Environ Biol Fish (2016) 99:249–263
DOI 10.1007/s10641-016-0471-3

Fishway approach behaviour and passage of three redhorse species (*Moxostoma anisurum, M. carinatum, and M. macrolepidotum*) in the Richelieu River, Quebec

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Received: 21 August 2014 / Accepted: 4 February 2016 / Published online: 8 March 2016

Abstract Fishways are increasingly constructed to maintain longitudinal connectivity for fish in numerous river systems where migrations are interrupted by anthropogenic barriers, although there is a paucity of information on the biological effectiveness of fishways for most species. We evaluated fishway approach behaviour, and quantified attraction and passage efficiency of three catostomid species (silver redhorse *Moxostoma anisurum*, river redhorse *M. carinatum* and shorthead redhorse *M. macrolepidotum*) that undertake annual obligate spawning migrations through the Vianney-Legendre vertical slot fishway at the St. Ours Dam, in the Richelieu River, Quebec, Canada. Use of PIT tagging alone enabled quantification of attraction and passage efficiency and these were; 51, 17 and 50 % for attraction efficiency and passage efficiencies were 88, 50, and 69 % for silver, river, and shorthead redhorse, respectively. Silver redhorse had significantly shorter entrance delay and passage duration times than shorthead redhorse. Attraction efficiency was different among release locations for silver redhorse, and passage efficiency increased with size for shorthead redhorse. For all species, failure to ascend the fishway was most likely to occur before the second turning basin (before the 32 m mark) in the fishway (84 % of failures). Silver redhorse had significantly lower passage failure rates than river and shorthead redhorse. Activity patterns in the three species during fishway passage were different; crepuscular activity patterns were observed in shorthead and river redhorse, whereas silver redhorse activity peaked between 23:00 and 02:00 then decreased through the remainder of the day. To further evaluate fishway approach behaviour we fitted an additional sample of each species with external radio tags, although nearly all radio tagged individuals ($n = 119$) rapidly moved downstream upon release immediately post-tagging. Subsequently, our results were confounded by the behavioural impairments associated with external radio tagging and fallback. These results demonstrate the value of multispecies fishway evaluations and highlight the variation among individual species fishway performance within a single genus.

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Keywords Fishway · Redhorse · Biotelemetry · Attraction and passage efficiency · Moxostoma

Introduction

Natural and anthropogenic barriers can indirectly influence migratory fish populations in rivers by reducing the quality of fish habitat, or directly preventing longitudinal or lateral movements (Dynesius and Nilsson 1994; Poff et al. 1997; Malmqvist and Rundle 2002). Fishways are frequently constructed to maintain longitudinal connectivity for fish in fluvial systems impacted by barriers by providing volitional passage for fish (Clay 1995). Biological evaluations of fishways are increasing (Roscoe and Hinch 2010), although recent syntheses have demonstrated that the majority of fishways are not efficient and further evaluations are needed to expand upon the 19 published studies drawn upon by Bunt et al. (2012). Over 200 fishways exist in Canada alone, emphasizing the paucity of such efficiency studies and the associated limited information for managers to base recommendations on (Hatry et al. 2013).

The inability of fish to successfully ascend fishways is thought to be associated with a combination of physiological limitations and behavioural choices (Peake 1997; Hinch and Bratty 2000). Assessments of fishway biological effectiveness typically utilise individual fish behavioural metrics collected from animal-borne electronic tags (Castro-Santos et al. 1996; Bunt et al. 2000; Cooke and Hinch 2013; Thiem et al. 2013). Use of electronic tags in fishway assessments enables the monitoring of individual fish entrance into and exit from fishways under natural conditions (Bunt et al. 2012; Cooke and Hinch 2013). Such techniques enable a robust assessment of attraction efficiency (defined as the proportion of fish tagged and released during the study that were located close enough to a fishway to have been attracted by the fishway's attraction flow) and passage efficiency (the total number of fish detected entering a fishway divided by the total number of fish detected exiting the fishway (Bunt et al. 2012).

Many fishway evaluation studies have been conducted on salmonids and other popular game fish (Roscoe and Hinch 2010), particularly in North America, and there is comparatively little known about the behaviour of non-commercially important and fish that are not endangered (e.g. 45 % ($n = 43$) of the peer reviewed studies from Roscoe and Hinch (2010) focused on salmonids alone, studies from North America showed that 78 % ($n = 39$) of studies were performed on either endangered or commercially important species). Additionally, most electronic tagging studies tend to focus on a single species and have not explored comparative passage and behaviour within a single spawning season, particularly among congenerics. Catostomids represent a common family of non-game fish that often dominate abundance and biomass at fishways in North America (e.g. Schwalme et al. 1985; Bunt et al. 2001; Pratt et al. 2009), are susceptible to river fragmentation due to their obligate spring migrations (Cooke et al. 2005; Reid et al. 2008) and thus represent a suitable group to study.

Annually, five redhorse (*Moxostoma* spp.) species undertake upstream spawning migrations in the Richelieu River in Quebec, Canada. Copper redhorse (*M. hubbsi*) are federally endangered in Canada (COSEWIC 2004) and the Richelieu River represents a stronghold for the species. River redhorse (*M. carinatum*) are federally listed as a species of special concern (http://www.cosewic.gc.ca) yet are locally abundant in the Richelieu River. Shorthead and silver redhorse (*M. macolepidotum* and *M. anisurum,* respectively) are also locally abundant, as are greater redhorse (*M. valenciennesi*). These fishes rarely occur together outside of their spawning season due to their different habitat and feeding preferences (Mongeau and Dumont 1992). The Vianney-Legendre vertical slot fishway, provides a unique opportunity to compare fishway passage and approach behaviour (downstream of the dam) of members of the *Moxostoma* genus as they migrate upstream towards spawning grounds near the Chambly Dam, Quebec (a large spawning area in the Chambly rapids of the Richelieu River about 60 km upstream of the St. Ours dam (Mongeau and Dumont 1992; COSEWIC 2004). The objective of this study was to evaluate fishway approach behaviour and to quantify the attraction and passage efficiency of silver, river and shorthead redhorse at the Vianney-Legendre vertical slot fishway during the peak of their respective spawning migrations, using electronic tagging techniques. Additionally, we sought to determine potential reasons for variations in attraction or passage efficiency, such as bank side approach to the fishway, and areas of difficult passage within the fishway.

Methods

Study site and fish collection

The study was conducted during spring (May-June) 2012 at the Vianney-Legendre vertical slot fishway located on the Richelieu River near St. Ours, Quebec, Canada (45°52′N 73°09′W). A detailed description of the fishway can be found in Thiem et al. (2011b). Briefly, the fishway is comprised of 15 vertical slots (0.6 m width), with a total rise of 2.65 m. The fishway is divided into 12 rectangular basins (3.5 × 3.0 m), two turning/resting basins with curved walls (2.75 m radius), and a large entry and exit basin (*see* Fig. 1). Each rectangular basin has a height drop of 0.15 m. The three redhorse species examined in this study (silver, river and shorthead) were captured directly from a fish trap located at the top of the fishway which was lifted daily. The fish trap is a 2.2 × 2.0 m cage designed so that fish cannot exit the fishway with the general purpose of enumerating fish that have moved up the fishway. Using nets or electrofishing to capture fish was not possible given the presence of federally endangered copper redhorse and concerns regarding their incidental capture. We assumed that capture in the fish trap of large numbers of each redhorse species indicated optimal timing of migration, and thus individuals from each species were tagged as encountered. Water temperatures during peak migrations were stable in 2012 and subsequently tagging for a given species occurred within a relatively narrow temperature range (for silver and shorthead redhorse temperatures at tagging were 13.8 ± 0.08 °C and temperatures for river redhorse tagging were 19.3 ± 0.06 °C) coinciding with the timing of peak migration for each species (migrations for each species peak in April to late May for silver and shorthead redhorse and late May to early June for river redhorse).

Equipment and fish tagging

A passive integrated transponder (PIT) array was installed in the fishway: the array consisted of 15 antennas, beginning at antenna 15 downstream and ending at antenna 1 upstream (Fig. 1) (see Thiem et al. (2011b) for more information on the PIT antenna array). This type of PIT antenna array has been used successfully in the past to track fish passage (Castro-Santos et al. 1996; Thiem et al. 2011b; Steffensen et al. 2013; Thiem et al. 2013). Antennas sequentially scanned via multiplexers and positive detection of a unique tag identification number resulted in a date and time stamp stored in a datalogger (Oregon RFID, Oregon, USA). Antenna detection efficiency was 91 ± 1.8 % for the size of tags used in this study (i.e., 23 mm tags; Burnett et al. 2013) with typical read range distances from each antenna of approximately 0.40 m. In addition, a radio antenna array consisting of 14 antennas (three and five element yagi antennas, AF Antronics, Urbana, Illinois) connected to four datalogging digital radio receivers (three SRX 600 s and one SRX 400, Lotek Wireless, Newmarket, ON) was installed to monitor downstream approach behaviour of redhorse. Multiple antennas connect into each receiver via an ASP-8 antenna switcher (Lotek Wireless) and the antennas scanned sequentially through each radio frequency on each antenna for a period of 8 s. Three receivers were positioned on the dam, one on the west which had six antennas connecting into it, one in the center of the dam which had one antenna feeding into and one on the east bank which had four antennas feeding into it. The fourth receiver was positioned

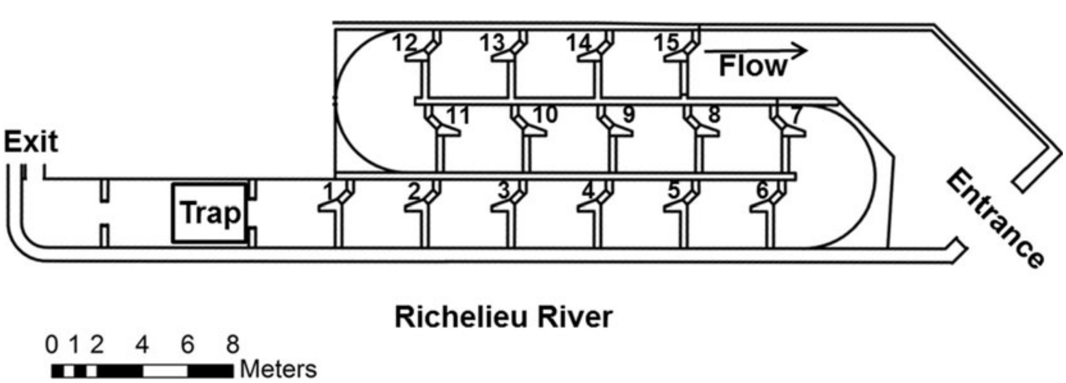

Fig. 1 A schematic of the fishway showing the fishway entrance and exit, the location of the fish trap, the flow direction, and each basin labelled with its corresponding PIT antenna number

downstream of the dam and had three antennas feeding into it (see Fig. 2). The use of coded radio transmitters resulted in the use of five radio frequencies, thus reducing scan time, and the entire scan cycle was less than 120 s. Radio antenna locations and their approximated detection areas) were mapped during radio antenna installation (Fig. 2). Detection areas near the dam face (north side of the dam) were tested using a transmitter attached to a weight tied to very long rope. Antennas were then tuned (through adjusting the gain or the power of each antenna through the SRX receivers) to receive only faint signals from the transmitter, this was carried out along the dam face for each antenna, thus delineating the extent of reception. Similarly, the other detection areas shown in Fig. 2 were mapped using a boat, rope and a weight attached to a transmitter with tuning adjustments made onshore to define detection areas.

Fish were tagged immediately after capture from the trap at the top of the fishway. Three redhorse species ($n=39$ silver redhorse, $n=38$ river redhorse, $n=39$ shorthead redhorse) were tagged externally with coded radio tags (149 MHz, 30 × 8 mm, 8 g weight in air, 4 g in water, burst rate 2 s, 90 day battery life, Sigma Eight Inc., Newmarket, Ontario, Canada) at the base of the dorsal fin (Fig. 3) and with unique PIT tags (23 × 3.85 mm HDX: Texas Instruments, Dallas, USA) injected into their coelom. An additional group of fish was only fitted with PIT tags only ($n=120$ silver redhorse, $n=70$ river redhorse, $n=120$ shorthead redhorse). External radio tagging was accomplished using six gauge hypodermic needles, and 20 gauge stainless steel wire was used to secure tags. Tagging methods were similar to those previously used on several species (Collins et al. 2002). Plastic backing plates were also used on each side of the fish to minimize any pressure on the fish's dorsal musculature back caused by the tag attachment process, and to reduce drag during high speed swimming. The total tag burden, including backing plate and wire, weighed ~12 g in air, and never exceeded 2 % of weight based on length-weight relationships (Table 1). The coefficient of determination (R^2) values generated for the three species log-log (loglength-logweight) relationships are comparable to those reported in Mongeau and Dumont (1992) for the three redhorse species. Total length (TL) of each fish was measured along with a determination of sex accomplished through visual identification (abdominal pressure and gamete extrusion as well as the presence of tubercles on caudal fins and snout). The same experienced tagger attached all radio tags. Fish were tagged

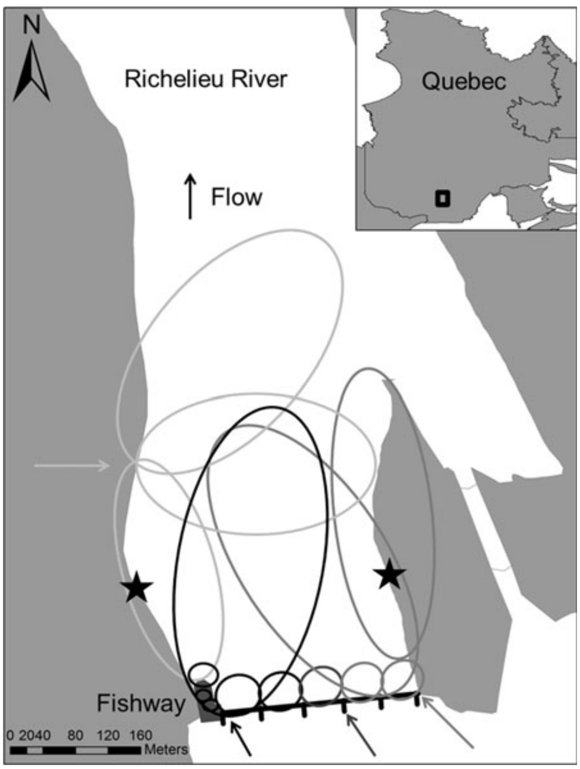

Fig. 2 Schematic overhead view of the Richelieu River downstream of the St. Ours dam, arrows point to the location of each radio receiver and radio antenna detection cells are shown and shaded differently for their respective receivers. The fishway is just to the right of the fishway label. Two reception cells are shown within the fishway with a third just outside the fishway entrance.★ Indicates fish release locations

Fig. 3 An attached radio tag and plastic backing plate held in place by stainless steel wire below the dorsal fin of a shorthead redhorse

Table 1 Tag burden as a proportion of body weight for three redhorse species captured at the Vianney-Legendre fishway in the spring of 2012. R^2 values for the length-weight relationship for each species generated from unpublished data are also shown

Species	Sex	Mean (% of body weight) ± SE	R^2 ($\log_{10}$length:$\log_{10}$weight)
Silver redhorse	Female	0. 56 ± 0.02	0.86
	Male	0.77 ± 0.06	0.93
River redhorse	Female	0.47 ± 0.03	0.83
	Male	0.54 ± 0.04	0.80
Shorthead redhorse	Female	1.41 ± 0.06	0.94
	Male	1.88 ± 0.06	0.85

in V-shaped troughs with flow through ambient river water supplied during each tagging event. Holding tanks for recently tagged fish had a constant supply of fresh river water. In all cases, tagging occurred with the head and gill complex of fish submerged in fresh water to minimize stress and fish required only light restraint administered by the individual holding the fish during radio tag attachment. Anesthetics were not used given the assumption that there would be a protracted behavioural recovery period, and provided with some earlier experiences tagging greater redhorse (*Moxostoma valenciennesi)* where all ($n = 5$) of the fish anaesthetized suffered acute mortality (Cooke, *unpublished data*).

Tagging of the three redhorse species was carried out between the 9th and 25th of May, 2012. Silver and shorthead redhorse were all tagged from May 9–11 and May 17. River redhorse were all tagged from May 24–25. The fishway and downstream approach locations were continuously monitored using fixed antenna (radio and PIT) arrays between May 9 and July 10, 2012.

In contrast to the previous experiments (i.e., Thiem et al. 2013) fish used for the determination of passage success were not held in recovery basins for 1–2 h prior to experimentation but were tagged immediately after capture from the fish trap at the top of the fishway. Following tagging fish were held in a recovery tub for a short time (~15 min) and then were released ~150 m downstream of the dam face (north side of the dam) in equal numbers of species and sex, on alternate banks of the river (see Fig. 2), to evaluate whether sex or bankside approach influenced attraction and/or passage efficiency. Bankside approach was investigated to find out if fish approaching the dam along the west bank (the bank which the fishway is situated on) had greater attraction efficiency than fish approaching the dam from the east bank.

Data analysis

Attraction efficiency was defined as the number of fish detected in the fishway divided by the total number of fish released, and was separated by species, sex, and release bank. Passage efficiency was calculated as the total number of fish detected entering the fishway (most downstream baffle) divided by the total number of fish detected exiting the fishway (passing the most upstream baffle). We defined passage success as a fish that entered the fishway (detected on the two most downstream PIT antennas, e.g. antennas 15 and 14) successfully moving past the most upstream baffle (as indicated from PIT antennas) which was determined using the PIT antenna array. Passage duration was determined by calculating the time taken from a fish's first detection on the most downstream baffle to the first detection of a fish passing through the most upstream baffle. Differences in fish length, entrance delay (defined as the time from release to the time to first detection in the fishway), and passage duration among species were analyzed using independent sample t-tests assuming unequal variances (Ruxton 2006). River redhorse were not included in the entrance delay and passage duration comparisons due to small sample sizes. To determine whether differences existed among species attraction efficiency we used a Kruskal-Wallis one-way ANOVA with significant differences examined further using Dunn's Method of pairwise comparisons. To determine whether differences existed among species passage efficiency we used a one-way ANOVA with differences examined further using the Holm-Sidak method of pairwise comparisons. To examine if differences in entrance delay and passage duration existed within and among species as well as between sex and bank release we used two-way ANOVAs, with Bonferonni post-hoc tests used to identify significantly different groups. Silver redhorse entrance delay and shorthead redhorse passage duration data were transformed using the natural logarithm function in order to meet the assumption of normality. Similarly, silver redhorse data for passage duration was normalized using a reciprocal transformation. To determine the probability of detection and successful passage of each species we used multiple logistic regression analysis incorporating length, sex and release bank as predictor variables. Differences in passage failure rates (passage failure being defined as a fish that has entered the fishway, e.g. detection at PIT antennas 15 and 14 the two most downstream antennas, failing to achieve passage success) at locations (antennas) in the fishway were tested by first converting antenna locations to distance metrics, with antenna 15 (the most downstream antenna) being equal to a distance of 0 and antenna 1 (the most upstream antenna) being equal to 56.2 m. Distance metrics were then used in LogRank survival analyses to determine if differences in passage failure rates at incremental distance locations occurred between species. LogRank survival analysis was also used to investigate whether passage failure locations differed within a species based on sex, with Holm-Sidak post hoc tests used to identify significantly different groups. Diel activity was examined using stacked bar graphs created in SigmaPlot, day and night periods were based on local sunrise/sunset conditions for the middle of the study period (05:30 and 20:30 h). All analyses were performed and all assumptions for analyses were checked according to Field (2009) with a significance level of $p<0.05$ used for all analyses. Statistical analyses were performed using SigmaStat (SigmaPlot 11, Systat Software Inc.) and PASW Statistics 18 (SPSS, IBM 2009, USA).

Results

The phenology of migration was such that silver redhorse (12.3 ± 0.1 °C, 11.4–15.1 °C; first detected entry into fishway, e.g. detected at both PIT antennas 15 and 14, May 11 2012) and shorthead redhorse (12.3 ± 0.1 °C, 11.4–15.1 °C; first detected entry into fishway, May 12 2012) were present first in the fishway and river redhorse (18.5 ± 0.1 °C, 17.4–19.4 °C; May 21, 2012, first detected entry into fishway) appeared shortly thereafter. All captured individuals were mature and ripe based on the ease with which gametes could be expelled as well as external characteristics (e.g. tubercles). Females of each species were significantly longer (TL) than males (silver redhorse, $t=5.64$, df = 118, $p<0.001$; river redhorse, $t=2.88$, df = 59, $p=0.003$; shorthead redhorse, $t=8.61$, df = 118, $p<0.001$; Tables 2 and 3).

Radio telemetry study

In general, radio-tagged fish rarely approached the fishway entrance and presumably moved downstream en masse following release. There was insufficient radio telemetry data collected to enable statistical analyses, subsequently summary information is presented in Table 2. Female silver redhorse were detected downstream of the fishway more often (70 %, $n=27$, of female silver redhorse were detected) and were present for longer in the array than any other group of radio tagged fish (Table 2). Approximately 30 %, $n=6$, of male silver redhorse and female shorthead redhorse were detected downstream of the fishway while comparatively fewer male shorthead redhorse (~15 %, $n=3$) and river redhorse of either sex (~10 %, $n=4$) were detected downstream of the fishway. A single female silver redhorse was considered to be attracted to the fishway and that same individual successfully ascended the fishway.

PIT telemetry study

Attraction efficiency differed significantly between the three redhorse species (Table 3) (H = 24.43; df = 2; p <0.001). Pairwise comparisons revealed that attraction efficiency was higher for shorthead and silver redhorse compared to river redhorse (Q = 3.87, $p<0.05$; Q = 3.78, $p<0.05$, respectively) but did not differ between shorthead and silver redhorse. Passage efficiency differed significantly between the three redhorse species (Table 3) (F = 5.94; df = 2; $p=0.003$). Pairwise comparisons revealed that silver redhorse differed in passage efficiency with both river and shorthead redhorse ($t=2.93$; $p=0.004$, and $t=2.59$; $p=0.011$, respectively). Shorthead and river redhorse passage efficiency values did not differ significantly.

Silver redhorse had shorter entrance delays and shorter passage duration than shorthead redhorse (Table 3) ($t=-2.43$; df = 95; $p=0.017$ and $t=-3.79$; df = 42, $p<0.001$, respectively). Within species, female silver redhorse had significantly lower entrance delays than male silver redhorse, and there was no effect of release bank nor an interaction effect of release bank and sex on silver redhorse entrance delay (Table 4). There

Table 2 Summary information for three species of redhorse that were radio and PIT tagged and were released downstream of the Vianney-Legendre fishway in the spring of 2012

Species (n)	Sex (n)	Total length (mm)	Percent detected in the array (n)	Average number of days fish were detected in the array	Percent reaching fishway entrance (n)	Percent successful passage (n)
silver redhorse (39)	M (20)	519 ± 8.2 415–559	30 (6)	2.7	0	0
	F (19)	559 ± 5.4 496–590	73.7 (14)	4.7	2.6 (1)	2.6 (1)
river redhorse (38)	M (19)	588 ± 4.7 537–641	10.5 (2)	3	0	0
	F (19)	601 ± 8.1 528–654	10.5 (2)	1.5	0	0
shorthead redhorse (39)	M (20)	395 ± 3.8 367–429	15 (3)	1	0	0
	F (19)	434 ± 5.5 404–486	31.6 (6)	1.8	0	0

was no effect of sex or release bank and no interaction effect of sex and release bank, on passage duration among silver redhorse (Table 4). For shorthead redhorse, there was no effect of sex or release bank and no interaction effect of sex and release bank, on entrance delay (Table 4). There was a significant interaction effect of sex and bank release on passage duration among shorthead redhorse (Table 4), and post-hoc tests revealed that male shorthead redhorse released on the east bank had significantly longer passage duration than females released on the east bank ($p = 0.007$).

There was a higher probability of detecting silver redhorse if they were released on the east bank rather than the west bank, and a higher probability of passing silver redhorse if they were female and released on the east bank (Table 5). The probability of detecting and passing river redhorse was unrelated to length, sex, or release bank (Table 5). The probability of detecting shorthead redhorse was unrelated to length, sex, or release bank, although the probability of passage was increased as fish length (TL) increased (Table 5).

Generally for all three species, passage failure was most likely to occur at or before the 32 m point (antenna 7) in the fishway (84 %), with few failures occurring after this point (16 %) (Figure 4). Failures at the 32 m mark accounted for the largest proportion of failure (19 %) locations in the fishway. Failure to ascend the fishway was significantly different between species ($\chi^2 = 9.7$; df = 2; $p = 0.008$). Silver redhorse had a significantly lower rate of failure than both river redhorse ($p = 0.004$) and shorthead redhorse ($p = 0.008$). There was no significant difference in the rate of failure between river and shorthead redhorse ($p = 0.40$) (Fig. 4). Within species, there was no significant difference in failure rates between males or females ($p > 0.20$ for all species).

Water temperature ranged between 11 and 21 °C, progressively increasing over the course of the study period with a drop in water temperature occurring at the beginning of June (Fig. 5). River discharge maintained an elevated level between May 12 and May 25, peaking on May 25 (~590 m^3/s) and decreasing afterwards. River discharge exhibited two smaller peaks on May 29 (~520 m^3/s) and on June 2 (~490 m^3/s). All passage events for silver redhorse and a high proportion of passage events for shorthead redhorse occurred during the elevated but fairly uniform discharge period (~540–560 m^3/s) between the May 12 and 25. Most of the passage events for river redhorse occurred before May 30 with one lone event on the June 11. The spike in discharge on May 29 coincided with the passage of one river redhorse.

Silver and river redhorse demonstrated similar activity patterns during fishway passage, with similar levels of activity during the day and at night, while shorthead redhorse were more active during the day (73 % of records) than at night (Fig. 6). Silver redhorse were most active during the early morning (01:00–05:00 h) (Fig. 6a). River redhorse were most active in the hours before sunset (17:00–20:00 h) (Fig. 6b). Shorthead redhorse activity was high in the hours after sunrise (06:00–12:00 h) and before sunset (20:00 h), although activity within the fishway decreased during the afternoon (14:00–17:00 h) (Fig. 6c).

Table 3 Summary information for three species of redhorse PIT tagged and released downstream of the Vianney-Legendre fishway in the spring of 2012

Species (*n*)	Sex (*n*)	Total length (mm)	Release bank[a](*n*)	Attraction efficiency % (*n*)		Passage efficiency % (*n*)		Entrance delay (h)[c]		Passage duration (h)[c]	
				By release bank	Species as a whole	By release bank	Species as a whole	By release bank	Species as a whole	By release bank	Species as a whole
silver redhorse (120)	M (58)	519 ± 5.6 410–610	East (27)	41 (11)	50 (60)	100 (11)	88[b] (53)	194 ± 24 (9)	153 ± 10 63–308 (45)	0.9 ± 0.2 (9)	7 ± 4 0.4–140 [b] (38)
			West (31)	32 (10)		70 (7)		164 ± 20 (9)		0.9 ± 0.2 (6)	
	F (62)	559 ± 4.3 482–624	East (33)	82 (27)		85 (23)		135 ± 14 (20)		11 ± 9 (16)	
			West (29)	41 (12)		100 (12)		137 ± 29 (7)		8 ± 7 (7)	
river redhorse (70)	M (36)	595 ± 5.4 521–660	East (21)	10 (2)	17 (12)	50 (1)	50[b] (6)	–	71 ± 33 38–103 (2)	–	2 ± 0.6 1–3 [b] (3)
			West (15)	5 (1)		100 (1)		–		1 (1)	
	F (34)	622 ± 7.9 533–709	East (14)	14 (2)		50 (1)		–		–	
			West (20)	35 (7)		43 (3)		71 ± 33 (2)		3 ± 0.8 (2)	
shorthead redhorse (39)	M (59)	392 ± 3.0 343-436	East (29)	38 (11)	51 (61)	55 (6)	69[b] (42)	191 ± 31 (10)	190 ± 11 69–409 (52)	119 ± 22 (5)	51 ± 11 0.3–217[b] (35)
			West (30)	47(14)		64 (9)		201 ± 19 (13)		47 ± 22 (8)	
	F (61)	432 ± 3.6 368–500	East (31)	61 (19)		68 (13)		176 ± 19 (16)		20 ± 12 (10)	
			West (30)	57 (17)		82 (14)		193 ± 23 (13)		52 ± 22 (12)	

[a] Fishway is located on the west bank

[b] Passage efficiency data and passage duration (h) as reported in Hatry et al. 2014

[c] Numbers in parentheses are the number of individuals for which entrance delay and passage duration could be determined

Table 4 Results of two-way ANOVA performed for two passage variables, entrance delay and passage duration, with sex, bank release, and sex x bank as effects for three redhorse species at the Vianney-Legendre fishway in the spring of 2012

Species	Passage variable	Sex			Release bank			Sex × Release bank		
		F	df	p	F	df	p	F	df	p
silver redhorse	Entrance delay	4.70	1, 41	*0.036*	0.30	1, 41	0.30	0.38	1, 41	*0.54*
	Passage duration	1.10	1, 34	*0.30*	0.60	1, 34	0.44	0.52	1, 34	*0.47*
shorthead redhorse	Entrance delay	0.25	1, 48	*0.62*	0.37	1, 48	0.55	0.016	1, 48	*0.90*
	Passage duration	5.72	1, 31	*0.023*	0.18	1, 31	0.68	9.82	1, 31	*0.004*

Discussion

In this study we set out to compare the behaviour of three redhorse species during their spawning migration using a combination of radio and PIT telemetry. Research focused on behaviour downstream of a vertical slot fishway as well as behaviour and passage of fish through the fishway. Few studies have used a multispecies approach to study the effectiveness of fishways (Roscoe and Hinch 2010) and no studies that we are aware of have employed both radio and PIT telemetry to study upstream passage behaviour (both downstream of and inside a fishway) by multiple species in a single season (Bunt et al. 2012). Thiem et al. (2013) used PIT telemetry to examine multispecies passage success at the Vianney-Legendre fishway which included silver, river, and shorthead redhorse. However, this study was not designed to enable calculation of attraction efficiency as all fish were released within the fishway. The results from Thiem et al. (2013) suggested that passage efficiency of the three redhorse species was low (ranging between 30 and 45 % for the three species). A previous study of fish use of the Vianney-Legendre fishway in 2005 (Fleury and Desrochers 2006) identified a combined passage efficiency of 85.9 % for six catostomids (comprising copper, greater, river, shorthead and silver redhorse, and white sucker (*Catostomus commersoni*), and passage efficiency was estimated to be 55.6 % for river redhorse. However, like the Thiem et al. study (2013) attraction efficiency could not be calculated in the Fleury and Desrochers (2006) study as all the fish were released within the fishway. Fleury and Desrochers' (2006) preliminary results are similar to those obtained in the current study.

Table 5 Results of logistic regression analysis examining the probability of detection and passage at the Vianney-Legendre fishway in the spring of 2012 for three redhorse species

Variable	Detection			Passage		
	silver redhorse	river redhorse	shorthead redhorse	silver redhorse	river redhorse	shorthead redhorse
Constant: β ± SE	−1.48 ± 3.27	−8.22 ± 6.71	−3.99 ± 3.56	0.61 ± 3.26	−7.44 ± 7.87	−7.16 ± 3.83
p	0.65	0.22	0.26	0.85	0.35	0.062
Length (mm): β ± SE	0.0081 ± 0.0055	0.012 ± 0.010	0.011 ± 0.0075	0.0039 ± 0.0054	0.0082 ± 0.012	0.016 ± 0.0080
p	0.14	0.25	0.16	0.48	0.49	0.050
Odds ratio, interval	1.01, 1.00-1.02	1.01, 0.99–1.03	1.01, 1.00–1.03	1.00, 0.99–1.01	1.01, 0.99–1.03	1.01, 1.00–1.03
Sex (F or M): β ± SE	−0.81 ± 0.44	−1.08 ± 0.91	−0.26 ± 0.47	−0.91 ± 0.44	−0.48 ± 0.99	−0.25 ± 0.50
p	0.065	0.24	0.58	0.040	0.63	0.62
Odds ratio, interval	0.45, 0.19–10.05	0.34, 0.057–2.02	0.77, 0.31–1.94	0.40, 0.17–0.96	0.62, 0.088–4.31	0.78, 0.29–2.08
Release bank: β ± SE	−1.15 ± 0.40	0.33 ± 0.81	0.052 ± 0.37	−1.05 ± 0.40	0.47 ± 0.99	0.30 ± 0.40
p	0.004	0.69	0.89	0.008	0.63	0.46
Odds ratio, interval	0.32, 0.14–0.70	1.39, 0.28–6.8	1.05, 0.51–2.19	0.35, 0.16–0.76	1.59, 0.25–10.23	1.35, 0.62–2.94
Likelihood ratio p	<0.001	0.125	0.143	0.001	0.599	0.024

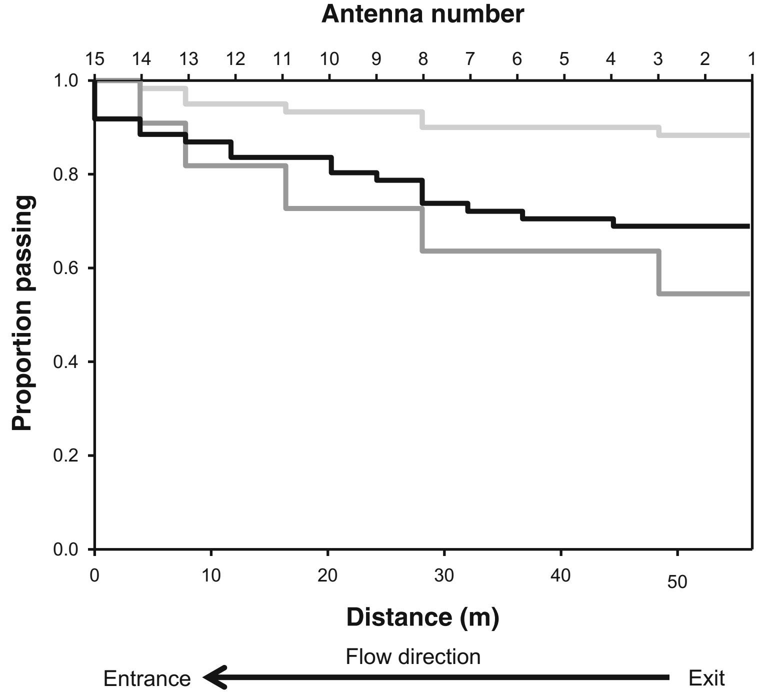

Fig. 4 Proportional maximum upstream distance achieved by three redhorse species attempting to ascend the Vianney-Legendre fishway in the spring of 2012, determined using LogRank survival analysis. Flow in this figure is moving from right to left. The *coloured lines* represent passage by different species (— silver redhorse; — river redhorse; — shorthead redhorse)

Tag attachment of all three species in this study occurred at the peak of their respective spawning migrations, which was determined by the abundance of fish captured in the fish trap at the top of the fishway. The timing of the spawning migrations of the three species experienced in 2012 is consistent with the findings of Reid (2006) for the Grand, and Trent rivers in Ontario and the Muskegan River in Michigan. Reid (2006) identified that silver and shorthead redhorse typically began their spawning migrations in early to mid-May when water temperatures were between 10 and 14 °C and that river redhorse began their spawning migration in late May with water temperatures ranging from 16 to 20 °C. The same sequence is suggested by the progression of the gonadosomatic index of five redhorse species present at a large spawning area in the Chambly rapids of the Richelieu River about 60 km upstream St. Ours dam, during the spring period

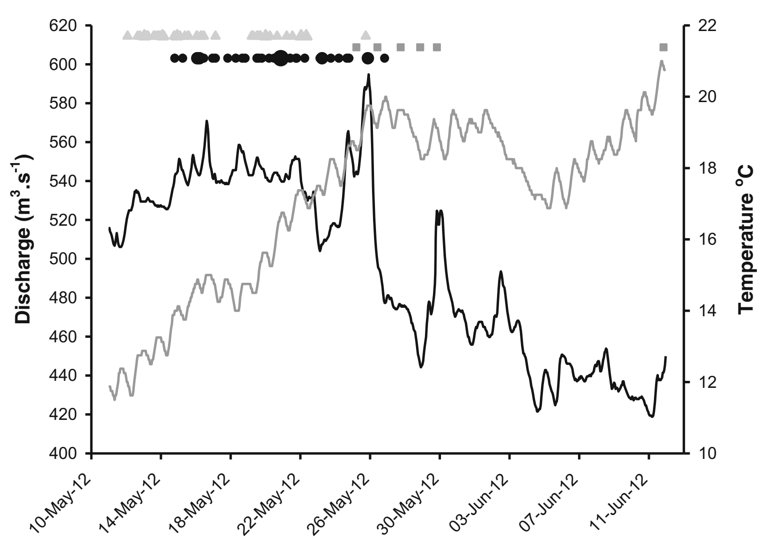

Fig. 5 River discharge ($m^3.s^{-1}$) and water temperature (°C) for the Richelieu River during passage events by three redhorse species at the Vianney-Legendre fishway in the spring of 2012. *Larger symbols* indicate passage by more than 1 individual. Symbols represent; —Temperature (°C), — Discharge $m^3.s^{-1}$, ▲ silver redhorse, ■ river redhorse, ● shorthead redhorse

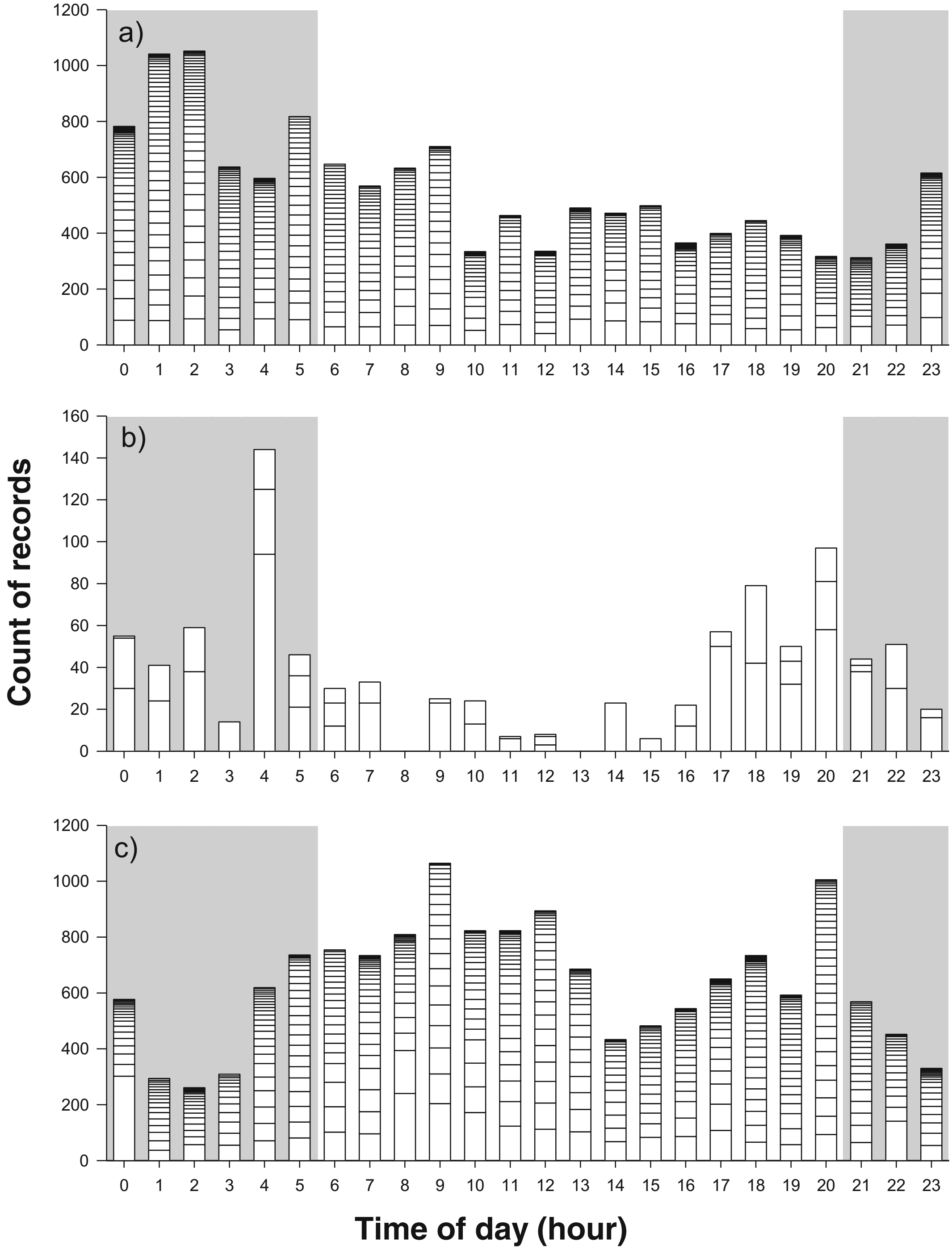

Fig. 6 Diel fishway use by **a** silver redhorse, **b** river redhorse, and **c** shorthead redhorse in the Vianney-Legendre fishway in the spring of 2012. . Stacked bars show the contributions of individuals and data is pooled over the entire study period. *Grey shading* indicated approximate night periods and no shading indicates approximate day periods based on local sunrise/sunset conditions for middle of the study period (~05:30 and 20:30)

(Mongeau and Dumont 1992). Sizes for sexually mature silver, river, and shorthead redhorse from the current study were also comparable with the sizes reported by Reid (2006) and similar to the current study, Reid (2006) determined that female of each species were all larger than males. Passage events for silver and shorthead redhorse all took place during a period of elevated discharge and rising water temperatures in the middle of May. River redhorse passed the fishway in lower numbers up until May 30 with only one additional fish passing the fishway after this date. This information is consistent with knowledge of other catostomid migrations which typically take place during times of elevated river discharge and rising water temperatures (*see* Lucas and Baras 2001) associated with spring freshet conditions and is thought to be advantageous to passage past natural barriers.

Based on the paucity of data garnered from fish that were double-tagged with radio and PIT tags relative to the large amount of data returned from those individuals carrying only the PIT tag, it appears that there was a tagging effect experienced by redhorse after radio tag attachment. Other reasons for low radio tag detection could include tag failures or poor performance of the telemetry array. However, that conclusion is not supported by data gathered from the PIT telemetry array which only detected one double-tagged fish inside the fishway – the same individual recorded on the radio receiver. Extensive testing of the radio telemetry array and occasional manual tracking confirmed that the array was indeed functioning properly. Fish that only received PIT tags were otherwise handled in the exact same manner as those that were double tagged (i.e., radio and PIT tags). Greater redhorse in the Grand River, ON were tagged externally in a previous study using a similar approach to what we used here (*see* Bunt and Cooke 2001). In that study fish were tagged on spawning grounds downstream of a barrier and tracked to identify post-spawn habitat use and movements. Bunt and Cooke (2001) noted that greater redhorse moved downstream immediately after tagging which was assumed to be their natural post-spawning behaviour. Additionally, externally tagged white suckers were successfully quantified passing the Mannheim weir on the Grand River, Ontario (Bunt et al. 1999). The fish tagged in our study were mature and ripe so it is unlikely that the reason for fallback was due to immediate spawning post-release and subsequent fallback as a natural process To our knowledge there are no studies that evaluate the effects of different telemetry tagging techniques on redhorse. We conclude that the presence of the tag (which was placed in an area commonly used for external tagging and was designed to be small and weigh <2 % of the body weight of the fish; Bridger and Booth 2003) or the tagging procedure itself was sufficient to alter their behaviour relative to fish that were only tagged with PIT tags. Anecdotally (Cooke, unpublished data), we are aware of several failed telemetry studies on redhorse although a commonality in those studies was the use of anesthesia and none of them were published. However, there are also some successful examples of anesthesia and tag attachment in redhorse (e.g. Grabowski and Isely 2006; Grabowski and Jennings 2009; Banish et al. 2009) emphasizing that there appears to be much interspecific variation in sensitivity to handling and tagging. As such, the reasoning for why the telemetry component failed is unclear, likely complex, and may warrant further research. Regardless, it is important to report such experiences to inform future telemetry studies (Thiem et al. 2011a).

River redhorse were not included in the analyses related to entrance delay and passage duration because sample sizes were too low. Hatry et al. (2014) suggests that “the low numbers of river redhorse passed in 2012 may be explained by the installation of a gill net (5-in. mesh size) across the entrance to the fishway on May 28, 2012, for a separate attempt to capture broodstock for the critically endangered copper redhorse (*Moxostoma hubbsi*). The gill net was in place from approximately 9:00 to 17:30 for 2 weeks following its installation, and several river redhorse were captured in this net.” Silver redhorse had significantly lower entrance delay and passage duration times than shorthead redhorse. Similar trends regarding passage duration for silver and shorthead redhorse were identified in Thiem et al. (2013); however, sample sizes did not allow for robust statistical analysis. Within species, female silver redhorse had lower entrance delay times than males while male shorthead redhorse had shorter passage duration times than females. These differences may be explained by the different bioenergetic costs of migration experienced by fish of different sizes; smaller fish must expend more energy to move at the same speed as larger fish but to save energy can move at slower speeds (Lucas and Baras 2001). This may explain why female silver redhorse entrance delay times and female shorthead redhorse passage duration times were shorter than their male counterparts as for both species females were significantly larger than males. There may also be differences in sex-specific reproductive hormone titers which could influence motivation; however, we are unaware of any endocrine studies on redhorse.

Passage efficiencies for silver, river, and shorthead redhorse were higher than passage efficiencies for the same three species at the same fishway reported by Thiem et al. (2013) (30, 31, 46 %, respectively) 2 years earlier. Thiem et al. (2013) could not measure attraction efficiency but a study evaluating modified vertical slot fishways conducted on white suckers (a confamilial) in the Big Carp River, Ontario, reported attraction efficiencies of between 73 and 84 % over a three season study period (Pratt et al. 2009). While attraction efficiency was lower at the Vianney-Legendre fishway for silver and shorthead redhorse (~50 %) tagged fish from this study had already succeeded in locating the fishway entrance at least once and this may influence their behaviour. We had anticipated that there would be higher attraction efficiency for fish released on the same bank (west) as the fishway because of the shorter distances involved with travelling to the fishway entrance. Additionally, fish released on the west bank needed only to swim upstream along the bank to find the fishway which we assumed would be easier for individuals, rather than swimming across the river and locating the fishway entrance. However, for silver redhorse there was a higher probability of being detected in the fishway if fish were released on the opposite bank (east) to the fishway. A possible explanation for this is the nature of the modulated attraction flow patterns coming out of the fishway; flow is designed to pass out towards the middle of the river rather than down the west bank (Fleury and Desrochers 2006). During the current study attraction flows via the pass-through chamber beneath the fishway augment fishway discharge from ~1 m^3/s by an additional 6.5 m^3/s creating the flow patterns observed. Detailed hydraulic studies conducted simultaneously with detailed tracking studies would be needed to further elucidate the pattern we observed. Passage success was more probable in larger shorthead redhorse than smaller ones, however, this trend was not observed for silver redhorse. This hypothesis is possible that because shorthead redhorse are in general of considerably smaller size than silver and river redhorse that the relationship between size and swimming capacity plays a greater role in their ability to pass the fishway (Lucas and Baras 2001).

The majority of passage failures amongst all three redhorse species occurred at or before antenna 7 located just downstream from the second turning basin in the fishway. As an explanation for the high number of failures around antenna 7 it has been suggested that since the fishway turns back on itself once in this section (the fish are swimming the “wrong” way, (they are facing downstream) that this may disorient them somehow. This type of passage behaviour is somewhat different to that shown by the same three species but similar to passage failure patterns shown by other catostomids (white and longnose suckers, *Catostomus commersoni* and *C. catostomus* respectively) in the same fishway (Thiem et al. 2011b, 2013). Silver redhorse had lower failure rates than both river and shorthead redhorse suggests that they have either greater physiological or swimming capacity (e.g. ability to recover from exercise, greater aerobic capacity) or have sensory or behavioural attributes, compared to the other species, allowing them to optimize route selection through the fishway. A comparative physiological study of the same three species identified that silver redhorse performed the worst out of the three species, suggesting the poorest physiological capacity (Hatry et al. 2014) and perhaps the presence of heightened sensory or behavioural attributes necessary for successful fishway ascent. Of note is that all of the tagged fish had previously ascended the fishway so the tagged individuals all had the ability to do so prior to tagging. A study by Hinch and Bratty (2000) at a fishway on sockeye salmon (*Oncorhynchus nerka*) showed that fish which successfully passed through the fishway had lower average, minimum and maximum, swim speeds than fish which failed to pass the fishway suggesting that choosing the right path through an area of varying flow is an important factor in passage success.

Activity patterns in the fishway were quite different among the three redhorse species. The activity patterns for shorthead redhorse and river redhorse are generally crepuscular. We observed that silver redhorse activity was greatest around midnight and then generally decreased throughout the rest of the 24 h period. Previous studies have reported daytime, afternoon and evening activity peaks for other catostomids (Schwalme et al. 1985; Bunt et al. 1999) and based on our work there appears to be extensive variation in diel passage activity even among congeneric species.

Conclusion

This study provided new information regarding the passage of silver, river, and shorthead at the

Vianney-Legendre fishway. Contrary to a previous behaviour study on these three species, our work revealed attraction efficiencies for silver, river and shorthead redhorse as well as passage efficiencies for silver and shorthead redhorse that were much higher than previously reported at the Vianney-Legendre fishway (Thiem et al. 2013). However, our results were similar to those observed by Fleury and Desrochers (2006) in a preliminary study during the initial operation of the fishway. Fish passage metrics such as entrance delay, passage duration, attraction efficiency, passage efficiency, and failure locations are usually reported incompletely from fishway evaluations (Roscoe and Hinch 2010; Bunt et al. 2012) but are useful for fisheries managers as spawning failures stemming from inadequate fish passage at dams can have severe consequences on migratory fish populations (Wilcox and Murphy 1985) and ecosystems in general (Holmlund and Hammer 1999). Although the radio telemetry component of the study failed, it does point to the need for tag validation studies when conducting tracking studies of redhorse given their apparent sensitivity to a technique that is generally regarded as minimally invasive (Bridger and Booth 2003). Moreover, it demonstrates how different tagging approaches have the potential to influence passage and attraction efficiency estimates (Cooke and Hinch 2013). The immense interspecific variation in behaviour and passage of three congenerics emphasizes the challenges faced by engineers in attempting to design fishways that pass entire diverse fish communities.

Acknowledgments Guillaume Lemieux, Florent Archambault, Sylvain Desloges, Keith Stamplecoskie, Robert Lennox, Lauren Stoot and Nicholas Burnett provided expert field assistance. Parks Canada (André Brunelle, Jean Larochelle and Guy Noël) provided site access and logistic support. Project funding was provided by an NSERC (National Sciences and Engineering Research Council of Canada) HydroNet Strategic Network Grant, NSERC RTI Grant, Natural Resources Canada, Fisheries and Oceans Canada, and the Canadian Wildlife Federation. Significant financial and in kind contributions were also provided by the Quebec MNRF. Cooke was supported by the Canada Research Chair program, and Hatry was supported by an NSERC-CGSM (Alexander Graham Bell) scholarship, an Ontario graduate scholarship (OGS) as well as additional graduate scholarships from Carleton University. This project was conducted in accordance with the guidelines of the Canadian Council on Animal Care administered by the Carleton University Animal Care Committee (B10-12). Comments from peer review improved this manuscript.

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