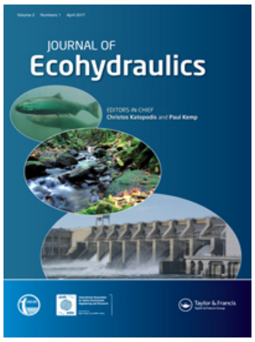

Journal of Ecohydraulics

ISSN: 2470-5357 (Print) 2470-5365 (Online) Journal homepage: https://www.tandfonline.com/loi/tjoe20

Evaluating riverine hydrokinetic turbine operations relative to the spatial ecology of wild fishes

Daniel P. Struthers, Lee F.G. Gutowsky, Eva Enders, Karen Smokorowski, Doug Watkinson, Eric Bibeau & Steven J. Cooke

To cite this article: Daniel P. Struthers, Lee F.G. Gutowsky, Eva Enders, Karen Smokorowski, Doug Watkinson, Eric Bibeau & Steven J. Cooke (2017) Evaluating riverine hydrokinetic turbine operations relative to the spatial ecology of wild fishes, Journal of Ecohydraulics, 2:1, 53-67, DOI: 10.1080/24705357.2017.1287530

To link to this article: https://doi.org/10.1080/24705357.2017.1287530

Published online: 06 Mar 2017.

JOURNAL OF ECOHYDRAULICS, 2017
VOL. 2, NO. 1, 53–67
http://dx.doi.org/10.1080/24705357.2017.1287530

Evaluating riverine hydrokinetic turbine operations relative to the spatial ecology of wild fishes

Daniel P. Struthers[a], Lee F.G. Gutowsky[a], Eva Enders [b], Karen Smokorowski [c], Doug Watkinson[b], Eric Bibeau[d] and Steven J. Cooke[a]

[a]Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, Ottawa, ON K1S 5B6, Canada; [b]Fisheries and Oceans Canada, Freshwater Institute Science Laboratory, Winnipeg, MN R3T 2N6, Canada; [c]Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences, ON P6A 6W4, Canada; [d]Department of Mechanical Engineering, University of Manitoba, Winnipeg, MN R3T 0C4, Canada

ABSTRACT

Hydrokinetic turbines (HTs) are being proposed for placement in riverine landscapes around the globe. Here, we implanted 40 adult lake sturgeon and 40 adult walleye with acoustic telemetry transmitters to monitor their lateral and vertical space use at the Canadian Hydrokinetic Turbine Testing Centre (CHTTC) located in the Seven Sisters Generating station (GS) tailrace on the Winnipeg River, Manitoba. Specifically, we tested whether fish behaviour was influenced by the operation of HTs relative to control periods, and estimate the threat of HTs towards lake sturgeon and walleye across seasons. The behaviour and habitat use of both species was not influenced by HT operations. Greater numbers of walleye were present when the discharge rate was $\geq$ 950 m^3s^{-1}, which is $\geq$ 77 m^3s^{-1} greater than the average discharge rate (873 m^3s^{-1}) measured during the study period. Given the patterns of seasonal residency, movement, and depth use, lake sturgeon appeared more prone to interacting with HTs during spring and early summer months (i.e. May and June), whereas risk to walleye would be highest throughout the summer and autumn months. In the vicinity of the acoustic receivers, available habitat (areas with large boulders, and transitions between swift flow in the channel and slacker water near the shoreline) was used significantly more often by walleye than lake sturgeon. Lake sturgeon utilized similar depths where HTs would be installed (i.e. $\geq$ 6.5 m), while walleye commonly occupied shallower depths at the HT testing centre making the former more susceptible to interactions with substrate-HT's. Collectively, these are some of the first field-based results on fish behaviour and ecology while a riverine-HT is in operation. The findings present useful information to help guide best practices for commercial scale HT operations within river systems where lake sturgeon and walleye reside.

ARTICLE HISTORY
Received 27 May 2016
Accepted 21 January 2017

KEYWORDS
Spatial ecology; Lake Sturgeon; Walleye; hydrokinetic turbines; biotelemetry

Introduction

Hydrokinetic turbines (HTs) generate electricity from the kinetic energy of swift flows in marine and freshwater environments. HTs are increasingly being utilized to generate hydropower in the tailraces of existing hydropower facilities (Cada and Bevelhimer 2011; Liu and Packey 2014; Yuce and Muratoglu 2015). As with all hydropower developments in North America, ecological risk assessments are necessary for understanding potential impacts and to inform siting, mitigation, or compensation activities (Hart et al. 2002; Smokorowski and Pratt 2007). In most jurisdictions, HT proposals are reviewed by government agencies to investigate potential environmental impacts to fish and fish habitat arising from the installation and operation of HTs. To comply with regulations, HT developments are designed to minimize the risk of physical (i.e. entrainment, blade strike, and overpressure injuries), physiological, and behavioural impacts on fish populations (Cada and Bevelhimer 2011). Nevertheless, certain fishes may be indirectly attracted to HTs, since structures are placed in areas where swift flow may be, for example, ideal for spawning (e.g. 0.5–1.5 ms^{-1} for lake sturgeon *Acipenser fulvescens* [Auer 1996; McKinley et al. 1998]) and therefore overlapping with important habitat (Schilt 2007; Cada et al. 2007; Loures and Pompen 2015). To date, few evaluations have assessed species-specific movement and space-use of wild fishes, which could assist managers and the energy industry to adapt HT designs and operations to minimize ecological risk (Linkov et al. 2006).

Lake sturgeon and walleye (*Sander vitreus*) are two species found in large rivers across north-central and northeastern North America (Scott and Crossman 1973; Craig 2000). These species are known to be positively rheotactic and migrate upstream to the base of hydroelectric facilities to spawn and/or to forage on entrained prey. Lake sturgeon populations are at risk of human-induced impacts, particularly due to poaching, fishing, and hydropower development (Peterson

CONTACT Daniel P. Struthers danstruthers88@gmail.com

et al. 2007; Auer and Dempsey 2013). Through the 1800–1900s, overharvesting and habitat alteration severely reduced population sizes across much of their geographic range (Houston 1987; Auer 1996; Peterson et al. 2007). In Canada, the lake sturgeon is considered endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and recommended for federal protection (COSEWIC 2006). Walleye, by contrast, is a highly targeted commercial and recreational species in North America (Craig 2000; Fetherman et al. 2015). Although stocking and fishing restrictions are assisting their recovery and conservation (Zorn 2015), many walleye populations in the Arctic, Hudson Bay, and Atlantic drainage basins have been reduced in size due to overfishing and habitat degradation (Post et al. 2002). Populations of lake sturgeon and walleye are likely to face further environmental impacts associated with hydropower development, climate change, increased water consumption, and habitat degradation (Auer 1996; Post et al. 2002; Wilson and McKinley 2004). Both lake sturgeon and walleye populations reside in close proximity to the Canadian Hydrokinetic Turbine Testing Centre (CHTTC) in the Winnipeg River, Manitoba, where HTs are undergoing pre-commercial testing. These populations may be susceptible to blade strike, noise, electromagnetic field (EM field), and chemical contamination that may affect survival, behaviour, and movements (Cada et al. 2006; USDOE 2009; VanZweiten et al. 2014).

HT operations can place aquatic animals and their associated habitat at risk of harm (VanZweiten et al. 2014). The probability of entrainment and blade strike could increase with higher occurrences of upstream and downstream movements past the area where the HTs have been installed and tested. Additionally, blade interactions may be more frequent if fish are utilizing similar depths where HTs are operating. Acoustic telemetry was used to retrieve biologically derived data as it is an established method for evaluating the behaviour and movement ecology of wild fishes (Cooke et al. 2004; Hussey et al. 2015). The goal of this research was to evaluate the spatial ecology of lake sturgeon and walleye in relation to short intermittent HT operational tests in the tailrace of the Seven Sisters Generating Station (SSGS) powerhouse in Manitoba, Canada. Specifically, our objectives were to: (1) determine whether lake sturgeon and walleye habitat use is influenced by intermittent HT testing, and (2) characterize seasonal residency, movement, and depth use of these fishes in the testing area to gauge the threat of HTs on these fish populations. The study was designed to determine whether, and to what extent, risks may be expected for these fishes in Boreal Shield rivers where HTs are planned or currently operational. This serves more as a conservative screening evaluation for ecological impacts of riverine-HT operations, which will aid environmental managers in developing management strategies for these devices.

Methods

Study location

This study was conducted at the CHTTC that is situated between 0.4 and 1.2 rkm downstream of the SSGS powerhouse (50° 07' 14″N; 96° 01' 02″W), on the Winnipeg River, Manitoba. The SSGS tailrace extends 1.2 km in length with an average width of ~50 m (Figure 1). Flow velocity at the CHTTC measured ≥ 2 ms^{-1} (data obtained from University of Manitoba) at the thalweg during the study period (9 June 2014–6 July 2015) with an average rate of 873 (range: 394–1122) m^3s^{-1} from the SSGS powerhouse throughout the acoustic monitoring period (data received from Manitoba Hydro). The SSGS is a run-of-river facility where discharge is continuous through the year and fluctuates with available upstream flow. Discharge fluctuated through the study period, with peak discharge occurring through August and September ($\bar{x} = 1046$ m^3s^{-1}), and lowest rates occurring in November 2014 ($\bar{x} = 667$ m^3s^{-1}) and May 2015 ($\bar{x} = 522$ m^3s^{-1}). The thalweg depth within the SSGS tailrace ranged between 9 and 15 m when accounting for bathymetry and discharge fluctuations from the SSGS powerhouse.

Fish capture and transmitters

Fish capture and surgical implantation procedures were conducted during the period of 20 May–2 June 2014. Multi-panel multifilament gill nets with large mesh size (200–300 mm) and boat electrofishing were used to capture lake sturgeon. Gill net panels were placed in deep pools situated downstream of the Seven Sisters GS tailrace where lake sturgeon and walleye are known to reside (Hrenchuk 2009). The gill nets were set at dusk (~1700–2100 CDT) and pulled at dawn (~12 hr soak time). Walleye were also captured with a combination of fine- (10–20 mm) and large- (200–300 mm) meshed multi-panelled gillnets, as well as with boat electrofishing during the crepuscular and nocturnal periods. Immediate mortality was not observed for lake sturgeon or walleye. On capture, the lake sturgeon and walleye were placed in holding tanks filled with ambient river water prior to surgical procedures.

Tags included dedicated presence/absence transmitters (n = 40; V13-1L; lifespan: 818 days; nominal delay = 90 s, Vemco, Halifax, NS) and those with sensors (n = 40; V13AP-1L; lifespan: 649 days; nominal delay = 90 s, Vemco, Halifax, NS) that alternate between transmitting a depth reading (maximum depth: 50 m; Accuracy: ± 2m; Resolution: 0.5m) and an acceleration profile (i.e. tri-axial accelerometers; maximum range of 3.43 ms^{-2}). The transmitters were

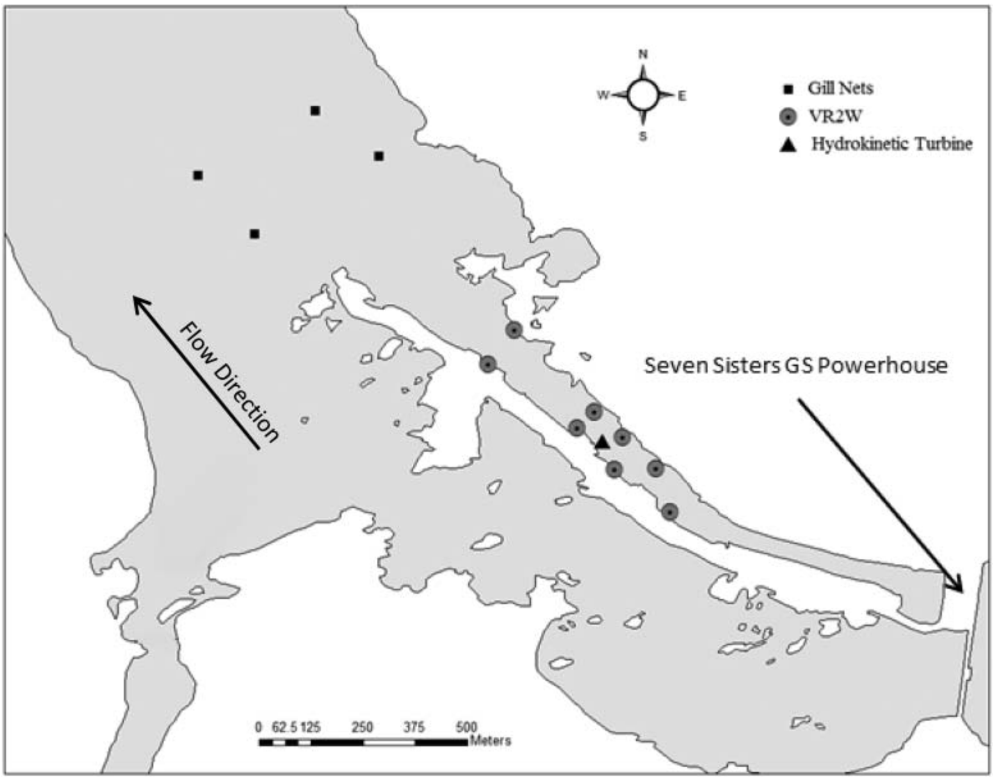

Figure 1. An overview of the receiver array located at the HT testing centre (CHTTC) located in the tailrace of the Seven Sisters GS on the Winnipeg River, MB. The map illustrates (1) the 8 VR2Ws that were used to passively-monitor lake sturgeon and walleye, (2) the location of the substrate-anchored HT, and (3) the locations where fish were captured with gill nets.

divided equally between lake sturgeon ($n = 40$) and walleye ($n = 40$) for both transmitter models (i.e. 20 V13-1L and 20 V13AP-1L per species). All transmitters propagate a unique coded ID at 69 kHz.

Tagging procedures

Individuals were held in a fine-mesh cradle that was submerged in a holding tank filled with ambient river water that was refreshed between net pulls, and were ventrally-orient to immobilize and access the incision location. The head and gills remained submerged to maintain normal respiration during the tagging procedure. All surgical tools, nitrile gloves, and tags were disinfected using a 10% povidone–iodine solution (Betadine®, USA). A small incision (~2 cm) was made with a scalpel on the midline positioned slightly posterior to the pectoral girdle. Either a V13 or V13AP acoustic transmitter was inserted posteriorly into the coelom cavity, followed by three interrupted sutures (3-0 polydioxanone-II violet monofilament; Ethicon USA) to close the wound. No anaesthetic was used on lake sturgeon to allow fish to recover quickly due to their slow metabolism and to minimize physiological stress. All surgeries took less than 5 minutes to complete. The total length (TL, measured to the nearest mm) and weight (kg, to the nearest g) was recorded during the tagging procedure. Each lake sturgeon was returned to a holding tank and released 10–15 minutes post-surgery below the netting site (~0.5 km).

Similarly, individual walleye ($n = 40$) were intracoelomically implanted with either a V13 or V13AP acoustic transmitter. Certain aspects of the surgical procedure (i.e. tool disinfection, gloves worn, and incision closure procedure) were identical to the methods used on lake sturgeon. Stage-4 electroanesthesia (Summerfelt and Smith 1990) was administered to walleye using a Portable Electrosedation Unit (PES; Smith-Root, USA; Vandergroot et al. 2011) prior to surgical implantation to immobilize fish during surgery. The PES was set to 100 hz, 25% duty cycle, and 40 volts, with the electrode spaced 50 cm apart. Pulsed direct current is an appropriate anaesthetic for adult walleye because it provides a surgery window of 250-350 s, and fish recover quickly with minimal impact to vertebral integrity (Vandergroot et al. 2011). Upon stage-4 anaesthesia, walleye were placed supine in a padded v-shaped trough. Ambient river water was continuously pumped over the gills using a recirculating flow-through pump system during the surgical period of less than five minutes. A small incision was made slightly posterior to the pectoral girdle on the ventral mid-line, and a transmitter was inserted posteriorly into the coelomic cavity, followed by three interrupted sutures to close the wound. The TL (measured to the nearest mm) and weight (kg, to the nearest g) was recorded for each individual during the tagging procedure. Each fish was given 5-10 minutes to recover from surgery by being placed in a holding tank that was filled with ambient river water, then subsequently released downstream of the SSGS.

None of the tagged lake sturgeon or walleye died during surgical procedures. All tagged fish were below the 2% tag to fish weight ratio as a means to minimize the chance of altering their natural movement behaviour due to transmitter presence (Gallepp and Magnuson 1972; Ross and McCormick 1981; Rogers and White 2007). Fish handling and surgical procedures were approved and followed the Canadian Council on Animal Care protocol (AUP #101065). This research project was approved by Manitoba Water Stewardship, Fisheries Branch under Scientific Collection Permit No 14-14.

Acoustic receivers

Passive monitoring of free-ranging lake sturgeon and walleye individuals was completed with an array of 8 acoustic monitoring receivers (VR2W; Vemco, NS, Canada) that were positioned at the CHTTC (50° 07′ 25″N; 96° 01′ 31″W; Figure 1). Five of the eight receivers included collocated sentinel tags (V16; 500-700s delay) that were used to assess detection efficiency (DE) across turbine operational periods to assess array performance during the monitoring period (Melynchuk 2012; Kessell et al. 2013). Each receiver was anchored with 36 kg granite blocks and tethered to shore with 6.35 mm galvanized steel cable. The receivers were affixed to 9.53 mm multi-strand braided line that was positioned between the granite block and a sub-surface buoy that was placed ~1–2 m above the substrate in 3–6 m of water. Stationary range testing (Webber 2009; Kessel et al. 2013) was completed in the tailrace to determine the maximum detection radius of the VR2Ws situated within the tailrace prior to mooring the VR2W receiver array. The detection range was found to be between 50-75 m due to ambient noise and turbulent environment. On finding the optimal detection range of the VR2Ws, the receivers were spaced throughout the CHTTC at various distances away from the substrate-mounted HT to maximize the detection coverage within the testing area. For each receiver, a river distance in kilometres (rkm) was measured using the path tool in Google Earth (distance range: 30–310 m). The measurements were determined by the sum of linear distances taken mid-channel from the substrate-mounted HT to each receiver located at the CHTTC. The listening stations recorded transmitted data from the tags, which provided presence-absence, depth information (i.e. hydrostatic pressure sensors), and locomotory activity (i.e. tri-axial accelerometer sensors). Data were downloaded from all receivers 10 August 2014, 10 April 2015 and 6 July 2015. After each data download, receivers were immediately anchored within 2 m of the initial anchoring site.

Database management

Surgical procedures may potentially influence behaviour of tagged fish (Rogers and White 2007; Cooke et al. 2011). To minimize the probability of including biased biological information, the first week of all acoustic telemetry data was omitted from the database. As such, the monitoring period was 9 June 2014 through to 6 July 2015, inclusive. Additionally, false-positive transmissions can occur when multiple transmissions collide as they are simultaneously detected by a receiver that results in an erroneous tag ID being recorded (Skalski et al. 2002; Pincock 2011). These were identified and removed in the Vemco User Environment (VUE, version 2.0.6) as single detections from unidentifiable coded transmitters. The database was further assessed by comparing the order of detections recorded by the receiver array for each tagged fish. If a fish was detected at an unrealistic speed between two consecutive detections (i.e. movement velocity of >5 ms^{-1}), they were further investigated and removed if deemed erroneous (Skalski et al. 2002; Pincock 2011). Occasionally, the sensor tags can transmit false detections that result in negative values. As such, sensor transmissions that were less than zero were filtered from the database prior to performing analyses.

Duplicate detections were filtered from the database by removing consecutive detections from each individual fish that was detected less than the minimal tag delay (<50 s). If a fish suddenly stopped moving (i.e. no change horizontally, vertically, or swimming speed), data were further inspected and removed if considered to be erroneous (i.e. fish had expelled the tag, dead fish). Data filtration was completed using the R Statistical Environment (R Core Development Team, 2014), MS Access (2010), and VUE software. The internal clocks of the VR2Ws drift over time, therefore time of arrival for detections were corrected using the VUE software prior to implementing the data filter queries.

The detections were summarized according to meteorological season (i.e. based on month [1. *spring* (March–May), 2. *summer* (June–August), 3. *autumn* (September–November), and 4. *winter* (December–February)], species, and turbine status (two states: 1) ON, 2) OFF). Daily discharge data (m^{3}s^{-1}) were provided by Manitoba Hydro and daily water temperature data were available on request from the township of Powerview-Pine Falls, MB (Figure 2). Daily solar information was acquired online (www.ptaff.ca) for the study area and was used to determine day ($\geq$ local sunrise and $<$ local sunset) and night ($\geq$ sunset and $<$ sunrise) diel periods.

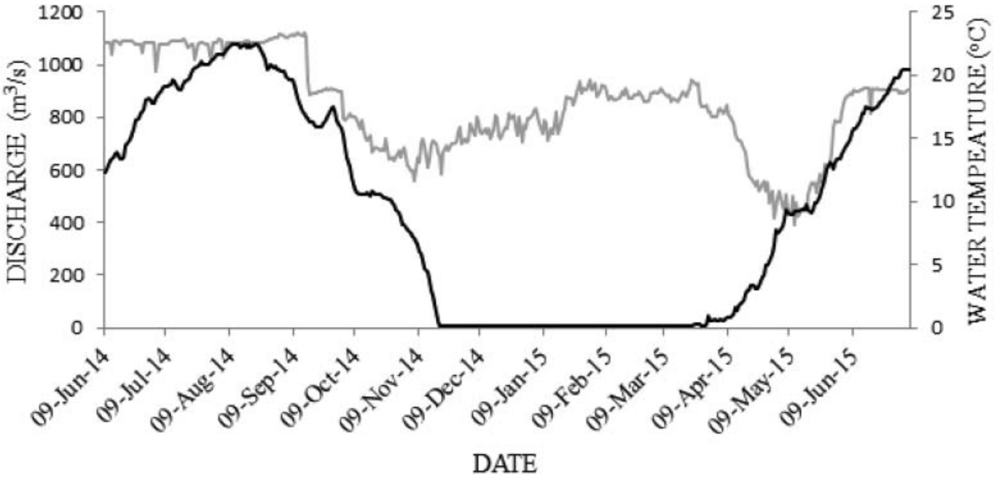

Figure 2. Mean daily discharge from the Seven Sisters GS powerhouse (grey) and the daily water temperature readings (black) in the Winnipeg River between 9 June 2014 and 6 July 2015.

The HT was installed in September 2013 and has been intermittently tested by Clean Current Power Systems Inc. (Vancouver, BC, Canada) at the CHTTC (Figure 3). The device was substrate-anchored within the SSGS tailrace (~800 m from the powerhouse) at a depth of 11 m and positioned 4.5 m above the substrate (i.e. a nominal depth of 6.5 m). The HT is shrouded with a horizontal axial-flow orientation that was designed for substrate operation.

Data analyses

DE was assessed by calculating the proportion of expected daily transmissions based on the nominal average delay (600 s) from five sentinel tags that were collocated with five of the eight receivers in the array. For these five receivers, we calculated the number of detections from the sentinel tags that were not collocated. In other words, detection histories were summarized for receivers that had a collocated sentinel tag by including detections that were only from non-collocated sentinel tags in the array. By not including detections from collocated tag-receiver pairs, the DE was being assessed at meaningful detection distances within the array. Because we were interested in examining ecological responses temporally, the *DE* was evaluated seasonally using a one-way analysis of variance (ANOVA) to evaluate the performance of the receiver

Figure 3. Ducted axial-flow hydrokinetic turbine that was installed and being testing by Clean Current Power Systems (Vancouver, BC) at the *Canadian Hydrokinetic Turbine Testing Centre* on the Winnipeg River, MB, Canada.

array. As such, the term "season" was included in the one-way ANOVA to evaluate the seasonality for *DE*.

Operational tests of a substrate-HT occurred across three distinct testing periods at the CHTTC: (Test 1) 30 July 2014 to 24 August 2014; (Test 2) 9 September 2014 to 12 September 2014; (Test 3) 16 November 2014 to 20 November 2014. The relationship between lake sturgeon and walleye behaviour and HT operations was assessed using fish presence. Fish presence was calculated as the proportion of the tagged individuals detected daily across each testing period. This metric accounted for the variability in the number of fish present in the system over the course of the study periods, since some fish were harvested by anglers over time. Each testing period was preceded by a non-operational period of equal length to allow for balanced comparisons for each turbine status (i.e. turbine status: (1) ON, (2) OFF). Each paired testing and non-testing period was separated by an extended period of time (i.e. 7–59 days) that helped to control for temporal autocorrelation. Lake sturgeon were not included in the modelling here due to low sample sizes on a daily basis ($\leq$3 individuals), but rather were described in the results section to explain noteworthy trends. Explanatory variables included average distance from the HT (DST, continuous) and turbine status (ON or OFF). Dam discharge was coded as a fixed categorical factor (DISC) because there were two distinct daily mean dam discharge rates (high: $>950\ m^3s^{-1}$; low: $<750\ m^3s^{-1}$).

Continuous covariates were centred [i.e. (value-mean)/standard deviation] to help ensure model convergence. Because turbine status was a paired variable (i.e. before and during) with temporal dependency, we included an additional nested variable, turbine operating regime (three before and after periods), as a random effect. The response variable (proportion of total tagged walleye detected in a day) was modelled using a binomial generalized linear mixed-model (GLMM) with restricted maximum-likelihood (REML) estimation (Zuur et al. 2009). Model averaging was performed if ΔAICc was < 2 (Symonds and Moussalli 2011; Barton 2014) with model coefficients being plotted using the "coefplot2" package (Bolker and Yu-Sung 2011). The relative importance (RI) of the predictor variables in the top models was assessed by taking the sum of the Akaike weights over all of the models in which the parameter of interest appeared (Barton 2014).

For a broader assessment of walleye and lake sturgeon in the vicinity of the CHTTC, seasonal residency, movement frequency, and depth use data were passively collected using the acoustic telemetry equipment across the full monitoring period (9 June 2014–6 July 2015) rather than only for the distinct HT operation periods. Residency is defined as habitat-use on a daily basis (Schroepfer and Szedlmayer 2006). As such, residency was evaluated using a seasonal residency index (SR_I) that calculates the number of days a fish was detected at the CHTTC across the number of days in a given season (Lusseau 2005; Reubens et al. 2013). This provided proportional data range between 0 and 1 (e.g. 0 = no residency, 1 = full residency). This metric was calculated and assessed only for individuals that persisted in the system for the full duration of the study, given that some individuals were removed and would produce temporal biases if included in analyses. The SR_I was generated for each season and further summarized by diel period. Fish size (TL) was standardized prior to model selection. Movement frequency was calculated as the count of sequential detections from an upstream river position (rkm) to a downstream position, or vice versa, within the CHTTC. Movement frequency at the CHTTC was calculated as the number of movement events for each tagged fish for each study month and further summarized by diel period. Again, lake sturgeon were not included in the modelling process due to low sample sizes on a daily basis ($\leq$ 5 individuals). Instead, the general trends in the data for lake sturgeon are presented and discussed. Several months, December to March, were omitted from the models for the walleye movement due to low numbers of observations. To improve normality in the data, a log transformation was applied to the movement response variable, which was specified as a count process. The terms for month, water temperature and discharge were found to be collinear when visualizing the data with pairplots and assessing variance-inflation, and could not be included in the same model. For the depth data, an average value was calculated for each detected individual when a minimum of 10 detections were recorded in a given diel period for each monitoring day. These depth values were then modelled according to season, fish size and discharge.

Several models were hypothesized and compared using second-order AIC (Mazerolle 2015) for fish presence, seasonal residency, movement frequency, and depth use. Each response variable and predictor were first examined for influential observations, collinearity, and relationships between the response and all explanatory variables using a variety of visualization options including Cleveland dotplots, scatterplots, and conditional box and whisker plots. All candidate models were validated by plotting the residuals and testing for overdispersion (i.e. the occurrence of more variance in the data than predicted by a statistical model; Bolker et al. 2009) using methods described by Zuur et al. (2009). Model selection was implemented using Linear Mixed-Modelling (LMM) in the "nlme" package (Pinheiro et al., 2015) and the R statistical software (R core team 2014). Adding random effect of Fish.ID for modelling SR_I, movement frequency, and depth use as fish were repeatedly sampled. The inclusion of covariance structures to improve residual variance was assessed with the likelihood ratios test. Optimal model coefficients were fitted with REML and final models were validated using approaches described by Zuur et al. (2009). Descriptive results provide the mean and standard error values in parentheses.

Results

The tagged walleye ranged in size from 175 to 724 mm TL, whereas the lake sturgeon ranged from 710 to 1785 mm TL. Throughout the study period, the acoustic receivers recorded 2,680,116 detections, of which 2,255,111 (84%) were retained as valid detections after data filtering. During the study period, two transmitters were returned by recreational anglers. Seven additional walleye were determined to have either died or were harvested by recreational anglers. When investigating the data gathered across a larger telemetry array located between the SSGS and the adjacent downstream facility, MacArthur Falls GS, there was no evidence that any lake sturgeon died during the study period (unpublished data). DE of the VR2W array was similar across all four seasons ($F = 1.55$ df = 1, 3, $P = 0.213$) with an average *DE* of 0.39 (± .02 SE), or 39%, throughout the monitoring period.

The top models for the fish presence data (where ΔAIC_c was < 2) included discharge (M1), discharge and turbine status (M5), and an interaction between discharge and turbine status (M6, Figure 4, Table 1). These three models differed little in the ability to describe the proportion of walleye at the CHTTC (Table 1). Model averaging identified that discharge was the most important factor in the candidate set (RI = 1.00), followed by turbine status (RI = 0.53) and discharge × turbine interaction (RI = 0.23; Figure 4). There was a lower proportion of walleye detected in the system when discharge was ≤750 m^3s^{-1} ($\bar{x}$ =0.15 ± 0.02) in comparison to when discharge was ≥950 m^3s^{-1} ($\bar{x}$ =0.23 ± 0.04). Although an important factor in the top candidate models (Table 1), turbine status posed no significant effect on the proportion of walleye detected in the system based on the regression estimates (Figure 4) and examining the plotted data (Figure 5).

For the SR_I, there were two top models generated (where ΔAIC_c was < 2), with each including all respective fixed terms as well as interactions either for season*species or season*fish size (Table 1). The inclusion of a covariance structure for species and season was found to improve residual variance (L-ratio = 252.3, P <0.0001). SR_I at the CHTTC was considerably higher for walleye than lake sturgeon during the spring, summer, autumn, but both species were minimally present in the winter season (Figure 6). SR_I was similar for walleye and lake sturgeon during the winter season. Overall, residency was greater for walleye (SR_I: $\bar{x}$ =0.20 ± 0.02) than lake sturgeon (SR_I: $\bar{x}$ =0.06 ± 0.006) at the CHTTC during the study period. For walleye, the highest residency occurred in summer (SR_I: $\bar{x}$ =0.24 ± 0.3) and autumn (SR_I: $\bar{x}$ =0.23 ± 0.2), whereas residency was lower in spring (SR_I: $\bar{x}$ =0.18 ± 0.16) and lowest in winter (SR_I: $\bar{x}$ =0.05 ± 0.04). Overall, residency for lake sturgeon was relatively low throughout

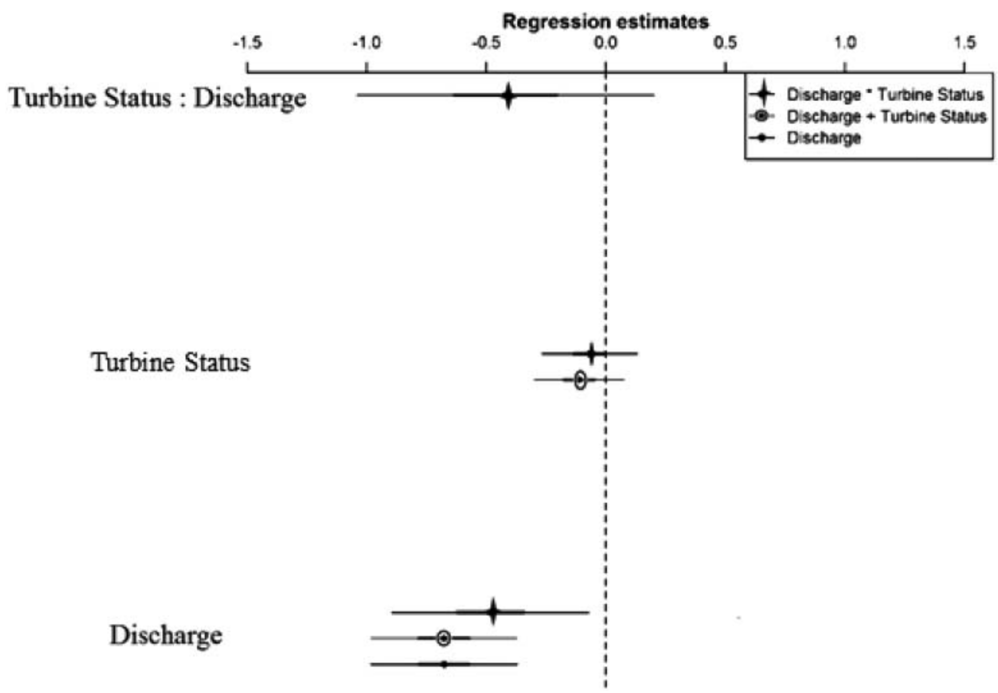

Figure 4. Model-averaged regression estimates for the three best models (1. Discharge: Turbine Status; 2. Discharge + Turbine Status; 3. Discharge) for walleye presence (i.e. the proportion of tagged individuals present during operational testing) at the CHTTC. The dependent variable is the proportion of fish present at the CHTTC for HT testing operations (i.e. turbine status: (1) ON and (2) OFF).

Table 1. Model selection statistics from the GLMMs for Fish Presence and the GLMs for SRI, Movement Frequency, and Depth Use on the Winnipeg River, MB. K is the number of parameters; AICc is the bias-corrected Akaike Information Criterion; ΔAICc is the difference in bias-corrected AIC between a given model and the top ranked model; wAICc is the relative weight of the bias-corrected AIC; Cumul.Wt is the cumulative Akaike weights and; L-Lik is the log-likelihood of the models.

Response	Model no.	Model terms	*K*	AICc	ΔAICc	wAICc	Cumul.Wt	*L*-Lik
Fish presence	**M1**	**Discharge**	**3**	**293.53**	**0**	**0.47**	**0.47**	**−143.6**
	M5	**Discharge + turbine status**	**4**	**294.44**	**0.9**	**0.3**	**0.77**	**−142.93**
	M6	**Discharge*turbine status**	**5**	**294.97**	**1.44**	**0.23**	**0.99**	**−142.04**
	M4	Distance*Turbine status	5	304.09	10.56	0	1	−146.61
	M2	Distance	3	304.46	10.92	0	1	−149.06
	M3	Turbine status	3	305.68	12.15	0	1	−149.67
	M7	Distance + turbine status	4	306.27	12.73	0	1	−148.84
Seasonal residency (SR_I)	**M2**	**Season + species + TL + diel + season*species**	**19**	**−404**	**0**	**0.7826**	**0.7826**	**222.594**
	M1	**Season + species + TL + diel + season*TL**	**19**	**−401.3**	**2.6048**	**0.2128**	**0.9954**	**221.291**
	M6	Season + species	14	−392.7	11.254	0.0028	0.9982	211.2247
	M5	Season + species + TL	15	−390.46	13.498	0.0009	0.9991	211.2317
	M3	Season + species + TL + diel + diel*species	17	−388.93	15.021	0.0004	0.9995	212.7575
	M4	Season + species + TL + diel	16	−388.4	15.556	0.0003	0.9999	211.3416
	M7	Season	13	−386.08	17.868	0.0001	1	206.7977
	M 8	Intercept only	10	−384.02	19.934	0	1	202.4603
		Movement frequency (#)						
	M1	**Month + diel + TL + month*TL**	**26**	**1639.3**	**0**	**0.999**	**0.999**	**−792.44**
	M6	Month	17	1654.21	14.896	0.0006	0.9996	−809.586
	M5	Month + diel	18	1655.95	16.635	0.0002	0.9999	−809.393
	M4	Month + diel + TL	19	1658.09	18.767	0.0001	1	−809.393
	M3	Month + diel + TL + diel*TL	20	1659.84	20.518	0	1	−809.199
	M2	Month + diel + TL + month*diel	26	1663.64	24.319	0	1	−804.604
	M7	Intercept only	10	1680.26	40.943	0	1	−829.945
Depth use (m)	**M3**	**Month + diel + species**	**19**	**11281.3**	**0**	**0.6003**	**0.6003**	**−5621.53**
	M1	**Month + diel + species + diel*species**	**20**	**11282.2**	**0.8246**	**0.3975**	**0.9978**	**−5620.92**
	M2	Month + diel + species + diel*month	26	11292.8	11.43	0.002	0.9998	−5620.12
	M4	Month + diel	18	11297.4	16.072	0.0002	1	−5630.58
	M5	Month	17	11329.8	48.489	0	1	−5647.8
	M6	Intercept only	10	11771.6	490.27	0	1	−5875.76

the entire monitoring period at the CHTTC ($\bar{x}$ =0.06 ± 0.06; range = 0.01–0.27). Although there was no significant difference in residency for lake sturgeon across the seasons, the SRI was relatively higher during the spring season. A substantial proportion (~50%) of the tagged lake sturgeon returned to the CHTTC between May and June 2015, which coincides with spawn timing and the preferred water temperature for spawning.

The models were improved by allowing the residual variance to be dependent on the "month" term

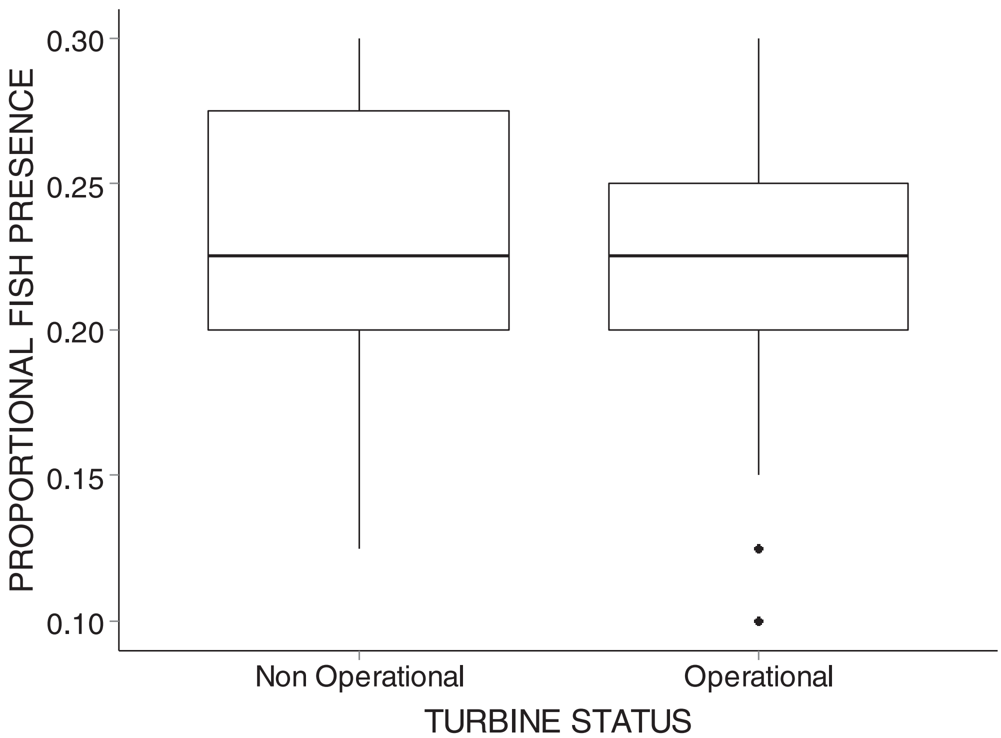

Figure 5. The proportion of tagged walleye that were residing at the Canadian Hydrokinetic Turbine Testing Centre (Seven Sisters GS tailrace; Winnipeg River, MB) according to turbine status.

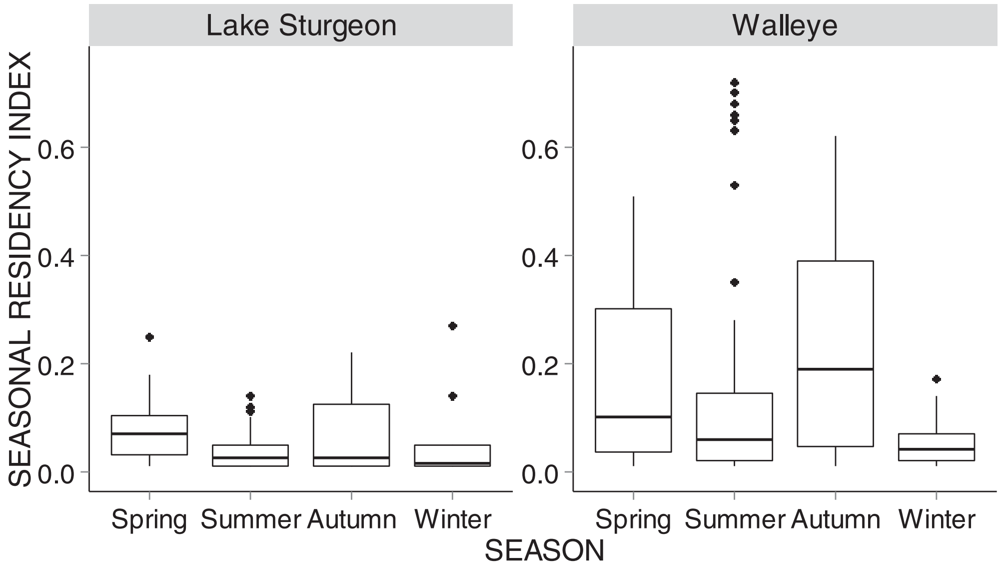

Figure 6. Seasonal Residency Indices (SRI) for lake sturgeon and walleye for autumn (September–November), spring (March–May), summer (June–Aug), and winter (Dec–Feb) at the CHTTC located on the Winnipeg River, MB.

(L-ratio = 17.3, $P = 0.015$). The optimal model for explaining walleye movement frequency included the terms for month, diel period, fish size, and the month*fish size interaction (Table 1). There was no considerable change in movement frequency between day ($\bar{x}$ =9.6 movement events ± 0.8) and night ($\bar{x}$ =8.9 movement events ± 0.7). Walleye moved more frequently during September ($\bar{x}$ = 10.1 movement events ± 1.0) and October ($\bar{x}$ = 12.4 movement events ± 1.9), while lateral movement through the CHTTC was less frequent in spring and summer months (Figure 7). According to the telemetry data, there were no walleye detected making lateral movements through the CHTTC between December and March. The detected lake sturgeon were found to make minimal movements at the CHTTC across the monitoring period, with movements apparently only occurring in May ($\bar{x}$ = 3.8 movement events ± 0.53) and June ($\bar{x}$ = 8.9 movement events ± 3.4), and more frequently during the day ($\bar{x}$ = 6.12 movement events ± 1.5) in comparison to night ($\bar{x}$ = 3.6 movement events ± 0.5).

The two best fitted models (where ΔAIC_c was < 2) for explaining depth use included month, diel period, species, and the interaction between species and diel period. The residual variance was improved when

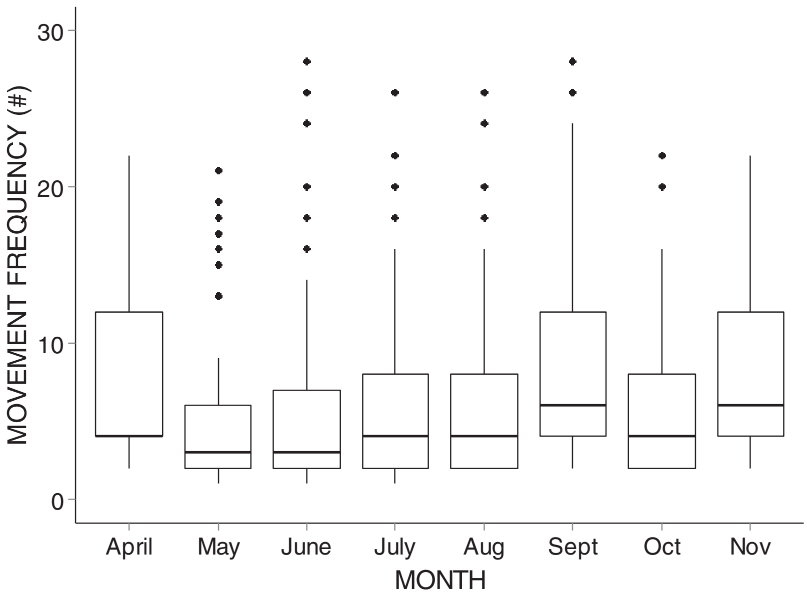

Figure 7. Movement frequency of walleye throughout the calendar months at the Canadian Hydrokinetic Turbine Testing Centre (CHTTC).

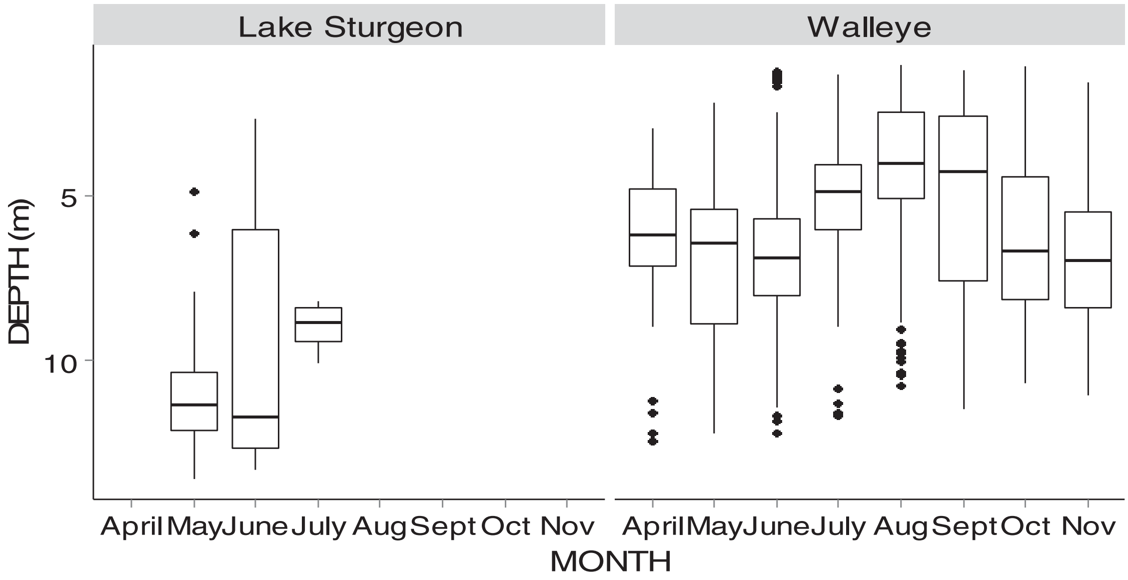

Figure 8. Depth use across the calendar months for lake sturgeon and walleye at the CHTTC located on the Winnipeg River, MB.

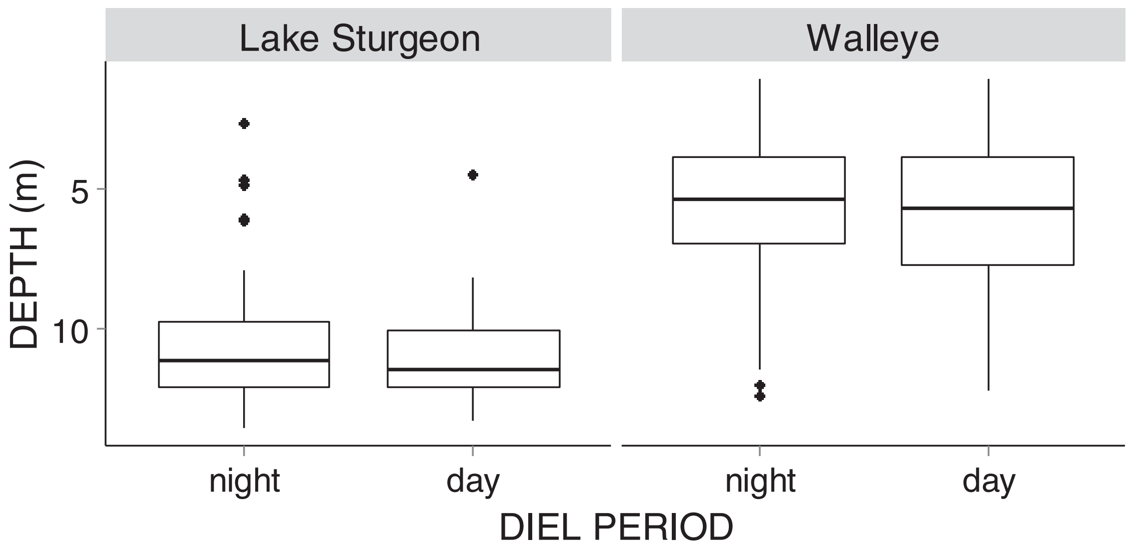

Figure 9. Depth use by lake sturgeon and walleye between diel periods (i.e. day and night) at the CHTTC located on the Winnipeg River, MB.

dependent on the "month" model term (L-ratio = 130.1, P < 0.0001). Walleye were generally found to reside in shallower depths ($\bar{x}$ =5.6 m ± 0.17) than lake sturgeon ($\bar{x}$ =10.6 m ± 0.23). Depth use varied considerably through the calendar months, with walleye moving into greater depths during May (6.9 m ± 0.15) and June ($\bar{x}$ =6.7 m ± 0.11), while residing in relatively shallower depths in August ($\bar{x}$ =4.3 m ± 0.10) and September ($\bar{x}$ = 5.1 m ± 0.13). The detected lake sturgeon were found to only generate depth data in May, June, and July, with greatest variation in depth use for lake sturgeon in the month of June (Figure 8). Notably, the tagged lake sturgeon were also found to reside in shallower depths in July ($\bar{x}$ = 8.9 m ± 0.27) and deeper in May ($\bar{x}$ = 11.1 m ± 0.18). For both species, there was no substantial change in depth selection between diel periods (Figure 9).

Discussion

That HTs could interfere with the ecology and behaviour of wild fish residing in areas where operations occur is a concern for fisheries managers (Cada et al. 2006; VanZweiten et al. 2014). The normal operation of a singular substrate-HT located in tailrace environments may not impede habitat use for walleye given that there was no considerable change in fish presence at the CHTTC between turbine operational regimes. The lake sturgeon were minimally present (≤ 3 individuals) during the experimental operations, making population-level inferences difficult. Moreover, testing operations did not occur during the lake sturgeon spawning period when a notable proportion (50%) of the tagged fish were detected at the CHTTC. With operations occurring outside of the period when lake sturgeon are known to occupy the testing area, we are unable to draw inferences about behaviour and ecology in relation to HT operations. As noted earlier, the DE was found to be 0.39 (39%), meaning that over half of the potential detections may not have been recorded by the receiver array when a tagged fish was residing within the local vicinity. This could lead to underestimates in results presented here for evaluating the threat of HTs in relation to the residency, movement, and depth use. This may have been more of an issue for the lake sturgeon since they are demersal and resided deeper in the water column where detections could have been missed by line of sight issues or attenuation of the acoustic transmission due to turbulence and entrained air. However, the proportion of recorded detections from the sentinel tags was statistically similar between the seasons of the study period indicating that it was appropriate to compare the data temporally.

The number of walleye residing in proximity of the HT was related to discharge rates from the SSGS powerhouse, with more fish residing at the CHTTC when discharge was >950 m^3s^{-1}. The relationship between discharge and walleye behaviour has been documented in relation to hydropower operations in previous work. For example, Murchie and Smokorowski (2004) found that peak activity for walleye could potentially be related to discharge from hydropower facilities. Refugia may become inundated and cause walleye to relocate to new holding locations. Additionally, DiStefano and Hiebert (2000) found a positive rheotactic response from walleye in the tailwaters of a peaking generating station when water was released during the spawning season (4 March–24 April). Dam operators should consider the flow rate prior to adjusting operation schedules as this variable can either elevate or reduce the risk of exposure of wild fishes to HT devices depending on the season. Greater numbers of walleye were attracted to tailraces during periods of high flow, particularly during the spawning period in the spring, which could place them at greater risk from HT exposure.

Ecological risk

For lake sturgeon, the residency index was low across all seasons. However, seasonal residency was higher in the spring, which coincides with a brief period in late-May and early-June when a large proportion (55%) of individuals were detected at the CHTTC. This coincides with the spawning season that commonly occurs between late-April and early-June throughout their geographical range, which has been correlated to water temperature and discharge rates in previous studies (Peterson et al. 2007; Forsythe et al. 2012). Several individuals were detected at the CHTTC in May and June when water temperatures ranged between 9.8 and 16°C. From this finding here and previous work, HT operation schedules should be adjusted (e.g. number of HTs operating, reduce maintenance activities) in relation to seasonality and water temperature. In this instance, some of the lake sturgeon moved into the SSGS tailrace briefly in the spring season as the water temperature approached the optimal for spawning, then immediately moved downstream away from the CHTTC.

The results show depth variation and increased movement for lake sturgeon at the CHTTC during May and June 2014. During the spawning period, the lake sturgeon rapidly change depths and moved frequently throughout the CHTTC in the month of June. As water temperatures range between 6 and 16°C, lake sturgeon demonstrate porpoising behaviour with the approaching spawning period (Bruch and Binkowski 2002). Also, male adults are known to search for ovulating females at the spawning grounds (Bruch and Binkowski 2002), which may explain the varied depth-use and movement behaviour during the months of May and June. When residing at the CHTTC, Lake sturgeon frequent depths where HTs and anchoring structures are positioned (i.e. ≥ 6.5 m). Adjusting operations and maintenance activities during this time of the year could be beneficial to lake sturgeon to reduce the risk of deleterious harm or altering natural spawning behaviours of lake sturgeon. However, lake sturgeon would be at lower risk in the summer, autumn and winter months as tagged individuals minimally utilized or moved throughout the habitat at the CHTTC during these seasons.

The tagged walleye utilized habitat at the CHTTC considerably more than lake sturgeon throughout the study period. Walleye are known to have fidelity below hydropower facilities (McConville and Fossum 1981; Murchie and Smokorowski 2004) and to make minimal movements downstream from hydropower stations. The detected walleye are likely utilizing the SSGS tailrace to forage in the open-water season due to the swift conditions. The SSGS powerhouse restricts any further upstream movement, and provides an environment to opportunistically feed on entrained fishes passed through the SSGS powerhouse. Based on the seasonal residency findings, the walleye population may be more likely to be at risk of HT impacts (i.e. blade strike, EM field, chemical leaking; Yuce and Muratoglu 2015) throughout the summer, and autumn, while at lower risk in spring and winter seasons. The walleye would likely move downstream in search of deeper, slower refugia when discharge and water temperatures are reduced and become suboptimal for foraging (i.e. $\leq$ 5° Celsius; Paragamian 1989) with the progression of winter. Across the monitoring period, walleye moved more frequently within the CHTTC compared to lake sturgeon. Movement frequency was elevated during September and October in the area where the HT was tested. This is similar with previous studies that have shown that walleye movement can be elevated in the autumn season (Schupp 1972; Holt et al. 1977). Although there was a small proportion of walleye residing at the CHTTC during the winter season, lateral movements were not documented here between December 2014 and March 2015. This trend in greater movement in the summer and autumn months and lower in the winter and spring is likely related to water temperature (Holt et al. 1977; Paragamian 1989), foraging behaviour (Bozek et al. 2011), and/or discharge (DiStefano and Hiebert 2000).

Movement frequency did not change according to diel period for the walleye detected at the CHTTC. This is a variable for which the literature is inconsistent, with some studies finding no differences in movement (Ager 1976; Holt et al. 1977) and others finding greater movement frequency during the nocturnal period (Prophet et al. 1989; DiStefano and Hiebert 2000). This is likely because walleye are a photophobic species (Ryder 1977; Einfalt et al. 2012). However, differences in movement between diel periods can be confounded by environmental parameters that change ambient light conditions, such as water clarity and depth availability (Ryder 1977; DiStefano and Hiebert 2000). Water passing through the CHTTC is swift (i.e. $\geq$ 2 ms^{-1}), which may have resulted in similar movement frequency between day and night periods as walleye generally employ a "sit-and-wait" tactic for capturing prey rather than actively searching in swift conditions.

Although walleye frequently move and reside at the CHTTC across the summer and autumn seasons, the average depth-use ($\bar{x}$ =5.6 m) was not within the range where the HT and anchoring structures were positioned ($\geq$ 6.5 m). In addition, there were no depth detections throughout December to March, which corresponds with their lower residency rate and lack of movements during this period. However, walleye do occasionally utilize depths where the substrate HT was positioned, particularly in the months of May ($\bar{x}$ =6.9 m), June ($\bar{x}$ =6.7 m), October ($\bar{x}$ =6.4 m), and November ($\bar{x}$ =6.7 m). These months were also characterized by high rates of movement and residency. Walleye are likely at greater risk from substrate-HTs and anchoring structures during these months when considering residency, movement frequency, and depth use collectively. Overall, entrainment, blade strike, ambient noise and EMF likely have a negligible threat to walleye in the presence of a singular HT that is substrate-anchored in tailrace environments within Canadian Boreal Shield watersheds. However, the threat to walleye and lake sturgeon from substrate-HTs may depend on the turbidity, bathymetry, and hydrodynamics found in tailrace environments, which could influence habitat utilization of the populations within these systems.

Management implications

There are challenges and limitations with using acoustic telemetry technology for HT research in swift and noisy environments (Thornstad et al. 2000, 2013; Cooke et al. 2012). Although aquatic telemetry provides opportunities to investigate the spatiotemporal movement and behaviour of fishes (Hussey et al. 2015), its use in performing biological assessments relative to hydropower operations can be limited by environmental and biological factors. The acoustic transmitter transmission signal is attenuated and refracted as it passes through water (Kessel et al. 2013). When used around hydropower operations, the DE of acoustic hydrophones can be hampered by entrained air, noise, turbulent water (Thorstad et al. 2000), as well as by the biology of the species being studied (Cooke et al. 2012). As indicated in the results, the DE of the acoustic array was 0.39, or 39%. This may have hampered our ability to record tagged fish using the area where the HTs were undergoing operational tests, thus underestimating entrainment risk. Alternatively, researchers may use VHF radio telemetry to track the movement of fishes around hydropower developments, such as to investigate dam passage and fishway usage (Gowans et al. 1999; Suzuki et al. 2016). In these turbulent environments, radio telemetry is advantageous as the transmissions typically have a longer range because the signal is propagated through air to a fixed or mobile receiving station, although greater water depth does restrict range (Thorstad et al. 2013). As such, the radio transmissions are less likely to be disrupted in rocky and turbulent riverine environments compared with acoustic telemetry (Cooke et al. 2012; Cooke and Thorstad 2012). It is important to note, however, that there are a number of recent developments (different coding schemes, different frequencies) in the acoustic telemetry realm that may be better suited to HT investigation. Nevertheless, high-resolution studies that look at direct interactions of fishes with HTs may not be appropriate using telemetry technology due to "observer" errors such as large detection ranges and transmission interference in noisy, rocky, and deep-water environments, whether using radio or acoustic telemetry. Instead other tools have proven to be appropriate for evaluating fishes in close vicinity of HTs during field testing such as action cameras (Hammar et al. 2013) and sonar imagery (Viehman and Zydleski 2015). These tools have been used to directly identify turbine entrainment frequency and behavioural alteration for wild fishes relative to HT operations.

Ultimately, the questions and environmental context of the research should determine which tools and techniques are appropriate.

The tested HT at the CHTTC is representative of commercial-level operations. As such, this study will help to guide best management practices for commercial operations for in-stream hydrokinetic projects that are expected at existing hydropower stations. Riverine hydrokinetic devices installed at existing hydropower stations will likely be deployed as arrays that include multiple HT devices operated in series. In this study, we investigated a single substrate-mounted HT. However, there are current proposals for commercial hydrokinetic energy projects consisting of several dozen devices in a river system (Schweizer et al. 2011; Seitz et al. 2011). The behavioural responses from wild fishes would likely be related to the HT array size, as well as, the quantity of ambient turbulence, noise, and EMF that is generated. Additionally, the risk of blade strike is directly proportional to the size of fishes and the density of HTs installed (Cada et al. 2011). HT operators need to consider the entire fish community and how they may be affected by operations, particularly if there are rheotactic and migratory species present. Furthermore, the consideration of using several small or a single large turbine to meet operational demands need to be investigated in relation to ecology and behaviour of wild fishes.

As indicated here and in marine HT assessments (Hammar et al. 2013), singular HTs are not likely hazardous to wild fishes (NAI 2009; EPRI 2011b). However, environmental managers should use the precautionary approach before and during full-scale operations for HTs in rivers. The local ecology of native fauna and the environmental context should be key considerations with the installation of riverine-HT arrays (Viehman and Zydleski 2015). Various species and life stages should also be addressed when investigating potential impacts of HTs (Castro-Santos and Haro 2015). While operational schedules may not be flexible for commercial-scale operations, energy companies can minimize scheduled maintenance and pre-commercial testing activities during periods when fish are most likely to be present at the testing site. Similar to conventional hydropower stations, research efforts could be directed at assessing deterrent and monitoring systems designed for HT devices. Such devices may reduce the risk of entrainment by deterring fish from passing through the turbines. Further research is warranted to continue investigating HTs within tailraces for other species, across seasons, and with different anchoring systems (e.g. substrate-, barge-anchored). This research provides important insights into the spatial ecology of wild fish where riverine HTs are operational as a means to guide the HT operational in similar systems where lake sturgeon, walleye, and other species with similar life histories may reside.

Acknowledgments

We would like to acknowledge B. Gardner, D. Leroux and A. Hossein Birjandi for their assistance in the field. S.J. Cooke and E. Bibeau are supported by the Natural Sciences and Engineering Research Council of Canada and the Canadian Research Chairs Program. D.P. Struthers received a scholarship in support of this project from Fish Futures Inc.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Canadian Hydrokinetic Turbine Testing Centre of the University of Manitoba.

ORCID

Eva Enders http://orcid.org/0000-0003-2103-0359
Karen Smokorowski http://orcid.org/0000-0003-1530-7024

References

Auer NA. 1996. Importance of habitat and migration to sturgeons with emphasis on lake sturgeon. Can J Fish Aquat Sci. 53:152–160.
Barton K. 2014. MuMIn: Multi-model inference. R package version 1.12.1. Available from: http://CRAN.R-project.org/package=MuMIn
Bolker BM, Yu-Sung S. 2011. coefplot2: coefficient plots. R package version 0.1.3.2.
Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHH, White JSS. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol Evol. 24:127–135.
Bozek MA, Haxton TJ, Raabe JK. 2011. Chapter 5: walleye and sauger. In Barton BA, editor. Habitat, biology, management, and culture of walleye and sauger. Bethesda (MD): American Fisheries Society; p. 133–199.
Bruch RM, Binkowski FP. 2002. Spawning behaviour of lake sturgeon (*Acipenser fulvescens*). J Appl Ichthyol 18:570–579.
Cada GF, Loar J, Garrison L, Fisher R, Neitzel D. 2006. Efforts to reduce mortality to hydroelectric turbine-passed fish: locating and quantifying damaging shear stresses. Environ Manage. 27:898–906.
Cada GF, Ahlgrimm J, Bahleda M, Bigford T, Stavrakas S, Hall D, Moursund R, Sale M. 2007. Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments. Fisheries 32:174–181.
Cada GF, Bevelhimer MS. 2011. Attraction to and avoidance of instream hydrokinetic turbines by freshwater aquatic organisms (No. ORNL/TM-2011/131). Oak Ridge (TN): Oak Ridge National Laboratory (ORNL).
Cada GF, Bevelhimer MS, Riemer KP, Turner JW. 2011. Effects on freshwater organisms of magnetic fields associated with hydrokinetic turbines. ORNL/TM-2011/244. Oak Ridge (TN): Oak Ridge National Laboratory.
Castro-Santos T, Haro A. 2015. Survival and behavioral effects of exposure to a hydrokinetic turbine on juvenile

Atlantic salmon and adult American shad. Estuaries and Coasts. 38:203–214.
Cooke SJ, Hinch SG, Lucas MC, Lutcavage M. 2012. Biotelemetry and biologging. In Zale AV, Parrish DL, Sutton TM, editors. Fisheries techniques, Volume 3. Bethesda (MD): American Fisheries Society; p. 819–881.
Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ. 2004. Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol. 19:334–343.
Cooke SJ, Thorstad EB. 2012. Is radio telemetry getting washed downstream? The changing role of radio telemetry in studies of freshwater fish relative to other tagging and telemetry technology. In Advances in Fish Tagging and Marking Technology. Am Fish Soc Symp 76:349–369.
Cooke SJ, Woodley CM, Eppard MB, Brown RS, Nielsen JL. 2011. Advancing the surgical implantation of electronic tags in fish: a gap analysis and research agenda based on a review of trends in intracoelomic tagging effects studies. Rev Fish Biol and Fish. 21:127–151.
COSEWIC (Committee on the Status of Endangered Wildlife in Canada). 2006. COSEWIC assessment and update status report on the lake sturgeon *Acipenser fulvescens* in Canada. Ottawa: Canadian Wildlife Service, Environment Canada.
Craig JF. 2000. Percid fishes: systematics, ecology and exploitation. Oxford: Blackwell Scientific Publications.
DiStefano RJ, Hiebert JF. 2000. Distribution and movement of walleye in reservoir tailwaters during spawning season. J Fresh Ecol. 15:145–155.
Einfalt LM, Grace EJ, Wahl DH. 2012. Effects of simulated light intensity, habitat complexity and forage type on predator–prey interactions in walleye *Sander vitreus*. Ecol Fresh Fish. 21:560–569.
EPRI (Electric Power Research Institute). 2011b. Evaluation of fish injury and mortality associated with hydrokinetic turbines. . Report no. 1024569. Palo Alto (CA): EPRI.
Fetherman ER, Lepak JM, Harris DJ. 2015. Optimizing triploid walleye production in Colorado. Fort Collins (CO): Colorado Parks and Wildlife Services, Department of Natural Resources.
Forsythe PS, Scribner KT, Crossman JA, Ragavendran A, Baker EA, Davis C, Smith KK. 2012. Environmental and lunar cues are predictive of the timing of river entry and spawning-site arrival in lake sturgeon *Acipenser fulvescens*. J Fish Biol. 81:35–53.
Gallepp GW, Magnuson JJ. 1972. Effects of negative buoyancy on the behavior of the bluegill, *Lepomis macrochirus Rafinesque*. T Am Fish Soc. 101:507–512.
Gowans ARD, Armstrong JD, Priede IG. 1999. Movements of adult Atlantic salmon in relation to a hydroelectric dam and fish ladder. J Fish Biol. 54:713–726.
Hammar L, Andersson S, Eggertsen L, Haglund J, Gullstrom M, Ehnberg J, Molander S. 2013. Hydrokinetic turbine effects on fish swimming behaviour. PLoS One. 8:0084141.
Hart DD, Johnson TE, Bushaw-Newton KL, Horwitz RJ, Bednarek AT, Charles D, Velinsky DJ. 2002. Dam removal: challenges and opportunities for ecological research and river restoration. BioScience 52:669–682.
Holt CS, Grant GD, Oberstar GP, Oakes CC, Bradt DW. 1977. Movement of walleye, Stizostedion vitreum, in Lake Bemidji, Minnesota as determined by radio-biotelemetry. T Am Fish Soc. 106:163–169.
Houston JJ. 1987. Status of the lake sturgeon, *Acipenser fulvescens*, in Canada. Can Field Nat. 101:171–185.
Hrenchuk CL. 2009. Influences of water velocity and hydropower operations on spawning site choice and recruitment success of lake sturgeon, Acipenser fulvescens, in the Winnipeg River [MSc Thesis]. Winnipeg, MB (Canada): The University of Winnipeg; p. 153.
Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG. 2015. Aquatic animal telemetry: a panoramic window into the underwater world. Science. 348:1255642.
Kessel ST, Cooke SJ, Heupel MR, Hussey NE, Simpfendorfer CA, Vagle S, Fisk AT. 2013. A review of detection range testing in aquatic passive acoustic telemetry studies. Rev Fish Biol Fish. 24:199–218.
Linkov I, Satterstrom FK, Kiker G, Batchelor C, Bridges T, Ferguson E. 2006. From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. Environ Int. 32:1072–1093.
Liu Y, Packey DJ. 2014. Combined-cycle hydropower systems – the potential of applying hydrokinetic turbines in the tailwaters of existing conventional hydropower stations. Renew Energ. 66:228–231.
Loures RC, Pompeu PS. 2015. Seasonal and diel changes in fish distribution in a tropical hydropower plant tailrace: evidence from hydroacoustic and gillnet sampling. Fisheries Manag Ecol. 22:185–196.
Lusseau D. 2005. Residency pattern of bottlenose dolphins *Tursiops spp*. in Milford Sound, New Zealand, is related to boat traffic. Mar Ecol Prog Series. 295:265–272.
Mazerolle MJ. 2015. AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c). R package version 2.0-3. Available from: http://CRAN.R-project.org/package=AICcmodavg
McConville DR, Fossum JD. 1981. Movement patterns of walleye (*Stizostedion v. vitreum*) in Pool 3 of the upper Mississippi River as determined by ultrasonic telemetry. J Freshwater Ecol. 1:279–285.
Murchie KJ, Smokorowski KE. 2004. Relative activity of brook trout and walleyes in response to flow in a regulated river. N Am J Fish Mana. 24:1050–1057.
NAI (Normandeau Associates, Inc.). 2009. An estimation of survival and injury of fish passed through the Hydro Green Energy hydrokinetic system, and a characterization of fish entrainment potential at the Mississippi Lock and Dam No. 2 Hydroelectric Project (P- 4306), Hastings, Minnesota. Prepared for Hydro Green Energy LLC. Houston (TX); p. 82.
Paragamian VL. 1989. Seasonal habitat use by walleye in a warmwater river system, as determined by radiotelemetry. N Am J Fish Mana. 9:392–401.
Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2015. nlme: linear and nonlinear mixed effects models. R package version 3.1-122. Available from: http://CRAN.R-project.org/package=nlme
Pincock DG. 2011. False detections: what they are and how to remove them from detection data. Document#: DOC-004691 version 02 April 13, 2011. Amirix Systems Inc. Available from: http://www.vemco.com/pdf/false_detections.pdf (February 3, 2012).
Peterson DL, Vecsei P, Jennings CA. 2007. Ecology and biology of the lake sturgeon: a synthesis of current knowledge of a threatened North American Acipenseridae. Rev Fish Biol Fisher. 17:59–76.
Post JR, Sullivan M, Cox S, Lester NP, Walters CJ, Parkinson EA, Paul AJ, Jackson L, Shuter BJ. 2002. Canada's recreational fisheries: the invisible collapse? Fisheries. 27:6–17.
Prophet CW, Brungardt TB, Prophet NK. 1989. Diel behavior and seasonal distribution of walleye, *Stizostedion*

vitreum Mitchill, in Marion Reservoir, based on ultrasonic telemetry. J Freshwater Ecol. 5:177–185.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for statistical computing, Vienna, Austria. Available from: http://www.R-project.org/

Reubens JT, Pasotti F, Degraer S, Vincx M. 2013. Residency, site fidelity and habitat use of Atlantic cod (*Gadus morhua*) at an offshore wind farm using acoustic telemetry. Marine Environ Res. 90:128–135.

Rogers KB, White GS. 2007. Analysis of movement and habitat use. In telemetry data analysis and interpretation of freshwater fisheries data. Bethesda (MD): American Fisheries Society; p. 625–676.

Ross MJ, McCormick JH. 1981. Effects of external radio transmitters on fish. Prog Fish-Culturist. 43:67–72.

Ryder RA. 1977. Effects of ambient light variations on behavior of yearling, subadult, and adult walleyes (*Stizostedion vitreum vitreum*). J Fish Res Board Can. 34:1481–1491.

Schilt CR. 2007. Developing fish passage and protection at hydropower dams. Appl Anim Behav Sci. 104:295–325.

Schroepfer RL, Szedlmayer ST. 2006. Estimates of residence and site fidelity for red snapper *Lutjanus campechanus* on artificial reefs in the northeastern Gulf of Mexico. Bull Mar Sci 78:93–101.

Schupp DH. 1972. The walleye fishery of Leech Lake. Minnesota: Minnesota Department of Natural Resources, Division of Game and Fish, Section of Fisheries.

Schweizer PE, Cada GF, Bevelhimer MS. 2011. Estimation of the risks of collision or strike to freshwater aquatic organisms resulting from operation of instream hydrokinetic turbines. FY 2010 Annual Progress Report. Prepared for the Wind and Water Power Program. Washington (DC): U.S. Department of Energy; p. 39.

Scott WB, Crossman EJ. 1973. Freshwater fishes of Canada. Ottawa (ON): Fisheries Research Board of Canada; pp. 185.

Seitz AC, Moerlein K, Evans MD, Rosenberger AE. 2011. Ecology of fishes in a high-latitude, turbid river with implications for the impacts of hydrokinetic devices. Rev Fish Biol Fish. 21:481–496.

Skalski JR, Townsend R, Lady J, Giorgi AE, Stevenson JR, McDonald RD. 2002. Estimating route-specific passage and survival probabilities at a hydroelectric project from smolt radiotelemetry studies. Can J Fish Aquat Sci. 59:1385–1393.

Smokorowski KE, Pratt TC. 2007. Effect of a change in physical structure and cover on fish and fish habitat in freshwater ecosystems – a review and meta-analysis. Env Rev. 15:5–41.

Summerfelt RC, Smith LS. 1990. Anesthesia, surgery and related techniques. In Schreck CB, Moyle PB, editors. Methods for fish biology. Bethesda (MD): American Fisheries Society; p. 213–272.

Suzuki FM, Dunham JB, Silva LGM, Alves CBM, Pompeu PS. 2016. Factors influencing movements of two migratory fishes within the tailrace of a large neotropical dam and their implications for hydropower impacts. River Res Appl. DOI: 10.1002/rra.3105

Symonds MR, Moussalli A. 2011. A brief guide to model selection, multi-model inference and model averaging in behavioural ecology using akaike's information criterion. Behav Ecol Sociobiol. 65:13–21.

Thorstad EB, Økland F, Rowsell D, McKinley RS. 2000. A system for automatic recording of fish tagged with coded acoustic transmitters. Fish Manage Ecol. 7:281–294.

Thorstad EB, Rikardsen AH, Alp A, Økland F. 2013. The use of electronic tags in fish research–an overview of fish telemetry methods. Turk J Fish Aqua Sci. 13:881–896.

USDOE (United States Department of Energy). 2009. Report to Congress on the potential environmental effects of marine and hydrokinetic energy technologies. Washington (DC): UDDOE; p. 633.

Vandergoot CS, Murchie KJ, Cooke SJ, Dettmers JM, Bergstedt RA, Fielder DG. 2011. Evaluation of two forms of electroanesthesia and carbon dioxide for short-term anesthesia in walleye. N Am J Fish Manage. 31:914–922.

VanZwieten J, McAnally W, Ahmad J, Davis T, Martin J, Bevelhimer M, Cribbs A, Lippert R, Hudon T, Trudeau M. 2014. In-stream hydrokinetic power: review and appraisal. J Energy Eng. 141:04014024.

Viehman HA, Zydlewski GB. 2015. Fish interactions with a commercial-scale tidal energy device in the natural environment. Estuaries Coasts. 38:241–252.

Webber D. 2009. VEMCO acoustic telemetry new user guide. Halifax: Vemco.

Wilson JA, McKinley RS. 2004. Distribution, habitat, and movements. In LeBreton GTO, Beamish FWH, McKinley RS, editors. Sturgeons and paddlefish of North America. Dordrecht: Kluwer Academic Publishers; p. 40–72.

Yuce MI, Muratoglu A. 2015. Hydrokinetic energy conversion systems: a technology status review. Renew Sust Energ Rev. 43:72–82.

Zorn TG. 2015. Contribution of hatchery-reared walleyes to populations in Northern Green Bay, Lake Michigan. N Am J Aquacult. 77:409–422.

Zuur A, Ieno EN, Walker N, Saveliev AA, Smith GM. 2009. Mixed effects models and extensions in ecology with R. New York (NY): Springer Science & Business Media.