Technical Report 2005-1

IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

EVALUATION OF ADULT PACIFIC LAMPREY PASSAGEAND BEHAVIOR IN AN EXPERIMENTAL FISHWAY AT BONNEVILLE DAM

A Report for Study Codes ADS-P-008 and ADS-P-00-10

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For

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

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Abstract

Tests were conducted in an experimental fishway at Bonneville Dam in 1999, 2000, and 2002 to evaluate behavior and swimming performance of adult Pacific lamprey *Lampetra tridentata*. These tests were initiated after results from radiotelemetry studies indicated that lamprey did not readily pass dams on the Columbia River. The experimental fishway used for all tests had an 8.2 m long x 1.2 m wide experimental section and was designed with three different configurations: 1) a pool-and-weir with three overflow weirs, each with a 0.5 m square submerged orifice and a 0.6 m wide overflow section, 2) a simulated count window with picketed crowder, and 3) a model entrance with a single 30.5 cm vertical slot weir. Individual trials commenced by placing five to ten lamprey in the downstream end of the fishway. Movements past weirs and other fishway structures were observed at viewports built into the sides of the experimental channel and were recorded using video cameras. Two to eight replicates of each test were performed both during the day and at night.

With the fishway in the pool-and-weir configuration, we ran a total of 120 trials using 625 fish and evaluated the following conditions: time of day, presence of velocity refuges in the orifices, presence of a step at the base of one of the orifices, presence of a diffuser grating upstream from one of the weirs, and surgically implanted radio transmitters.

We found that the fish were generally more active at night than during the day, which was consistent with radiotelemetry data. At the baseline (standard operation) condition, lamprey required a mean of 54.9 min to ascend the three weirs, averaging about 3.0 min to pass through an individual orifice during a 1 to 2 hr test period. The addition of velocity refuges within orifices decreased the mean passage time through the orifice by over 1.0 min ($P < 0.01$) and mean passage through the entire fishway by about 10.0 min, but had little effect on the mean passage success rate ($P = 0.80$); 71 and 66% of lamprey successfully passed all three weirs with and without the refuges in place. The overall passage rate decreased from 69 to 49 % ($P < 0.01$) when we added a 20.3 cm high step downstream from the center orifice to simulate the configuration of the Bradford Island fishway at Bonneville Dam. Lamprey took longer to pass through an orifice ($P < 0.01$) when a diffuser grating was installed just upstream from the orifice, however presence of the diffuser did not significantly affect the percentage of lamprey that successfully passed though the fishway ($P = 0.28$) as more fish passed the modified weir via the overflow section. Passage times through the affected orifice improved ($P = 0.02$) with the installation of a solid plate just upstream from that orifice, which allowed lamprey to attach. Eighty and seventy-three percent of fish with and without surgically implanted radio transmitters passed all three weirs, and these values were not significantly different ($P = 0.65$).

Tests with the simulated count window were conducted with and without count window lights on and a picket lead weir in place. We found that approximately the same proportion of fish passed regardless of whether or not count window lights were on ($P = 0.86$) or the picket lead weir was in place ($P = 0.58$), indicating that the count window lights were not a significant passage obstacle.

Tests with the entrance weir in place were used to evaluate bulkhead shape, head level, time of day, and presence or absence of a lower flow alternative entrance or a

ramp bypass. We again found that lamprey were more active at night than during the day in all trials ($P < 0.01$). Modifying the head level via the weir was the most effective method for increasing passage success. Nighttime passage rates increased from 4% with 45.7 cm of head to 78% with 15.2 cm of head ($P = 0.04$). Bulkhead shape had less effect on passage. Nighttime passage rates were 34% with square bulkheads in place and 41% with round bulkheads ($P = 0.19$). The addition of a second channel with lower flow also had a significant effect on passage. With 45.7 cm of head in the main channel, the passage rate increased from 3% to 44% when a channel with 15.2 cm was available ($P < 0.01$). None of the 400 lamprey used in tests of a bypass ramp opted to use the ramp. Fish would often collect at the base of the ramp, but they made no attempts to ascend during the 1 h tests we conducted. In subsequent ramp experiments performed in 2004, lamprey took longer than 1 hr to approach and start ascending ramps.

Introduction

Pacific lamprey, *Lampetra tridentata*, are a native anadromous species that were historically abundant throughout the Columbia and Snake rivers (Close et al.,1995; Jackson et al.,1997). Lamprey have ecological significance as well as cultural importance to Native Americans who traditionally harvested the fish for sustenance, medicinal, and ceremonial purposes. Current returns of lamprey to the Columbia River are significantly lower than past levels (Kostow,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 in the past half century. 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 dams were designed for passing adult salmonids with no consideration for physically, physiologically, and behaviorally dissimilar species such as lamprey (Beamish,1980; HardistyPotter,1971; Osborne,1961).

Recent radiotelemetry studies suggest that lamprey have difficulty negotiating fishways designed for salmonid passage (Moser et al.,2002a; Moser et al.,2002b). 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. Lamprey had difficulty entering fishways and, once inside, were delayed or obstructed in collection channels and transition areas that are influenced by tailwater. The lamprey also showed poor passage success in areas near the top of the ladders. 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.

To date, few researchers have quantified the swimming performance of Pacific lamprey. Bell (1990) found that lamprey could sustain speeds of 0.9 m/s, with burst speeds up to 2.1 m/s when swimming in a flume with steady flow, however it is unclear whether or not lamprey were allowed to attach to the substrate and rest during these trials. Mesa et al. (2003), found that lamprey consistently swam at speeds of less than 1.0 m/s when swimming in a Blazka-type respirometer lined with plastic mesh to prevent them from attaching to the respirometer walls. Beck (1995) found that although lamprey can successful pass through submerged orifices at fishway weirs, they take up to 4.5 minutes (mean) to pass a single orifice and are often observed swimming downstream through the fish ladder. Studies on sea lamprey (HaroKynard,1997) have revealed more fish swimming downstream than upstream at some weirs.

There is still uncertainty about what conditions attract and motivate adult lamprey to move upstream and the mechanisms that are most critical to successful passage in fishways. In the series of tests described here, we evaluated lamprey swimming performance and behavior via the systematic manipulation of an experimental fishway to identify problems and potential solutions associated with passage for adult lamprey both within existing fishways and at fishway entrances.

Methods

Lamprey used in this study were collected in a trap at Bonneville Dam on the lower Columbia River. We captured fish as they ascended the fishway at night during May – August, 1999, 2000, and 2002. Prior to testing, the fish were held at least 12 hours in covered aluminum holding tanks (92 x 152 x 122 cm) that were supplied with flowing Columbia River water. In 1999, we used 313 lamprey with total lengths ranging from 53.5 – 77.0 cm (median = 66.5 cm; Figure 1). In 2000, 412 lamprey with total lengths ranging from 50.0 – 78.5 cm (median = 65.5 cm) were used in these experiments. In 2002, we used 950 fish with lengths of 43.5 – 80.0 cm (median = 67.0 cm).

The experimental fishway where tests were conducted consisted of an 11.6 m long x 1.2 m wide flow-through aluminum tank (Figure 2, Figure 3) with Columbia River water supplied by two 35.6 cm diameter pipes capable of generating flows of 835.3 liters per second. The fishway was comprised of five main sections (listed from the upstream end): 1) a 1.2 m long flow inflow section in which water upwelled through the floor, 2) a 0.6 m long by 2.4 m deep exit section bounded by a perforated plate back and perforated plate formed into fykes to allow lamprey to enter but inhibited exits at the downstream end, 3) an 8.2 m long by 2.4 m deep experimental section on a 1:10 slope, 4) a 0.8 m long by 2.4 m deep acclimation section bounded by a removable perforated plate on the upstream end and a permanent perforated plate on the downstream end, 5) and an outflow section which had an open bottom and contained an adjustable height wall (15.2 cm increments) on the upstream end to control the pool height in the fishway. Viewports set into the sides of the experimental fishway allowed observations of fish behavior during the trials.

Before the start of each trial, 5 to 10 lamprey (typically 10) were placed in the acclimation section of the tank for at least 10 minutes with water flowing at test conditions. Trials were initiated by removing the upstream perforated plate to allow fish access to the experimental section. Tests were run for 2 h in 1999 and for 1 hr in 1999, 2000, and 2002. Tests were shortened from 2 h to 1 h in 1999 after we determined that over 90% of the fish successfully ascended the experimental fishway in the first hour of the trial. During the trials, fish behavior was observed using viewports placed in the sides of the experimental fishway and recorded on video tape to determine modes and times of passage. Infrared lamps were mounted in the fishway at key locations so that observations could be made at night using nightvision goggles and on video cameras that could record under infrared lighting. At the end of each trial period, the fishway was drained and final locations were recorded for each fish. We performed 2 to 8 replicates (typically 4) of each test during both day and night trials. Data collected during these trials included the proportion of fish that successfully ascended the experimental fishway, time to ascend (defined as the time from lifting of the intake screen to fishway exit for each fish), and time to pass the middle weir (defined as the time from fish entry into the camera view until exiting upstream).

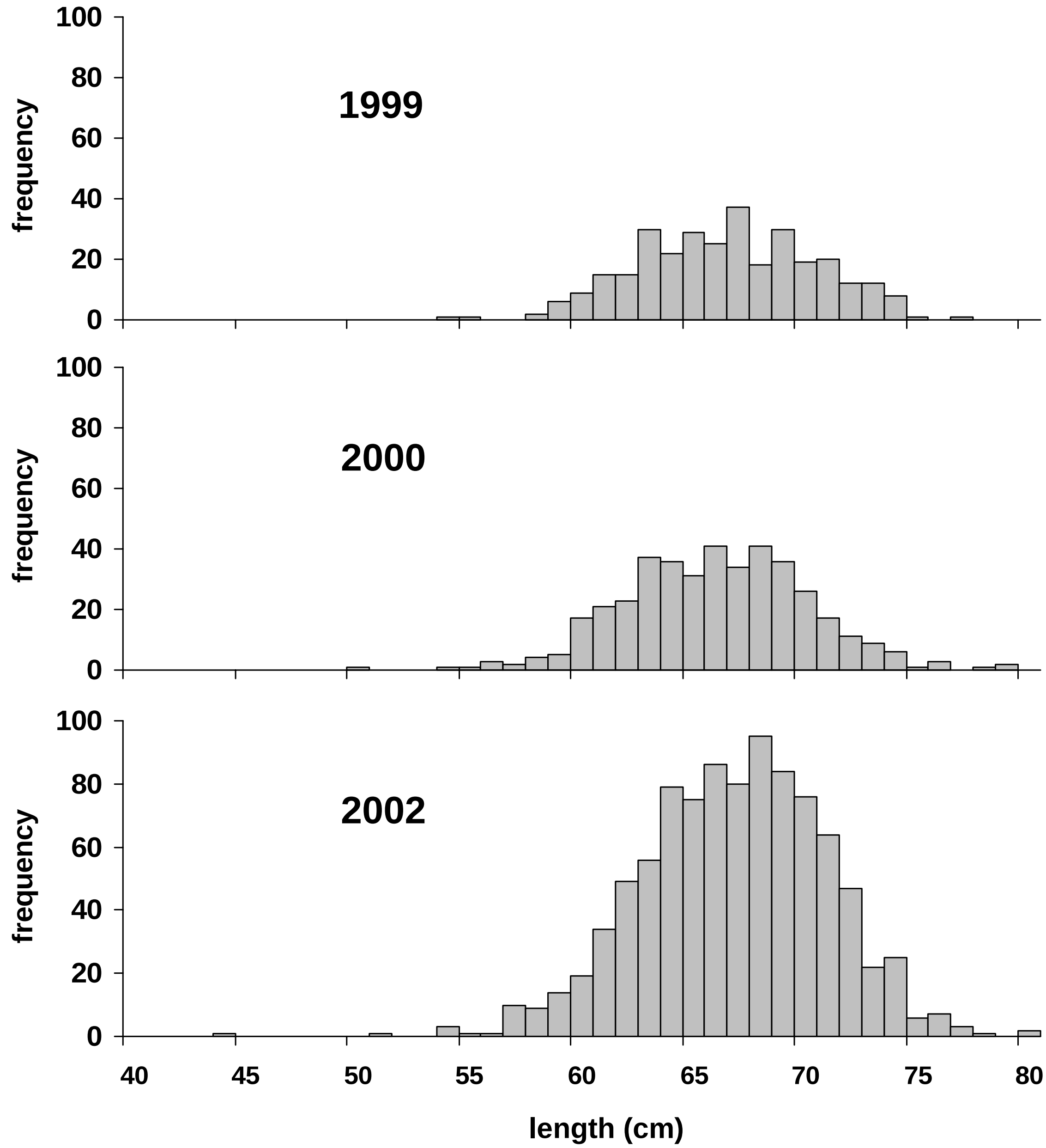

Figure 1. Length frequency distributions for 313, 412, and 950 lamprey used in experiments in 1999, 2000, and 2002.

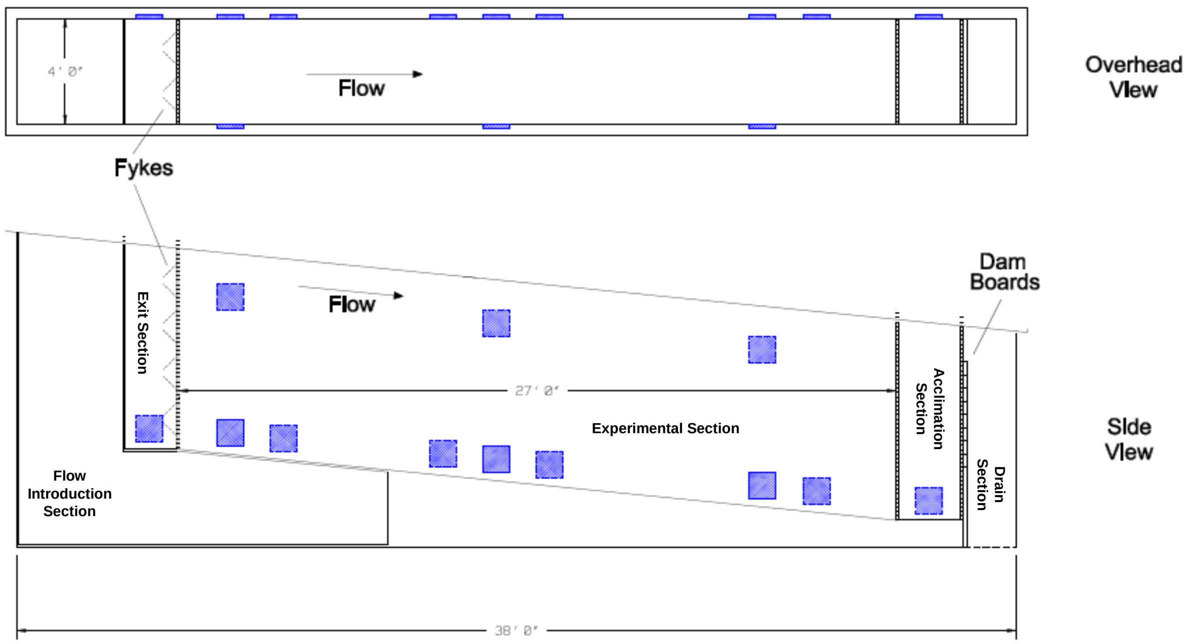

Figure 2. Basic configuration of the experimental fishway set up in the Bonneville Dam Adult Fish Facility (AFF). Squares represent view port locations.

Figure 3. Picture of experimental fishway operating with overflow/orifice weirs in place.

During 1999, we installed three 2.3 m high x 1.2 m wide weirs within the experimental section to simulate conditions in a pool-and-weir type fishway (Figure 3, Figure 4). The weirs were spaced at 3.0 m increments to maintain a head level of 0.3 m at each weir. Each weir had one 0.6 m wide x 0.6 m high overflow section and one 0.5 m wide x 0.5 m high submerged orifice that was positioned flush with the floor of the fishway. All observations were made at the second and third upstream weirs. At the end of a trial, all fish that were upstream of the third weir were considered to have successfully passed through the fishway. Water velocity (m/s) was measured at a variety of depths both upstream and downstream of the weirs using a Marsh McBirney flowmeter[1]. Water velocities ranged from 0.5 to 2.7 m/s at the submerged orifice (Table 1) and from 0.3 to 1.5 m/s at the overflow (Table 2).

Three main sets of tests were carried out in 1999 (Table 3). For the first two sets of tests we varied the depth of water flowing over the top of the weir (0.3 or 0.4 m overflow depth) and presence or absence of velocity refuges within orifices. Each of the four treatments were replicated and each replicate group of fish was tested during both day and night. For each replicate we alternated starting the test during the day and at night, to avoid any potential effects of habituation or learning.

The velocity refuges were created by securing rows of artificial rocks (10.2 cm wide x 10.2 cm high) to the bottom of the fishway upstream from, within, and downstream from the orifice to create zones of low velocities near the floor through which lamprey could swim. Rows of artificial rocks were situated every 35 cm and staggered so there was 70 cm between one rock and the rock directly upstream. Velocity refuge trials ran for one and two hour durations. The initial test trials ran for 2 h each and were conducted under normal fishway conditions with flow over weirs. The second set of trials ran for 1 h each with the water depth lowered in the fishway so that flow was through the submerged orifices only to isolate the impact of the velocity refuges on passage efficiency through orifices. The latter group of tests was run during the day and at night, with and without refuges.

A third set of trials investigated the effect of surgically implanting 7.7 g (<2% of the lamprey body weight) radio transmitters (Lotek MCFT-3BM) into lamprey. Twenty control fish were handled but not implanted and 20 lamprey were implanted with transmitters prior to use in test trials. The fish were anaesthetized and the transmitters were implanted following the methods of Moser et al. (2002a). The fish were allowed to recover from the surgical procedure for at least 12 h. All of these tests took place during the day and with 0.3 m of water flowing over the weir crest. We tested the following independent variables: presence or absence of radio transmitters and presence or absence of velocity refuges. Following experimentation, we removed the radio tags and released the fish upstream from Bonneville Dam.

Initial tests conducted in 2000 used the same pool-and-weir setup as in 1999 to validate previous findings (Table 3). All tests in 2000 were run with 0.3 m of water depth over the tops of weirs and all trials lasted for one hour. For the first set of tests in

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[1] Does not constitute endorsement by UICFWRU or NOAA Science Center.

2000, we observed passage behavior under three lighting conditions: 1) during the day with ambient light, 2) at night with the room lights (fluorescent) on, and 3) at night with infrared (IR) lights on. IR lights were placed at orifices and overflow sections of the fishway and they permitted observation of fish behavior using night-vision goggles and video cameras capable of recording IR images.

For the second set of tests, we added a 20.3 cm high step, similar to that found in the Bradford Island ladder at Bonneville Dam, just downstream from the middle weir's orifice. Fish behavior with the step was tested during the day and night with IR lighting (i.e., for each replicate the same group of fish were tested during the day and then at night as in 1999). Results from these trials were compared to results from the first set of trials without the step.

For the third set of tests, we removed the step and assessed passage behavior with a 1.2 m wide x 1.5 m long diffuser panel mounted in one of two positions upstream from the middle weir (Figure 4). In a working fishway, diffuser gratings are metal grids that make up the floor of the fishway between some weirs. Water upwells through these grates to supplement flow in the fishway. From radiotelemetry, we learned that areas with diffuser grating can impede lamprey passage, possibly because lamprey are unable to attach to grating material. In the experimental fishway, the diffuser grating was installed in two positions: adjacent to and just upstream from the middle weir, and midway between the second and third upstream weirs. With the gratings positioned adjacent to the middle weir, we also tested the efficiency of three different modifications: 1) no water flowing through the grate, 2) with a 15.2 cm x 30.5 cm mounted over the diffuser grating in the high flow section just upstream from the orifice. The plates provided an attachment area for lamprey moving through the orifice. All tests were replicated and each replicate group of fish was tested during day and night.

The second series of trials for 2000 involved removing the three weirs and installing a simulated count window in the experimental channel (Figure 5). In an operational fishway, fish are crowded into a narrowed, well-lit section of the fishway so that they can be counted at the viewing window. Water is added to the fishway near the count windows through a picketed lead from the auxiliary water channel (AWC). Spacing of the pickets allows lamprey access to the AWC, and once inside, lamprey may have difficulty exiting. Radiotelemetry indicated that lamprey have poor passage efficiency in sections of the Bonneville Dam fishways containing count windows. We hypothesized that lamprey avoided bright lighting at count stations and/or that fish got trapped in the AWC.

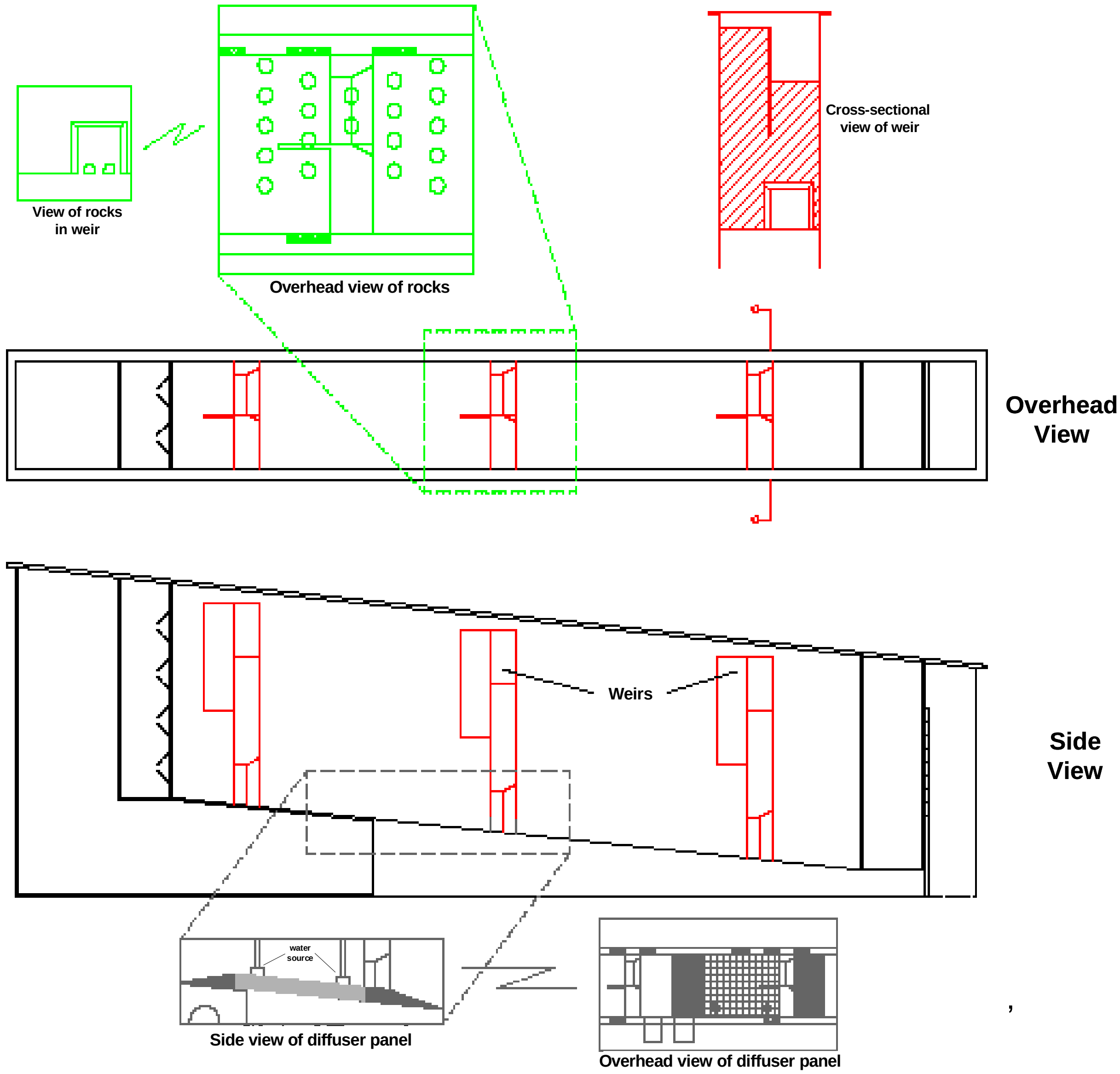

Figure 4. Diagram showing placement and structure of overflow weirs, orifices, a diffuser panel, and velocity refuges.

Table 1. Water velocities measured in the vicinity of the submerged orifice in the experimental pool-and-weir fishway with and without velocity refuges.

Treatment	Flow x cm off the bottom (m/s)				
Location	x = 5	x = 10	x = 23	x = 30	x = 46
Without refuges, 0 cm depth at overflow					
3 cm downstream of weir #1	-	2.35	-	2.19	-
3 cm upstream of weir #1	-	1.52	-	1.31	-
36 cm downstream of weir #2	-	1.83	-	-	-
3 cm downstream of weir #2	-	2.13	-	-	-
3 cm upstream of weir #2	-	1.83	-	1.37	-
With refuges, 0 cm of depth at overflow					
3 cm downstream of weir #1	-	1.07	-	1.92	-
3 cm upstream of weir #1	-	0.85	-	1.46	-
With refuges, 30 cm of depth at overflow					
30 cm downstream of weir #2	0.76	-	1.49	-	0.91
3 cm downstream of weir #2	0.73	-	2.68	-	0.0
3 cm upstream of weir #2	0.46	-	1.92	-	0.91
30 cm upstream of weir #2	0.85	-	2.68	-	0.24

Table 2. Water velocities measured within the vicinity of the overflow section of the experimental pool-and-weir fishway.

Treatment	Flow x cm off the bottom (m/s)				
Location	x = 5	x = 10	x = 15	x = 20	x =30
30 cm of depth at overflow					
46 cm downstream of weir #2	-	-	1.34	-	-
15 cm downstream of weir #2	0.46	1.49	1.07	-	-
center of weir #2	0.58	0.98	1.31	1.43	1.43
15cm upstream of weir #2	0.34	-	0.61	-	0.61

Table 3. Combinations of variables tested in the pool-and-weir experimental fishway at the Bonneville Dam AFF in 1999 and 2000 including diel timing, lighting conditions, trial duration, number of trial replicates, overflow depth, presence or absence of surgically implanted radio transmitters, velocity refuges, a step at one orifice, and a diffuser grating. Treatments with the same analysis group letter were compared statistically.

Time (D/N)	Lighting	Duration (h)	# of reps	Depth (m)	Radio	Refuges	Step (cm)	Diffuser Position	Diffuser flowing	Diffuser plate	Analysis group
						1999					
D	ambient	2	4	0.3	-	no	-	-	-	-	a
N	IR	2	4	0.3	-	no	-	-	-	-	a
D	ambient	2	4	0.3	-	yes	-	-	-	-	a
N	IR	2	4	0.3	-	yes	-	-	-	-	a
D	ambient	2	4	0.4	-	no	-	-	-	-	a
N	IR	2	4	0.4	-	no	-	-	-	-	a
D	ambient	2	4	0.4	-	yes	-	-	-	-	a
N	IR	2	4	0.4	-	yes	-	-	-	-	a
D	ambient	1	4	0	-	no	-	-	-	-	b
N	IR	1	4	0	-	no	-	-	-	-	b
D	ambient	1	4	0	-	yes	-	-	-	-	b
N	IR	1	4	0	-	yes	-	-	-	-	b
D	ambient	1	2	0.3	no	yes	-	-	-	-	c
D	ambient	1	2	0.3	no	no	-	-	-	-	c
D	ambient	1	2	0.3	yes	yes	-	-	-	-	c
D	ambient	1	2	0.3	yes	no	-	-	-	-	c
						2000					
N	IR	1	4	1	-	-	-	-	-	-	d e f
D	ambient	1	8	1	-	-	-	-	-	-	d e f
N	room	1	4	1	-	-	-	-	-	-	d

Table 3. Continued

Time (D/N)	Lighting	Duration (h)	# of reps	Depth (m)	Radio	Refuges	Step (cm)	Diffuser Position	Diffuser flowing	Diffuser plate	Analysis group
N	IR	1	4	1	-	-	20.3	-	-	-	e
D	ambient	1	4	1	-	-	20.3	-	-	-	e
N	IR	1	4	1	-	-	-	weir	yes	none	f g
D	ambient	1	4	1	-	-	-	weir	yes	none	f g
N	IR	1	4	1	-	-	-	center	yes	none	f
D	ambient	1	4	1	-	-	-	center	yes	none	f
N	IR	1	4	1	-	-	-	weir	no	none	g
D	ambient	1	4	1	-	-	-	weir	no	none	g
N	IR	1	4	1	-	-	-	weir	yes	large	g
D	ambient	1	4	1	-	-	-	weir	yes	large	g
N	IR	1	4	1	-	-	-	weir	yes	small	g
D	ambient	1	4	1	-	-	-	weir	yes	small	g

To simulate a count window area, we divided the upstream half of the experimental section down the middle using a 2.4 m high solid wooden wall. A picketed lead was placed just downstream from and to one side of the divider to direct fish toward the narrowed, count window section (Figure 5). The count window area was lit using a bank of incandescent flood lights to simulate lighting conditions at a working count station. We ran tests with and without the picketed lead in place and with the count window lights on and off to determine the degree to which lamprey enter the AWC and whether or not they avoid the lighted count window (Table 4). Once again, tests were run both during the day and at night.

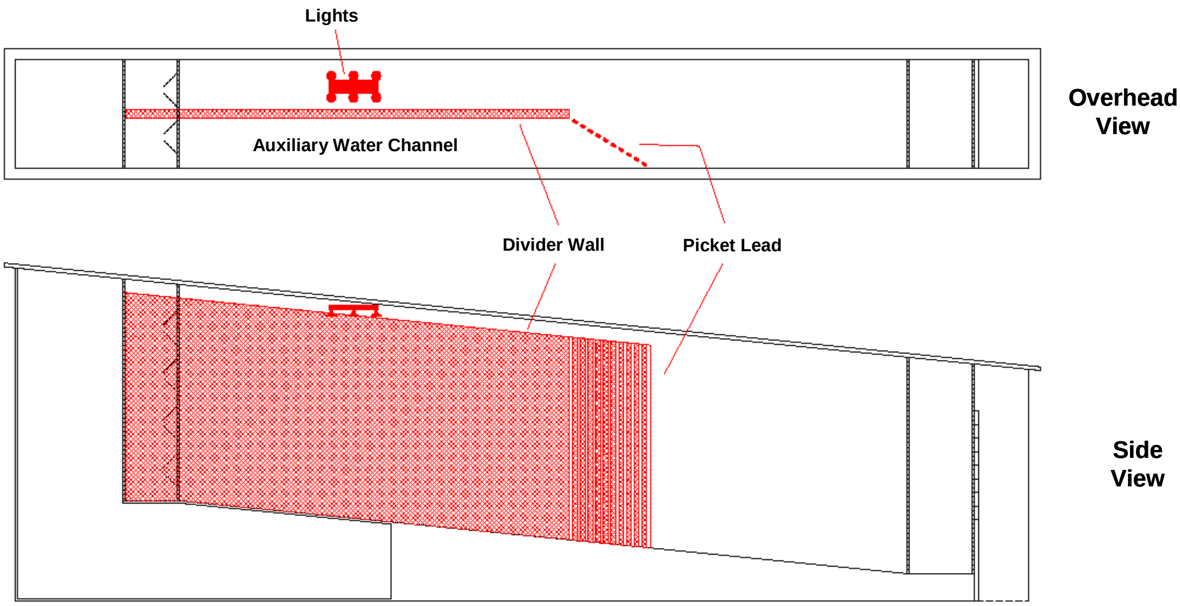

Figure 5. Diagram showing placement of count window lights, a divider, and picket lead weir.

Table 4. Count window tests performed in the experimental fishway at the Bonneville Dam AFF in 2000 including diel timing, trial duration, number of trial replicates, status of count window lights, and presence or absence of a picket lead weir.

Time	Duration (h)	# of Replicates	CW lights (on/off)	Picket Weir (in/out)
Night	1	4	On	In
Day	1	4	On	In
Night	1	3	Off	In
Day	1	3	Off	In
Night	1	4	On	Out
Day	1	4	On	Out

In 2002, we removed the count window structures, and installed a single vertical slot weir in the center of the fishway to simulate conditions at a fishway entrance (Figure 6). The entrance weir was 2.0 m high with a single 0.3 m wide vertical slot. Entrance tests compared efficiency of squared and rounded bulkheads while maintaining a 30.5 cm gap (Table 5). The rounded bulkhead circumscribed a circle with a diameter of 20.5 cm. These two designs were tested with 15.2, 30.5, and 45.7 cm of head differential at the weir. As in previous years, each replicate group of fish was tested during both day and night during these trials. Velocities at the entrance weir ranged from 0.7 – 3.3 m/s (Table 6).

We also tested the efficiency of two potential lamprey bypass options. The first involved the installation of a 0.6 m wide ramp (Figure 7) that led up and over the entrance weir and into an exit chute. Water upwelled from a headbox at the upstream end of the chute and flowed down the chute and ramp. A fyke net placed midway up the chute prevented fish from reentering the lower fishway after ascending the ramp and chute. Four different ramp designs were tested: 1) a steep uncovered ramp (13:2 slope), 2) a steep ramp with a cover situated 5.0 cm over the surface of the ramp, 3) a shallow uncovered ramp (1:1 slope), and 4) a shallow ramp with a cover. Lamprey could access the uncovered ramp at any point throughout the water column. The covered ramp, however, was only accessible via a 0.6 m wide by 5 cm high opening at the base of the ramp flush with the floor of the fishway. All tests were run with 0.5 m of head at the entrance weir and low, medium or high flows (0.3, 0.6, and 1.2 m/s within the exit chute) on the ramp.

These bypass tests involved the installation of a 2.4 m high divider which separated the vertical slot entry, the experimental section upstream from the entrance weir, and the exit section of the fishway (Figure 8). The volume of water available to one side of the fishway was reduced by placing dam boards just upstream from the exit section. Tests were run with 30.5 and 45.7 cm of head on the high flow side of the divider and 7.6 and 15.2 cm of head on the low flow side. We were unable to run tests with the highest flows (45.7 cm of head) on the high flow side and the lowest flows (7.6 cm of head) on the low flow side due to difficulties in maintaining the large flow differential. Once again, we ran tests both during the day and at night for each replicate group of fish.

Video tapes of each trial were used to determine passage times and modes of passage through key sections of the fishway. The entire cross-section of the fishway could not be monitored at any one time and individual fish could not be distinguished, therefore passage times were recorded for all upstream movements regardless of whether or not a single fish fell back and re-ascended. The times reported are the mean passage times for all fish that passed in front of the camera for a given replicate.

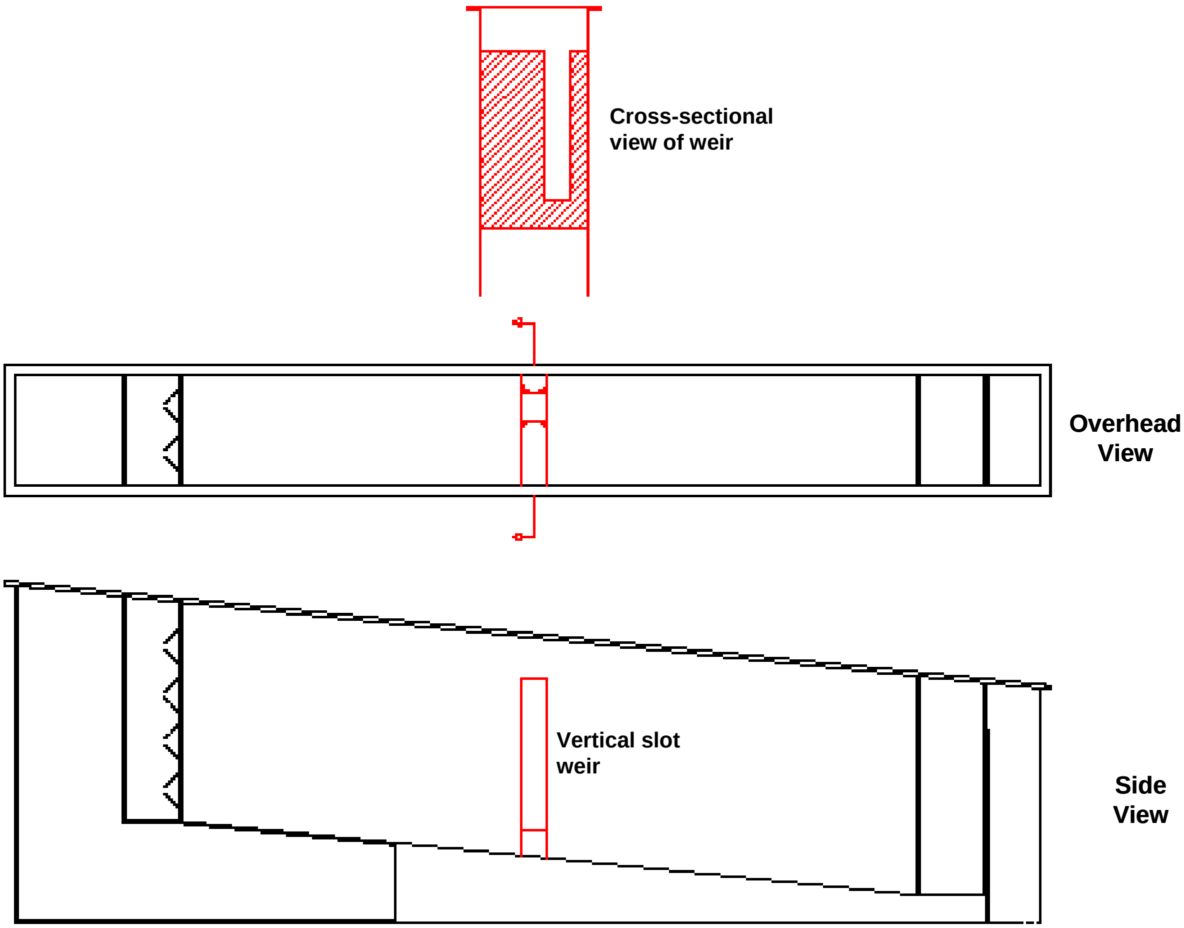

Figure 6. Diagram showing placement of a vertical slot weir with squared or rounded bulkheads.

Table 5. Combination of variables tested in the experimental fishway at the Bonneville Dam AFF in 2002 when an entrance weir was in place including diel timing, number of trial replicates, entrance bulkhead shape, whether or not the entrance was divided, head differential at the entrance, and ramp treatments. For slotted entrance tests, head levels are stated for both sides of the divider. All trials lasted for one hour.

Time	# of	Bulkhead	Divided	Head	Ramp		
(day/night)	reps	shape	Entrance?	(cm)	Type	covered?	flow
Bulkhead Shape Tests							
Day	4	squared	-	45.7	-		-
Night	4	squared	-	45.7	-	-	-
Day	4	squared	-	30.5	-	-	-
Night	4	squared	-	30.5	-	-	-
Day	4	squared	-	15.2	-	-	-
Night	4	squared	-	15.2	-	-	-
Day	4	rounded	-	45.7	-	-	-
Night	4	rounded	-	45.7	-	-	-
Day	4	rounded	-	30.5	-	-	-
Night	4	rounded	-	30.5	-	-	-
Day	4	rounded	-	15.2	-	-	-
Night	4	rounded	-	15.2	-	-	-
Slotted Entrance Test							
Day	4	rounded	Yes	45.7/15.2	-	-	-
Night	4	rounded	Yes	45.7/15.2	-	-	-
Day	4	rounded	Yes	30.5/15.2	-	-	-
Night	4	rounded	Yes	30.5/15.2	-	-	-
Day	4	rounded	Yes	30.5/7.6	-	-	-
Night	4	rounded	Yes	30.5/7.6	-	-	-
Ramp Bypass Tests							
Day	4	rounded	-	45.7	steep	no	low
Night	4	rounded	-	45.7	steep	no	low
Day	4	rounded	-	45.7	steep	no	med
Night	4	rounded	-	45.7	steep	no	med
Day	4	rounded	-	45.7	steep	yes	med
Night	4	rounded	-	45.7	steep	yes	med
Day	4	rounded	-	45.7	shallow	no	med
Night	4	rounded	-	45.7	shallow	no	med
Day	4	rounded	-	45.7	shallow	yes	high
Night	4	rounded	-	45.7	shallow	yes	high

Table 6. Water velocities measured at the simulated fishway entrance.

Treatment	Flow x cm off the bottom (m/s)		Flow at the surface (m/s)
Location	x=10	x = 40	
Squared Bulkheads, 15.2 cm of head			
2cm upstream of weir	1.22	0.91	0.73
2cm downstream of weir	1.16	1.58	1.55
2.4m downstream of weir	0	0.37	1.19
Squared Bulkheads, 30.5 cm of head			
2cm upstream of weir	1.62	1.55	0.85
2cm downstream of weir	1.92	2.35	2.29
2.4m downstream of weir	0	0.34	1.52
Squared Bulkheads, 45.7 cm of head			
2cm upstream of weir	2.07	1.37	0.76
2cm downstream of weir	2.47	2.99	2.87
2.4m downstream of weir	0	0.79	2.38
Rounded Bulkheads, 15.2 cm of head			
2cm upstream of weir	1.19	0.73	0.91
2cm downstream of weir	2.29	2.07	1.83
2.4m downstream of weir	0	0.33	0.73
Rounded Bulkheads, 30.5 cm of head			
2cm upstream of weir	1.37	1.1	1.04
2cm downstream of weir	2.77	2.1	1.89
2.4m downstream of weir	0	0.58	1.07
Rounded Bulkheads, 45.7 cm of head			
2cm upstream of weir	1.86	1.25	0.55
2cm downstream of weir	3.32	2.8	-
2.4m downstream of weir	0	0.49	0.64

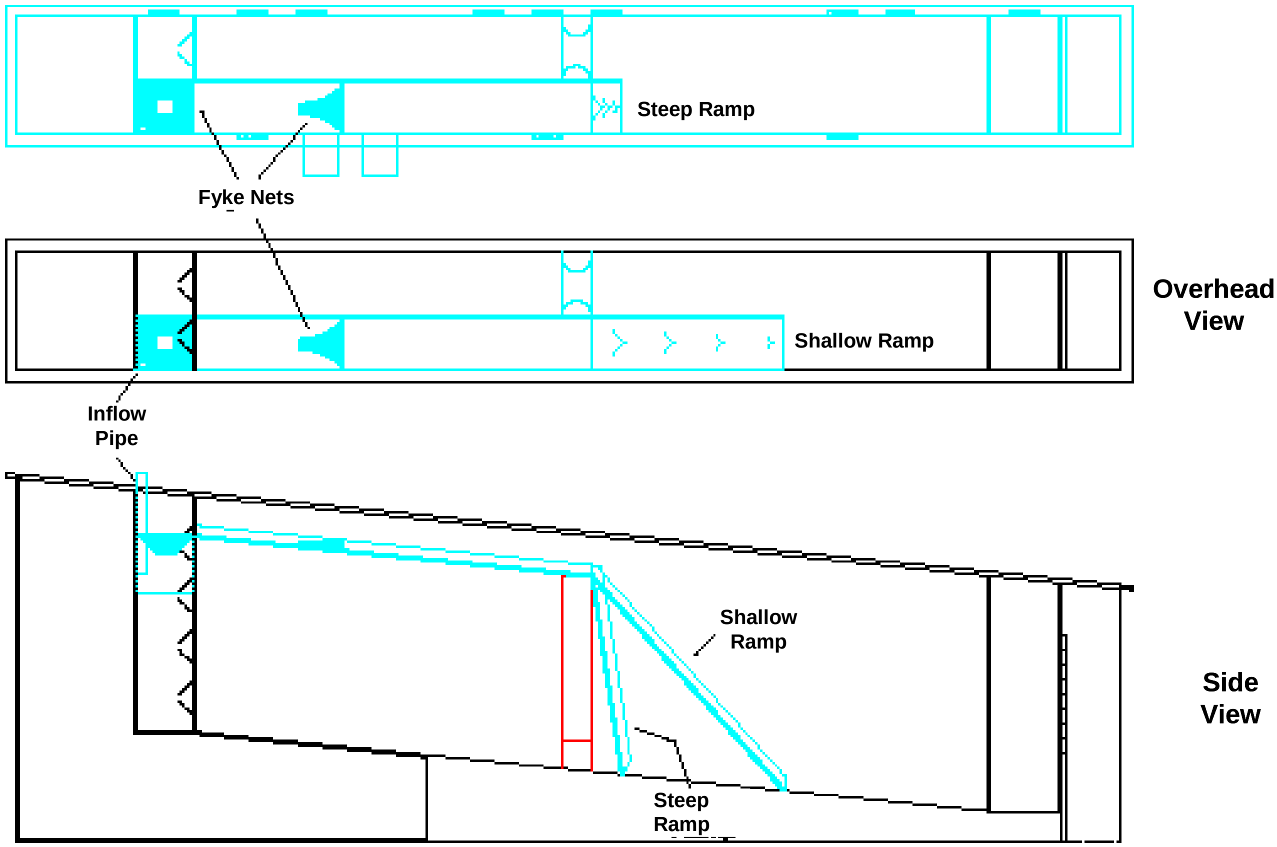

Figure 7. Diagram showing placement and structure of a steep and a shallow bypass ramp.

Data Analysis

We used multiway factorial analysis of variance (ANOVA, Proc GLM, SAS Institute Inc., 2001) to determine the effect of different factors on passage efficiency. Statistically significant factors were then analyzed using a Tukey-type multiple comparison test to reveal specific differences among treatments (Zar,1999). Treatment groups were compared using Kruskal-Wallis nonparametric analysis of variance when the data failed to fit model assumptions. When time of day had a significant interactive effect with other factors being analyzed, the analyses were rerun separately for day and night tests. A separate ANOVA was used to determine differences between groups of naïve fish and those that had been used in previous trials. Use was included in the overall model when it had a significant effect on passage success. Multifactorial analysis of variance (MANOVA) was used to analyze the count window experiments because we were interested in determining whether treatments had a significant effect on the channel selected by individual lamprey. Since fish were used in more than one trial.

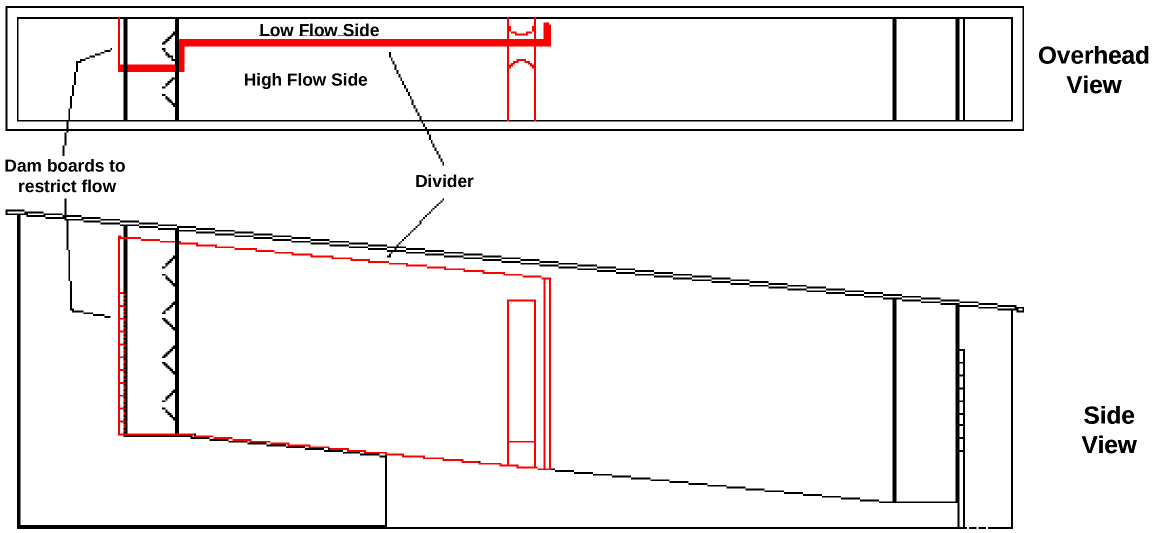

Figure 8. Diagram showing placement of a vertical slot entrance, a divider, and dam boards used to differentially control flow through two portions of the entrance weir.

Results

Pool-and-Weir Fishway Tests

In pool-and-weir tests, we completed 120 trials using 625 total fish. For individual trials, the percentage of fish that successfully passed all three weirs ranged from 0.0 to 100.0% with a mean of 68.9% and a median of 78.9%. Fish passing via the submerged orifice took between 1 s and 43.3 min; those passing over the top of the weir took from 1 s to 8.4 min. Times to pass through the entire fishway ranged from 5.2 to 87.0 min. Sixty-nine percent and 63 % of the naïve fish and those that were used in previous trial successfully passed all three weirs and there was no significant difference between these values ($F_{(1,52)}$ = 1.25, p = 0.2690)

The first set of trials ran for two hours each. Passage efficiencies for seven of the eight treatment groups were at least 90.0%. For the eighth treatment group, during the day with 0.3 m of depth at the overflow and no velocity refuges in place, passage efficiencies ranged from 60.0 to 90.0% (Figure 9). There were no significant differences in passage success among the eight different treatment groups as indicated by the Kruskal-Wallis test, a nonparametric analysis of variance (χ^2 = 10.63, p = 0.1554). Median passage efficiencies were 95.0% during the day and 100% at night. When refuges were absent, 95.0% of lamprey successfully passed all three weirs, whereas 100% of lamprey passed when refuges were in place. Median passage efficiencies were 100% when the depth of water running over the weir crests was 0.3 and 0.4 m. Overall, lamprey took a mean of 46.3 min to pass through the fishway without refuges and 35.7 min to pass through the fishway when refuges were in place (t = 3.37, p = 0.0004; Table 7). During daytime trials with 0.4 m of depth, lamprey took 3.0 min (mean) to pass without refuges in place and 3.7 min to pass when refuges were present (t = -0.97, p = 0.1697; Table 8). Because IR lighting was not used in 1999, very few lamprey were observed passing the weir at night. Of the lamprey that were observed passing during daytime trials, 28.6% passed over the top of the weir when no refuges were present and 13.8% passed over the top of the weir when refuges were in place (χ^2 = 1.84, p = 0.1753).

When we shortened the trial length to one hour and lowered the depth of water within the fishway so that no water flowed over the weirs, overall mean passage efficiencies were 68.4% and there were no significant differences among treatment groups (Figure 10; $F_{(3,12)}$ = 0.33, p = 0.8035). When refuges were absent, 65.5% of lamprey successfully passed all three weirs and 71.3% of lamprey passed when refuges were present. Highly turbid conditions prevented observations during night trials. During day trials, fish passed the submerged orifice in 2.4 min in the absence of refuges and 1.0 min when refuges were present (t = 3.16, p = 0.0014; Table 8). Fish took 39.0 min to pass through the entire fishway when no refuges were present and 34.2 min with refuges at the center weir (t = 1.14, p = 0.1300; Table 7).

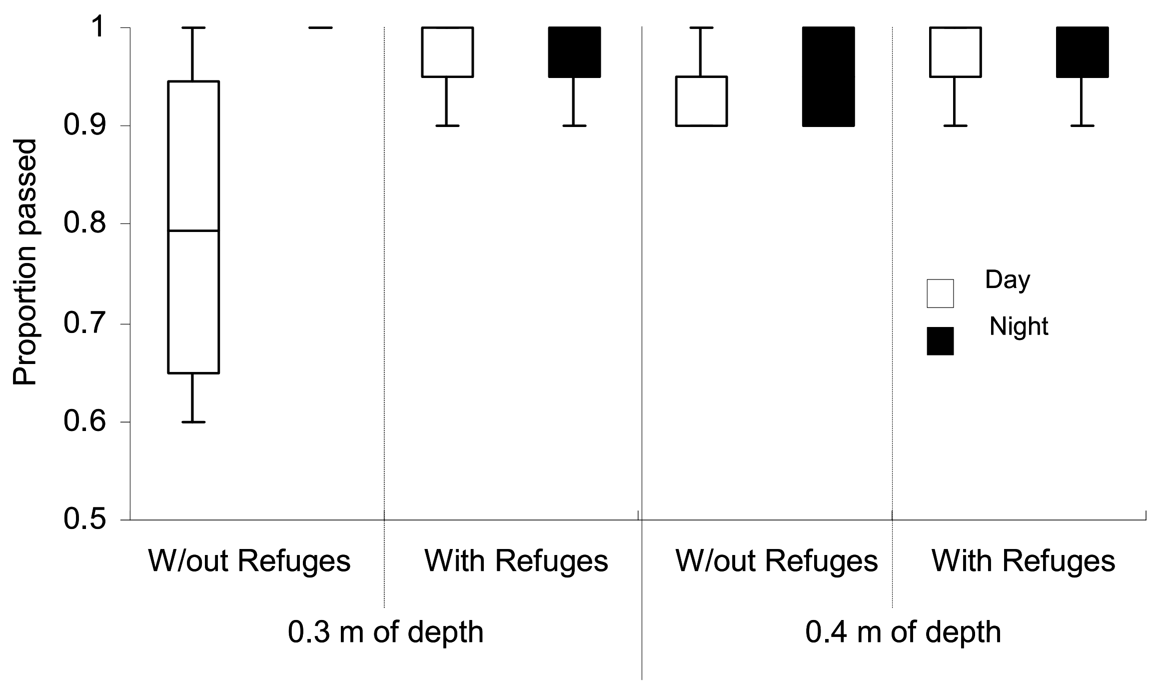

Figure 9. Box plot showing the distribution of passage efficiencies for groups of fish passing through an experimental fishway with and without velocity refuges placed around submerged orifices, during the day and at night with two water levels. The following quartiles are plotted (from bottom to top): minimum, lower quartile, median, upper quartile, and maximum.

Table 7. Mean time to pass through the pool-and-weir fishway from removal of the intake screen until fish passed the third upstream weir in 1999 and 2000.

	Total mean passage time (min)			
	Daytime		Nighttime	
Treatment	n	mean (±sd)	n	mean (±sd)
1999				
30.5 cm of depth, w/o refuges	19	56.7±18.9	4	46.5±3.3
30.8 cm of depth, w/ refuges	35	42.1±19.3	12	33.8±10.4
39.6 cm of depth, w/o refuges	15	47.7±12.5	18	34.2±15.1
39.6 cm of depth, w/ refuges	19	28.4±12.2	3	15.4±2.1
0 cm of depth, w/o refuges	29	39.0±14.8	34	39.7±15.0
0 cm of depth, w/ refuges [1]	21	34.2±14.4	-	-
Untagged	17	32.2±13.9	-	-
Radio tagged	16	32.4±17.1	-	-
2000				
Nighttime w/ IR lights	-	-	19	39.3±9.3
Nighttime w/ room lights	-	-	24	40.7±10.9
Daytime (ambient light)	35	45.1±11.3	-	-
Step @ center weir[2]	-	-	-	-
Diffuser	10	40.5±10.7	16	35.5±14.6
Diffuser (no flow)	2	41.4±18.6	9	49.0±13.0
Diffuser w/ 30.5 cm plate	8	41.5±11.1	24	28.9±10.8
Diffuser w/ 15.2 cm plate	15	37.0±12.0	25	36.4±12.2
Diffuser (centered)	0	-	17	41.4±9.2

1. No observations at night due to turbid water conditions.
2. All observations focused on lip at second upstream weir.

In eight trials where we tested the effect of surgically implanting radio transmitters into lamprey, mean passage efficiencies were 76.3% and there were no significant differences among any of the four treatment groups (Figure 11; $F_{(3,4)} = 0.60$, $p = 0.6503$). Eighty percent of fish with surgically implanted radio transmitters successfully passed all three weirs and 72.5% of fish without transmitters had successful passage. Times to pass a single weir ($t = 0.61$, $p = 0.2739$; Table 8) and time to pass through the fishway ($t = 0.02$, $p = 0.4904$; Table 7) were similar among treatment groups. Untagged lamprey took 3.9 min to pass the second upstream weir and 32.2 min to pass through the fishway and radio-tagged lamprey took 3.5 and 32.4 min.

Manipulating the lighting in the AFF had a significant effect on passage success ($F_{(2,13)} = 5.66$, $p = 0.0171$; Figure 12). During the day, with ambient light conditions, the mean passage rate was 57.8%. This was significantly lower than the passage rate for fish at night using only infrared light (91.8%) according to a post hoc Tukey-type multiple comparison test. During nighttime trials, with the AFF room lights illuminated, 60.0% of fish successfully passed through the fishway. This was not significantly different from daytime trials or nighttime trials with infrared lighting.

Table 8. Mean time to pass a submerged orifice or an overflow weir in 1999 and 2000. All observations occurred at the second upstream weir. Times were calculated from the first time a lamprey came into camera view until it completely passed over the weir or through the orifice.

	Time to pass weir (min)							
	Submerged Orifice				Overflow			
	Daytime		Nighttime		Daytime		Nighttime	
Treatment	n	mean (±sd)	n	Mean (±sd)	N	mean (±sd)	n	mean (±sd)
1999								
30.5 cm of depth, w/o refuges [1]	-	-	-	-	-	-	-	-
30.8 cm of depth, w/ refuges	13	4.8±3.2	7	2.7±1.7	8	1.2±1.7	5	0.2±0.2
39.6 cm of depth, w/o refuges	25	3.0±2.6	5	1.3±1.3	10	0.6±1.0	2	0.2±0.2
39.6 cm of depth, w/ refuges	24	3.7±2.5	0	-	4	0.9±1.4	2	0.2±0.0
0 cm of depth, w/o refuges	24	2.4±1.7	0	-	0	-	0	-
0 cm of depth, w/ refuges	18	1.0±0.9	0	-	0	-	0	-
Untagged	17	3.9±1.6	-	-	4	0.4±0.4	0	-
W/ radio tag	9	3.5±1.7	-	-	5	0.5±0.4	0	-
2000								
Nighttime w/ IR lights	-	-	11	4.1±2.4	-	-	0	-
Nighttime w/ room lights	-	-	27	2.8±1.0	-	-	1	1.5
Daytime (ambient light)	39	3.4±2.0	-	-	4	0.6±0.8	-	-
Step @ center weir	8	3.8±3.1	9	5.1±8.0	3	0.1±0.1	0	-
Diffuser	11	4.7±6.0	17	8.7±8.9	7	1.5±3.1	0	-
Diffuser (no flow)	3	15.9±23.7	12	9.7±10.8	2	0.3±0.2	0	-
Diffuser w/ 30.5 cm plate	7	8.6±11.7	20	3.7±2.5	8	0.3±0.4	0	-
Diffuser w/ 15.2 cm plate	6	3.2±3.0	15	3.4±2.5	5	0.1±0.1	0	-
Diffuser (centered)	-	-	12	4.5±3.6	-	-	0	-

1. Trials were not videotaped.

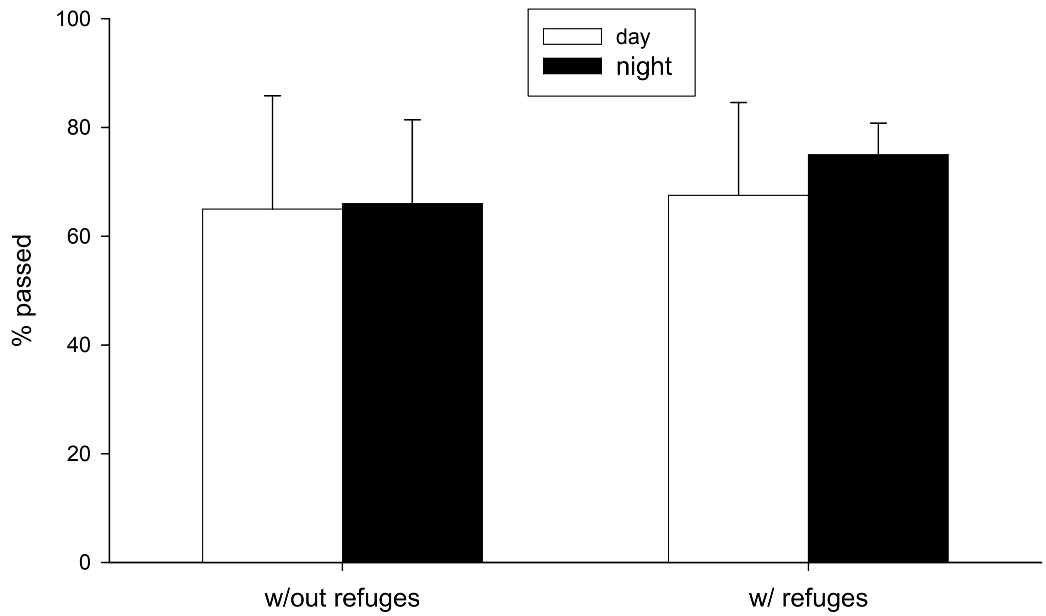

Figure 10. Mean percentage of lamprey that successfully passed a simulated fishway during one-hour long daytime and nighttime trials in 1999 with and without velocity refuges in place at the orifices when no water was flowing over the tops of the weirs.

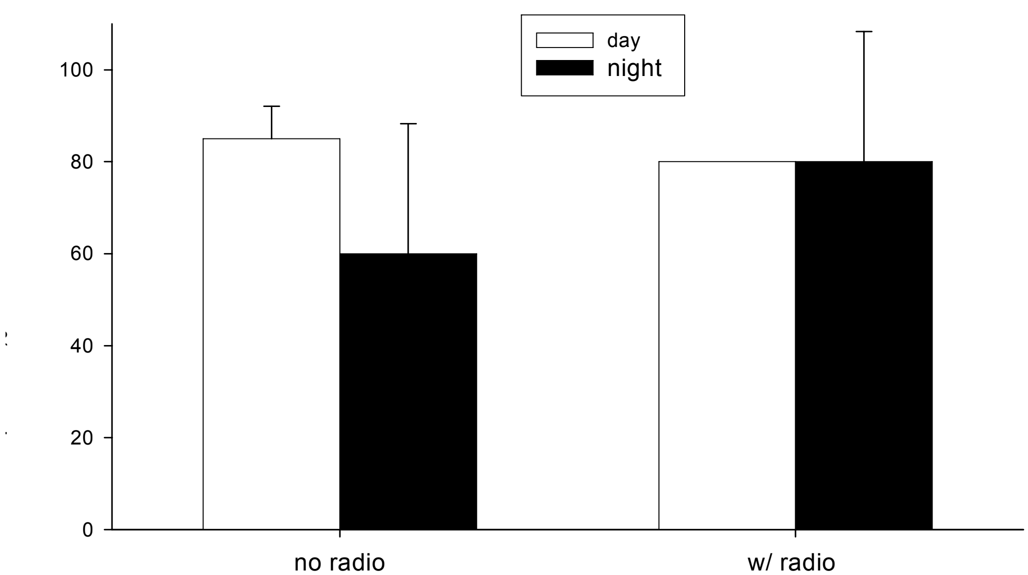

Figure 11. Mean percentage of lamprey that successfully passed a simulated fishway during one-hour trials with and without surgically implanted radio transmitters.

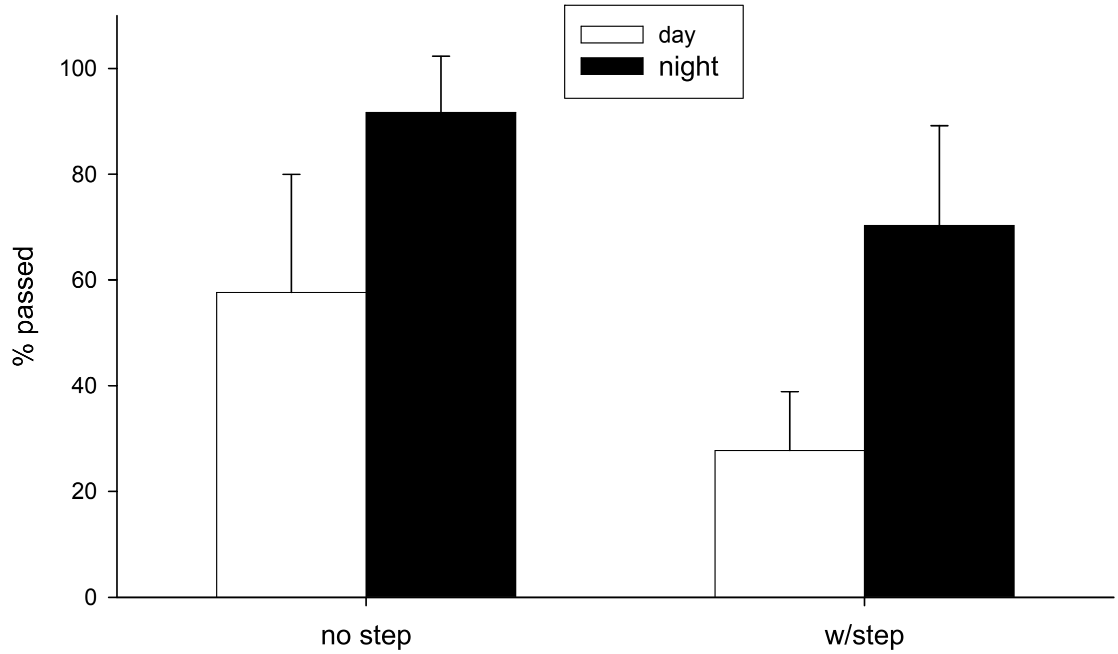

Figure 12. Mean percentage of lamprey that successfully passed a simulated fishway during the day with ambient lighting and at night with fluorescent room lights and with infrared lighting.

During 20 day and night trials to test the effect of adding a step downstream from the middle weir's orifice, there were significant differences among the four treatment groups ($F_{(3,16)}$ = 8.77, p = 0.0011; Figure 13). Mean passage efficiencies were 48.9% when the step was in place and 69.1% when the step was absent ($F_{(1,16)}$ = 9.26, p = 0.0077). Mean times to pass the submerged orifice were 3.6 min in the absence of a step and 4.5 min when the step was present (t = 0.93, p = 0.1779; Table 8).

When the diffuser grating was in place and adjacent to the center weir, the mean passage time through the downstream orifice was 7.1 min as opposed to 3.6 min in the absence of the diffuser (t = 3.79, p = 0.0001; Table 8). During daytime trials, a significantly higher proportion of lamprey were observed passing via the overflow when the diffuser was in place (χ^2 = 7.51, p = 0.0061). Overall passage time through the entire fishway was not significantly longer (t = 0.97, p = 0.1671) with a diffuser present (37.4 min) than when it was absent (43.3 min) (Table7). Time of day had a significant effect on passage rate ($F_{(5,22)}$ = 3.88, p = 0.0113; Figure 14); more fish passed during nighttime trials (83.5%) than daytime trials (49.3 5%; $F_{(1,22)}$ = 13.40, p = 0.0005). The addition of a diffuser grate did not significantly effect passage rates in either of the two positions tested ($F_{(1,22)}$ = 1.34, p = 0.2818); 69.1% of lamprey passed when no grate was in place, 52.5% passed when the diffuser was just upstream of the middle weir, and 67.6% passed when the grate was centered between the second and third upstream weir.

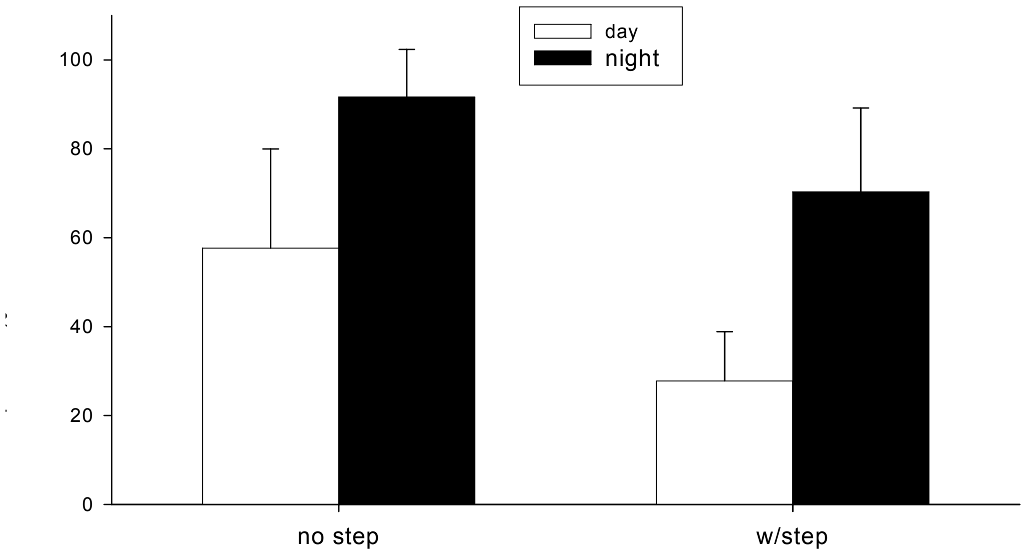

Figure 13. Mean percentage of lamprey that successfully passed a simulated fishway during one-hour day and night trials with and without the presence of a step adjacent to and downstream from one of the orifices.

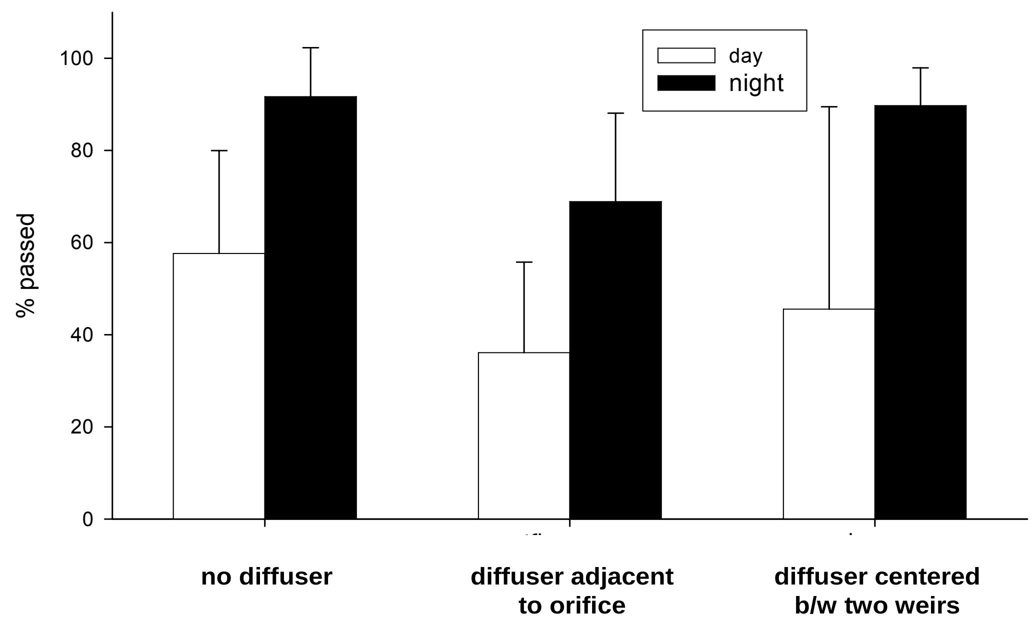

Figure 14. Mean percentage of lamprey that successfully passed through a simulated fishway during one-hour day and night trials with no diffuser grating, with a diffuser placed adjacent to and upstream from the second upstream weir, and with a diffuser centered between the second and third upstream weirs.

Passage times through the downstream orifice decreased from 7.1 min to 3.4 min when a 15.2 cm plate (t = 2.05, p = 0.0231; Table 8) was attached to the diffuser just upstream from the orifice. Passage times were 5.0 min when a 30.5 cm plate (t = 1.08, p = 0.1436; Table 8) was added in this same location. Total passage times through the entire fishway decreased from 37.3 min to 32.1 min with the addition of the 15.2 cm plate (t = 1.61, p = 0.0567; Table 7) and were 36.6 min with the 30.5 cm plate (t = 0.25, p = 0.4015; Table 7).

In 32 day and night trials to test the effects of eliminating flow through the base of the grate or adding solid plates to the grating adjacent to the orifice, there were significant differences in passage efficiency among the eight treatment groups ($F_{(7,24)}$ = 9.48, p < 0.0001; Figure 15). Although there were significant differences among the experimental treatments ($F_{(3,24)}$ = 6.56, p = 0.00210), none of the modifications significantly increased the passage rate. Without modifications, 52.5% of fish passed all three weirs, 57.4% passed when a 15.2 cm long plate was in place, 60.6% passed when a 30.5 cm plate was in place, and 21.3% passed when no water was pumped through the grate. A Tukey-type multiple comparison test revealed that the no flow treatment was the only treatment that produced a significant effect.

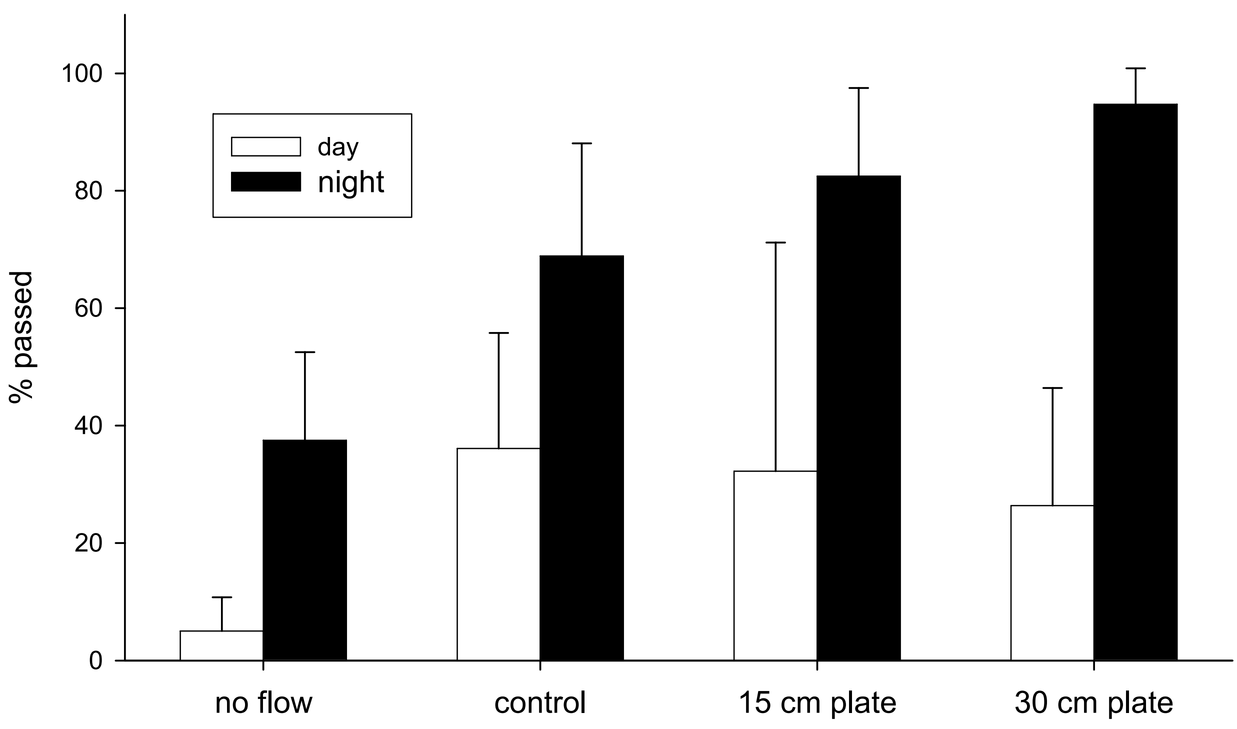

Figure 15. Mean percentage of lamprey to successfully pass through a simulated fishway during one-hour day and night trials with a diffuser grating placed adjacent to and upstream from the second upstream weir (control), with no water flowing through the diffuser, with a 15 cm solid plate attached to the diffuser adjacent to the orifice, and with a 30 cm solid plate attached to the diffuser adjacent to the orifice.

Count Window Tests

Results from a MANOVA test on 22 trials with the count window setup indicated that time of day, presence of count window lights, and a picketed lead had no significant effect on which side of the divider fish chose to swim through (Figure 16). During daytime trials, 35.7% passed on the count window side and 17.4 % passed on the auxiliary side. There was no significant difference ($F_{(1,8)} = 0.20$, $p = 0.6670$) in passage rates between trials with naïve fish and those with fish that had been used in previous trials. At night, 28.2 % passed via the count window and 25.6 % passed via the auxiliary side (*Wilk's* $\Lambda = 0.95$, $F_{(2,15)} = 0.38$, $p = 0.6913$). Thirty percent of the 56.7% of fish that passed did so via the count window side when the count window lights were off, and 32.6% (of 52.1%) when the lights were on (*Wilk's* $\Lambda = 0.98$, $F_{(2,15)} = 0.15$, $p = 0.8589$). When the picketed lead was in place, 33.7% of fish passed on the count window side and 25.2% passed on the auxiliary side. When the lead was removed, 28.8% passed on the count window side and 15.0% passed on the auxiliary side (*Wilk's* $\Lambda = 0.93$, $F_{(2,15)} = 0.57$, $p = 0.5752$).

Entrance Tests

We completed 28 tests evaluating lamprey behavior at simulated fishway entrances, consisting of 112 separate trials that used a total of 879 fish. For individual trials, passage efficiency ranged from 0 to 100%. Fish took from 1 s to greater than 16 min to pass the entrance bulkhead. For the bulkhead shape tests, day and night trials were analyzed separately because there was a significant interaction between time of day and head level ($F_{(2,36)} = 8.04$, $p = 0.0013$). At high head levels (i.e. 45.7 cm), passage efficiencies were low (≤ 10%) regardless of the time of day. Passage rates were significantly higher for trials with naïve fish (mean = 34.2%; $F_{(1,24)} = 7.13$, $p = 0.0130$) than for trials with fish that had been used in previous trials (21.3%).

During nighttime trials, passage success varied among the different treatments ($F_{(11,12)} = 12.14$, $p < 0.0001$; Figure 17). Mean passage rates were 32.5% with squared bulkheads and 50.8% with rounded bulkheads ($F_{(1,12)} = 8.98$, $p = 0.0110$). Sixteen lamprey took a mean of 3.0 min to pass the squared bulkhead, and 32 lamprey took 1.4 min to pass the rounded bulkhead. Water velocity, determined by head differential, significantly affected passage success ($F_{(2,12)} = 49.39$, $p < 0.0001$). Mean passage efficiencies were 78.5%, 42.5%, and 4.0% at night when there was 15.2, 30.5, and 45.7 cm of head at the entrance weir. Each of these were significantly different based on post hoc comparisons using Tukey's HSD test. Twenty-four lamprey passed through the entrance in 0.8 min with 15.2 cm of head (Table 9) and the same number of fish took 3.8 min on average with 30.5 cm of head. No lamprey were recorded passing through the entrance when there was 45.7 cm of head.

During daytime trials, there were no significant overall differences among treatment groups ($F_{(11,12)} = 0.95$, $p = 0.5331$; Figure 17). Mean passage rates were 11.7% when squared bulkheads were in place and 15.8% with rounded bulkheads in place. Eight different lamprey that successfully passed the squared entrance bulkhead did so in an average of 5.2 min, and 13 lamprey passed the rounded bulkhead in 2.8 min. With head levels of 15.2, 30.5, and 45.7 cm, passage efficiencies were 22.5%, 17.5% and 1.3%. Nine lamprey passed the entrance bulkhead in an average of 0.6 min when there was 15.2 cm of head (Table 9). When there was 30.5 cm of head, 12 lamprey passed in 6.6 min. No lamprey were observed passing the bulkhead when there was 45.7 cm of head, so passage time could not be determined for this treatment.

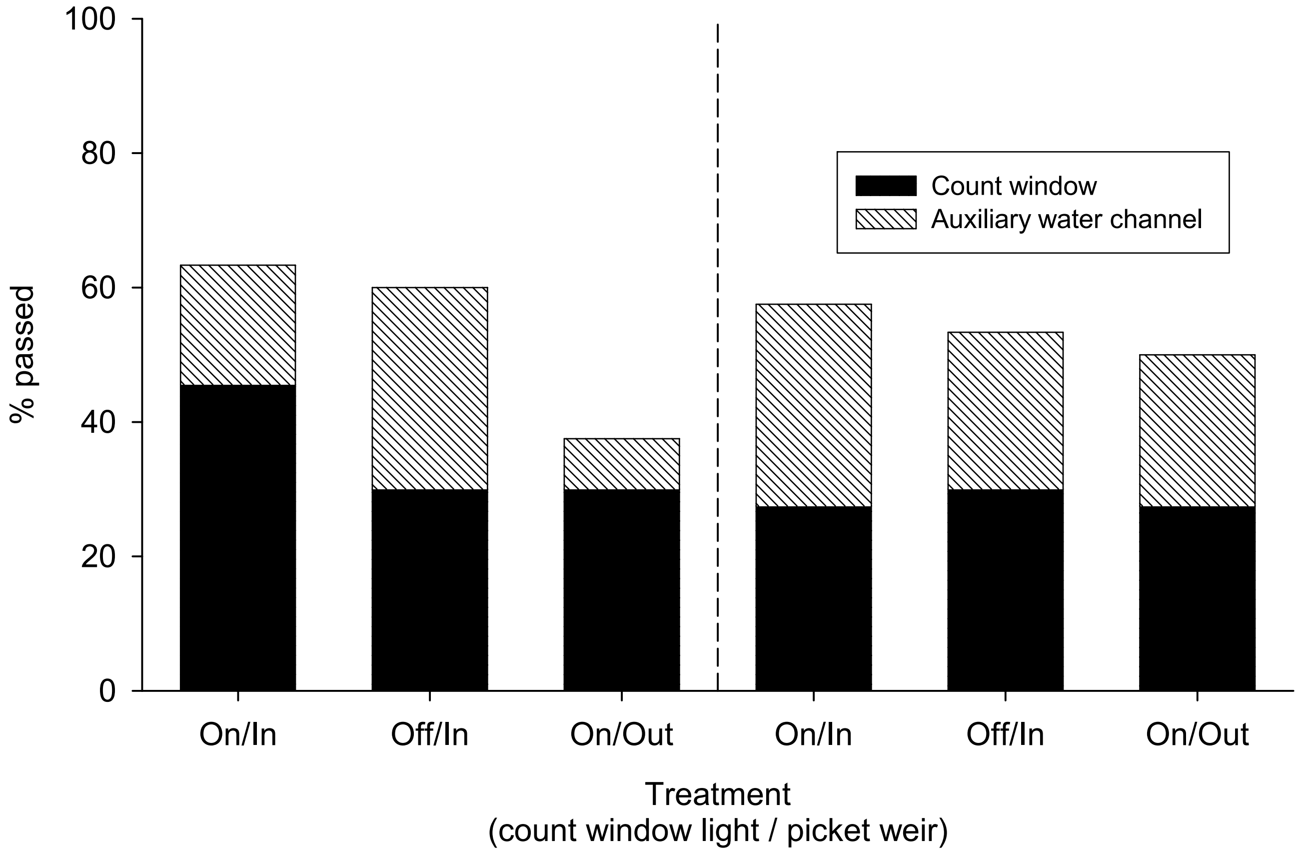

Figure 16. Mean percentage of lamprey that successfully passed through a simulated count window and the proportion of lamprey that passed on each side of divider during one-hour day and night trials with (In) and without (Out) the presence of a picketed lead and with count window lighting on and off.

Table 9. Mean time to pass a simulated entrance weir in 2002. Times were calculated from lamprey entry into the camera view until it completely passed the entrance weir.

Treatment	n	Time to pass entrance weir (min) Day mean (±sd)	n	Night mean (±sd)
Square, 45.7 cm of head	0	-	0	-
Square, 30.5 cm of head	5	7.1±4.1	5	6.0±6.1
Square, 15.2 cm of head	3	0.8±1.0	11	1.3±1.7
Round, 45.7 cm of head	0	-	0	-
Round, 30.5 cm of head	7	4.9±5.4	19	2.4±2.5
Round, 15.2 cm of head	6	0.3±0.4	13	0.3±0.5
Divided, 45.7/15.2 cm of head	8	0.6±1.4	14	0.6±0.7
Divided, 30.5/15.2 cm of head	12	0.6±0.6	23	0.3±0.4
Divided, 30.5/7.8 cm of head	9	0.9±1.0	25	0.3±0.6

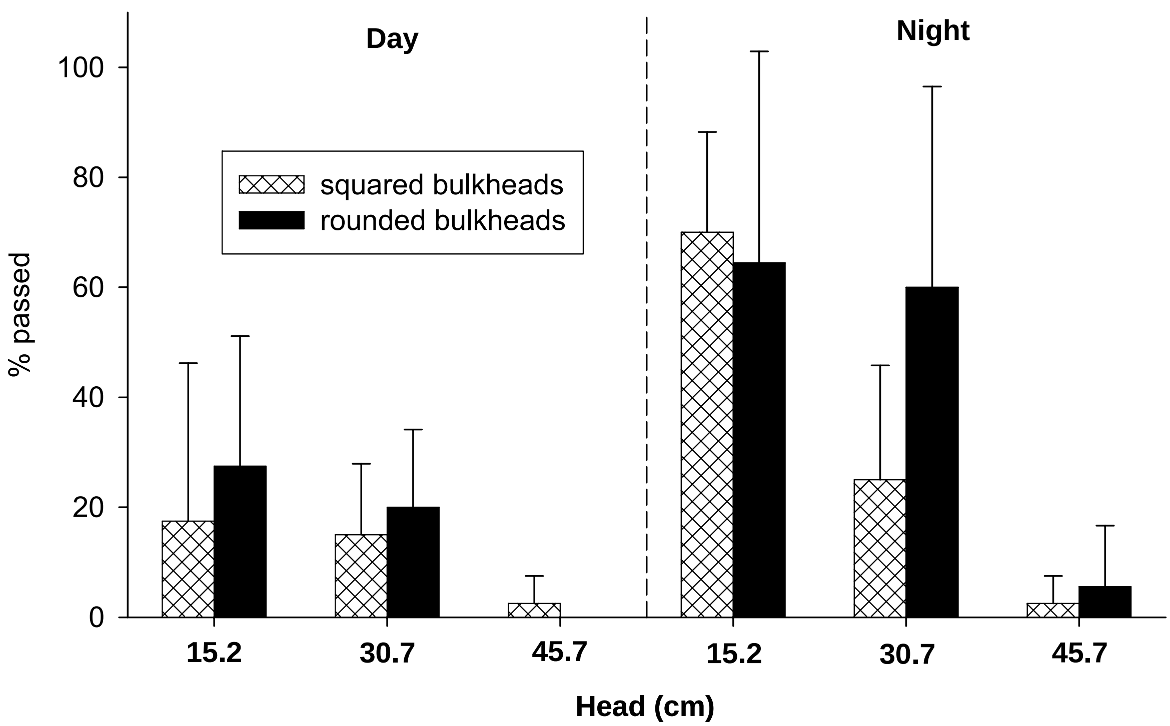

Figure 17. Mean percentage of lamprey that successfully passed a simulated fishway entrance during one-hour day and night trials with squared or rounded bulkheads and 15.2, 30.5, and 45.7 cm of head at the entrance.

The presence of a divider that provided a low flow section on one side of the simulated entrance (15.2 cm versus 30.5 cm of head) significantly increased passage success when compared to trials with rounded bulkheads only ($F_{(1,32)}$ = 17.91, p = 0.0002; Figure 18). Passage efficiencies were 29.0 and 57.1% during day and night trials and these values were significantly different ($F_{(1,32)}$ = 15.30, p = 0.0004). An average of 21.4% of the fish successfully passed the weir when no divider was in place, compared to 57.5% that passed when the divider was in place. Thirty-six lamprey passed the entrance bulkhead in 3.7 min when the divider was absent, and 91 lamprey passed the bulkhead via the low flow side in 0.5 min when the divider was present (Table 9). No attempts were made to observe the fish that passed on the high flow side when the divider was in place.

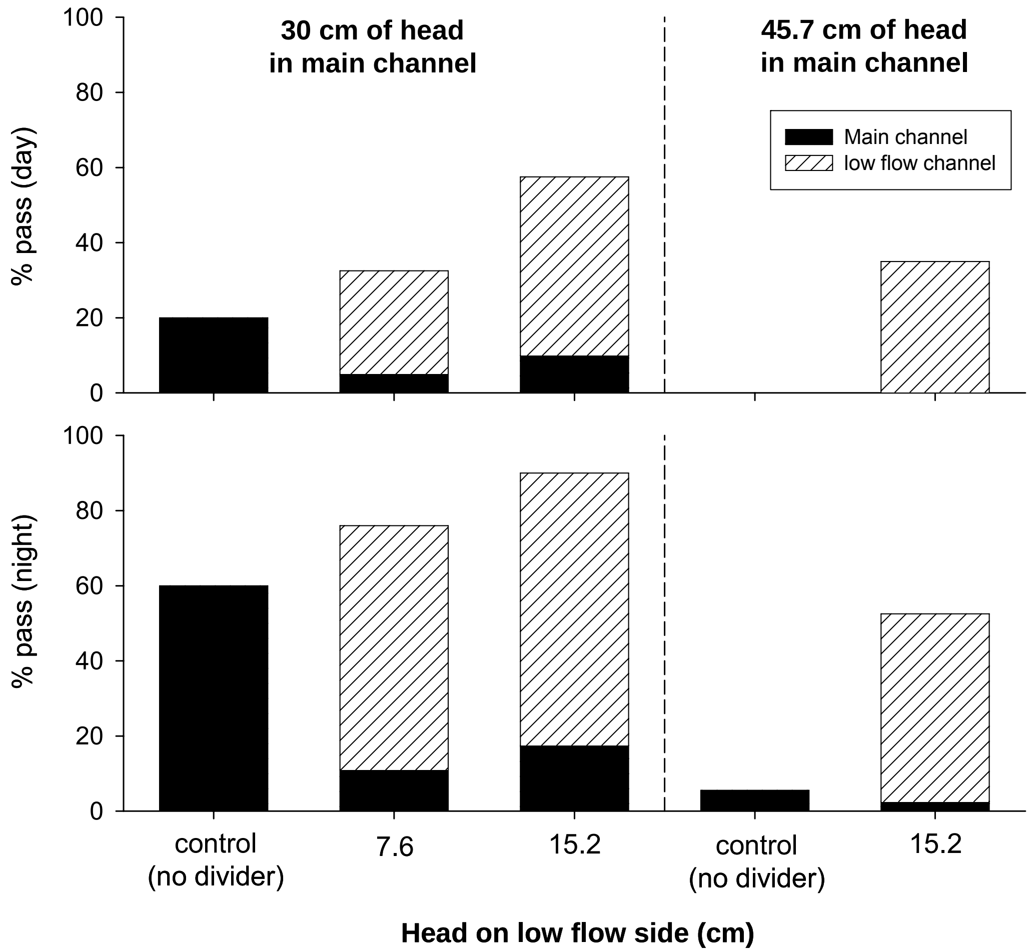

Figure 18. Mean percentage of lamprey that successfully passed a divided fishway entrance and the percentage of fish that passed on each side of the divider during one-hour day and night trials under five different flow treatments: with no divider in place and 30.5 or 45.7 cm of head at the entrance, with 30.5 cm of head on the high flow side and 7.6 or 15.2 cm of head on the low flow side, and with 45.7 cm of head on the high flow side and 15.2 cm of head on the low flow side.

In 23 out of 24 trials in which fish passed the entrance when the divider was present, a significantly higher percentage of fish successfully passed via the low flow side (85.6%; $p < 0.025$, χ^2 test; Figure 18). Overall passage rates were higher during night trials (73.3%) than day trials (41.7%; $F_{(1,18)} = 10.83$, $p = 0.0055$). There were no significant differences in passage efficiency among the three velocity treatments tested ($F_{(2,18)} = 3.31$, $p = 0.0598$); 43.8% of lamprey passed the entrance weir when there was 15.2 cm of head on the low flow side and 45.7 cm of head on the high flow side, 55% passed with 7.6 cm and 30.5 cm of head, and 73.8% passed with 15.2 cm and 45.7 cm of head. Because tests could not be run with 7.6 cm of head on the low flow side and 45.7 cm of head on the high flow side it was not possible to test for interactions between flows on each side of the divider.

In 40 trials with a ramp in place that allowed passage up and over the entrance weir, not a single lamprey used the ramp for passage during the 1 h tests. During preliminary trials we placed lamprey on the ramp and they climbed it without difficulty. However, when water was flowing through the entrance bulkhead, lamprey were not attracted to the base of the ramp. Increasing the amount of water flowing down the ramp provided no additional reaction from the fish within the 1 h duration of these tests

Discussion

General Discussion

We made several critical assumptions throughout this study. We assumed that lamprey used in trials were representative of the general population, although all fish were collected as they passed by an overflow weir. To help account for this, we blocked the corresponding submerged orifice while the trap was in place. We also assumed that both hydraulics and fish behavior were similar in experimental and existing fishways and that fish behavior was unaffected by handling.

Results from this study suggest that lamprey have difficulty passing fishway structures. The single most important factor affecting passage success appeared to be water velocity. Reducing flows at entrances produced the most notable improvement in fish movement. Pacific lamprey have critical swimming speeds of about 0.85 m/s (Mesa et al.,2003). Velocities at fishway entrances approach and exceed 2.0 m/s (Clay,1995), surpassing the swimming abilities of these fish. In these high flow areas, lamprey attach to the substrate with their suctorial disc, surge forward, and then reattach. Consequently, lamprey passage may be difficult in high flow, or turbulent areas that lack suitable attachment points. Having relatively smooth surfaces for attachment in high velocity areas and gradual transitions to high flow are important design considerations for lamprey passage structures. Lamprey are most vulnerable in the time between attachments. Any rapid changes in water velocity or direction can easily change a fish’s trajectory and prevent it from reattaching. Without a quick reattachment, the fish are often swept downstream to areas of low velocities where they can re-orient.

Pool-and-Weir Type Fishways

The addition of velocity refuges within orifices decreased the amount of time that fish took to pass through the orifice and increased the proportion of fish which made use of the orifice. Although overall passage rate was unaffected by the addition of refuges, the passage efficiency was quite high in all of the trials; without refuges in place, 92% of lamprey successfully passed all three weirs in two-hour trials, and 66% of lamprey passed in one-hour trials. Also, the modification was made to one of three weirs in the test ladder. Had all three weirs been modified, a measurable improvement in passage times may have been realized. Adding refuges to the orifices seemed to allow more fish to pass via the orifice. These fish that may have passed over the top of the weir in the absence of refuges. Adding refuges reduced flows at the base of the orifice from about 2 m/s to 1 m/s. As noted above, providing lower velocity avenues for passage appears to be beneficial for adult lamprey. Similar strategies have been used successfully in other fishways. Bunches of plastics bristles affixed to the base of the Isohaara fishway in the Kemijoki River in Northern Finland were used to reduce flows through the vertical slot section (Laine,2001) and aid in the passage of European river lamprey, *L. fluviatilis*. Also, groups of hard plastic bristles or natural or synthetic branches have been used on sloped ramps to aid in upstream migration of catadromous eel (Clay,1995). In these designs, the elvers wormed their way up the ramp in much in the way a snake would climb a slope.

Few lamprey passed a weir using the overflow section, although those that did so passed the weir quicker than those passing via the submerged orifice. Average passage times for fish as they passed over the top of the weir were 38 s, whereas fish passing through the orifice took an average of 3 min 20 s to do so. However, times were only calculated for fish that successfully passed the weir and do not include fish that may have attempted to pass but were pushed downstream and out of view of our cameras. Fish attempting to pass via the overflow rarely made multiple attempts to do so. It appears that fish that did not pass on the first try generally sought other routes to pass. Also, bubbles near the surface made it difficult to view a fish through its entire passage and therefore it was difficult to determine when a fish first arrived at the weir top.

Lamprey passage did not appear to be affected by the presence of surgically implanted radio transmitters. Times to pass a weir were similar for tagged and untagged fish, and more tagged fish successfully passed all three weirs than untagged fish. In studies on swimming performance of tagged and untagged fish by Mesa et al. (2003), lamprey with surgically implanted radio transmitters had significantly lower critical swimming speeds (81.5 ± 7.0 and 86.2 ± 7.5 cm/s respectively), however the difference was minor and may not have produced biologically significant differences in our tests.

Lamprey were reliably more active at night, with highest levels of activity when only the IR lights were in use. This finding is consistent with the nocturnal nature of lamprey behavior (HardistyPotter,1971). Pacific lamprey have also exhibited high levels of nighttime activity in radiotelemetry studies (Moser et al.,2002a).

Passage was inhibited by the presence of a step at the base of orifices. Our observations indicated that lamprey usually approach orifices along the base of the fishway. When they get to a point where they can no longer move forward, they quickly attach to the substrate (generally the fishway floor). When a step is in place, lamprey approaching along the floor must swim up and over a lip and through a large current differential. When attempting to pass over the lip, most of their forward momentum is perpendicular to the flow of water. Lamprey appear to have difficulty redirecting that momentum and re-attaching to the fishway flow before getting pushed downstream. At Bonneville Dam, orifices in the Washington Shore fishway are designed with orifices situated flush against the floor of the floor of the fishway, whereas at the Bradford Island ladder orifices are raised by approximately 20 cm. In our experiments, we placed a step at only one of the three weirs and presence of the step significantly decreased overall passage success. We believe that the cumulative effect of having a step at each and every orifice would have an even greater impact on lamprey passage. Repositioning the orifice or ramping the floor of the fishway downstream from existing orifices may aid lamprey in passing through this section of the Bradford Island ladder. Radiotelemetry studies (Moser et al.,2002a; Moser et al.,2002b; Moser et al.,2005) found little difference between mean annual passage efficiency for lamprey entering the Bradford and Washington shore ladders, however, passage efficiencies were relatively high (>75%) in this portion of the fishway compared to other areas.

Diffuser gratings on the floor of the fishway can be a significant obstacle to lamprey, especially when grates span the entire floor between consecutive weirs. In places with diffusers, lamprey cannot attach to the floor. Although the numbers of lamprey successfully passing through the experimental fishway were similar with and without a diffuser in place, lamprey passed through a single downstream orifice in as little as half the time when the diffuser was absent. With the installation of a 15.2 cm solid plate over the diffuser, passage times through the orifice were similar to those when the diffuser was absent. There may have been a more significant effect on passage rate if the diffuser had spanned the entire space between two consecutive weirs. The diffuser was tested in two positions: adjacent to the downstream, and centered between two weirs. The two main areas of concern are the upstream side of the downstream orifice and the downstream side of the upstream orifice. This experiment tested for the former but not the latter condition.

Count Window Area

We tested two hypotheses regarding lamprey passage at count window areas: 1) lamprey exhibit negative phototaxis and avoid the lighted count window area, and 2) lamprey enter the AWC which is lacking outlet designed for fish passage. Once inside the AWC, fish can exit by swimming back downstream, passing through vents in the wall that separate the auxiliary side from the flow control section of the fish ladder, or by moving directly into the forebay through passage over or under the Tainter gate at the upstream end of the AWC (Moser et al. 2003).

In our tests we determined whether fish were actively avoiding the lighted count window and to what extent fish were gaining access to the AWC though a picketed lead. We found that lamprey were not avoiding the count window lights, as the percentage of fish using each side of the fishway was unrelated to lighting treatment. However, approximately half of the lamprey used in each trial entered the AWC even when the picket lead weir was in place. Lamprey easily passed through the 2 cm spacing between the bars of the picketed lead. In our tests, lamprey appeared to enter whichever side they came to first. These experiments may be underestimating the problem because our count window setup was greatly simplified. In our design, the AWC and the count window channel each accounted for half of the flume's width. At Bonneville Dam, the constricted count window area is about 1 m wide, or 7% of the fishway width at this location. This difference greatly increases a lamprey's likelihood of first coming in contact with the picket lead and directly entering the AWC.

Fishway Entrances

Compared to the other structures we tested, lamprey seem to have the most difficulty at fishway entrances. With conditions similar to those currently found at main fishway entrances at the lower Columbia River dams (approximately 45.7 cm of head and squared bulkheads), no more than 1 out of 10 lamprey successfully passed the entrance weir in any given one hour trial. Radio telemetry has shown higher entrance success at dams, however, fish generally take longer than one hour to enter fishway after first approach (Moser et al.,2005). The extra flow and turbulence found at fishway entrances can be a critical deterrent to lamprey passage. Lamprey congregate outside fishway entrances in large numbers, further suggesting that these entrances block or delay lamprey passage. Flows at these entrances tend to be high – upwards of 2.4 m/s – in order to attract upstream migrating adult salmonids.

In our experiments, head level had a significant effect on lamprey passage. Decreasing the head level at the entrance by 15.2 cm increased nighttime passage rates by 39%. An additional drop in head of 15.2 cm raised the percentage of fish with successful passage by another 36%. Lamprey are largely nocturnal, as opposed to salmonids which tend to be active primarily during the day. Modulating flows during the night could potentially aid lamprey entry without impacting listed salmonids. However, preliminary tests of this idea that were done using radio-tagged lamprey gave no indication that reducing flow at night was effective at the Bonneville Dam spillway entrances (Moser et al. 2002a). Further testing is warranted, as sample sizes for the initial tests were quite low.

An alternate solution may be to provide structural modifications at entrances. In our study, we found that rounding an entrance bulkhead can improve the number of lamprey passing that entrance and lower the time an individual fish takes to pass the weir. Nighttime passage rates increased by 18% when rounded bulkheads were in place. The spillway entrances at Bonneville Dam have already been modified with rounded bulkheads. Radio tracking of adult lamprey at these entrances after the modifications were made further indicated that rounding entrance bulkheads improves lamprey entrance success (Moser et al. 2002a, Moser et al. 2003).

Lamprey Bypasses

Designing a fishway to effectively accommodate both lamprey and salmonids may not be feasible. Rather than completely restructuring the existing fishway to accommodate lamprey passage, a more reasonable option may be to develop a separate fishway to aid lamprey passage. One of the primary questions in developing such a fishway is how to separate lamprey from other species, such as salmon, steelhead, and shad. Lamprey are unique in their ability to squeeze through small spaces, in their willingness and ability to ascend vertical, or near-vertical structures, and in their nocturnal lifestyle. These differences in behavior might be exploited when designing lamprey-specific structures that permit lamprey to enter without negative effects to other species.

We first tested the concept of reducing flows through one portion of the fishway entrance in order to determine whether lamprey would find and use the lower flow channel. Using a solid divider to split the channel within and upstream from the vertical slot weir, we were able to test passage performance under a variety of different flow combinations. In all situations, there were significant improvements in passage as compared to when the divider was not in place. We found that a majority of the lamprey passed via the low velocity side when that option was available. For a system like this to work, it appears as though the actual difference between the flows on each side of the divider is critical. When there were large differences between the velocities, there was a slight drop in overall passage, suggesting that it may have been difficult for lamprey to locate the lower flow channel. We manipulated velocities by restricting the amount of water flowing into the low flow channel. This will be difficult in a full-scale fishway. A reasonable alternative might be to install an extra series of weirs on the low flow side of a divider, thus lowering the head differential and flow velocity at each individual weir.

In this study, lamprey did not use the ramp designed to bypass a fishway entrance. Results from these tests were inconclusive because lamprey were either not attracted to the ramp or that the lamprey required longer than one hour to begin ascending the ramp. In 2004, we tested the use of another ramp design and ran tests overnight for eight hours. Greater than 87% of lamprey used in these trials successfully ascended the ramp, however, on average fish took 1.85 h to begin ascending the ramp and only 25 % of fish did so within one hour. Lamprey can and do climb vertical ramps, but may do so only as a last resort. When placed on the ramp, lamprey ascended without difficulty. Different placements of a ramp-type entrance may prove more successful. Future bypass research should likely focus on determining optimal ramp placement and configuration for effectively attracting lamprey to base of the ramp.

References

Beamish, R. J., 1980. Adult biology of the river lamprey (*Lampetra ayresi*) and the Pacific lamprey (*Lampetra tridentata*) from the Pacific coast of Canada. Canadian Journal of Fisheries and Aquatic Sciences, 37:1906-1923.

Beck, L., 1995. Fish behavior at submerged orifices, overflow weirs, and vertical slots in the fish ladder at Bonneville second powerhouse 1993 - 1994. U.S. Army Corp of Engineers special report. Report number CENPP-OP-SRF. 44 pp.

Bell, M., 1990. Fisheries Handbook of Engineering Requirments and Biological Criteria, 3rd edition. US Army Corps of Engineers, North Pacific Division., Portland, Oregon.

Clay, C. H., 1995. Design of fishways and other fish facilities, 2nd edition. CRC Press, Inc., Boca Raton, Florida.

Close, D. A., M. Fitzpatrick, H. Li, B. Parker, D. Hatch, and G. James, 1995. Status report of the Pacific lamprey (*Lampetra tridentata*) in the Columbia River Basin. 1995 Status Report, Report to Bonneville Power Administration. Report number DOE/BP-39067-1. For Project number 94-026. 40 pp.

Hardisty, M. W., and I. C. Potter, editors, 1971. The biology of lampreys. Academic Press, London, New York.

Haro, A., and B. Kynard, 1997. Video evaluation of passage efficiency of American shad and sea lamprey in a modified Ice Harbor fishway. North American Journal of Fisheries Management, 17:981-987.

Jackson, A. D., D. R. Hatch, B. L. Parker, and D. A. Close, 1997. Pacific lamprey research and restoration. 1997 Annual Report for Bonneville Power Administration. Report number DOE/BP-39067-3. For Project number 1994-026. 97 pp.

Kostow, K., 2002. Oregon lampreys: Natural history status and problem analysis. Report by Oregon Department of Fish and Wildlife. 112 pp.

Laine, A., 2001. Restoring salmonid stock in boreal rivers: Problems of passage at migratory obstructions and land-derived loading in production areas. University of Oulu, Oulu Finland.

Mesa, M. G., J. M. Bayer, and J. G. Seelye, 2003. Swimming performance and physiological responses to exhaustive excercise in radio-tagged and untagged Pacific lamprey. Transaction of the American Fisheries Society, 132:483-492.

Moser, M. L., A. L. Matter, L. C. Stuehrenberg, and T. C. Bjornn, 2002a. Use of an extensive radio reciever network to document Pacific lamprey (Lampetra tridentata) entrance efficiency at fishways in the lower Columbia River, USA. Hydrobiologia, 483:45-53.

Moser, M. L., P. A. Ocker, L. C. Stuehrenberg, and T. C. Bjornn, 2002b. Passage efficiency of adult Pacific lamprey at hydropower dams on the lower Columbia River, USA. Transaction of the American Fisheries Society, 131:956-965.

Moser, M. L., D. A. Ogden, and C. A. Peery, 2005. Migration Behavior of adult Pacific lamprey in the Lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2002. Report to the US Army Corps of Engineers, Portland District. 65 pp.

Osborne, M. F. M., 1961. The hydrodynamic performance of migratory salmon. Journal of Experimental Biology, 38:365-390.

Zar, J. H., 1999. Biostatistical Analyses, 4th edition. Prentice-Hall, Inc., Upper Saddle River, New Jersey.