GREAT LAKES FISHERY COMMISSION

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Hydraulic, hydrological, and biological characteristics of effective sea lamprey barriers

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Hydraulic, Hydrological, and Biological Characteristics of Effective Sea Lamprey Barriers

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Preliminary Executive Summary

The Great Lakes Fishery Commission (GLFC) is intensifying its reliance on low-head barriers and traps placed in tributary streams of the Laurentian Great Lakes as part of an integrated pest management program for controlling non-native, parasitic sea lamprey (*Petromyzon marinus*). Barriers currently in operation vary in their effectiveness at denying sea lampreys access to spawning habitat upstream. Identifying reasons for this variation will provide a basis for improved barrier designs.

A bi-national workshop entitled **Hydraulic, Hydrological, and Biological Characteristics of Effective Sea Lamprey Barriers** was funded by the GLFC and held 12 –14 March 2003. The workshop developed the research framework needed to identify hydraulic and biological features of effective sea lamprey barriers and initiated the conceptual development of a theme paper to guide future research on barriers, traps, and fishways.

The first day was devoted to identifying how best to define effectiveness at blocking sea lampreys, identifying hypotheses and corresponding predictions for the variation in effectiveness, assessing the data and time needed to test the predictions, and specifying the field research required to meet additional data needs. Three measures of effectiveness were considered: the number of years following barrier construction that sea lampreys reproduced successfully above a barrier, the number of times the stream section above a barrier was treated with lampricide relative to the expected frequency of treatment if that barrier were absent, and the cost of treatment following barrier construction relative the savings expected from building the barrier. The first measure was identified as the preferred choice for measuring effectiveness from a scientific perspective. Following this, seven hypotheses for the variation in barrier effectiveness and their corresponding data requirements were examined. They were:

1) some barriers are more susceptible to sea lamprey passage because they are at greater risk of losing the 12 inch drop, due to factors such as lake effects on the tailrace or spatial (among stream) and temporal (among year) variation in the frequency, duration, magnitude, or timing of floods;

2) some streams provide thermal conditions more favorable for sea lamprey passage than others because of spatial and temporal variation in water temperature and its corresponding effects on the timing of migrations and on swimming, jumping, and possibly climbing ability;

3) some barriers are better than others at denying sea lampreys access to the face of the barrier or, when the barrier is inundated, access to sections upstream of the barrier, because spatial or temporal variation in the hydraulics of the tailrace below the barrier hinders sea lamprey movement upstream;

4) some barriers are better than others at preventing sea lamprey movement over the barrier because spatial or temporal variation in the thickness of the nappe or the incident angle at which it strikes the tailrace hinders sea lamprey movement upstream;

5) some barriers are better than others at preventing sea lamprey movement along the sides of streams because of differences in the types and geometries of abutments and armoring used to secure barriers to the stream bank;

6) some barriers may appear to be better than others at preventing sea lamprey passage because of spatial and temporal variation in the numbers of sea lampreys available to pass, which will vary with run size and with the effectiveness of any associated trap; and,

7) some barriers are better than others at preventing sea lamprey passage because of among barrier variation in the size and geometry of the lip at the top of the crest.

The second day was devoted to initiating the development of the barrier and trapping theme paper. This objective was addressed by breaking the process of fish movement within streams into four components: movement leading up to a barrier, searching for a way around a barrier, passage over or around a barrier, and the fate of individuals that successfully pass. Key research questions and concerns for sea lampreys and non-target fishes were identified for each component and these were integrated with (a) the outcomes from day 1, earlier passage workshops, and SLIS II papers examining barriers, (b) the objectives of GLFC-funded barrier projects already underway, and (c) pertinent research priorities for trapping (without pheromone) from the Pheromone and Trapping Task Force. From this, titles for 16 key research priorities were specified:

1) Predicting the timing and magnitude of runs for sea lampreys and non-target species

2) Frequency and consequences of early- and late-season movements by sea lampreys

3) Sea lamprey migration and dispersal behaviour in support of trapping

4) Determination of the passage needs for non-target fishes: propensity to migrate and distance traveled upstream

5) Hydraulic, hydrological and biological criteria for effective sea lamprey barriers (day 1)

6) Quantitative studies of the behaviour of sea lampreys and non-target species at barriers and traps

7) Quantitative studies of the behaviour of sea lampreys and non-target species in traps

8) Compilation of traditional and anecdotal knowledge regarding the behaviour and activities of sea lampreys and non-target fishes at barriers and traps

9) Examination of attractors and distracters for sea lampreys and non-target species

10) Experiments with funnel and trap design configurations

11) New and improved designs of barriers, fishways, and traps

12) Test of new spillway design types against lamprey passage and human safety concerns

13) Quantification of the effectiveness of blocking and trapping sea lampreys, including the level needed for successful sea lamprey control.

14) Quantification of the effectiveness of non-target fish passage

15) Evaluation of the Interim Policy on Barrier Placement (completed)

16) Decision analysis for the implementation and operation of sea lamprey barriers (underway)

Many of these priorities could be developed and researched through a single research project. Their priority in terms of immediate versus long-term need requires further consideration. Overall, the list provides a thorough basis for the development of a vigorous research plan for barriers and traps that will support the GLFC's commitment to including barriers and traps as part of a sea lamprey control program that is ecologically and economically sound, and socially acceptable.

Introduction

In its vision statements on integrated sea lamprey management for the previous and current decades, the Great Lakes Fishery Commission (GLFC) pledged to decrease its reliance on chemical lampricides and achieve 50% of sea lamprey suppression through alternative-control methods (Great Lakes Fishery Commission 1992, 2001). Deployment of barriers in streams is one conventional method that will be used more intensively. These barriers block the movements of maturing sea lampreys thereby denying them access to spawning habitat upstream and eliminating or reducing the need to chemically treat streams or portions of streams

Two key management concerns regarding the use of sea lamprey barriers are their effectiveness at blocking sea lampreys and their possible detrimental effects on non-target fishes through restrictions on movement. Efforts to reduce reliance on lampricides could be compromised if sea lampreys periodically pass the barriers, because of the high fecundity of these fish. Alternatively, large-scale effects on non-target species, such as losses of species above barriers, could heighten conservation concerns.

Initiation of barrier and passage research has taken considerable time to get underway, despite several GLFC-funded workshops (Katopodis et al. 1994, McDonald et al. 2002). Possible reasons for the delay include (i) the unusual and challenging passage needs of the barrier program, which requires selective blocking of sea lampreys and passing of other non-target species, as opposed to passage of all fishes present, (ii) the size and complexity of the passage needs, given the extent of the Great Lakes basin and the number of fishes potentially needing to pass, (iii) the lack of any formal framework and corresponding plans for prioritizing and executing the passage research, and (iv) difficulty placing key information needs into a hypothesis-testing framework that would appeal to grant reviewers.

A useful approach to jumpstart the research process would be to hold a workshop focusing on a specific, recognizably important research question pertaining to sea lamprey barriers and develop the research framework needed to answer it. Relative to earlier workshops, this approach would have the advantages of being more specific and focused. The question selected was "What are the hydraulic, hydrological, and biological criteria that characterize effective sea lamprey barriers?"

Within this context, the bi-national workshop entitled **Hydraulic, Hydrological, and Biological Characteristics of Effective Sea Lamprey Barriers** was held 12 –14 March 2003. It had two objectives:

(i) to develop the research framework needed to identify hydraulic and biological features that make barriers effective at blocking sea lampreys; and,

(ii) to initiate the conceptual development needed to draft a theme paper guiding future research on barriers and traps.

We focused on the characteristics of effective barriers for five reasons. First, blocking sea lampreys is the fundamental purpose for building barriers and existing barriers appear to differ in their effectiveness at achieving this objective (McDonald et al.

2002, Lavis et al. 2003). The issue of effectiveness at blocking (passing) fish extends to non-target species, as well. Second, this research question is tractable and offers considerable potential for the development of hypotheses addressing barrier effectiveness. Third, the hypotheses developed will provide an appealing, hypothesis-driven segue into research examining the behaviour of sea lampreys and non-target fishes at barriers, two key research priorities identified in earlier workshops. Fourth, testing the hypotheses will identify general characteristics of effective barriers and these characteristics could be used to improve future barrier designs. Fifth, it is at barriers where key successes (and challenges) regarding blocking (and passing) fishes are going to occur. Taking a "problem-out" approach is arguably more likely to satisfy management needs than either cursory "top-down" or intensive "bottom-up approaches" (Walters 1986, Walters and Korman 1999).

Hydraulic, Hydrological, and Biological Characteristics of Effective Barriers

Quantifying Effectiveness of Barriers

The passage of individual sea lamprey at a barrier is not feasible to measure across all of the barriers at this time. Moreover, this measure could be unsuitable in situations where lampreys pass, but do not reproduce successfully upstream. In lieu of this, the following three measures of effectiveness were considered.

The first measure was the probability that sea lampreys failed to reproduce successfully above the barrier during the period of operation (option 1),

$$1 - \frac{N_R}{T}$$

where N_R is the number of years sea lampreys reproduced successfully above the barrier and T is the period of barrier operation.

The second measure was the probability of eliminating a chemical treatment over the period of barrier operation (option 2),

$$1 - \frac{N_T}{N_E}$$

where N_T is the number of lampricide treatments made and N_E is the number of treatments expected over the period of barrier operation had the barrier not been in place.

The third measure was the cost of treatments following barrier construction (C) relative the savings expected from building a barrier (S) (option 3).

$$S - C.$$

The probability that sea lampreys failed to reproduce above the barrier was considered the best measure in terms of conducting research addressing the blocking or trapping of sea lampreys and the design of barriers and traps aimed at improving this objective. Moreover, data for this measure should be available, or practical to obtain in situations where they are not available. Detection surveys for larval sea lampreys are carried out above barriers on a three-year cycle. The surveys detect the presence of sea lampreys, information key to estimating N_R, and survey crews collect more extensive data, including lengths and densities, when larval sea lampreys are found. Evidence regarding the specific year(s) the barrier failed could be determined from age-length keys. The adequacy of this approach could be a source of concern in situations where escapement has occurred several years in a row and where the lengths of age classes overlap considerably. In such situations, aging larvae using statoliths would be a more precise method for determining the year of escapement. It is also a more intensive and expensive method owing to the need to preserve larval lampreys via freezing instead of formalin and the added costs of processing the statoliths.

The probability of eliminating lampricide treatments above the barrier during the period of operation is a measure also worth considering. However, the number of lampricide treatments required should not be scaled to the period of operation (T), as done in the past, but to the number of lampricide treatments expected during that period of operation (N_E). This measure is less suitable for the context of our workshop objectives because the presence of larval sea lampreys above a barrier, which indicates sea lampreys have passed, may not necessarily warrant treatment of that stream section because of issues related to anticipated costs and benefits of that treatment in relation to the success of overall control program. In addition, the measure may be inherently more variable and less accurate because many of the barriers have not been in operation very long. For example, consider a four-year old barrier on a stream that historically was treated every four years. If sea lampreys colonized above the barrier in just one year, the effectiveness based on successful reproduction above the barrier (option 1) would be 0.75. Assuming the stream section above the barrier was treated, the effectiveness based on treatments saved (option 2) would be 0, highlighting the potential significance of just one year of escapement. Alternatively, if the stream section above the barrier was not treated, the effectiveness based on treatments would be 1, despite any escapement, indicating how variable this measurement option could be.

The cost based measure was not considered to be appropriate for research needs, although it certainly is important in terms of the broader management of the barrier program.

Two additional issues were raised regarding the measurement of effectiveness. First, there was concern that if the benchmark for barriers was 100% effectiveness then barriers could be judged against a higher standard than chemical treatments, which are never 100% effective. In the end, it was decided that 100% was a reasonable target to seek, even though it may not be reached. Some higher barriers are probably close to being 100% effective (e.g. Denny's Dam), but realistically issues of local geography, fish passage, and cost will require building smaller barriers on most of our candidate streams. In these situations, we will have build barriers that are as practical and effective as possible for the location. Second, the accuracy of the effectiveness measures is important to the sea lamprey managers. Therefore, we should seek to estimate both point measures of effectiveness and the risk associated with these measures. Moreover, it is important that the measures be meaningful conceptually, and measured accurately and economically.

Evidence of Variation in Effectiveness

The participants reviewed the data of Lavis et al. (2003) summarizing the effectiveness of barriers in terms of blocking sea lampreys (Table 1). It was concluded that the discussion should focus on fixed-crest barriers because newer, seasonally operated barriers have a very short history of operation and their design and operation is fundamentally different from that of fixed-crest barriers. The participants also felt there was adequate evidence of variation in effectiveness among barriers and it was noted that comparisons of effectiveness across years were possible for some streams and could be used effectively to test some of the hypotheses developed below.

Hypotheses for the Variation in Effectiveness

Seven hypotheses for the presence of sea lampreys above barriers were examined. The hypotheses are not mutually exclusive, but examining them separately allowed us to (i) generate specific predictions and identify their data needs, (ii) assess which predictions can be tested most readily, and (iii) identify future data needs, and thereby jumpstart research on barrier design and lamprey passage.

Hypothesis 1. Some barriers are more susceptible to sea lamprey passage than others because they are at greater risk of losing the 12-inch drop due to factors such as lake effects on the tailrace or spatial (among stream) and temporal (among year) variation in the frequency, duration, magnitude, or timing of floods.

The height of low-head sea lamprey barriers is currently designed around smaller-scale and more frequent variations in stream flow, and not larger-scale, infrequent flooding events. A vertical drop of 12 inches between an overhanging crest and the tail water is assumed to constitute a barrier to sea lampreys, based on the limited data provided by Youngs (1979). For most barriers, the vertical drop is expected to be less than 12 inches when flooding events occur.

This hypothesis predicts that the probability of sea lampreys getting past a barrier and breeding upstream will be proportional to the probability of losing the 12-inch drop during the period of sea lamprey migration. It could be tested comparatively across streams and, for streams with adequate data, temporally across years.

Our ability to test this prediction is limited at this time. In addition to data regarding the probability of sea lampreys getting past the barrier, the test will require data specifying the probability of losing the 12-in drop during the period of sea lamprey migration. The magnitude of the drop, and hence height of the tailrace, during the rare flood events are the data of greatest importance and of limited availability. A minimum of two years, and preferably five years, of data collection under varying flows is recommended. Water level loggers are just being installed at barriers and installation at all barriers should be complete within a year. Some barriers are located on or near streams with gauging stations and it is possible to predict water levels at the barrier from flow measurements made at the gauging station. This comparative approach may be the best option available for a large fraction of barriers. The lower accuracy and precision

Table 1. Summary of the periods of operation and the effectiveness of sea lamprey barriers (from Lavis et al. 2003).

Stream	Lake Basin	Country	Year Built[1]	Type[2]	Years Operated	Years Effective	Upstream Length Not Treated (km)
Harris R.	Huron	Canada	1958	FCDI	41	41	7[3]
Black Sturgeon R.	Superior	Canada	1966	FCDI	33	33	79
French R.	Huron	Canada	1970	FCDI	29	29	58[3]
Saugeen R[5].	Huron	Canada	1970	FCDF	29	29	80
Betsie R.	Michigan	U.S.	1974	FCLH	25	25	59
Weston Cr.(Manistique R)	Michigan	U.S.	1974	FCLH	25	25	118
Miners R.	Superior	U.S.	1978	FCLH	21	21	2
Gimlet Cr. (Pancake R.)	Superior	Canada	1979	FCLH	20	20	5
Sturgeon R.	Huron	Canada	1979	FCLH	20	20	20
Stokely Cr.	Superior	Canada	1980	FCLH	19	16[4]	13
Koshkawong R.	Huron	Canada	1980	FCLH	19	19	15
West Br. Whitefish R.	Michigan	U.S.	1980	FCLH	19	19	51
Duffins Cr.	Ontario	Canada	1980	FCLH	19	18	27
Credit R.	Ontario	Canada	1981	FCDF	18	0	0
Little Manistee R.[5]	Michigan	U.S.	1982	FCDI	17	14	56
Carp R.	Superior	Canada	1983	FCLH	16	13[4]	12
Manitou R.	Huron	Canada	1983	FCLH	16	15	12
Middle R.	Superior	U.S.	1983	FCLH	16	12[4]	29
East Br. AuGres R.	Huron	U.S.	1983	FCLH	16	15	39
Days R.	Michigan	U.S.	1983	FCLH	16	16	18
East Twin R.	Michigan	U.S.	1983	FCDI	16	14	10
Sheppard Cr. (Goulais R.)	Superior	Canada	1984	FCLH	15	15	14
Brule R.	Superior	U.S.	1984	FCLF	15	13	72
Misery R.	Superior	U.S.	1984	FCLH	15	0[4]	0
Graham Cr.	Ontario	Canada	1984	FCLH	15	14	22
Colbourne Cr.	Ontario	Canada	1984	FCLH	15	15	15
Albany Cr.	Huron	U.S.	1985	ACLH	14	2	9
Shelter Valley Cr.	Ontario	Canada	1985	FCLH	14	13	20
Still R.	Huron	Canada	1986	FCLH	13	13	13
Echo R.	Huron	Canada	1986	FCLH	13	11	42
Wolf R.	Superior	Canada	1987	FCLH	12	7[4]	17
Grafton Cr.	Ontario	Canada	1987	FCLH	12	12	8
Bowmanville Cr.	Ontario	Canada	1988	FCDI	11	11	10[3]
Normandale Cr.	Erie	Canada	1988	FCLH	11	11	2
Forestville Cr.	Erie	Canada	1988	FCLH	11	11	2
Fox R.[5]	Michigan	U.S.	1988	FCDI	11	11	n/a
Jordan R.	Michigan	U.S.	1988	GFE	11	1	34
Pere Marquette R.	Michigan	U.S.	1988[6]	GFE	2	0	0
Port Britain Cr.	Ontario	Canada	1989	FCLH	10	10	9
Clear Cr.	Erie	Canada	1989	FCLH	10	10	21
Little Otter Cr.	Erie	Canada	1990	FCLH	9	9	28
Kewaunee R.[5]	Michigan	U.S.	1990	FCLH	9	8	12
McIntyre R.	Superior	Canada	1993	VEL	6	2	29
Black R.	Ontario	U.S.	1994	FCDI	5	0	0
Youngs Cr.	Erie	Canada	1995	FCDI	4	3	4
Big Carp R.	Superior	Canada	1995	ICF	5	1[4]	17
Big Cr.	Erie	Canada	1995	ICF	4	1	30
W. Br. Fish Cr.	Ontario	U.S.	1995	FCDI	4	3	40

Table 1. (continued)

Stream	Lake Basin	Country	Year Built[1]	Type[2]	Years Operated	Years Effective	Upstream Length Not Treated (km)
Venison Cr.	Erie	Canada	1996	FCLH	4	4	18
Cobourg Br.	Ontario	Canada	1996	FCLF	3	3	13
White R.[5]	Michigan	U.S.	1996	FCDI	3	0	0
Blind R.[5]	Huron	Canada	1997	FCDI	2	2	24[3]
Trout R.	Huron	U.S.	1997	FCDI	2	0	0
Nuns Cr.	Huron	U.S.	1997	FCDI	2	2	5
West Br. Rifle R.	Huron	U.S.	1997	FCLF	2	2	11
Little Calumet R.[5]	Michigan	U.S.	1997	FCLH	2	2	40
Salmon R.	Ontario	Canada	1997	FCLH	2	2	23
Browns Cr.	Huron	Canada	1998	FCLH	1	0	0
Shiawassee R.[5]	Huron	U.S.	1998	FCDI	1	1	63
Manistique R.[5]	Michigan	U.S.	1999	FCDI	0	-	0
Ocqueoc R.	Huron	U.S.	1999	CLHE	0	-	36
Total					684[7]	616[7]	1413

[1] Prior to 1978, the Great Lakes Fishery Commission did not provide funding for barrier construction.

[2] FCDI=existing fixed crest dam improvement; FCDF=construction of a fixed crest dam with a fishway; FCLH=construction of a fixed crest low head sea lamprey barrier; FCLF=construction of a fixed crest low head sea lamprey barrier incorporating a fishway; ACLH=construction of an adjustable crest sea lamprey barrier; GLE=construction of a gradient field electrical sea lamprey barrier; VEL=construction of a velocity sea lamprey barrier; ICF=construction of an inflatable crest sea lamprey barrier; CLHE=construction of a combined fixed crest low head and gradient field electrical sea lamprey barrier.

[3] Estimated distance for streams that have not been treated above the barrier.

[4] Some larvae were produced upstream of the barriers on the following rivers and creeks (years) as a result of field research where sterile and untreated male and untreated female adult sea lampreys were introduced into those areas: Middle River (1996-1999), Misery River (1994-1999), Wolf River (1994-1999), Carp River (1996-1999), Stokely Creek (1996-1999), and Big Carp River (1997-1999).

[5] Multi-purpose structures modified to block sea lampreys where funding was from a source other than the Great Lakes Fishery Commission.

[6] A pumped discharge, false weir fishway was incorporated into the Pere Marquette R. electrical barrier in 1999. The barrier had not been operated since 1990.

[7] Years operated and years effective prior to 1995 are not included in totals.

of these predictions relative to direct measurement are a concern, however, because the magnitude of the 12-inch drop is small.

The data requirements of this section could also be used to turn the question on its head and ask what value of vertical drop best explains the escapement observed over time at a given barrier. This approach could help assess whether a 12-inch drop provides an acceptable level of control under field conditions.

Hypothesis 2. When the 12-inch drop is lost, some streams provide thermal conditions more favorable for sea lamprey passage than others because of spatial and temporal variation in water temperature and its corresponding effects on the timing of sea lamprey migrations and on sea lamprey swimming, jumping, and possibly climbing ability.

This hypothesis integrates the hydrological mechanisms that influence the operational height of the barrier (Hypothesis 1) with a key environmental variable influencing the timing of migration and the swimming ability of sea lampreys. One prediction is that the probability of observing sea lampreys above a barrier that has lost its 12-inch drop during the period of lamprey run will be higher when water temperatures are warmer than when water temperatures are cooler.

As with hypothesis 1, our ability to test this prediction will require information regarding the probability of losing the 12-inch drop. Testing this prediction will also require water temperature data. Water temperature data are available from temperature loggers on all streams where traps are operated. In the event of situations where water temperature data are unavailable, it should be possible to predict water temperature reliably from air temperature data obtained from the weather service.

An alternative prediction is that the probability of observing sea lampreys above a barrier that has lost its 12-inch drop during period of lamprey run will increase with the number of days water temperature exceeds a specified threshold. Testing this prediction will require a stronger examination of the effects of water temperature on sea lamprey swimming ability and migration to assess what the temperature threshold might be. McAuley (1996) was identified as a key source of information for temperature effects on swimming performance. The water temperature at which sea lampreys migrate is more controversial. On the one hand, observations of lampreys congregating and moving upstream under the ice, and prior to the normal operation of traps and fishways, have been made. On the other hand, water temperature information from trap operations is often used to infer the thermal conditions under which sea lampreys migrate. There is uncertainty regarding these data because the times when sea lampreys aggressively enter traps do not necessarily reflect when they arrive at the barrier site, or when migration begins, and the period of trap operation does not necessarily encompass the entire period when sea lampreys are moving within streams.

Hypothesis 3. Some barriers are better than others at denying sea lampreys access to the face of the barrier or, when the barrier is inundated, access to sections upstream of the barrier, because spatial or temporal variation in the hydraulics of the tailrace below the barrier hinders sea lamprey movement upstream.

With low-head barriers, the sheet of water (nappe) plunging over the crest creates a hydraulic jump whereby the plunging nappe hits the tailrace and tends to leap upwards and roll back upstream toward the barrier (Fig 1a). Certain conditions of flow and tailrace geometry can lead to the jump becoming submerged and the creation of a vortex at the base of the barrier. Similar horizontal vortices can occur at the sides of the barrier (Fig 1b).

These vortices could impede sea lamprey migration. If, for example, sea lampreys at the base of the barrier exhibit rheotaxis they could enter the backward flowing water at the top of the jump (Fig. 1a) or the sides of the barrier (Fig. 1b) and head downstream rather than upstream. Further, the presence of these vortices could impede sea lamprey passage even at times when a barrier is inundated.

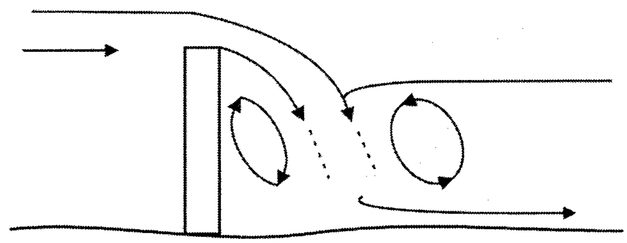
This hypothesis predicts that the probability of sea lampreys getting past the barrier decreases as the presence, form, or vorticity of the hydraulic jump below the barrier changes. By form we mean, for example, whether the jump is uniform across the tailrace or broken up. By vorticity we mean the rate at which the water moves within the vortex.

This is a poorly researched area within the context of the barrier program, but participants felt our ability to model and predict the flow should be reasonably good. For example, it is possible to use historical flow data to determine what flow pattern existed within the tailrace at a previous point in time and examine how the sea lampreys responded. Direct observation of how sea lampreys respond to hydraulic jumps will need to be conducted using large-scale model or field conditions to ensure the turbulence is high enough. Data requirements include (i) identifying the flow conditions over which the submerged jump occurs (see Leutheusser and Birk 1991), (ii) characterizing the nappe dimensions at the time when the submerged jump is present (for individual streams), and (iii) characterizing the vorticity when the jump does occur (for individual streams across years). We suggest obtaining these data via measurements made in physical models and the field, rather than with computational models, which are exceedingly complicated and would require verification anyway. As necessary, we also recommend examining the longitudinal aspects of the jump first and then the horizontal aspects.

Hypothesis 4. Some barriers are better than others at preventing sea lamprey movement over the barrier because spatial or temporal variation in the thickness of the nappe or the incident angle at which it strikes the tailrace hinders sea lamprey movement upstream.

Sea lampreys have been observed swimming with their bodies partially out of water (Youngs 1979, Hansen 1980), which could allow them to swim inside or on top of the sheet of water plunging over a barrier. Swimming part way out of water would reduce friction and increase swimming efficiency in the fast flow with the water beneath providing support. Variation in the angle and thickness of the nappe is expected to vary among barrier designs, and over time at the same barrier, in response to changes in water flow.

a)



b)

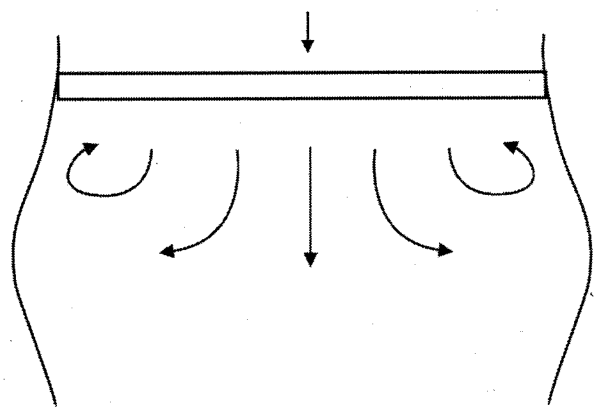


Figure 1. Schematic presentations of the hydraulic jump that can occur at the base of low-head barriers. a) Side view showing vertical vortices. b) Top view showing horizontal vortices. Based in part on Leutheusser and Birk (1991).

This hypothesis predicts the probability of sea lampreys getting past the barrier increases when the angle of the nappe decreases and the thickness of the nappe increases. Minimum requirements for testing this prediction would be measurements or reliable predictions of the angle at which the nappe strikes the tailrace and of the thickness of the nappe. Empirical measurements would be the cheapest and most accurate way of obtaining these data. In the field, measurements for the angle of the nappe would have to be collected directly. Measurements for the thickness of the nappe can be obtained from headwater elevation above the spillway. Thorough examination of this hypothesis will likely require the use of physical models in the laboratory. These models would examine the consistency of nappe geometry across flows of different magnitude. They would also be used to examine the responses of sea lampreys to different nappe conditions and test the initial premise that sea lampreys can exploit certain nappe conditions.

Hypothesis 5. Some barriers are better than others at preventing sea lamprey passage along the sides of streams because of differences in the types and geometries of abutments and armoring used to secure barriers to the stream bank.

This hypothesis is less precise than earlier hypotheses in terms of the mechanisms that allow passage. However, it recognizes that the placement, form, and height of abutments relative to the depth of the stream bank and the frequency of floods, as well as how abutments are secured to the stream bank (armoring), vary among barriers. This variation could influence the opportunity for sea lampreys to attach to surfaces, to climb shallow inclines or slither through wet grass at the sides of a barrier, or to pile on top of one another near the side of the barrier until some individuals can flip over the barrier. For example, abutments for the barrier at Duffins Creek taper into the bank at an angle (Fig 2). As water levels rise, the areas at the side can provide a drop of less than 12 inches, which allows sea lampreys to pile up and flip over the barrier. Alternatively, the abutment for the barrier at Days River is vertical (Fig. 2). As water levels rise, this design may be less susceptible to sea lamprey escapement at the sides, providing the abutment is secured tightly to the stream bank.

One prediction that could be tested expediently is whether the probability of sea lampreys passing the barrier decreases as the abutment height relative to bank full flow increases. This prediction could be tested across barriers. The test would require information on bank full flow, valley geometry, and stream cross section at the barriers, as well as upstream and downstream of the barriers.

Hypothesis 6. Some barriers may appear to be better than others at preventing sea lamprey passage because of spatial and temporal variation in the numbers of sea lampreys available to pass, which will vary with run size and with the effectiveness of any associated trap.

This hypothesis incorporates a barrier's role as a potential device for trapping sea lampreys, as well as a potential device for blocking their movement upstream. It further recognizes that traps at barriers may differ in trapping efficiency and that trapping animals reduces the remaining fraction of the run available to move beyond the barrier.

The hypothesis predicts that for a given trap efficiency the probability of sea lampreys being upstream of the barrier will increase with increasing run size and, for a given run size, the probability will decrease with increasing trap efficiency. The predictions can be tested across barriers, and across years for individual barriers, using a multiple regression approach. The test will require information on run size and trap efficiency and these should be available for a significant number of the barrier streams. The test would likely require two years and data should be available in the SLIMS database.

Hypothesis 7. Some barriers are better than others at preventing sea lamprey passage because of among barrier variation in the size and geometry of the lip at the top of the crest.

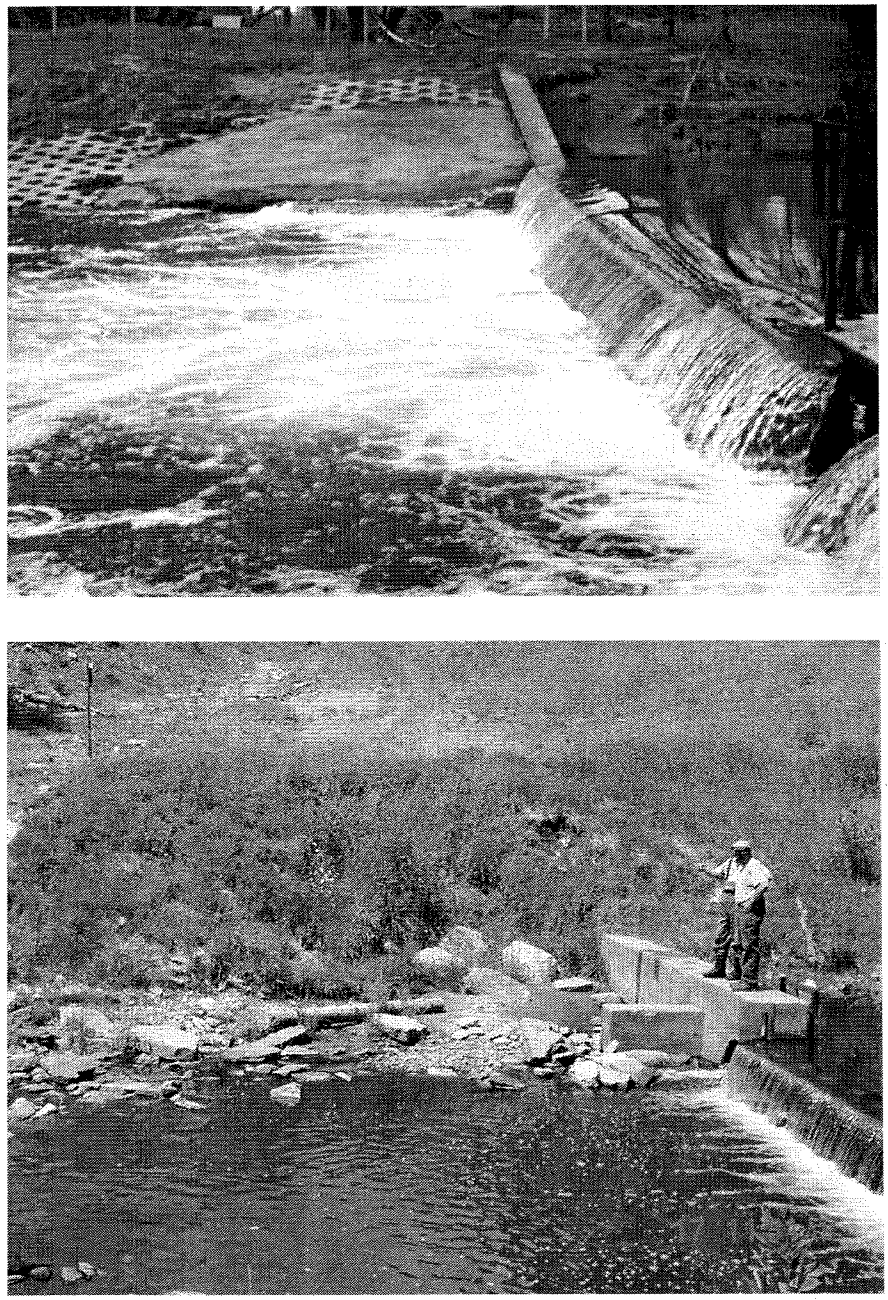


Figure 2. Different abutment and armoring designs used at sea lamprey barriers. Top. An angled, sheet metal abutment is shown on the far side of Duffin's Creek, ON. Bottom. A vertical, concrete abutment is shown on the far side of Day's River, MI.

Most sea lamprey barriers have a lip at the top of the crest that extends in the downstream direction. This lip detaches the flow from the face of the barrier to prevent attached sea lampreys from working their way up or around the barrier. The size of the lip varies from two to six inches in width. The angle at which it extends away from the barrier also varies among designs.

The reason for installing the lip needs to be validated. Such validation is best carried out using physical models because barriers lacking a lip are exceptional and altering the presence of a lip on existing barriers is not straightforward. Some barriers have been retrofitted with a lip. For these it may be possible to examine sea lamprey escapement before and after the addition or alteration of the lip.

There also is no information about whether certain lip widths or angles are better than others at impeding lamprey movements. Therefore, one testable prediction involving existing barriers would be that the probability of sea lampreys successfully reproducing upstream will be lower at barriers with a wider lip than those with a narrower lip. This prediction could be tested relatively expediently and would require the collection of data pertaining to lip width. In addition, the data on lip angle could be collected simultaneously and analyzed in an exploratory manner using a multiple regression approach.

Additional Hypotheses

Two other potential explanations for the presence or absence of sea lampreys above barriers were identified. They were (i) the presence of native lampreys inhibits upstream colonization of sea lampreys through interspecific competition and (ii) upstream colonization of sea lampreys is facilitated by mistakes made by trap operators or provisioning of passage by the public. It was decided that these were not worth pursuing at this time. The first explanation is currently based on observations at Stokely Creek and there is considerable disagreement over its merit. The second explanation is a debatable possibility and we lack the data needed to examine it rigorously. Any mistakes might be best addressed by improving the ergonomics of trap designs.

Research Needs for Barriers, Fishways, and Traps

This section identifies and briefly describes 16 key research priorities expected to provide the foundation for a research framework for sea lamprey barriers and traps. These priorities were developed by considering the entire fish passage question from the perspective of a fish moving through a stream. Accordingly, figure 3 organizes fish movement and passage as a sequence of four components: (i) migration or dispersal within a stream, (ii) search for a way around or over any barrier encountered, (iii) passage across, around, or over the barrier, and (iv) fate (survival and reproduction) following passage. These components are separated by three probabilistic events: encountering a barrier (P_e), finding a way around it (P_f), and passing successfully (P_s). Workshop participants considered research needs for each passage component from the viewpoints of blocking or trapping sea lampreys, passing non-target species (upstream and downstream), characterizing the physical environment encountered by the fishes,

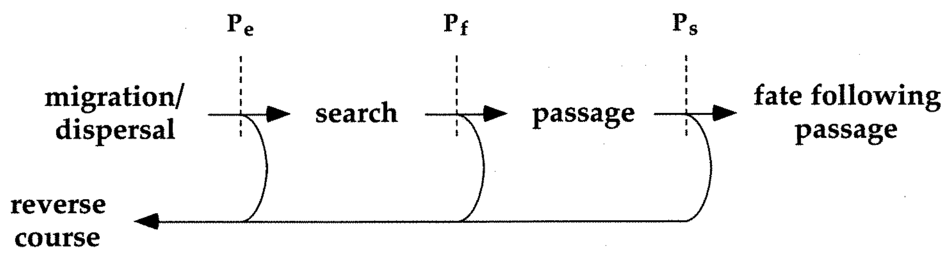


Figure 3. A framework for examining the components of fish movement and passage from the perspective of a fish.

designing effective barriers, traps, and fishways, and identifying special technological tools needed to expedite the research.

Proposed Research Priorities

1) Predicting the timing and magnitude of runs for sea lamprey and non-target species

This research priority is vital to the seasonal operation of traps, fishways, and seasonal barriers. The timing of runs is important for selecting the opening and closing times of seasonal devices. The magnitude of runs is important for designing the size of traps and fishways and for planning for their operation. This information is also important for assessing the overlap between the phenology of sea lamprey migrations and the phenology of migrations exhibited by non-target species, and hence whether seasonally-operated, inflatable and electrical barriers provide meaningful opportunity for fish passage outside of the period when sea lampreys are migrating (Klingler et al. 2003).

2) Frequency and consequences of early- and late-season movements by sea lampreys

Control agents have observed sea lampreys moving in streams before and after the normal period of operation for fishways and seasonal barriers. It is presumed that the earlier migrants move back downstream without reproducing, and re-enter the stream later during the normal migratory run, and that late migrants have inadequate time to reproduce successfully. The reproductive fate of these migrants is unknown and important to effective control given the high fecundity of this species.

3) Sea lamprey migration and dispersal behaviour in support of trapping

Our basic knowledge of sea lamprey movements is inadequate. General predictive models of when and how sea lampreys move within streams and rivers, as well as where they take refuge, could be used to support efforts to optimize trap placement and improve the attraction and retention of sea lampreys in traps. Such information could be particularly helpful in large systems. How sea lampreys respond after encountering a barrier and whether they leave the stream and move to an adjacent tributary is also an important concern.

4) *Determination of the passage needs for non-target fishes: propensity to migrate and distance traveled upstream*

This research is important to help identify species with special passage needs, to prioritize species for fish passage research, and to guide the design of fishways. There are over 170 fish species in the basin and over 100 of these have been observed in sea lamprey streams and rivers. The timing and extent of seasonal movements are poorly known or unknown for most species, with species of economic importance (e.g. salmonids) or species exhibiting strong seasonal runs (e.g. suckers) being exceptional.

5) *Hydraulic, hydrological and biological criteria for effective sea lamprey barriers (day 1)*

Existing barriers differ in their effectiveness at blocking sea lampreys. This variation is likely due to a complex interaction between (i) the biology of sea lampreys (e.g. magnitude and timing of migration, swimming performance), (ii) among stream variation in stream hydrology (e.g. frequency of flooding) and the hydraulic conditions below the barrier, and (iii) variation in barrier design (e.g. crest height, armoring, and lip design). Identifying the characteristics of effective barriers will assist with the design of more effective, new barriers.

6) *Quantitative studies of the behaviour of sea lampreys and non-target species at barriers and traps*

This research is critical to improving our effectiveness at denying sea lamprey passage upstream, as well as guiding sea lampreys into traps and sorting them from non-target fishes. It is also critical to improving our effectiveness of passing non-target species. Needed are general models or investigations of how sea lampreys and non-target fishes search for ways around barriers, how the intensity of this behaviour changes over the migratory season, the types of behaviour exhibited during this search, how search behaviour differs between sea lampreys and other non-target species, and how search behaviour is influenced by stream morphology, flow, and other physical factors that might facilitate (e.g. attraction flow) or disrupt this behaviour. Identifying non-target species that would normally move upstream, but do not approach barriers or fishways is also an important priority.

7) *Quantitative studies of the behaviour of sea lampreys and non-target species in fishways and traps*

This research is critical to improving the effectiveness of sea lamprey trapping through improved trap retention. It is also critical to the effectiveness of passing non-target fishes. Needed are general models or investigations of how sea lampreys pass natural obstacles and existing barriers and the role of attachment behaviour. Also needed are investigations of how sea lampreys and non-target species differ in volitional swimming performance, exploitation of hydraulic complexities, and motivation to pass obstacles during the migratory period or in response to the magnitude or nature of the obstacle. The behaviour **in** fishways and traps is presented separately from the behaviour **at** barriers and traps because the hydraulic conditions in the two situations can be very different, suggesting the challenges faced by the animals and their corresponding behavioural responses may also be very different.

8) *Compilation of traditional and personal knowledge regarding the behaviour and activities of sea lampreys and non-target species at barriers, traps, and fishways*

Field personnel with the contract agents possess a potentially rich source of qualitative observations and information about the behaviour of sea lampreys and non-target fishes in the wild. This information has considerable value for guiding research efforts by providing ideas for new research directions, providing guidance on research directions considered less promising based on past experience, and providing information important to management decisions. Unfortunately, much of this knowledge is not formalized in print, can vary among personnel and agencies, and is at risk of being lost as personnel retire.

9) *Examination of attractors and distracters for sea lamprey and non-target species*

This research is vital to efforts to attract and retain sea lampreys in traps and to facilitate passage of non-target fishes. Needed under this priority is a clearer understanding of what makes attraction flow attractive to fishes (e.g. velocity, turbulence, pressure waves), other stimuli that could function as attractors (e.g. light, pheromones) or distracters, the senses lampreys and non-target fishes use to detect these attractors and distracters, and the potential to **combine** these attractors and distracters in ways that enhance the control of sea lamprey and the passage of non-target fishes.

10) *Experiments with funnel and trap design configurations*

A more formal experimental approach to funnel and trap design will help improve our effectiveness at attracting and retaining sea lampreys in traps, as well as attracting and passing non-target fishes. Valuable areas of research include the placement and orientation of these devices within the stream, the placement and configuration of trap and fishway entrances, optimization of the sizes and configurations of traps and fishways in relation to the anticipated sizes of migratory runs and the ergonomics and economics of trap operation, and the maintenance of attraction flows through the development of more effective self-cleaning screens at the upstream intake of fishways.

11) *New and improved designs of barriers, fishways, and traps*

In addition to improving existing barrier, trap, and fishway technologies, there is the need to develop and explore entirely new designs arising either from experience outside of the basin (e.g. windmill style traps used in Alaska) or from the research advances expected from priorities 1-10.

12) Test of new spillway design types against lamprey passage and human safety concerns

Sea lamprey barriers can create complex flow patterns of potential danger to swimmers, canoeists, and kayakers (Fig. 1). As such, human safety is emerging as a significant concern for barrier placement and design. Barrier designs that minimize the complex vortices below the barrier are achievable, but how effective these alternative designs are in terms of blocking sea lampreys or passing jumping fishes needs to be assessed rigorously.

13) Quantification of the effectiveness of blocking and trapping sea lampreys, including the level needed for successful sea lamprey control.

This research is needed to critically evaluate our success at blocking and trapping sea lampreys, as well as assess the effectiveness of new barrier and trap designs or features. Research needs include a greater understanding of how effective barriers and traps need to be for successful sea lamprey control and whether highly efficient traps could eliminate the need for barriers.

14) Quantification of the effectiveness of non-target fish passage

This research is needed to critically evaluate our success at passing non-target fishes, as well as assess the effectiveness of new barrier and fishway designs or features. Research needs include an improved understanding of how effective barriers and fishways need to be in terms of maintaining species and genetic diversity and maintaining ecosystem services, some minimum understanding of passage rates and these ecological attributes in the absence of barriers (for reference and interpretation), and whether some minimum amount of passage is "good enough" both ecologically and socially.

15) Evaluation of the Interim Policy on Barrier Placement (completed 2003)

The GLFC developed an *Interim Policy on the Placement of Sea Lamprey Barriers* in response to an earlier basin-wide assessment of the effects of sea lamprey barriers on non-target fishes. Fish distribution and passage databases have been created and pilot field exercises implementing the policy have been conducted to demonstrate that the policy can be carried through on sites being considered for barrier construction.

16) Decision analysis for the implementation and operation of sea lamprey barriers (underway)

While the GLFC is committed to supporting research advances aimed at improving the effectiveness and operation of sea lamprey barriers, fishways, and traps, new barriers and fishways will be built before the needed research can be completed. This research priority will develop plans maximizing the potential for us to learn (about implementation and operation) as we go from the newly constructed barriers and fishways.

Conclusion

This list of research priorities provides an initial, thorough foundation for the development of a vigorous research framework supporting the GLFC's commitment to including barriers and traps as part of a sea lamprey control program that is ecologically and economically sound, and socially acceptable. The key issues behind many of these priorities could be developed and critically examined in a single research project. The order in which they should be addressed is an outstanding need.

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