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RESEARCH ARTICLE

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Interactions of a temperate North American fish community with a very low head hydropower facility in Ontario, Canada

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Abstract

Efforts are underway to re-evaluate the use of existing instream infrastructure (e.g., weirs, water control dams) for the purposes of hydroelectric generation, with new very low head turbine technology that is purportedly "fish friendly" making retrofitting a viable option. This is the case at Wasdell Falls on the Severn River, ON, Canada, where the first very low head (VLH) turbines in Canada were put into operation at a long-standing low-head dam site. There is little information regarding fish usage of areas upstream from these structures and how this may relate to entrainment risk. Therefore, we assessed the risk of entrainment based on fish use of the forebay areas upstream from the infrastructure, including the forebay of three operating VLH turbines. Acoustic telemetry was used to determine movements and entrainment events of eight north temperate fish species. Entrainment through the VLH turbines did not occur over the course of one year, however, several fish did move downstream via other paths (e.g., over the water control structure). Forebay use was exclusive to rock bass, smallmouth bass, northern pike and largemouth bass, whereas channel catfish, walleye, white sucker and pumpkinseed avoided the forebay. When near the dam, fish tended to select deeper areas located away from the VLH forebay. Fish use of the VLH forebay was limited to brief forays indicating exploratory movements rather than prolonged residence. The findings suggest that entrainment risk at this VLH turbine site is low for the species and life stages studied.

KEYWORDS
entrainment, hydropower, telemetry, turbine, very low head, VLH

1 | INTRODUCTION

Hydroelectric generation is one of the more common forms of power generation globally (Sahin, Stewart, Giurco, & Porter, 2017). Conventional hydropower has historically made use of high head (>100 m tall) dams with expansive storage reservoirs on large rivers. These dams have large physical and ecological footprints and often result in substantial changes in riverine conditions as a result of reservoir creation, habitat fragmentation and alterations in downstream flow (Morita & Yamamoto, 2002; Sabater, 2008). However, there are many smaller-sized rivers with hydroelectric potential. Installing turbines that are efficient at lower head height (<30 m), or very low head (<2 m) require less storage, thus having the potential to lessen the environmental consequences for individual dams (Fraser & Deschênes, 2007; Loots, Dijkb, Bartac, Vuurend, & Bhagwane, 2015). Nonetheless, low-head dams still have a suite of negative consequences on aquatic ecosystems (e.g., fragmentation [Smith, Meiners, Hastings, Thomas, & Colombo, 2017]), and alteration of sediment transport (Casserly et al., 2020). Beyond hydropower production, low head dams are used to separate introduced/invasive species from native fish communities, for navigation, water taking and flood control purposes. Although there is a growing trend towards removal of low head dams (e.g., Maloney, Dodd, Butler, & Wahl, 2008), in some cases removal may not be possible and therefore adding utility without additional ecological impacts may be desired. As a result, low-head hydroelectric operations are an attractive addition to existing structures.

A relatively recent addition to the current array of low-head turbine technologies is that of the very low head turbine (hereafter referred to as "VLH turbine"). The VLH turbine (MJ2 Technologies, France) can operate at a very low head of 1.4–4.2 m, with a generating capacity of up to 500 kW, flow rates, which meet US Department of Energy fish friendliness guidelines (Odeh, 1999), and overall conditions approaching run of the river (Fraser & Deschênes, 2007; Kemp, Williams, Sasseville, & Anderson, 2014). These fish friendliness guidelines are a set of parameters identified for turbines as the limit at which there is minimal risk to the condition of fish that may become entrained (defined as the voluntary or involuntary passage of fish; Harrison et al., 2019) through the turbines (Odeh, 1999). The VLH turbine has drawn much interest due to its ability to make use of very low head sites, the potential for this turbine to be set up on existing infrastructure, and the lower construction material requirements allowing for reduced installation costs (Fernando & Rival, 2014). With their lower head height, the area immediately upstream from the infrastructure (forebays) of VLH facilities is unique. Most notably, there is no large reservoir inherent to high head generating facilities. Thus, previous studies on reservoir forebay usage by fish are not as applicable to forebay usage in facilities, which cause minimal disruptions to the natural flow. Indeed, Harrison et al. (2019) suggested that forebay configuration and dam characteristics likely have a strong influence on entrainment rates.

VLH turbines have been installed at multiple sites in Europe but have yet to be implemented widely in North America. The features of this type of turbine coupled with the approximately 80,000 potential 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. VLH turbines have been tested for direct impacts on fish resulting from entrainment on a number of European fish species and some North American Salmonids with encouraging results (Lagarrigue, 2013; Lagarrigue & Frey, 2010; Lagarrigue, Voegtle, & Lascaux, 2008), with low rates of mortality found on the earlier studies and negligible mortality on later studies of newer generations of the VLH turbines. It is for these reasons that some have labelled VLH turbines as being "fish friendly". However, none of these studies assessed upstream fish movements as a risk factor. In 2015 the first VLH turbines in North America were put into operation at Wasdell Falls on the Severn River in Ontario, Canada (Kemp et al., 2014), and these now serve as the test site to better understand the risk of entrainment to resident fish species.

To achieve a better understanding of the risk of entrainment through the VLH Turbines, we carried out a study of the movement of the fish community upstream from the infrastructure complex using acoustic telemetry. Our primary goal was to characterize the entrainment risk to different fish species across multiple seasons. The secondary goal was to characterize fish usage of the forebay. To achieve these goals, we implanted acoustic telemetry transmitters in eight different fish species and tracked their movements over ~1-year period. Most of the previous studies of VLH technology have focused on the consequences of entrainment rather than the likelihood of entrainment (reviewed in Algera, Rytwinski, et al., 2020, Algera, Ward, et al., 2020). Entrainment risk for resident fish populations is an important metric in understanding the potential ecological consequences of hydropower development (Harrison et al., 2019). Given the lack of research on this topic in small to middle-sized rivers with low head dams, this research addresses an important gap in VLH turbine risk assessment and more broadly in fish-hydropower interactions.

The combination of low head height causing lesser disruptions in water flow and the fact that the forebay areas are shallower than those of high head turbines create differences, which should influence habitat usage and forebay residency times. Since there is no drastic change in depth or structure between the forebay areas and the areas further upstream, it is possible that fish usage of the areas near the turbines would be comparable to other areas of the river. As a result of this, we had predicted that some tagged fish would become entrained through the VLH turbine, but that this would be based on relative abundance not necessarily behaviourally driven movements of a single species.

2 | METHODS

2.1 | Study site

This study was carried out at Wasdell Falls, Ontario (44.780804, −79.293895) on the Severn River (Figure 1). This site supports three, third-generation VLH turbines; the infrastructure at the site is composed of a water control dam on the east side and the trio of VLH turbines on the west side of a central island.

In terms of habitat, the VLH and water control dam forebays are more consistent in depth (Figure 1c) than the areas further upstream. The forebays themselves are devoid of instream woody debris and have low macrophyte abundance but do provide eddies on the sides with reduced current (Figure 2). The substrate in the forebays is mostly bedrock with some cobble and there is no riparian cover on either side of the VLH forebay. Upstream from the forebays, the west bank had little overhead cover while the east bank had some in the form of canopy cover and docks.

2.2 | Fish capture and tagging

Fish capture was carried out through a combination of boat electrofishing and angling within 3 km upstream from the infrastructure and fish were released after tagging at the site of capture. We tagged all fish of adequate size to support an acoustic tag (tag mass < 1.5% of the mass of the fish (Brown, Cooke, Anderson, & McKinley, 1999) between June 14th and July 25th, 2017.

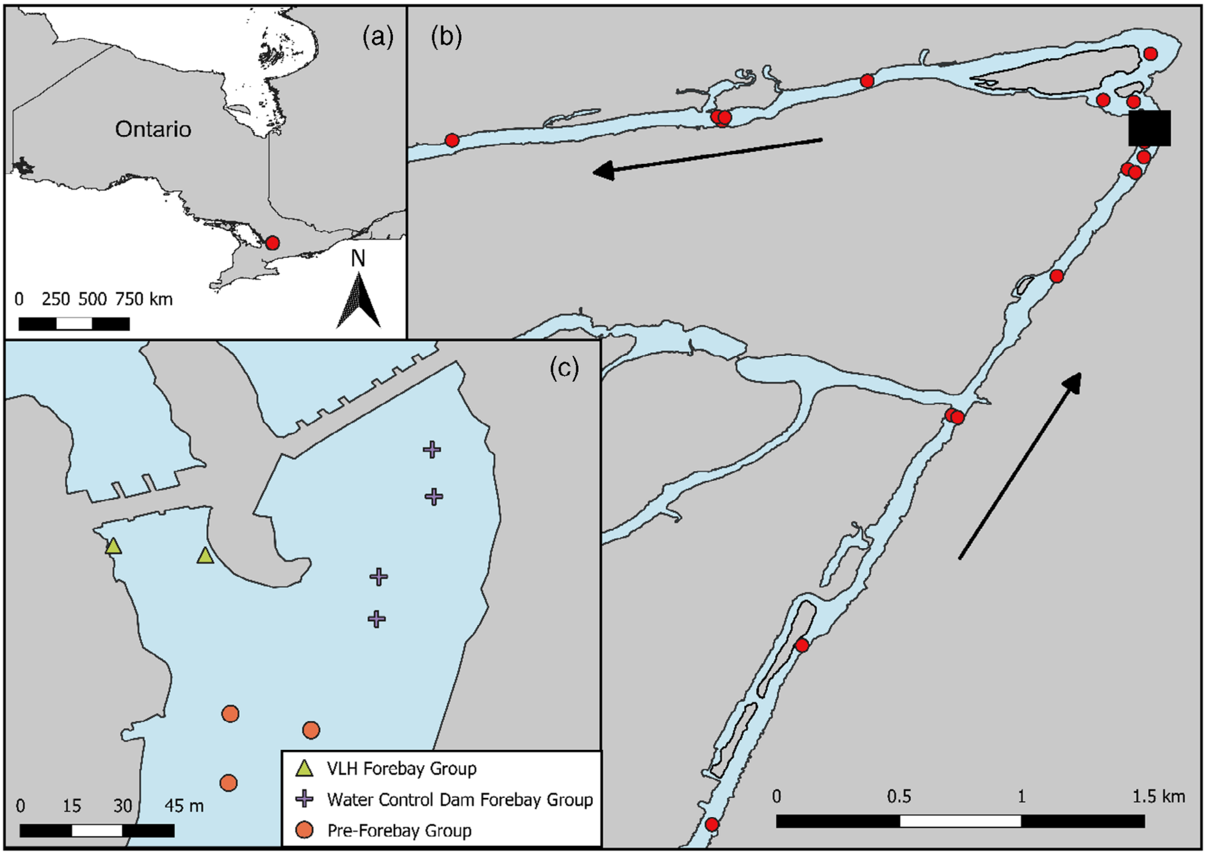

FIGURE 1 (a) Location of the study site (Wasdell Falls) within Ontario, Canada (red dot); (b) Locations of stations in the entire acoustic telemetry receiver (red dots) array deployed from summer 2017 to fall 2018 on the Severn River with arrows showing flow direction and black square showing inset of (c); and (c) Closeup of receiver array and station groupings upstream of the VLH turbines at Wasdell Falls. Note that these are stations of deployment and that not all receivers were deployed concurrently [Color figure can be viewed at wileyonlinelibrary.com]

A total of 138 fish were tagged (Table 1) across eight species including smallmouth bass (*Micropterus dolomieu*), largemouth bass (*Micropterus salmoides*), rock bass (*Ambloplites rupestris*), walleye (*Sander vitreus*), northern pike (*Esox lucius*), channel catfish (*Ictalurus punctatus*), white sucker (*Catastomus commersoni*) and pumpkinseed (*Lepomis gibbosus*). The acoustic telemetry tags used were Juvenile Salmonid Acoustic Telemetry System tags (JSATS; Lotek Wireless, Newmarket, ON) and emitted coded signals at 10 s intervals for the duration of tag battery life. Surgeries were carried out on the water shortly after capture with fish immobilized using electro-immobilization gloves (Reid et al., 2019). JSATS were surgically implanted into the abdominal cavity of the fish using the methods outlined in Veilleux et al. (2018). Fish were retained for ~1 hr before releasing at the site of capture.

2.3 | Acoustic telemetry array

Tagged fish were tracked with an acoustic telemetry array (Figure 1b) set upstream and downstream from Wasdell Falls and were in operation from the spring of 2017 to the fall of 2018. The acoustic telemetry array was composed of 24 model WHS 4200 receivers (Lotek Wireless, Newmarket, ON) distributed over an approximately 6 km distance (3 km upstream and 3 km downstream of the VLH Turbine site). These receivers were downloaded multiple times over the duration of the study, and some were redeployed at different locations (thus resulting in a total of 26 different stations). There was a much higher density of stations upstream, and within the forebays of the water control dam and the VLH Turbines, so that we could determine fish movements in these areas with greater certainty. Detection efficiency was assessed by the deployment of 4 activated tags at set distances away from 6 representative receivers (7 to 30 m) where they were left for 1 to 4 hr (Kessel et al., 2014).

2.4 | Data filtering and analysis

Filtering and analysis of acoustic telemetry data were carried out in R statistical environment version 3.6.0. (R Core Team, 2019). Multiple filtering methods were used to remove false detections, which are common with this form of technology. Filtering was carried out at the overall array level, and within the upstream and downstream groups separately. This method of acoustic telemetry filtering is commonly used in noisy environments (Algera, Ward, et al., 2020). After filtering,

FIGURE 2 (a) Very Low Head turbines at Wasdell Falls looking downstream. (b) Water control dam on East side of island from VLH turbines. (c) VLH turbines looking from downstream to upstream [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 General information on eight species acoustically tagged in summer 2017, upstream of the very low head turbines at Wasdell Falls on the Severn River, Canada. Number tagged indicates the number of individuals tagged with JSATS (acoustic telemetry tags) in each species

Species	Number tagged	Min length (mm)	Max length (mm)	Mean length (mm)	Standard deviation (mm)
Smallmouth bass	68	189	397	276	49
Rock bass	43	159	228	183	15
Largemouth bass	7	211	463	355	85
White sucker	6	315	520	421	83
Channel catfish	6	292	350	312	20
Northern pike	4	475	717	594	106
Walleye	3	282	328	306	23
Pumpkinseed	1	-	-	-	-
Total	138				

receiver stations were grouped to aid in the identification of broader areas of movement. The array in the area immediately upstream from the infrastructure was subdivided into three station groups: 1) within the forebay of the VLH turbines, 2) within the water control dam forebay, and 3) the area immediately upstream from the forebays (Figure 1c). Abacus and bubble plots to aid in the identification of individual fish movements (Figures 3 and 4) were created through the GLATOS R package (Holbrook, Hayden, Binder, Pye, & Nunes, 2019) to aid in visualizing fish movements over the duration of the study.

Chi-squared tests were run using Microsoft Excel's "chitest" function on contingency tables (Microsoft Corporation, 2019). The first test table is composed of the number of individuals, of the four species detected in the forebay area (rock bass, smallmouth bass, largemouth bass and northern pike) to determine whether relative proportions of species detected in each area of the forebays were statistically similar to each other. A second chi-squared test was run on these proportions but including the relative proportions of species using all the fish which were tagged. A chi-squared test was also run

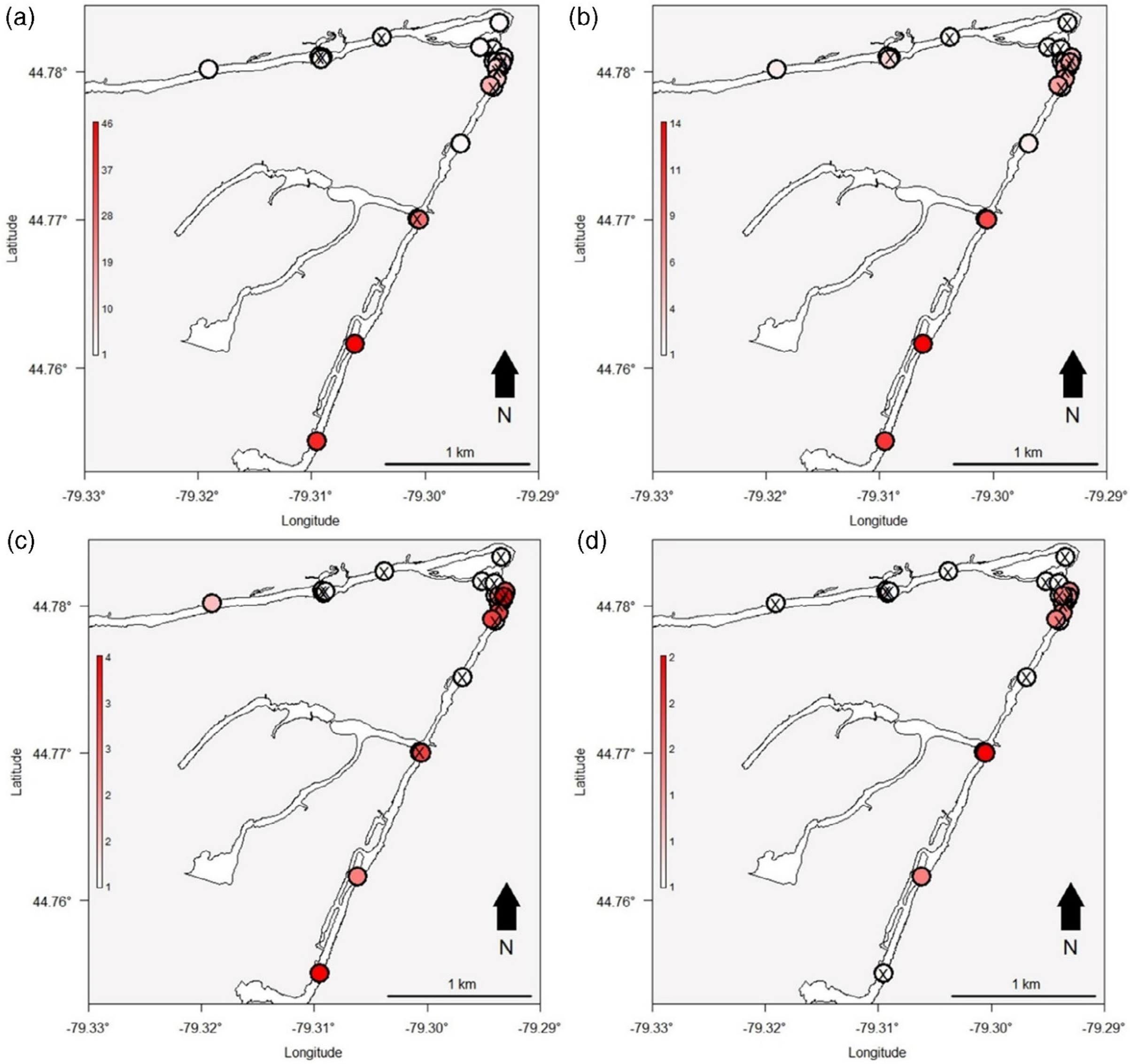

FIGURE 3 Plots of the study area on the Severn River with the VLH site at Wasdell Falls in the upper right of each map. Each plot shows number of detections per station for (a) smallmouth bass, (b) rock bass, (c) largemouth bass, and (d) northern pike. Higher numbers of detections are denoted by a darker bubble shade while a complete lack of detections is denoted by a crossed bubble. Note that in higher station densities crosses may be visible through other stations [Color figure can be viewed at wileyonlinelibrary.com]

on a contingency table of the average cumulative minutes per individual fish within each forebay group and species.

3 | RESULTS

We found that detection efficiencies were at their highest within a 15 m radius of the receivers. Detection efficiencies ranged from 70 to 72% and 26 to 66% at 7 and 19 m respectively, likely due to changes in bathymetry affecting acoustic range. Although these detection ranges were small, they were sufficient to create good coverage (gates) in key locations to assess the spatial ecology of fish. Of the 138 fish tagged we found that none of the fish moved downstream via the VLH turbines, although we did find that 5 fish were detected downstream from the infrastructure. Three fish were last detected at the flood control dam forebay before being detected downstream, suggesting that they passed over that infrastructure and not the VLH (specifically: largemouth bass (280 mm, 24th of July 2017), rock bass (185 mm, 20th of July 2017), and smallmouth bass (269 mm, 21st of June 2017). The other two fish (of the 5 detected downstream) took undetermined routes, possibly from further upstream where there are alternate paths via canals; these fish were a rock bass (204 mm, first detected downstream on 23rd of June 2017) and a smallmouth bass (225 mm, first detected downstream on 17th of June 2017). These movements were identified through visual identification of detections in the filtered data.

Of the tagged fish, northern pike, smallmouth bass, rock bass and largemouth bass were detected within the three forebay station

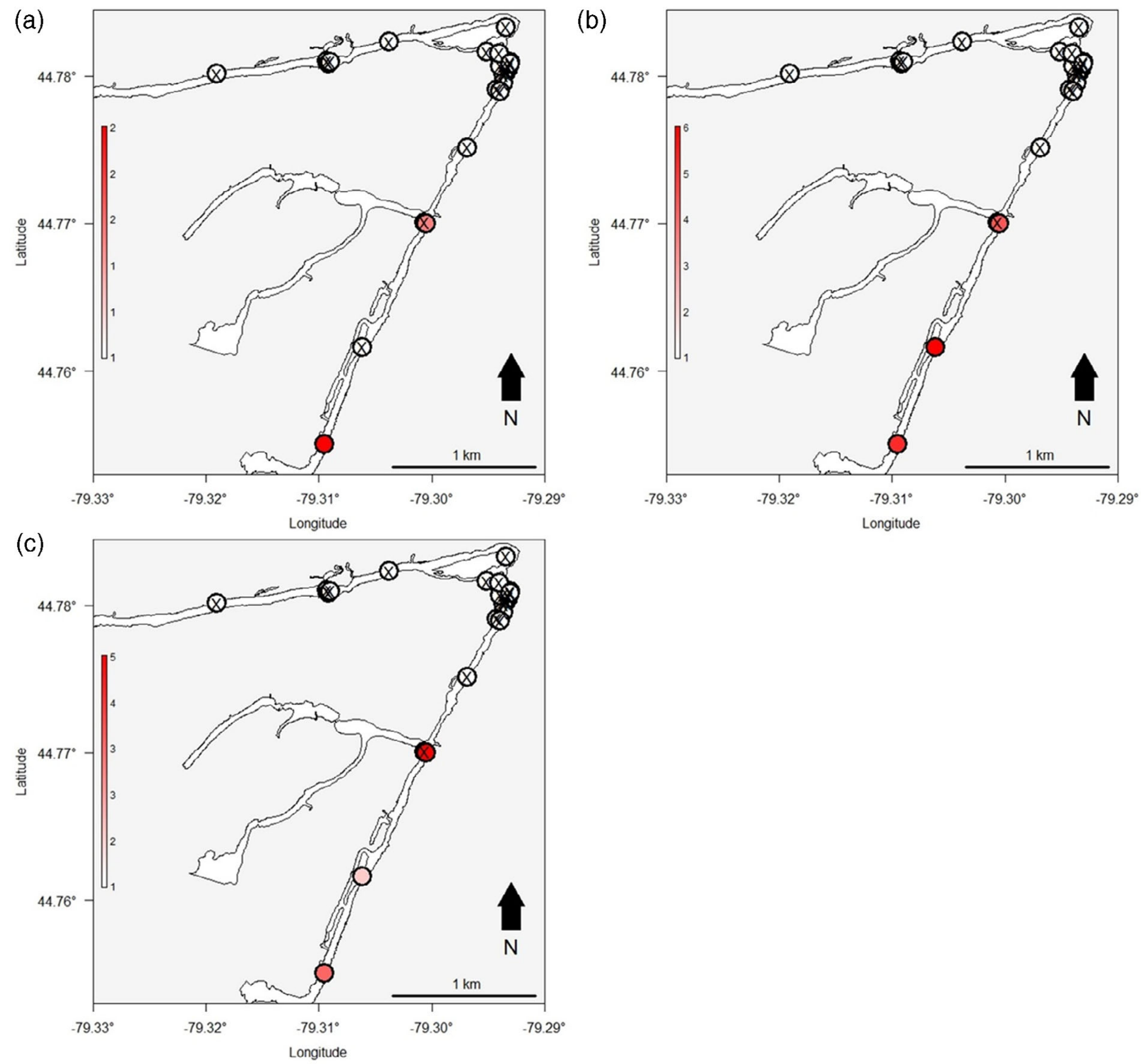

FIGURE 4 Plots of the study area on the Severn River with the VLH site at Wasdell Falls in the upper right of each map. Each plot shows number of detections per station for (a) walleye, (b) channel catfish, and (c) white sucker. Higher numbers of detections are denoted by a darker bubble shade while a total lack of detections is denoted by a crossed bubble. Note that in higher station densities crosses may be visible through other stations [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 The frequencies of individual fish tagged as a proportion of the total number of fish tagged and those detected in each of the 3 station groups within the forebay areas upstream from the VLH turbines at Wasdell Falls, Ontario

	Smallmouth bass	Rock bass	Largemouth bass	Northern pike
Total tagged	0.56	0.35	0.06	0.03
Pre-Forebay group	0.53	0.27	0.13	0.07
Control dam Forebay	0.44	0.28	0.22	0.06
VLH Forebay	0.50	0.29	0.14	0.07

groupings. Of these species, rock bass and smallmouth bass had the highest number of detections. Largemouth bass and northern pike made up a larger proportion of the fish detected in the forebay areas than the relative frequency in which they were tagged (Table 2).

The proportions (relative frequency of the number of individuals of each species) were similar to each other within species groups across all of the forebay areas ($p = 0.996$, Table 3). The species proportions in the forebay areas followed the same proportions seen in the overall sample of fish tagged ($p = 0.573$, Table 3), indicating that there is no difference in forebay occupancy by species. The control dam had higher average cumulative residency times spent by the four species than in the other two forebay areas ($p < 0.001$, Table 3).

In terms of seasonal use of the forebay area, rock bass was detected in the VLH and pre-forebay station groups (Figure 1c)

TABLE 3 Species differences on mean cumulative residency time, proportion of individuals tagged, and proportion of individuals tagged including proportions from overall tagged sample acoustically tracked in the forebay areas upstream of VLH turbines at Wasdell Falls, Ontario. Significant values (*p*-value<0.05 with a Bonferroni corrected *p*-value of 0.004) using Chi-Square tests are denoted by *

Tested variables	χ^2	Df	*p*-value
Mean cumulative time (mins)	36.02	6	<0.001*
Proportion of individuals	0.65	6	0.996
Proportion of individuals including proportions from overall tagged sample	7.62	9	0.573

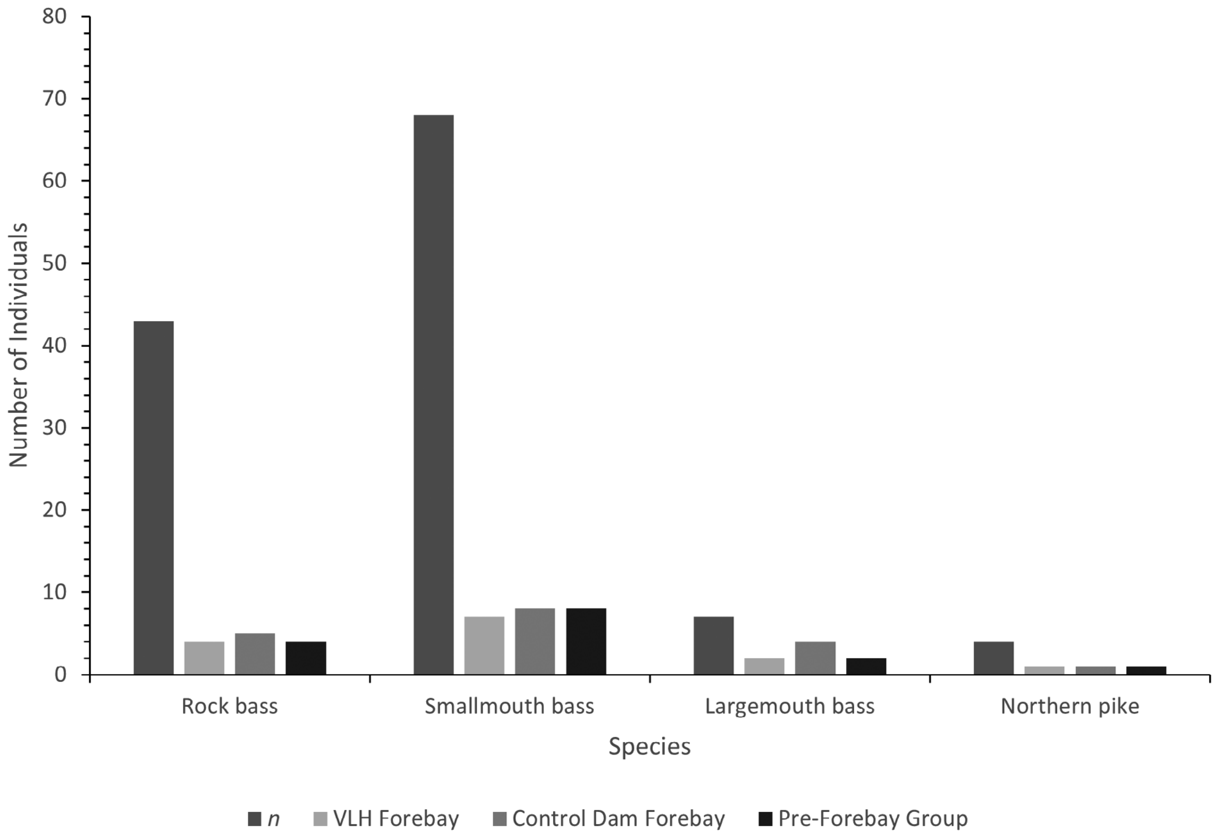

FIGURE 5 The total number of individual fishes of the species detected within the forebay areas at the Wasdell Falls generating complex on the Severn River (in Ontario, Canada) in each of the three forebay station groups over the course of the study. *n* represents the overall number of individuals of each species tagged

between June and late October 2017. While in the flood control dam forebay they were detected up till November 2017. Largemouth bass was detected in the VLH and pre-forebay station groups from July to mid-September, and until the end of October in the flood control dam forebay. Smallmouth bass was detected at all three station groups between late August and late October 2017. Northern pike was detected in a more limited timeframe of eight days in September 2017 for the flood control and pre-forebay groups; in the VLH forebay, pike detections occurred on one day in September. There were isolated detections of rock bass and smallmouth bass in the VLH forebay during the winter (December fifth, 2017, and February 20th, 2018) but beyond these data, there were no more detections of any fish within the forebay areas. However, fish were detected upstream from the forebay areas up until late August 2018.

Of the station groupings upstream of the infrastructure, the flood control dam forebay seemed to experience the most use across the four species detected in the immediate area of the infrastructure (Figures 5 and 6). In viewing the average cumulative residency time per species (Figure 6), it is evident that the control dam grouping had the most cumulative time of detections for rock bass and northern pike, relative to the other areas. Largemouth bass had a higher average cumulative residency time in the pre-forebay area, while smallmouth bass had larger residency times across both the control dam and VLH forebays. Largemouth bass seemed to use the flood control dam forebay more so than habitats upstream (Figure 3c). From

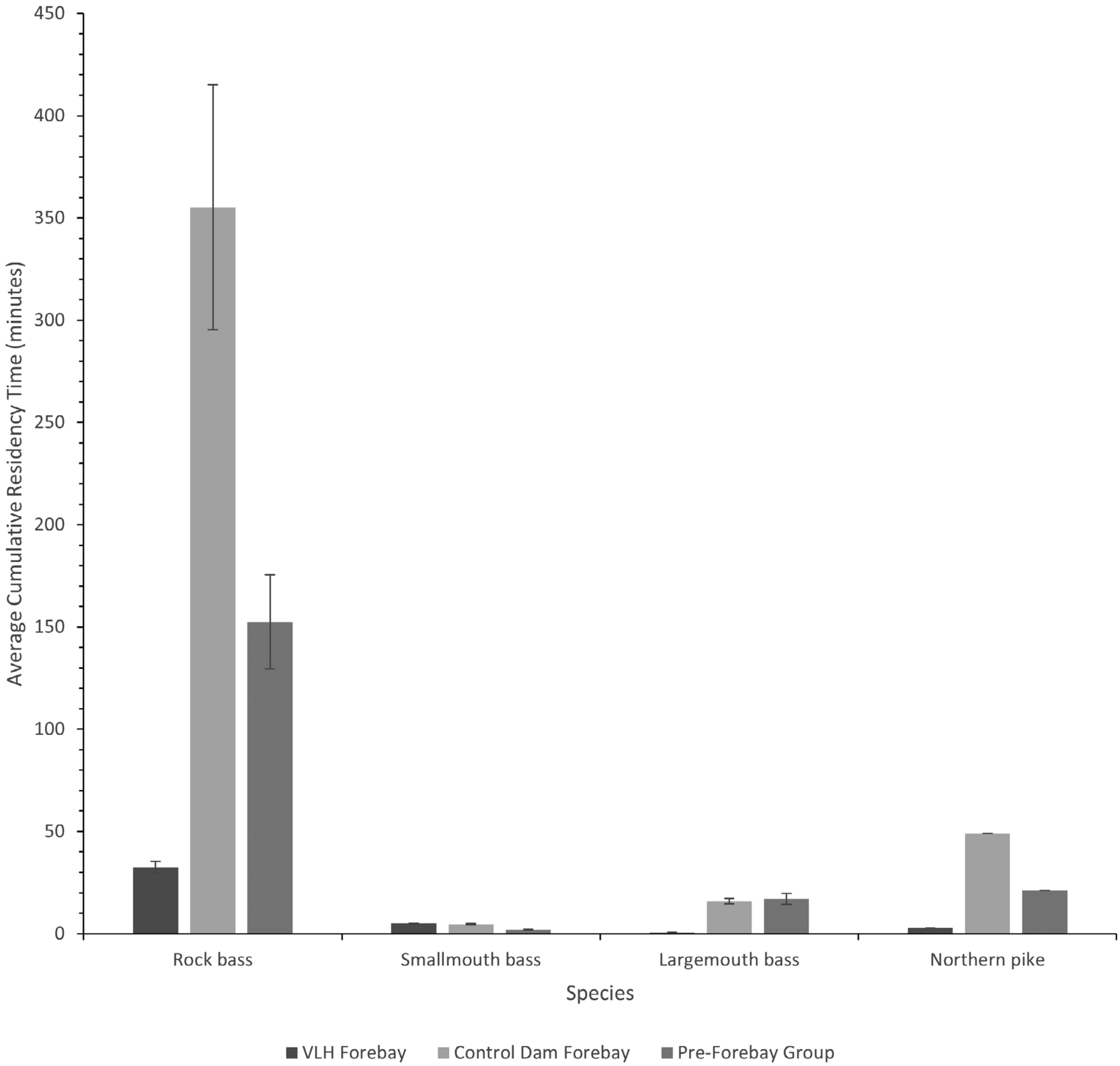

FIGURE 6 The average cumulative residency time (minutes with standard error) per species and location within the forebay areas upstream of infrastructure at Wasdell Falls on the Severn River, Canada

the filtered telemetry data (Figure 4) there was no evidence of tagged walleye, white sucker or channel catfish using the forebay areas.

Through an examination of cumulative residency time-averaged per species and the number of individuals detected (Figures 5 and 6), we found that rock bass tended to stay for much longer periods in the control dam forebay, but that there were not as many individual fish detected. The smallmouth bass tended to enter the three areas of the forebay but had low residency times.

4 | DISCUSSION

With the growing interest in wider usage of the VLH turbines, water resource managers require knowledge of the risk posed by this technology to the fish communities on their respective waterways. Determining the likelihood of entrainment is a critical component of a comprehensive assessment of risk on the local fish community. In addition, low head turbines, in general, have very different forebays than conventional turbines, and studies regarding fish movements in these conditions are limited. Research specifically on the risk of entrainment in VLH turbines has not been carried out previously. In conducting this study, we found that the proportions of species entering the forebay areas were similar to the overall proportions of species in the tagged fish community, showing that fish usage of the forebay areas was not specific to certain species. Furthermore, no fish were entrained through the turbines over the duration of this study.

4.1 | Fish passage

While there has been much research on the entrainment of migratory fishes (reviewed in Harrison et al., 2019 and Algera, Rytwinski, et al., 2020, Algera, Ward, et al., 2020), resident fish that make use of habitat upstream of hydroelectric infrastructure also have the possibility of becoming entrained (Coutant & Whitney, 2000). Juvenile resident fish are generally more at risk of entrainment due to lower sustained swim speeds (Peake, 2008). Conversely, entrainment of resident fishes can have population-level impacts if fecund adult females are entrained (Martins et al., 2014). Entrainment of non-salmonids often occurs episodically as congregations of fish become entrained after moving near infrastructure (Martins et al., 2014).

Contrary to our prediction that there would be some fish movement through the turbines, the passage of the tagged fish through the VLH turbines did not occur throughout this study, supporting the idea that the risk of entrainment through the VLH turbines is extremely low. Five tagged fish were detected downstream, none of which appeared to pass through the turbines. Of the five fish, three appeared to pass through the flood control dam, and two likely moved downstream by another route (e.g., via indirect side channels) as they were not detected within the rest of the upstream array. There is connectivity between the upstream and downstream sections via a longer 11 km side channel, which has a lock on it. Since there is a large amount of recreational fishing in this section of the river, it is also possible that the movements of these two fish occurred via livewell transfers. Regardless of the route, it is very likely that it was not via the VLH turbine as it had good receiver coverage and the forebay was acoustically shielded from the VLH turbine area by the island in the middle of the river. The reasons for the lack of entrainment are likely due to factors inherent in the design of the VLH series of turbines, especially that of the low intake velocity (from 3 to 21 cm s^{-1}) (Site Operator, personal communication, June 30, 2019). Low velocity means that the tagged fish species have maximum sustained swimming speeds (U_{crit}) that are greater than the draw of the turbine, and burst swimming speeds that are much higher than the U_{crit} of each species (e.g., Peake, 2008), allowing them to avoid involuntary entrainment. For the centrarchid species used in this study, smallmouth bass has U_{crit} values ranging from 65 to 98 cm s^{-1} (Peake, 2004), largemouth bass from 30 to 50 cm s^{-1} (Crans, Pranckevicius, & Scott, 2015; Farlinger & Beamish, 1977). Rock bass has U_{crit} values ranging from 18 to 31 cm s^{-1}. Adult northern pike of 42–62 cm has U_{crit} ranging from 38.3 to 47.4 cm s^{-1} (Jones, Kiceniuk, & Bamford, 1974). It should be noted that during the study period, juvenile smallmouth bass was observed congregating immediately ahead of the turbine and holding in the current where they were presumably feeding (Personal observation, June 2018).

Fish passage events downstream via the flood control dam were limited. There were a number of factors that could have impacted these passage events. Fish usage of this forebay was greater than that of the VLH forebay (Figure 6), as a result, fish would have a higher chance of movement downstream via this infrastructure simply due to longer durations of presence in the vicinity. Some may have passed the instream barrier of their own volition, or possibly after death. For example, if the fish was dead and floating downstream on the surface it may have drifted over the flood control dam side of the infrastructure. This would be difficult to accurately determine using acoustic telemetry as detections would occur if the fish remained within the detection radius of a receiver, regardless of its condition.

4.2 | Forebay usage

The area of the control dam forebay area is more consistent in depth and has more cover (in the form of docks) than the other two areas upstream of the infrastructure. White sucker and walleye were species that would be expected to be seen in the forebay area even in a limited fashion during downstream spawning movements (Bellgraph, Guy, Gardner, & Leathe, 2008; Doherty, Curry, & Munkittrick, 2004). These fish were tagged further upstream but were not detected in any of the forebays.

The species detected in the forebay areas were present at statistically similar proportions to the overall numbers of fishes tagged per species. Fish usage of the water control dam also seemed to occur for a longer duration (from summer to late fall) and seemed to indicate a seasonal propensity during the summer across all four species for movements into the VLH and pre-forebay areas. As summer progressed and changed into fall, the fish seemed to prefer the deeper areas found in the flood control dam forebay, presumably for increased thermal stability in comparison to the shallows. After early February 2018, there was a lack of detections of any fish within the forebay areas which is indicative of overwintering elsewhere.

Fish usage of the forebay areas appeared to be less in most species compared to the rest of the upstream sections (except for largemouth bass). Brief movements into the forebay areas could be the result of fish foraging for prey (Martins et al., 2013). Habitat quality and quantity seem to be the most apparent differing factors which would affect fish use of the forebay areas. The habitat in the area immediately upstream of the turbines is lacking in structure and other habitat characteristics which could be attractive to fish, including macrophytes, deeper portions, woody debris and boulders (Todd & Rabeni, 1989). Unlike conventional hydroelectric facilities which may have a larger reservoir upstream, there is no great increase in depth at the forebay to the turbines. Attempts at electrofishing and angling in the area were relatively unsuccessful in comparison to further upstream (Personal observation, Summer 2017). Furthermore, all species did not seem to remain for extended periods in these forebays in comparison to areas further upstream (Figure 3 and Figure 4).

Although our detection ranges were somewhat small and overall receiver efficiency moderate, the tags used here were coded and emitted signals at 10 s intervals – an interval that is ~6 times (or more) frequent than typical r-code tags used in acoustic telemetry studies. As such, the likelihood of detecting resident fish moving through various reaches of the system would be quite high. We used JSATS tags because they tend to perform well in areas with entrained air and turbulence (i.e., near dams) and because they are coded such that code collisions are uncommon. As with all telemetry technologies, there are trade-offs, which in our case included the high number of false detections arising from the use of JSATS and the aforementioned apparent low detection efficiency.

4.3 | Species life histories and movements

Rock bass, smallmouth bass and largemouth bass were the only species detected in the forebay areas. Rock bass tends to be more sedentary than other fishes we tagged with a previous study finding an average home range of 100 m in riverine habitats (Gatz & Adams, 1994). However, some lacustrine homing populations of rock bass and smallmouth bass can move multiple kilometers per day to reach suitable spawning grounds (Gerber & Haynes, 1988). Smallmouth bass, largemouth bass and rock bass typically spawn in the spring at temperatures between 13 and 24°C, (Lukas & Orth, 1995: Lane, Portt, & Minns, 1996). Smallmouth bass, rock bass and largemouth bass prefer to spawn in <2 m of water with smallmouth and rock bass preferring boulders, cobble, gravel and logs while largemouth prefer macrophyte cover and softer substrates (Lane et al., 1996). The tagged fish in this study did not exhibit movements indicative of attempts to pass through the structures at Wasdell Falls or stay in the forebay areas (as fish staging to spawn might), therefore these behaviours are indicative of fishes with smaller home ranges or suitable spawning areas within the reaches upstream and downstream of the dam.

Fish usage of the forebays could also be explained as a function of fish home range affinity; smaller home ranges would account for the fish captured and released upstream, which were not subsequently detected at the forebay areas. In general, riverine fishes tend to have smaller home ranges than those that live in lacustrine environments, and home ranges generally tend to increase with body size (Minns, 1995; Rosten, Gozlan, & Lucas, 2016). As a result, smaller species like rock bass caught in the vicinity of Wasdell Falls likely would not move very far. More fish were captured in sections of the river 2–3 km upstream from the site. Therefore, the home range would explain the low detection rates of the fish found in the forebay areas. Channel catfish and walleye were only captured and released at the furthest range of the study area (~3 km from Wasdell Falls) and were not detected at all in the areas near the infrastructure.

5 | CONCLUSIONS

Our results indicate that (1) entrainment through the VLH Turbines of any tagged fish did not occur; (2) fish movements into the forebay area from upstream were limited; and (3) of the forebay areas, the control dam forebay experienced the highest amount of use. Since no tagged fish went through the VLH Turbines, and forebay usage is limited to those fish resident to the vicinity of the forebay, the risk of entrainment to the fish community at this site is low. Future investigations could be carried out at different sites to look at other species and their interactions with low head infrastructure, as other sites may experience more fish usage of forebay areas or species-specific entrainment events (Harrison et al., 2019). There are still issues associated with potential VLH turbine sites acting as a barrier to movement. However, this site has had an existing structure for the past century, so assessing additional habitat fragmentation due to the VLH was not an objective of this study. We focused on adult fish so future research should focus on juveniles or smaller-bodied species (e.g., native cyprinids or percids) that have lower sustained swim speeds and would presumably be more vulnerable to entrainment (Harrison et al., 2019). Movements in the forebays were restricted to half of the species that were surveyed in the 3 km stretch upstream with differing area usage by species. While the results of this study may not be extrapolated to forebay usage in all low head sites due to variability, these results do provide insight into how usage can differ from forebays at sites supporting conventional (high head) infrastructure. The VLH Turbines continue to show promise in terms of interactions with ichthyofauna, with a lack of entrainment in this north temperate fish community. Future use of this turbine technology in riverine systems with resident fish populations would appear to be a lower risk endeavour than conventional turbines. Furthermore, a controlled entrainment experiment where fish were forced to pass through the VLH turbines at Wasdell Falls revealed very low mortality (Tuononen, Cooke, Timusk, & Smokorowski, 2020). When combined with our findings here on infrequent forays into the VLH forebay, at least at this site the overall risk to fish populations is negligible.

In terms of expanded future use in Canada, the VLH turbine could yield socio-economic benefits in remote areas of Canada where access to reliable hydroelectric generation with a low ecological footprint is difficult. Here, the VLH turbines could provide remote communities with an alternative to the widespread use of diesel generators (Mariano & Cañizares, 2013). In combination with other renewable power sources and storage systems, communities may have the ability to be more self-sufficient rather than relying exclusively on imported fossil fuels. It is in these remote communities that the benefits of VLH turbines could be most substantial. These benefits should be balanced with inherent risks to the creation or maintaining of low head sites including habitat fragmentation by careful site evaluation and selection.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A.

A.1. | Additional methods

A.1.1. | Study site

This site has previously supported two other hydroelectric generating ventures over the past century. The three VLH turbines are third generation VLH model 4,000 s which can be independently operated. The river both upstream and downstream has many cottages and thus receives increased recreational activity during the summer.

A.1.2. | Tagging of fish

All fish received an external identification marker, using anchor tags for larger individuals and fin clips of the pectoral fins for smaller individuals. The incisions on tagged fish were closed using monofilament sutures (Ethicon© PDS® II, 3/0).

A.1.3. | Array

The receivers in the array were secured to ropes connected to floats and cinder blocks to hold the receiver vertically within the water column. The cinder blocks were then tethered to shore using stainless steel aircraft cable.

JSATS model SR626 were used for smaller fishes (≥73.3 g), with a weight of 1.1 g, with a battery life of 341 days and model SR48 were used for larger fishes (≥233.3 g) with a weight of 3.5 g, and a battery life of 914 days.

A.1.4. | Data

Detection efficiencies were calculated through linear deployment of 3 tags leading away from two representative receivers for ~19 hr. From these data the number of detections of each tag which were recorded, and the number of detections which should have been recorded (based on tag signal rate), were used to calculate efficiencies as a percentage (as per Kessel et al., 2014).

Initially the data were filtered using the 10 s burst rate and detection times to separate expected detection sequences from false detections (which would not have constant 10 s intervals). Next the data were filtered by number of detections per timeframe; the threshold for this was 2 detections within 3,600 s of each other. Finally, a conditional filter was applied that removed any remaining false detections based on fish movement to the downstream section of the study site, removing unusual detections upstream after the fish had been detected multiple times below the dam. Filtering the data brought the total number of detections from ~1.5 million, down to ~400,000.

The cumulative average residency time in minutes per individual within each station group was calculated by multiplying raw detections within each group by 10 (per 10 s burst rate) to obtain seconds of residency, then dividing by 60 to obtain minutes, and then dividing by number of individuals of each species detected in each respective forebay area.