Development of a Separator for Juvenile Lamprey, 2007-2008

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Report of research by

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EXECUTIVE SUMMARY

The goal of this work was to increase survival of juvenile lamprey during their seaward migration past hydropower dams in the lower Snake and Columbia Rivers. Our specific objectives were to:

1) develop a juvenile lamprey separator that separates juvenile lamprey from salmonid fry, and subyearling and yearling juveniles in the bypass systems at Snake and Columbia River Dams, and
2) determine the feasibility of modifying the raceway screens at collector dams to allow juvenile lamprey to pass to the river while retaining juvenile salmonids for transportation.

We conducted laboratory experiments to inform design of a juvenile lamprey separator. Flume experiments were conducted at night to determine: 1) whether increased light intensity or current velocity stimulates juvenile lamprey activity, 2) whether separator orientation (horizontal, angled, or vertical) differentially achieves separation, and 3) whether separator material is important. We tested two separator materials: a 6.5 × 6.5 mm stainless steel, woven-wire mesh, and a stainless steel perforated plate with staggered, oval holes 25 × 6 mm in size. During each 1-h trial, we recorded activity and separator passage for a group of 10 lamprey macrophthalmia. Five replicate trials were made for each experimental treatment group.

In addition, we conducted sieve experiments of longer duration (>16 h) with both macrophthalmia and ammocoetes. In these experiments, 10 lamprey were released into a sieve apparatus in which each compartment was separated from the next by increasingly smaller mesh sizes (12 to 6.5 mm). To escape into the larger holding tank, lamprey had to pass either vertically or horizontally through each separator. We also tested for passage when the lamprey had to move with or against a low sieve current velocity. Each morning we recorded the number of lamprey in each compartment and measured total length and width at the eye for each fish.

Laboratory experiments revealed that lamprey were stimulated by both intense light and increased current velocity, but that they quickly adapted to these conditions and became inactive after only 5-10 minutes. Fish moved successfully through both the perforated plate and the woven mesh. However, the sieve experiments revealed that mesh size $\leq$ 6.5 mm could obstruct the very largest macrophthalmia (those >150 mm in length and 10 mm in width at the eye).

We found that macrophthalmia were reluctant to swim down through a horizontal or angled separator, but that they moved readily through material that was oriented vertically. In contrast, ammocoetes moved freely through both horizontal and vertical separators. Macrophthalmia moved more often through the separator when swimming with the current and passed easily through the separator when swimming upward, even against a current. Based on these results, we concluded that lower lamprey retention noticed at the Lower Monumental Dam Juvenile Fish Bypass is probably due to installation of raceway vertical screens that allow juvenile lamprey to pass. We recommend field testing of lamprey-friendly screens at other fish bypass facilities along with monitoring to ensure that lamprey-friendly raceway screens do not negatively affect salmonid fry or other species.

CONTENTS

INTRODUCTION

Both anadromous and resident lamprey populations in the Columbia River Basin represent important cultural and ecological resources, and both forms are in decline. A petition to list both Pacific lamprey *Lampetra tridentata* and western brook lamprey *Lampetra richardsoni* as endangered or threatened under the U.S. Endangered Species Act was submitted in 2002 to the U.S. Fish and Wildlife Service. Lamprey declines have also raised concern among tribal agencies throughout the Columbia River Basin (Close et al. 2002).

Pacific lamprey is an anadromous, parasitic species. Adults spawn in freshwater tributaries to the Columbia River, and juveniles (ammocoetes, Figure 1) bury into silty substrate and assume a sedentary life style for up to 7 years (reviewed in Close et al. 2002). During this period, ammocoetes may move downstream during freshets; however, the extent of these freshwater movements and mechanisms behind them are not well understood (Beamish and Levings 1991). After freshwater rearing, ammocoetes metamorphose, developing eyes and mouth parts for the parasitic phase in seawater. Metamorphosed juveniles (macrophthalmia) then migrate from freshwater to the sea, much like juvenile salmonids.

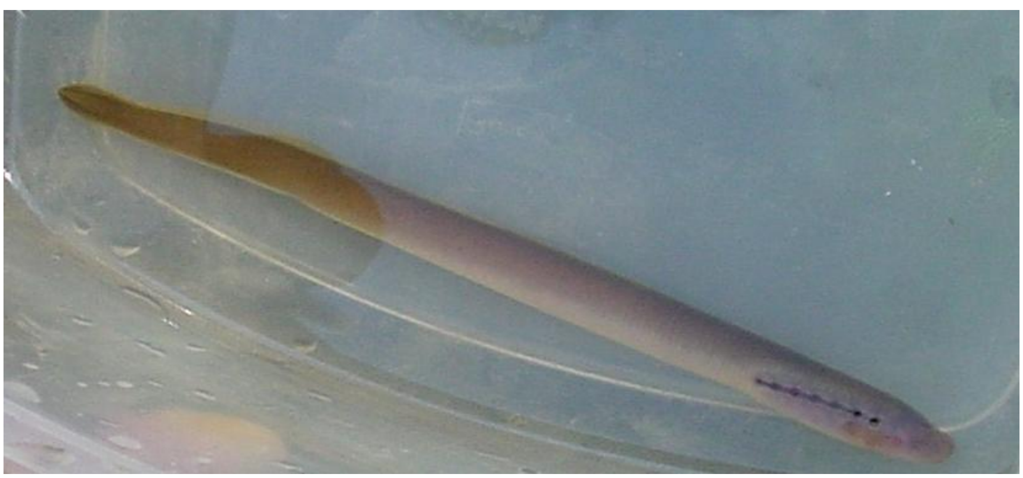

Figure 1. Juvenile lamprey prior to metamorphosis (ammocoete) collected in the Snake River drainage. Photo courtesy of J. M. Capurso.

Western brook lamprey is a resident, non-parasitic lamprey form. This species also resides for extended periods in freshwater tributaries to the Columbia River. After the freshwater residence period, Western brook lamprey becomes sexually mature and spawns in freshwater without making a seaward migration (Pletcher 1963). However, as is the case for Pacific lamprey, Western brook lamprey ammocoetes exhibit downstream movements during freshwater residence, and these movements may be extensive (J. Stone, U.S. Fish and Wildlife Service, personal communication). The extent and reason for these movements is not known.

The Columbia Basin Pacific Lamprey Technical Workgroup (a subgroup of the CBFWA Anadromous Fish Committee) has identified the need to improve lamprey passage and survival at Columbia River hydropower dams as the highest priority for lamprey recovery. During both seaward migration of macrophthalmia and downstream movement of ammocoetes, anadromous and resident lampreys may encounter up to 8 or 9 hydropower projects on the Columbia and Snake Rivers. Recently, the research of Moursund et al. (2001) documented impingement of lamprey at juvenile bypass facilities (Figure 2). These researchers determined that lamprey are more likely to suffer mortality as a result of screen impingement than from negative effects of passing downstream over dam spillways or through turbines. Consequently, Moursund et al. (2002, 2003) recommended that bar screens be sized to reduce lamprey impingement and improve lamprey survival.

Figure 2. Pacific lamprey macrophthalmia impinged on screens at the John Day Juvenile Bypass System. Photo courtesy of the Columbia River Intertribal Fish Commission.

Studies to assess lamprey survival through the juvenile bypass systems (JBSs) at McNary and John Day Dam have indicated that lamprey survival after guidance into the JBS is high. An extensive program to tag juvenile lamprey using passive integrated transponder (PIT) tags has been undertaken during the past few years (Moursund et al. 2002, 2003; R. Moursund, Pacific Northwest National Lab., personal communication). This work determined that juvenile lamprey in the McNary and John Day JBS exhibited high survival, and that lamprey show downstream rates of movement similar to those of salmonids.

Macrophthalmia and ammocoetes collected at the JBS are inadvertently transported downstream on barges or trucks during operations to transport juvenile salmonids past dams. It is not known whether transportation is detrimental to lamprey or not. However, the ability to separate lamprey at these dams would allow release of both anadromous and resident lamprey juveniles back into the river after collection. In addition, developing ways to separate juvenile lamprey from juvenile salmonids may have other important applications. During freshets lamprey can occur in very large numbers and become impinged on screens, resulting in screen blockage and lamprey mortality. Methods to separate lamprey at JBS exit raceways may provide insights into ways to reduce other sources of juvenile lamprey mortality at dams.

There is already some indication that behavioral separation of juvenile lamprey from bypass water is feasible. Some juvenile lamprey are currently separated at the Porosity Control Unit located just upstream from the separator at Lower Monumental Dam. In the past, plates in the Control Unit have been composed of materials with relatively small bar spacing (Johnson Bar Screen or perforated plate). More recently, perforated plates with oblong holes of approximately 0.6 wide by 2.5 cm long have been used (K. Fone, U.S. Army Corps of Engineers, personal communication; Figure 3). In addition, mesh in raceway screens at this bypass facility is sized at 6.5 by 6.5 mm. Coincident with the use of these plates and raceway screens, there has been apparently greater separation of juvenile lamprey at this location.

The objectives of this study were to:

1) Develop a juvenile lamprey separator that separates juvenile lamprey from salmonid fry, subyearling, and yearling juveniles in the bypass systems at Snake and Columbia River Dams, and

2) Determine the feasibility of modifying the raceway screens at collector dams to allow juvenile lamprey to pass to the river while retaining juvenile salmonids for transportation.

METHODS

Downstream migrating Pacific lamprey macrophthalmia were collected on a daily basis from the juvenile bypass system at McNary Dam on the Columbia River, USA. These fish were lightly anaesthetized with tricaine methanesulfonate (MS-222) and enumerated following capture by smolt evaluation personnel. Late-stage lamprey ammocoetes were also collected from the upper Umatilla River by biologists of the Confederated Tribes of the Umatilla Indian Reservation using a backpack electrofisher. Immediately after capture, all fish were transferred to large holding tanks (200 L) with flowing Columbia River water and held at ambient temperature prior to use in our experiments. Holding tanks for ammocoetes had buckets filled with Umatilla River sediment so that the fish could bury themselves during the holding period. All holding tanks were fitted with opaque lids and provided near-dark conditions during both day and night.

Our experiments were conducted at the McNary Dam covered flume area at the juvenile bypass channel (Figure 3). This area is equipped with a 1.5- by 10-m covered flume. Columbia River water of ambient temperature was diverted into the flume, and flow rate was controlled via an inlet valve. The entire experimental area was covered to allow accurate control of lighting and minimize disturbance during experimentation.

Figure 3. Experimental covered flume area at the McNary juvenile bypass channel (left) and flume insert apparatus shown in the dewatered flume (right).

Flume Experiments

For the flume experiments, five factors were used for evaluation: flow rate, flow direction (fish moving downstream vs. upstream to pass the separator), separator material, separator angle, and light condition. To test the effects of these factors on macrophthalmia movements, we made visual observations of fish behavior in an experimental apparatus installed in the covered flume (Figure 3). The apparatus featured fine mesh panels at both the downstream and upstream ends to allow roughly laminar flow of ambient Columbia River water through the flume insert.

For each experiment, flow direction, separator material, and separator angle were held constant during five consecutive, replicate trials. For downstream trials, the initial flow rate was < 0.5 cm/s, and was set using wooden stop logs positioned at a height of 37.5 cm within the guides at the downstream end of the separator test area (Figure 4).

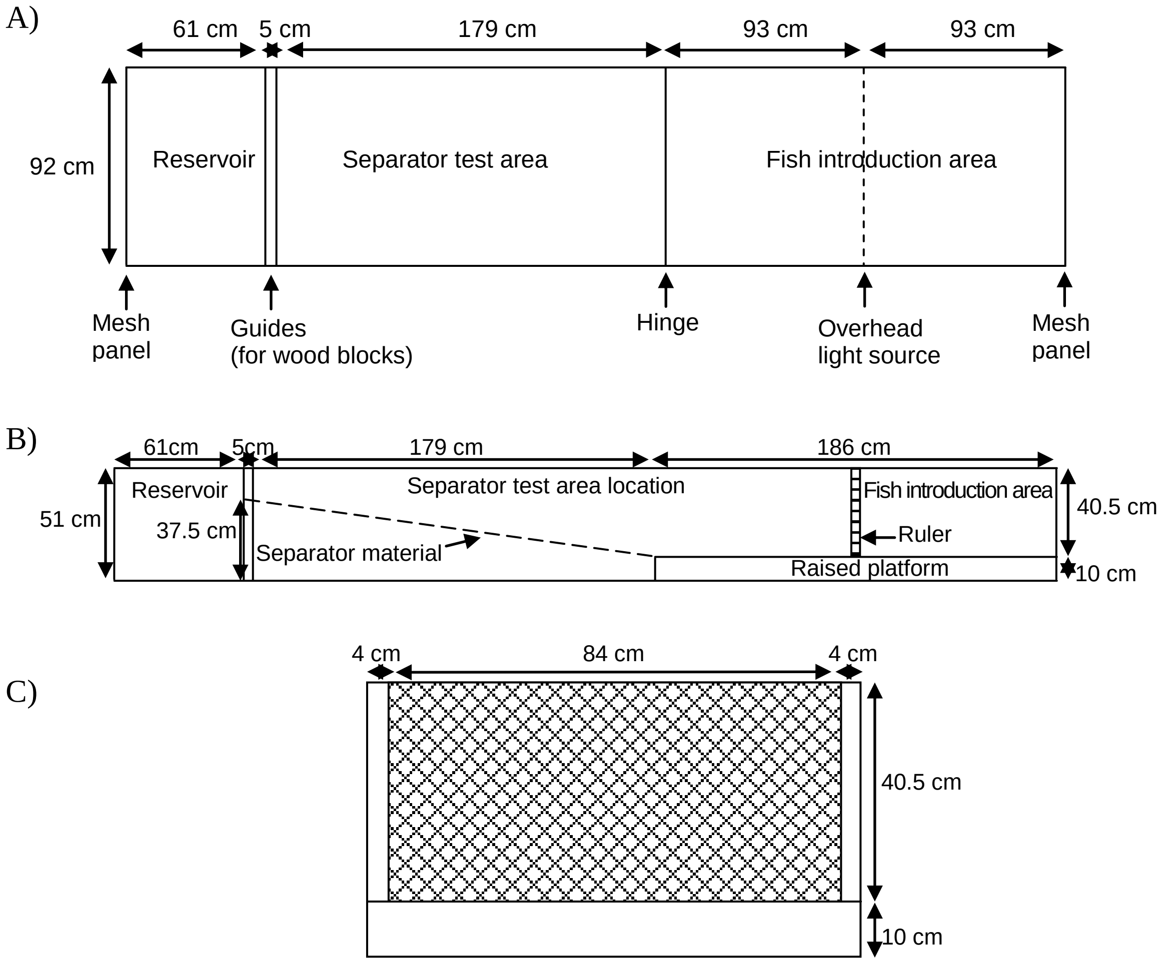

Figure 4. Dimensions of flume apparatus: A) Top view, B) Side view with separator at 8.7° angle, and C) End view of mesh panel (same dimensions on both ends).

For each trial, 10 macrophthalmia were released into the fish introduction area and allowed to acclimate under red lighting (100-250 lumens/m^2) produced by an overhead light source (Figure 4). After 20 min, the fish introduction area was bathed in intense white light (1,500-2,500 lumens/m^2). After another 20 min, the flow rate was increased to approximately 25 cm/s. This was achieved by removing the stop logs from the guides, allowing complete free flow of water through the flume insert.

For upstream trials, the lower flow rate was not used because the stop logs created unworkable water levels in the flume. For these trials, only the light conditions were changed, with the initial red light for 20 min, and then bright, white light used for the second half. Hence, upstream trials (where the fish introduction area was downstream from the separator) lasted only 40 min.

Two separator materials were tested: a 6.5- × 6.5-mm stainless steel woven wire mesh (mesh) and stainless perforated plate (plate) with staggered, punched, oval holes 25- × 6-mm in size (Figure 5). These materials were selected because they replicated materials currently in use at the Lower Monumental Dam juvenile fish bypass facility. After installation of similar plate in the Porosity Control Unit and mesh in the holding raceways, fewer juvenile lamprey were noted (K. Fone, U.S. Army Corps of Engineers, personal communication).

Flow rates under all conditions were measured at various points within the flume apparatus using a magnetic flow meter (Marsh-McBirney).[†] Underwater light intensities (both red and white light) were also measured using a StowAway® LI data logger at a

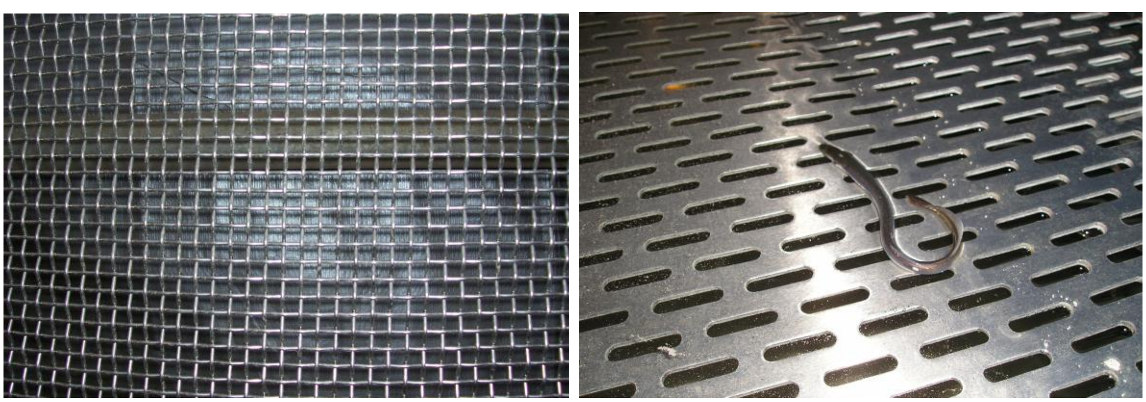

Figure 5. Separator materials tested: 6.5-mm square, woven stainless steel mesh (left), and 25- × 6-mm stainless steel perforated plate (bottom).

[†] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

number of locations in the flume insert, both at the start and end of trials. During trials, the data logger remained above the flume in order to measure ambient light conditions above water in the greater closed flume area.

During each trial, visual observations were made of fish behavior and manually scored. When the screen was horizontal or angled, the number of fish passing over the separator material was noted. A pass over the mesh was scored when the entire length of the lamprey passed onto the separator, and a new attempt was scored if the entire length of the lamprey had passed back into the fish-introduction area. When the screen was vertical, the number of fish approaching the screen was noted, and an approach was scored when a fish came into contact with the screen. A new approach occurred only after a fish had moved at least one body length away from the screen. The number of passes through the screen material, and the number of passes back were also noted. In addition, the number and location of fish attached to the floor or sides of the apparatus were noted every 5 min throughout the trials. At the end of each trial, fish were collected and either returned to holding tanks, or used for the sieve trials (described below).

Sieve Experiments

To test whether macrophthalmia or ammocoetes would pass through separator materials given a longer time period, we conducted overnight experiments using a "sieve" arrangement (Figure 6). Ten fish were released into the fish-introduction area, and the sieve was then placed in a large (500-L), holding tank with constant flowing Columbia River water. The sieve was oriented so that lamprey could pass either horizontally through vertical separators (horizontal sieve) or vertically through horizontal separators (vertical sieve). For vertical sieve experiments, lamprey could be required to move either downward or upward to escape the sieve. In addition, flow into the tank could be directed onto the sieve so that lamprey had to move either with or against the flow to escape the sieve.

On the next morning, the number of lamprey present in each compartment and the number out in the holding tank were noted. Fish from each compartment were then anaesthetized using clove oil diluted in Columbia River water (1:10,000). Total length and width at the eye (widest point along the body) of each fish was measured (nearest mm). After experimentation, all fish were released into the McNary Dam juvenile bypass system.

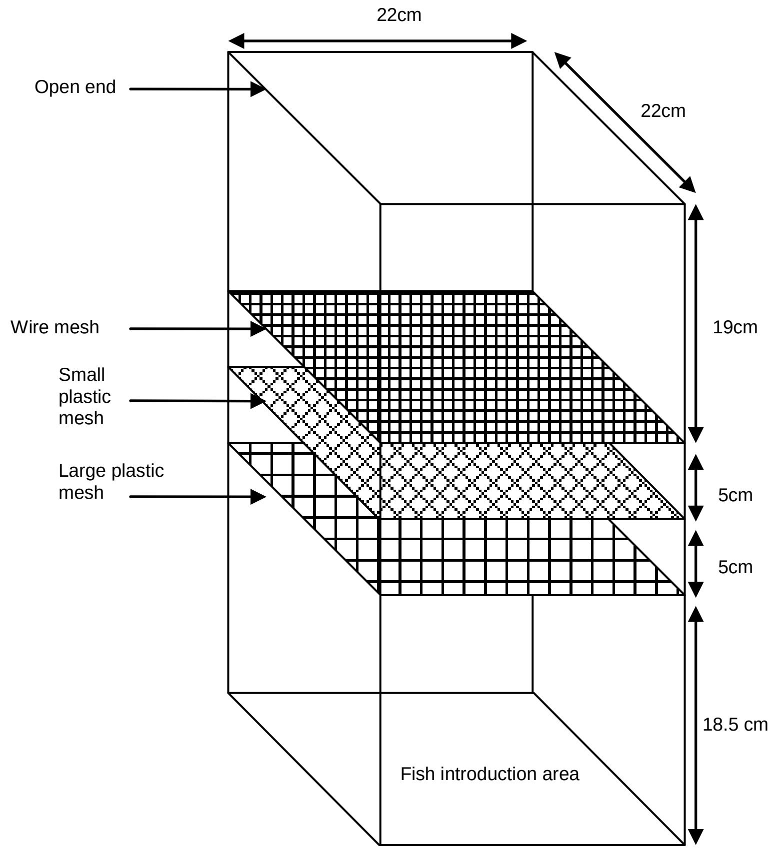

Figure 6. Sieve with three separator materials in vertical upward orientation. From bottom to top: stainless steel woven wire mesh (6.5 × 6.5 mm), small punched plastic mesh (9 × 7 mm), and large diamond-shaped punched plastic mesh (12 × 12 mm with 15 mm at widest point). When the sieve was oriented for downward movement of lamprey, the effective depth of the fish introduction area was 11 cm because 8 cm of the chamber was out of the water.

RESULTS

Flume Experiments

Lamprey macrophthalmia for experimentation were collected from 21 May to 5 June 2007, and from 19 May to 27 May 2008. In addition, late-stage ammocoetes were collected from the upper Umatilla River on 27 May 2008. We conducted some preliminary daytime trials of lamprey behavior in the flume on 22-23 May 2008. Lamprey showed no activity during these trials, so all subsequent experimentation was conducted between 1800 and 0300 PDT each night. In 2007, we tested two materials at two orientations: angled and vertical (Table 1). Also in 2007, we conducted one experiment in which the lamprey were required to swim against the current (upstream) to pass through the separator. In 2008, all experiments were conducted such that lamprey moved downstream with the current (Table 1). For these experiments we tested both separator materials at three orientations: horizontal, angled, and vertical.

Table 1. Experiments conducted with macrophthalmia in the flume at the McNary juvenile bypass facility. On each night, 5 replicate trials were conducted using 10 lamprey in each trial. DS = separator downstream from the fish introduction area; US = separator upstream from the fish introduction area.

Date	Flow direction	Screen type	Screen angle (degrees)
29 May 07	DS	Mesh	8.7
30 May 07	DS	Mesh	90
31 May 07	US	Mesh	8.7
4 Jun 07	DS	Plate	90
5 Jun 07	DS	Plate	8.7
20 May 08	DS	Plate	90
21 May 08	DS	Plate	0
22 May 08	DS	Plate	8.7
26 May 08	DS	Mesh	8.7
27 May 08	DS	Mesh	0
29 May 08	DS	Mesh	90

In nearly all experiments, lamprey exhibited heightened activity immediately after release in the flume, but quickly acclimated to the apparatus and attached to the floor and walls (Figure 7-9). Lamprey were routinely stimulated to move about when exposed to white light, but again acclimated to this treatment after only a few minutes (Figures 7-9). Similarly, fish that were stimulated by the increase in flow also acclimated quickly and attached to the substrate again after 5-10 min (Figure 7-9). The largest number of passage events through the separator was recorded when it was oriented vertically, regardless of material (Figures 7 and 8). In general, lamprey were reluctant to move upstream against the low current velocity and remained attached at the downstream end of the apparatus during this treatment, regardless of light conditions (Figure 9).

We noted similar behaviors during experiments conducted in 2008. Macrophthalmia moved most readily downstream through vertically oriented plate or mesh, but were reluctant to move downward through either a horizontal or angled separator (Figure 10). On 28 May 2008, we attempted to test behavior of ammocoetes in the flume apparatus. However, all of the ammocoetes quickly moved through the vertically oriented mesh and escaped into the lower reservoir of the apparatus (Figure 11). To avoid loss or damage to ammocoetes, we terminated any further flume testing with this life stage.

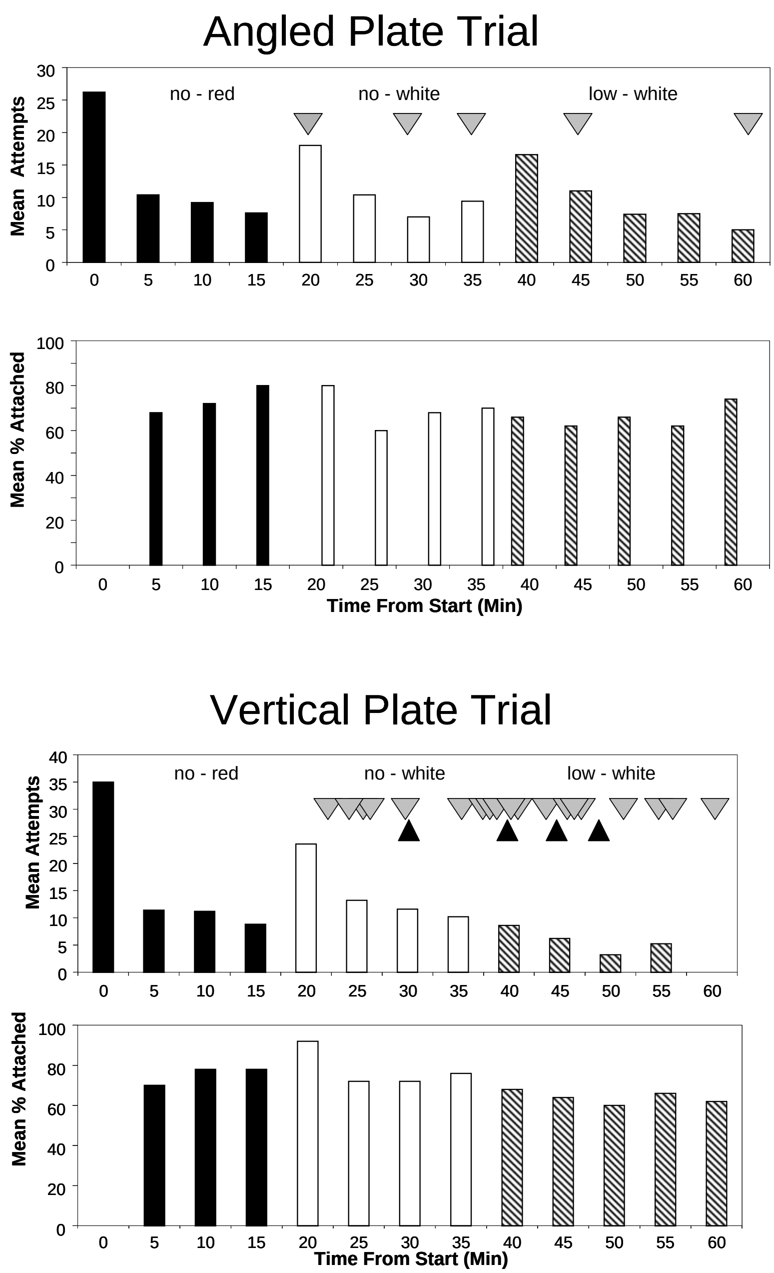

Figure 7. Individual fish activity (mean number of attempts at the separator) and group activity (mean % of the group that were attached to substrate) at each 5-min interval during flume trials using angled perforated plate (top) and vertically oriented plate (bottom) in 2007. Dark bars indicate periods with no flow and red light, white bars are no flow and white light, and hatched bars are low flow and white light. Gray triangles indicate time of passage downstream through the separator, and black triangles are passage events back upstream through the separator.

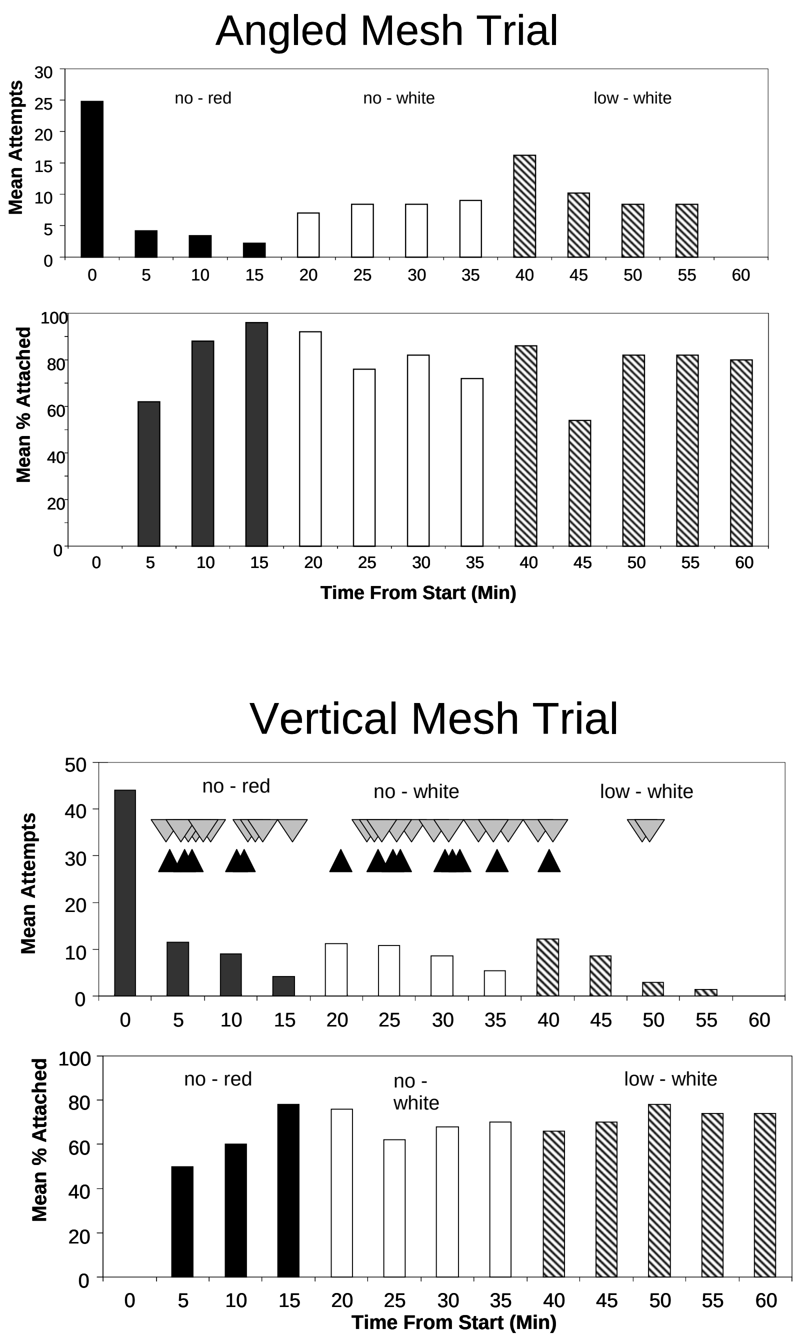

Figure 8. Individual fish activity (mean number of attempts at the separator) and group activity (mean % of the group that were attached to substrate) at each 5 min interval during flume trials using angled mesh (top) and vertically-oriented mesh (bottom) in 2007. Dark bars indicate periods with no flow and red light, white bars no flow and white light, and hatched bars low flow and white light. Gray triangles represent the time of passage downstream through the separator and black triangles are passage events back upstream through the separator.

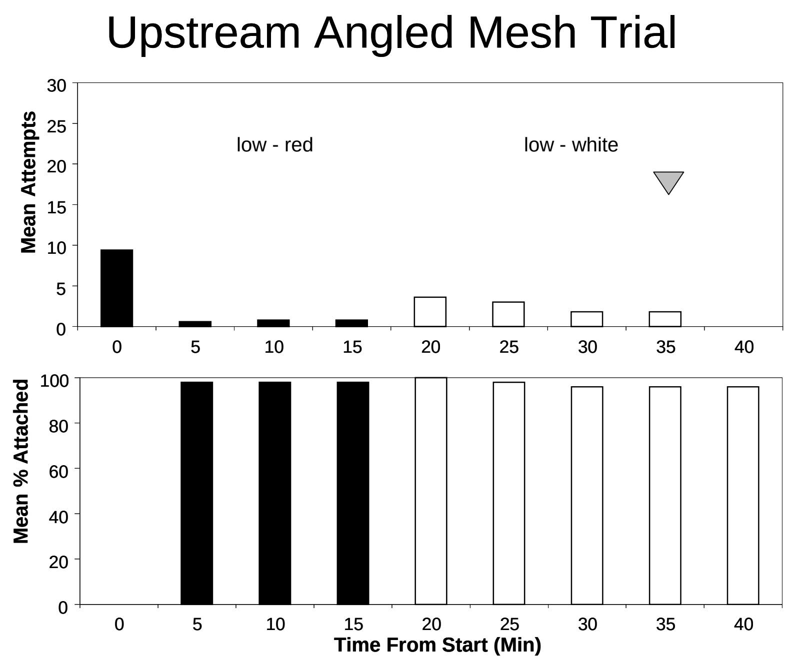

Figure 9. Individual fish activity (mean number of attempts at the separator) and group activity (mean % of the group that were attached to substrate) at each 5-min interval during flume trials using angled mesh in 2007, where fish were required to swim upstream to pass through the separator. Dark bars indicate periods with low flow and red light; white bars low flow and white light. Gray triangle indicates the time of the single passage made going upstream through the mesh.

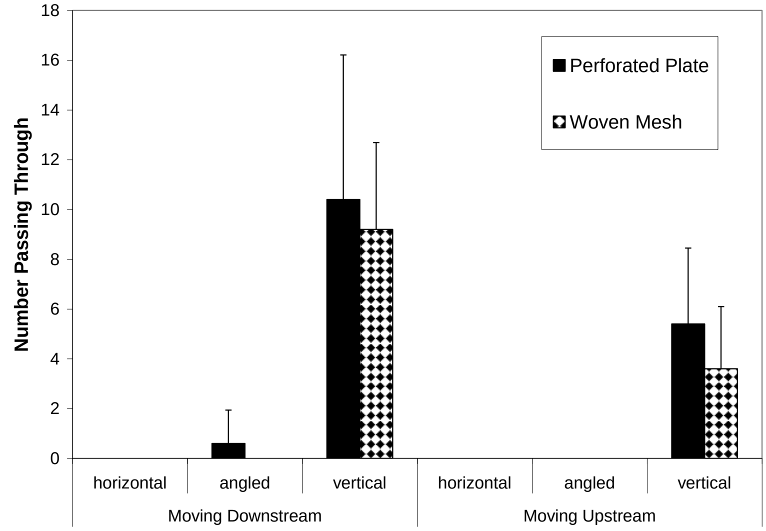

Figure 10. Mean number of macrophthalmia that passed downstream through the separator (dark bars = plate, stippled bars = mesh) when it was oriented horizontally, at a 9° angle, and vertically (left panel) in 2008. The right panel indicates the mean number of these fish that moved back upstream through the separator in each treatment.

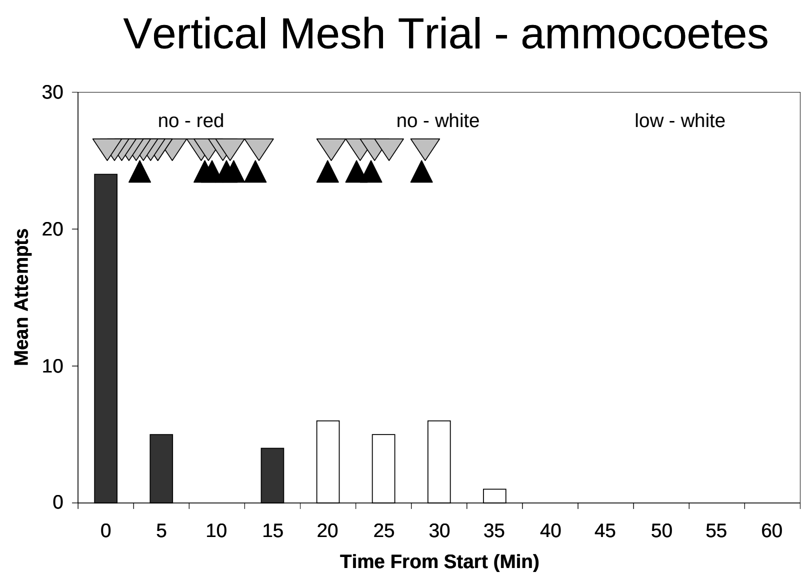

Figure 11. Ammocoete activity (number of attempts at the separator) during each 5-min interval of a single flume trial using angled mesh in 2008. Dark bars indicate no flow and red light, and white bars are white light with no flow. Thereafter, all ammocoetes had passed into the lower reservoir. Gray triangles indicate times of passage made going downstream, and black triangles indicate times of passage back up through the separator.

Sieve Experiments

In 2007, we conducted sieve trials in which macrophthalmia moved horizontally through a vertically oriented set of separators (horizontal sieve). In this experiment most of the lamprey exited the sieve and were found in the holding tank (compartment 4) or in compartment 3 (i.e., they did not move through the 6.5-mm square metal mesh, Figure 12). Fish that did not move through the 6.5-mm metal mesh were at the upper end of the size distribution that we tested (Figure 12), indicating that only the largest lamprey are obstructed by this mesh size.

Also in 2007, we conducted vertical sieve trials in which the macrophthalmia had to move downward through the same series of horizontally oriented separators. In contrast to the horizontal sieve trials, we found that most of the lamprey remained in the sieve, and that 44% did not even leave the introduction area. Fish that remained in the sieve were from a broad range of sizes, indicating that they were not prevented from moving through the separators on the basis of physical size (Figure 13).

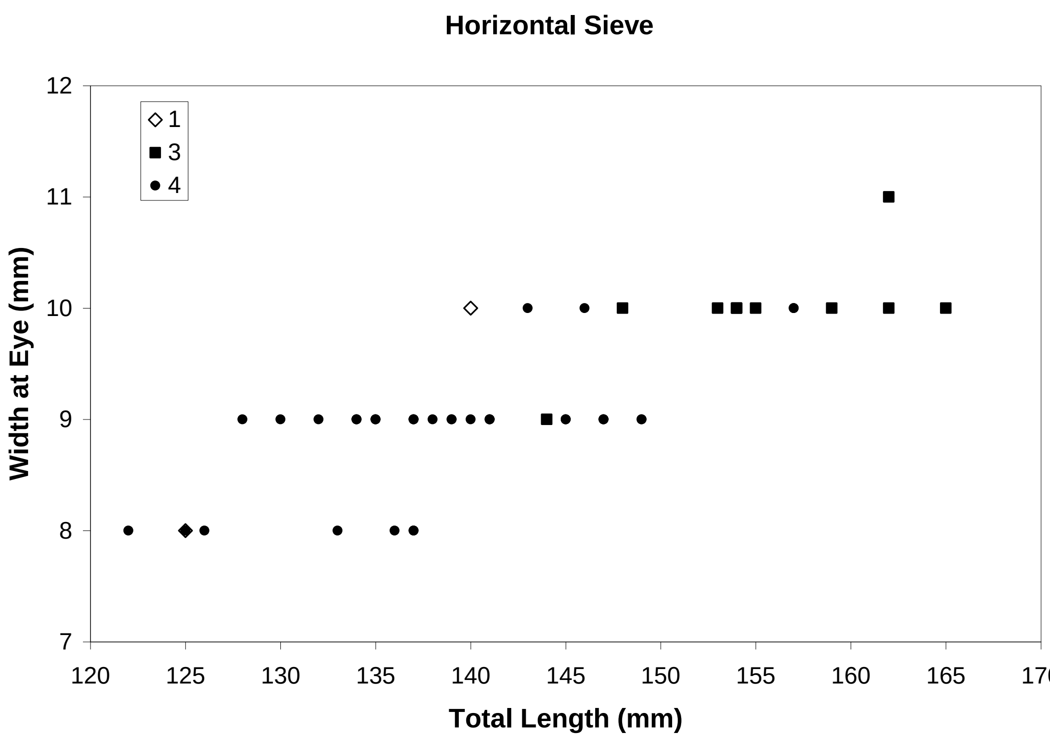

Figure 12. Pooled total length and width at the eye of macrophthalmia found in each compartment after the horizontal sieve experiment conducted in 2007: 1 is the fish-introduction area (open diamond), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (dark square), and 4 is the holding tank (circle).

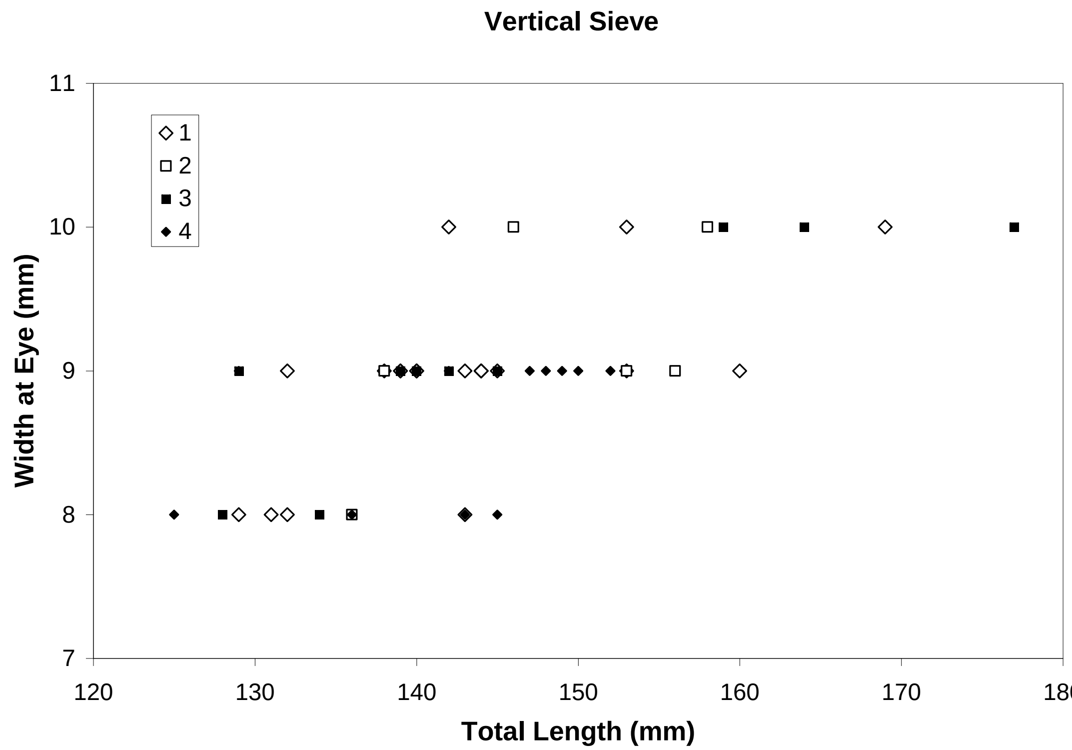

Figure 13. Pooled total length and width at the eye of macrophthalmia found in each compartment after the vertical sieve experiment conducted in 2007: 1 is the fish-introduction area (open diamond), 2 is the compartment separated from the holding tank by 9- ×7-mm plastic mesh (open square), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (dark square), and 4 is the holding tank (circle).

In 2008 we repeated these experiments using ammocoetes. Due to the low numbers of ammocoetes available, we were only able to conduct one replicate of the horizontal sieve and 3 replicates of the vertical sieve experiments. As was the case for macrophthalmia, ammocoetes moved easily through the vertically oriented separators in the horizontal sieve (Figure 14). However, whereas the macrophthalmia in 2007 were reluctant to move downward through the separators, the ammocoetes moved downward easily and were mostly found in the holding tank (Figure 15). The ammocoetes were somewhat smaller than the macrophthalmia, having a mean total length of 137 mm (range = 116-165 mm) and a mean width of 6.5 mm (range = 5-8 mm).

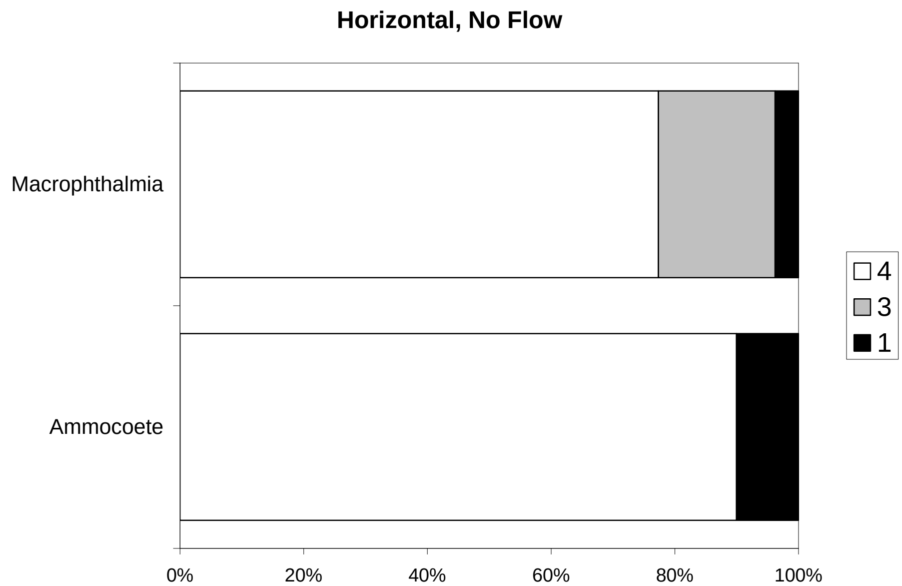

Figure 14. The pooled percentage of macrophthalmia and ammocoetes found in each compartment following the horizontal sieve experiment: 1 is the fish-introduction area (black), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (light gray), and 4 is the holding tank (white).

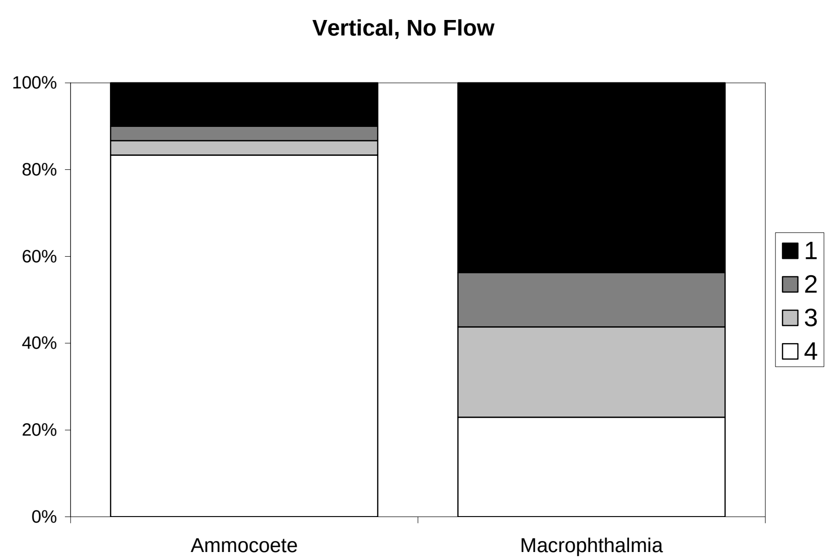

Figure 15. The pooled percentage of macrophthalmia and ammocoetes found in each compartment following the horizontal sieve experiment: 1 is the fish-introduction area (black), 2 is the compartment separated from the holding tank by 9- ×7-mm plastic mesh (dark gray), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (light gray), and 4 is the holding tank (white).

In 2008, we conducted more vertical sieve experiments with macrophthalmia. First, we oriented the sieve so that macrophthalmia had to move upwards to escape into the holding tank (vertical, upward movement). Fish were tested in no flow, and where they had to swim upwards against a low flow (<25 cm/s). In both cases, macrophthalmia moved upward readily and were found primarily in the holding tank (Figure 16). In both cases there was no apparent effect of fish size (Figures 17 and 18).

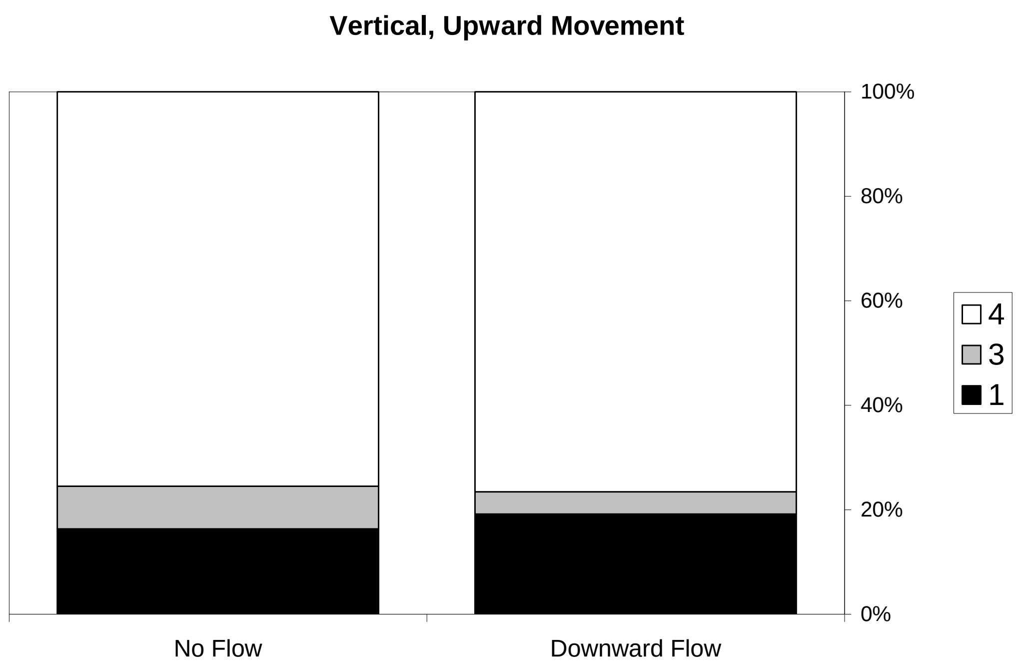

Figure 16. The pooled percentage of macrophthalmia found in each compartment following the vertical sieve experiment where fish moved upwards in no flow and against a low downward flow: 1 is the fish-introduction area (black), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (light gray), and 4 is the holding tank (white).

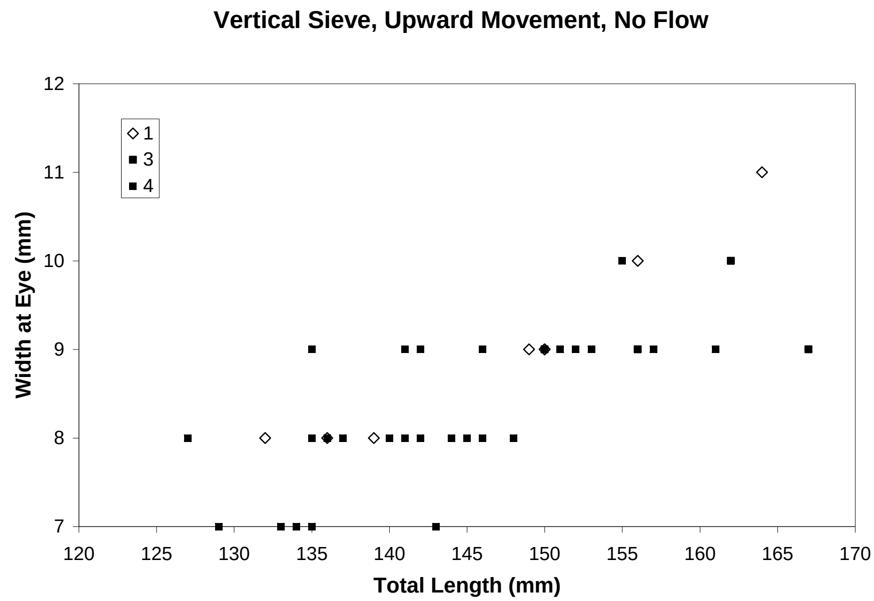

Figure 17. Pooled total length and width at the eye of macrophthalmia found in each compartment after the vertical upward sieve experiment with no flow: 1 is the fish-introduction area (open diamond), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (dark square), and 4 is the holding tank (circle).

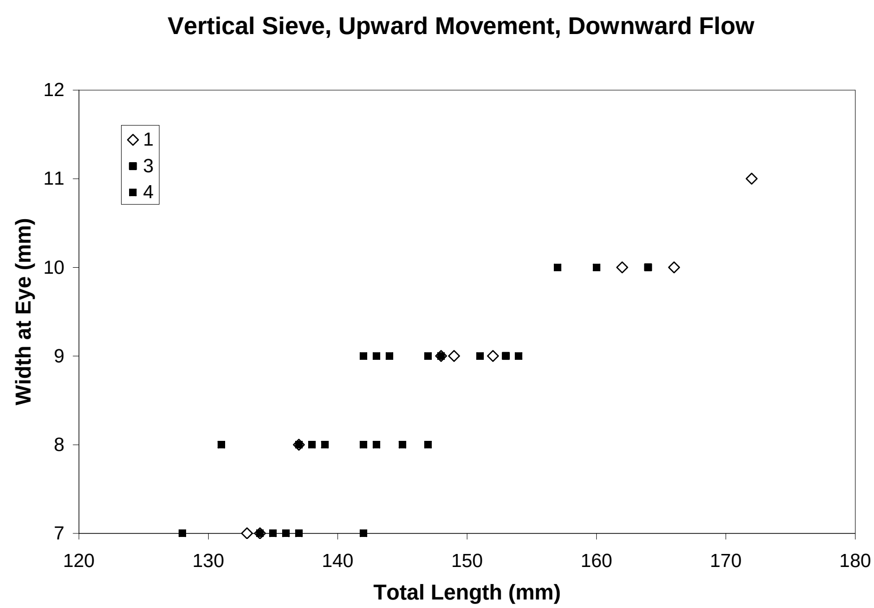

Figure 18. Pooled total length and width at the eye of macrophthalmia found in each compartment after the vertical upward sieve experiment with downward flow: 1 is the fish-introduction area (open diamond), 3 is the compartment separated from the holding tank by 6.5-mm square mesh (dark square), and 4 is the holding tank (circle).

The final set of experiments in 2008 was designed to evaluate whether macrophthalmia could be induced to move downward when exposed to a downward flow. In these trials, the sieve was oriented vertically, and macrophthalmia had to move downward in the direction of a low (< 25 cm/s) downward flow in order to escape the sieve. In this case, macrophthalmia were even more reluctant to move downward than in vertical downward trials without flow (Figure 19). Over 85% of the fish were still in the sieve at the termination of the trial, and most of these were still in the fish-introduction area (Figure 19). There was no evidence that fish size was a factor in retaining fish in the sieve, as fish from a broad range of sizes were found in the introduction area at the end of each trial (Figure 20).

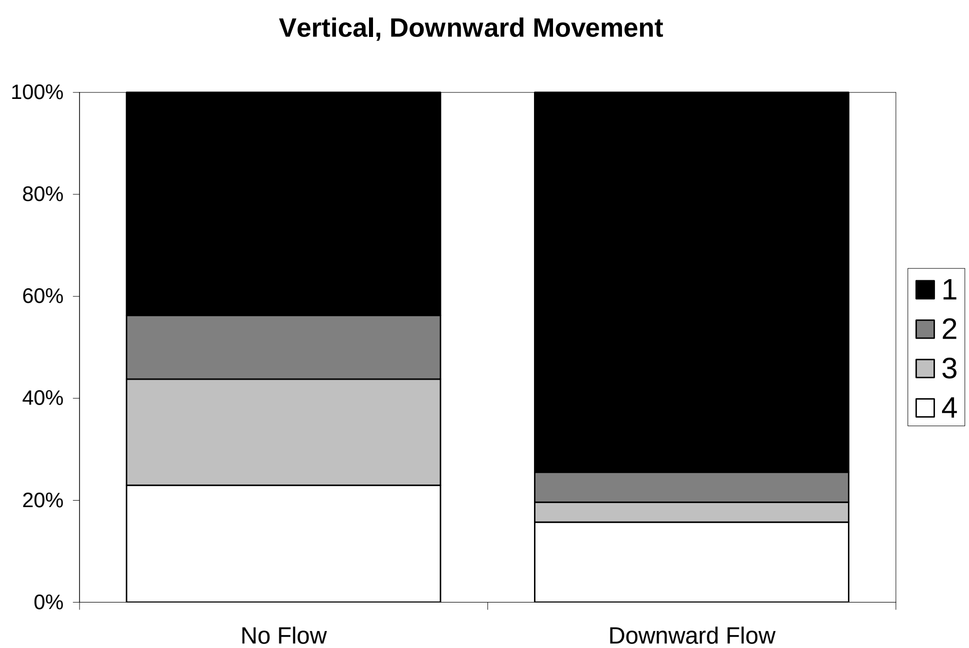

Figure 19. The pooled percentage of macrophthalmia found in each compartment following the vertical sieve experiment where fish moved downwards in no flow and with a low downward flow: 1 is the introduction area (black), 2 is the compartment separated from the holding tank by 9 ×7 mm plastic mesh (dark gray), 3 is the compartment separated from the holding tank by 6.5 mm square mesh (light gray), and 4 is the holding tank (white).

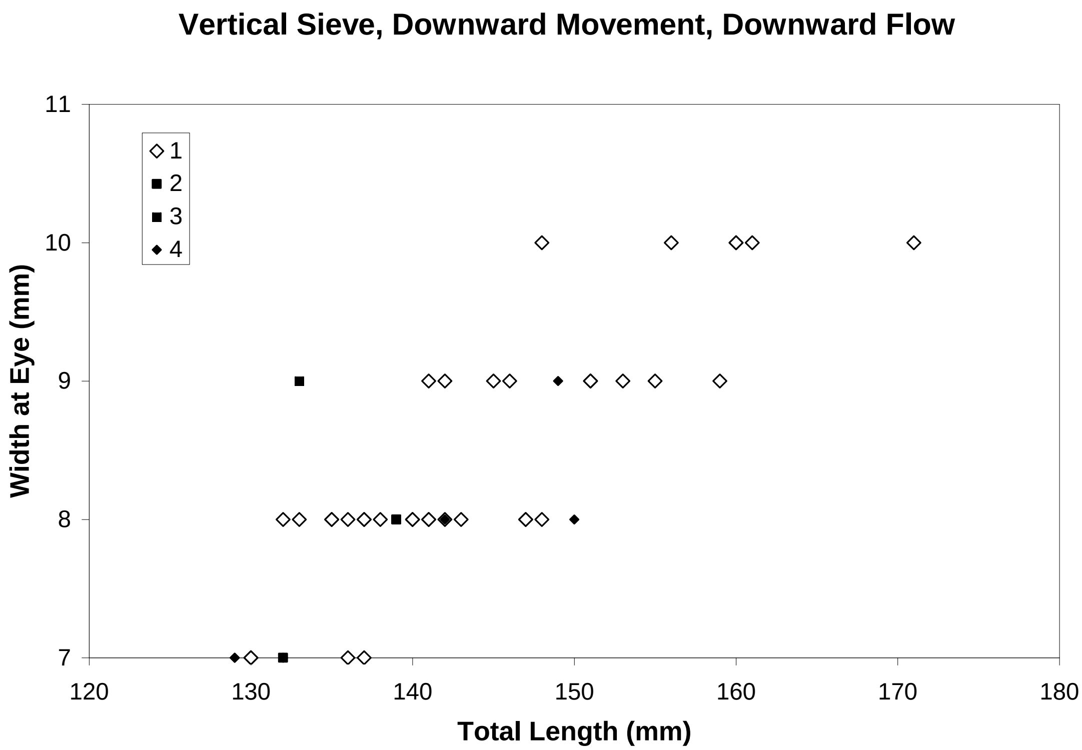

Figure 20. Pooled total length and width at the eye of macrophthalmia found in each compartment after the vertical downward sieve experiment with downward flow: 1 is the introduction area (open diamond), 2 is the compartment separated from the holding tank by 9- × 7-mm plastic mesh (3 is the compartment separated from the holding tank by 6.5-mm square mesh (dark square), and 4 is the holding tank (circle).

DISCUSSION

In these experiments, we tested the utility of separating juvenile lamprey from juvenile salmonids by exploiting their negative phototaxis. Juvenile Pacific lamprey are nocturnal and avoid bright lighting (Moursund et al. 2000). Using Columbia River macrophthalmia, Moursund et al. (2001) were able to elicit an avoidance response in both flowing and static water conditions with both constant white light and a white strobe light. We therefore used varying light and flow conditions to determine whether lamprey could be behaviorally separated.

Lamprey exhibited nocturnal behavior, with increased activity during the period from 1800 h to midnight. In test runs, we found that macrophthalmia were completely quiescent during the day. Dauble et al. (2006) also reported the lack of activity by macrophthalmia during the day, and that activity increased in early evening. In general, during daylight the fish quickly found a place to attach to the substrate and were unaffected by changes in flow or light.

When juvenile lamprey were exposed to both increased light intensity and increased current velocity in our experiments, they generally exhibited a short-term increase in activity. As did Moursund et al. (2001), we were able to elicit short-term bursts of activity by increasing light intensity, but fish seemed to acclimate to this condition rapidly (after 5-10 min). Similarly, when flow was increased they showed an immediate increase in activity, but then quickly acclimated and attached to the substrate again.

Macrophthalmia were not uniformly active during periods of higher light intensity or flow. In all experiments, over half of the individuals we tested were attached to the substrate at any given time interval during the 1-h flume experiments. This behavior was similar to behavior reported by Dauble et al. (2006): they found that 16% of their test fish remained attached during an entire 12-h period, and that remaining fish were active for only about 25% of the night.

Macrophthalmia were reluctant to move downward through a horizontally oriented separator. In our 1-h flume experiments, no lamprey passed through the separator when it was oriented horizontally, and very few passed through when it was angled at 9° (Figure 11). Even when lamprey were given 24 h to find a downward passage route in our sieve experiments, relatively few (21%) moved downward and out of the sieve (Figure 15). This was in stark contrast to the behavior of both ammocoetes and adult lamprey. Both of these life stages immediately seek a passage route downward when stressed (Quintella et al. 2007; Moser et al. 2008).

The ammocoetes we tested seemed to move downward readily. In the sieve tests, 83% of the ammocoetes moved downward and out of the sieve (Figure 15). In addition, the ammocoetes moved easily through vertically oriented separators (Figure 14) and were able to actually escape our flume apparatus by passing through small seams in the floor.

While based on small sample sizes, these data suggest that lamprey taxis changes with metamorphosis. Macrophthalmia adopt a more horizontal mode of movement, whereas ammocoetes are motivated to move vertically and seek cover in the substrate. This is probably an important mechanism of seaward migration in anadromous lampreys. Similar changes in rheotaxis have been described for metamorphosing salmon smolts. With metamorphosis, salmon smolts become less aggressive, swim more frequently in the direction of the current, and become more tolerant of light, resulting in seaward movement (Hoar 1951; Veselov et al. 1998).

In general, macrophthalmia were more reluctant to move upstream against the low velocities in our experiments. While juvenile lamprey could easily stem the low current velocities in our experiments (Dauble et al. 2006), they showed a clear preference for downstream movement through the separator (Figure 11). In the only test in which the separator was upstream from the introduction area, very few lamprey showed any activity at all, and over 90% of the fish remained attached throughout the trials (Figure 9).

Clearly both flow direction and macrophthalmia orientation is important. Macrophthalmia were reluctant to move downward in a static sieve experiment, but even fewer fish moved downward when we introduced a downward flow in the sieve experiments (Figure 19). In contrast, macrophthalmia moved upward readily, and would even do so against a downward current flow to escape the sieve (Figure 16).

While separator orientation and site were critically important to passage, the separator material was less important. Macrophthalmia moved through both materials we tested: 6.5-mm square woven stainless steel mesh and 25- by 6-mm stainless steel perforated plate. There was some indication from the sieve trials that openings of 6.5 mm or smaller may obstruct the largest macrophthalmia (those with total length $\geq$150 mm and width at eye $\geq$10 mm, Figure 12).

Based on these results, it seems likely that the reduced lamprey retention observed at the Lower Monumental Dam juvenile bypass facility was due to installation of new raceway screens, and not the new plate at the Porosity Control Unit. The new raceway screens were oriented vertically and provided juvenile lamprey with egress from the holding raceways. In contrast, the perforated plate installed at the Porosity Control Unit was oriented horizontally. Base on our findings, it is highly unlikely that juvenile lamprey were finding egress at this location because they would have to swim downward to do so.

In conclusion, our laboratory findings and field observations at Lower Monumental Dam indicated that use of vertically oriented material having openings of at least 6.5 mm is needed to reduce juvenile lamprey retention and impingement at the holding raceways of juvenile bypass facilities. However, replacing raceway screens may have unforeseen consequences for salmonid fry and other small fishes. Consequently, we recommend field testing of any new lamprey-friendly material to ensure that it does not negatively impact other species.

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