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Alternative Sea Lamprey Barrier Technologies: History as a Control Tool

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ABSTRACT

Currently, application of lampricides and installation of low-head barriers are the only proven means of sea lamprey (*Petromyzon marinus*) control in the Great Lakes. While sea lamprey cannot climb or jump over low-head barriers, many desirable migratory species also cannot traverse barriers and are unintentionally blocked. Recently, there has been a push to reduce reliance on chemical controls as well as increase stream connectivity and flood conveyance. In response, the Great Lakes Fishery Commission (GLFC) continues to seek alternative methods of control. Great Lakes basin resource managers often request consideration of alternatives to both lampricide use and low-head barriers. Seasonal operation and alternative barrier designs (e.g. velocity barriers and electrical barriers) that incorporate additional features such as selective fish passage or flood conveyance are among the most commonly requested options. To date, alternative barrier technologies have been intermittently successful in the sea lamprey control program directed by the GLFC, yet continue to be proposed as alternatives to conventional low-head barriers. This document provides a comprehensive review on the current state of knowledge regarding the effectiveness of current and alternative barrier technologies and their historical use in the sea lamprey control program. This synthesis provides resource managers and sea lamprey control agents a reference and some tools to facilitate decision making around barriers that balance the critical need for invasive species control and fishery restoration.

KEYWORDS
Sea lamprey; barriers; invasive species management; connectivity; fish passage

Introduction

Dams and barriers interrupt aquatic connections between tributaries and their endpoints (i.e. high-order rivers, lakes, and oceans). Despite their negative effects, barriers are critical for invasive species control (McLaughlin et al., 2013), conserving headwater ecosystems by preventing upstream disease transmission (Bartholomew et al., 2005) and contaminant transfer (e.g. mercury, toxaphene, PCBS, etc.) (Giesy et al., 1995), and reducing gene flow when desirable (Avenetti et al., 2006). This review focuses on the key role barriers serve in the control of invasive sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes (hereafter Great Lakes) because it is one of the most successful vertebrate control programs globally (Siefkes, 2017). Control of sea lamprey is essential to the health and sustainability of the Great Lakes that support an economy based on fishing and tourism valued at more than $7 billion annually (Southwick Associates, 2012). Sea lamprey invaded the Great Lakes during the early 20th century and caused significant damage to the fishery and local economies. Since the 1950s, sea lamprey numbers were reduced to 10% of historical abundance through an integrated pest management (IPM) program (Siefkes et al., 2013) overseen by the Great Lakes Fishery Commission (GLFC). The IPM is implemented through authority provided by the 1955 Convention on Great Lakes Fisheries between the United States and Canada, by control agents—Fisheries and Oceans Canada (DFO) and the U.S. Fish and Wildlife Service (USFWS), contracted by the GLFC. Currently, the two primary elements of IPM for

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sea lamprey are lampricides and barriers—the latter being critical to the viability of the control program. 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, interrupt the lifecycle by blocking adult sea lamprey access to 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 higher up in a watershed as they more 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% (36 US, 41 CAN) of lowermost barriers (Figure 1). The remaining structures were constructed for other purposes including recreation, flood control, logging, navigation, and energy production. Barriers are also important for assessment trapping because sea lamprey tend to congregate below 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 (Table 1).

The 930 existing water control structures functioning as lowermost barriers to sea lamprey in the Great Lakes 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 and the manner in which sea lamprey passage is blocked (i.e. elevation difference and high water velocity) varies with each site. Existing structures are important to the Great Lakes' sea lamprey control program due to the sheer number of barriers (nearly 12:1 ratio of existing structures to purpose-built or modified barriers for sea lamprey control). Unlike barriers purpose-built for sea lamprey control, existing structures are owned by

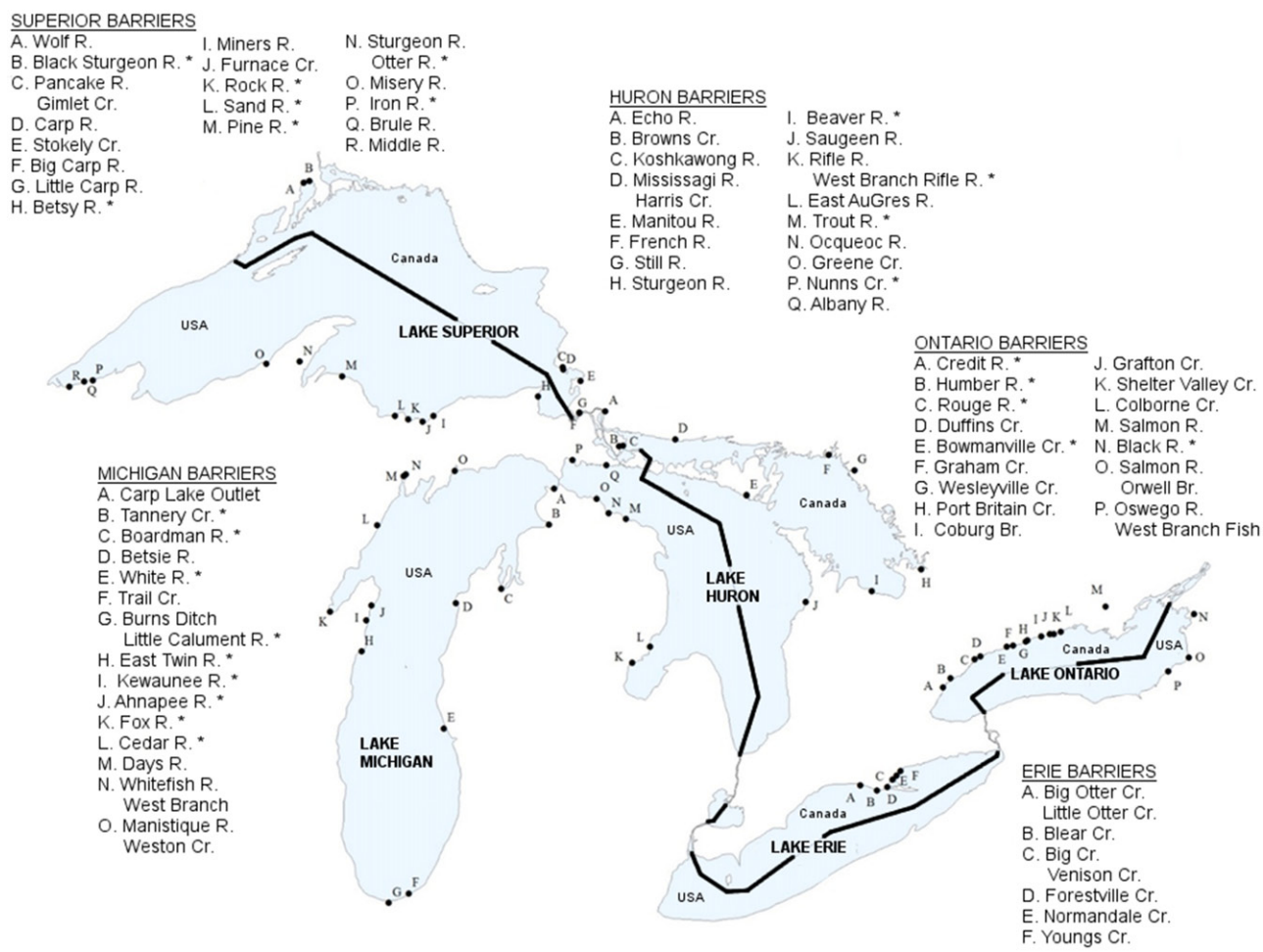

Figure 1. Locations of tributaries with sea lamprey barriers. Existing structures modified to block sea lamprey passage are indicated by an asterisk. (Sullivan and Mullett, 2018).

Table 1. Lowermost barriers to sea lamprey movement within the Great Lakes basin by type and category (e.g. purpose-built to block sea lamprey, existing structure modified to block sea lamprey, and existing structure that inherently blocks sea lamprey). Fixed-crest, non-hydro barriers are structures that maintain a minimum vertical differential between the crest and downstream water level without electrical generation. Hydropower barriers are primarily existing dams with electrical generation. Culverts/bridges include structures with perched inverts that block sea lamprey passage. Adjustable/seasonal-barriers are structures that have 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. Structures with seasonally operated fishways are included with adjustable/seasonal-barriers.

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[a]	11	1	33	*45*
Other	0	0	441	*441*
Total:	*50*	*27*	*930*	*1007*

[a]Includes Low-head and electrical barrier in Ocqueoc R.

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). Given the age of most barriers around the basin, many may need repair 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, mostly hydropower facilities, have designated fishways to allow some fishes to pass. 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.

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 largely stems from local drivers, such as maintaining hydrologic separation to protect upstream resources, for recreational activities, or negotiated by the GLFC to maintain sea lamprey control. In the case of rehabilitation or replacement, historically effective barriers designs, such as fixed-crest are preferred, but other alternatives have been accommodated to replace or modify existing structures. Great Lakes basin resource managers often request consideration by the GLFC of alternatives to both lampricides and low-head barriers for such purposes as fish passage, flood conveyance, navigation, and recreation. Seasonal operation and alternative barrier designs can potentially accommodate additional uses, however, 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 a research and development phase, they continue to be proposed as alternatives to conventional, permanent, low-head barriers.

Resource managers within the Great Lakes and beyond could benefit from better access to the current knowledge regarding the effectiveness of sea lamprey barrier technologies and their historical use in the sea lamprey control program; especially when evaluating dam removals and structure designs for new construction or modifications to existing barriers for invasive fishes. The evolution of a myriad of barrier technologies for sea lamprey provides an established framework for developing new or applying existing barrier technologies for other invasive fishes like bighead carp (*Hypothalmichthys nobilis*), silver carp (*Hypothalmichthys molitrix*), and common carp (*Cyprinus carpio*) (Escobar et al., 2018, Cuddington et al., 2014, Britton et al., 2011).

A detailed summary of recent barrier technologies has not been published and some resources may not be widely available; therefore, our objective was to transfer knowledge to resource managers and sea lamprey control agents in the form of a reference and some tools to facilitate decision making around barriers that balance the critical need for invasive species control and fishery restoration. To achieve that objective, a comprehensive review and synthesis of peer-reviewed and gray literature, sea lamprey control program operational protocols, sea lamprey barrier program review, unpublished research, and sea lamprey control agent field notes was conducted. First, an overview of each barrier type including a description of the underlying mechanism for blockage and history in the sea lamprey control program is provided. Next, barrier effects on sea lamprey and non-target species passage are addressed. Then current and potential applications, as well as best practice guidelines of technologies where data were sufficient are discussed. Promising, 'cutting-edge'

technologies, some of which are still in an experimental or developmental stage and require further evaluation, are also described.

Fixed-crest barriers

Overview

The fixed-crest design is the oldest and most common purpose-built barrier type in the Great Lakes basin. The design of fixed-crest barriers has been well proven to block sea lamprey movement in the Great Lakes. The fixed-crest barrier design uses an uninterrupted fixed-crest height and overhanging lip to maintain a vertical drop from the barrier crest (i.e. top of the barrier) to the tailwater (i.e. downstream pool) elevation (Figure 2). 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 tail water level and barrier crest, and the latter influences the ability of a sea lamprey to pass a barrier via swimming or climbing. Wigley (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 tail water. 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, a feat that is highly unlikely. 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.

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 30°, 45°, and 60° 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*),

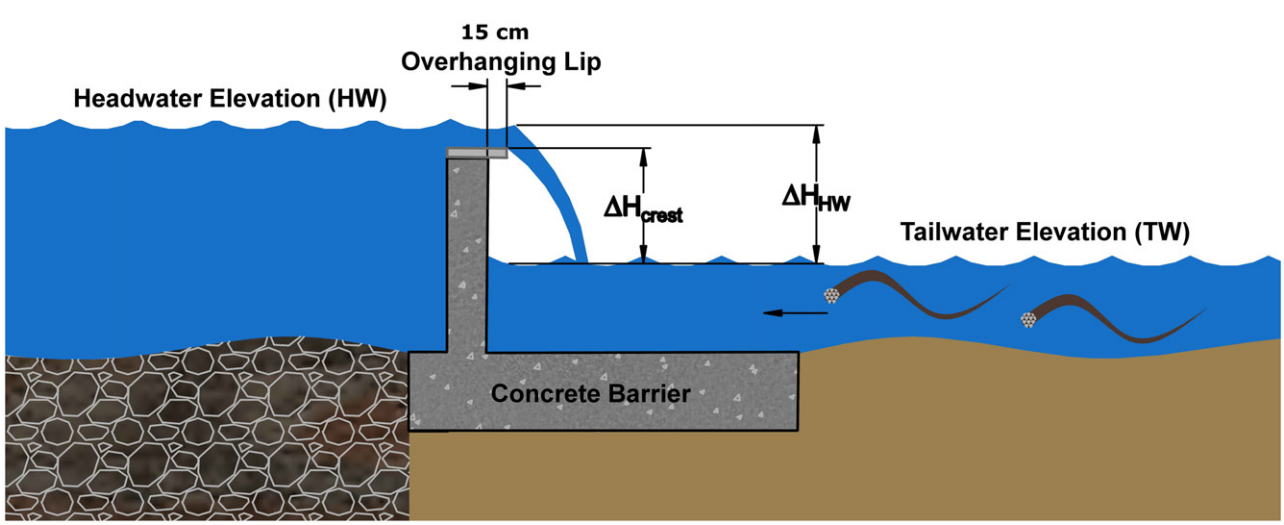

Figure 2. Diagram of typical fixed-crest sea lamprey barrier illustrating the difference between hydraulic head and vertical differential between barrier crest and tailwater elevation with 15 cm overhanging lip.

showed no evidence of attach-twitch-attach locomotion required for climbing (Moser et al., 2005).

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 by barriers. Purpose-built low-head fixed-crest barriers feature jumping pools that allow non-native steelhead (*Oncorhynchus mykiss*) and other Pacific salmons (*Oncorhynchus* spp.) to jump over the barrier, but are largely ineffective at passing common species that are unable to leap over the barrier (Porto et al., 1999; McLaughlin et al, 2006). Experimental trials with wetted ramps suggested 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). Fixed-crest barriers cannot block downstream movement of juvenile sea lamprey, but could be modified to do so.

Applications and design best practice

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. Several newly constructed fixed-crest barriers, like the Still River Barrier, ON, 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 was done in the French and Manitou River in Ontario. 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.

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 existing barriers and or natural falls occur. 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).

Seasonal- and adjustable-crest barriers

Overview

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). Adjustable-crest barriers 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. In some cases, sea lamprey enter tributaries as early as the fall prior to spawning (Applegate, 1950). For the remainder of the year, when sea lamprey are absent, 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 sea lamprey control program

standard to minimize the risk of sea lamprey escapement and operational cost, seasonal operation may need to be negotiated with partner agencies and stakeholders to move a project forward (SLBTT, 2000). Seasonal operation results in an agreed upon risk that infestation might occur from sea lamprey migrating into the system outside of the barrier operation period.

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 spring spawning non-target species and sea lamprey, 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. Velez-Espino et al. (2011) also suggested that sea lamprey production may be less sensitive to the duration of an active barrier than most non-target species. While fishways have been paired with seasonal-barriers in an attempt to enhance non-target passage, results have been mixed depending on location and species (Pratt et al., 2009). For example, Pratt et al. (2009) found the fishway at Big Carp River (Lake Superior) passed 64–88% of white suckers in 2004–2005, while the Coburg Brook (Lake Ontario) fishway passed only 7–10% in 2003 and 2005.

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 migrating into tributaries, but this requires detailed knowledge of the migration phenology in the target system and how that varies in response to environmental conditions. In addition to seasonal operation, adding trap and sort fishways can further reduce effects of barriers on non-target fishes; however, manual sorting with traps is still needed to minimize sea lamprey escapement (Pratt et al., 2009).

Applications and design best practice

Twelve purpose-built or modified adjustable-crest and seasonal-barriers function as lowermost barriers in Great Lakes tributaries (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, Ontario has a fixed-crest barrier with a seasonally operated fishway. One seasonally operated barrier installed in the Ocqueoc River, MI combines an electrical barrier with a fixed-crest barrier (See section on electrical barriers for more details). Seasonal- and adjustable-crest barriers typically consist of wooden or metal stoplogs, gates, or inflatable-crest weirs (e.g. Obermeyer gates). Canada hosts the only two installations of inflatable-crest barriers for sea lamprey control in Great Lakes tributaries, the Big Carp River on Lake Superior (Figure 3) and Big Creek on Lake Erie. Since installation in 1995, both sites experienced numerous technical malfunctions and power failures that led to sea lamprey escapement, particularly from Big Creek. These mechanized systems rely on a chain of sensors, processes, and computerized control systems, each vulnerable to failure. The experiences at Big Carp River and Big Creek highlight the need for redundancy in highly mechanized systems (see Figure 3(D) 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 potentially viable technology for sea lamprey control. 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 control agent staff using a combination of: (1) stream temperature (>5 °C); (2) historical trap catches from target stream or surrogate stream; (3) distance of barrier from stream mouth; (4) gradient; and (5) isothermic zone.
- Staffing and schedule of operation is negotiated between control agents and natural resource agencies in charge of fishery management.

Figure 3. Big Carp River 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 Big Creek River barrier. Photos courtesy of Department of Fisheries and Oceans Canada-Sea Lamprey Control Centre.

- Appropriate hydraulic and geotechnical analyses are performed to ensure the integrity of the stream and barrier are not compromised during operation.

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 (SLBTT, 2000). 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 under development, manually operated barriers are essential elements of the sea lamprey control program.

Weirs and screens

Overview

Barriers comprised of weir panels or mesh screens that block sea lamprey while still passing water (see Figure 4) 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

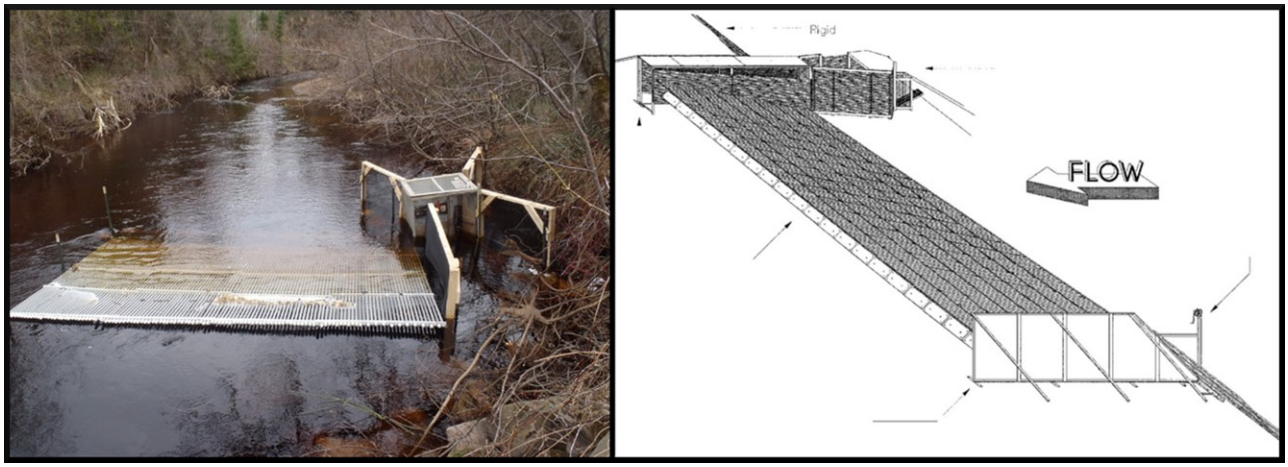

Figure 4. Experimental installation of a resistance weir with sea lamprey trap (right side of left panel) in the Marengo River, WI (left) and typical schematic of a resistance weir (right) (Klingler, 2015).

wood frames and fine wire mesh, these 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 overtopped. 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 transformers (i.e. out-migrating juveniles in the process of undergoing metamorphosis into the parasitic life stage). Although no permanent barrier in the Great Lakes basin today uses only a screen design, screens are still used extensively in trap design and small barriers in fishways.

Recent efforts have sought to use resistance weirs to control and aid trapping of sea lamprey (Klingler, 2015). Resistance weirs are comprised of an array of rectangular panels, made of evenly spaced tubular pickets, aligned parallel to the direction of flow (Tobin, 1994). 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 (Figure 4). 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 salmons 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.

Effects on species and life stages

Vertical screens (permanent and portable) block passage of adult sea lamprey and many non-target species (Hunn and Youngs, 1980). Inclined-plane screen traps capture recently transformed sea lamprey moving downstream (Applegate and Smith, 1951). Due to the fine screen spacing required to capture transforming sea lamprey, out-migrating non-target species are also likely affected. Because vertical mesh and inclined-plane screens were difficult to keep clear of debris, which led to high erosion during flooding events (Applegate and Smith, 1951), neither technology is currently in use in the Great Lakes as a sole barrier to sea lamprey. While preliminary data suggested resistance weirs also block passage of adult sea lamprey (Klingler, 2015), the effectiveness of resistance weirs is still under investigation and they have not yet been applied as a barrier in the Great Lakes. Regardless, resistance weirs have potential for sites where there is a need to block and remove sea lamprey during variable and high water events.

Applications and design best practice

Currently, no permanent installations of screen barriers or resistance weirs for sea lamprey control occur in the Great Lakes basin. A vertical screen barrier was constructed and operated in Bridgeland Creek (Little Thessalon River, Lake Huron) to aid in sea lamprey trapping. A high dam is located upstream of the vertical screen for hydropower; therefore, sea lamprey escapement is not possible. A resistance weir has been deployed by Toronto Region Conservation Authority in Duffins Creek, ON to capture migrating Atlantic Salmon (OMNRF, 2016). A resistance weir to facilitate

trapping of adult sea lamprey in the Cheboygan River watershed, MI, was installed as a proof-of-concept in 2018 in Pigeon River, MI and Black Mallard River, MI.

The main design requirements for a vertical mesh screen barrier are (Applegate and Smith, 1951):

- 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.
- Reduce risk of scour with properly designed erosion protection (i.e. rip rap).
- 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 no resistance weirs have been installed for management purposes, best practice guidelines have not been developed. The following general design criteria are based on experimental data (Klingler, 2015).

- 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).

Velocity barriers

Overview

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 sea lamprey passage, it is critical to characterize the swimming performance of target and non-target fishes in general.

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 passage 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 over a variable duration. This range is species-specific, but is typically considered to span durations of 20 s–200 min (Brett, 1964; Castro-Santos and Haro, 2006; Castro-Santos et al., 2013). 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 by 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, in each unsustainable swimming mode (prolonged and burst) generally follows 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 unsustainable swimming (e.g. prolonged and burst mode) can take several hours (See review by 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 somewhat from fatigue without losing ground (Kramer and McLaughlin, 2001). Thus, for a velocity barrier to be effective 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 for sea lamprey control as the difference in swimming performance between sea lamprey and other fishes may be exploitable. 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 and Sotiropoulos, 2010). There have been several attempts to categorize sea lamprey swimming performance using some variation of swim tunnel testing (Beamish, 1974; Hanson, 1980; Bergstedt et al., 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) (Figure 5). Nevertheless, recent advances in swimming performance testing and analytical techniques (Castro-Santos, 2005, 2006; Castro-Santos et al., 2013) have rendered any conclusions from historical data somewhat obsolete 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 swim performance data, often by a factor of two or more (Castro-Santos et al., 2013; Sanz-Ronda et al., 2015). In-depth investigation into sea lamprey performance using a state-of-the-art open flume that allows for volitional fish entry and swimming behaviors are ongoing at the U.S. Geological Survey S.O. Conte Anadromous Fish Research Center. Another ongoing study by 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.

Unlike most native fish in the Great Lakes, sea lamprey can attach to surfaces with their oral sucker. Generating 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. Adams 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 thereby interrupting the swim-attach-rest-release-swim mode of locomotion. When applied to a velocity barrier, such a 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 the ability of a sea lamprey to generate sufficient thrust to overcome water velocity. Reinhardt et al. (2009) found that sea lamprey without their dorsal fins fully submerged were unable to generate enough propulsion to scale a short (~2 ft long) wetted acrylic ramp with an inclination >20°, even using intermittent locomotion. The wetted ramp prevents sea lamprey from swimming and climbing due to shallow water depths and high water velocity.

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 (Figure 6). Caution must be used in the design as a velocity barrier for strong swimming fishes will also block any fishes of lesser swimming ability (i.e. small and large, gravid individuals). Design of a velocity barrier is further complicated by the lack of swimming performance data for many Great Lakes fishes, under varying environmental

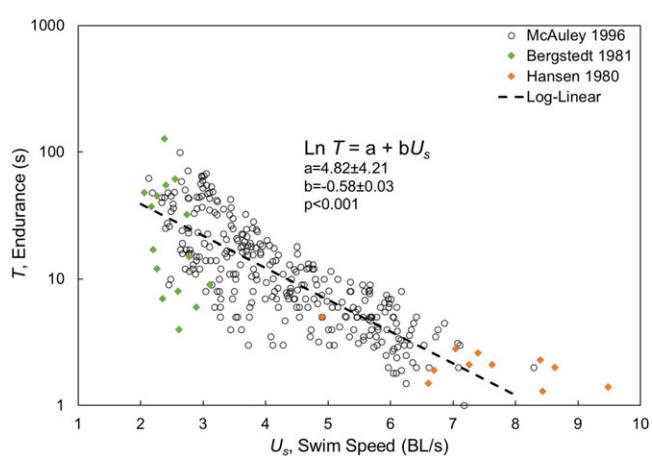

Figure 5. Sea lamprey swimming performance data from McAuley (1996), Bergstedt et al. (1981), and Hanson (1980). Swimming speeds are normalized by total body length (mm) and tests occurred over a range of water temperatures (6–24°C). A log-linear regression was fit to the data for demonstration purposes only (see text for model details).

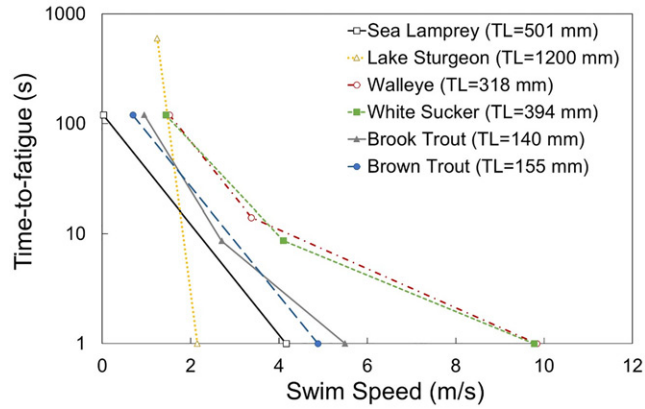

Figure 6. Comparison of swimming performance curves of fishes found in Great Lakes tributaries. Species with greater swimming capabilities will be situated towards the right of the plot. The swimming performance curve for sea lamprey was generated from McAuley (1996), Bergstedt (1981), and Hanson (1980) data; 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.

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.

Applications and design best practice

Currently, no purposefully designed sea lamprey velocity barriers occur in the Great Lakes. High velocities likely play a role in blocking sea lamprey at some fixed-crest barriers when inundated (i.e. vertical differential falls below 45 cm), although the number of sites where this occurs in currently unknown. In 1993, a velocity barrier pilot study was conducted on the McIntyre River, Ontario. 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. This barrier also had the unintended consequence of blocking gravid white sucker passage due to their larger cross-sectional area (Chase, 1996).

Velocity barriers are currently not in use 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 sea lamprey control program due to the misconception that velocity in excess of the maximum swim speed of sea lamprey (nearly 3 m/s at the time) was 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 (Hanson, 1980). 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 do not foul in a way that this function would be reduced remains a research priority. Although additional research on swimming performance of sea lamprey and many non-target, non-jumping fishes is still needed, velocity barriers have potential to be useful technologies where debris passage, navigation, non-target fish passage, and flood conveyance are desired.

No best practice guidelines are available for velocity barriers; however, the following general design criteria and highlighted research needs based on experimental data were identified (McDonald et al., 2002):

- 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. Here, some factor of safety may be required for unexpected conditions (i.e. debris or changes to substrate roughness) that could

compromise the velocity distribution throughout 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-adverse designs.

Electrical barriers

Overview

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 sea lamprey control program, with the first systems introduced to the Great Lakes during the 1950s (Hunn and Youngs, 1980) and reaching a peak of 162 sites by 1960 (Lavis et al., 2003). While use of electricity as a stand-alone 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 enhance trapping.

The first electrical barriers for sea lamprey control used alternating current (AC) electrical fields 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 during upstream migration, 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 the Graduated Field Fish Barrier (GFFB; Smith-Root) (Katopodis et al., 1994). The advantages of the GFFB system over original barrier designs was its 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 using 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 fishes (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 stand-alone electrical barriers, new pulsator technology (e.g. smaller, more portable units) has renewed research testing and deploying portable vertical mount electrodes with PDC to guide both upstream swimming adult sea lamprey (Johnson et al. 2014; Johnson et al., 2016) and downstream swimming juvenile sea lamprey (Johnson and Miehls, 2014; Miehls et al., 2017a) into traps. Operating under the same principles as permanent PDC systems, the vertical electrodes produce a more consistent voltage gradient throughout the water column and an overhead mounting system allows debris to be shed underneath. While initial results indicated an ability to nearly block all upstream migrating sea lamprey in the Ocqueoc River (Johnson et al., 2014), further management-scale tests are needed to confirm complete blockage.

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), orientation of the fish 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). Though PDC is less damaging than AC, larger bodied fish can still sustain injuries. 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 (Miehls et al. 2017a). Vertical mounted electrodes have also been shown in the laboratory to be somewhat effective at guiding downstream swimming juvenile sea lamprey into traps (Johnson and Miehls, 2014).

Applications and design best practice

The combined GFFB and fixed-crest barrier on the Ocqueoc River, MI is the only electrical barrier for sea

Figure 7. 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.

lamprey control currently in use in the Great Lakes (Figure 7). 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. Some of the major concerns with electrical barriers are a lack of species specificity, susceptibility to power failures, public safety, and ethical misconceptions (Swink, 1999). Any deployment of electricity in water poses some potential risk to human safety; however, modern electrical barrier systems are designed for safe operation. Current barriers use direct current which is safer for humans and fish, and the duty cycle, amount of time the system in energized, is very low (2–9% duty cycle). There have been no reports of serious injury or fatalities in humans resulting from electric fish barriers.

Although not installed directly to benefit sea lamprey control, four 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 between the Mississippi River Basin and the Great Lakes (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 $\sim$ 100 mm) can traverse the barriers when the electrical field is compromised by barge passage (Davis et al., 2017).

The design of permanent PDC electrical barriers generally follows manufacturer recommendations, but the following points should be noted (Katopodis et al., 1994):

- A site with preferably steep shoreline can minimize the size of the system and lower the risk of the river leaving its banks, resulting in sea lamprey escapement.
- A concrete control section to embed electrodes.
- Sufficient and redundant power source and controls.
- 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 (Swink, 1999).
- The Ocqueoc River barrier operates at 3-ms pulse duration and 10 pulses/s.

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. Nevertheless, 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 (resulting in a duty cycle = 9%) guided 75% of sea lamprey into adjacent traps in the Chocolay River, MI and Little Thessalon River, Ontario (Johnson et al., 2016).

Other non-physical barriers

Description of non-physical barriers

The more established 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 boats navigating in the water way. Barrier technologies that utilize deterrent stimuli like sound, light, or chemicals (e.g. carbon dioxide, chemosensory cues) have been suggested for sites where alteration of water flow is undesirable. The main advantage of non-physical barriers is the potential for taxon-specific responses without obstructing water flow (Noatch and Suski, 2012). 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 the research and development stage and have not been implemented in the sea lamprey control program. This section provides a brief description of non-physical barriers/guidance technologies using sea lamprey chemosensory cues, carbon dioxide, sound and bubbles, and strobe-light/continuous lights. A likely application of non-physical barrier technologies is in combination with other more proven technologies or for trap guidance.

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). 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 (Johnson et al., 2013). Johnson et al. (2015) found catch rates increased by 20–40% in wide (~40 m) streams with low adult sea lamprey abundance, while <10% increase was observed in generally narrow (<15 m) streams with high adult sea lamprey abundance. As a result, one compound, 3-keto petromyzonal sulfate (3KPZS), was registered with US and Canada regulatory agencies as a vertebrate pheromone biopesticide (Siefkes, 2017).

Alarm cues are odors produced by dead or injured sea lamprey that has 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 suggested 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/block chemosensory communication; and (3) the most effective approach for field deployment (i.e. with traps at barriers or in open river scenarios).

Carbon dioxide

Carbon dioxide (CO_2) is a non-physical barrier system that has recently been considered for control of adult and transformer sea lamprey movement. 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 transformers displayed agitation (i.e. erratic swimming, elevated activity, and twitching) when concentrations of CO_2 exceeded 40 mg/L and sea lamprey 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 CO_2 concentrations at approximately 85 mg/L, while transformers would swim away from areas with approximately 160 mg/L CO_2. Although 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 silver and bighead carps, 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 Canadian and U.S. Environmental Protection Agencies for pesticide applications) need to be addressed.

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., 2017; 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. non-random dispersal) manner. Sea lamprey likely detects low frequency sounds (<500 Hz) via the inner ear, a detection method conserved across all fishes. The sensitivity and hearing range of sea lamprey is not well understood and is the focus of an ongoing 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. (2017b) 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 other invasive fish movement when operated under specific air-flow rates and diffuser configurations (Zielinski and Sorensen, 2016). Miehls et al. (2017b) found no significant change in channel selection by sea lamprey during any combination of BAFF operation (sound, sound + bubbles, sound + light, bubbles, bubbles + light, bubbles + sound, light, and sound + bubbles + light). Although further refinement of the sea lamprey hearing capacity may help improve the design and efficacy of sound deterrents/barriers, more investigations are needed before sound-based systems could be implemented in the sea lamprey control program.

Strobe and continuous lights

The behavioral response of sea lamprey to constant and strobed underwater illumination for the purposes of increasing trap catch and blocking movement have been investigated (Miehls et al., 2017b; Stamplecoskie et al., 2012; Fredricks et al., 1996; Purvis et al., 1985). Light levels are known to influence fish behavior and because fish lack a movable iris, fish are unable to adjust to rapid changes in light level, like those associated with strobed light (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 if sea lamprey would avoid a 4100 Aquatic Guidance Lighting (Flash Technology Corporation of America) strobe light. The study found that adult sea lamprey were attracted by the strobe light, and concluded that a strobe light might still be useful in directing sea lamprey into traps. As part of the testing the Fish Guidance Systems BAFF, detailed in the previous section, Miehls et al. (2017b) 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 in traps set side by side in a laboratory (Stamplecoskie, et al., 2012) and field setting (Purvis et al., 1985). 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 lab 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.

Conclusions

The sea lamprey control program has generated a technologically diverse set of barrier designs that have historically focused on influencing or exploiting a single behavioral (e.g. non-physical barriers) phenological (e.g. seasonal-barriers), physiological (e.g. fixed-crest and velocity barriers), or morphological (e.g. screens and weirs) attribute to block or trap sea lamprey. Table 2 provides a summary of the primary blocking mechanism, applications/installations, advantages, and disadvantages of each purpose-built or modified barrier technology. While each technology has experienced a myriad of successes and failures, the fixed-crest design had the longest history of effectively blocking sea lamprey passage. The success of the fixed-crest design is partly owed to the relatively straightforward approach of blocking sea lamprey by exploiting their physiological limit to traverse an abrupt vertical differential of 45 cm. As a result, fixed-crest designs are the most common existing, purpose-

Table 2. Summary of purpose-built and modified barrier technologies types that are either in use (*) or in various stages of research and development (▲) in the sea lamprey control program.

Barrier Type	Blocking Mechanism	Installations/Applications	Advantages	Disadvantages	References
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	SLBTT, 2000
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	Pratt et al., 2009 SLBTT, 2000 Klingler et al. 2003
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	Applegate and Smith, 1951 Klingler, 2015
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	McAuley, 1996 McDonald et al., 2002 Adams and Reinhardt, 2008
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	Katopodis et al., 1994 Swink, 1999 Johnson et al., 2014 Johnson et al., 2016
Other non-physical▲	Environmental cues	• No installations • Research ongoing	• Minimal infrastructure • Species-specific	• Many uncertainties • Further refinements needed	Siefkes, 2017 Dennis et al., 2016 Klingler and Mullett, 2001 Miehls et al., 2017b Stamplecoskie et al., 2012 Fredricks et al. 1996 Purvis et al., 1985

built, and retrofitted barrier type in the Great Lakes. The next most common barrier type, adjustable-crest and seasonally operated barriers, also utilize the same blocking mechanism. Their deployment has not been hindered by blocking efficacy, but rather costs associated with staffing and risks associated with automated operation. To be effective tools to reduce sea lamprey spawning and need for chemical treatment, barriers must block nearly all individuals from accessing spawning habitat upstream. When properly designed for river flows that occur during sea lamprey migration, fixed-crest barriers have historically provided near 100% efficacy at blocking passage. Such high efficacy has unintentionally led to blockage of many native species with limited leaping abilities (McLaughlin et al. 2013). Regardless, the acceptably low risk of sea lamprey passing a fixed-crest barrier is a driving force behind their widespread occurrence

and continued reliance in the sea lamprey control program.

While fixed-crest barriers are the current standard for sea lamprey control barriers, mounting societal desire for increased connectivity and potential changes to hydrology across the basin will require evolving and alternative designs to achieve the same level of control. Alternatives barrier technologies such as resistance weirs, velocity barriers, and vertical mount electrodes with PDC have been shown, at least experimentally, to have potential to block sea lamprey passage; however, none have been deployed yet at a management-scale. Although these 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 (McAuley, 1996), and the GFFB (electrical barrier) experienced two unsuccessful iterations before being successfully deployed in the Ocqueoc River. Emerging technologies like CO_2 (Dennis et al., 2016), air bubbles and sound (Miehls et al. 2017b), and strobe lights (Miehls et al., 2017b; Stamplecoskie et al., 2012; Fredricks et al., 1996; Purvis et al., 1985) are potentially inappropriate for sea lamprey due to their different sensory biology and still require significant research and development to demonstrate their effectiveness as sea lamprey barriers. Despite the current success of the sea lamprey control program, it has experienced many unsuccessful alternative barrier designs (e.g. screens, AC electrical barriers). The lesson learned here, which also applies to invasive fish control globally, is that great caution should be exercised prior to implementing new and experimental barrier technologies at the management-scale. A less risky alternative is to deploy such tests below a secondary barrier.

Research on alternative barrier technologies also contributes to the understanding of sea lamprey biology and physiology, creating a natural feedback into the sea lamprey control program which employs an ethos of exploiting physiological vulnerabilities of sea lamprey for control (Siefkes, 2017). For example, velocity barrier development has fueled the ongoing characterization of swimming performance of sea lamprey (McAuley, 1996; Hoover and Murphy, 2018), attachment abilities (Adams and Reinhardt, 2008), and behaviors associated with intermittent locomotion (Reinhardt et al., 2009). These discoveries are critical to current GLFC efforts to accommodate both the desire to reestablish connectivity in Great Lakes tributaries and maintain sea lamprey control. To end the tension between connectivity and invasive species control, the GLFC is leading the selective, bi-directional fish passage (FishPass) project (http://www.glfc.org/fishpass.php). The mission 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 planning, 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.

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