History of alternative sea lamprey barrier technologies and design best practices

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Table of Contents

1. Introduction

Sea lamprey (*Petromyzon marinus*) invaded the Great Lakes in the early 20th century and caused significant damage to Great Lakes fishery resources. Since the 1950s, sea lamprey numbers were reduced to 10% of historical abundance through an integrated pest management (IPM) program overseen by the Great Lakes Fishery Commission (GLFC) and implemented by contracted control agents —Fisheries and Oceans Canada (DFO) and the U.S. Fish and Wildlife Service (USFWS). Two lampricides, 3-trifluoromethyl-4-nitrophenol (TFM) and 2',5-dichloro-4'-nitrosalicylanilide (niclosamide) are applied to Great Lakes tributaries to kill larval sea lamprey, while barriers, typically weirs and dams, block adult sea lamprey from reaching critical spawning habitat. Of the nearly 100,000 potential barriers to fish movement in Great Lakes tributaries (Moody et al., 2017), 1007 (866 US, 141 CAN) are lowermost barriers, that is, the first barrier to fish movement between a lake and tributary. Lowermost barriers are more important to sea lamprey control than barriers further upstream in a watershed as they effectively reduce access to spawning habitat, thereby reducing the amount of habitat requiring chemical treatment. Purpose-built sea lamprey barriers and existing structures modified or retrofitted to block sea lamprey comprise only 8% (38 US, 41 CAN) of lowermost barriers (Fig. 1-1) and eliminate the need to treat over 1,400 km of stream length with lampricide (Lavis et al., 2003). The remaining structures were constructed for other purposes including recreation, flood control, logging, navigation and energy production. While purpose-built barriers are maintained and operated by sea lamprey control agents, existing barriers are owned and maintained by private individuals, companies, or other government agencies. Barriers are also important for assessment trapping because sea lamprey tend to congregate at barriers, which increases trap encounter rate, and subsequent capture probability. Several types and sizes of lowermost barriers currently occur in the Great Lakes basin and are a key component of the Sea Lamprey Control Program (SLCP) (Table 1-1).

Table 1-1. Lowermost barriers to sea lamprey movement within the Great Lakes basin by type and category (purpose built, modified, existing).

Barrier Type	Purpose Built	Modified	Existing	Total
Fixed-crest, non-hydro	39	25	338	*402*
Hydropower	0	1	55	*56*
Culvert/Bridge	0	0	63	*63*
Adjustable/Seasonal*	11	1	33	*45*
Other	0	0	441	*441*
Total:	*50*	*27*	*930*	*1007*

*Includes low-head and electrical barrier in Ocqueoc R.

Pressures to reduce reliance on chemical controls and to increase stream connectivity and flood conveyance have prompted the GLFC to seek alternative sea lamprey control methods. Great Lakes basin resource managers often request consideration of alternatives to both lampricides and low-head barriers. Seasonal operation and alternative barrier designs can potentially accommodate additional uses, such as fish passage, flood conveyance, navigation, or recreation. To date, alternatives to fixed-crest barriers have had mixed, but limited, success depending on location and barrier type (McLaughlin et al., 2007). Although many alternative barrier technologies for sea lamprey control are still in research and development, they continue to be proposed as alternatives to conventional, permanent, low-head barriers.

Resource managers and control agents evaluating dam removals and structure designs for new construction or modifications to existing barriers could benefit from current knowledge regarding the effectiveness of barrier technologies and their historical use in the SLCP. To accomplish that goal, we conducted a comprehensive review of peer-reviewed and grey literature, SLCP operational protocols, sea lamprey barrier program review, unpublished research, and agent field notes. The results of the review are synthesized by barrier type used or proposed in the Great Lakes, which includes existing structures, fixed-crest, seasonal- and adjustable- crest, weirs and screens, velocity, electrical, and other non-physical barriers (barrier types defined in Table 1-2). Best practice guidelines and potential applications of technologies are provided where data were sufficient. Promising, ‘cutting-edge’ technologies, some of which are still in an experimental or developmental stage and require further evaluation, are also described. The intent of this synthesis is to provide resource managers and control agents a reference and tools to facilitate decision making that balance the critical need for invasive species control using barriers with fishery restoration.

Figure

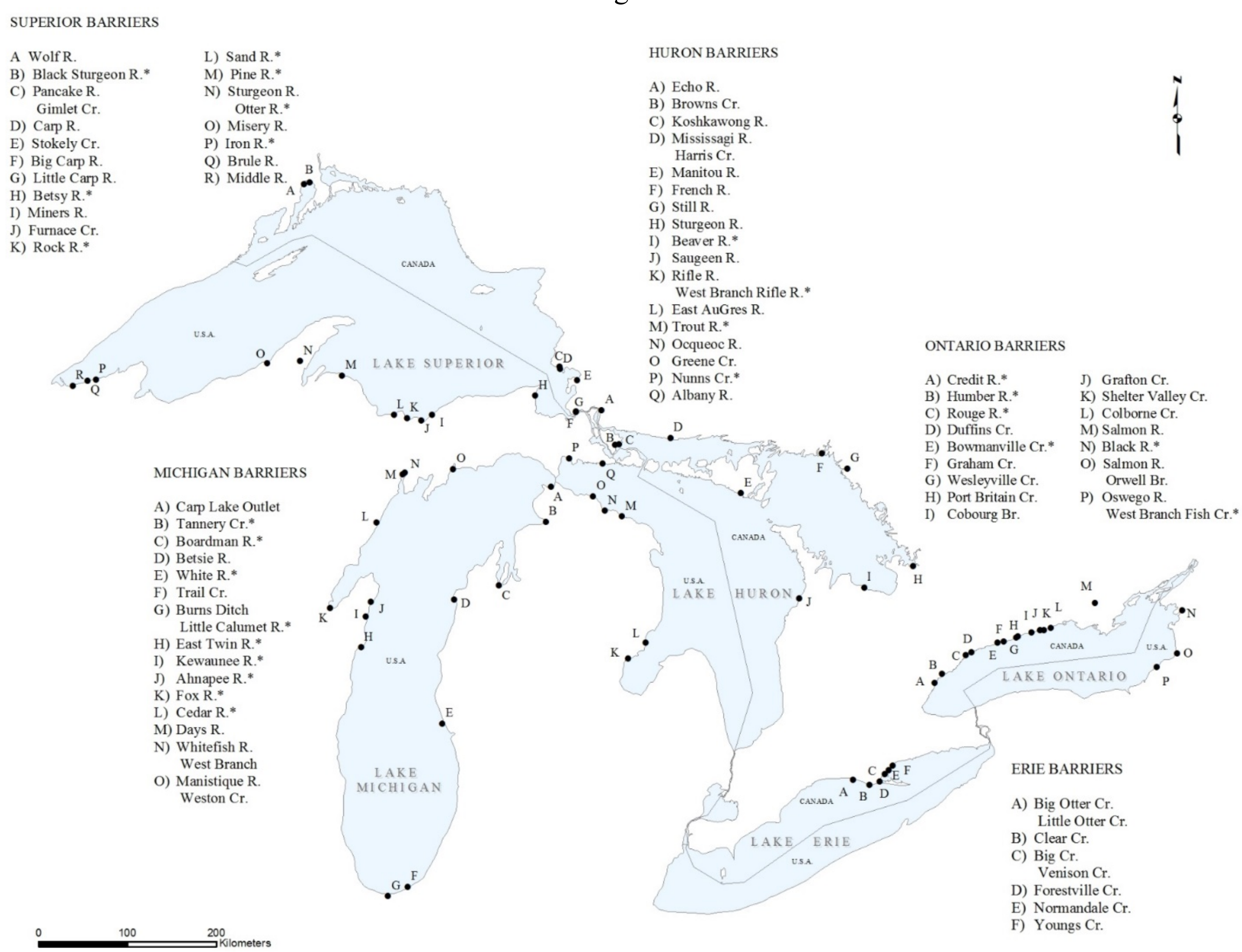

Figure 1-1. *Locations of tributaries with sea lamprey barriers. Existing structures modified to block sea lamprey passage are indicated by an asterisk. (Sullivan and Mullett, 2018)*

Table 1-2. Great Lakes SLCP barrier types that are either in use (*) or in various stages of research and development (●).

Barrier Type	Definition
Existing Structures*	Hydro-power dams, check structures, road crossings, and other existing structures that block sea lamprey passage outright or have been modified for that purpose.
Fixed-Crest*	Water control structure that maintains a minimum vertical differential between the crest and downstream water level.
Seasonal- and Adjustable-Crest*	Water control structure that has an adjustable or removable crest that can function as a barrier to sea lamprey passage at different times of the year or under variable flows.
Weirs and Screens●	Permeable weir panels or mesh screens that block sea lamprey while still passing water.
Velocity●	Regions of swift flowing water that cause sea lamprey to completely exhaust their swimming capabilities thereby blocking passage.
Electrical*	Electrical energy applied to water is transferred to fish as a deterrent to up-or downstream movement, which can lead to taxis (forced swimming), immobilization, and possibly trauma.
Non-physical	Technologies that use deterrent stimuli like sound, light, or chemicals (e.g., pheromones or alarm cues) to inhibit passage or guide movement.

2. Comparison of existing and purpose-built structures for sea lamprey control

2.1. Description of existing structures for sea lamprey control

In Great Lakes tributaries, 930 existing water control structures function as lowermost barriers to sea lamprey. These structures were originally built during the turn of the century for purposes other than blocking sea lamprey: power generation, recreation, flood control, erosion control, and transportation (Moody et al., 2017). Thus the types of existing structures are diverse (Fig. 2-1) and the manner in which sea lamprey passage is blocked (i.e., elevation difference, high water velocity) varies with each site. Existing structures are important to the SLCP due to the sheer number of barriers (nearly 12:1 ratio of existing structures to purpose-built or modified barriers for sea lamprey control). Existing structures are owned by private individuals, companies, or other government agencies and maintained to the specifications and regulations of the jurisdiction in which they are located. Guidance for the operation and maintenance of these structures for the purposes of sea lamprey control is provided by the control agents (SLBTT, 2000). Many of the existing structures are old and in disrepair and may no longer effectively serve as sea lamprey barriers.

In addition to blocking sea lamprey passage, existing barriers also impede passage of native or non-target fishes to varying degrees. While researchers have developed decision support tools that can identify the probability of fish being blocked at structures other than dams (Moody et al., 2017), site specific variables, such as temperature, hydraulic conditions, and time of day and year influencing fish passage are often unknown. A small number of existing structures have designated fishways to allow some fishes to pass the obstruction (Fig. 2-2). For example, the Menominee Park Mill Hydroelectric Project on the Menominee River, MI, has a fish elevator that allows native lake sturgeon (*Acipenser fulvescens*) to be manually sorted and passed upstream while all other fish are returned downstream.

2.2. Description of purpose-built or modified structures for sea lamprey control

Removal of existing structures has been motivated by aging infrastructure and societal desire to restore connectivity throughout Great Lakes tributaries. Rehabilitation or replacement of existing structures has largely been driven by local priorities, such as maintaining hydrologic separation to protect upstream resources, for recreational activities, or negotiated via the GLFC to maintain sea lamprey control. In the case of rehabilitation or replacement, historically effective barrier designs, such as fixed-crest are preferred, but other alternatives have been accommodated to replace or modify existing structures. Best practice guidelines for purpose-built barriers are provided in the following sections. Removal of an existing structure, however, is complicated by the potential positive (i.e., increase connectivity and native fish passage) and negative (e.g., invasive sea lamprey passage) ecological consequences (McLaughlin et al., 2013).

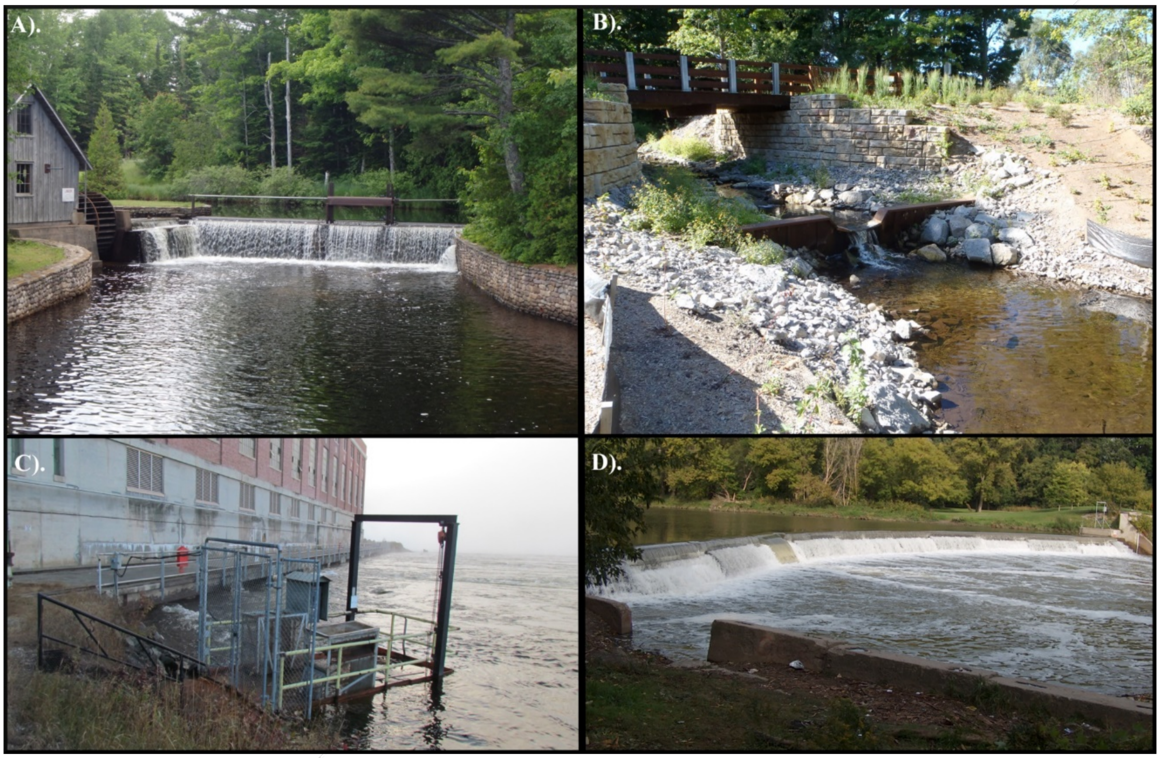

Figure 2-1. *Examples of existing structures that are lowermost barriers to sea lamprey passage: (A) Rock River Dam, MI (Lake Superior); (B) Wheelway culvert barrier on Tannery Creek, MI (Lake Michigan); (C) Alexander Generating Station on the Nipigon River, ON (Lake Superior); and (D) Humber River Dam, ON (Lake Ontario). Photos courtesy of the U.S. Fish and Wildlife Service and Fisheries and Oceans Canada.*

Figure 2-2. (A) *Menominee/Park Mill Hydroelectric Project on the Menominee River, MI (Lake Michigan). (B) Fish elevator raising lake sturgeon into sorting facility for processing. Grating on the elevator was sized to reduce capture of sea lamprey. Lake sturgeon are manually sorted and transported upstream via truck. All remaining fish are released downstream of the dam. Photos courtesy of the U.S. Fish and Wildlife Service and Eagle Creek Renewable Energy.*

3. Fixed-crest barriers

3.1. Description of fixed-crest barriers

The fixed-crest design is the oldest and most common purpose-built barrier type in the basin. The design of fixed-crest barriers has been well proven to block sea lamprey movement in the Great Lakes and are endorsed by the GLFC. The fixed-crest barrier design uses an uninterrupted fixed-crest height and overhanging lip to maintain a vertical drop from the barrier crest to the tailwater (downstream pool) elevation (Fig 3-1) (SLBTT, 2000).

Early accounts of fixed-crest barriers (Wigley, 1959; Stauffer, 1964) recommended a hydraulic head, which is the difference between upstream and downstream pool elevation, ΔH_{HW}, of 45-61 cm (18-24 in) to block sea lamprey passage. Hydraulic head, however, does not account for the vertical difference between the tailwater level and barrier crest, and the latter influences a sea lamprey's ability to pass a barrier via swimming or climbing. For example, a 61 cm (24 in) hydraulic head can occur at a barrier with a discrete drop in water level (Fig. 3-2A) or continuous flow over the crest (Fig. 3-2B), the difference between these cases being the crest elevation. Sea lamprey must climb the barrier with a discrete drop, but could swim over the barrier with continuous flow. Wigely (1959) noted that water flow was an important factor affecting sea lamprey passage and observed sea lamprey passing a barrier with 30 cm (12 in) hydraulic head by swimming over the crest or by attaching to the structure and maneuvering past via a series of rapid movements.

Precise fixed-crest barrier design criteria were developed by Youngs (1979), who found sea lamprey were incapable of passing a fixed-crest barrier with a 30 cm (12 in) differential between the barrier crest and surface of the tailwater. The Youngs (1979) barrier also had a minimum 1 cm (0.4 in) overhanging lip at the top of the barrier crest. Current fixed-crest barrier designs now require a minimum crest elevation that provides a drop of at least 45 cm (18 in) from the barrier crest to the surface of the tailwater with a minimum 15 cm (6 in) overhanging lip installed on the barrier crest (SLBTT, 2000). The purpose of the overhanging lip is to separate the falling water from the downstream face of the barrier, thus requiring sea lamprey to climb out of the water or to jump through a jet of water to pass over the barrier. The overhanging lip may also help guide sea lamprey to associated traps when a barrier is inundated (i.e., lower than 45 cm differential) (B. Paudel, personnel observation). While an overhanging lip may provide additional protection against sea lamprey passage, the actual effect it has on fixed-crest barriers to block sea lamprey is not well understood.

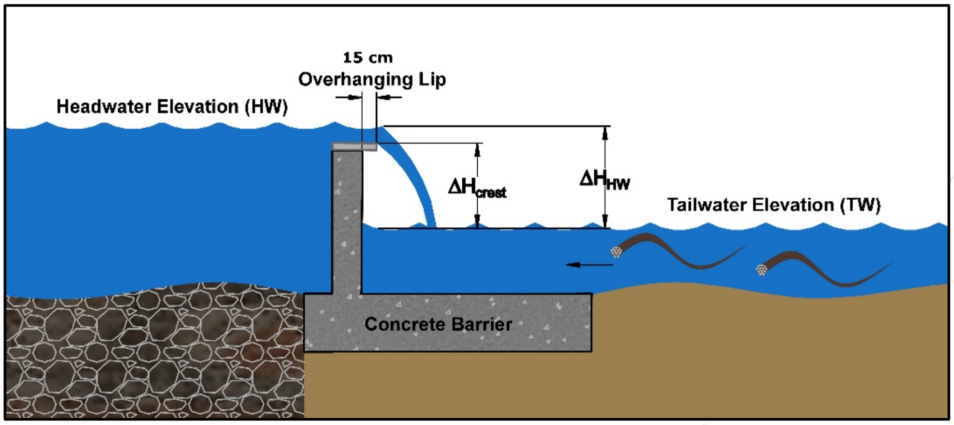

Figure 3-1. *Diagram of typical fixed-crest sea lamprey barrier illustrating the difference between hydraulic head,* $\Delta H_{HW} = HW - TW$ *, and vertical differential between barrier crest and tailwater elevation,* $\Delta H_{crest} = Crest - TW$ *.*

Sea lamprey employ a swim-attach-rest-release-swim pattern when attempting to pass over a fixed-crest barrier or inclined surface (Youngs, 1979 Reinhardt, et al., 2009). While undirected jumping of sea lamprey near barriers has been observed, sea lamprey passage attempts more closely resemble exerted swimming efforts rather than jumping (Youngs, 1979; Reinhardt et al., 2009). A laboratory study (Reinhardt, et al., 2009) examining sea lamprey swimming behaviors traversing wetted ramps angled 30º, 45º, and 60º from vertical reported no cases of sea lamprey attempting to jump over the ramp. Sea lamprey only suctioned onto the ramp surface to hold position, and in contrast to Pacific Lamprey (*Lampetra Tridentata*), showed no evidence of an attach-twitch-attach locomotion required for climbing (Moser et al., 2005).

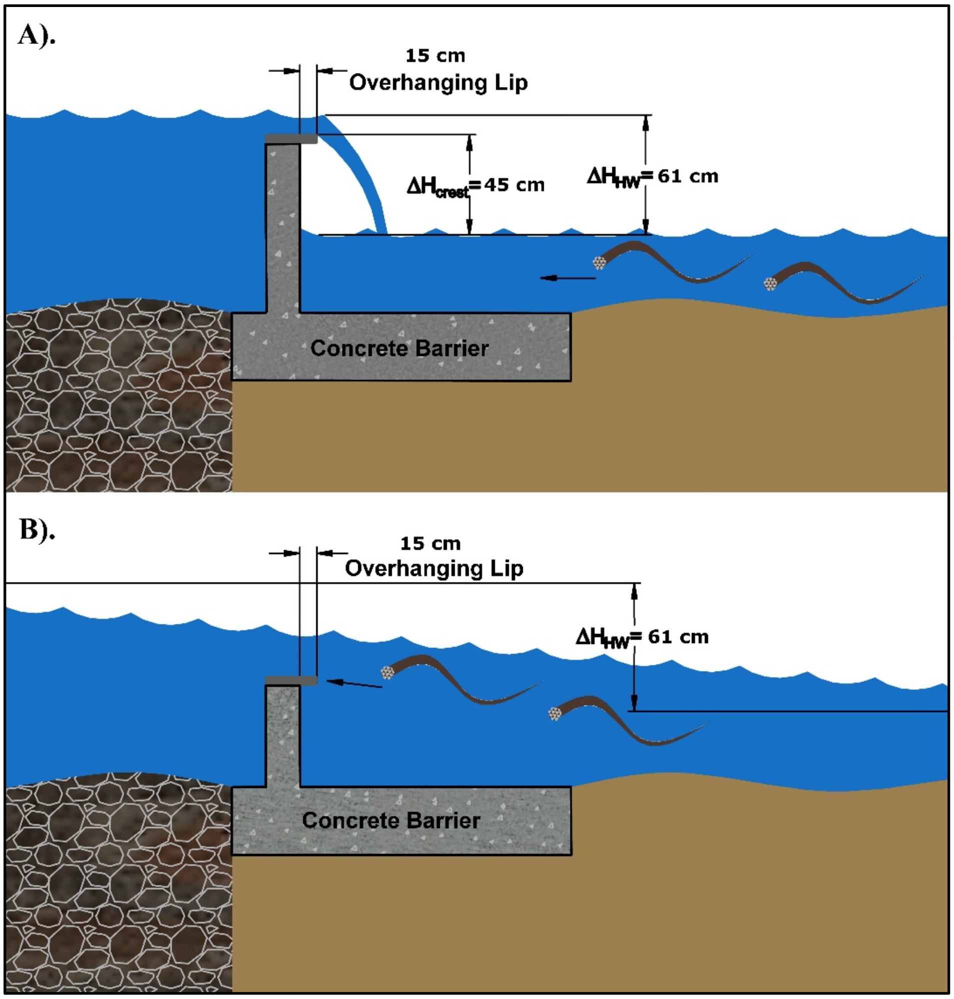

Figure 3-2. *Diagram of a fixed-crest barrier with 61 cm (24 in) of hydraulic head with* ***(A)*** *a vertical differential between crest height and tailwater elevation of 45 cm (18 in) and* ***(B)*** *no vertical differential between crest and tailwater. Sea lamprey must climb out of the water to pass condition* ***(A)*** *but can swim over the barrier in condition* ***(B)****.*

3.2. Installations of fixed-crest barriers in the Great Lakes basin

There are 402 (338 existing, 39 purpose-built, and 25 modified) fixed-crest structures acting as lowermost barriers in the Great Lakes. Barriers are constructed of a variety of materials including wood timbers, gabion baskets, steel sheet piling, poured concrete, rip rap, armor stone, or combinations of these materials (Fig. 3-3). A number of newly constructed fixed-crest barriers, like the Still River Barrier on Lake Huron, have aluminum stoplog crests for future flexibility, but are not seasonally operated. In its simplest form, a purpose-built fixed-crest barrier can be created by modifying the bedrock of the river bottom to create a sufficient vertical drop, as what was done in the French and Manitou River in Ontario.

Figure 3-3. *Examples of fixed-crest barriers: (A) purpose-built sheet pile barrier in Trail Creek, IN (Lake Michigan); (B) purpose-built sheet pile barrier at the Carp Lake outlet, MI (Lake Michigan); (C) upstream view and (D) downstream view of purpose-built sheet pile barrier in the Still River, ON (Lake Huron); (E) purpose-built concrete barrier with natural falls in the Wolf River, ON (Lake Superior); and (F) modified concrete Streetsville Dam in the Credit River, ON (Lake Ontario)(although repaired, sea lamprey have regularly escaped since 1980). Photos courtesy of the Great Lakes Fishery Commission and Fisheries and Oceans Canada.*

3.3. Design best practices for fixed-crest barriers

The main design requirements are (SLBTT, 2000):

- The barrier maintains a vertical differential of 45 cm (18 in) from the barrier crest to the surface of the tailwater up to as high a flood event as possible given site constraints (i.e., flood conveyance, public safety, property issues, etc.)
- A minimum 15 cm (6 in) overhanging lip installed on the barrier crest.
- Staging pool for potential upstream passage of fishes with strong leaping ability.

3.4. Applications

Detailed hydraulic and hydrologic analysis are required on a case-by-case basis to determine the feasibility of a fixed-crest barrier to cost effectively block sea lamprey. Fixed-crest barriers are generally suitable for sites where riverbed slope is high and there are existing barriers and or natural falls. Factors determining fixed-crest barrier feasibility include potential loss of vertical differential due to changes in watershed hydrology or lake levels, potential formation of an impoundment upstream, and acceptance from the community (when in an urban setting). Generally, water impoundments are restricted by provincial and state dam safety regulations. Barriers that create impoundments can also cause numerous physical and chemical changes to the river. Impoundments cause sediments to settle and, depending on the depth of water release, affect temperature regimes and dissolved oxygen levels, that is, water withdrawn from deep impoundments can be colder than normal and have low dissolved oxygen levels (Ward and Stanford, 1987). Small, low-head, structures with surface water releases where water flows over a fixed-crest can also affect temperature regimes by drawing warmer surface water. A study of several small dams in Michigan revealed that such structures can increase downstream water temperatures by as much as 5°C, which can cause shifts in downstream fish and macroinvertebrate communities (Lessard and Hayes, 2003).

Low-head dams and similar structures (e.g., fixed-crest barriers) can be susceptible to dangerous flow conditions that can pose a serious drowning hazard (Leutheusser & Birk, 1991). In conditions where the tailwater level rises above the crest of a structure, submerged hydraulic jumps, areas of flow dominated by vertical circulation and commonly referred to as "hydraulics" by canoeists, can form. These conditions are dangerous because objects or people can get entrained in the jump and trapped underwater near the barrier (Leutheusser & Birk, 1991). This phenomenon is not restricted to new barriers as several drowning incidents contributed to the removal of the existing barrier at the Shiatown Dam in the Shiawassee River, MI (Lake Huron) (Shiatown dam history from 1840 to 2016, 2018). Dangerous flow conditions at fixed-crest barriers is now considered in the design process and can be mitigated through proper hydraulic analysis.

3.5. Fixed-crest barrier effects on species and life stages

Fixed-crest barriers block upstream movement of adult sea lamprey ('target species') as well as many non-target species (Porto et al., 1999). Species that have limited leaping ability are particularly affected. Fixed-crest barriers cannot block downstream movement of juvenile sea lamprey, but could be modified to do so. Purpose-built low-head fixed-crest barriers feature jumping pools that allow steelhead (*Oncorhynchus mykiss*) and other Pacific salmons (*Oncorhynchus* spp.) to jump over the barrier, but are largely ineffective at passing non-jumping species. Experimental trials with wetted ramps suggest that ramps inclined between 10-20° may have potential to selectively pass small (85-550 mm total length) native fishes like creek chub (*Semotilus atromaculatus*) and white suckers (*Catastomus commersonii*) while blocking sea lamprey (Sherburne and Reinhardt, 2016).

4. Seasonal- and adjustable-crest barriers

4.1. Description of seasonal- and adjustable-crest barriers

Adjustable-crest barriers are similar to fixed-crest barriers but the crest height can be adjusted manually or automatically. Crest height adjustment is necessary at sites where greater flood conveyance is needed under high flow conditions (i.e., lower crest to increase spillway capacity and reduce flooding upstream) and sites that experience large fluctuations in tailwater levels (i.e., raise crest to maintain a 45 cm (18 in) vertical differential between crest and tailwater) (SLBTT, 2000).

Adjustable-crest barriers also have the advantage that they can be seasonally operated. Sea lamprey movement only needs to be blocked when adults are moving into tributaries to spawn and actively challenging the barrier. In some cases, sea lamprey move into tributaries as early as the fall prior to spawning. For the remainder of the year, sea lamprey are not present or no longer challenging the barrier and the barrier can be removed or crest lowered to pass flow, debris, sediment, boats, and non-jumping resident fish. Although year round barrier operation is the SLCP standard to minimize the risk of sea lamprey escapement and operational cost, seasonal operation may need to be negotiated with partner agencies to move a project forward (SLBTT, 2000). Seasonal operation results in an agreed upon risk that infestation might occur from early or late season migrating sea lamprey.

The benefit of a seasonally operated barrier is dependent on the differentiation between movement phenology of sea lamprey and non-target species (Klingler et al., 2003). Velez-Espino et al. (2011) demonstrated that due to an overlap of migration timing between sea lamprey and non-target species (Fig. 4-1A), a seasonal-barrier operated for a duration of 75 days, which is long enough to block 99% of adult sea lamprey, would result in blockage of 44-100% of migratory runs of non-target species (Fig. 4-1B). Velez-Espino et al. (2011) also suggested that the duration of an active barrier may impact non-target species production more than sea lamprey. Fishways have been paired with seasonal-barriers in an attempt to enhance non-target passage (Pratt et al., 2009).

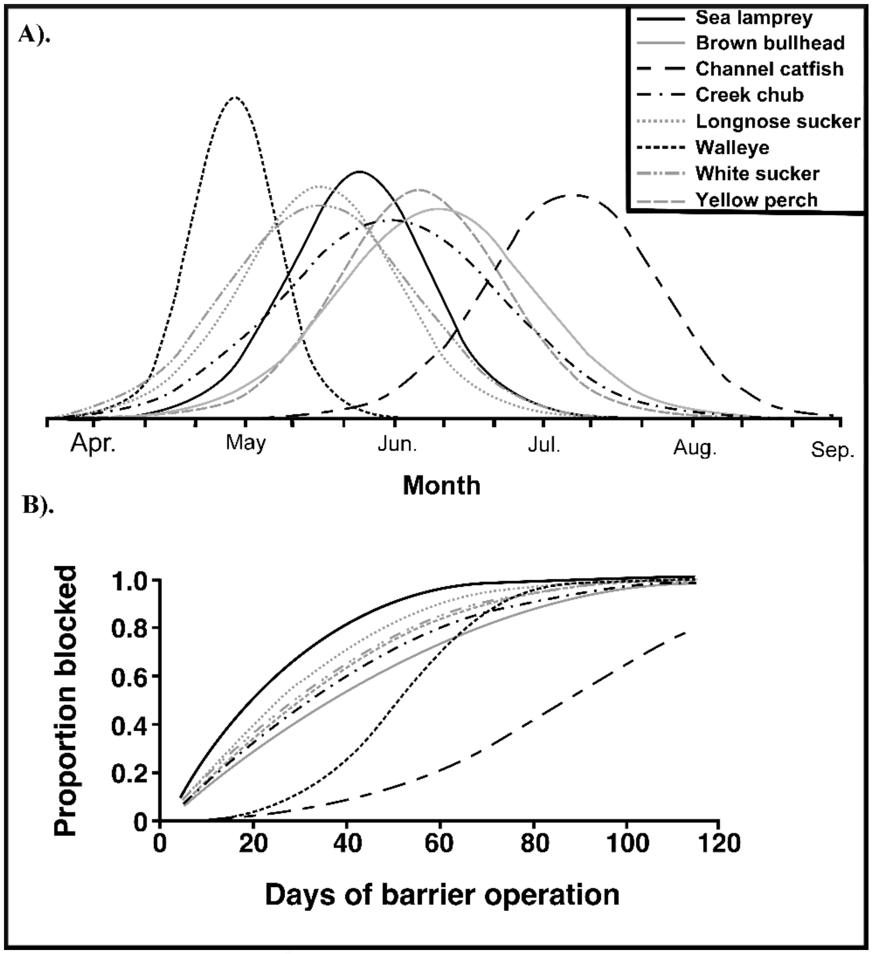

Figure 4-1. *(A) Overlap between migration phenologies of eight spring spawning species commonly found in Great Lakes tributaries and sea lamprey and (B) proportion of species blocked depending on duration of barrier operation. Figure adapted from figures 2 and 3 in Velez-Espino et al. (2011).*

4.2. Installations in the Great Lakes basin

Twelve purpose-built or modified adjustable-crest and seasonal-barriers function as lowermost barriers in tributaries of the Great Lakes (six in US and six in Canada). Note that not all adjustable-crest barriers are operated seasonally, and not all seasonal-barriers have adjustable-crests. For example, Cobourg Creek, ON has a fixed-crest barrier with a seasonally operated fishway. One seasonally operated electrical barrier is installed in the Ocqueoc River, MI (See Section 7.2 for more details). Seasonal- and adjustable-crest barriers typically consist of wooden or metal stoplogs (Fig. 4-2A and B), gates, or inflatable crest weirs (e.g. Obermeyer gates; Fig. 4-3). Canada hosts the only two installations of inflatable crest barriers for sea lamprey control in Great Lakes tributaries, the Big Carp River, ON on Lake Superior and Big Creek River, ON on Lake Erie (Fig. 4-4A - D). Since installation in 1995, both sites experienced numerous technical malfunctions and power failures that led to escapement of sea lamprey, particularly from Big Creek. These mechanized systems rely on a chain of sensors, processes, and computerized control systems, each vulnerable to failure, to function properly. The experiences at Big Carp River and Big Creek highlight the need for redundancy in highly mechanized systems (see Fig 4-4D for steel beam used to operate the inflatable crest barrier as a fixed-crest barrier when the computerized control system failed at the Big Creek River barrier). Due to recent advances in system controls and power redundancies, inflatable crest barriers are still considered a potential technology for sea lamprey control.

Figure 4-2. *Example of a manually operated seasonal-barrier in Orwell Creek, tributary of the Salmon River, NY, with (A) stoplogs installed during sea lamprey migration and with (B) stoplogs removed. Photos courtesy of Fisheries and Oceans Canada.*

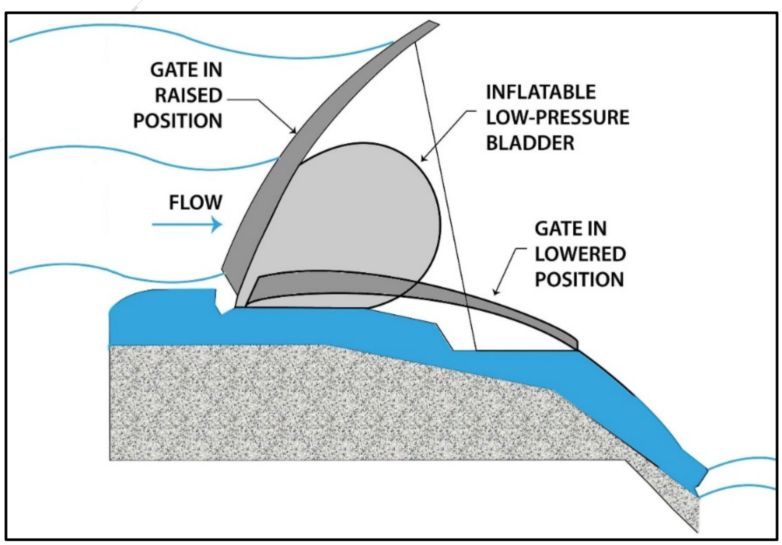

Figure 4-3. *Cross-sectional view of typical Obermeyer gate with inflatable bladder. Image courtesy of the city of St. Cloud, MN (http://www.ci.stcloud.mn.us).*

Figure 4-4. *Big Carp River, ON (Lake Superior) inflatable crest barrier, (A) not operating with inflatable barrier down, (B) in the operating position with inflatable barrier raised, (C) inflatable barrier raised during flooding, and (D) beam used to lift the inflatable-crest barrier when the computerized control system failed at the barrier on the Big Creek River, ON (Lake Erie). Photos courtesy of Fisheries and Oceans Canada.*

4.3. Design best practices

The main design requirements of the physical structure of seasonal- or adjustable-crest barriers are similar to those of fixed-crest barriers (SLBTT, 2000):

- The barrier maintains a vertical differential of 45 cm (18 in) from the barrier crest to the surface of the tailwater at a specified flood event.
- A 15 cm (6 in) overhanging lip installed on the barrier crest.
- A redundant power supply or alternate means to operate the barrier included with mechanized barrier operation.
- The operating window of the barrier is identified by the SLCP using a combination of (1) stream temperature (> 5ºC), (2) historical trap catches from target stream or surrogate

stream, (3) distance of barrier from stream mouth, (4) gradient, and (5) isothermic zone (SLBTT, 2000).

- Staffing and schedule of operation is negotiated between control agents and natural resource agencies responsible for fishery management.
- Appropriate hydraulic and geotechnical analyses are performed to ensure the integrity of the stream and barrier are not compromised during operation.

4.4. Applications

Adjustable- and seasonal-barriers are suited for many of the same applications as standard fixed-crest barriers. They are best suited to sites where competing interests in fish passage are considerable, boat navigation is required, maintaining natural channel morphology (i.e. sediment and large woody debris transport) is preferred, and standard fixed-crest barriers cannot pass high flows without causing unacceptable levels of flooding. In the case of mechanized barriers, the need for substantial supervision and maintenance make them ill-suited for remote locations where access is difficult or power is not available. While mechanized barriers (e.g., inflatable-crest barriers) are considered to be under development, manually operated barriers are essential elements of the SLCP.

4.5. Barrier effects on species and life stages

Similar to fixed-crest barriers, adjustable- and seasonal-barriers block upstream movement of adult sea lamprey (target) and non-target species (both migratory and resident) with limited leaping ability when the barriers are raised in the operating position. Adjustable- and seasonal-barriers cannot block downstream movement of juvenile sea lamprey, but could be modified to do so. Blockage of non-target fishes can be reduced when seasonal-barriers are only operated when adult sea lamprey are challenging the barrier. In addition to seasonal operation, adding trap and sort fishways can further reduce impacts on non-target fishes; however, manual sorting with traps is still needed to ensure sea lamprey do not escape (Pratt et al., 2009).

5. Weirs and screens

5.1. Description of weirs and screens

Barriers comprised of weir panels or mesh screens that block sea lamprey while still passing water have a similar history in sea lamprey control as fixed-crest barriers. Applegate and Smith (1951) described the functionality and application of various types of portable and permanent barriers featuring permeable screens. Commonly constructed using wood frames and fine wire mesh, weir and screen barriers were inexpensive to build, but difficult to maintain under high flows. When debris collects on wire mesh, water can no longer pass through, and the barrier is inundated. There were two basic types of mesh screen barriers, each aimed at different life stages of sea lamprey. Vertical screen barriers were primarily used to block adult sea lamprey moving upstream and sometimes direct them towards traps. Inclined plane screen traps were used to block and capture downstream migrating juvenile sea lamprey. An inclined plane screen trap was installed (1950) in the Carp Lake River, MI, (Lake Huron) (Fig. 5-1) and Big Garlic River, MI (Lake Superior) (Applegate and Smith, 1951) but both have since been removed. Although no permanent barrier in the Great Lakes basin uses only a screen design, screens are still used extensively in trap design and small barriers in fishways.

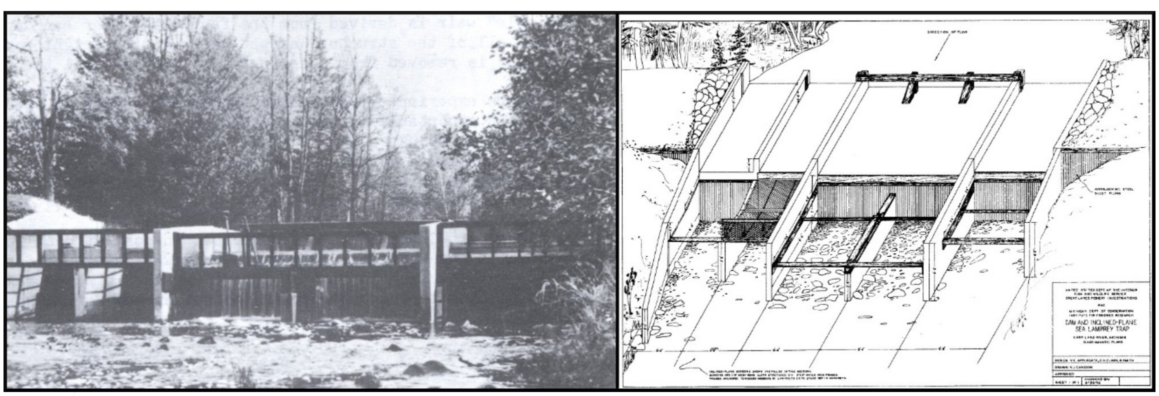

Figure 5-1. *Inclined plane sea lamprey trap installed in the Carp Lake River, MI (Lake Huron) (left) and typical design (right). Images from Applegate and Smith (1951).*

Recent efforts have sought to use resistance weirs to control and aid trapping of sea lamprey (Klingler, 2015). Resistance weirs are primarily comprised of an array of rectangular panels, made of evenly spaced tubular pickets, aligned parallel to the direction of flow. The upstream end of each panel is pinned to the river bottom while the downstream end is freely lifted and floated above the water surface by resistance boards (Fig. 5-2). Resistance weirs are advantageous over fixed-crest barriers by allowing water, debris, and boats to pass, yet inhibit upstream migration. Unlike vertical screen barriers, resistance weirs are also self-cleaning —as debris builds up, the panels will be submerged briefly and debris washed off by the flow. Resistance weirs have been used successfully as counting weirs for Pacific salmon on the U.S. west coast (Stewart, 2002). Similar to fixed-crest barriers, resistance weirs can be used to guide sea lamprey to traps integrated into the structure. While a promising technology, the effectiveness of resistance weirs to block sea lamprey movement is still under investigation and they have not yet been applied as a barrier in the Great Lakes.

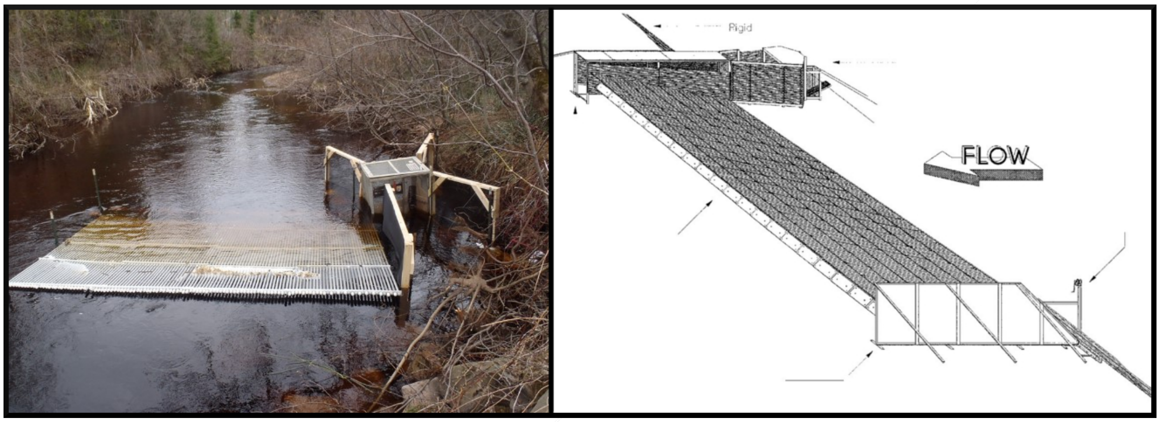

Figure 5-2. *Experimental installation of a resistance weir in the Marengo River, WI (left) and typical schematic of a resistance weir (right). Images courtesy of Greg Klinger – US Fish and Wildlife Service.*

5.2. Installations in the Great Lakes basin

Currently, no permanent installations of resistance weirs or screens for sea lamprey control occur in the Great Lakes basin. A vertical screen barrier is constructed and operated in the Little Thessalon River, ON (Lake Huron) to aid in sea lamprey trapping (Figure 5-3). A hydropower facility is located upstream of the vertical screen; therefore, sea lamprey escapement is not possible. A resistance weir has been deployed by Toronto Region Conservation Authority in Duffins Creek, ON (Lake Ontario) to capture migrating Atlantic Salmon (OMNRF, 2016). A resistance weir to facilitate trapping of adult sea lamprey in the Cheboygan River watershed, MI (Lake Huron) will be installed as a proof-of-concept in 2018 in the Pigeon River, MI.

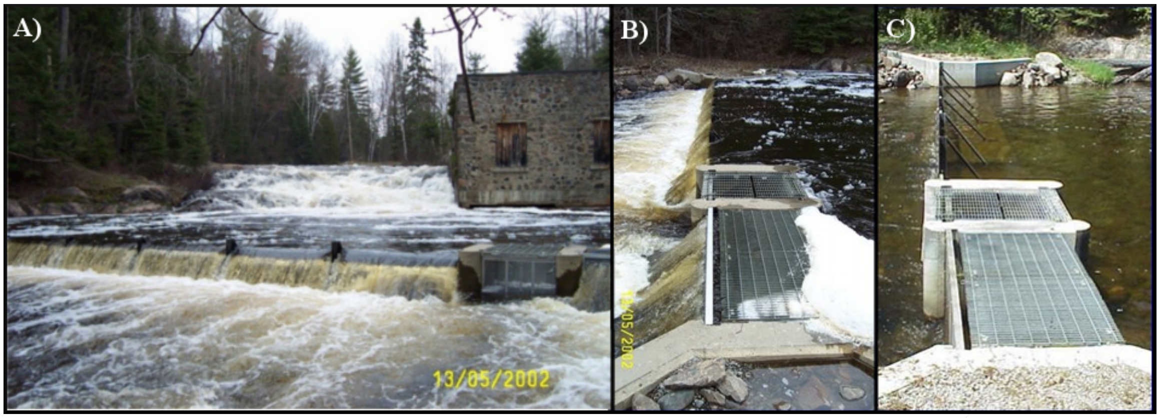

Figure 5-3. Vertical screen barrier for trapping in Little Thessalon River, ON (Lake Huron); (A) front view during high flow, (B) side view during high flow, and (C) side view during low flow. Photos courtesy of Department of Fisheries and Oceans Canada - Sea Lamprey Control Centre.

5.3. Design best practices

The main design requirements for a vertical mesh screen barrier are:

- Steel grates or racks with less than or equal to 1.3 cm (0.5 in) spacing.
- If possible, build the structure at an angle to flow or in a "V" shape to increase hydraulic conveyance and to direct debris towards the shoreline.
- Applegate and Smith (1951) required downstream inclined screens have at least 1.5 m (5 ft) of hydraulic head to prevent tailwater from interfering with installation or operation.

Because resistance weirs have only been used experimentally, best practice guidelines have not been developed. The following general design criteria are based on experimental data.

- Site is located in a relatively straight section of stream with a uniform and level river bottom consisting of bedrock, gravel, or cobble.
- Weir panels create a fence-like barrier and are typically constructed of tubular pickets (e.g. 2.5 cm (1 in) diameter PVC pipe).
- The resistance board is constructed of a buoyant material (e.g., wood) that can be protected from water damage.
- Weir panel frames and attachments are made of rigid framing material (e.g. aluminum members).

- A 20 cm (8 in) diameter PVC pipe was used at the upstream end of the panels for sea lamprey to swim into and be captured in a trap at the Marengo River, WI test site (Klingler, 2015).

5.4. Applications

Vertical mesh screens are no longer in use as a sole barrier to sea lamprey due in part to the difficulty of keeping screens clear of debris (Applegate and Smith, 1951). While early designs were subject to high erosion potential during floods, current design standards can reduce this risk with erosion protection (i.e. rip rap). Although still under development, resistance weirs have potential for sites meeting the criteria listed in Section 5.3, and where there is a need to block and remove sea lamprey during high water events.

5.5. Barrier effects on species and life stages

Both vertical screen and resistance weirs (permanent and portable) block passage of adult sea lamprey (Hunn and Youngs, 1980; Klingler, 2015) and many non-target species. Inclined plane screen traps capture recently metamorphosed sea lamprey moving downstream (Applegate and Smith, 1951).

6. Velocity barriers

6.1. Description of velocity barriers

Hydraulic conditions can be manipulated to create regions of fast flowing water that cause fish to exhaust their physiological swimming capabilities during passage attempts (i.e., velocity barriers). Velocity barriers can be characterized by extremely high velocities over short distances or more moderate velocities over a greater distance. In this way, velocity barriers are a product of not only water velocity, but also swimming ability. To assess the possibility of water velocity alone to block fish passage, it is critical to characterize swimming performance.

Performance can be characterized as the ability to traverse a velocity barrier (Haro et al., 2004), and results from the joint factors of endurance (the relationship between swim speed and time to fatigue) and behavior, particularly selected swim speed and attempt rate (Castro-Santos, 2004, 2005; Castro-Santos et al. 2013). Fish swimming endurance is often categorized by one of three modes: sustained, prolonged, and burst (Beamish 1978). Sustained swimming is fueled aerobically and can be maintained near indefinitely. Prolonged swimming is fueled by a mixture of anaerobic and aerobic metabolism that can be maintained for a range of speeds. This range is species-specific, but is typically considered to span durations of 20 s – 200 min (Brett, 1964; Castro-Santos & Haro, 2006; Castro-Santos et al., 2013), while burst mode swimming is fueled entirely by anaerobic metabolism and comprises fast starts and sprints (typically thought to be speeds resulting in fatigue in < 20 s; Beamish, 1978). The relative speed and fatigue time associated with each swimming mode varies with species, body morphology, fish size, condition, water temperature, water quality, and other variables (Adams and Parsons, 1998). The relationship between swimming speed, U_s, and fatigue time, T, for prolonged and burst swimming modes generally follow a log-linear model

$$\ln T = a + bU_s, \quad b < 0 \tag{1}$$

where a and b are the slope and intercept coefficients, unique to each mode and species, fit from experimental data. In some species the distinction between prolonged and burst swim modes is not clear and a single set of coefficients can be used for both. Typically, recovery from exhaustive bouts of prolonged and burst swimming can take several hours (See review in Kieffer, 2000).

While fish swimming fatigue is typically viewed as a continuous process (i.e., fish swim all out until exhaustion), sea lamprey employ intermittent locomotion by attaching to surfaces to recover from fatigue without losing ground (Kramer & McLaughlin, 2001). Thus, for a velocity barrier to be successful against sea lamprey passage; it must either prevent attachment or maintain conditions that exceed the maximum swim speed of sea lamprey.

Velocity barriers hold promise in the SLCP as there is potential to exploit the difference in swimming performance between sea lamprey and other fishes. Sea lamprey employ an anguilliform swimming mode (requires whole body undulations to generate thrust) that is generally slower and less efficient at high speed swimming compared to other body forms (Lighthill, 1969; Sfakiotakis et al., 1999; Borazjani & Sotripoulos, 2010). There have been several attempts to categorize sea lamprey swimming performance using some variation of swim tunnel testing (Beamish, 1974; Hansen, 1980; Bergstedt, 1981; McAuley, 1996). Despite variability in testing apparatus and environmental conditions, an approximate trend in swimming performance is apparent when swimming speed is normalized to body lengths per second (BL/s) (Fig. 6-1). However, recent advances in swimming performance testing and analysis techniques (Castro-Santos, 2005, 2006; Castro-Santos et al., 2013) have rendered any conclusions from historical data somewhat obsolete. This is because the chambers typically used to study swimming ability restrict important behaviors (Tudorache et al., 2007; Tudorache et al., 2010); when allowed to swim volitionally, species consistently outperform widely accepted data, often by a factor of two or more (Castro-Santos et al., 2013; Sanz-Ronda et al., 2015). In response, the GLFC has funded work by Castro-Santos, U. S. Geological Survey Conte Lab, to conduct an in-depth investigation into sea lamprey swim performance using a state-of-the-art open flume that allows for volitional fish entry and swimming behaviors. Another ongoing study by Hoover et al. at the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) is also investigating the swimming performance and attachment behaviors of sea lamprey in a large swim tunnel.

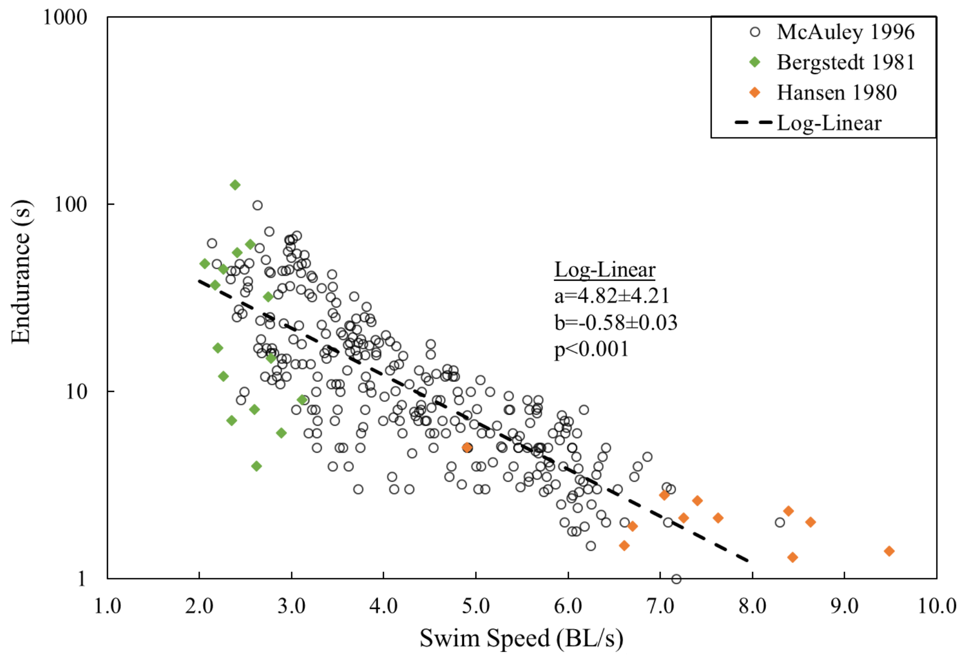

Figure 6-1. *Swimming performance data collected from McAuley (1996), Bergstedt (1981), and Hansen (1980). Swimming speeds are normalized by total body length and tests occurred over a range of water temperatures (6-24ºC). A log-linear regression following Eq. 1 was fit to the data for demonstration purposes only.*

Unlike most native species in the Great Lakes, sea lamprey can attach to surfaces with their oral disc. Generating a suction force up to 70 kPa (Adams and Reinhardt, 2008), sea lamprey can hold their position under high velocities, conserving energy for short bursts of high speed swimming. Currently, it is unknown how this suction force relates to the forces imposed on the sea lamprey by flow. Adam and Reinhardt (2008) found that surfaces with narrow grooves of 1 mm width and 3 mm depth can prevent sea lamprey from creating a lasting attachment. When applied to a velocity barrier, the surface treatment forces sea lamprey to swim against high water velocity, while depriving them of the opportunity to rest.

Water depth also plays an important role in a sea lamprey's ability to generate sufficient thrust to overcome water velocity. Reinhardt et al. (2009) found that sea lamprey not fully submerged (i.e., dorsal fins out of the water) were unable to generate enough propulsion to scale a short (~2 ft long) wetted acrylic ramp with an inclination >20º, even using intermittent locomotion. Here, the sea lamprey was prevented from swimming and climbing over the inclined surface due to shallow water depths and high water velocity.

6.2. Installations in the Great Lakes basin

Currently, there are no sea lamprey barriers in the Great Lakes basin that were purposefully designed as velocity barriers. High velocities likely play a role in blocking sea lamprey at some fixed-crest barriers when inundated (i.e., vertical differential falls below 18 in), although the number of sites where this occurs in currently unknown. In 1993, a velocity barrier pilot study was conducted on the McIntyre River, ON (Fig. 6-2). The McIntyre River barrier design was based on swimming performance tests with adult sea lamprey and scaled hydraulic models (McAuley, 1996). Initial reports on the barrier indicated success, but sea lamprey escapement was observed within a year. Although the exact cause of failure is unknown, a combination of barrier inundation, vandalism, and design defect (i.e. unable to maintain required velocity on the ramp during low flow periods) likely contributed. The McIntyre River barrier also had the unintended consequence of blocking gravid white sucker passage due to their larger cross-sectional area (Chase, 1996).

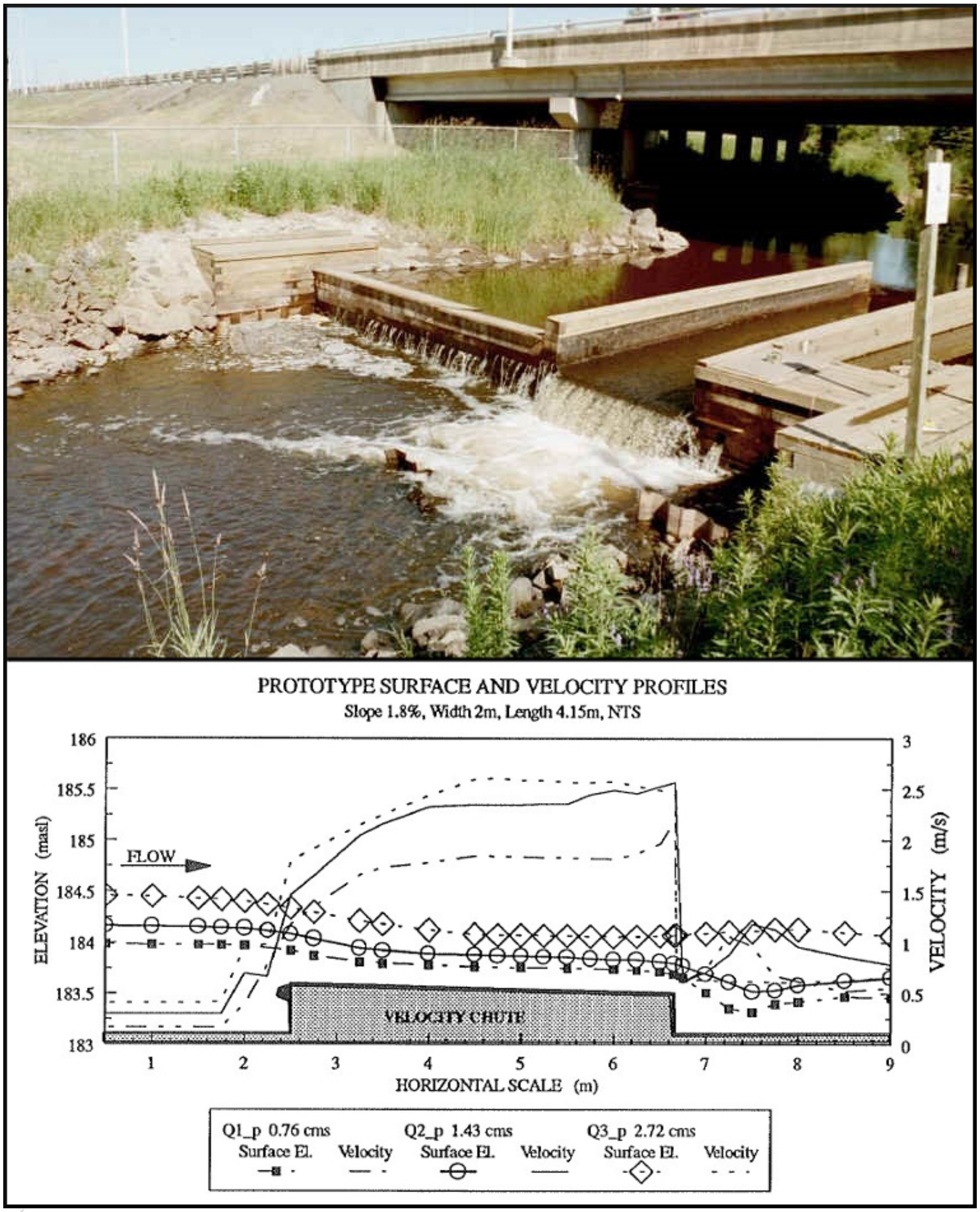

Figure 6-2. *Velocity barrier installation on the McIntyre River, ON (top) and velocity and water surface measurements obtained from scaled hydraulic modelling (bottom). The timber crib structure consisted of a fixed-crest barrier (left side) and velocity chute (right side). Field evaluations considered sea lamprey and white suckers. Image courtesy of McAuley (1996).*

Recent interest in velocity barriers has been driven by proposed replacement of the 6th Street Dam on the Grand River in Grand Rapids, MI. Here, an inflatable crest barrier is proposed to block sea lamprey passage during normal flows, but would act as a velocity barrier when the inflatable crest is lowered during high flows to address flood conveyance and public safety. In addition, reconstruction of the Harpersfield Dam in the Grand River, OH (Lake Erie) and Springville Dam in Cattaraugus Creek, NY (Lake Erie) incorporate velocity features (i.e., sloped dam faces that maintain high velocities) into their design.

6.3. Design best practices

Velocity barriers are not currently used in the SLCP, thus best practice guidelines are unavailable. The following general design criteria and highlighted research needs are based on experimental data:

- Barrier has a surface treatment that prevents sea lamprey attachment (Adams and Reinhardt 2008).
  - Frequent inspection and routine maintenance are required to prevent fouling of the surface treatment.
- Hydraulic analyses must be performed to accurately characterize water velocity profiles in all three dimensions. A factor of safety may be required for unexpected conditions (i.e., debris or changes to substrate roughness) that could compromise the velocity distribution throughout and downstream of the barrier.
- Improved swimming performance curves must be obtained for sea lamprey and any non-target species desired to pass the barrier.
  - More research is needed to identify important covariates and their influence on predictions of passability.
  - Targeted water velocities are estimated using Eq. 1, but more research is needed to understand variability in swimming speed so it can be incorporated into risk-averse designs.

6.4. Applications

Velocity barriers are not currently used due to the uncertainty in sea lamprey swimming ability and lack of success at the McIntyre River pilot study. Originally, velocity barriers were not considered in the SLCP due to the misconception that velocities in excess of the maximum swim speed of sea lamprey (nearly 3 m/s at the time) were required, and a hydraulic head greater than 12 inches would be needed to produce such velocities, which by itself was thought to be a barrier to sea lamprey passage (Hansen, 1981). Furthermore, there were no solutions to the issue of intermittent locomotion (i.e., sea lamprey attaching to the surface of the barrier and resting). Identifying surface treatments or materials that prevent sea lamprey attachment and are not compromised by environmental conditions or deteriorate over time remains a research priority.

Although additional research on swimming performance of sea lamprey and many non-target, non-jumping fish are still needed, velocity barriers have potential to be useful technologies where debris passage, navigation, non-target fish passage, and flood conveyance are desired.

6.5. Barrier effects on species and life stages

Velocity barriers can be designed to target a wide range of fish sizes and species, including adult sea lamprey. The advantage of a velocity barrier lies in its ability to differentially pass fish based on their swimming performance (Fig. 6-3). However, caution must be used in the design as a velocity barrier for strong swimming fish will also block any fish of lesser swimming ability (i.e., small and large, gravid individuals). This is further complicated by the lack of swimming performance data available for many Great Lakes fishes, under varying environmental conditions or life stages. While rapid water accelerations created near the upstream end of water conveyance structures (i.e., velocity barrier) can deter passage of some downstream swimming fish (Kemp et al., 2008), velocity barriers are generally ineffective at blocking downstream migrating fish.

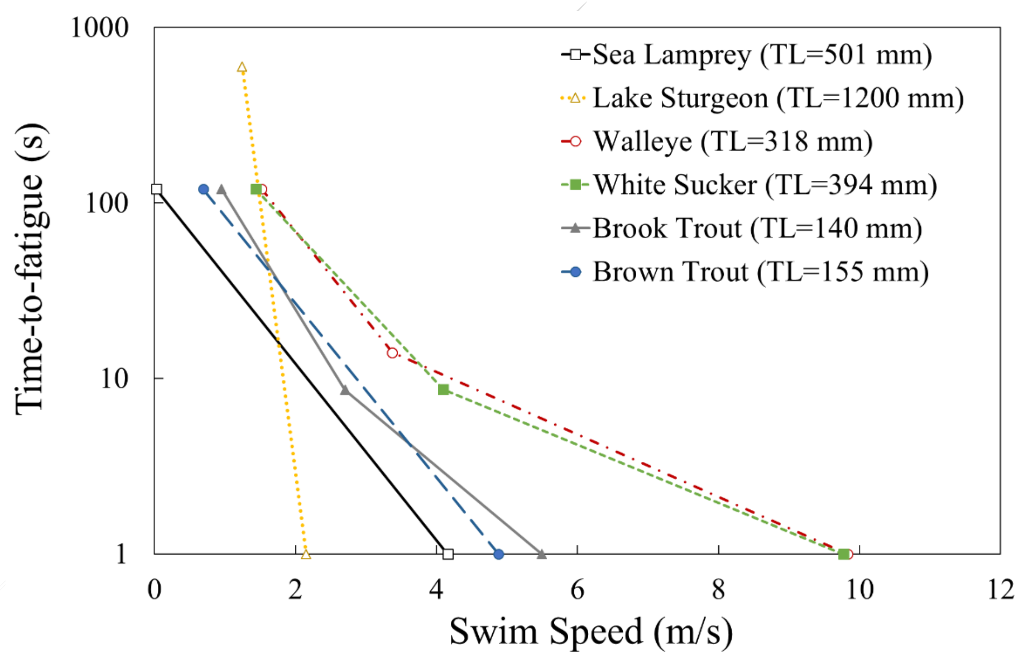

Figure 6-3. *Comparison of swimming performance curves of fishes found in Great Lakes tributaries. Viewed from left to right, species with greater swimming capabilities will be situated towards the right of the plot. The swimming performance curve for sea lamprey was generated from data in Fig. 9; lake sturgeon from Peake et al. (1997); walleye (Sander vitreus) and white sucker from Castro-Santos (2005); and brown trout (Salmo trutta) and brook trout (Salvelinus fontinalis) from Castro-Santos et al. (2013). Swim speeds normalized by body length were*

transformed to m/s using the average body length of the species used in each study. Data are for qualitative comparisons only as data collection methods and testing apparatus varied.

7. Electrical barriers

7.1. Description of electrical barriers

Low voltage electricity can serve as a potential barrier to fish passage because a portion of the energy applied to water is transferred to fish which can lead to taxis (forced swimming), immobilization, and possibly trauma (Noatch and Suski, 2012). Electrical barriers have a long history in the SLCP, with the first systems introduced to the Great Lakes in the 1950s (Hunn and Youngs, 1980) and reached a peak of 162 sites by 1960 (Lavis et al., 2003). While use of electricity as a standalone barrier to sea lamprey has declined over the last few decades, research continues on the potential of portable electrical systems to deter sea lamprey passage and to enhance trapping through electrical guidance.

The first electrical barriers for sea lamprey control used an alternating current (AC) electrical field dispersed throughout the water column using an electrode array that featured both bottom and vertically mounted electrodes (McLain et al., 1965). Although effective at blocking adult sea lamprey, the AC barrier caused excessive mortality in non-target species (Erkkila et al., 1956). In response, pulsed direct current (PDC) electrical barriers were introduced to reduce, but not eliminate, non-target mortality (McLain et al., 1965). In the late 1980's renewed interest in PDC electrical barriers began with the advent of Smith-Root's Graduated Field Fish Barrier (GFFB) (Katapodis, 1994). The advantages of the GFFB system over original barrier designs was the use of a bottom electrode mount that did not catch debris or ice and gradual introduction of the electrical field, reducing the potential for non-target mortality. Experiments on the GFFB in the Jordan River, MI demonstrated that with appropriate pulse settings, the system can be a complete barrier to sea lamprey passage with minimal to no apparent damage to sea lamprey or non-target fish (Swink, 1999). At peak, three GFFB systems were in operation (e.g., Jordan River, Pere Marquette River, and Ocqueoc River) for sea lamprey control. Due to poor hydraulic conditions (i.e., low velocity gradient and prone to floods) at two of the barrier sites, only the Ocqueoc River GFFB system remains.

Despite a decline in use of standalone electrical barriers, considerable effort has gone into testing and deploying portable vertical mount electrodes with PDC to guide both upstream swimming adult sea lamprey and downstream swimming juvenile sea lamprey into traps (Johnson et al. 2014; Johnson and Miehls, 2014; Johnson et al., 2016) (Fig. 7-1). Operating under the same principles as permanent PDC systems, the vertical electrodes produce a more consistent voltage gradient throughout the water column and a surface mounting system allows debris to be shed underneath. While initial results indicate an ability to block nearly all upstream migrating sea lamprey in the Ocqueoc River (Johnson et al., 2014), further management-scale tests are needed to confirm complete blockage.

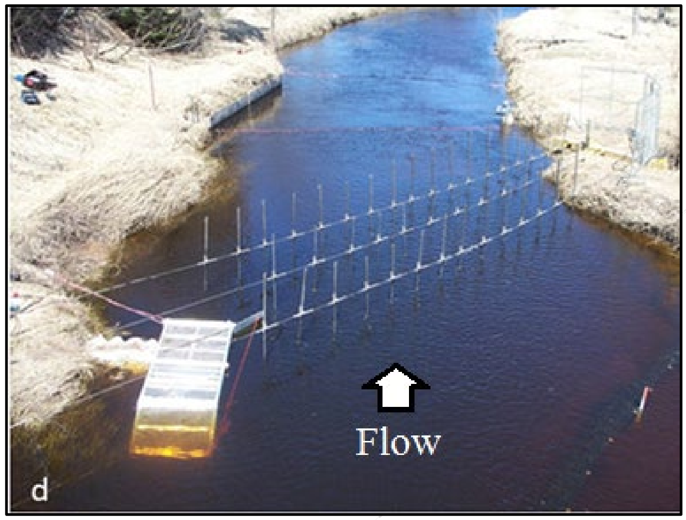

Figure 7-1. *Experimental application of a portable, vertical mount pulsed direct current (PDC) electrical barrier with trap in the Chocolay River, MI. Photo courtesy of Johnson et al. (2016).*

7.2. Installations in the Great Lakes basin

The combined GFFB and fixed-crest barrier on the Ocqueoc River, MI is the only electrical barrier for sea lamprey control currently in use in the Great Lakes (Fig. 7-2). Installed in 1999, the electrical barrier is only energized when the 45 cm (18 in) vertical differential between tailwater and crest is compromised due to high water. At all other times, the electrical barrier is not energized and the system functions as a standard fixed-crest barrier. Although not installed directly to benefit sea lamprey control, four additional GFFB electrical barriers are installed in the Chicago Area Sanitary and Shipping Canal (CSSC) to prevent passage of invasive fish like Silver and Bighead carps (*Hypopthalmichthys spp.*) between the Great Lakes and Mississippi River Basin (Moy et al., 2011; Davis et al., 2017). While seemingly effective at blocking large fish (i.e., large fish experience a greater voltage change than small fish), recent studies have demonstrated that small fish (total length ~ 100 mm) can traverse the barriers when the electrical field is compromised by barge passage (Davis et al., 2017).

Figure 7-2. *The combined GFFB and fixed-crest barrier on the Ocqueoc River, MI. Note the electrodes mounted along the barrier crest and vertical side walls. Photo courtesy of the Great Lakes Fishery Commission.*

7.3. Design best practices

The design of permanent PDC electrical barriers generally follows manufacturer recommendations, but the following points should be noted:

- A site with a steep shore line can minimize the size of the system and lower the risk of the river leaving its banks.
- A concrete control section to embed electrodes.
- Sufficient and redundant power source.
- A setting with a 2-ms pulse duration (in milliseconds) and 10 pulses/s completely blocked sea lamprey during a test in the Jordan River, MI.

Management scale applications of portable PDC electrical barriers have not yet occurred in the Great Lakes basin, so best practice guidelines are not available. The following general design criteria are based on experimental data.

- Operation and design follows manufacturer recommendations.
- Sites are routinely cleared of debris.
- A setting of five 1.8-ms pulses with four 8.2-ms off-periods in between pulses (resulting in a duty cycle = 9%) guided 75% of sea lamprey into adjacent traps in the Chocolay River, MI.

7.4. Applications

Only one permanent electrical barrier is in operation in the Great Lakes for sea lamprey control. At the Ocqueoc River, the electrical barrier essentially serves as a back-up to the fixed-crest barrier when the barrier becomes inundated during high flows. Electrical barriers could also be used to block sea lamprey movement in larger river systems where fixed-crest barriers are not feasible. Vertical mounted electrodes are advantageous for fish guidance because the electric field does not vary with depth, requires less power than grounded systems, and can be deployed quickly. The major areas of concerns with electrical barriers is the lack of species specificity, susceptibility to power failures, and public safety concerns or misconceptions. Any deployment of electricity in water poses some potential risk to human safety; however, many of the design features for modern electrical barrier systems provide for safe operation. Current barriers use direct current which is safer for humans and fish, and the duty cycle, amount of time the system is energized, is very low (2-9% duty cycle). There have been no reports of serious injury or fatalities related to electrical fish barriers.

7.5. Barrier effects on species and life stages

Electrical fields are non-selective. The amount of energy transferred to fish is dependent on species, size (i.e., small fish receive less energy than large fish), its orientation in the electrical field, and water conductivity. The permanent electrical barrier on the Ocqueoc River is intended to block upstream passage of adult sea lamprey. Portable systems with vertical mounted electrodes are also effective at blocking adult sea lamprey or guiding them into traps in rapid deployment situations (Johnson et al., 2016). While flow aids electrical barriers aimed at blocking upstream movement by washing stunned fish downstream, systems aimed at blocking/guiding downstream movement are more complex as any stunned fish would be inadvertently carried past the barrier. However, vertical mounted electrodes have been shown to be somewhat effective at guiding downstream swimming juvenile sea lamprey into traps in the lab (Johnson and Miehls, 2014).

8. Other non-physical barriers

8.1. Description of non-physical barriers

All barrier types described previously require some amount of physical infrastructure to support or act as a barrier to sea lamprey. A direct impact of the physical infrastructure is, to some degree, a modification of water flow and interaction with debris and boat navigation. Barrier technologies that utilize deterrent stimuli like sound, light, or chemicals (e.g., carbon dioxide, chemosensory cues) have been suggested for sites where effects on water flow are undesirable. The main advantage of non-physical barriers is the potential for taxon-specific responses without obstructing water flow (Noatch and Suski, 2012). The lack of a physical obstruction to movement emphasizes the need to understand how each stimulus affects individual species movement under a range of conditions. Because of this heightened awareness to potential failures, many non-physical barrier systems are still in research and development and have not been implemented in the SLCP. This section provides a brief description of non-physical barriers and guidance technologies using sea lamprey chemosensory cues, carbon dioxide, sound and bubbles, and lights. Application of non-physical barrier technologies is likely to be used in combination with proven technologies or for trap guidance.

8.2. Chemosensory cues

The potential use of chemosensory cues to attract (pheromones) or repel (alarm substances) adult sea lamprey has long been an emphasis of research in the Great Lakes (Teeter, 1980; Sorensen et al., 2005; Siefkes, 2017). These pheromones are naturally produced chemical substances that when released into the environment, affect the behavior or physiology of individuals of the same species. Sea lamprey migratory and spawning behaviors are strongly influenced by pheromones produced by larval sea lamprey and sexually mature males (Siefkes, 2017). These pheromones generally attract adult sea lamprey towards high quality spawning habitat and elicit sexual maturation. Laboratory and field studies have demonstrated that specific compounds from sea lamprey pheromones partially mediate upstream movement and when applied near a trap can increase catch rates by 10% (Johnson et al., 2013). As a result, one compound, 3-keto petromyzonal sulfate (3KPZS), was registered with regulatory agencies as a vertebrate pheromone biopesticide (Siefkes, 2017). In contrast, alarm cues are odors produced by dead or injured sea lamprey that have been shown to induce avoidance and flight responses in adult sea lamprey (Bals and Wagner, 2012). Laboratory and field studies have demonstrated that when alarm substances are applied alone or in conjunction with pheromones, migrating adult sea lamprey exhibit strong negative reactions (Bals and Wagner, 2012; Hume et al., 2015). While early chemosensory cue research has demonstrated great promise for applications to sea lamprey control, research continues to identify (1) key chemical compounds in pheromones and alarm substances that elicit the strongest response; (2) antagonists that can disrupt or block chemosensory communication; and (3) the most effective approach for field deployment (i.e., with traps at barriers or in open river scenarios).

8.3. Carbon dioxide

A non-physical barrier system that has recently been considered for control of adult and juvenile sea lamprey movement is carbon dioxide (CO_2). When applied to water, a portion of carbon dioxide will remain in solution while the rest hydrates to form carbonic acid which can dissociate, resulting in a reduction of water pH (Dennis et al., 2016). Dennis et al. (2016) found that both sea lamprey adults and juveniles displayed agitation (i.e., erratic swimming, elevated activity, and twitching) when concentrations of CO_2 exceeded 40 mg/L and experienced loss of equilibrium at concentrations above 120 mg/L. When tested in a shuttle-box design, adult sea lamprey would volitionally swim away from areas with concentrations at approximately 85 mg/L CO_2, while juveniles would swim away from areas with approximately 160 mg/L CO_2. Although the results are promising for use with sea lamprey, it is important to understand that CO_2 deterrents or barriers are not species specific. Kates et al., (2012) found that invasive bigheaded (silver and bighead) carp (*Hypohthalmichthys molitrix* and *H. nobilis*), bluegill (*Lepomis macrochirus*), and largemouth bass (*Micropterus salmoides*) all avoided areas with CO_2 above 100 mg/L. Before CO_2 can be utilized as a non-physical barrier tool for sea lamprey control, concerns over non-target impacts, water acidification, cost of CO_2 production, and regulatory permission (i.e., CO_2 would need to be registered with applicable regulatory agencies for pesticide applications) need to be addressed.

8.4. Sound and bubbles

Sound travels efficiently through water and is used by fish to mediate many life cycle functions. Several studies have shown that specific sounds can deter fish movement (Zielinski and Sorensen, 2017; Vetter et al., 2016; Wilson et al., 2008, 2011; Plachta and Popper, 2003; Welton et al., 2002; Knudsen et al. 1992) in a species specific and directional (i.e., not random dispersal) manner. Sea lamprey likely detect low frequency sounds (< 500 Hz) via the inner ear, a detection method conserved across all fish. However, the sensitivity and hearing range of sea lamprey is not well understood and is the focus of a recently GLFC funded investigation by the

Higgs laboratory at the University of Windsor. An early pilot study by Klingler and Mullett (2001) found sea lamprey avoided traps with sound generators producing 150-180 Hz sound. A follow up study by Miehls et al. (2017) investigated the ability of the Fish Guidance Systems Ltd. Bioacoustic Fish Fence (BAFF) to deter adult sea lamprey movement in a Y-channel choice test. The BAFF combines underwater sound projectors (pre-programmed to play chirps between 20 – 3000 Hz), air bubble curtain, and strobe light. The air bubble curtain served to entrain the sound produced by the sound projectors and reflect light from the strobes, creating a defined "wall" of sound and light to guide fish. Air bubble curtains alone have been found to deter movement of common carp (*Cyprinus carpio*), silver carp, and bighead carp when operated under specific air-flow rates and diffuser configurations (Zielinski and Sorensen, 2016). Miehls et al. (2017) found no significant change in sea lamprey channel choice during any combination of BAFF operation (sound, sound+bubbles, sound+light, bubbles, bubbles+light, bubbles+sound, light, and sound+bubbles+light) in a y-channel test. Although further refinement of the sea lamprey hearing capacity may help improve the design and efficacy of sound deterrents or barriers, more investigations are needed before sound-based systems could be implemented in the SLCP.

8.5. Lights

The behavioral response of sea lamprey to continuous and strobed underwater illumination for the purposes of increasing trap catch and blocking movement have been investigated (Miehls et al., 2017; Stamplecoskie et al., 2012; Fredricks et al., 1996; Purvis et al., 1985). Light levels have been known to influence fish behavior; fish lack a movable iris and are therefore, unable to adjust to rapid changes in light level, like those associated with strobe lights (Noatch and Suski, 2012). The potential for strobe lights alone to block sea lamprey movement was first investigated by Fredricks et al. (1996). Here, a two choice raceway flume was used to test sea lamprey avoidance of a 4100 Aquatic Guidance Lighting (Flash Technology Corporation of America) strobe light. The study found that adult sea lamprey were more attracted than repelled by the strobe light, and concluded that a strobe light might still be useful in directing sea lamprey into traps. As part of testing the Fish Guidance Systems BAFF, detailed in the previous section, Miehls et al. (2017) found sea lamprey did not avoid a strobe light but observed increased activity when the strobe light was activated. Constant underwater illumination was found to increase occurrences of sea lamprey to traps set side by side in a laboratory (Stamplecoskie, et al., 2012) and field setting (Purvis et al., 1985). However, when the traps had greater spacing similar results could not be replicated in the field (Stamplecoskie et al., 2012). The lack of response in the field was attributed to either a difference in simultaneous and sequential choice (i.e., in the laboratory setting, the sea lamprey encountered a lit and unlit trap at the same time whereas in the field, the traps were separated in space and not encountered at the same time) or a result of light attenuation caused by turbulence and turbidity (Stamplecoskie et al., 2012). Combined, these studies appear to indicate a potential role for underwater illumination to attract sea lamprey while having limited to no ability to deter or block sea lamprey movement.

9. Selective connectivity

To accommodate both the desire to re-establish connectivity and maintain sea lamprey or invasive fishes control, the GLFC is leading the selective, bi-directional fish passage (FishPass) project (http://www.glfc.org/fishpass.php). The goal of FishPass is to integrate existing and new technology and techniques reviewed above, to provide up- and down-stream passage of desirable fishes while simultaneously blocking and/or removing undesirable fishes (e.g., sea lamprey). While still in the planning stages, outcomes of FishPass could potentially be implemented at many sea lamprey barriers (purpose-built and existing) where there is a strong desire to couple sea lamprey control with native fish passage.

FishPass will be located on the Boardman (Ottaway) River (Lake Michigan), in Traverse City, MI at the current Union Street Dam site. The Union Street Dam will be replaced by a facility with an adaptive sorting channel (north bank) to allow for optimization of an integrated suite of technologies and techniques for selective fish passage and invasive species control, all while incorporating a nature-like river channel (south bank) into the design. Water velocity barriers, light guidance, video shape recognition, naturally occurring chemosensory and alarm cues, and eel ladder style traps are just some technologies that could be integrated at the facility to sort invasive fishes and effectively pass desirable fishes. The goal is to build a world-class technology and research center in a park-like setting (Fig. 9-1).

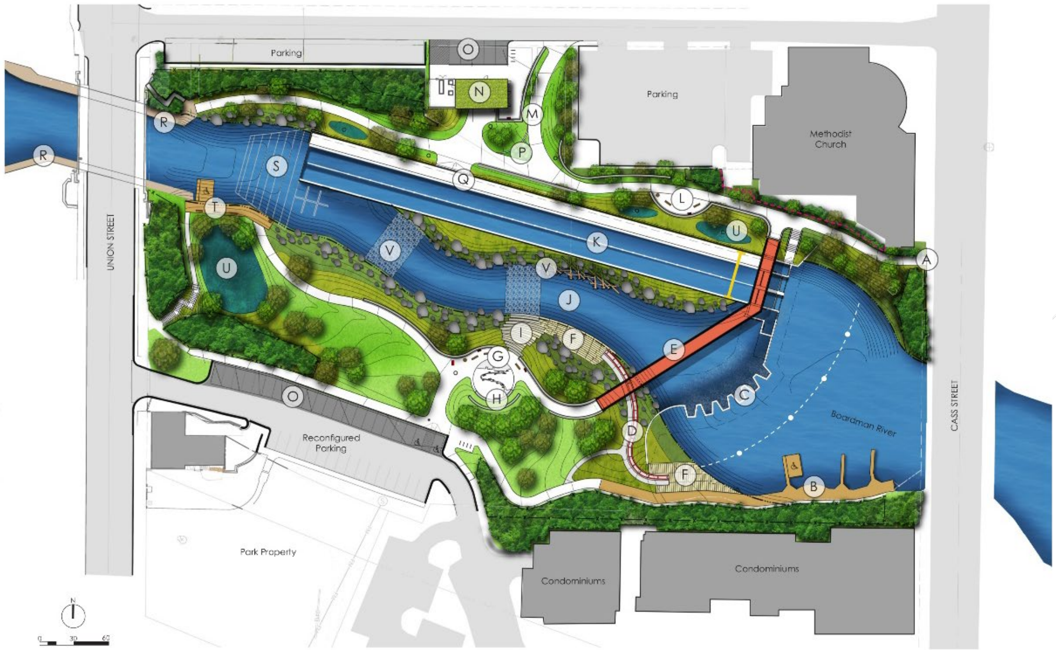

Figure 9-1. *Conceptual rendering of the FishPass facility. The Boardman River flows from bottom to top. Site features include: (A) new pedestrian connection to Cass St.; (B) rehabilitated boardwalk and accessible kayak launch; (C) labyrinth weir; (D) kayak portage rail; (E) pedestrian bridge; (F) kayak shore access; (G) interpretive overlook 1; (H) outdoor classroom and amphitheater; (I) fishing area; (J) bypass channel with boulder armoring and native vegetation; (K) fish-sorting channel; (L) interpretive overlook 2; (M)) service drive/pedestrian walk on city easement; (N) FishPass researcher building/public restrooms; (O) pervious pavers; (P) Turfstone vehicular access; (Q) research access way and security fence; (R) future boardwalk; (S) tailwater entrance pad; (T) boardwalk overlook and accessible kayak launch; (U) rain garden to manage building/parking runoff; and (V) stream habitat.*

10. Summary

The current inventory of lowermost sea lamprey barriers in the Great Lakes is comprised of approximately 1000 existing structures (i.e., originally built for purposes other than sea lamprey control) and nearly 100 purpose-built and modified barriers. Of the purpose-built and modified barriers, the fixed-crest design is the most common and has a long history of effectively blocking sea lamprey passage. Adjustable-crest and seasonally operated barrier designs are also in use, but escapement risks associated with automated operation and incomplete year-round blockage have hindered their deployment. Alternatives such as resistance weirs, velocity barriers, and vertical mount electrodes with pulsed direct current have been shown, at least experimentally, to have potential to block sea lamprey passage; however, none have been deployed at a management scale. Although alternative barrier technologies may appear ready for implementation, the history of experimental barriers in the Great Lakes has been inconsistent. For example, the velocity barrier installed in McIntyre Creek failed to effectively block sea lamprey (Chase, 1996), and the GFFB (electrical barrier) experienced two unsuccessful iterations before being successfully deployed as a redundant barrier in the Ocqueoc River. As demonstrated by the Ocqueoc River fixed-crest and GFFB barrier, redundancy in future barrier designs will be important as new technologies are proposed for alternatives to fixed-crest barriers. Finally, emerging technologies like CO_2, air bubbles and sound, and strobe lights still require significant research and development to demonstrate their effectiveness as sea lamprey barriers. Table 10-1 provides a summary of the primary blocking mechanisms, installations/applications, advantages, and disadvantages of each purpose-built or modified barrier technology.

Table 10-1. Summary of purpose-built and modified barrier technologies under investigation or in use in the SLCP.

Barrier Type	Blocking Mechanism	Installations/Applications	Advantages	Disadvantages
Fixed-crest	Vertical differential of 45 cm with 15 cm overhanging lip	➢ 64 purpose-built or modified ➢ Sites with high riverbed slope or existing barriers	➢ Historically effective blocking upstream migrating sea lamprey ➢ Reliable	➢ Cannot block downstream movement of sea lamprey ➢ Potential to lose vertical differential ➢ Blocks non-target species with limited leaping ability
Seasonal- and adjustable-crest	Same as fixed-crest barriers but crest height is adjustable	➢ 12 purpose-built or modified ➢ Same as fixed-crest barriers ➢ Sites with competing interests in fish passage, navigation, and flooding	➢ Modify crest elevation according to water level ➢ Pass non-target fish by removing barrier when sea lamprey are not present	➢ Mechanized systems require redundant power ➢ Manual or mechanized operation ➢ Seasonal operation causes risk for sea lamprey passage ➢ When in place, blocks non-target species with limited leaping ability
Weirs and screens	Physical exclusion	➢ No permanent, stand-alone installations ➢ Resistance weirs are under investigation, but could be used to block sea lamprey during high water events	➢ Pass water ➢ Resistance weirs can adjust height with water levels without operation ➢ Inclined-plane screens capture recently transformed sea lamprey moving downstream	➢ Screens collect debris ➢ Early designs failed due to erosion ➢ Block non-target species
Velocity	Create regions of swift flowing water that cause fish to completely exhaust	➢ No permanent, stand-alone installations ➢ High velocities likely contribute to sea lamprey blockage at fixed-crest barriers when inundated ➢ Significant research underway	➢ Differentially pass / block fish based on swim performance ➢ Less impact on navigation and debris collection	➢ Early attempt on McIntyre River unsuccessful ➢ Need more information on target and non-target fishes swim performance ➢ Block fishes with limited ability
Electrical	Voltage gradient	➢ 1 system installed in Ocqueoc River ➢ Operated seasonally with a fixed-crest barrier	➢ Effective at blocking all upstream fish movement ➢ Research on portable systems show potential to pair with traps ➢ Pass water	➢ Not species specific ➢ Historically high non-target mortality ➢ Susceptible to power failure ➢ Downstream blockage possible but complex
Other non-physical	Environmental cues	➢ No installations ➢ Research ongoing	➢ Minimal infrastructure ➢ Species specific	➢ Many uncertainties ➢ Further refinements needed

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