experienced a catastrophic partial decapitation

those experienced by the other species. This trend also occurs in the control group and seems to be caused by increased incidences of some abrasion-related injuries (lesions of the face, etc.).

The Wilcoxon signed-ranks test performed on the pooled injury scores within species and treatment groups (Table 5) showed a lack of significance in all but three groups, pointing to little change in fish condition between pre- and post-passage. For smallmouth bass (control and treatment) and northern pike (treatment), there was a significant change in condition between pre- and post-passage. However, the plotted mean condition scores by species and treatment (Fig. 5) revealed that injury severity did not change appreciably from pre- to post-passage, even for the three significant groups.

For examination of longer-term post-entrainment survival, the subset of fish tagged with acoustic tags was monitored for a seven-day period during which mortalities that occurred after entrainment were identified. We found that one largemouth bass (6.2% of all acoustically tagged largemouth bass) and one smallmouth bass (3.5% of all acoustically tagged smallmouth bass) of the treatment group and control

Table 4 Output from one-way PERMANOVAs run on raw injury scores found during the entrainment study on the VLH turbines at Wasdell Falls, Ontario, using Bray–Curtis dissimilarities exploring treatment (entrained and control), time (pre- and post-entrainment) and interactions effects within species groups

Species	Variable	Df	SumsOfSqs	MeanSqs	*F*.Model	R^2	Pr(> *F*)
Rock bass	Time	1	0.00826	0.008264	0.66568	0.00929	0.479
	Treatment	1	0.03425	0.03425	2.75873	0.03852	0.11
	Time:Treatment	1	0.00241	0.00241	0.19416	0.00271	0.683
	Residuals	68	0.84422	0.012415	0.94947		
Smallmouth bass	Time	1	0.10128	0.101277	7.4399	0.07455	0.004**
	Treatment	1	0.00333	0.003334	0.2449	0.00245	0.711
	Time:Treatment	1	0.00147	0.001468	0.1079	0.00108	0.816
	Residuals	92	1.25236	0.013613	0.92191		
Largemouth bass	Time	1	0.04184	0.041843	3.0369	0.04765	0.062
	Treatment	1	0.08676	0.086757	6.2965	0.0988	0.007**
	Time:Treatment	1	0.0055	0.005496	0.3989	0.00626	0.687
	Residuals	54	0.74404	0.013779	0.84729		
Northern pike	Time	1	0.04134	0.041342	4.7323	0.0898	0.016**
	Treatment	1	0.02507	0.025074	2.8702	0.05446	0.063
	Time:Treatment	1	0.00957	0.00957	1.0955	0.02079	0.325
	Residuals	44	0.38439	0.008736	0.83495		

This was run with 999 permutations, and significant values noted by **

group, respectively, appeared to be dead within this timeframe (Table 1) with mortalities occurring ∼ 4 h after passage. The other tagged fish (including northern pike, rock bass, and walleye) were recorded moving both upstream and downstream in ways that indicated that they were alive.

Discussion

This study was carried out to address the knowledge gap that exists regarding the effects of entrainment by VLH turbines on north temperate fish species more representative of typical North American communities. There is the potential for widespread use of this type of turbine in North America. Therefore, testing of entrainment effects on fish species beyond those studied in France (Lagarrigue et al., 2008; Lagarrigue & Frey, 2010; Lagarrigue, 2013) can provide water resource managers with a more complete understanding of the ecological risks, and allow for potential mitigations (Algera et al., 2020). In this study, we were able to identify sublethal and lethal injury rates across five common fish species and compare these measures across the treatment groups both before and after dam passage.

Through experimental entrainment, we observed that one northern pike experienced a catastrophic partial decapitation, which was the only immediate mortality in this study. The most common injuries observed in this study were abrasion related, including scale loss, eye cloudiness, dermal lesions, and minor external hemorrhaging. The lack of significance in the PERMANOVA tests (Table 4) in all interactions between treatment groups and time, along with the difference in mean pooled condition scores for both control and treatment fish point to handling effects as a probable contributor to these injuries. Previous studies on injuries resulting from holding in nets have reported fraying of fins, injury to the mouth and scale loss as common (Colotelo et al., 2013a, b). Similarly, these types of injuries were seen in the majority of fish used in this study. Overnight holding was necessary to observe specimens for mortalities caused by the capture and tagging procedure and to keep constant holding times across all fish, making the fish vulnerable to abrasion injuries in the mesh holding pens. The multidimensional analyses demonstrate a deviation in

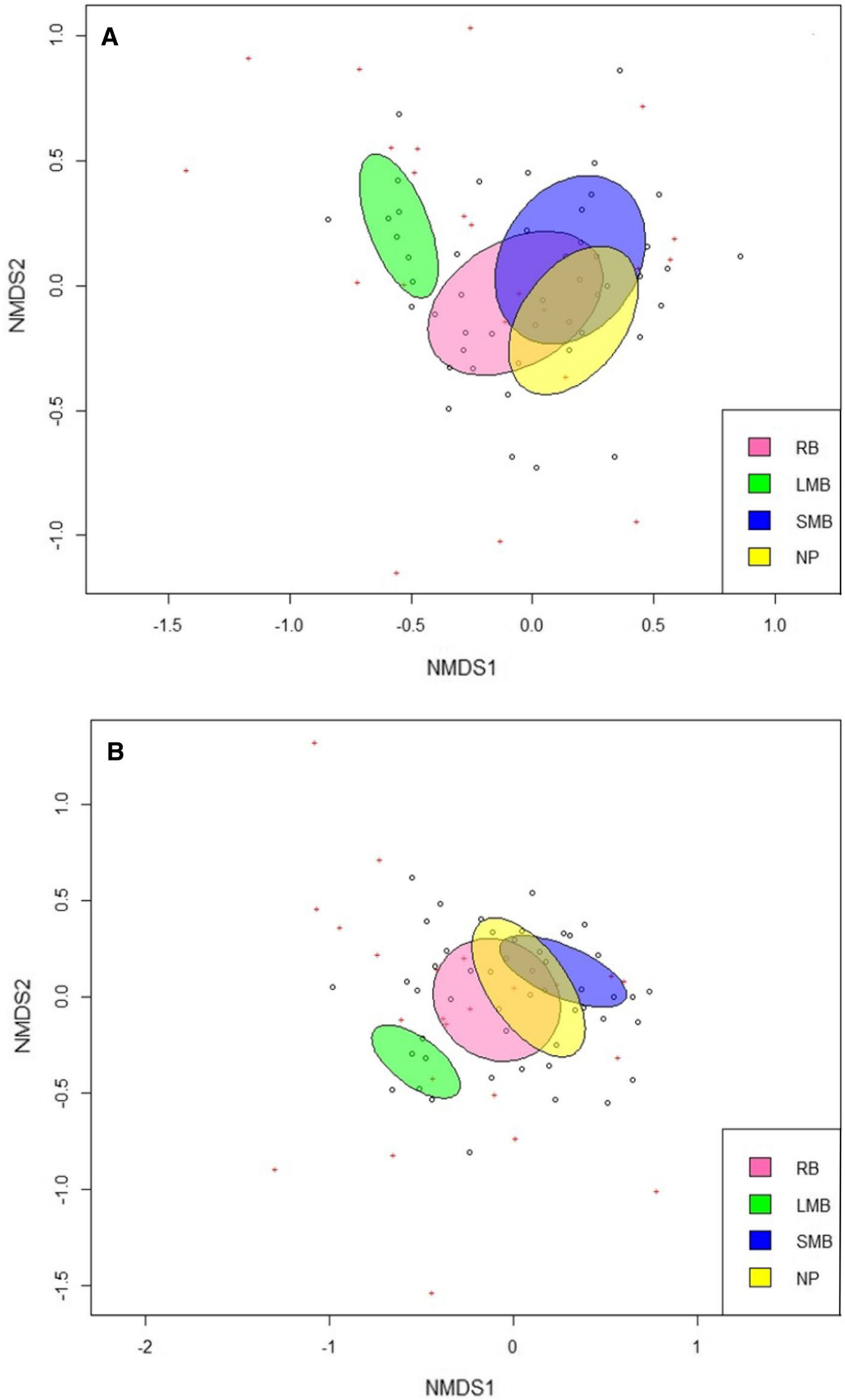
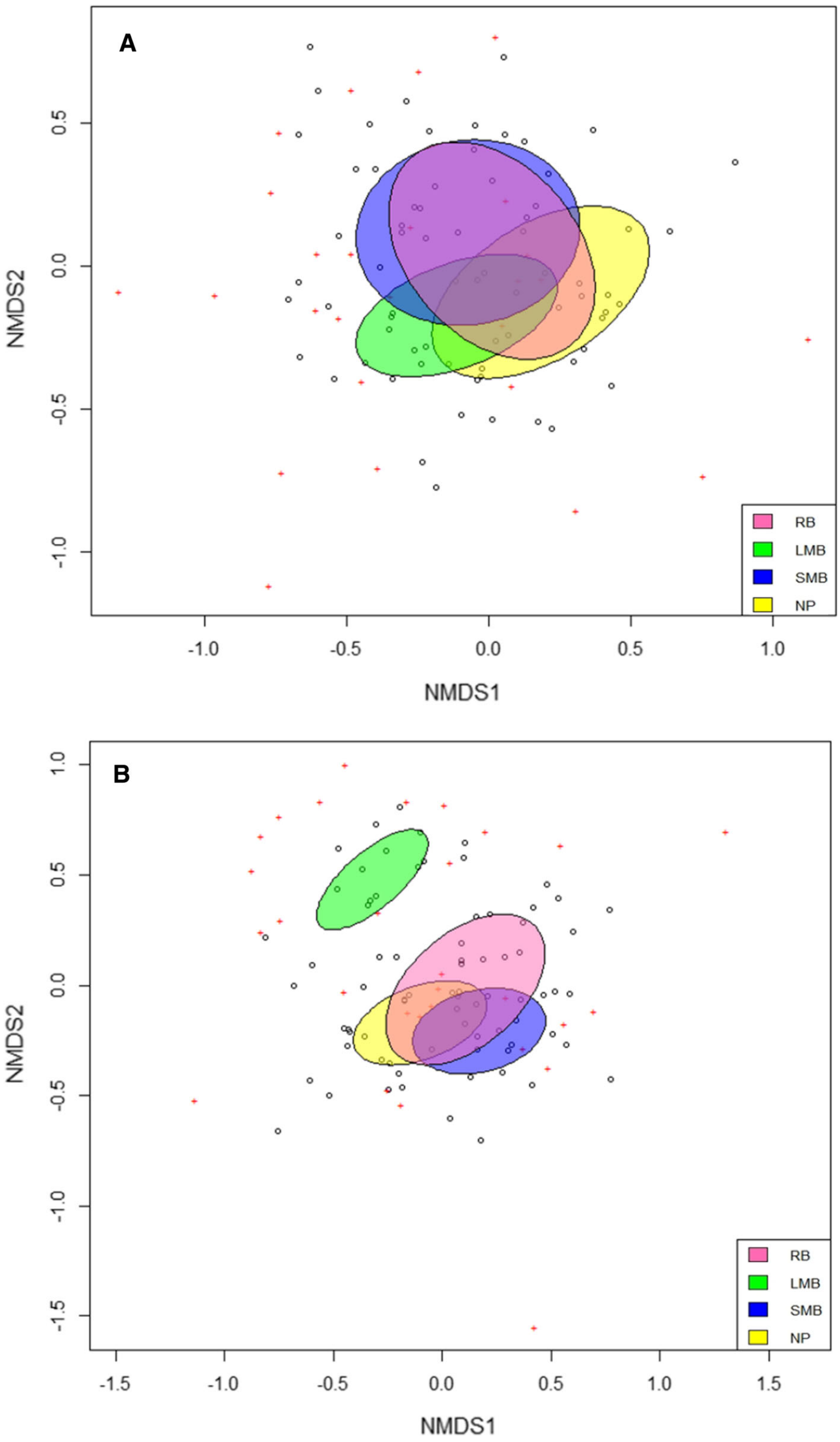


Fig. 3 NMDS ordinations on fish by fish injury data for the control group before passage over the VLH turbine at Wasdell Falls on the Severn River (**A**) and after passage (**B**) by species with NP, LMB, SMB, RB, and W representing northern pike, largemouth bass, smallmouth bass, rock bass, and walleye, respectively


A
NMDS1
NMDS2
RB
LMB
SMB
NP
B
NMDS1
NMDS2
RB
LMB
SMB
NP

◀**Fig. 4** NMDS ordinations on fish by fish injury data for the treatment group (entrained at the blade periphery and 50% blade opening) before passage through the VLH turbine at Wasdell Falls on the Severn River (**A**) and after (**B**) within the treatment group by species with NP, LMB, SMB, and RB representing northern pike, largemouth bass, smallmouth bass, and rock bass, respectively

injury patterns in the largemouth bass treatment group from before to after entrainment, suggesting that this species may be affected more than others by entrainment. The difference in the data spread in the treatment group NMDS for northern pike is not paralleled in the control group; however, this is possibly the result of visual assessment variability, since the pike within the treatment group had on average lower pooled injury scores post-passage than before (Fig. 5; Table 5). Difficulty in determining small changes in fish injury severity when the fish may have pre-existing injuries is a possible cause of this variation. Visual identification of injuries can be subjective and therefore can vary when overall differences are minor (Colotelo et al., 2014).

The VLH turbines operate with maximum pressure changes of 80 kPa/s, while the maximum allotted pressure changes to meet fish friendliness guidelines is 550 kPa/s (Fraser & Deschênes, 2007). During the course of this study, we observed no instances of barotrauma (commonly resulting from entrainment in conventional turbines), including injuries such as emboli in the eyes or fins, hemorrhages or bulging of the eyes, and anal bleeding (Stokesbury & Dadswell, 1991; Čada, 2001; Mueller et al., 2017). Since none of these injuries were observed in this study, the purported pressures generated by this type of turbine being much lower than that of conventional hydroelectric turbines (Fraser & Deschênes, 2007) seems to be corroborated in so far as its effects on entrained fish.

The single mortality caused by a catastrophic partial decapitation in a northern pike (Fig. 2) seems to parallel injuries caused by grinding or impingement between moving and non-moving structures (Cooke et al., 2011) on the VLH turbine. Some possible locations of grinding or impingement are between the turbine housing or trash-rack and the blade. Decapitation has also been reported as being caused by shear stress in conventional turbines (Stokesbury & Dadswell, 1991); however, this is unlikely the case here as the maximum velocity gradient through the shear zones in the VLH turbine is 10 $m^2\ s^{-1}$ (Fraser & Deschênes, 2007), while under fish friendliness guidelines, the maximum is 180 $m^2\ s^{-1}$ (Cooke et al., 2011).

In contrast to the earliest studies on VLH mortality (Lagarrigue et al., 2008; Lagarrigue & Frey, 2010), the rates of mortality in this study were lower and more similar to what was observed in the more recent

Table 5 Output from Wilcoxon signed-ranks tests within species and treatment groups using pooled injury scores of fish used in the entrainment study on the VLH turbines at Wasdell Falls, Ontario

Species	Group	Z	Asymp. sig. (2-tailed)
Rock bass	Control	$-.255^{c}$	.799
	Treatment	-1.036^{b}	.300
Smallmouth bass	Control	-3.151^{b}	.002**
	Treatment	-3.385^{b}	.001**
Largemouth bass	Control	-1.274^{b}	.203
	Treatment	-1.912^{b}	.056
Northern pike	Control	$-.649^{b}$	.516
	Treatment	-2.933^{b}	.003**

Specifically, between the before vs. after groups. Control fish were flushed over top of the crest gate of the turbine while treatment fish were flushed through the turbine

Significant values are noted with **

[a]Wilcoxon signed-ranks test

[b]Based on negative ranks

[c]Based on positive ranks

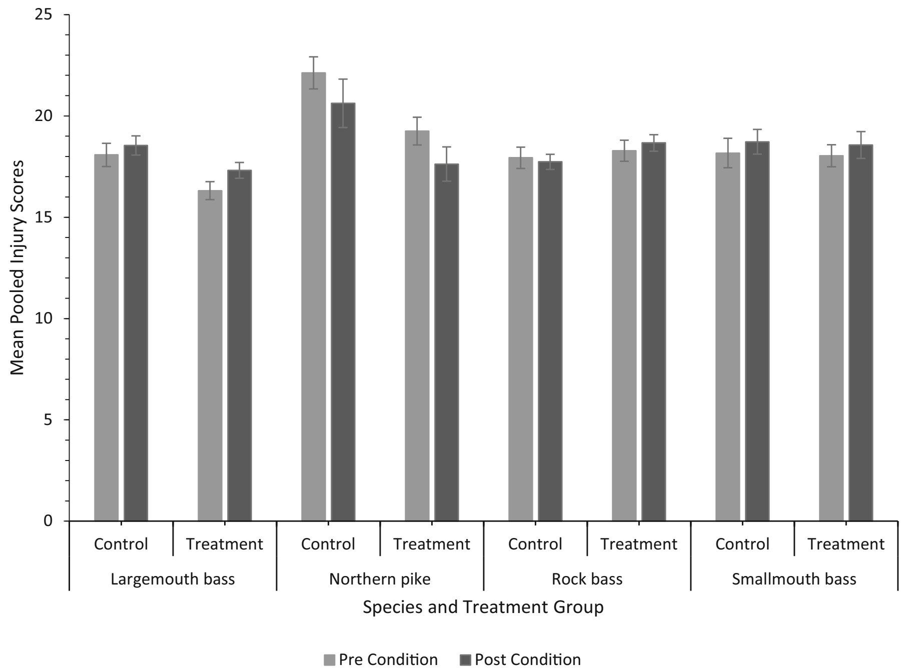


Fig. 5 Mean pooled injury scores for each species flushed through (treatment) and over (control) the VLH turbines at Wasdell Falls on the Severn River in Ontario showing before and after scores plotted with standard error

European tests (Lagarrigue, 2013). This is partially due to the fact that a design flaw causing impingement between the blade ends and the housing was rectified in the newest turbine design (Lagarrigue & Frey, 2010). Tests of the newest design found that mortality rates at the 50% blade opening and the periphery of the turbine ranged from 1.1 to 4.4% depending on the species and found a species-specific delayed (48 h) mortality rate ranging from 3.45% (for small carp and tench) to 6.7% (large rainbow trout) (Lagarrigue, 2013). The direct mortality rate from this study at Wasdell Falls (also housing the latest turbine design) was within this range, at 6.25% (1 of 16) of treatment northern pike. However, in the 2013 tests in France, 30 large rainbow trouts were entrained at 50% blade opening at the periphery of the turbine, and total sample size was in the hundreds. It should be noted that blade opening would vary greatly depending on flow conditions and seasonally (freshet). In addition, handling times were less as they made use of hatchery fish which do not necessarily require detailed assessment for pre-existing injuries (assuming the fish used are in good condition). Our study at Wasdell Falls had longer periods of injury assessment prior to entrainment due to use of solely wild-caught fishes.

Our longer-term delayed mortality rate obtained by telemetry was similar to that found by Lagarrigue (2013) at 6.25% of entrained largemouth bass but over a longer period of time (7 days). Our control fish delayed mortality rate within the smallmouth bass group was 5.56% within 7 days. This was in contrast to Lagarrigue (2013) who reported no immediate or delayed mortality in some of the larger fish within the control group (with the fish having been monitored for a shorter period of time). The telemetry data allowed us to identify the longer-term delayed mortality of these two fish, but since each fish was of a different treatment group and species, it seems that no specific group or species of fish was affected.

The entrainment apparatus worked well and allowed us to overcome the lack of draw which makes experimental entrainment difficult in turbines that operate with such low intake velocities. The low intake velocity of the VLH turbine (Fraser & Deschênes, 2007) means that the mortality risks are further reduced by the fact that all of the species involved should be able to easily escape near entrainment events with their maximum critical swim speeds being well above the normal operating flow into the turbines. Smallmouth bass, largemouth bass, walleye, rock bass, and northern pike all have critical swimming speeds ranging from 18 to 114 cm s^{-1} (Jones et al., 1974; Farlinger & Beamish, 1977; Peake et al., 2000; Peake, 2004a, b; Crans et al., 2015) while at the turbine, velocity ranged from 3 to 21 cm s^{-1} (Site Operator, personal communication, June 30, 2019).

It should also be considered that over the course of a typical year, resident fish would be at lower risk overall than was demonstrated here for two main reasons. First, this study selected the most harmful experimental conditions demonstrated in France (Lagarrigue, 2013), specifically to demonstrate the potential worst-case scenario and to minimize the use of wild-caught fish. Lagarrigue (2013) found that entrainment close to the hub and at mid-blade had lower mortality rates than the periphery. Also blade openings of 100%, and 75% were found to have lower mortality rates than 50% blade opening. As such, over the course of a year under different operating conditions, and with variable entrainment locations relative to the hub, entrained fish would likely be impacted less than what was shown here. Second, the fish in our study were forcibly flushed through the turbine, when in reality, most fish could avoid entrainment all together given their swimming abilities relative to the low intake velocity of the turbine. Nonetheless, future work could expand the number of species to capture an even wider range of fish body types, swimming ability, and sizes to see if our results are supported more broadly. In addition, technology such as the sensor fish (Deng et al., 2007) could be used to obtain more detailed profiles of pressure, acceleration, rotation, and other physical parameters experienced by fish during entrainment.

Overall, the results of this study support the purported minimal impact upon fishes caused by entrainment within the VLH turbine. Even with these worst-case variables acting against the tested fish, we did not see many of the injuries commonly associated with other conventional hydroelectric turbines and mortality was very low. Therefore, the very low head series of turbines continue to show promise with regard to its minimal impact on entrained fishes with physical traits beyond those of the few previously tested European species.

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