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Wetted Ramps Selectively Block Upstream Passage of Adult Sea Lamprey

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Abstract: Dams fragment stream habitat and fishways around dams typically serve few species that are strong swimmers or jumpers. We test a prototype wetted ramp designed to allow upstream passage of small-bodied fishes while blocking upstream movement of invasive sea lamprey in the Laurentian Great Lakes. We tested short, smooth ramps with 5-10 mm water depth in various combinations of ramp angle, water flow and swim channel width with the aim to selectively block adult migrating sea lamprey while passing sub-adult white suckers (*Catostomus commersonii*) and creek chubs (*Semotilus atromaculatus*). Sea lamprey easily passed a 0.75 ramp at 5° angle, but very few individuals passed a similar ramp at 10° angle and none passed a longer ramp at the 5° angle. Limiting the amplitude of tailbeats in a narrow channel did not hamper lamprey or the other species. Greater water flow, and thereby greater immersion depth on the ramp fostered passage for all species. Smaller-bodied individual of creek chubs and white suckers performed best on the ramp. We show that wetted ramps could be incorporated into fishways at low-head dams to aid passage of smaller-bodied fishes while also blocking the spawning migration of adult sea lamprey.

Keywords: sea lamprey; low-head ramped weirs; invasive species; barriers; fish passage; size effects

1. Introduction

Stream fragmentation threatens fish diversity, with millions of instream barriers in the US alone hindering fish movement (Nilsson et al. 2005; Pohl 2003). Although many barriers have fishways, their effectiveness varies and the number of species that can pass them is limited (Baudoin et al. 2015). Improving stream connectivity for fishes needs balancing with other ecological and economic needs (Rahel & McLaughlin 2018, Pratt et al. 2009). For example, in the Laurentian Great Lakes re-connecting fragmented river habitat competes with reducing access of invasive sea lamprey to spawning grounds (Lavis et al. 2003; Jungwirth 1998). Low-head dams, which are widely installed into streams of that region, block upstream movement of sea lamprey and non-jumping finfishes. Modifications to the dams, including adjustable-crest barriers, trap-and-sort fishways, and use of odorants and other signals to divert lampreys are being explored (Zielinki et al. 2019) These methods are still under development or have other shortcomings (Velez-Espino et al. 2011, Zielinski et al 2019, Zielinski et al 2020), prompting ongoing search for further solutions.

This study evaluates the potential for wetted ramps, also called "low-head ramped weirs" (Amaral et al. 2019) to selectively prevent the upstream migration of adult sea lamprey. Previous research on wetted ramps has demonstrated their potential to pass fish of various shapes and swimming abilities (Kivari 2016; Sherburne and Reinhardt 2016; Baker and Boubee 2006) despite the challenge of a shallow water depth (Baudoin et al. 2015). However, studies have produced mixed results regarding their effectiveness in selectively blocking adult sea lamprey (Sherburne and Reinhardt 2016; Reinhardt et al. 2017). In tests with sea lamprey, smooth wetted ramps inclined at 10° blocked 85% of them, with steeper inclines proving impassable. Yet, when finfish species were tested under similar conditions, passage rates were generally low (0-40%) and varied widely among species (Sherburne and Reinhardt 2016, Reinhardt et al. 2016, Kivari 2016). This study aimed to refine the design of wetted ramps to fully block adult sea lamprey upstream migration, while allowing greater passage success of finfish species.

Based on previous findings (Sherburne and Reinhardt 2016), we tested the effect of two ramp inclinations and lengths (Baker & Boubee 2006, Amaral et al. 2019), water discharge over the ramps and ramp width on upstream passage of adult sea lamprey and two common riverine Great Lakes fishes (creek chub *Semotilus atromaculatus* and white sucker *Catostomus commersonii*). We predicted that steeper and longer ramps would reduce passage success of lamprey while greater discharge (and thereby greater water depth on the ramp) would foster passage of all three test species. Sea lamprey are anguilliform swimmers with a wide tail beat amplitude (Tytell et al. 2010, Corniuk 2020). We hypothesized that narrowing the swim channel would hamper sea lamprey, but not finfish, passage by limiting their lateral tail movements and thereby reducing their swimming efficiency.

2. Materials and Methods

2.1. Study Location and Animals

The experiments were carried out at Hammond Bay Biological Station (HBBS) near Cheboygan, Michigan, and at the Saline Fisheries Research Station (SFRS) in Saline, Michigan. The experiments with sea lamprey were conducted during Year One at HBBS while finfishes (white sucker and creek chub) were tested in both Year 1 (SFRS) and Year 2 (HBBS and SFRS). Adult migrating sea lamprey were collected from traps in the Cheboygan River, the Ocqueoc River, and the Carp Lake Outlet. They were stored in two 2000-liter holding tanks until used in the experiments. The suckers used at HBBS were collected from Black Mallard Creek via seine nets and held in a separate holding tank. Some sea lamprey were held for several days (10-20 days, longer for the test of the extended ramp), while all finfish were tested within 72 hours of capture. Individuals were used only once. White suckers and creek chubs for Year 2 were caught in the Saline River near the research station using a backpack electroshocker. Adult sea lamprey were tested during the sea lamprey migratory period (late April to early June). Tests with chubs and suckers were carried out after the experiments with lamprey in Year 1 and in the fall of Year 2. The water temperature in holding and experimental tanks averaged 13.5°C (range 12-15°C).

2.2. Experimental Setup and Procedures

2.2.1. Sea Lamprey

For sea lamprey trials, plastic ramps were constructed, measuring 1 m L x 0.50 m W with an additional 0.25m submerged onramp at the downstream end to guide fish into the channel. Treatment 1 had a rectangular wetted channel 90 mm wide and 50 mm deep. Treatment 2 had a square channel of 50 mm x 50 mm and was designed to limit the tailbeat amplitude of sea lamprey attempting to swim up. Ramps were marked at 50 mm increments to the maximum height of 0.75 m. A bundle of 5 mm diameter tubes at the top of the ramps laminarized the ramp flow. A successful passage was defined as any time a fish touched these flow straighteners. For sea lamprey tests, ramps were placed in a 700 l rectangular tank (1.5 m x 0.75 m x 1m) that was divided into three sections: downstream staging pen, ramp plus supports, and 20 l head tank plus supports and submersible recirculation pump(s). Water was recirculated for the duration of each test with a small input of colder lake water to offset heat created by the pumps. After three tests, the water was fully exchanged. Figure 1 shows the arrangement used at SFRS. The setup was kept dark during observations to simulate nighttime migratory conditions. An infrared camera and IR lights were used to record animal behavior. All video was recorded at 30 frames/s using a digital video recorder (DVR).

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Figure 1. Experimental setup (de-watered) used for the experiments with suckers and chubs at the Saline Research Station. Shown is the ramp with narrow (5 cm) channel.

Each test run involved four individual sea lamprey observed for four hours. Three fish in each test run were individually marked by small reflective tags attached to two locations along the dorsal fin by monofilament line and one fish was left untagged. Fish size was measured after each test run. The sea lampreys averaged 480 mm total length (45 mm SD, range 190 – 570 mm) and 233 g (52.5 g SD) in weight.

Three experimental variables were manipulated during sea lamprey tests: ramp inclination, channel width, and flow rate. Angles of 5° and 10° from the horizontal were chosen based on previous research with similar designs (Sherburne & Reinhardt 2016, Reinhardt et al. 2016). Two levels of discharge were tested, 0.3 L/sec ("low flow") and 0.6 L/sec ("high flow"). An additional treatment was tested in late June of Year 1: an extended ramp of 1.75m length with 50 mm width wetted channel and 0.6 L/sec flow. Table 1 lists the treatment combinations, including water velocity and depth in the wetted channels.

2.2.2. Finfish

The observations of chubs and suckers were carried out in a similar manner to the sea lamprey test, but using only one angle (10°) because the 5° ramp was easy to pass for lamprey (see Result section). The experimental apparatus at SFRS was similar to that at HBBS, with the main difference being a slight reduction (~15%) in overall tank size. Three untagged individuals of the same species but distinctly different sizes were picked for each test run and their lengths were measured after concluding the 4-h recordings. Creek chubs averaged 16.4 cm (3 cm SD, range 9- 25 cm) in total length, while white suckers averaged 22.8 cm (6.4 cm SD, range 8 – 38 cm).

Table 1. Treatment combinations used in the wetted-ramp-style experiment and resulting water velocities and water depths on the ramps.

Species	Ramp Angle	Channel Width	Flow Rate (l/s)	Flow Velocity (m/sec)	Mean Water Depth (mm)
Lamprey	5°	50 mm	0.3	0.44	8.3
Lamprey	5°	50 mm	0.6	0.94	16.7
All species	10°	50 mm	0.3	1.05	6.7
All species	10°	50 mm	0.6	1.17	11.7
Lamprey	5°	50 mm	0.3	0.82	5
Lamprey	5°	50 mm	0.6	1.05	16.7
All species	10°	50 mm	0.3	1.00	4
All species	10°	50 mm	0.6	1.15	8.4

2.3. Data Extraction and Analysis

Each ramp was divided into three sections: entrance (0-100 mm from the waterline), mid ramp (100-400 mm), and top (400-700 mm). Apart from determining 'successful passage' (i.e. reaching 0.75m on the ramp plane), we extracted from the video for each 'attempt': mean height on the ramp plane (MH) to the closes, swimming speed over the ramp (ground speed) and tail beat frequency (for lamprey only). An 'attempt' to climb was analyzed anytime a fish reached at least 100 mm on the ramp plane. Mean height for an individual was calculated by averaging the greatest heights achieved during each attempt, up to a maximum of the first 10 observed attempts for that individual. For calculating mean height, each successful passage event was included as value of 0.75 m. Swim speed was determined by counting the number of frames it took a fish to travel a specified distance and dividing this number by the frame rate. Swim speeds (m/sec) were standardized to fish body lengths (BL/sec) for most analyses. Tail beat frequency (in Hz) was defined as the number of full undulations of the tail in one recorded second (30 video frames) in the mid-ramp section. This number was counted to the nearest 1/4 tailbeat. Where a full 30 frames could not be counted, no tailbeat frequency was recorded for that attempt.

The means of sea lamprey and finfish entry velocity (swim speed over ground, measured at 0-150 mm from entry point onto the ramp), mid-ramp swim speed (between 200 and 400 mm from entry point) and mean height achieved on the ramp plane were analyzed using a 2-way factorial ANOVA after pooling data from the narrow and wide wetted channels (see Results). A t-test was used to compare mean tailbeat frequency between angles of inclination. We transformed data using square root (for swim speeds) and an inverse square root transformations ($-1/\sqrt{x}$ for mean heights) to achieve normal distribution. Some data for suckers and chubs were analyzed by a Kruskal-Wallace test where data transformation did not achieve normality.

3. Results

3.1. Passage Success Rates and Effect of Channel Width

The rate of successful passage over the 1m long wetted ramp was much greater for the two finfish species (97% combined, or 39/40 chubs and 29/30 suckers) than for sea lamprey (38% of 104 attempting individuals). Passage success of lamprey was much higher at the 5° angle than at 10° (74% vs. 2.4%). The two sea lamprey that passed the 10° ramp did so in the treatment with narrow channel and high flow.

The performance of lamprey was very similar on the narrow (50 mm) vs. wider (90 mm) wetted channels (t-tests on mean height on ramp, entry & mid-ramp swim speed: all NS). Therefore, the data from the two widths were pooled for the analysis of the other treatment effects. White suckers, but not creek chub, achieved greater mean height (MH) on the narrow channel (suckers: 73 cm vs. 60 cm, U=191, $p_{(\alpha)}$=0.001; chubs: 71 cm vs. 68 cm, U=270, NS). Ramp width did not have any significant effect on observed swim speeds of sucker or chubs (entry speed: $F_{1,69}$= 0.7, NS; for mid-ramp speed: $F_{1,69}$= 0.04, NS) and therefore the data from two widths were pooled for subsequent analyses.

3.2. Effect of Ramp Angle and Water Flow

Ramp angle did not affect the swim speed of lamprey near the middle of the ramp (Figure 2c, $F_{1.90}$= 0.01, NS), but at the 5° ramp inclination the mean entry speed onto the ramp and mean height (MH) achieved on the ramp were significantly greater (MH: $F_{1.90}$= 102, $p_{(\alpha)}$<0.001; entry velocity: $F_{1.90}$= 8.16, $p_{(\alpha)}$ =0.005) (Figure 2a/2b). Analysis of lamprey tail beat frequency and swim speed on the ramp suggested that greater effort was required at the 10° inclination to reach the same average ground speed as in 5° treatments (0.38 BL/s). At the 10° angle, sea lamprey showed much greater average tail beat frequencies while on the ramp (Figure 3, $F_{1,90}$=107, $p_{(\alpha)}$<0.0001).

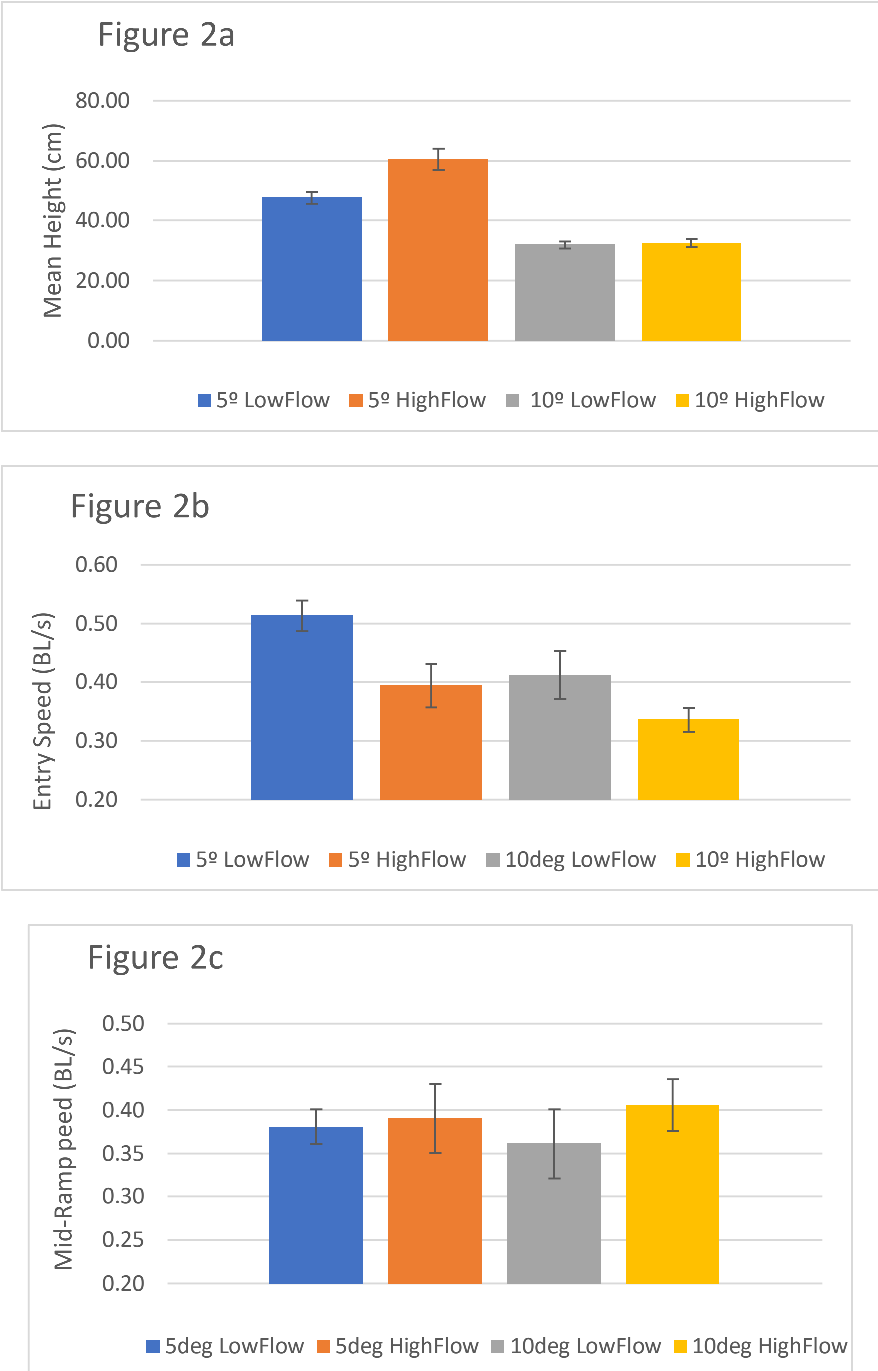

Figure 2. Mean height (2a), mean length-adjusted swim speed at entry (2b) and mean length-adjusted swim speed at mid ramp (2c) achieved by adult sea lamprey on modified wetted ramp style devices set to 5 or 10° inclination at two flow rates. N=92. Error bars=standard errors .

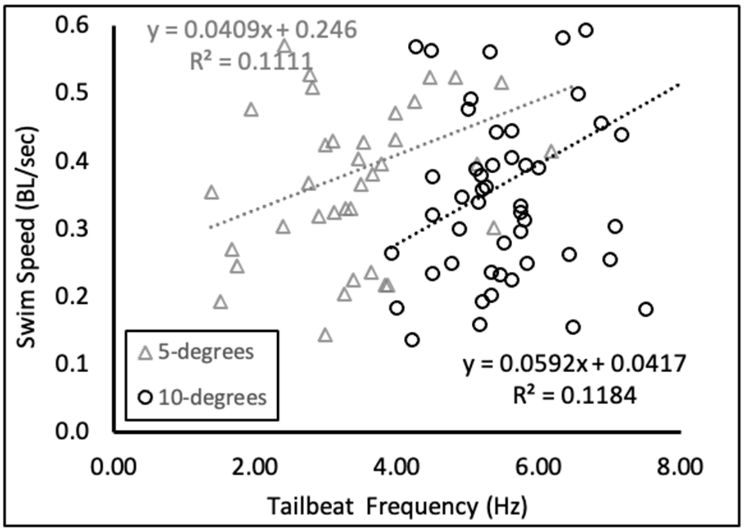

Figure 3. Tail beat frequencies vs. length-adjusted swim speed (over ground) of adult sea lamprey swimming up a wetted ramp set at two different angles of inclination.

The higher flow rate benefited the passage of lamprey. Their success rate was 51% at high flow versus 18% at low flow (pooled data from 5° and 10° treatments). Lamprey reached a significantly greater MH in high-flow treatments compared to low flow (48 cm vs. 40 cm $F_{1,90}$=10.44, $p_{(\alpha)}$=0.002, Figure 2a). In the low flow treatment, lamprey mean entry speed onto the ramp was about 20% greater (0.45 BL/s for low flow vs 0.37 BL/s for high flow, $F_{1,90}$= 10.44, $p_{(\alpha)}$= 0.002. Figure 2b) but mean mid-ramp swim speed was similar (0.37 BL/s at low flow vs 0.4 BL/s at high flow, $F_{1,90}$= 0.67, NS. Figure 2c). The majority of observed lamprey (22/40) accelerated on the lower part of the ramp when water flow was high, but only 28% (15/54) achieved, on average, positive acceleration at low flow (two-sample proportion test: Z=2.65, $p_{(\alpha)}$=0.008). The flow rates we used did not affect MH of creek chubs (U=181, NS) or white suckers (U=76.5, NS). Flow rate also did not affect entry or mid-ramp swim speeds of chubs and suckers (entry speed: $F_{1,69}$= 2.4, NS; mid-ramp speed: $F_{1,69}$= 0.8, NS).

When comparing performance of the two species, creek chubs achieved a greater mid-ramp speeds (mean of 3.7 BL/s) than suckers (2.6 BL/s) ($F_{1,69}$= 17.6, $p_{(\alpha)}$<0.001, Figure 4), but this was largely caused by the different size ranges of the two species in our experiment. There was no discernible effect of fish length on entry speeds, but on the ramp larger individuals achieved lower absolute mean swim speeds (in m/s), with swim speed reduced by about 25% for every 100 mm increase in length (Figure 5). After controlling for the effect of body length, the two species swam at similar speeds on the ramp (ANCOVA of mid-ramp speeds in m/s with body length as covariate, $F_{1,70}$=0.56, NS).

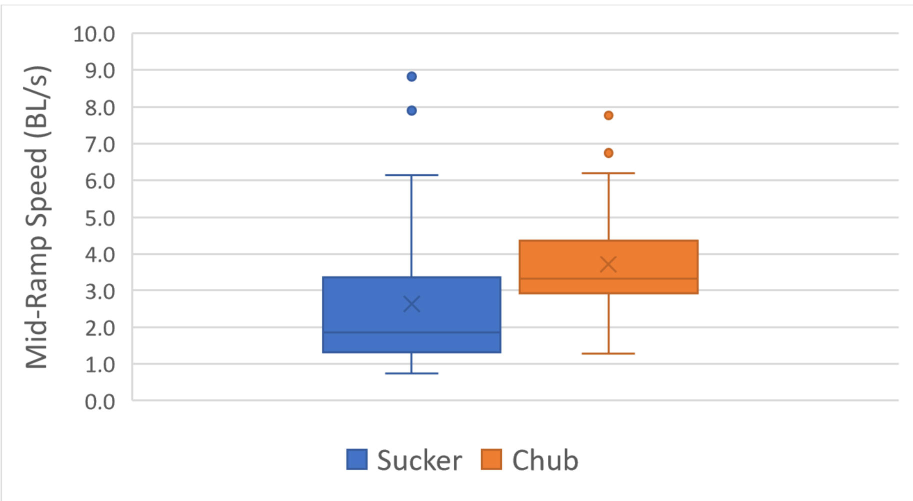

Figure 4. Length-adjusted swim speeds of creek chubs and white suckers over a wetted ramp. The box shows 25th-75th percentile range, mean (x), median, the whiskers denote 5th and 95th percentiles.

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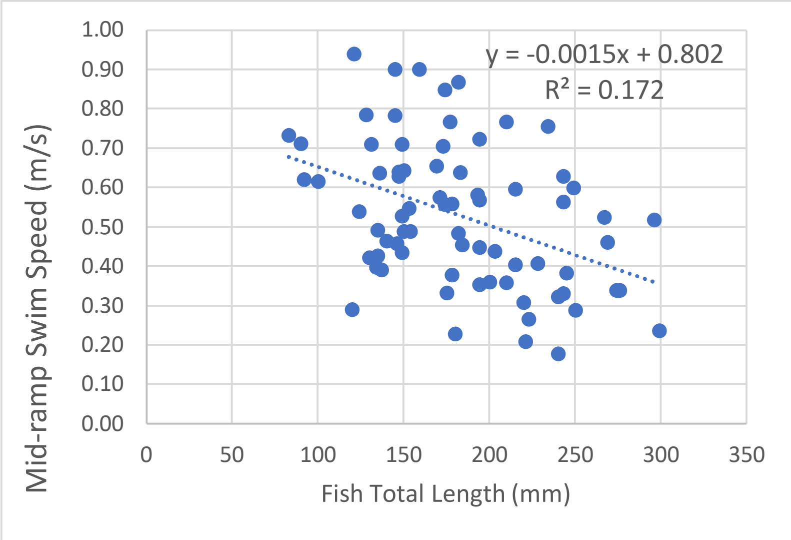

Figure 5. Swim speed (m/s) over ground vs total body length of creek chubs and white suckers attempting to swim up a wetted ramp. N=73.

3.3. Effect of Ramp Length

Due to time constraints, we tested only sea lamprey on the 1.75 m/5° ramp. None of 27 tested lamprey reached the top of the extended ramp. The maximum achieved distance on the extended ramp was 57 cm, reached by two individuals. The MH achieved on this ramp was 46 ± 6.8 (SD) cm, which was less than the 60 cm observed on the standard ramp at the same angle/flow (Figure 2a, t=9.4, $p_{(\alpha)}$<0.001).

4. Discussion

We report the successful use of a wetted ramp as a selective upstream migration barrier against an invasive fish species while maintaining adequate passage rates for other fish species. In some configurations, the wetted ramps blocked 100% of the adult sea lamprey tested but enabled upstream passage of most of the finfish we tested. As expected, a steeper ramp angle reduced the upstream distance fish reached and greater ramp length eliminated passage of lamprey. We found no support for our hypothesis that sea lamprey upstream movement could be inhibited by limiting their tail beat amplitude.

4.1. Passage Success Rates and Effect of Ramp Inclination

The angle of a passage device can be a strong determinant of fish passage (Noonan *et al.* 2012, Baudoin et al. 2015; Sherburne & Reinhardt 2016) and strongly affected selective blocking of lamprey in this study. A ramp angle of 10° stopped all but two of the >50 sea lamprey we tested, while a 5° angle allowed 74% of tested lampreys to reach the top of the ramp. No lamprey passed the 1.75 m ramp at 5° angle, but since those fish were tested later in the migratory season and did not swim up a far as individual tested earlier on the shorter ramp, it is possible that a 1.75 m/ 5° ramp is passable by migrating sea lamprey in top condition. The cause of poorer performance of sea lamprey on the steeper ramp was probably a combination of greater water velocity, decreased water depth, and greater effect of gravity (Baudoin et al. 2015). Water velocity is a limiting factor for fishway design and often dictates which species are capable of using a particular fishway (e.g. Haro *et al.* 2004; Beamish 1974; Baudoin et al. 2015). As water velocity increases, the number of species that can use a fishway decreases as fewer and fewer species are capable of sustained swimming long enough to traverse the device (Baudoin et al. 2015). Adult sea lamprey are capable of using vertical slot fishways with similar water velocities to those found on the ramps tested here (~1.0-1.25 m/sec vs. 0.4-1.2 m/sec in our experiments) (Pereira *et al.* 2016; Pratt *et al.* 2009) and are estimated to have a maximum sprint swimming velocity of ~4 m/s (Katopodis *et al.* 1994; Hanson 1980), which means that the water velocities alone did not prevent successful passage of sea lamprey in our study. When we add water velocity on the ramp to the ground speed we calculated from the video, our lamprey swam on the

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ramp at maximum observed speed of about 1.5 m/s. We posit that the challenge of fast water to swim against was amplified by the limited water depth on the wetted ramp. When fish swim at or near the air-water interface the potential thrust is reduced surface waves increase resistance (Webb et al 1991). Corniuk (2020) found that adult sea lamprey swimming in 10 mm water depth used greater tail beat frequencies and larger tail beat amplitude to achieve the same swim velocity as fully-submerged individuals, which suggests lower swimming efficiency in very shallow water. The wetted-ramp configurations we tested blocked very few of the white suckers and creek chubs. Similar success rates have been seen in galaxid species swimming on wetted ramps with comparable angles and water depths (Baker & Boubee, 2006). The finfish we studied likely succeeded where lamprey failed due to their greater maximum swimming speeds (Katopodis *et al.* 1994; Tytell & Lauder, 2004; Beamish 1974). White suckers are fairly strong swimmers and can pass fishways against swift currents when fully submerged (Haro et al 2004, Lewandowski et al. 2021). Kivari (2017) tested the same two finfish species as we did on similar wetted ramps and found a much lower passage rate, which was probably due to the comparatively greater water velocity and lower water depth on the ramps in Kivari's study (2017).

4.2. Effect of Channel Width, Water Flow, Fish Size

Our expectations that reduced wetted channel width would impede sea lamprey in their passage over the wetted ramp was not met. Corniuk (2020) measured an average tail beat amplitude for adult sea lamprey in shallow (10 mm) water of 0.11 BL, or about 50 mm, which was the width of the narrow ramp in our experiment. Nearly all of the sea lamprey tested on the narrow ramp made contact with the sidewalls of the device as they swam up and in a few cases, lamprey wedged themselves between the walls of the water channel to hold their position. Although sea lamprey are not capable of using their oral disc to aid in climbing like the Pacific lamprey (*Entosphenus tridentatus*) (Reinhardt *et al.* 2009), their ability to use surface structures as climbing aids has been well documented (D'Aguiar 2011; Reinhardt & Hrodey 2019). We conclude that curtailing the tailbeat amplitude of lamprey isn't a promising method for impeding their upstream passage. Creek chubs and white suckers were not hampered by the narrow channel width we tested either, indeed suckers seemed to gain a slight benefit from the narrower ramp, possibly aided by the greater water depth that resulted from constricting the width of water flow.

Increasing the pump discharge resulted in greater water depths on the ramps, which increased the relative submersion depth of fish using those devices. This was expected to increase performance of both fish groups as swimming ability is positively correlated with propulsive surface area (Webb 1971) and that surface area is diminished in very shallow water. At the low flow rate, lamprey entered the ramp at greater velocity but then lost speed, while at high flow a majority of observed individuals managed to accelerate and thereby swim farther up the ramp. The suckers and chub we tested seemed largely unaffected by the tested flow conditions. Both species passed the 10° ramp with relative ease. However, we observed that larger individuals of the two species achieved lower ground speeds on the ramp. Previous research showed that wetted ramps are more challenging for larger-bodied individuals (Kivari 2016, Reinhardt et al. 2016) and fishes with a less-fusiform body shape (Sherburne & Reinhardt, 2016). Kivari (2016) used high-speed video recordings to show how larger creek chubs and white suckers apparently struggle more than smaller individuals when swimming on wetted ramps.

5. Conclusions

Wetted-ramps could provide a suitable alternative or addition to traditional fish passage designs, especially where small-bodied fishes are a management concern (Baudoin et al. 2015, Ovidio & Phillipart 2002, Knapp et al. 2019). No single fishway design is likely to pass all fish species (Pratt *et al.* 2011; Baker 2014, Baudoin et al. 2015), but a combination of ramps with varying configurations, may allow a fairly wide range of target species to use wetted-ramp fishways (Doehring *et al.* 2011, Amaral et al. 2019). More research will be required to find what additional species can pass wetted-ramp-style fishways of various lengths and angles, how water temperature impacts passage over wetted ramps (Reinhardt unpublished data) and what engineering solutions will be needed to maintain wetted ramps within the design parameters of water depth and velocity and avoid fouling under field conditions. Wetted-ramp-style fishways also have the potential to meet the need for selective upstream fish passage of native species at the lowhead barriers currently used for sea lamprey control throughout the Great Lakes Basin. If our findings hold up under field conditions, wetted ramps could be used as a sorting component within existing fishways alongside other methods for separating migrating adult sea lamprey from native fishes (FishPass 2024).

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Conflicts of Interest: The authors declare no conflict of interest.

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