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Biological effectiveness of an inexpensive nature-like fishway for passage of warmwater fish in a small Ontario stream

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Abstract – Few studies have been conducted to evaluate the effectiveness of nature-like fishways, particularly in low gradient warmwater streams with diverse fish communities. We evaluated a nature-like fishway that was installed to facilitate upstream passage at a low head dam on Indian Creek near Spencerville, Ontario, Canada. A passive integrated transponder (PIT) array was used to quantify attraction and passage efficiency for 391 PIT tagged warmwater fish, represented by seven species. Attraction efficiency for the three most common species, common shiner (*Luxilus cornutus*), creek chub (*Semotilus atromaculatus*) and white sucker (*Catostomus commersonii*), was 63.3%, 83.7% and 65.6%, respectively, and passage efficiencies were 5.1%, 38.4% and 25%, respectively. Creek chub were able to locate the fishway in less time than white sucker and common shiner; however, took longer to successfully pass. Manipulation of creek chub release locations was used to separate issues of attraction and passage and revealed that passage efficiency was highest (76.2%) for those released within the fishway and intermediate for those released at the entrance (42.1%). This multispecies fishway improved stream connectivity, but additional work is needed to fine tune its configuration. Similar projects that engage stakeholders in nature-like fishway construction are a promising approach for the thousands of small dams that occur on low gradient streams around the globe, but those studies should incorporate a biological evaluation to ensure that attraction and passage efficiency are optimised.

Key words: fishway; PIT; fish passage; migration

Introduction

The threats facing rivers and their associated biodiversity can be broadly classified as habitat degradation, water pollution, invasive species, barriers (dams, weirs, etc.), flow modification and overexploitation (Malmqvist & Rundle 2002; Dudgeon et al. 2006). Broad scale environmental changes such as nitrogen deposition, warming and shifts in precipitation and runoff patterns are further superimposed upon all of those threat categories (Vörösmarty et al. 2010). The underlying driver for all of these threats is human activity. Collectively, changes in environmental conditions, habitat or ability to access habitats either laterally (e.g., floodplain pools) or longitudinally (e.g., upstream/downstream migrations) due to reductions in connectivity can have devastating consequences on fish populations (Richter et al. 1997) and the ecological services that they provide (Holmlund & Hammer 1999). Given that longitudinal connectivity is critical for most fluvial fish (Rosenberg et al. 2000), there have been many efforts devoted to developing fishway structures to facilitate passage of fish at barriers (Lucas & Baras 2001).

Early fishways were heavily engineered and typically constructed from concrete and metal, and have

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become increasingly sophisticated in their design (Lucas & Baras 2001; Roscoe & Hinch 2010; Makrakis et al. 2011). Of late, nature-like fishways are becoming a popular fishway design, especially for low head dams. These fishways adopt a design philosophy known as physiomimesis, which is ecologically minded and aims to mimic natural river systems (Wildman et al. 2003). The majority of these designs are aesthetically pleasing and are also relatively inexpensive to construct, reasonable to maintain and are suitable for a variety of species. Local geology and height of the barrier tend to dictate the level of complexity and expense, with extensive land acquisitions typically needed for higher barriers. Compared to larger engineered structures which are typically designed for one to two fish species, nature-like fishways are intended to pass entire fish communities. This type of fishway design has been implemented across Europe, Australia and Japan (Wildman et al. 2003). Nature-like fishways are also becoming recognised as an alternative means of fish passage in Canada and the United States.

Although fishways are frequently installed at barriers, there is a general assumption that they work and they are rarely the subject of biological assessment (Roscoe & Hinch 2010). When assessments do occur, they are often based solely on documenting fish that are captured in traps at the top of the fishway (Roscoe & Hinch 2010). However, that approach fails to identify how many fish were unable to find the entrance to the fishway (i.e., attraction efficiency) and how many that did enter, but failed to fully ascend the fishway (i.e., passage efficiency). Both of these metrics are required to fully assess the biological effectiveness of a fishway at passing target species (Bunt et al. 2012; Noonan et al. 2012). Furthermore, there have been few biological assessments that address multiple species in North America as most are focused on coldwater fish such as salmonids (Roscoe & Hinch 2010). Moreover, few studies examine problems on small streams, despite the fact that nature-like fishways have the potential to restore passage to the many thousands of small streams blocked by low head dams. Rosenberg et al. (2000) estimated that the number of small dams in North America outweigh the number of large dams 20 to 1, with an estimated 800,000 small dams/barriers around the world.

Here, we present a biological evaluation of the Indian Creek nature-like fishway, located in south-eastern Ontario, Canada. The fishway was constructed in 2006 using volunteer labour under the direction of the South Nation River Conservation Authority. The objective of the project was to facilitate fish passage around a small dam (11.1 m wide, 1.45 m high) that was originally built for sawmill operation (Mancini & Langlois-Anderson 2006). Because of the emphasis on engaging volunteers in fishway construction, the fishway cost approximately $15,000 to construct (Mancini & Langlois-Anderson 2006), whereas larger engineered structures can cost upwards of millions of dollars. Using the Indian Creek nature-like fishway as a model, we conducted a biological evaluation to determine if such “low technology” and inexpensive fish passage designs could serve as a tool to restore passage at the thousands of barriers that exist on small streams around the world (Bunt et al. 2012). Our specific objective was to determine attraction and passage efficiency for a warmwater fish assemblage during the spring spawning migration period. Given that most of the species that reside in the system are sufficiently small and of little direct economic value (i.e., not gamefish), they have not been the subject of previous electronic tagging studies to determine movement in a reliable manner. As such, it is not possible to derive reasonable species-specific hypotheses or predictions. However, all of the species in the system are spring spawners and are known to be rheotactic (Scott & Crossman 1973; Bunt et al. 2001). In Indian Creek, suitable spawning habitat for most species can be found throughout the system, but there is more fluvial habitat upstream of the dam than downstream. Moreover, the dam itself generates a lentic area that is <100 m in longitudinal length such that fish would not have to travel far from the dam to reach lotic habitats favoured by most of the species that reside in the system.

Materials and methods

Study site

Indian Creek (44°48′22.45″N, 75°36′12.89″W) is a tributary of the South Nation River and is located in south-eastern Ontario, Canada. The Indian Creek watershed drains an area of 41 km^2, contributes 16.7% of the flow to the Spencerville subwatershed of the South Nation River, and had a mean annual daily discharge of 3.06 m^3·s^{-1} in 2011 (Mancini & Langlois-Anderson 2006; Environment Canada 2012). A small dam (11.1 m wide and 1.45 m high) is located approximately 3 km upstream from the confluence between Indian Creek and the South Nation River and effectively prevents upstream passage of the entire fish community to approximately 85% of the Indian Creek. The Indian Creek fishway was constructed in 2006 (Fig. 1) and various species have been known to use the fishway (based on electrofishing surveys) including brown bullhead (*Ameiurus nebulosus*), white sucker and creek chub (Langlois-Anderson, unpublished data). The fishway

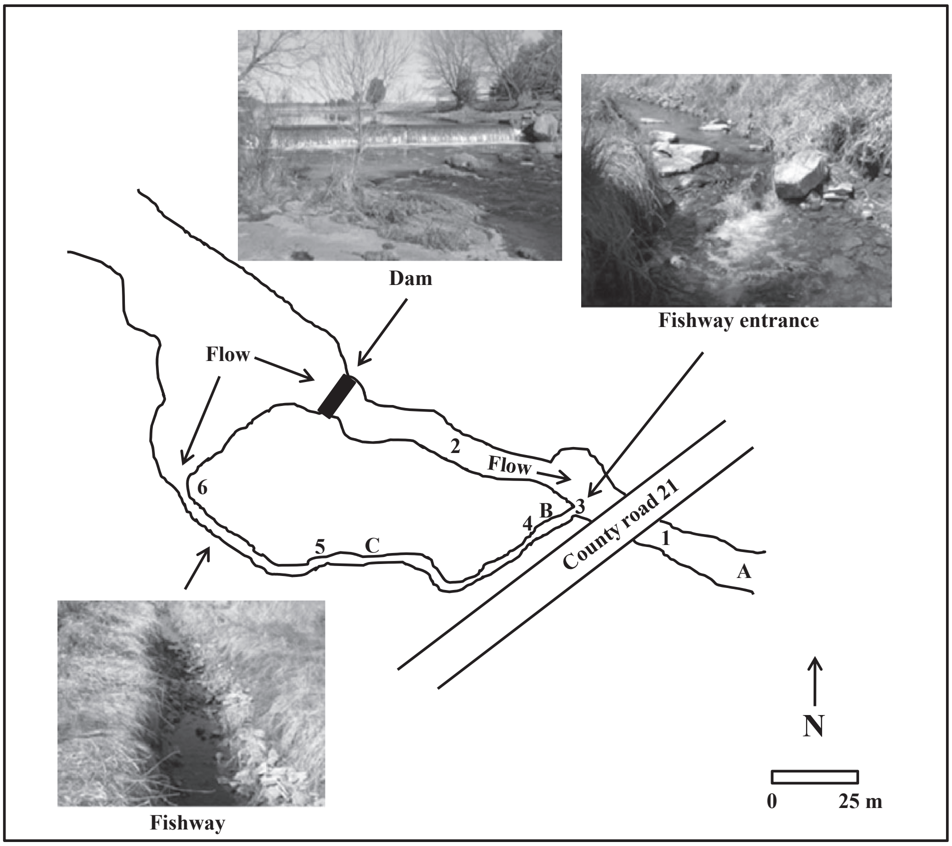

Fig. 1. Indian Creek and nature-like fishway schematic, south-eastern Ontario, Canada. Numbers (1 to 6) indicate PIT antenna locations used to determine fish movements and letters (A, B and C) are representative of the different fish release sites (see Methods).

entrance is located approximately 70 m downstream from the dam face and the width of the entrance is 1.1 m at benthos. The fishway is 116 m long and consists of pools and riffles with an overall slope of 1.25% from the top of the notch to the point where the fishway meets Indian Creek. There are seven pools (each 16.6 m long), and each one is 0.2 m higher than the previous (Mancini & Langlois-Anderson 2006). The riffles were designed to create a water velocity of 0.8 m·s^{-1}, and were built using rocks 10–20 cm in diameter (Mancini & Langlois-Anderson 2006). The fishway exit is located approximately 50 m from the dam.

Experimental design

We used a passive integrated transponder (PIT) antenna array consisting of six antennas to quantify fishway attraction and passage efficiency at this site (Fig. 1). This method is an effective, inexpensive method for tracking freshwater fish (Castro-Santos et al. 1996; Gibbons & Andrews 2004) and facilitates continuous, remote monitoring of movements in streams. The PIT antenna array was installed from 1 to 4 April 2011. Pass over antennas were installed at the fishway entrance (one antenna) and within the fishway (three antennas; 8, 71 and 116 m from the fishway entrance, respectively) and consisted of 12 awg THHN wire connected to diamond mesh polyethylene fencing material held in place on the stream floor using cobble. Each pass over antenna was connected to a remote tuner board and connected to a multi-antenna data logger (Oregon RFID, Portland, OR, USA) via lengths of twinaxial cable. Two pass through antennas were also installed and these covered the entire stream width and were located approximately 70 m downstream of the fishway entrance, and upstream of the fishway entrance, but approximately 35 m downstream of the dam (antennas 1 and 2; Fig. 1). Antenna capacitor units were tuned to maximise detection range (approximately 0.5 m) following installation. As antennas were connected in groups of three to multi-antenna data loggers, each data logger scanned sequentially through all three antennas at a rate of approximately 3.3 Hz per antenna. Multi-antenna data loggers were powered by 12 V direct current step down transformers running on 120 V alternating current outlets. Weekly maintenance at the site involved data logger downloads, antenna maintenance, time synchronisation of data loggers and retuning of antennas as required.

Fish were captured as encountered between 1 April and 13 May 2011 via both active backpack electrofishing and passive fyke netting. Sampling and tagging encompassed the period during which the fish in Indian Creek (i.e., warmwater assemblage) were expected to be engaged in upstream spawning migration based on previous work on similar species in Ontario at a Denil fishway in a comparatively larger river (Bunt et al. 2001). Electrofishing was conducted immediately downstream of the barrier and extended to approximately 500 m downstream. A fyke net (0.635-cm stretched mesh) captured upstream moving fish approximately 100 m downstream of the barrier. The net was set at 45° to the stream and was set for approximately 20 h, on five separate occasions between 5 May and 12 May. Captured fish were transferred to a holding cooler, where they were measured, tagged and received a small caudal fin clip to rapidly confirm tagging in case of later recapture. Uniquely coded PIT tags (22 × 3.9 mm HDX, Texas Instruments, Dallas, TX, USA) were inserted into the coelomic cavity using a 6-gauge injector (Baras et al. 1999). Care was taken to minimise air exposure and anaesthetics were not used. All tagged fish were held for a short period of time (<30 min) in insulated containers with aerated water to ensure recovery and were subsequently transferred back into the creek at a common release point approximately 100 m downstream of the dam (Fig. 1; release site A). The majority of fish were captured and tagged from 6 to 12 May when releases comprised 324 individuals pooled over five sampling occasions and peaked on 10 May with the capture of 136 individuals. Outside of this period, the number of fish released on any given day did not exceed 25 individuals.

Due to local abundance, we varied release locations of an additional group of creek chub to separate issues of attraction from passage efficiency and to examine the potential problem imposed by a particularly challenging section in the lower reaches of the fishway. This section consists of a small drop in the fishway due to underlying shallow bedrock, which in turn causes a section of increased slope and faster water velocity, which we considered could potentially impede passage. Forty additional creek chub captured in the fyke net on 11 May ($n = 20$) and 12 May ($n = 20$) were released at sites B and C (approximately 6 m and 60 m into the fishway, respectively; Fig. 1). Release site B fish ($n = 19$, 175.5 ± 8.2 mm·TL) were released just inside the fishway between antenna 3 and antenna 4 (downstream of the challenging section). Release site C fish ($n = 21$, 165.4 ± 4.4 mm·TL) were released between antenna 4 and antenna 5, upstream of the shallow bedrock area. There was no significant size difference (TL) among the two creek chub experimental release groups ($t = 1.117$, df = 38, $P = 0.271$).

Hourly water temperature data were recorded from instream thermal loggers (DS1921Z iButton, Maxim Integrated Products, San Jose, CA, USA) for the duration of the study. The corrected discharge data for Spencerville were provided by the Water Office of Environment Canada on 22 November 2011 (Environment Canada 2011). Hourly discharge values for Indian Creek were estimated by multiplying total discharge by 0.167, the relative contribution of the Indian Creek catchment area (41 km^2) to the total catchment area (246 km^2) at the gauging site (Mancini & Langlois-Anderson 2006).

Data analysis

Movements of the fish were recreated by examining date and time records for individual fish and antenna locations throughout the study. Attraction efficiency was calculated as the proportion of fish detected on the fishway entrance antenna (antenna 3) compared to the proportion of tagged individuals detected on antenna 1 and 2. Passage efficiency represented the proportion of fish successfully ascending the fishway compared to the proportion entering the fishway. As 149 of 391 tagged fish were not detected by any antenna, the fate of 38.1% of tagged individuals is unknown in this study. Categorical data (detected, not detected) were evaluated using logistic regression analysis to determine if fish length, capture method (backpack electrofishing or fyke net) or capture/release date had an effect on subsequent detection of PIT tagged individuals below the dam or at the fishway. This analysis was conducted using the four most abundant species (common shiner, creek chub, rock bass *Ambloplites rupestris* and white sucker). Any further analysis was only conducted on detected fish. Individuals were deemed to have been successfully attracted to the fishway if they were detected at antenna 3. Successful passage was defined as detection at antenna 6.

As only three (common shiner, creek chub and white sucker) of the seven tagged species had adequate sample sizes following detection (i.e., >50 individuals), detailed analyses focussed on these species. Time to attraction was calculated as the time it took to reach antenna 3 from first detection. Nine common shiner, seven creek chub and one white sucker were first detected at the attraction antenna (antenna 3) possibly due to code collisions resulting from simultaneous movements through antenna 1 and were therefore removed from the calculation of attraction time. Passage duration is defined as the time it took the fish to move from antenna 4 to antenna 6, effectively the length of the fishway. Total passage delay is the time it took the fish to move from first detection to antenna 6. For the creek chub experimental release, passage efficiency was calculated separately for each of the release sites and attraction efficiency was excluded as the release sites (B and C) were already within the fishway. Because fish from release site C were released near the middle of the fishway, their passage duration is not reported.

Where sample sizes permitted, statistical tests were only performed on the three most abundant species. Differences in mean length of fish attracted to the fishway were compared with those not attracted using independent sample *t*-tests. Likewise, differences in the mean length of fish passing the fishway were compared with those attracted, but not passed using independent sample *t*-tests. We used a Pearson product-moment correlation to test for an association between passage duration and total length of creek chub, as this was the only species to ascend the fishway in adequate numbers. We tested for a difference in the mean time to attraction at the fishway among species using a one-way analysis of variance (ANOVA), with a Tukey's HSD test used to ascertain homogenous groups following a significant result. Where appropriate, data were first tested for the assumptions of normality and homogeneity of variance following the methods outlined by Grafen & Hails (2002), and transformed and reassessed if necessary. In addition, the assumption of multi-colinearity was assessed for the logistic regression analysis. All statistical analyses were deemed significant at $P < 0.05$ and conducted using SPSS statistical software (Version 18; SPSS Inc., Chicago, IL, USA). All data are presented as mean ± standard error (SE) unless otherwise stated.

Results

Of the seven species tagged during this study, all were detected at antenna 1 (Table 1). Attraction efficiency was variable among species and ranged from 58.3% (rock bass) to 100% (brown bullhead and pumpkinseed *Lepomis gibbosus*) (Table 1). Six of the seven species attracted to the fishway were able to successfully ascend it, with passage efficiencies ranging from 5.1% (common shiner) to 57.1% (brown bullhead) (Table 1). Attraction efficiencies for the three most commonly occurring species were 63.3% (common shiner), 83.7% (creek chub) and 65.6% (white sucker). Passage efficiency for these same three species was 5.1%, 38.4% and 25%, respectively (Table 1). In addition, four creek chub passed the fishway more than once (i.e., they repeatedly traversed the fishway) by exiting over the dam face 24–72 h after first ascension, locating the entrance once more and reascending the fishway. The probability of detecting common shiner, rock bass and white sucker was unrelated to length, capture method or date of capture (Table 2). In contrast, there was a higher probability of detecting larger creek chub following tagging, and a lower probability of detecting individuals captured later in the study (Table 2).

Common shiner and white sucker were able to pass the fishway relatively quickly (1.2 ± 0.2 h and 4.3 ± 2.1 h, respectively); however, time to attraction was typically prolonged (116.2 ± 14.9 h and 66.3 ± 24.0 h, respectively; Table 3). Creek chub time to attraction was 32.6 ± 7.7 h, with passage through the fishway typically taking 19.4 ± 12.8 h (Table 3) and there was no correlation between creek chub TL (log transformed) and passage duration (Pearson correlation: $r_p = 0.184$, $P = 0.304$) for release site A. There was a significant difference among species in terms of time to attraction (Log-transformed) (one-way ANOVA: $F_{2,135} = 13.144$, $P < 0.001$). *Post hoc* comparisons (Tukey's HSD) revealed that creek chub took significantly less time to locate the fishway entrance (attraction time) in comparison with common shiner, with white sucker attraction time not significantly different

Table 1. Fish species tagged for evaluation of the Indian Creek nature-like fishway. Fishway performance was evaluated using an automated PIT logging system. Numbers in parentheses indicate sample size (*n*).

Species	TL (mm)	Number tagged	Number detected	Attraction efficiency (%)	Passage efficiency (%)
Brown bullhead *Ameiurus nebulosus*	166.9 ± 7.5	9	7	100.0 (7)	57.1 (4)
Common shiner *Luxilus cornutus*	142.9 ± 0.9	145	97	63.9 (62)	5.1 (5)
Creek chub *Semotilus atromaculatus*	170.3 ± 2.6	121	86	83.7 (72)	38.4 (33)
Pearl dace *Margariscus margarita*	118.0 ± 2.0	4	4	75.0 (3)	25.0 (1)
Pumpkinseed *Lepomis gibbosus*	129.5 ± 6.1	6	4	100.0 (4)	25.0 (1)
Rock bass *Ambloplites rupestris*	157.6 ± 2.7	41	12	58.3 (7)	0.0
White sucker *Catostomus commersonii*	178.9 ± 4.2	65	32	65.6 (21)	25.0 (8)

Table 2. Results of logistic regression analysis assessing variables affecting detection of upstream movements following insertion of PIT tags into four species of fish released downstream of the Indian Creek nature-like fishway.

	Species			
Variable	Common shiner	Creek chub	Rock bass	White sucker
Constant: β ± SE	6.43 ± 10.47	12.19 ± 7.13	24.42 ± 21.43	3.05 ± 2.8
P	0.54	0.09	0.25	0.27
Length (TL mm): β ± SE	0.02 ± 0.02	0.02 ± 0.01	−0.01 ± 0.02	−0.01 ± 0.01
P	0.17	0.02	0.78	0.25
Odds ratio, interval	1.03, 0.99–1.06	1.02, 1.00–1.04	0.99, 0.95–1.04	0.99, 0.98–1.01
Capture method: β ± SE	−0.13 ± 1.51	0.37 ± 0.51	4.80 ± 5.57	−0.25 ± 0.59
P	0.93	0.47	0.39	0.68
Odds ratio, interval	0.88, 0.05–16.80	1.44, 0.53–3.92	121.53, 0.00–6.66E + 06	0.78, 0.26–2.49
Capture date: β ± SE	−0.07 ± 0.08	−0.12 ± 0.06	−0.23 ± 0.19	−0.01 ± 0.02
P	0.39	0.04	0.24	0.55
Odds ratio, interval	0.93, 0.79–1.10	0.89, 0.80–0.99	0.80, 0.55–1.17	0.99, 0.95–1.03
Model fit	χ^2 (1) = 4.21, $P < 0.05$	χ^2 (1) = 12.60, $P < 0.01$	χ^2 (1) = 4.74, $P < 0.05$	χ^2 (1) = 2.24, $P > 0.05$
R^2 (Cox & Snell)	0.03	0.10	0.11	0.03

Table 3. Attraction time, passage duration and passage delay for common shiner, creek chub and white sucker using the Indian Creek nature-like fishway. Numbers in parentheses indicate sample size (*n*).

	Time to attraction (h)		Passage duration (h)		Passage delay (h)	
Species	Mean ± SE	Range	Mean ± SE	Range	Mean ± SE	Range
Common shiner	116.2 ± 14.9 (53)	0.04–338.5	1.2 ± 0.2 (5)	0.7–1.6	189.1 ± 61.9 (5)	1.0–390.3
Creek chub	32.6 ± 7.7 (65)	0.03–359.9	19.4 ± 12.8 (33)	0.4–319.1	51.7 ± 15.5 (33)	0.5–386.0
White sucker	66.3 ± 24.0 (20)	0.1–411.8	4.3 ± 2.1 (8)	0.9–18.6	217.5 ± 72.5 (8)	1.4–494.8

from creek chub or common shiner. As part of the experimental evaluation focused on creek chub, release site B fish had a passage efficiency of 42.1% (n = 8), and a passage duration of 7.0 ± 4.3 h (range 0.5–31.7 h). Release site C had a higher overall passage efficiency of 76.2% (n = 16).

There was no significant difference in the size of common shiner attracted to the fishway compared with those not attracted ($t = 0.795$, df = 143, $P = 0.428$). In contrast, creek chub attracted to the fishway were significantly larger, on average, than those that were not attracted ($t = 2.245$, df = 119, $P = 0.027$). However, among creek chub that successfully entered the fishway, size was not related to passage success ($t = -0.321$, df = 70, $P = 0.749$). There was no significant difference in the size of white sucker attracted to the fishway compared with those not attracted ($t = -1.607$, df = 63, $P = 0.113$), and in the size of white sucker passing the fishway, compared with those attracted to but not passing the fishway ($t = -1.224$, df = 19, $P = 0.236$).

Water temperature ranged from 2.75 °C to 25.5 °C, progressively increasing throughout the study period (Fig. 2). Few individuals caught early in the study period (4–14 April) when lower water temperatures predominated (9.2 ± 0.1 °C) successfully ascended the fishway (Fig. 2). The majority of fish were caught from 4 to 16 May when water temperature averaged 13.3 ± 0.1 °C. Whereas white sucker passed over a wide range of temperatures (range 8.7–18.0 °C), creek chub and common shiner did not pass until water temperature increased to 12–20 °C. Water discharge

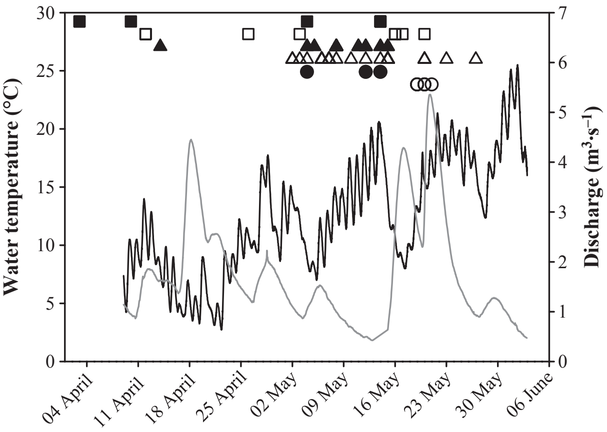

Fig. 2. Water temperature (—) and stream discharge (—) in Indian Creek for the duration of the fishway evaluation (9 April–2 June 2011). Symbols represent dates of capture for successfully passed common shiner (●), creek chub (▲) and white sucker (■), and dates of passage for common shiner (○), creek chub (△) and white sucker (□).

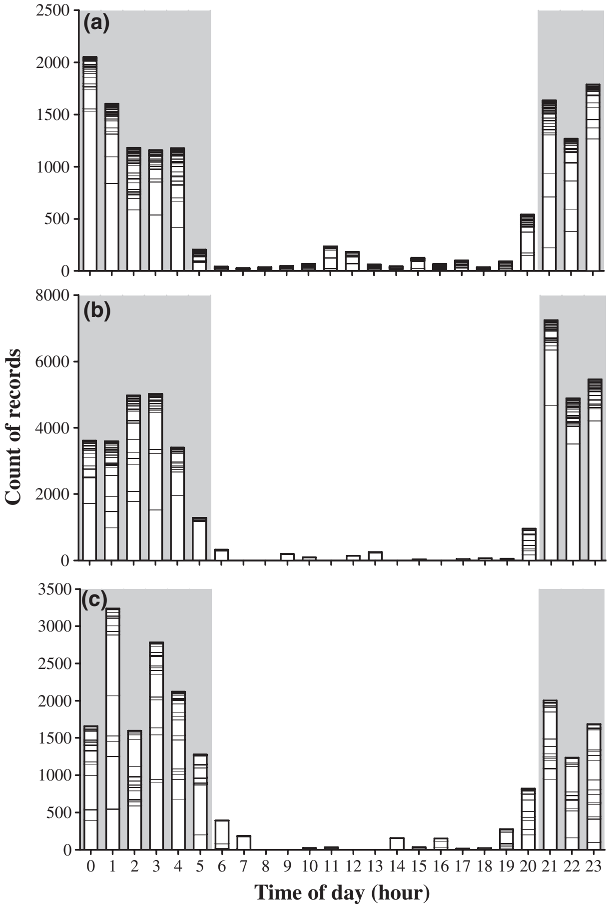

Fig. 3. Diel fishway use by (a) common shiner, (b) creek chub and (c) white sucker. Stacked bars show the relative contributions of individuals and data are pooled over the entire study period. Grey shading indicates approximate night periods and no shading indicates approximate day periods based on local sunrise/sunset conditions during the middle of the study period (approximately 0530 and 2030). Note that *y*-axes possess different scales.

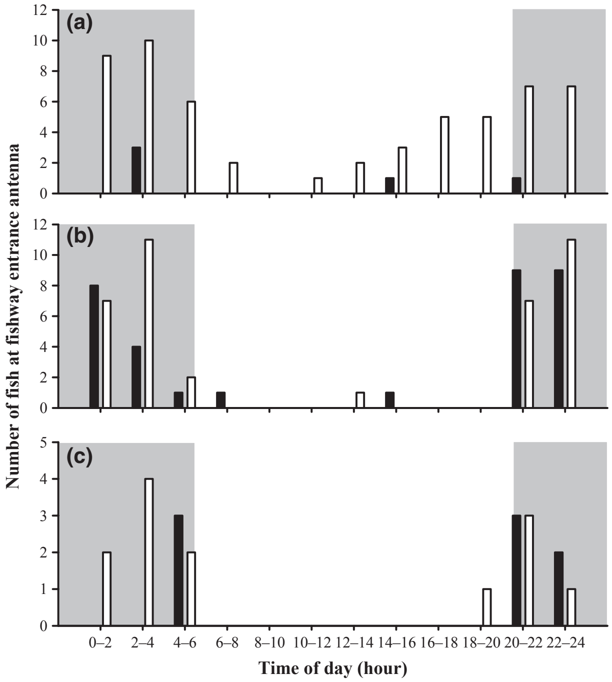

Fig. 4. Diel fishway use at the entrance antenna by (a) common shiner, (b) creek chub and (c) white sucker. Bars show the relative contributions of those individuals that successfully passed (■) and those individuals that did not pass (□). Grey shading indicated approximate night periods and no shading indicates approximate day periods based on approximate local sunrise/sunset conditions for the study period (approximately 0530 and 2030).

exhibited three spikes from 14 to 19 April, 16–18 May and 20–22 May. From 20 to 22 May, the discharge peaked at 5.4 $m^3 \cdot s^{-1}$ and common shiner passed during this period of high discharge. Minimum discharge during the study occurred from 10 to 13 May and was 0.43 $m^3 \cdot s^{-1}$. The majority of fish captures and creek chub passage occurred during the lowest period of water discharge; however, white sucker passed during a range of discharges.

The majority (>90%) of activity for all three species occurred during the night periods (Fig. 3). Common shiner (Fig. 3a) and white sucker (Fig. 3c) were most active in the early morning hours, whereas creek chub (Fig. 3b) were most active in the late evening hours. Similar patterns are observed at the attraction antenna (antenna 2) for fish that were able to pass and those that were attracted, but did not pass (Fig. 4). Common shiner (Fig. 4a) exhibited movement throughout the day, with the greater number of counts in the early morning (0000–0600 h) for both fish that passed and fish that did not pass. Creek chub (Fig. 4b) and white sucker (Fig. 4c) had very few counts during the middle of the day. More creek chub passed in the evening hours (2000–2300 h), and those that were unsuccessful in passing the fishway had greater counts during crepuscular periods while white sucker exhibited reverse patterns.

Discussion

Attraction and passage efficiency at the Indian Creek fishway was highly variable among species and these metrics ranged from 58 to 100% and 0 to 57%, respectively. These results differ from the meta-analysis provided by Bunt et al. (2012), in which nature-like fishways typically exhibit low attraction efficiencies and high passage efficiencies in comparison with conventional fishways. Aarestrup et al. (2003) reported an attraction efficiency of 91% and passage efficiency of 60% for brown trout (*Salmo trutta*) passing a 130-m long nature-like fishway and suggested that fishway dimensions acted as a behavioural barrier causing trout to reverse their direction and leave the fishway entrance, thus contributing to low passage efficiency estimates. Calles & Greenberg (2005) examined the attraction and passage efficiencies of brown trout in 150-m long

(50–53% and 100%, respectively) and 370-m long (14–20% and 91–92%, respectively) nature-like fishways. Lower attraction efficiencies were attributed to poor attraction flow and an inability of fish to locate the entrance, while high passage efficiencies were attributed to the swimming ability of brown trout. A later study (Calles & Greenberg 2007) re-examined the same fishways for use by multiple species and considerable variation in efficiency among species was documented. For example, attraction and passage efficiency for the common bream (*Abramis brama*) was 10% and 100%, respectively, while roach (*Rutilus rutilus*) exhibited attraction and passage efficiencies of 23% and 50%, respectively. Little information exists with which to compare the performance of species studied at Indian Creek in other nature-like fishways; however, assessments at conventional fishways are available. Pratt et al. (2009) reported attraction efficiency that ranged from 97 to 98% and 82 to 85% for the white sucker at two small vertical slot fishways in southern Ontario and passage efficiencies of 36–88% and 6–9%. Thiem et al. (In press) reported passage efficiencies of 75.8% of white sucker through a large vertical slot fishway in southern Quebec. O'Connor et al. (2003) provides the only passage efficiency estimates for creek chub with which to compare the findings of this study, with creek chub exhibiting a passage efficiency of 29% through a vertical slot fishway. Neither attraction information exists for creek chub, nor do attraction or passage efficiency estimates exist for common shiner.

Duration of fishway passage varied among the three most common species. Common shiner had the shortest passage duration, followed by white sucker and creek chub. Swimming performance is a key element in fish passage (Katopodis et al. 2001); therefore, duration could vary from the individual's reluctance to swim at higher water velocities or even an inability to swim at these velocities (Bunt et al. 2012). The Indian Creek fishway was built for an optimal water velocity of 0.8 $\text{m}\cdot\text{s}^{-1}$. Thiem et al. (In press) have recorded white suckers ascending a vertical slot fishway with velocities >1.5 $\text{m}\cdot\text{s}^{-1}$, while common shiner have been reported to ascend velocities upwards of 0.6 $\text{m}\cdot\text{s}^{-1}$ (Ficke et al. 2011). Bunt et al. (2001) recorded Denil fishway passage by creek chub up to water velocities of approximately 0.6 $\text{m}\cdot\text{s}^{-1}$. It is possible that passage duration was influenced by water level within the fishway. Creek chub took the longest to pass and only passed during times of lowest discharge. With a maximum depth of 0.2 m during optimal conditions, it is possible that fish did not have enough water to ascend and remained in the pools for longer periods of time. By manipulating the release locations of creek chub to examine the effect of a particularly challenging section in the lower reaches of the fishway on passage efficiency, we were able to increase passage efficiency from 42.1% to 76.2%. Although a similar approach was not used for other species, this provided preliminary evidence to explain the low passage efficiencies observed in this study.

Successful passage events were preceded by entrance delays in this study. Delayed passage can have severe consequences for migrating fish. For example, Caudill et al. (2007) demonstrated that slow dam passage of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) resulted in reproductive failure. Delays associated with dam passage have also been observed to negatively affect sockeye salmon (*O. nerka)* reproductive success, although were more likely to impact females than males (Roscoe et al. 2011). While the causes of delayed passage in the above studies are unknown, depletion of energy reserves through hyperactivity either before or during passage represents one possible explanation, and has been linked with passage failure in other studies (e.g., Hinch & Bratty 2000). It is possible that the passage delays experienced by fish at the nature-like fishway in this study negatively affected their reproductive success. However, the activity levels of fish and their reproductive success were not monitored, and we assumed that successful fishway passage at Indian Creek was universally beneficial for all species given the study was undertaken during known spawning periods. The fallback (presumably over the dam) and reascension of a small number of creek chub shortly after passage was unexpected in this study. Given the small number of occurrences of fallback in comparison with the number of ascensions, we assume that the fishway exits a sufficient distance from the dam to discount any population-level consequences. Furthermore, the reascension by these four individuals indicates that their first passage event was not energetically costly, or that they had sufficiently recovered to undertake a second successful ascent.

The Indian Creek nature-like fishway improved connectivity for stream fishes to approximately 85% of the creek upstream of the barrier. The approach adopted here, whereby stakeholders were engaged in the construction of this nature-like fishway, represents a promising model for the numerous barriers to fish passage that occur on low gradient streams around the globe. However, biological evaluations should be a requirement for any new (and existing) fishways to ensure that attraction and passage efficiency are optimised (Bunt et al. 2012). Based on the findings of this study, a number of modifications could be made to the Indian Creek fishway to possibly improve overall efficiency. To improve attraction flows, placement of instream structures such as boulders or logs could be used to manipulate hydraulic conditions in and around the entrance and also to provide navigational direction towards the entrance and away from the dam (Katopodis et al. 2001). To address the apparent passage challenge (i.e., shallow bedrock areas) in the lower reaches of the fishway, it may be necessary to increase channel depth at this location. To inform future nature-like fishway design, we advocate for not simply making such modifications, but doing so and evaluating the hydraulic and biotic responses to such changes, similar to the approach reported by Bunt (2001) for Denil fishways.

Nature-like fishways are beneficial as they use natural materials, mimic natural riffles and pools, provide passage to a wide variety of species as well as habitat to other aquatic organisms and they have an inland stream focus suitable for low to medium barriers (Katopodis et al. 2001; Beatty et al. 2007). Although this fishway was not universally successful at passing all species, or all individuals of a single species, it did demonstrate the utility of nature-like structures as an affordable alternative to conventional fishways. Given the need for fishway studies focussed on species other than salmonids (Roscoe & Hinch 2010), this study also provides necessary attraction and passage efficiency information for small-bodied fish in a small waterway. Little or no comparable information exists for fishway use by many of the species studied here, thus our findings complement the small number of existing community fishway studies conducted in comparatively large waterways and typically on larger species (e.g., Bunt et al. 2001; Thiem et al. In press).

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References

Aarestrup, K., Lucas, M.C. & Hansen, J.A. 2003. Efficiency of a nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish 12: 160–168.

Baras, E., Westerloppe, L., Melard, C. & Philippart, J.-C. 1999. Evaluation of implantation procedures for PIT-tagging juvenile Nile tilapia. North American Journal of Fisheries Management 61: 246–251.

Beatty, S.J., Morgan, D.L. & Torre, A. 2007. Restoring ecological connectivity in the Margaret River: Western Australia's first rock-ramp fishways. Ecological Management and Restoration 8: 224–228.

Bunt, C.M. 2001. Fishway entrance modifications enhance fish attraction. Fisheries Management and Ecology 8: 95–105.

Bunt, C.M., van Porten, B.T. & Wong, W. 2001. Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics. Ecology of Freshwater Fish 10: 212–219.

Bunt, C.M., Castro-Santos, T. & Haro, A. 2012. Performance of fish passage structures at upstream barriers to migration. River Research and Applications 28: 457–478.

Calles, E.O. & Greenberg, L.A. 2005. Evaluation of nature-like fishways for re-establishing connectivity in fragmented salmonid populations in the River Emån. River Research and Applications 21: 951–960.

Calles, E.O. & Greenberg, L.A. 2007. The use of two nature-like fishways by some fish species in the Swedish River Emån. Ecology of Freshwater Fish 16: 183–190.

Castro-Santos, T., Haro, A. & Walk, S. 1996. A passive integrated transponder (PIT) tag system for monitoring fishways. Fisheries Research 28: 253–261.

Caudill, C.C., Daigle, W.R., Keefer, M.L., Boggs, C.T., Jepsen, M.A., Burke, B.J., Zabel, R.W., Bjornn, T.C. & Peery, C.A. 2007. Slow dam passage in adult Columbia River salmonids associated with unsuccessful migration: delayed negative effects of passage obstacles or condition-dependent mortality? Canadian Journal of Fisheries and Aquatic Sciences 64: 979–995.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z., Knowler, D., Lévêque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L.J. & Sullivan, C.A. 2006. Freshwater biodiversity: importance, threats, status, and conservation challenges. Biological Reviews 81: 163–182.

Environment Canada. 2011. Spencerville discharge data. Water Office, Environment Canada. Available at http://www.wateroffice.ec.gc.ca/graph/graph_e.html?stn=02LB007. Last accessed 22 November 2011.

Environment Canada. 2012. Spencerville discharge data. Water Office, Environment Canada. Available at http://www.wateroffice.ec.gc.ca/graph/graph_e.html?stn=02LB007. Last accessed 23 February 2012.

Ficke, A.D., Myrick, C.A. & Jud, N. 2011. The swimming and jumping ability of three small great plains fishes: implications for fishway design. Transactions of the American Fisheries Society 140: 1521–1531.

Gibbons, J.W. & Andrews, K.M. 2004. PIT tagging: simple technology at its best. BioScience 54: 447–454.

Grafen, A. & Hails, R. 2002. Modern statistics for the life sciences. Oxford: Oxford University Press.

Hinch, S.G. & Bratty, J.M. 2000. Effects of swim speed and activity pattern on success of adult sockeye salmon migration through an area of difficult passage. Transactions of the American Fisheries Society 129: 604–612.

Holmlund, C.M. & Hammer, M. 1999. Ecosystem services generated by fish populations. Ecological Economics 29: 253–268.

Katopodis, C., Kells, J.A. & Acharya, M. 2001. Nature-like and conventional fishways: alternative concepts? Canadian Water Resources Journal 26: 211–232.

Lucas, M.C. & Baras, E. 2001. Migration of freshwater fishes. Malden, MA: Blackwell Science Ltd.

Makrakis, S., Miranda, L.E., Gomes, L.C., Makrakis, M.C. & Junior, H.M.F. 2011. Ascent of neotropical migratory fish in the Itaipu reservoir fish pass. River Research and Applications 27: 511–519.

Malmqvist, B. & Rundle, S. 2002. Threats to the running water ecosystems of the world. Environmental Conservation 29: 134–153.

Mancini, S.B. & Langlois-Anderson, N. 2006. Indian Creek Fish Passage. Technical Document: South Nation Conservation Authority.

Noonan, M.J., Grant, J.W.A. & Jackson, C.D. 2012. A quantitative assessment of fish passage efficiency. Fish and Fisheries 13: 450–464.

O'Connor, L.M., Pratt, T.C., Hallett, A.G., Katopodis, C., Bergstedt, R.A., Hayes, D.B. & McLaughlin, R.L. 2003. A performance evaluation of fishways at sea lamprey barriers and controlled modifications to improve fishway performance. Ontario: Final report of research conducted for the Great Lakes Fishery Commission.

Pratt, T.C., O'Connor, L.M., Hallett, A.G., McLaughlin, R.L., Katopodis, C., Hayes, D.B. & Bergstedt, R.A. 2009. Balancing aquatic habitat fragmentation and control of invasive species: enhancing selective fish passage at sea lamprey control barriers. Transactions of the American Fisheries Society 138: 652–655.

Richter, B.D., Braun, D.P., Mendelson, M.A. & Master, L.L. 1997. Threats to imperiled freshwater fauna. Conservation Biology 11: 1081–1093.

Roscoe, D.W. & Hinch, S.G. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries 11: 12–33.

Roscoe, D.W., Hinch, S.G., Cooke, S.J. & Patterson, D.A. 2011. Fishway passage and post-passage of up-river migrating sockeye salmon in the Seton River, British Columbia. River Research and Applications 27: 693–705.

Rosenberg, D.M., McCully, P. & Pringle, C.M. 2000. Global-scale environmental effects of hydrological alterations: introduction. BioScience 50): 746–751.

Scott, W.B. & Crossman, E.J. 1973. *Freshwater fishes of Canada*. Fisheries Research Board of Canada, Bulletin 184.

Thiem, J.D., Binder, T.R., Dumont, P., Hatin, D., Hatry, C., Katopodis, C., Stamplecoskie, K.M. & Cooke, S.J. In press. Multispecies fish passage behaviour in a vertical slot fishway on the Richelieu River, Quebec, Canada. River Research and Applications, DOI: 10.1002/rra.2553.

Vőrösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Reidy Liermann, C. & Davies, P.M. 2010. Global threats to human water security and river biodiversity. Nature 467: 555–561.

Wildman, L., Parasiewicz, P., Katopodis, C. & Dumont, U. 2003. An illustrated handbook on nature-like fishways – Summarized version American Rivers, Washington, D.C. Available at: http://www.americanrivers.org/library/reports-publications/handbook-on-nature-like-fishways.html.