GREAT LAKES FISHERY COMMISSION
2002 Project Completion Report[1]

Fish Passage: Concepts, Application and Evaluation – Great Lakes Tributary Streams

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Improving the design and operation of fishways, traps, and barriers: An annotated bibliography

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IMPROVING THE DESIGN AND OPERATION OF FISHWAYS, TRAPS, AND BARRIERS:

AN ANNOTATED BIBLIOGRAPHY

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Summary Report
for the
Great Lakes Fishery Commission Sponsored Workshop

Fish Passage: Concepts, Application and Evaluation – Great Lakes Tributary Streams

2-3 February 2001

S. O. Conte Anadromous Fish Research Center
USGS/BRD Leetown Science Center
Turner Falls, MA

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Executive Summary

The Great Lakes Fishery Commission (GLFC) considers the placement of low-head barriers in streams tributary to the Great Lakes to be the most effective of currently available alternatives to chemical control of parasitic sea lamprey (*Petromyzon marinus*). A key consideration for the Barrier Program is the development of barrier and trap designs that are effective in controlling sea lamprey, yet also effective in allowing the normal movements of other fish species.

Accordingly, the international workshop **Fish Passage: Concepts, Applications, and Evaluation - Great Lakes Tributary Streams** was funded by the GLFC and held 2 - 3 February 2001 at the S. O. Conte Anadromous Fish Research Center in Turner Falls, MA, USA. The objectives of the workshop were to (i) initiate the development of a long-term, coordinated research program integrating biological and engineering considerations for the trapping of sea lamprey and the passage of nontarget fishes at barriers; and, (ii) develop initial design considerations for an experimental facility or facilities for the trapping and passage research. Workshop participants included assessment biologists, research scientists, and engineers from Canada, the United States, and the United Kingdom with expertise in the biology and control of sea lamprey, the migration and passage of nonsalmonid fishes, and the design of barriers and fishways. The workshop was held at the Conte Research Center because of its state-of-the-art fish passage facilities.

Four research themes were addressed sequentially at the workshop. Theme 1 identified aspects of the behaviour, physiology, and ecology of sea lamprey that could be exploited to improve control via barriers and traps. Lamprey traps in the absence of barriers were recognized as an ideal solution to the passage issue providing trap efficiency can be made high enough for traps to be effective for control purposes. Attachment behaviour, and responses to water flow and pheromones, were identified as aspects of lamprey biology that could be exploited further and additional research on the instream migratory behaviour and sensory biology of sea lamprey is needed. A trap design combining the responses of lamprey to attractant flows and pheromones, with current engineering designs for sorting fishes within traps, also was proposed.

Theme 2 addressed ways of identifying nontarget fishes that need to pass low-head barriers, prioritizing these species for passage research, identifying specific research needs, and evaluating the effectiveness of fish passage efforts from the perspective of minimizing habitat and population fragmentation by barriers. It was questioned whether there were adequate data currently available to identify species with passage needs. Information on movements provided in common reference texts for fishes is anecdotal and dated, and there is growing recognition that different life stages of nonsalmonid fishes may be moving within streams, and between streams and lakes, in complex ways. Further research quantifying the movements of fishes was recommended and the strategy of deploying barriers on an experimental basis was raised.

Theme 3 considered the new knowledge needed to improve the design of barriers, traps and fishways as well as ways of assessing the performance of these designs. Existing measures of fish swimming performance may be of limited use in the context of fish passage. New measures need to consider the differences in performance observed between voluntary and forced swimming, the tendency for fishes to avoid fatigue under more natural conditions, and the ability of fishes to exploit temporal and spatial variation in water flow. New methods of evaluating the performance of fishways and monitoring the instream movements of fishes also were presented.

Theme 4 synthesized and prioritized the research questions that emerged from themes 1 to 3 and then focused on the type(s) of facility(ies) needed to address these. The number of research questions identified was large and there was not strong consensus on their priority. The two questions asked most frequently were "What level of spawner removal is required to control lamprey?" and "What are the long- and short-term effects of barriers on communities of stream organisms?" There was considerable interest in a Great Lakes facility for fish passage research and a list of key general requirements, specifications, and potential concerns was compiled.

This workshop delivered a rich, diverse resource of ideas for conducting research leading to improvements in the devices used for trapping sea lamprey and for allowing the passage of nontarget fishes at barriers. It is recommended the GLFC exploit this resource through a smaller, focused workshop where key personnel from within the Great Lakes basin identify and coordinate specific research projects and identify areas of expertise and resources that are lacking.

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Summary of Presentations

THEME 1 – Lamprey Biology

Trapping, blocking, enhancing passage, behavior and study difficulties (laboratory and field)

Bill Swink - Introductory remarks

- Routine behavior of lamprey in lab tanks is to attach, especially if there is little or no current. They also congregate in large numbers, especially in preferred corners.
- Lamprey are very tolerant of electrical fields compared to teleosts.
- Lamprey will stage in rivers even before ice out. They will migrate upriver (either actively or attached to a host?) in winter and then drift back downstream.
- Lamprey behavior may change during the lamprey run. For example, lamprey appear to be more light sensitive during the early part of the run. Is this related to the gradual loss of sight?
- Closing remarks: Although passage of non-target teleosts around barriers is important, the GLFC barrier program needs to ensure that sea lampreys do not escape upstream as a result. Stock-recruitment studies indicate that a few spawning pairs (perhaps as few as one) might repopulate a stream with larvae. As the barriers are constructed to eliminate chemical lampricide treatments, any appreciable escapement by lampreys will defeat that goal, causing us to build the barrier **and** still treat the stream.

Research needs

- Need a method to effectively trap sea lampreys in streams without barriers.
- What are the implications of attachment behavior with respect to laboratory studies on sea lamprey?
- Is there any evidence that lamprey are attracted by electrical fields? (See the early work of Kleerekoper).
- What are the implications of early lamprey migration to seasonal barrier operation?

Rod McDonald on the Canadian lamprey trapping program

Observations on lamprey behavior at traps:

- Attractant water flow is necessary to attract lamprey to any degree to our solid-wall permanent traps, which make up the greatest portion of the Canadian trapping network. Too much flow will prevent access to the trap or cause injury/mortality to either the lamprey or incidentally-caught fish once inside. While we are beginning to appreciate that we can achieve (equally?) good catches (at least at some sites) with less attractant flow than previously utilized, yet reducing the attractant flow below some minimum level reduces the number caught in the trap.
- Lamprey can be guided to a trap via an underwater pipe (pipe used in these tests -- at Echo & Still river barriers -- was 6" diameter steel, up to 48 ft. in length). This means that one trap can be used to collect lamprey from both sides of a creek, or from more than one location along a barrier. Lamprey will also pass through at least 50 feet of 6" flexible underwater pipe while moving from a trap into a holding device (example from St. Mary's River).

- Lamprey will attach tenaciously to many types of surfaces, and show a preference for attachment adjacent those sites where flow is leaking through apertures in the surface.
- Lamprey have impressive climbing ability, and have been found at 30 feet up an angled dam face, partially exposed to air (North Creek dam, Big Creek). Animals are attached perhaps 80% or more of the time, and inch their way up the face by moving diagonally back and forth for several feet at a time.
- Pacific lamprey, and anadromous sea lamprey (from Andrew Hallett), will pyramid on top of one another at dam faces, thereby climbing several feet out of the water, possibly over a barrier in the process. Great Lakes sea lamprey have not been observed using this behaviour to any effective degree, but will certainly pile together while climbing natural rock faces (falls on Little Thessalon River).

Research needs:

- What are optimal attractant flows? Is there an attraction associated with turbulence?
- How can we improve the measuring of effectiveness of traps? Current method is by mark-recapture. Trap effectiveness is normally expressed as percentage of run, effectiveness as high as 80% are reported for traps (from Kasia Mullet).
- What level of effectiveness would be required to use trapping for control *vs.* assessment purposes? This is really a stock-recruitment rather than a trap effectiveness issue; i.e. you could use a host of traps with low 'efficiency" and produce the same result as a few traps with high efficiency.

Kasia Mullet on the US trapping program

- Most of the traps used in the US program are portable and are designed mainly for assessment. However, most new barriers in the US are now using built-in traps.
- Portable traps appear to be most effective when hung at the surface at a barrier. This is because once lamprey encounter a structure they are unable to pass, they eventually comes to the surface in search for a way to bypass the structure. This is probably the same phenomenon as when lampreys begin to attach and slide up a vertical surface. When they are unable to find a way past, they eventually look for a way over. This is not the same behavior you would see if there were not a barrier blocking the upstream migration. When there is no barrier, lampreys usually move along the bottom of the stream.
- *Is light an attractant*? When used at night, at paired traps, higher numbers of lamprey were captured in the lighted trap. Although lampreys were guided to the lit side of the trap (even if the lit trap was alternated) it is not known whether the same total number of lampreys would have been captured if no light had been used. We can guide lampreys into a trap when they are in the immediate vicinity, but we have not been able to show that we can to draw lampreys from a further distance. Light is used in Europe to fish for lamprey at night. Strobe lights had no effect on attached lamprey, but there is some evidence that light will attract swimming lamprey (Hammond Bay pilot projects).
- *Potential of using barrier on Ocqueoc River as a research site?* This is low head plus electrical barrier, with traps on either side, which have identical trapping efficiency. In 1999, only one trap was operated and trap efficiency was 69%. In 2000, traps on both sides of the river were operated and trap efficiency was again 69%. During the year two traps were operated, the total catch was evenly split between the two traps. This suggests that the

Ocqueoc River barrier would be a good place to test different trap designs (e.g. trap funnels). It should also be a good place to test attractants and repellants.

- *Is sound useful for guiding lamprey?* In a study at the Misery River using paired traps (actually fyke nets), a sound device was set directly in front of funnel opening and appeared to be able to guide lamprey away from the speaker if a lamprey was within 3-4 feet of the speaker. However, as far as potential applications, there is some concern that lampreys will become accustomed to sound. At distances around 5 feet or greater, it did not appear to affect lampreys.
- There is some evidence that lamprey will spend more effort searching for an easy way forward past an obstacle than taking a route that is challenging but which they can pass. Examples include the Wolf River, Ocqueoc River, and St. Mary's River rapids.

Research needs:

- How do lampreys respond to changes in velocity encountered in a stream? At what velocity will lampreys alter their course and seek faster or slower water?
- How does the orientation of an introduced discharge to the main flow of the river affect lamprey behavior? If it is perpendicular to the main flow of the water, will it cause a lamprey to "turn" into it? What velocity does the flow have to be to encourage the lamprey to change direction and follow it?
- How well do lampreys find "attractant water" in turbulent flow situations, such as power plants?
- Can we take advantage of partial barriers that slow down the upstream migration of lampreys long enough for a lamprey to become vulnerable to trapping? Will a lamprey traverse the face of the barrier for a period of time before making an attempt to pass over it?
- What funnel design is most effective to capture and retain lampreys? Is a funnel alone sufficient? Does a facing with a funnel behind it increase trap efficiency (encouraging lampreys to stay in the vicinity of the funnel before actually passing through it)?
- How much of a role does sight play in lamprey behavior around barriers and traps? What do they see? What senses are mainly used when navigating upstream? What causes lampreys to be "cautious" about committing to a trap?
- How many chances do we have to intercept an individual lamprey before it turns and leaves the barrier/trap vicinity or river?
- How does the density of spawners in an area affect behavior and commitment of lampreys at barriers/traps?
- How can we better exploit the probing behavior of a lamprey to build a more effective trap?
- How can we close the gap between and 70% and 100% efficient trap?

Andrew Hallett on barriers

Barrier height and effectiveness

- What is the appropriate height for a sea lamprey barrier? Applegate (1951) recommended 50 cm under average flow conditions, but there is a lot of inconsistency in barrier height. Hunn and Youngs concluded that a 30 cm barrier with an overhanging lip was highly effective while a 15 cm height was not.
- *Example of a successful barrier*: Duffins Cr. barrier, Ajax, ON, built in 1980. This is a barrier with built-in trap (with a 60-70% trap efficiency), overhanging lip, and crest height of 50 cm at average flow, 15 cm at double flow and no crest when flow double again. There are

1-3 flood flow events each year where crest height criteria are lost. Despite failures, only one TFM treatment was required since construction in 1980 compared to once every 3 years prior to construction. Approximately 30 streams have similar barriers - they have been similarly successful. Part of the assessment of effectiveness problem is that only 3 of these 30 streams have flow gauges. Use of hydrology / hydraulics as risk model at barriers consistently underestimates subsequent stream treatment frequency.

Research needs:

- Why has the Duffins Cr. barrier has been so successful?
- What factors other than height complement a low-head barrier's effectiveness? (e.g. stream temperature, larval abundance upstream of the barrier, condition factor of spawning sea lamprey, response of lamprey to spillway/tailrace hydraulics, migration timing etc.).
- need to better understand the effects of hydraulics in tailraces and spillways on behaviour, and physiological limitations.

Passive sorting in traps

Evaluation at three barriers with fishways and traps:

- Big Carp R. in Sault Ste. Marie. This barrier has an inflatable crest, a vertical slot fishway (two slots in series) and two built-in traps in series. Up to 95% sorting of lamprey from the rest of the catch has been observed in experimental design with narrow opening entrance funnels between traps. The highest attraction flow is on the trap side of the barrier. A total of 36 species have been found in this trap.
- Cobourg Br., Lake Ontario - total of 25 species found in trap.
- Big Cr, Lake Erie - total of 26 species found in trap.
- Combining catch records from these three vertical slot, trap and sort fishways, a total of 45 species have been found.

Research needs:

- More thought needs to be given to the required trap capacity. A low capacity may be restricting movement into the fishway. How much of the problem can be addressed by more frequent operation?
- How can we improve sorting to eliminate handling of larger fishes? Are there ways we could better manipulate their movement / attract / guide them within the fishway?
- Where is our limit on fish passage coming from? Is it the number of fish entering the fishway? Is it that after entering, they fall back, and do not enter the traps?
- What is the fate of fishes that are released from our traps?

Velocity Barrier

- The velocity barrier is an attractive idea because non-target fishes would not require handling for passage at these barriers, unlike with the vertical slot, trap-and-sort fishways.
- Generally speaking, fish shorter than 25 cm do not pass the velocity barrier.
- The experimental installation of the velocity barrier on the McIntyre River has not blocked sea lamprey yet. Escapement could be occurring through the flume, or past the barrier. Because the dam is flooded so regularly, it is difficult to identify where lamprey get through.
- Given recent findings regarding the accuracy of swim performance tests, can a new envelope model be made for sea lamprey? Can we further improve non-target passage?

Research needs:

- Better estimates of swim performance in sea lamprey and key non-target fish, and the difference between them.
- A better experimental facility than the McIntyre R. site, where flow though the flume can be regulated, and where other escapement opportunities are ruled out.

Mary Moser on Pacific lamprey (*Lampetra tridentata*)

Studies on upstream passage at Bonneville Dam (and 3 other dams on the Columbia River) from 1996-2000 with 200-350 radio-telemetered lamprey per year. Lamprey were collected from the fishway, tagged (surgical implant) and then displaced ~3 km downstream. There was 90-95% return of tagged fish to dams which indicates little if any stress associated with the tagging. Overall passage efficiency at the four lower Columbia dams in 1998-2000 ranged from 12 to 57% of lamprey compared to ~90% for salmonids.

Observations on lamprey passage:

- 60-70% of lamprey upstream passage occurs at night
- diffuser gratings are a real problem for lamprey passage since lamprey will not attach
- lamprey will use attach-leap behavior to negotiate high velocity currents. The threshold velocity for this behavior is 8 ft/sec (based on tests in experimental flume).
- Is there a role of light in guiding night-time lamprey passage? Trials with red, white or no light showed no differences.
- Lamprey will enter submerged orifices
- Transit time for tagged lampreys was bimodal; either 7h or 24h. Interpretation? (may relate to time of initial approach).

Research Needs:

- How much passage is needed to re-build Columbia River lamprey populations?
- Testing is needed to assess the efficacy of placing plates over diffuser grates to provide attachment sites for lamprey and to determine whether slotted entrances will improve entrance efficiency.
- Need to determine why vertical slot fishways at Bonneville Dam are problematic for lamprey

Alex Haro on lamprey (*Petromyzon marinus*) passage at Cabot station fishway

Two year study of lamprey behavior in pool & weir fishway on Connecticut River, using video monitoring in lower and midsections.

- Fishway is a modified Ice Harbor type, with 32 cfs, 1' drop per pool, 66 pools in total, 660' length and a 1:10 slope.
- Most of lamprey movement is at night.
- Equal amount of upstream and downstream movement, especially at lower weirs.
- Lamprey spend great majority of time attached rather than swimming
- Video showing lamprey in current of submerged orifice (8'/sec) attached and flopping about. Successful negotiation of orifice velocities, after many attempts.

Research needs:

- compare swimming performance between anadromous and Great Lakes forms of sea lamprey
- examine potential for lamprey to ascend dams via submerged gates or other non-traditional routes

Peter Sorensen on lamprey migratory behavior

Lamprey migration into rivers from lakes is likely mediated by two different, albeit related behavioral mechanisms which are outlined below:

1. Finding a stream from lake

- Lamprey likely start locating streams in late winter. Stream selection is based on odorous cues (pheromones) released by larvae.
- Larvae are found in only 7% of Great Lakes tributaries suggesting pheromones play an essential role in stream selection. This supposition is strengthened by the fact that several studies in the Great Lakes show no evidence of homing to the natal stream (see Bergstedt and Seelye, 1995). There appears to be some anecdotal evidence that homing could be occurring in the Connecticut River (comment from Steve Gephard).
- A key component of the larval pheromone is petromyzonal sulphate (PS) and although behaviorally active, it lacks the activity of whole larval odor, suggesting that at least one unidentified component exists.
- The pheromone is active even at low water temperatures and can attract adult lamprey to specific regions of a raceway test maze, suggesting it could be used in trapping in early spring in river mouths.

2. Swimming upstream

- Lamprey stage at river mouths when temperature is low.
- Once ambient temperatures exceed 12° C, slight increases in temperature accelerate upstream movement and staging ceases.
- Once in a warm stream, lamprey are strongly rheotactic. The strength of this response appears to be modulated by odor. Lamprey lacking functional olfactory systems eventually migrate from streams in significant numbers.
- The strength of upstream swimming in lamprey is also influenced by temperature which interacts with odor in a synergistic fashion.
- Migratory lamprey are not attracted by sex pheromone until sexually mature suggesting that odor driven responses seen in upstream migrants are influenced by the larval pheromone (PS).
- Role of current strength in attraction is unknown.

Research Needs:

- Can the larval pheromone be used to draw early-migratory adult sea lamprey into traps located in the lake/river mouths and if so, might catch rate be enhanced using flow and/or directed pheromone plumes?
- Can the larval pheromone be used to increase riverine trap capture efficiencies as well? If so, how important would flow and time of day be?
- What difference might enhanced lake and riverine trapping efficiencies make to lamprey control?
- Can means of extracting large quantities of the pheromone be devised?
- What is the complete chemical identity of the larval pheromone?

John Kelso on upstream movement and in-stream populations

River	Emigration rate	Distance to barrier (km)	Mean Annual flow (m^3/s)	Average daily movement rate (km/day)
Wolf River	49%	5.9	6.8	0.11
Pancake River	22%	7.4	2.8	0.17
Bad River	0	>50	13	1.33

Observations on river movements:

- In a river system, the type of habitat where sea lampreys will be found is highly predictable.
- Sea lamprey will be found attached in high flow, to boulder and in brush/log piles.
- Sea lamprey move both during the day and night but most will be trapped at night
- There are among-stream and within-stream, among-year differences in emigration and upstream travel.
- Emigration appears to be affected by the location of the barrier to upstream passage i.e. barriers near stream mouth increase emigration.
- Sea lampreys show limited fidelity to a nest and may change mates.
- Of the sea lampreys that remain in a stream, not all move upstream.
- A large number of female sea lampreys are present at time of spawning but the number of nests in relation to the numbers of adults is low.

Observations from lamprey fishery in New Zealand:

- At some sites as many as 6000 animals can be trapped in one night using traditional trapping techniques. However, the number of lampreys in the run is not known.
- Main trap design is a bank side weir with a fall back net
- Mats with roughened surfaces will attract lamprey to attach, lamprey harvested from mats
- Lamprey will also scale vertical flooded surfaces to attach

Research Needs:

- Factors that affect stream fidelity, upstream movement and paths of movement.

Chuck Coutant on A Sea Lamprey Trap Incorporating Induced Flow and Pheromones

A new perspective on a sea lamprey trap is provided that integrates sensory capabilities, behavior and performance of lamprey into trap design and evaluation. A new perspective is needed because artificial barriers associated with traps can block movements of other species, which can be detrimental to their sustainability. Because of this blockage, proposed new barriers are expected to engender opposition. Also, barriers can be overtopped by high spring flows, allowing lamprey to pass, thus defeating their primary purpose.

Key attributes of upstream-migrating lamprey that the proposed design incorporates are:

- Need for a low-velocity current for lamprey to move upstream.
- Attraction to chemical substances (pheromones) produced by larvae and opposite sexes.
- Surface-oriented migration, often at night.
- Ability to pack many lampreys into a container.
- Ability of lamprey to enter and pass through appropriately sized pipes and hoses.

- Ability to pass through slots of graded sizes, excluding other species.
- Ability to enter traps not associated with barriers when traps are located where there is a flow leading toward the trap.

The proposed trap is designed to:

- Be located in still water, not rapid flows, where induced turbulent flow can be generated and controlled,
- Have an attraction flow that mimics natural riverine flows in terms of velocities and turbulence,
- Float at the surface to rise and fall with water elevation,
- Use pheromone(s) added to the attraction flow to enhance attraction,
- Use a graded-slot entry into a trap to sort lamprey from other species,
- Incorporate an exit pipe from the primary trap for lamprey access to a shoreline holding tank, from where lamprey can be harvested.

A sketch of such a trap is shown as Figure 1. It is presented as a testable hypothesis to guide focused research. Lamprey otherwise unguided in a quiet pool would be attracted to a plume of mildly turbulent water emitted from a floating trap, especially if the plume also contained small amounts of larval or sex pheromone. An attraction flow would also be provided through the trap. Lamprey would enter the trap and pass through slots of graded sizes to separate lamprey from other species, allowing the other species to return to the water body. The chamber most likely to retain lamprey would be fitted with an exit hose running a low-velocity flow of water containing pheromone. This hose would lead to a shoreline holding tank from which lamprey could be emptied periodically. Pheromone would most conveniently be added to this holding tank flow, which would pass down the hose and into the trap and mix with the attraction flow in the trap. Attraction flows could be generated by submersible pumps on the trap or by a shore-based pump, as shown in the figure. Because a complete blockage is not provided, several traps may be needed for each watercourse to accomplish near total removal of migrating lampreys.

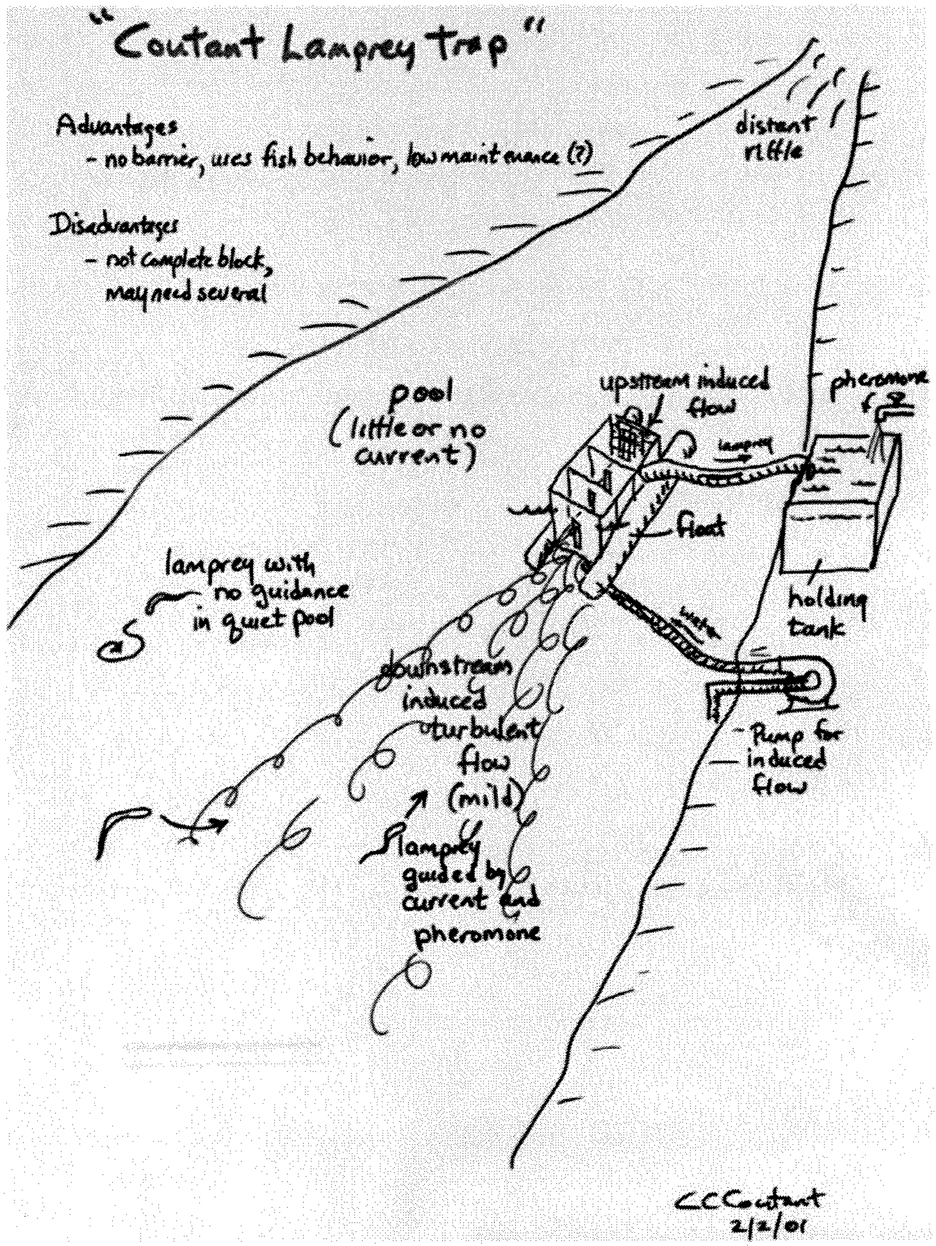

Figure 1. Schematic of the Coutant Lamprey trap

THEME 2 - Nontarget Species
Biology and Passage Requirements

Rob McLaughlin - Introductory remarks

- There are roughly 175 potential nontarget fishes within the Great Lakes.
- We know little about the behaviour and ecology of many of these species.
- Where do we start in determining which species may be impacted by barriers and in prioritizing species for fish passage research?
- Background synopsis of Biological Impacts Of Low-head Dams (BILD) project.
    - loss of extra two species upstream of a barrier, on average.
    - barriers restrict movements of nonjumping fishes.
    - lentic/lotic generalists tend to be underrepresented above barriers.

Steve Gephard on the perspective from the East Coast

- Many fishes are migratory.
- Classes of migration - anadromy, catadromy, adventitious, potamodromy, resident.
- These classes are really describing a continuum in terms of migratory behaviour.
- There was discussion from the group as to whether migration or movement was the key factor and whether focusing on migration could overlook important movements, made by few individuals, related to dispersal, gene flow, and redistribution of populations.
- There was also considerable discussion and concern from the group regarding the effort required to quantify movement (number of species, cost, etc.).
- For the east coast, comparison of the timing of sea lamprey migrations with those of nontarget species suggests there is considerable overlap and, therefore, not much opportunity for seasonal barriers to prevent lamprey migrations while allowing movement of nontarget species at other times.

Nick Mandrak on broad-scale ecological concerns

- Several attendees are in the process of identifying ichthyofaunal regions for the Great Lakes.
- Many sources of data are outdated, e.g. Fishes of Illinois (1979), Fishes of Indiana (1945).
- Compiling these data is a considerable challenge, e.g. extracting information from books, finding electronic sources, data sources being resistance to donation.
- Much of the focus has been on VTE species, but many fishes, including "coarse" fishes, are potentially important economically (see statistics on GLFC website).
- Roughly 85 species are listed as being of conservation concern and this could create difficulty because almost any potential barrier stream may have a listed species in it.
- Assessments used to list species are based on what (often little) is known.
- *Moxostoma* as an example. They can be much commoner than we think owing to historical inefficiencies in sampling them. They also may be very mobile. Are they a possible model species for metapopulation studies?
- Many Great Lakes fishes are found in both lentic and lotic habitats suggesting the possibility of movement between these habitat types, as well as extensive movement within streams, and therefore the possibility of fragmentation by barriers.

Marco Rodriguez on the importance of ecology and movement

- An important issue that was not being addressed directly in the discussions was population fragmentation and its impact on the colonization and extinction dynamics of fishes.
- Ecology can be an aid rather than a hindrance.
- An analysis of measures of impact (fragmentation) in relation to existing ecological and morphological information was suggested (based on the 4th-corner problem, Legendre and Legendre. 1998. Numerical Ecology).
- These data could complemented by observational field data on fragmentation.
- A field study based on mark-recapture methods and application of diffusion models was suggested.
- Fish traps at the extremities of study sections (absorbing boundaries) would serve to quantify departures of marked individuals from the sections.

Martyn Lucas on studies of fish migration in Europe

- Migration can be defined as "a strategy of adaptive value, involving movement of part or all of the population in time, between discrete sites existing in an n-dimensional hypervolume of biotic and abiotic factors, usually but not necessarily involving predictability or synchronicity in time, since interindividual variation is a fundamental component of populations" (Lucas and Baras, 2001. Migration of Freshwater Fishes).
- Based on this definition roughly 65% of the freshwater fishes described in Scott and Crossman's Freshwater Fishes of Canada are migratory (see Lucas and Baras, 2001. Migration of Freshwater Fishes).
- Degree of migratory behaviour may vary considerably among populations and environments because it is an adaptive strategy.
- Larval life stages of many fish may be sensitive to small, turbulent structures but there tends to be a strong focus on adult fishes.
- In Europe, many juvenile fishes are exhibiting upstream movements/migrations.
- Barriers may alter habitat in ways that affect lateral connectivity important to juvenile stages of many fishes.

Rob McLaughlin - Remarks preceding discussion

- There is value in considering large-scale issues of movement, population structure, and fragmentation.
- There is growing evidence that a multi-scale perspective to movement/fragmentation is needed for effective management.
- Policy (e.g. *Interim Policy of Barrier Siting*) is being driven by large-scale concepts, such as biological integrity, species diversity, and production.
- Therefore, don't we need to assess passage at larger scales, beyond just number of fish passing at a barrier, to ensure passing fish contribute in biologically meaningful ways to the fish assemblage upstream?
- Scientifically, the fish passage problem presents an opportunity to link the interaction between the behaviour, physiology, and ecology of fishes at barriers with the colonization and extinction processes thought to determine species diversity and assemblage composition in the stream.

Research Needs

- Do we have adequate baseline data to proceed with a barrier program?
- Need to develop a framework for investigating nontarget species that considers the number of species found in Great Lakes streams, their diverse life histories and potentially diverse migratory behaviour, and the limitations with existing information. Is the functional hierarchy from the workshop proposal adequate?
- Need to assess what we can learn from existing data. Are there adequate literature data to carry out the analysis proposed by Rodriguez? Are existing data on the extent and timing of movements adequate to assess the potential for habitat fragmentation by barriers, the specific species impacted, and the efficacy of using seasonal barriers (e.g. Gephard)?
- Can we extract useful information from existing trap data? Which species try to pass? How repeatable are their numbers from year to year? Timing of their movements relative to sea lamprey?
- Can we assume that apparently 'sedentary' species will not be impacted by barriers? They are showing up in traps. Are these movements important to (meta)population dynamics? What are the habitat fragment sizes above barriers and how do these correspond with minimal viable population sizes for various species?
- Can barrier installation be done experimentally, with the option of removal upon signs of impact? How long do we monitor? How do we balance the precision gained from intensive studies of individual streams with the need for generality? Can we assume stream fish assemblages will be restored if barriers are removed?
- How do we prioritize species for study? Are there species (e.g. listed species) which we need to study in greater detail to assess their potential for being impacted by barriers, or to assess whether their conservation designation is warranted (e.g. Mandrak)?
- Need to take a broader view of fish passage. One which includes downstream as well as upstream movement, and juvenile (small) fish(es) as well as adult (large) fish(es) (e.g. Lucas).
- Need to consider how barriers influence habitat and the lateral connectivity important to young fishes (e.g. nursery habitats).
- Need to consider how ecology can affect fish passage. If a fish is capable of passing, will it? Is passage a behavioural decision based on ecological conditions (e.g. population density, availability of spawning habitat below the barrier) as well as swimming capacity? What species do not pass, but might in the absence of a barrier?

THEME 3. Barriers, fishways and traps
New perspectives on design and evaluation

Scott McKinley - Introductory Remarks

- We need to emphasize consideration of environmental changes and barriers to passage from the perspective of the fish.

Gord McDonald on measuring swimming performance

- History of different "gaits" of swimming and U_{crit} estimation.
- McAuley thesis - measurement of swimming performance for lamprey and nontarget species to build his semi-permeable velocity barrier - appropriate strategy?
- Endurance-speed curve for rainbow trout.
  - endurance is 8 at ~4 lengths/s and declines at decreasing rate with speed.
  - but fish exhibit less endurance when accelerated rapidly than when slowly.
  - fish appear to require tune-up time for blood pressure, heart rate, etc.
- Why are fish so slow re "physiological adaptation"?
  - possibly a protective reflex for gill function.
- Key issue is that past swimming performance measurements (used for passage designs) have been made for nonvolitional swimming.
- Volitional measurements probably differ significantly, meaning that existing swimming measurements may not be of much use.

Comments

- Steve McCormick argues that traditional measurements may be useful in ranking passage abilities of fishes.
- What are the right aspects of performance to measure in the context of fish passage?
- George Lauder's lab is analyzing the biomechanics of simple manouevers and working towards more complex ones. They are using a comparative approach, salmon vs. bluegill.

Ted Castro-Santos on performance in fishways

Evaluating fishway performance

- To date there are no standardized approaches to how we measure fishway performance, however two variables stand out as reasonable candidates: likelihood of passage and transit time. Likelihood of passage is actually the end result of an exponential process; it is helpful to think of failure rate as an instantaneous function of head gain when trying to identify problem areas within fishways, and when making comparisons between fishways. Transit time is not exponential, but should also be normalized to units of head gain.
- Attraction to a fishway entrance is equally important as passage success.
- Probability of entry per unit time is a helpful way of quantifying this variable, since this approach takes into account both the probability of entry and the amount of delay incurred.
- Both passage success and entry rate can be quantified and standardized using event-time (survival analysis) techniques.

Swimming performance and velocity barriers

- Using the swim speed – fatigue time relationship that describes each of the three distinct gaits of steady swimming, one can predict the maximum distance a fish should be able to traverse against a given water velocity.

- The nature of the swim speed-fatigue time relationship is poorly described at burst speeds, with scant information on very few species.
- Their research suggests that available data underestimate maximum performance.
- Although fish will try to maximize the distance traversed, their performance is generally less than their physiological capacity. Fish appear to avoid fatigue.
- Predictive models for constructing velocity barriers need to take into account the entire population and not be limited to means or medians. Generalized models can provide guidance when designing passage structures or velocity barriers, but cannot replace actual studies on local populations of interest.

Chuck Coutant on a lamprey trap design

- We tend to think of performance being linked to body shape, but lamprey represent a quirk in that they exhibit very good swimming performance.
- Further, existing swimming performance measurements gloss over individual variability
  - poor performers were often ignored or omitted, but are important.
- Russians have recognized a significant role for turbulence.
  - performance at a given speed decreases as turbulence increases.
- see Theme 1 for a new perspective on trap design.

George Lauder on swimming performance in unsteady flows

- His laboratory is examining the function and kinematics of the propulsive elements (fins, body trunk) used by fishes and comparing these findings with the assumptions of hydrodynamic models of swimming.
- The measurements involve high-speed video and digital particle image velocimetry.
- There is growing evidence that fishes are very sensitive to heterogeneity in water flow.
- The movement of water past objects creates donut-shaped vortices.
- The concepts of drag wake and thrust wake were introduced.
- With drag wake around objects in the water.
  - vortices can be constructive or destructive.
  - a key question is whether fish can exploit these vortices while swimming.
  - involves fine tuning their body deformations to shed the vortices.
- Thrust wake
  - can vortices created by the dorsal fin be similarly exploited by the caudal fin?
- The notion that we might predict performance from morphology alone should be viewed skeptically.

Ben Letcher on monitoring movements in the field using PIT tags

- Movement of fishes in streams is critical to understanding how fish use habitat and to population modeling.
- Aside from radiotagging, assessing movement on a large number of fish on a fine spatial scale is difficult.
- PIT tag antennas placed in streams can record the times when individually tagged fish pass the antenna.
- Multiple antennas can be linked via wireless modems and remotely controlled and monitored via satellite uplink.

Research Needs

- Are existing measures of swimming performance meaningful in the context of fish passage (McDonald, Coutant, Lauder)? Do they at least provide a ranking of swimming performance or likelihood of passing? How are these estimates affected by volitional vs. nonvolitional swimming protocols? By turbulent vs. laminar flow?
- What alternative approaches/measures need investigation (McDonald, Lauder)? Need to examine the hydraulic conditions presented by the barriers/fishways being used and how fishes respond to these. Further, how do these correspond with the conditions presented by natural barriers and with the way fishes respond to natural barriers?
- Are models of optimal attack speed (Castro-Santos) appropriate for passage across low-head barriers or through fishways at low-head barriers?
- Need to assess whether passage is delayed in ecologically meaningful ways at the fishways currently in operation.
- Need to consider perceptual differences between lamprey and nontarget fishes that could be exploited for passage purposes?
- Need greater consideration of the options available for monitoring fish movements, and their suitability and utility for the different research needs surrounding fish passage at traps and barriers.

THEME 4. Research Requirements
Questions and Facilities

Gavin Christie - What questions do we need to answer?
Research Approaches

- Build stuff and see what happens
- Look at what current traps/structures have done
- Experimental management strategy
- Experimental facility(ies)
- Basic research - physiology, ecology, behaviour, hydraulics and hydrology (field and laboratory)
- Integrated/coordinated research strategy using an array of approaches
- Big picture/strategy evaluation
- Evaluate role of research findings in decision making

Synthesis of Questions Posed by Participants

Participants were asked to identify their three most pressing questions following the presentations and discussion from themes 1 to 3. The questions and responses are summarized into conceptual categories below (Table 1). When compared with the previous workshop funded by the GLFC, the number of research questions identified was large and there was not strong consensus on their priority. The two questions raised most frequently (by 8 of 33 participants) were "What level of spawner removal is required to control lamprey?" and "What are the long- and short-term effects of barriers on communities of stream organisms?" The other emerging priorities included (i) commitment of time and money to research, monitoring, and learning (Table 1a), (ii) interactions between the sensory abilities of sea lampreys and non-target fishes and environmental cues including pheromones, attraction flows, and in-stream structure (Table 1b,d), (iii) the behaviour of fishes at barriers, and (iv) improving traps designs such that barriers are unnecessary.

Table 1a) Questions Related to Policy

No. of Responses	Question
3	What is the commitment in time and dollars to sea lamprey research?
2	(Can we) Stop the madness?-> Strategy for learning?
2	(Can we) Include long-term monitoring with potential for change or barrier removal?
1	What are the consequences of not controlling sea lamprey?
1	What does the trade-off curve between lamprey prey and nontargets look like?
1	Definition of an acceptable level of nontarget mortality/impact?
1	What are the characteristics of streams that we have to protect when building barriers? What do we value?

1	What are the tradeoffs in dollars and ecological costs between alternative control methods?
1	What facilities and funds are available for this research and how do we decide (their allocation?)?
1	How committed is the GLFC to applying the research findings?
1	Can our strategy involve (barrier?) removal if an alternative is found?
1	Should fishways be operated forever? Can costs be reduced over time regardless of whether lamprey are present or absent?
1	How can we deal with removal of existing dams? Keep lamprey out of upstream habitat - (yet) move fish upstream?

Table 1b) General Questions Regarding the Biology of

(i) sea lamprey

No. of Responses	Question
8	What level of spawner removal is required to control lamprey?
3	What pheromone differences will change lamprey (movement) trajectories?
3	What are the optimal physical/hydraulic conditions for lamprey attraction?
2	How do lamprey use natural structure during upstream movement? How do we exploit this?
2	What senses are functioning in adult lamprey and how do we manipulate (capitalize on) them?
1	Is the movement of lamprey upstream on (while attached to a) fish a problem?
1	Allocation of animals(nontarget fishes) to lamprey in large streams?
1	What are the critical cues that govern movement/migration (of lamprey?)?
1	How committed are migrating adult lamprey to a selected river?
1	What is the relationship between diel pattern of lamprey movement with season and river mile?
1	How are senses integrated to control behaviour?

(ii) nontarget species

1	What do we need to know about nontarget species before moving ahead? Predictions?
1	Which nontargets are we most concerned with?

(iii) sea lamprey in relation to nontarget species

2	What behaviours can separate lamprey from nontarget species with 100% efficiency?
1	What are the critical cues that govern movement/migration (of lamprey? nontargets?)?

1	What is the timing of the sea lamprey run? How long are they in the stream? How does this relate to trap results (for nontargets?)?
1	How does the swimming ability of lamprey overlap (compare) with that of nontargets?
1	What are the effects of turbulence on fish swimming behaviour?

Table 1c) Barrier effects

No. of Responses	Question
8	What are the long- and short-term effects of barriers on stream communities (not just fishes)?
2	What is the behaviour of lampreys at barriers? What do they do and how can we exploit that?
1	What are the consequences of the barrier program on lamprey?
1	What is the temporal and spatial production response of lampreys to barriers?
1	Why do some barriers (e.g. Duffins Creek) work (even though they may get inundated)?
1	What other instream structures could block lamprey?
1	How do we measure nontarget effects?
1	How can we measure effects on stream fish?
1	What is the scale of applicability for effects analysis?
1	What are acceptable levels of upstream movement for fishes?
1	Are there other ways to mitigate the effects of barriers, e.g. habitat improvements?

Table 1d) Traps and Fishways

No. of Responses	Questions
3	Are there sea lamprey traps that can work without barriers (including pheromone traps)?
3	What are the factors affecting fish attraction and performance in fishways (including life-history, physiology, behaviour)?
2	How can we increase trap efficiency from 70 to 100%?
1	Are fishways the solution to barrier effects?
1	What are the biological responses to fishways?
1	What is the behaviour of fishes at existing fish passes?
1	What are the sorting/trapping mechanisms (available) for fishways?
1	What fishway design will pass >90% of nontarget species?
1	How should we measure passage success? What fraction of fish need to pass? Scale?
1	What is the utility of a sea lamprey fishway?

Gavin Christie - How can we best address the questions (Research facilities)?

Key criteria

- (allow studies of) fish passage and the blocking and trapping lampreys
- flexible/multifunctional (e.g. studies of larval and adult lampreys)
- adequate for replication of experimental and control treatments
- complementary with existing facilities, e.g. Conte, Hammond Bay
- What models do we follow? (e.g. Conte, ORBITF -> design only)
- Conte criteria
    - large amounts of water
    - gravity fed
    - large and long enough flumes
    - anadromous runs of fish in river
    - need for stream channels for ecological experiments
    - adequate replication
    - temperature/environmental control difficult with large volumes of water
- ability to create recirculating system with two channels
- other example - Mississippi (Montesello Nuclear)
    - five long stream channels
    - fed from pump house
    - possible example of what not to do (because it is dormant)
- source of water important
    - alternative/multiple sources
    - quality
    - ability to not recirculate
- use of existing facilities
    - is what we need elsewhere?
- issues/logistics of transporting fishes
    - inside and outside of Great Lakes
    - direct access to fish
    - use of substitutes, e.g. Atlantic lamprey for Great Lakes lamprey
- proximity of facility to species of concern (especially with a broad research program)
- potential to use existing barrier sites
    - large structures/partnerships
    - multiple/smaller-scale structures
- use of model or portable flumes
    - portability
    - use at multiple sites, replication
- applicability of results from experimental facility to field situations
    - Conte experience – it is early in the game to judge transferability
- hydraulics - is it OK to scale up? Correspondence with scaling in fishes?
- ability to compare current vs. new (barrier/trap?) designs in the facility
- scale
    - costs and resources needed
    - partnership and facilities
    - how do we create partnerships?

- Great Lakes needs may be smaller scale, but do we consider needs outside of the basin?

- building vs. operating and maintenance costs
- maintaining low overhead and operations costs
- useful for dynamics/stream population of larvae studies
- balance natural vs. controlled conditions
- need for both field and laboratory (facility) studies in an integrated coordinated program
- more rearing facilities
- flexibility
- align with university resources
- long-term strategy
- downstream passage facility

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