ADULT PACIFIC LAMPREY BYPASS STRUCTURE DEVELOPMENT: TESTS IN AN EXPERIMENTAL FISHWAY, 2004-2006

A Report for Study Code ADS-P-00-8

by

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For

U.S. Army Corps of Engineers
Portland District, Portland OR

2008
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Abstract

A series of experiments were conducted in an experimental fishway at Bonneville Dam in 2004–2006 to evaluate adult Pacific lamprey (*Lampetra tridentata*) swimming performance and behaviors. The 11.6 × 1.2 m experimental fishway was a flow-through aluminum tank with variously configured ramp and channel structures. Experiments were designed to inform construction of lamprey passage structures at dams. Lamprey behaviors, passage times, and passage efficiencies were monitored using half-duplex passive integrated transponder (HDX PIT) tags and combinations of HDX antennas. Experiments were performed at night with randomized replicates whenever practical.

The 2004 experiments tested lamprey passage efficiency up ramps with different slopes and under a variety of flow conditions on the ramp and through the flume. In these tests, the majority of tagged fish ascended the ramp under all treatment conditions but lamprey passage times differed significantly in response to flow levels. An additional test using ‘seed fish’ in the ramp head box was inconclusive.

In 2005, the flume was divided into three equal channels and attraction flows were manipulated to evaluate relative lamprey use of channels adjacent to walls versus mid-flume. Lamprey preferentially used channels adjacent to the flume walls, and this preference increased as flow through the outside channels decreased. Lamprey passage times also increased with concentrated flow through the center channel.

The 2006 experiments compared the effects of two types of lamprey rest boxes (broad-crested and one-way passage designs) located in the middle of a ramp. There was little difference in lamprey behavior between rest boxes under various flow treatments, and fish that ascended the ramp appeared to be unaffected by either rest box type. As in other experiments, lamprey did tend to find the ramp faster when ramp flow was higher. Additional tests in 2006 compared the effectiveness of several devices (water jets, air bubble streams, waterfall) for attracting lamprey to the base of a ramp when lamprey passage was unrestricted in the flume. Lamprey passage efficiency was highest during the water jet treatment, but differences among tests were not statistically significant.
Introduction

The Pacific lamprey, *Lampetra tridentata*, is a native anadromous species that was historically abundant throughout the Columbia and Snake rivers (Close et al. 1995; Jackson et al. 1997). Lampreys are culturally significant to indigenous peoples of the Pacific Northwest who have traditionally harvested adult fish for sustenance, ceremonial, and medicinal purposes (Close et al. 2004). The fish are ecologically significant as a source of marine-derived nutrients, as consumers and processors of benthic matter, and as a prey species (Close et al. 2002). Several factors, including habitat degradation, water pollution, stream impoundment, declining abundance of prey, and direct eradication efforts have contributed to the decline of lamprey. Recent studies suggest that Pacific lamprey abundance has steadily decreased in the Columbia River basin and in other regional rivers since the early 1960's (Close et al. 2002; Kostow 2002). To spawn in the upper reaches of the Columbia and Snake River basins, lamprey must successfully negotiate up to 9 hydroelectric dams during their spawning migration. Fishways at these and other dams were designed for adult salmonids without consideration for physically, physiologically, and behaviorally dissimilar species such as lamprey (Osborne 1961; Hardisty and Potter 1971; Beamish 1980).

Recent radiotelemetry and half duplex PIT-tag studies suggest that lamprey have difficulty negotiating fishways designed for salmonid passage (Moser et al. 2002a; Moser et al. 2002b; Moser et al. 2005; Cummings 2007; Daigle et al. in review). In studies at Bonneville Dam, the most downstream dam on the Columbia River, less than half of the radio-tagged lamprey that approached the dam successfully passed upstream. Lampreys had difficulty entering fishways and, once inside, were delayed or obstructed in collection channels and transition areas. Lamprey also showed poor passage success in areas near the ladder tops. These areas have brightly-lit count window stations, picketed weirs, and serpentine weirs which contribute to a complex environment of artificial lighting, physical barriers, and turbulent, confusing currents.

The experiments described in this report were a continuation of a series of tests designed to evaluate lamprey passage behaviors and to study what conditions attract and motivate adult lamprey to move successfully upstream in fishways. The first experiments were described in Daigle et al. (2005), and evaluated lamprey behaviors in response to time of day, presence of velocity refuges in weir orifices, simulated count window lights, ramp bypass structures, and the presence of a step or diffuser grating at the base of orifices. The follow-up experiments described here evaluated lamprey responses to: 1) a fishway ramp and the effects of ramp flow volume, ramp angle, and attraction flow at the ramp entrance; 2) a divided fishway with differing flow velocities at each channel entrance; 3) two styles of mid-ramp lamprey “rest boxes”; and 4) three methods of attracting lampreys to the ramp entrance (water jets, air bubble streams, and waterfalls).

Methods

**Fish collection.** – Adult lampreys used in this study were collected in a trap in the Washington-shore fish ladder at Bonneville Dam (described in Moser et al. 2002b). Fish were collected at night as they ascended the fishway in June and July of 2004-2006. Prior to use in experimental fishway tests, fish were held at least 12 h in covered aluminum tanks (92×152×122 cm) inside the Bonneville Dam adult fish facility (AFF). Tanks were supplied with constantly flowing Columbia River water.
Ten to 20 lamprey were collected during the night prior to each fishway test. Weights and lengths were taken for each fish (Appendix Figure 1) and a half duplex passive integrated transponder tag (HDX-PIT) was sutured to those used in the fishway test. Tags were encased in surgical tubing and then attached about 1 cm posterior to the base of the rear dorsal fin. All tests were scheduled to begin at 2300 h and ran until 0700 h the next day. Fish were generally observed during the first and last hours of each test.

**Experimental flume.** – All experiments were conducted in an 11.6 ×1.2 m flow-through aluminum tank (Figure 1). The fishway configuration was modified for each series of tests. In all cases Columbia River water was continuously passing through the structure. Viewports set into the sides of the fishway allowed infrared-lit observations of the fish. In addition, up to four half-duplex PIT-tag readers were arranged in various configurations to assess lamprey movements within the experimental fishway and test structures.

A removable screen at the downstream end of the fishway initially restricted fish movements. The test periods began when the screen was removed after a period of fish acclimation of at least 10 min in all tests. At the end of each test, tag loss (if any) was noted, the final location of each fish was recorded, and all fish were removed from the experimental fishway and released upstream from Bonneville Dam.

**Test design and data analyses.** – The series of tests we ran over the three study years were designed to evaluate factors potentially affecting lamprey behaviors, passage success and passage rates through experimental structures. These tests are described separately for each year (see below). We usually ran four replicates of each test in each year and all tests were run at night. Replicates were randomized within test whenever possible. The exceptions to this design occurred when fishway construction requirements made randomization impractical (i.e., adjusting flume ramp angle in 2004 and adding flume weirs in 2005). All tests ran for at least six hours but analysis was limited to what occurred in the first six hours to standardize results across test replicates and treatments.

The 2004 experiments included seven tests with a sloped wooden ramp inside the fishway (Figure 2). The ramp was 30.5 cm (12 in) wide, with sides 10.2 cm (4 in) high (in all years). Ramp lengths differed with ramp angle and were 5.59 m (220 in), 4.57 m (180 in), and 3.56 m (180 in). The first four tests were randomly ordered and tested the effects of 1) the amount of water flowing down the ramp and 2) the presence/absence of water flow through the flume and past the base of the ramp (Figure 3). Tests 1-4 all had a ramp slope angle of 35º and included five ‘seed’ lamprey in a box located at the ramp top to provide attractant to test fish. These tests evaluated the effects of ramp flow (high, low) and the effects of flow along the base of the fishway (on, off) (Figure 2). High ramp flow was 1.76 gal s\(^{-1}\) (6.66 L s\(^{-1}\)) and low flow was 0.54 gal s\(^{-1}\) (2.04 L s\(^{-1}\)) (Appendix Table 1). Test 5 was paired with test 4 to evaluate the effects of the ‘seed’ fish. Tests 6 (45º) and 7 (60º) evaluated the effects of ramp slope. In all 2004 tests, fish could not move upstream in the fishway beyond the base of the ramp (in contrast to studies in 2006; see below).

The 2005 experiments included three tests to evaluate lamprey use of a divided fishway and more specifically whether lamprey preferred relatively low flow velocity entrances adjacent to the walls. In all tests, fish could select among three entrances, one adjacent to each side of the fishway and one in the fishway center (Figure 4). In test 1, velocity was similar at all three entrances. In test 2, a wooden weir was added to each outside channel to reduce flow in those channels. Weirs were 0.20 m (8 in) wide with a 0.10 m (4 in) radius, and had 0.08 m (3 in) wide slots. A second weir was added to each channel in test 3, further reducing flow (see Appendix
Table 2 for flow measurements). These tests were not randomly ordered due to the logistics of installing and removing the additional weir sections. Total flow through the flume was reduced with successive tests to maintain similar conditions in the middle channel.

The 2006 experiments had two main objectives: 1) comparing the effectiveness of two types of in-ramp lamprey rest boxes, and 2) evaluating three methods of attracting lamprey to ramps. Tests were randomized within each objective (Figure 5). The two types of rest boxes included a “one-way” design where fish passed through a small fyke with a plastic funnel made of 1.2 cm mesh into a relatively turbulent rest box and could not retreat downstream, and a “broad-crested” design with a larger resting area and no one-way valve (Figure 6). Dimensions of the one-way box were 0.61 m (24 in) long, by 0.61 m (24 in) deep, by 0.30 m (12 in) long with a 1.22 m (48 in) long entrance chute that was 0.15 m (6 in) deep and wide. Dimensions of the broad-crested box were 1.83 m (72 in) long by 0.61 m (24 in) deep, by 0.30 m (12 in) wide. For each rest box type, the total ramp length was 4.57 m (180 in). Tests 1-4 evaluated these rest box types at low and high ramp flows, with a barrier that prevented fish from moving upstream in the flume beyond the ramp (Figure 6). The 2006 ramp attraction experiments (tests 5-8) were to evaluate features that might attract lamprey to a ramp adjacent to a wall in an unrestricted flume channel (compare to the restricted channel design in the 2004 tests and tests 1-4 in 2006). The attractants included a water jet treatment (four jets aimed towards the underwater section of the ramp), an air bubble treatment (two air bubble lines from a compressor outside the flume created a pathway along the lower section of the ramp), a waterfall treatment (a head box above the ramp surface provided attraction flow), and a control treatment. All eight tests in 2006 had a ramp adjacent to one fishway wall.

In all tests in all years, data collected by PIT-tag readers were used to calculate lamprey passage times, and/or passage efficiencies through test areas. Passage efficiency was defined as the percentage of lamprey that passed a given site. Passage times were defined as the first (or, in some cases, last) detection at an antenna to the first detection at the subsequent antenna. Passage times were compared using analysis of variance (ANOVA, Proc GLM, SAS Institute Inc., 2000), where the basic model for a randomized design with subsampling was:

Response = Test + Replicate(Test)

The Replicate(Test) term controlled for subsampling, or replicate, error. The main treatment effects were further analyzed using Duncan’s multiple range and/or Tukey’s studentized range tests (Zar 1999) after pooling replicates. Passage efficiency differences among treatments were compared using Pearson’s chi-square tests.
Figure 1. Isometric and side views of the experimental lamprey fishway installed in the Bonneville Dam adult fish facility (AFF) in 2004-2006. Structures inside the fishway were modified in a series of tests to evaluate lamprey passage times and passage efficiency under different designs and operations.
Figure 2. Isometric and side views of the experimental fishway in 2004 when ramp angle and ramp flow tests were conducted. The head box at the top of the ramp included “seed fish” to attract test lamprey in all test except test 5. Fish could move up the ramp, but not upstream in the fishway beyond the base of the ramp. Letters represent HDX PIT detector (antenna) labels.
Figure 3. Schematic of the lamprey ramp experiments in 2004. Tests 1-4 were randomly ordered and evaluated the effects of ramp flow volume (high, low) and fishway flow (on, off) with ramp angle = 35°. Tests 4, 6 and 7 evaluated the effects of ramp angle with constant ramp flow (low) and flume flow (on). “Seed” lamprey were present in the ramp head box in all tests except Test 5: tests 4 and 5 evaluated the effects of including “seed” lamprey with all other conditions constant (ramp flow = low; flume flow = on; ramp angle = 35°).
Figure 4. Isometric, overhead, and side views of the divided experimental fishway in 2005. In test 1, lamprey attraction flow was equal from all three channels. To reduce flow from the side channel entrances, additional upstream weirs were added in tests 2 and 3. Letters represent HDX PIT detector (antenna) labels.
Figure 5. Schematic of the lamprey experiments in 2006. Tests 1-4 were randomly ordered and evaluated the effects of two types of lamprey rest boxes (one-way, broad-crested) at two ramp flow volumes (high, low). Tests 5-7 were randomly ordered and evaluated the effects of three lamprey attraction mechanisms (water jets, air bubbles, waterfall) positioned at the lower end of the 45º ramp.
Figure 6. Isometric views of the experimental fishway in 2006 tests of lamprey rest boxes. Inserts show the design details of the one-way and broad-crested rest box designs. In these tests, fish could move up the ramp, but not upstream in the fishway beyond the base of the ramp. Letters represent HDX PIT detector (antenna) labels.
Results - 2004 Experiments

**Ramp flow** – We examined two metrics of passage time. One included the time lamprey spent at the base of the ramp, passing antenna B, and ascending the ramp (first detection at antenna B to first detection at antenna C). The other was the time lamprey required to ascend the ramp (last detection at antenna B to first detection at antenna C). During three of four passage time comparisons lamprey moved up the flume ramp significantly faster when flow in the ramp was at the low treatment level (Figure 8). Mean passage times for high versus low ramp flow treatments were: 1.21 vs. 0.33 h (flume flow off) and 1.21 vs. 0.84 h (flume flow on) from first B to first C antenna (Figure 2); means were 0.51 vs. 0.20 h (flume flow off) and 0.47 vs. 0.18 h (flume flow on) from last B to first C.

There were no differences ($\chi^2$ tests, $P \geq 0.480$) in the proportions of fish that reached the C antenna under high versus low ramp flow treatment. Passage efficiency ranged from 87.5-90% from antenna A to antenna C and from 89.7-94.7% from antenna B to antenna C (Table 1).
Figure 8. Pooled mean passage time (h, solid circles) for lamprey that ascended the test ramp under each ramp flow (high, low) and flume flow (off, on) treatment combination. Left panel: time from first detection at the B antenna to the first detection at the C antenna. Right panel: time from last detection at the B antenna to the first detection at the C antenna. Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles. Numbers above boxes = total n for test.

Table 1. Mean passage efficiencies (Release-A, Release-B, Release-C, A-B, A-C and B-C). There were no significant differences except in the case of Test 2 vs Test 4, where the proportion of lamprey that passed from antenna A to antenna B under low-flow, flume off was lower than under low-flow, flume on (0.625 vs. 1.000; P = 0.024).

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**Ramp angle** – Lamprey passage times from the first detection at B antenna to the first detection at C antenna differed among ramp angle treatments (Figure 9). Mean passage times were 0.84 h (35°), 0.31 h (45°) and 0.40 h (60°). Differences in these means were significant (P < 0.05) for 35° vs 45° and 35° vs 60° treatments, but not for 45° vs 60° treatments (least
significant difference [LSD tests]. Passage times from last detection at B antenna to first
detection at C antenna record did not differ among treatments, suggesting that ramp angle did
not affect fish behavior after fish had committed to ascending. Mean times were 0.18 h (35°),
0.17 h (45°) and 0.17 h (60°)

There were no differences ($P \geq 0.071$, $\chi^2$ tests) in the proportions of fish that reached the C
antenna under the three ramp angle treatments. Passage efficiency was 89.7% (35°), 100.0%
(45°) and 89.2% (60°) between antenna A and antenna C, and it was 89.7% (35°), 100.0% (45°)
and 97.5% (60°) between antenna B and antenna C (Table 1).

![Figure 9](image)

**Figure 9.** Pooled mean passage time (h, solid circles) for lamprey that ascended sections of the test
ramp, by ramp angle. Left panel: from first detection at the B antenna to the first detection at the C
antenna. Right panel: from last detection at the B antenna to the first detection at the C antenna. In all
tests, flume flow was on and ramp flow was low. Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th
percentiles. $P$ values are for ANOVAs. Numbers above boxes = total $n$ for test.

**Flume flow** – During the flow tests (1-4), we also examined time lamprey required to enter
the ramp using two metrics: passage time from release to first detection at B antenna, and
passage time from first A detection to first B detection (Figure 2). While lamprey regularly
entered the ramp more rapidly when there was flume flow, this was only statistically significant
for the passage time between antenna A and B when the ramp flow was high (Figure 10). The
differences in means among replicates (an error term) for these comparisons were relatively
large (i.e., means differed by a factor of > 2), which made it difficult to detect treatment
differences. Mean passage times from release to first B antenna for the two flume flow
treatments at high ramp flow were: 2.20 h (flume off) vs. 1.31 h (flume on). For low ramp flow
they were 2.32 h (flume off) vs. 1.62 h (flume on). Mean passage times from first A to first B
detections were 1.36 h (flume off) vs. 0.40 h (flume on) at high ramp flow and 0.84 h (flume off)
vs. 0.60 h (flume on) at low ramp flow.
There were no differences ($\chi^2$ tests, $P \geq 0.081$) in the proportions of fish that reached the B antenna under the two flume flow treatments. Passage efficiency ranged from 92.5-100% from antenna A to antenna B (Table 1).

Figure 10. Pooled mean passage time (h, solid circles) lamprey used to initiate ascension of the test ramp, by flume flow (off, on) and ramp flow (high, low) treatment combinations. Left panel: time from release to the first detection at the B antenna. Right panel: time from the first detection at the A antenna to the first detection at the B antenna. Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles. Solid circles = means. $P$ values are for ANOVAs. Numbers above boxes = total $n$ for test.

‘Seed fish’ tests – In the seed fish evaluation (Test 4 versus 5), lamprey passage times did not differ significantly ($P > 0.15$) between release and first records at any of the three antenna sites, or between antenna sites. Mean passage times from release to antenna C were longer for the tests with seed fish (2.46 h) than without seed fish (1.74 h), and this difference was significant ($P < 0.05$) when replicates were pooled. Passage time variability was quite high among replicates, particularly for replicates of Test 5 that were conducted late in the season. Notably, treatments were not randomly ordered (Figure 3) with the ‘no seed fish’ tests run in early July versus mid- to late June for the ‘seed fish’ tests.

Although slightly more fish passed up the ramp with seed fish in the head box, differences in the percentages of fish that reached the B or the C antenna were not significant ($\chi^2$ tests, $P \geq 0.147$) for the two tests (Tests 4 and 5). Passage to antenna B was 100% with seed fish and 94.7% with no seed fish. Passage to antenna C was 89.7% with seed fish and 84.5% with no seed fish (Table 1).
Results - 2005 Experiments

Channel selection – The experiments in 2005 tested whether lamprey route selection differed among three adjacent channels. Our null hypothesis was that lamprey had an equal probability of entering each channel. In test 1, flow rates in all three channels were similar (Appendix Table 2). While lamprey tended to first enter channels adjacent to flume walls (south and north), these differences were not significant ($\chi^2 = 5.35, P = 0.069$) (Figure 11). The result was similar for the last entrance location in test 1 ($\chi^2 = 5.09, P = 0.078$). In tests 2 and 3, successively lower flow passed through the outside channels, and lamprey use of the outside channels increased (Figure 11). In these tests, lamprey were significantly more likely to first enter the outside channels ($\chi^2 = 7.00, P = 0.030$, test 2; $\chi^2 = 14.35, P < 0.001$, test 3) and to last enter the outside channels ($\chi^2 = 6.26, P = 0.044$, test 2; $\chi^2 = 12.25, P = 0.002$, test 3). Results were pooled across replicates in each test.

![Graph showing channel selection results](image)

**Figure 11.** The mean (+ 1 sd) percentage of lamprey that used each channel (south, middle and north: gray bars indicate first detections at channel entrance and white bars are last detections at channel entrances. Channel water velocities were decreased in the south and north channels with each successive test (Test 1 = high flow, Test 2 = moderate flow, Test 3 = low flow).

Passage time – Lamprey passage times were compared in two basic ways: 1) by the channel fish first entered, across tests; and 2) by test, across channels. When lamprey were grouped by the channel they first entered, passage times from release to first detection at antenna A (Figure 4) did not differ ($P > 0.69$) among tests (Figure 12). Mean times from release to first south channel entrance were 0.42 h (test 1), 0.40 h (test 2), and 0.59 h (test 3) ($P = 0.778$). Mean times from release to first north channel entrance were 0.47 h (test 1), 0.54 h (test 2), and 0.72 h (test 3) ($P = 0.747$). Sample sizes for fish first entering the middle channel were ≤ 5 in all tests (Figure 12).

When lamprey were grouped by test, mean passage times from release to antenna A did not significantly ($P > 0.12$) differ within each test as a function of which channel was first entered.
Mean lamprey passage times from release to first detection at antenna B did not differ \((P > 0.44)\) among tests when fish were grouped by first channel detection site (Figure 13). However, when all replicates were combined, mean passage times for fish first detected in the north channel were significantly different among tests: \(0.54\) h (test 1), \(0.57\) h (test 2), and \(0.95\) h (test 3) \((P < 0.05, \text{Tukey's test})\). The result was similar when the last channel detection site was used to group fish.

Within each test, mean passage times from release to antenna B did not differ by which channel lamprey first or last entered \((P > 0.33)\). Pooling replicates indicated a significant difference among channels \((P < 0.05, \text{Tukey's test})\) in test 2, with times of \(0.52\) h (to south channel), \(0.57\) h (to north channel), and \(1.03\) h (to middle channel). Results were similar for passage times based on first and last channel detection sites (Figure 13).

Once inside a channel for the final time, most lampreys moved from antenna A to antenna B in less than \(0.25\) h (Figure 14). Differences were not significant by test within channel \((P \geq 0.14)\) or by channel within test \((P \geq 0.05)\). However, when all replicates were pooled, passage times through each channel were longer \((P < 0.05, \text{Tukey's tests})\) in test 3 (Figure 14).
**Effects of fish size** – Lamprey weight was not correlated ($P > 0.05$) with passage time metrics in any 2005 test. Similarly, lamprey weight and/or length did not differ with the first channel entrance site ($P > 0.05$); however, this test was limited by small samples entering the middle channel in some cases.

![Graph showing time to pass (h) for different channels and tests](image)

Figure 13. Pooled mean passage time (h, solid circles) lamprey used to pass from release to first detection at Antenna B, by the locations of the first (gray bars) and last (white bar) channel entrance sites. Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles, except where sample sizes were limiting. Channel water velocities decreased in the south and north channels with each successive test.

**Results - 2006 Experiments**

**Rest boxes** – In general, rest box type (one-way, broad-crested) had little effect on lamprey passage times while ramp flow during these comparisons had modest effects (Figure 15). At low ramp flow, mean passage times from first detection at antenna B to first detection at antenna C were 1.41 h (one-way) and 1.15 h (broad-crested). Means at high flow were 0.69 h (one-way) and 0.72 h (broad-crested). These differences were not significant ($P > 0.64$). Mean passage times from first detection at antenna C to first detection at antenna D during low flow were 0.19 h (one-way) and 0.10 h (broad-crested) ($F = 3.5, P = 0.112$); means at high flow were 0.29 h (one-way) and 0.16 h (broad-crested) ($F = 5.2, P = 0.063$). The latter difference was significant ($P < 0.05$, Tukey’s test) when all replicates were pooled. Mean passage times from first detection at antenna B to first detection at antenna D during low flow were 1.56 h (one-way) and 1.25 h (broad-crested); means at high flow were 0.98 h (one-way) and 0.89 h (broad-crested). Neither difference was significant ($P > 0.44$).

Within rest box type, lamprey tended to enter and move through sections B-C and B-D more quickly at high flow but through section C-D more slowly at high flow (Figure 15). Means from first detection at B to first at C with the one-way weir were 1.41 h (low flow) and 0.69 h (high flow); this difference was significant when all replicates were pooled ($P < 0.05$, Tukey’s test).
Similarly, fish moved faster from the last record at B to first at C during high flow (0.03 h) than during low flow (0.06 h). Mean passage times with the broad-crested weir from first B to first C were 1.15 h (low flow) and 0.72 h (high flow), a non-significant difference. Means from first C to first D were 0.19 h (low flow) and 0.29 h (high flow) with the one-way weir and were 0.10 h (low flow) and 0.16 h (high flow) with the broad-crested weir. The latter difference was significant when all replicates were pooled ($P < 0.05$, Tukey's test). Means for the first B to first D section were 1.56 h (one-way, low flow), 0.98 h (one-way, high flow), 1.25 h (broad-crested, low flow), and 0.89 (broad-crested, high flow); no differences were significant.

We also compared the number of times lamprey (total $n = 58$) were observed attaching to the ramp floor while ascending a 60 cm section of ramp under the two flow conditions. Mean numbers of attachments during the low flow treatment were 14.3 attachments ($n = 15$ lamprey, one-way box) and 15.5 attachments ($n = 17$ lamprey, broad-crested box). This was significantly ($P \leq 0.008$, pooled ANOVA) less than attachments made during the high flow treatments: one-way mean = 29.2 attachments ($n = 15$), and broad-crested mean = 21.6 attachments ($n = 11$).

Lamprey passage efficiency did not significantly ($P > 0.12$, $\chi^2$ tests) differ among rest box types and ramp flow levels (Figure 16). Mean passage from antenna A to antenna D was 77% (one-way box, low flow), 66% (one-way box, high flow), 65% (broad-crested box, low flow), and 52% (broad-crested box, high flow). Passage from antenna B to antenna D was nearly identical to those from A to D. Mean passage efficiency from antenna C to antenna D (through the rest boxes) were 97% (one-way box, low flow), 100% (one-way box, high flow), 96% (broad-crested box, low flow), and 100% (broad-crested box, high flow) (Figure 16).
Figure 15. Pooled mean passage times (h, solid circles) for lamprey to ascend sections of the test ramp, by ramp flow (high, low) and rest box type (one-way, broad-crested). Left panel: from first detection at the B antenna to the first detection at the C antenna (below the rest box). Center panel: from first detection at the C antenna to first detection at the D antenna (includes rest box). Right panel: from first detection at the B antenna to the first detection at the D antenna (includes full ramp and rest box). Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles. Statistics are for ANOVAs.

Figure 16. Pooled mean lamprey passage efficiency from antennas A, B, and C to antenna D with two rest box types (one-way, broad-crested) and two ramp flow conditions (low, high).
**Ramp attraction** – The first attraction experiment compared the percentages of lamprey that were first recorded at the base of the ramp (antenna B) versus at the upstream end of the flume (antenna D). Mean percentages at antenna B were 13% (control), 25% (water jets), 13% (air bubbles), and 15% (waterfall) (Figure 17); these differences were not significant with all replicates pooled ($\chi^2 = 2.9, P = 0.402$).

![Figure 17. Mean (+ 1 sd) percentages of lamprey that were first detected at the ramp bottom (Antenna B) and not at the upstream end of the flume (Antenna D), for a control group and with three types of attraction mechanisms (water jets, air bubbles, waterfall).](image)

The second attraction experiment compared lamprey passage times from release to first detection at antenna B and from first detection at antenna A to first detection at Antenna B (Figure 18). Mean times from release to B were 1.70 h (control), 0.86 h (water jets), 1.44 h (air bubbles), and 1.47 h (waterfall). These differences were not significant ($F = 1.7, P = 0.219$) in the complete model. When replicates were pooled, mean lamprey passage times were significantly lower ($P < 0.05$, Tukey’s test) for the water jet treatment. Mean times from antenna A to B were 0.87 h (control), 0.50 h (water jets), 0.77 h (air bubbles), and 0.77 h (waterfall). These differences also were not significant ($F = 1.4, P = 0.293$) in the complete model. When replicates were pooled, mean lamprey passage times were significantly lower ($P < 0.05$, Tukey’s test) for the water jet treatment than for the control.

Ramp ascension times (from antenna B to antenna C) differed significantly ($F = 3.7, P = 0.046$) among treatments (Figure 19), though sample sizes were relatively small. Mean times were 2.40 h (control, $n = 9$), 2.76 h (water jets, $n = 14$), 3.56 h (air bubbles, $n = 6$), and 1.42 h (waterfall, $n = 15$). The Tukey’s comparison of means indicated lamprey ascended faster during the waterfall treatment than the air bubble treatment.
Figure 18. Pooled mean passage times (h, solid circles) for lamprey to arrive at the bottom of the ramp (first detection at Antenna B) from release (gray bars) and from first detection at Antenna A (white bars), for a control and three types of attraction (water jets, air bubbles, waterfall). Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.

Figure 19. Pooled mean passage time (h, solid circles) for lamprey to pass from the bottom to the top of the ramp (Antenna B - Antenna C) for a control group and with three types of attraction mechanisms (water jets, air bubbles, waterfall). Box plots indicate 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles.
Relatively few lamprey reached antenna C in any treatment (Figure 20). Mean passage efficiency was 23% (control), 35% (water jets), 15% (air bubbles), and 38% (waterfall). When all replicates were pooled, these differences were not significant ($\chi^2 = 6.62, P = 0.085$). Comparisons between individual treatments and the control were also not significant ($P > 0.16$).

![Graph showing mean (+ 1 sd) percentages of lamprey that successfully ascended the ramp (detected at Antenna C), for a control group and with three types of attraction mechanisms (water jets, air bubbles, waterfall).]

**Discussion**

**General Comments.** – The adult Pacific lamprey experiments described here were designed to inform development of lamprey passage structures (LPSs) (e.g., Moser et al. 2006) and guide modifications to existing fishways at Columbia and Snake River dams. In these experiments and on test structures, ramps appear to be a good lamprey passage alternative when compared to the turbulent, high-velocity orifice-and-weir fishways designed for adult salmonids. One of the challenges of using ramps, however, will be to successfully attract fish to the ramp entrances. This was particularly evident in the 2006 experiments, where lamprey could move in an unrestricted fashion within the flume where a ramp was attached to only one wall.

As in other lamprey studies, PIT-tagged fish in these tests generally moved faster between antenna sites when water velocities were low. An apparent exception to this pattern occurred when there was no flow through the test flume. This suggests that some level of attraction flow orients fish upstream and/or stimulates upstream movement and searching behaviors. Providing adequate attraction flow is critical in areas like fishway transition pools, where turbulent or low-velocity currents may disorient lamprey, as has also been the case for salmon (e.g., Keefer et al. 2007).
While we think it is reasonable to assume that behaviors of lamprey used in these experiments reasonably reflect behaviors by naïve, untagged fish, we recommend caution in directly extrapolating results to behaviors in fishways or LPS systems. For example, although the test flume was constantly replenished with fresh Columbia River water, the scale and configuration of the flume was restricted. Fish collection, handling, or tagging effects may have also affected experimental results. All study fish were collected in traps inside the Washington-shore ladder, for example, potentially selecting for fish that were able to ascend the fishway.

**2004 Experiments.** – In 2004, lamprey could either remain in the release area or enter and move up the ramp. On average (all tests and replicates), 94% of the lamprey moved up the ramp and were recorded at the uppermost antenna. The percentages of fish reaching the ramp top did not appreciably differ with flow volume in the ramp, flow through the flume, or ramp angle. These results collectively indicated that the ramp was effective at passing lamprey, although this was the only alternative for upstream passage in these tests.

Lamprey passage speeds did differ, significantly in some cases, among the various test treatments. For example, fish moved up the ramp more slowly at the high ramp flow treatment. As mentioned above, fish also moved from the release area to the base of the ramp more rapidly when flow was passing through the flume. In the ramp angle tests, there was some evidence that lamprey were slower to enter the low angle (35°) ramp. However, after fish committed to ascending, passage times were similar among the three angle treatments (35°, 45°, 60°). This result suggests that the environment at the transition from the flume floor into the ramp itself may be important in attracting or passing lamprey. We did not evaluate flow conditions in the transition area, but it is possible that a hydraulic jump or other hydraulic feature in this area differed among ramp angles in a way that affected fish behavior.

The ‘seed fish’ test in 2004 was inconclusive as neither passage times nor passage efficiencies differed among the two treatments. However, it was impossible to verify if this test was valid because we had no way to assess whether residual lamprey odors were present in the test without lamprey in the headbox. Lamprey have a well developed olfactory system and strongly react to the presence of conspecific pheromones (Vrieze and Sorensen 2001), and it seems probable that some level of attractant existed in all tests. We recommend refined experimental testing if managers wish to use pheromones or other odors to attract lamprey in fishways or LPS devices.

**2005 Experiments.** – The 2005 tests clearly indicated that lamprey prefer routes adjacent to walls, where velocities were lowest in all tests (including the control). This is consistent with observed behaviors in fishways, near count windows, and in previous experiments. When discharge was equal through the three channels, less than 15% of the lamprey first entered the middle channel, or less than half of what would be expected if all channels were used equally (i.e., 33%). As discharge through the outside channels was reduced, lamprey use of the middle channel decreased further and was less than 6% when flow was highest in the middle channel.

There was also evidence that concentrated flow through the middle channel resulted in slower passage times, regardless of which channel was entered. This may reflect more confusing attraction cues or more turbulent flow patterns when discharge differed among channels. This may be important for structure placement and/or design in fishways or LPS, particularly at sites with turbulent flows, though some of this effect may be diminished in a fishway.
**2006 Experiments.** – The 2006 rest box tests suggested there were only minor if any differences in lamprey performance related to rest box type. Fish passage times tended to be slightly, and mostly non-significantly, faster through the broad-crested rest box. Effects of ramp flow (high, low) on fish passage times were mixed and generally inconclusive, though there was some evidence that higher ramp flow attracted fish to more quickly enter the ramp. We note that passage times were most variable for the time to “discover” and enter the ramp, while passage times up the ramp itself were more constant. Observations of lamprey attachments to the ramp in 2006 clearly showed that fish used their suctorial disk more frequently during the high ramp flow treatment, consistent with the more frequent surging and reattaching behavior observed at higher flows by Daigle et al. (2005) and others. This behavior did not appear to be swimming *per se*, but was a lunging movement, with smaller upstream gains at higher flow.

Passage success on the ramp was considerably lower in 2006 (52-77% per test) than in 2004. In part, this reflects flume configuration differences, as fish could freely move throughout the flume in the 2006 attraction tests without entering the ramp, in contrast to 2004. Importantly, the rest boxes did not appear to affect passage success. More than 96% of the fish that passed up the ramp section below the rest boxes eventually reached the antenna above the boxes. In other words, after fish committed to ascending the ramp, most were successful with both rest box designs.

In the 2006 attraction tests, water jets performed slightly better than air bubbles, a waterfall, or the control in first attracting lamprey to the ramp. However, in all tests most fish initially passed the ramp and were recorded at the upstream end of the flume. This suggests that either the attraction techniques were ineffectual or that lamprey were initially attracted to the relatively large and uniform flow through the flume and easily moved the short distance to the flume end. Presumably, this would be a typical scenario in a relatively large and unconstricted fishway. Mean ramp discovery times following release and from first detection at the most downstream flume antenna were lowest during the water jet treatment by approximately 50%. Results of the attraction tests are most transferable to situations where lamprey are known to congregate and in areas where they can easily enter but not necessarily exit a structure (e.g., makeup water channels).

Ramp passage success during the 2006 attraction test was the lowest among the ramp experiments. The highest passage efficiency to the top of the ramp (38%) was during the waterfall treatment, closely followed by the water jet treatment (35%). These were higher, but not statistically different from the control (23%) and air bubble (15%) treatments.
References


Appendix

Figure 1. Lamprey weight (g) distributions, by year and test.

Table 1. 2004 ramp flow volumes in $L\cdot s^{-1}$ (gal•s$^{-1}$), by test.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Description</th>
<th>Ramp volume</th>
<th>Flume on/off*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High ramp flow/ flume off</td>
<td>6.66 (1.76)</td>
<td>Off</td>
</tr>
<tr>
<td>2</td>
<td>Low ramp flow/ flume off</td>
<td>2.04 (0.54)</td>
<td>Off</td>
</tr>
<tr>
<td>3</td>
<td>High ramp flow/ flume on</td>
<td>6.66 (1.76)</td>
<td>On</td>
</tr>
<tr>
<td>4</td>
<td>Low ramp flow/ flume on</td>
<td>2.04 (0.54)</td>
<td>On</td>
</tr>
<tr>
<td>5</td>
<td>Without seed fish</td>
<td>2.04 (0.54)</td>
<td>On</td>
</tr>
<tr>
<td>6</td>
<td>45 degree ramp</td>
<td>2.04 (0.54)</td>
<td>On</td>
</tr>
<tr>
<td>7</td>
<td>60 degree ramp</td>
<td>2.04 (0.54)</td>
<td>On</td>
</tr>
</tbody>
</table>

* presence/absence only
Table 2. Current velocities in m s\(^{-1}\) measured using a Marsh-McBirney flow meter downstream from the center of each channel, and within each channel 2 ft upstream from each weir. Three measurements, at 15.2 cm (6") , 45.7 cm (18") and 76.2 cm (30") above the flume floor, were averaged for each location. Slot velocities were calculated using the upstream measurement; each slot was 18% of the channel.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Channel</th>
<th>Downstream</th>
<th>Slot 1</th>
<th>Upstream 1</th>
<th>Slot 2</th>
<th>Upstream 2</th>
<th>Slot 3</th>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>0.21</td>
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