Radiotelemetry Investigations of Adult Pacific Lamprey Migration Behavior: Evaluation of Modifications to Improve Passage at Bonneville Dam, 2000

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EXECUTIVE SUMMARY

Hydropower dams on the Columbia River may contribute to declines in abundance of Pacific lamprey *Lampetra tridentata* by restricting access of adults to historical spawning locations. From 1997 to 1999, we used radiotelemetry to examine passage of adult lamprey through specific areas at Bonneville, The Dalles, and John Day Dams. These studies indicated that lamprey have the greatest difficulty entering the fishways (particularly at spillway entrances) and passing through collection/transition areas and count stations at these dams. The objectives of our research in 2000 were

1) to assess general behavior, passage success, and migration rates of radio-tagged adult lamprey,

2) to evaluate the effects of lights at fish count stations on lamprey passage at night,

3) to evaluate effects of lower water velocities and structural modifications at the Bonneville Dam spillway entrances on lamprey entrance efficiency,

4) to determine fate of lamprey overwintering in the lower Columbia River, and

5) to monitor the movement and distribution of radio-tagged adult lamprey released upstream from The Dalles Dam.

We captured 733 adult lamprey in traps at Bonneville Dam and surgically implanted 349 of them with radio transmitters: 271 with a 7.7-g transmitter and 78 with a 4.5-g transmitter. Of these fish, 299 were released approximately 3 km below Bonneville Dam and 50 were released 15 km upstream from The Dalles Dam. For fish released below Bonneville Dam, median travel time from release to first detection at the dam was 6.4 d, and there was no effect of tag size on travel time.

The percentage of radio-tagged lamprey that approached Bonneville Powerhouse 2 was lower than in previous years, probably due to reduced discharge from Powerhouse 2 in 2000. Overall passage efficiency (the percentage of lamprey that passed over the dam of those that approached the dam) at Bonneville Dam was slightly higher than in previous years (47%). Median time from the first detection outside a fishway entrance to the last detection at the ladder exit was 4.4 d.

Lamprey were most active at the fishway entrances during the night, and individual fish often made multiple entrances. As in previous years of this study, entrance success was lowest at orifice entrances. Periodic closures of the orifice gates at Powerhouse 1 had no apparent effect on lamprey entrance success at Powerhouse 1. Entrance success at the spillway entrances in 2000 was higher than in previous years of

study. Reducing velocity during the night at these entrances did not appear to improve entrance efficiency. Consequently, improvement in entrance efficiency at the Bradford B-Branch entrance may be attributed to structural modifications to the bulkhead adjacent to this entrance (it was rounded to provide more attachment areas for lamprey).

Intensive monitoring of the count station area at the tops of both the Bradford and Washington-shore fish ladders indicated that lamprey were not obstructed by lighting from the count windows. Lighting experiments at the Adult Fish Facility count window in 2000 also indicated that lamprey did not avoid count station lights. However, we found that lamprey were delayed and fell back most frequently in the serpentine weir sections of the count station. Further study is needed to determine why this area is an obstacle for adult lamprey.

The fate of Pacific lamprey that do not get over the hydropower dams is unknown. We documented the upstream migration of some Pacific lamprey after they had overwintered in the Columbia River main stem. Further study is needed to determine whether a significant number of lamprey are able to migrate above the dams in their second year in freshwater and to determine the fate of the large number of fish that were not relocated again after failing to pass over Bonneville Dam.

CONTENTS

INTRODUCTION

Pacific lamprey *Lampetra tridentata* abundance in the Columbia River basin has declined dramatically in recent years. This parasitic, anadromous lamprey occurs along the coast of western North America from Alaska to southern California (Scott and Crossman 1973). In the Columbia River, adult lamprey undertake a free-swimming, spawning migration into fresh water during late spring and summer, and lamprey abundance has historically been monitored by counting adults as they pass viewing stations located in fishways at hydropower dams.

While these lamprey counts are not an accurate means of estimating absolute abundance, they provide a good measure of relative abundance patterns (Starke and Dalen 1995). Comparison of counts made at dams in the lower and middle Columbia River revealed a fourfold to tenfold decrease in yearly abundance during the past four decades (Close 2001). In addition, concerns that lamprey are declining have prompted recent commercial harvest restrictions in the Willamette River, a tributary of the Columbia River (T. Rien, Oregon Department of Fish and Wildlife, pers. commun.).

Hydropower dams on the Columbia River may have contributed to declines in lamprey abundance by restricting access to historical spawning locations. While the distribution of lamprey spawning sites in upriver areas prior to dam construction is not well documented, there are historical accounts of lamprey in the headwaters of both the Columbia and Snake Rivers (Kan 1975; Hammond 1979; Simpson and Wallace 1982). Lamprey must pass four hydropower dams to reach the confluence of the Columbia and Snake Rivers, and up to five additional dams to attain spawning areas in the upper reaches of these rivers.

We have used radiotelemetry to establish that passage of lamprey at the lower Columbia River dams is significantly lower than that of salmonids. For example, less than half of the radio-tagged lamprey that approached Bonneville Dam in 1997-1999 were able to successfully pass upstream (Vella et al. 2001; Ocker et al. 2001), whereas passage efficiency for salmonids is typically greater than 90% (Bjornn et al. 2000a, b).

In 1997-1999, we used radiotelemetry to examine passage of adult Pacific lamprey through specific areas within the fishways at Bonneville, The Dalles, and John Day Dams. Over the past decade an extensive array of fixed-site radio receivers and antennas has been established on and around these dams to assess adult salmonid passage at discrete areas in each fishway (Moser et al. in press a). We used this receiver array to document passage success of radio-tagged lamprey at each area and to identify obstacles to lamprey passage.

Specific areas where lamprey are obstructed or delayed were identified as fishway entrances, collection/transition areas at the bottom of the fishways, and count station areas at the top of the fishways (Ocker et al. 2001). In contrast, lamprey exhibited relatively rapid and successful passage through the pool and weir sections of the fishways where they were exposed to rapid currents.

The goal of lamprey radiotelemetry research in 2000 was to assess lamprey passage and to evaluate measures taken to improve lamprey passage at the lower Columbia River dams. The specific objectives of this research were

1) to assess general behavior, passage success, and migration rates of radio-tagged adult Pacific lamprey,

2) to evaluate effects of count station lighting on lamprey passage at night,

3) to evaluate effects of lower water velocities and structural modifications at the Bonneville Dam spillway entrances on lamprey entrance efficiency,

4) to determine fate of lamprey overwintering in the lower Columbia River, and

5) to monitor the movement and distribution of radio-tagged adult lamprey released upstream from The Dalles Dam.

METHODS

Study Area

We collected and radio tagged adult lamprey at the Adult Collection and Monitoring Facility on the Washington shore of Bonneville Dam, river kilometer (RKm) 235. We released radio-tagged fish approximately 3 km downstream from the dam at the Hamilton Island boat ramp on the Washington shore (RKm 231) and at the mouth of Tanner Creek (RKm 232) on the Oregon shore (Fig. 1). In 2000, we also released fish from two locations approximately 15 km above The Dalles Dam (RKm 308): at Wishram on the Washington shore and at Celilo Park on the Oregon shore.

At Bonneville Dam, there are two powerhouses oriented perpendicular to river flow, with a spillway between them (Fig. 1). A complex system of fishways allows fish to pass at the southern powerhouse (PH1), at the spillway, and at the northern powerhouse (PH2). At The Dalles Dam, fish may pass upstream via a fishway adjacent to the spillway on the north shore (North Fishway), or via a complex system of entrances and collection channels that lead to a fishway at the powerhouse (East Fishway, Fig. 2). John Day (RKm 347) and McNary (RKm 467) dams have similar fishway configurations: one fishway is adjacent to the spillway on the north shore (North) and one is at the powerhouse on the south shore (Figs. 3 and 4). At all dams, fish can also pass upstream during operation of the navigation locks; however, we monitored lamprey passage via this route only at Bonneville Dam (Fig. 1).

Lamprey passage was monitored by fixed-site receivers located on each dam (Figs. 1-4), at the dam tailraces, and at the mouths of major tributaries. Receiving stations in the tailraces and in tributaries had a scanning receiver with a Yagi aerial antenna. At the dams, receiving stations had digital spectrum processors coupled with a scanning receiver and one or more underwater coaxial cable antennas (range < 9 m) to receive transmissions on a number of frequencies simultaneously. These receivers were strategically positioned to allow assessment of passage through discrete areas of the fishways: entrances, collection channels, transition areas, ladders, and counting stations.

Both the outside and inside of each fishway entrance was monitored by at least one antenna. Collection channels were defined as the areas between a fishway entrance and the pool and weir sections of the fishway. Transition areas were defined as the pool and weir sections of the fishway that were inundated by tailwater, while ladders were pool and weir areas not inundated by tailwater. Counting stations, usually near the top of the ladders, allow enumeration of all fish passing through the ladder. Counting stations

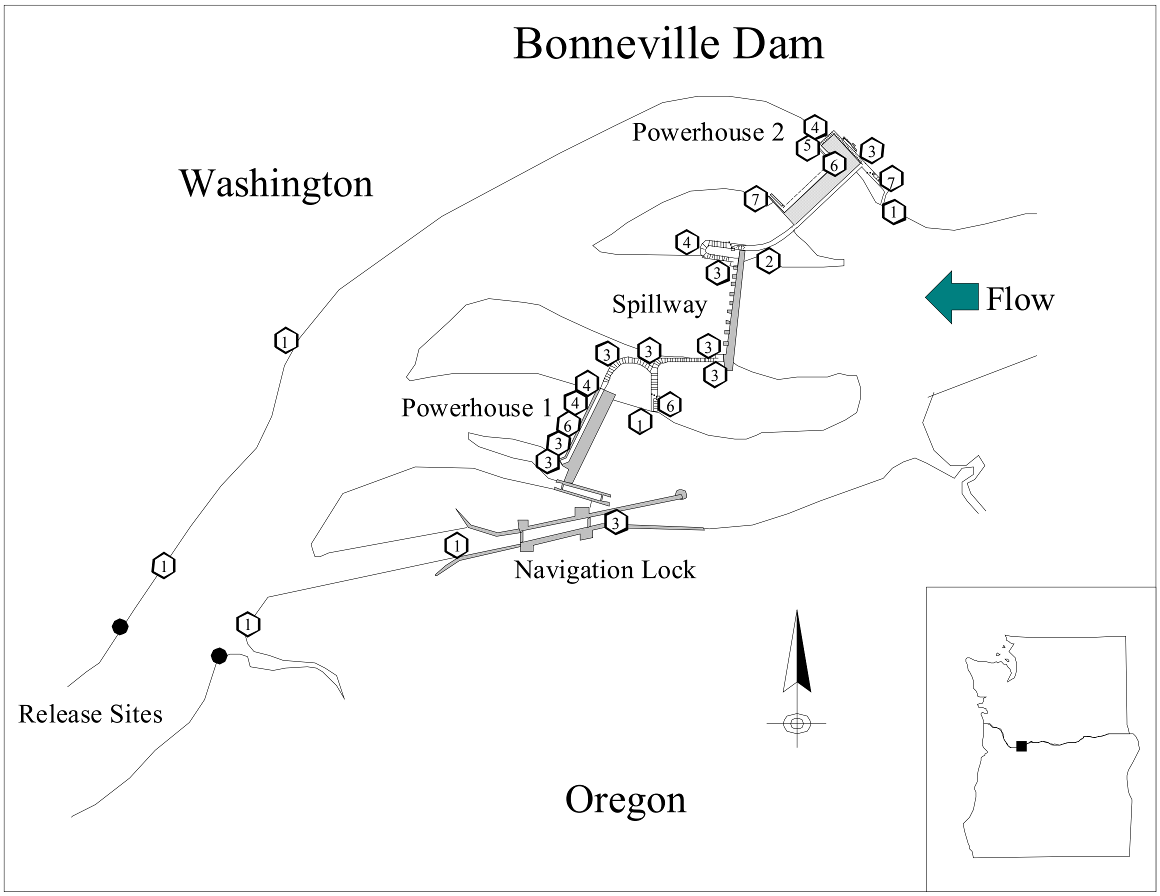


Figure 1. Study area at Bonneville Dam (solid square in insert). Release sites used in 2000 are indicated by solid dots. Radio receiver sites with the number of antennas used at each site are indicated by hexagons.

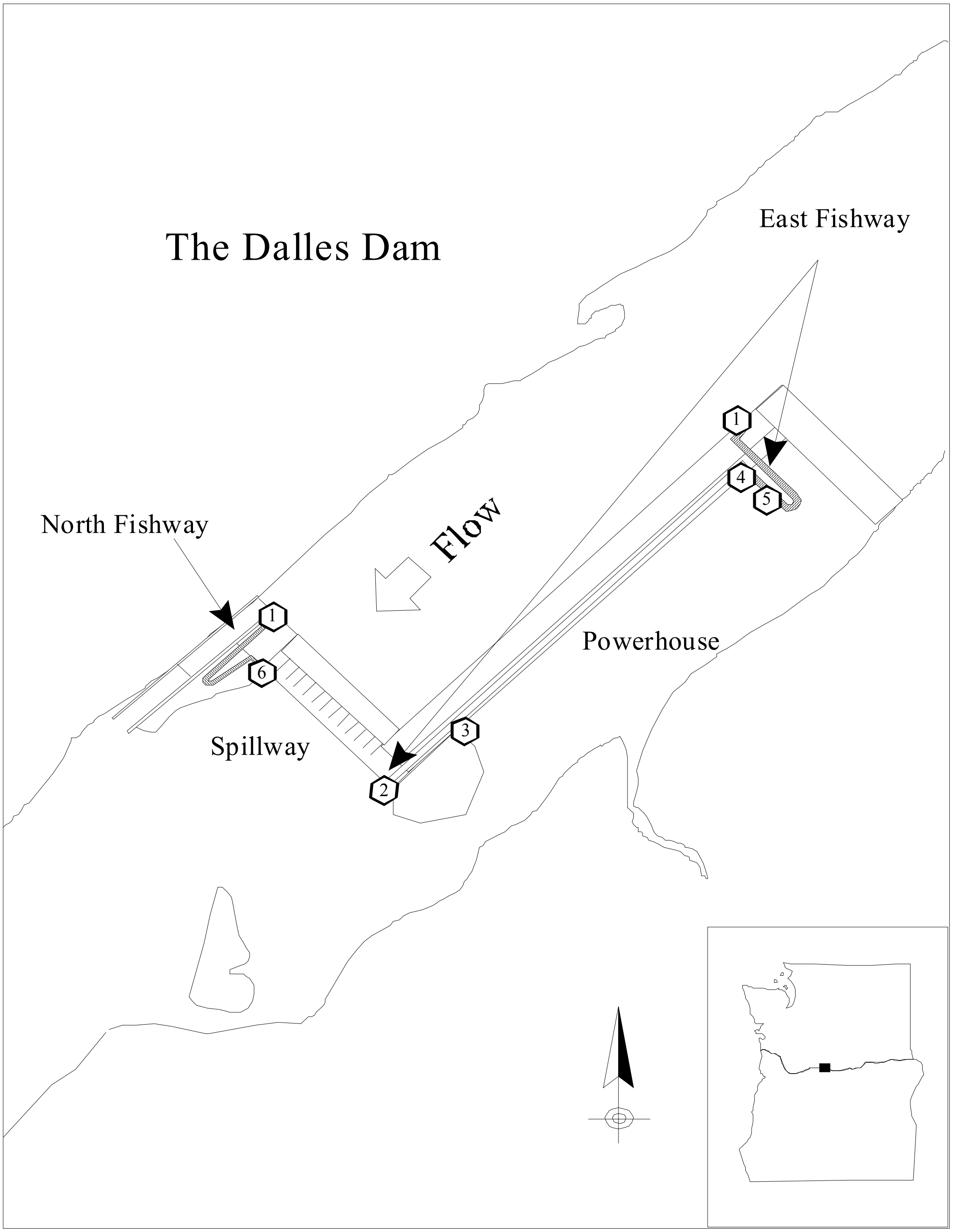


Figure 2. Study area at The Dalles Dam (solid square in insert). Receiver sites and the number of antennas at each receiver are denoted with hexagons.

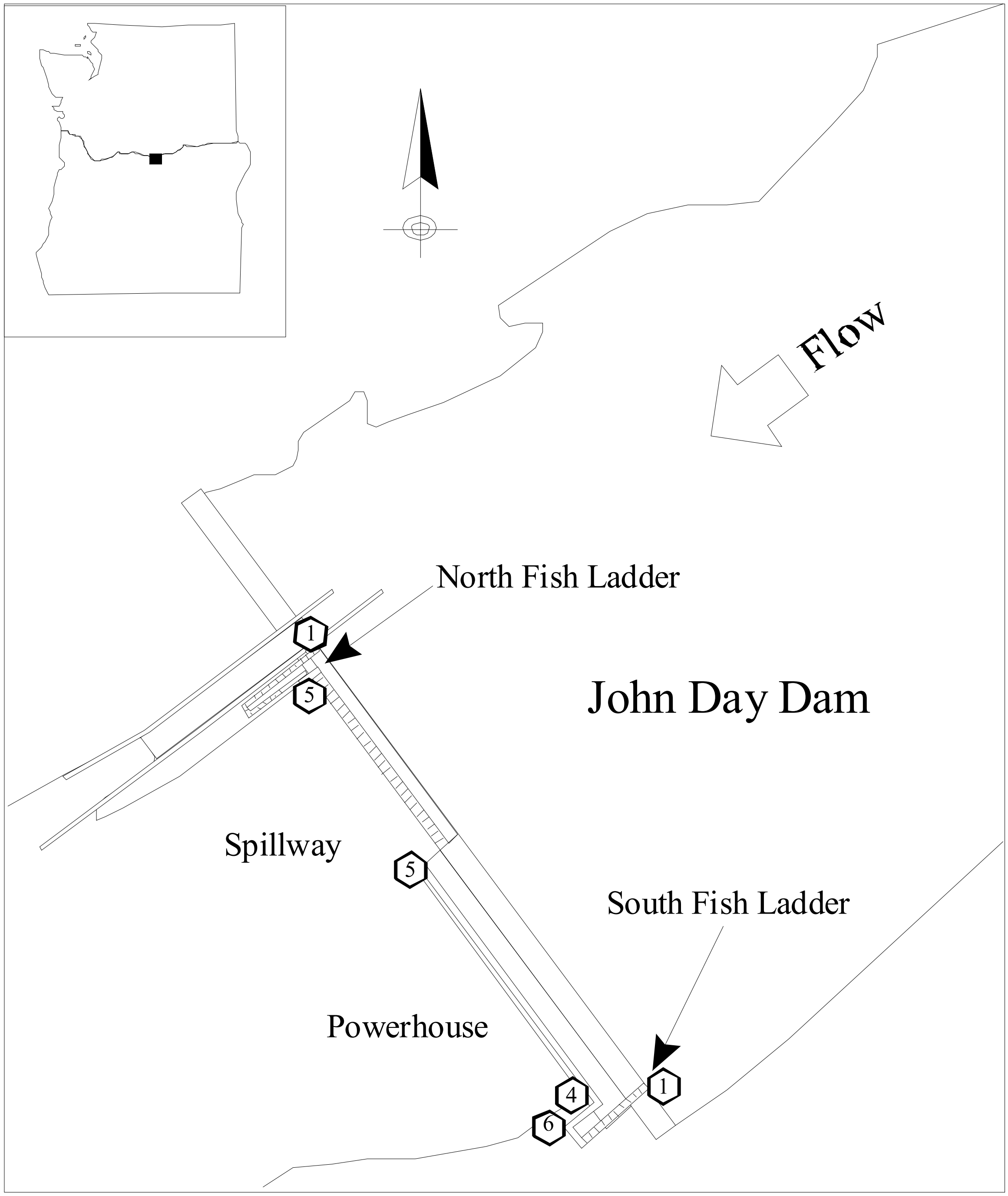


Figure 3. Study area at John Day Dam (solid square in insert). Receiver sites and the number of antennas at each receiver are denoted with hexagons.

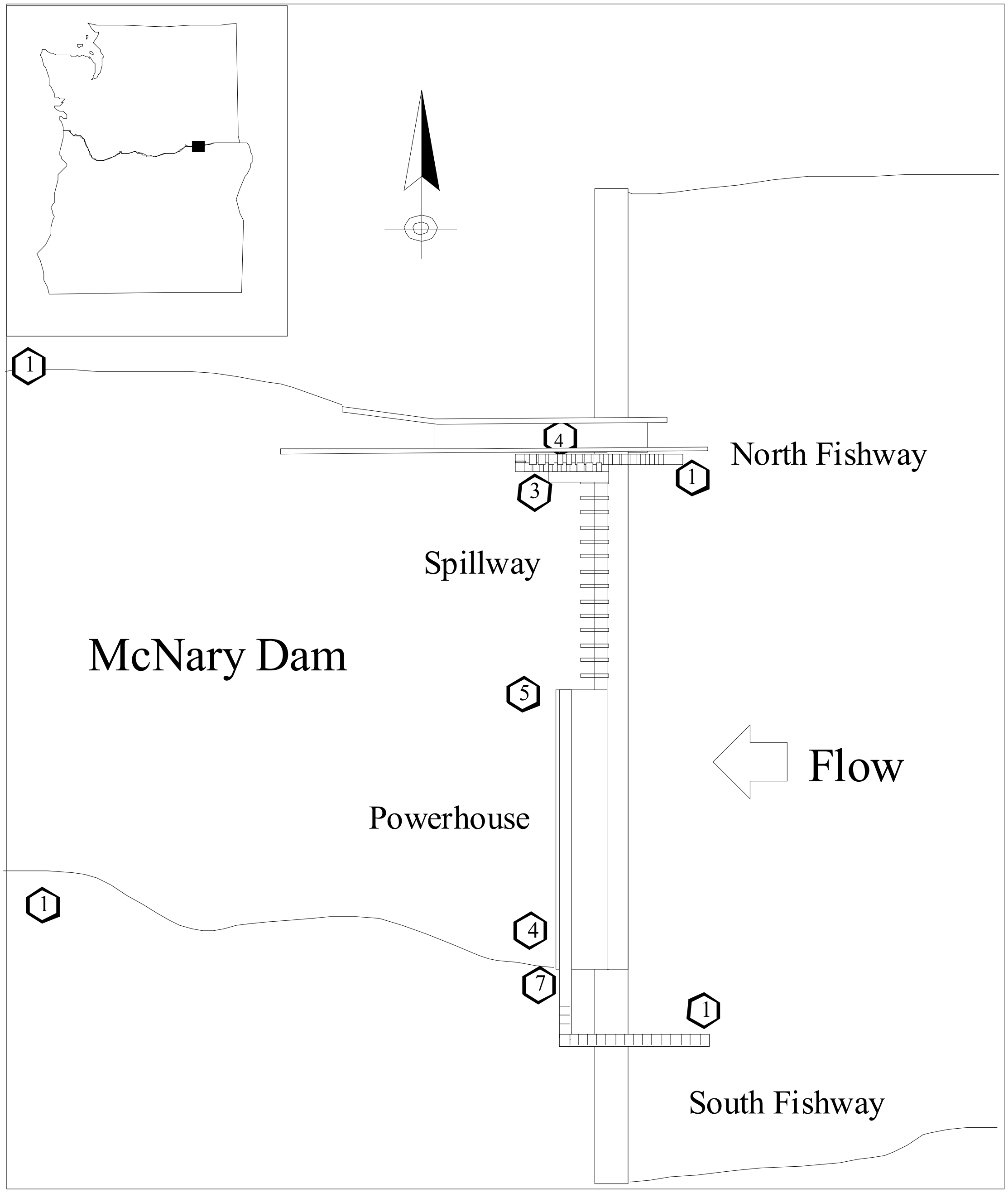


Figure 4. Study area at McNary Dam (solid square in insert). Receiver sites and the number of antennas at each receiver are denoted with hexagons.

included a picketed lead that crowds fish into a narrow, brightly-lit channel which is viewed from the side through a window. Slot or overflow weirs upstream from the window that lead to the fishway exit were also included in the counting station area.

In 2000, we intensified monitoring at the count station areas to allow identification of specific regions that impeded lamprey progress. At the top of the Bradford Island fishway at Bonneville Dam, one antenna was positioned immediately downstream from the counting window (at the upstream end of the picketed lead, Fig. 5). There were three antennas located in the serpentine slot weirs above the counting window, and an antenna at the top of the serpentine weir area.

Two additional antennas were positioned in the make-up water channel that runs parallel to the serpentine weir area (Fig. 5). At the top of the Washington-shore fishway, an antenna was placed immediately downstream from the counting window (upstream end of picketed lead), four antennas were positioned through the serpentine weir area, and one antenna was placed at the fishway exit (Fig. 6). Two additional antennas were placed in the make-up water channel.

We also focused on the performance of fishway entrances in 2000. At the powerhouses, lamprey could enter the fishways via orifice entrances that consisted of relatively small, shallow openings (2 m below the surface and 2 m wide × 1 m deep) into a collection channel that runs along the base of each powerhouse. At the ends of the powerhouses and spillways there are larger main entrances (3-4 m wide × 3-6 m deep, depending on tailwater elevation) that lead into the collection channel and up to a pool and weir ladder. Water velocities at the entrances regularly exceed 2.4 m/s. Water released over the spillway creates turbulent conditions at the entrances on either end of the spillway. In contrast, at main entrances on the ends of the powerhouses and at the orifice entrances there is relatively calm water, and fish approaching at these locations are not exposed to excessive turbulence.

Finally, we tested the efficacy of structural and operational modifications at Bonneville and The Dalles Dam fishway entrances. The entrance bulkhead edge at the Bonneville Dam southern spillway entrance (Bradford B-Branch) was changed from a square edge to a rounded one so that lamprey could remain attached as they moved along the bulkhead and into the fishway. Tests to determine whether lowering water velocity at the Bonneville Dam spillway entrances would improve lamprey entrance success were also conducted. Velocity at the entrances was decreased from approximately 2.4 m/s to 1.2 m/s at night (2100 to 0400 h) at alternating spillway entrances during the period from 25 July to 1 October 2000.

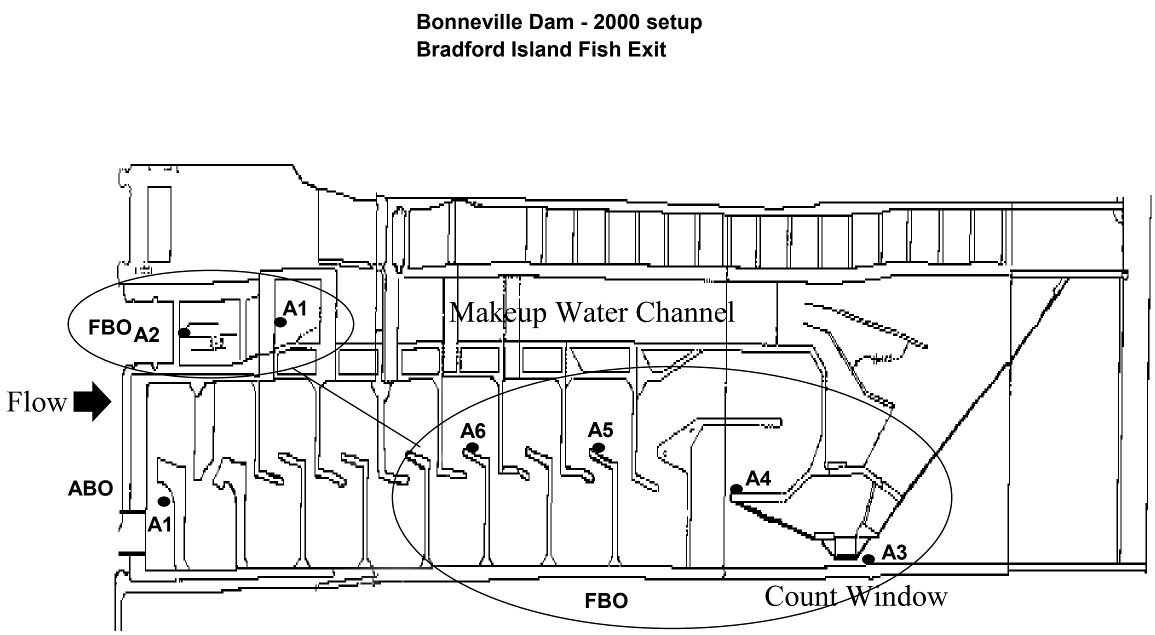


Figure 5. Location of the receivers (FBO and ABO) and individual antennas (FBO A3 at the counting window; A4, A5, and A6 in the serpentine weir section; A1 and A2 in the makeup water channel; and ABO A1 at the ladder exit) at the top of the Bradford Island fishway in 2000.

Bonneville Dam- 2000 Setup
WA Shore Fish Ladder

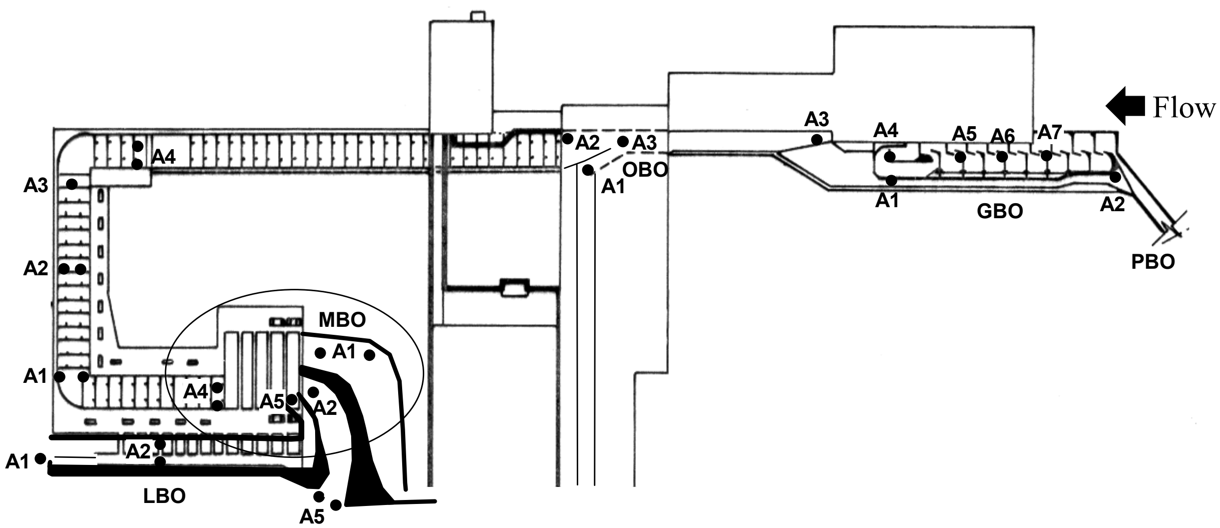


Figure 6. Location of the receivers (GBO and PBO) and individual antennas (GBO A3 at the counting window; A4, A5, A6, and A7 in the serpentine weir section, A1 and A2 in the makeup water channel, and PBO at the ladder exit) at the top of the Washington-shore fishway in 2000.

We analyzed the resulting 2 × 2 contingency table of lamprey entrance efficiency using the chi-square statistic (Zar 1984). In addition, orifice entrances at Bonneville Dam Powerhouse 1 (Fig. 1) were alternately opened and closed during the period from 1 April to 31 October 2000, and all orifice entrances at The Dalles Dam were closed in 2000 to assess effects on salmonid entrance success. The orifice openings at Bonneville Dam Powerhouse 2 were not monitored in 2000.

Tagging and Tracking

We captured lamprey during the night in two traps at the Adult Fish Collection and Monitoring Facility on the Washington shore at Bonneville Dam (described in Ocker et al. 2001). Lamprey were anesthetized using either 70 ppm tricaine methane sulfonate (MS222) or 60 ppm clove oil, measured (length and girth to the nearest mm) and weighed (nearest g). A radio transmitter representing less than 2% of the fish body weight was then surgically implanted into the body cavity of each fish. We used either 7.7-g (3.7 g in water), or 4.5-g (2.9 g in water) radio transmitters (hereafter referred to as large and small). All transmitters were uniquely coded to allow identification of individual fish and had a battery life of at least 7 months.

Fish to be tagged were transferred to a surgery cradle partly submerged in a 16-L bath of 50-ppm MS222 or 60-ppm clove oil. Surgical tools and tags were sanitized in a solution of zephiran chloride and rinsed in a freshwater bath. A 3-cm incision was made approximately 1 cm off the ventral midline using a 3-mm fixed-depth disposable scalpel, with the posterior end of the incision ending in line with the anterior insertion of the first dorsal fin. The tag was inserted into the body cavity, and the antenna was threaded through the body wall approximately 3 cm posterior to the incision using a cannula. The incision was closed with at least five individual stitches of 3-0 absorbable surgical suture made with a 19-mm needle.

After closing, a hypodermic needle was inserted into the incision, and the wound was irrigated with 0.75 cc of oxytetracycline and coated with an antibiotic ointment as a prophylactic measure. The fish were allowed to recover in an aerated tank for approximately 2 hours prior to release. Radio-tagged lamprey were relocated using a portable receiver from a vehicle or vessel and by detections at the fixed-site receiving stations (Figs. 1-4).

Data from fixed-site receivers were downloaded every 1-2 weeks and processed following protocols detailed in Moser et al. (In press a). For each area of interest (entrances, collection channels, transition areas, ladders, and counting stations) we determined the number of lamprey that approached an area and the proportion that successfully passed through that area (passage efficiency). Lamprey moved both upstream and downstream in the fishways (Matter et al. 2000). For analysis, we determined the farthest upstream position attained by each fish, even if it required several attempts to reach this position. At Bonneville Dam count station areas, we also computed the amount of time lamprey held position in specific areas by subtracting the first time of detection at a given antenna from the first time of detection at the next antenna upstream.

We used weighted analysis of variance to compare arcsin-transformed square roots of the passage efficiencies for each area in each year at Bonneville Dam (Zar 1984). Transformed passage efficiencies (radians) were weighted by a factor of 0.25 n-1, where n was the number of lamprey that approached each area of interest (Sokal and Rohlf 1998). The arcsin transformation normalized the proportion data, and the weighting factor stabilized variance. Passage efficiency at each area was assumed to be conditionally independent from efficiency at downstream areas. At Bonneville Dam, we compared overall passage efficiencies among fishways at PH1, PH2, and the spillway (the overall passage efficiency was the percentage of fish that passed through each fishway of those that approached each fishway).

A similar analysis was used to compare overall passage success between the two fishways at each of the other dams. Analysis of variance was also used to compare overall passage success at all dams in all years (overall passage efficiency being the percentage of fish that passed each dam of those that approached each dam). In all cases, Tukey's studentized range test was used to make multiple comparisons (Zar 1984). For John Day Dam, we compared passage efficiencies of fish released in The Dalles pool ("naive fish") to those of fish released below Bonneville Dam (these were fish that had successfully passed over Bonneville and The Dalles Dams). We tested for equality of proportions using a chi-square test (Zar 1984).

In November to May of 1999-2000 and 2000-2001, we monitored lamprey during routine surveys with a portable receiver (mobile tracking). Limited monitoring was also conducted at the fixed sites (i.e., only a subset of the fixed sites were operated in the winters). In winter of 1999-2000, fixed sites and portable receivers required changes toY2K format and were not available for monitoring in December-February. In November-April of 2000-2001, a monthly transect of the mainstem from McNary Dam to the I-205 crossing (including all major tributaries) was searched with a portable receiver from a vehicle. During these surveys we detected lamprey tagged in 1999 that had 14-month transmitters and fish tagged in 2000 with 7-month transmitters.

Count Station Lighting Experiments

We measured ambient lighting during day and night at both the Bradford Island and Washington shore counting windows at Bonneville Dam using continuously recording light meters. In addition, we measured the spectral quality of light at the Bradford Island counting window using a spectroradiometer. This instrument measures light intensity at specific wavelengths and provides a measure of light quality. We conducted spectroradiometer measurements under various lighting scenarios: crowder lights on only, overhead spotlights on only, all lights on, and all lights off.

We manipulated lighting at the experimental counting station located at the Adult Fish Collection and Monitoring Facility. On consecutive nights (2200-0400) we alternated a dark treatment (control) with a white light and a red light treatment. Light intensity was measured continuously at the window throughout the experiment. The number of lamprey captured in the trap located immediately upstream from this counting window was recorded for each treatment and the number of lamprey caught per hour was compared on each pair of nights (white-dark and red-dark) using paired *t*-tests (Zar 1984).

RESULTS

Trapping and Tagging

We operated the lamprey traps nightly from 9 May to 3 October. The trap positioned farthest downstream in the Washington-shore bypass ladder (Trap 1) was fished for 1,586 hours and captured 487 lamprey (CPUE = 0.31 lamprey/h). The upper trap (Trap 2) was fished for 1,076 hours and captured 246 lamprey (CPUE = 0.23 lamprey/h). We tagged 349 lamprey between mid-May and late September, but missed the an early peak in the run (Fig. 7). The lamprey we collected ranged in length from 50 to 80 cm and weighed from 165 to 825 g (Fig. 8).

Lamprey selected for tagging were 62-80 cm in length and weighed 405-825 g. In general, we used the larger tag (n = 271) on fish having a girth of greater than 11.5 cm and the small tag (n = 78) on fish having a girth of at least 10.5 cm (Fig. 9). Consequently, the large tag was only used on the largest lamprey we collected (Figs. 8 and 9) and represented 0.9-1.7% of lamprey body weights.

The small tags were 0.7-1.1% of the lamprey body weights. Unfortunately, the smaller tags were not delivered until mid-season; therefore, only large fish were tagged through the month of June. We used MS222 as anesthetic on 28 fish early in the season (10 May-8 June), and again on 30 fish after we started using the smaller tags (18-22 July). All other lamprey were anesthetized using clove oil.

We released 299 fish below Bonneville Dam: 155 on the Washington shore and 144 on the Oregon shore. We were able to determine the sex of all but 40 of these fish: there were 166 females and 93 males. An additional 50 fish were released upstream from The Dalles Dam: 25 on the Washington shore and 25 on the Oregon shore. There were 25 females and 19 males in this group. Mean size of the sexed fish was 70.6 cm for females and 70.2 cm for males. The mean size of all fish we were unable to sex was 70.0 cm.

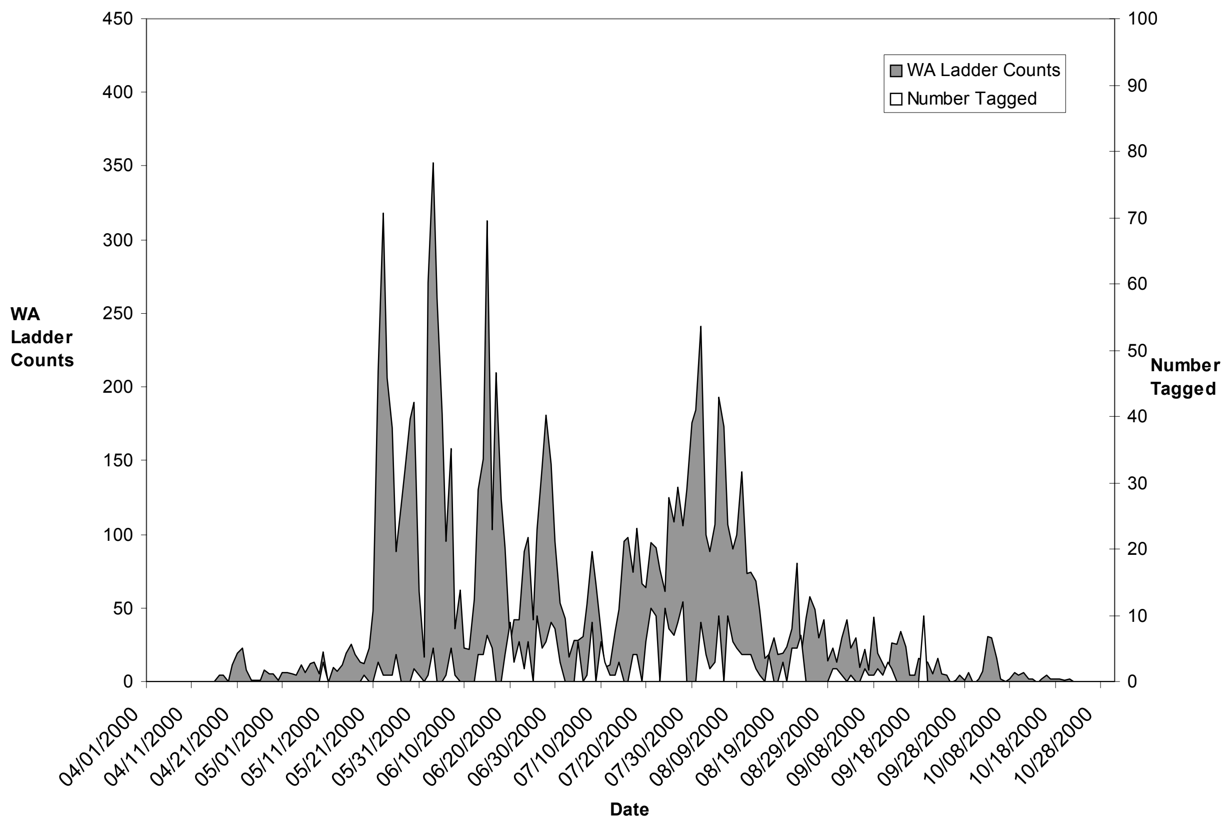
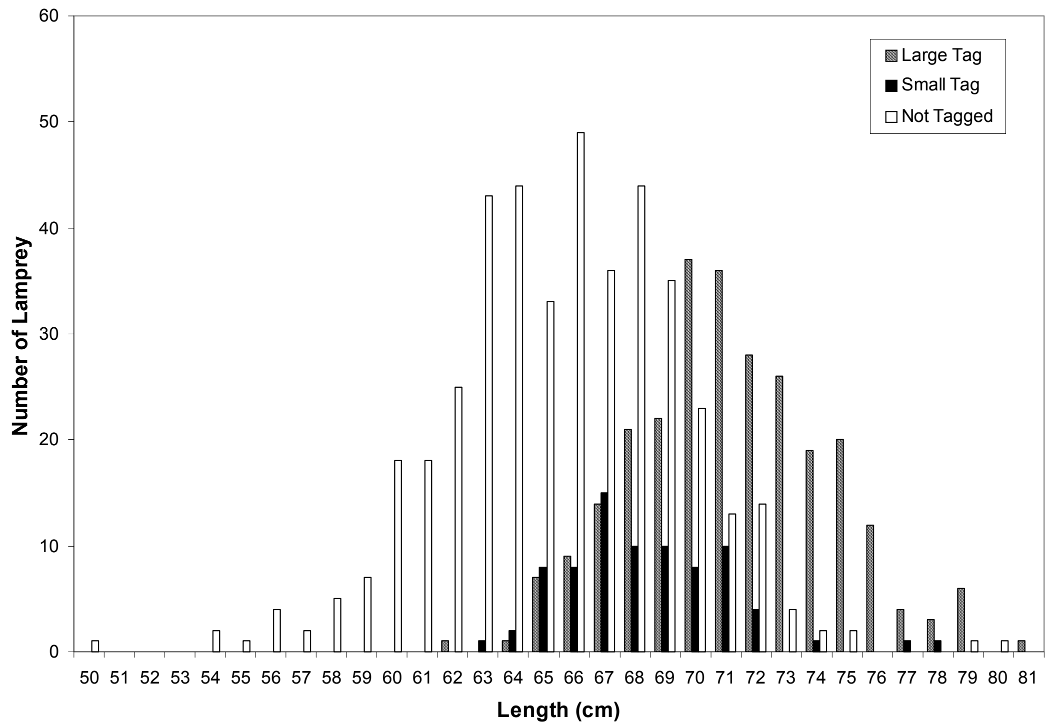


Figure 7. Daily counts of adult Pacific lamprey at the Washington-shore count station (shaded area) and the number of lamprey radio-tagged on each day in 2000.



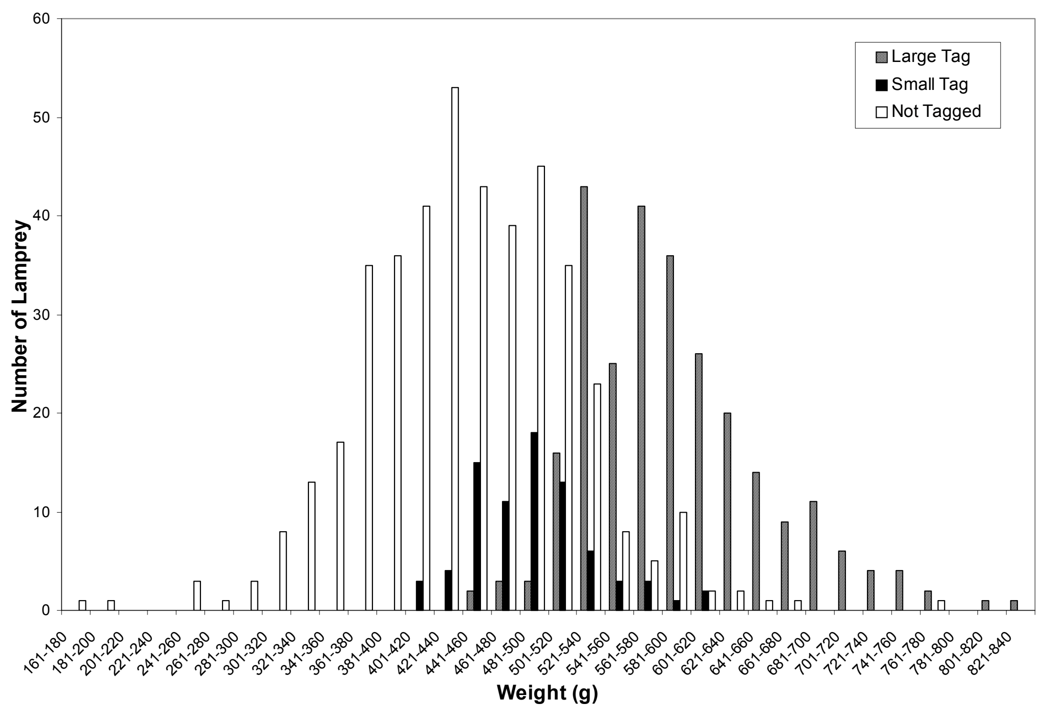


Figure 8. Length frequency (cm total length) and weight (g) of lamprey captured but not tagged (Not Tagged), lamprey tagged with the 7.7-g transmitter (large), and lamprey tagged with the 4.5-g transmitter (small).

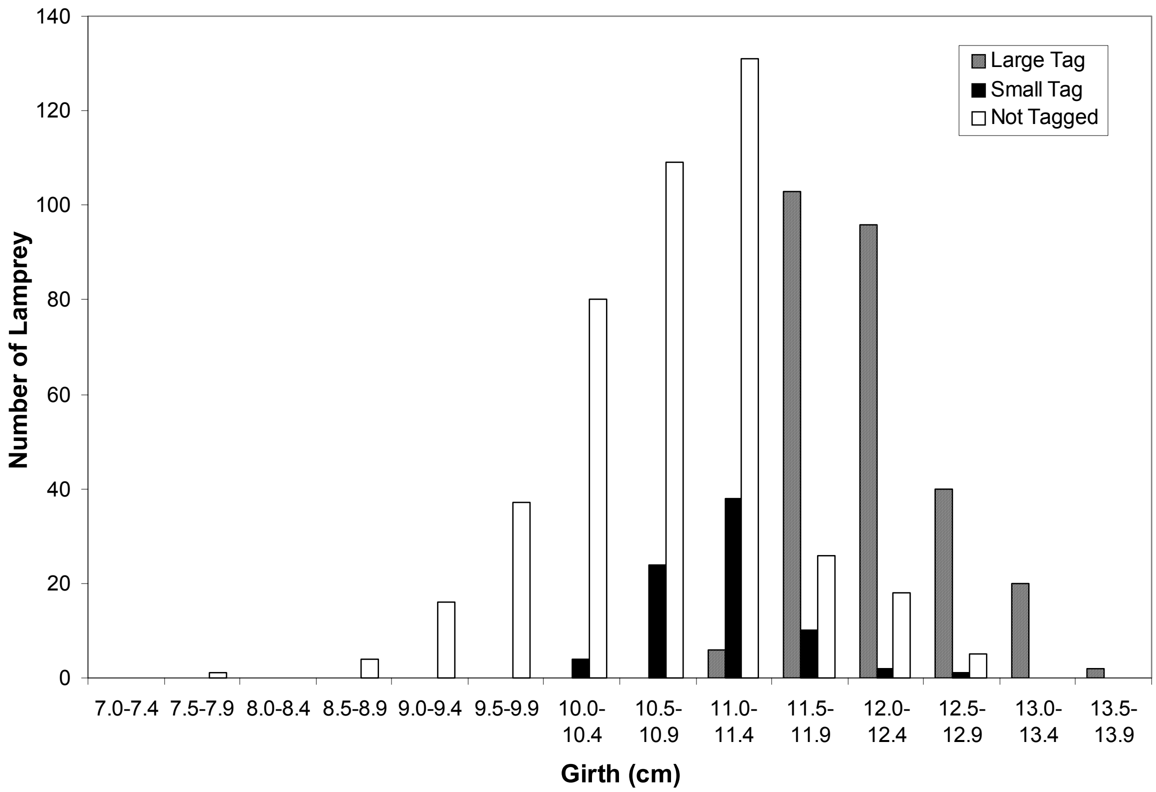


Figure 9. Girth frequency (cm at insertion of first dorsal fin) of lamprey captured but not tagged (Not Tagged), lamprey tagged with the 7.7-g transmitter (large), and lamprey tagged with the 4.5-g transmitter (small).

Bonneville Dam

Of the 299 fish released below Bonneville Dam, 35 were detected only at the release site (2 of these were never detected after release). Of the remaining 264 lamprey, 260 were detected at entrances to the fishways (i.e., 87% of the fish we released subsequently approached the dam). The median travel time from release to first detection at Bonneville Dam was 6.4 d (range = 0.3-111.2 d, SD = 13.0 d).

A higher percentage of the fish anesthetized with MS222 were not detected at the dam (19%) than those anesthetized with clove oil (10%). However, in 1998, 11% of the 205 lamprey we released did not approach the dam and in 1999, 9% of the 199 lamprey we released did not approach the dam. In both 1998 and 1999, only MS222 was used as an anaesthetic. There was no apparent effect of tag size on the percentage of fish that were not detected at the dam: 27 of the 219 fish with large tags were not detected (12%) and 8 of the 80 fish with small tags were not detected (10%). Median travel times from release to first detection at the dam were also similar among tag size groups (Fig. 10).

As in previous years, lamprey approached the fishways at Bonneville Dam primarily during the night (Fig. 11). Often individual lamprey made multiple approaches over the course of several days before entering a fishway or falling back downstream. For analysis of diel activity patterns, we used only the first detection at the entrance into a fishway. Because lamprey migration rates to the dam were highly variable, we believe that the timing of these detections is indicative of diel activity patterns, rather than a function of release time. The numbers of first approaches peaked between 2100 and 0100 hours and were low during the rest of the night and day (Fig. 11).

To determine whether lamprey were differentially attracted to entrances at Powerhouse 1 (PH1), Powerhouse 2 (PH2), or the spillway, we divided the number of fish that approached fishway entrances at each of these dam sections by the total number of lamprey that approached the dam (n = 260). In many cases individual lamprey approached the entrances more than once and/or were detected at entrances in more than one dam section.

For this analysis, we used the first approach of a given fish at each section. In 2000, a slightly higher percentage of the lamprey approached PH1 than the other two sections, the percentage of fish that approached PH2 was lower than at the other two sections, and the percentage of fish that approached at PH2 was lower than in previous years of tracking (Fig. 12). As in the previous years of study, PH1 had priority in 2000 (i.e., most of the flow was either through PH1 or the spillway, as opposed to PH2).

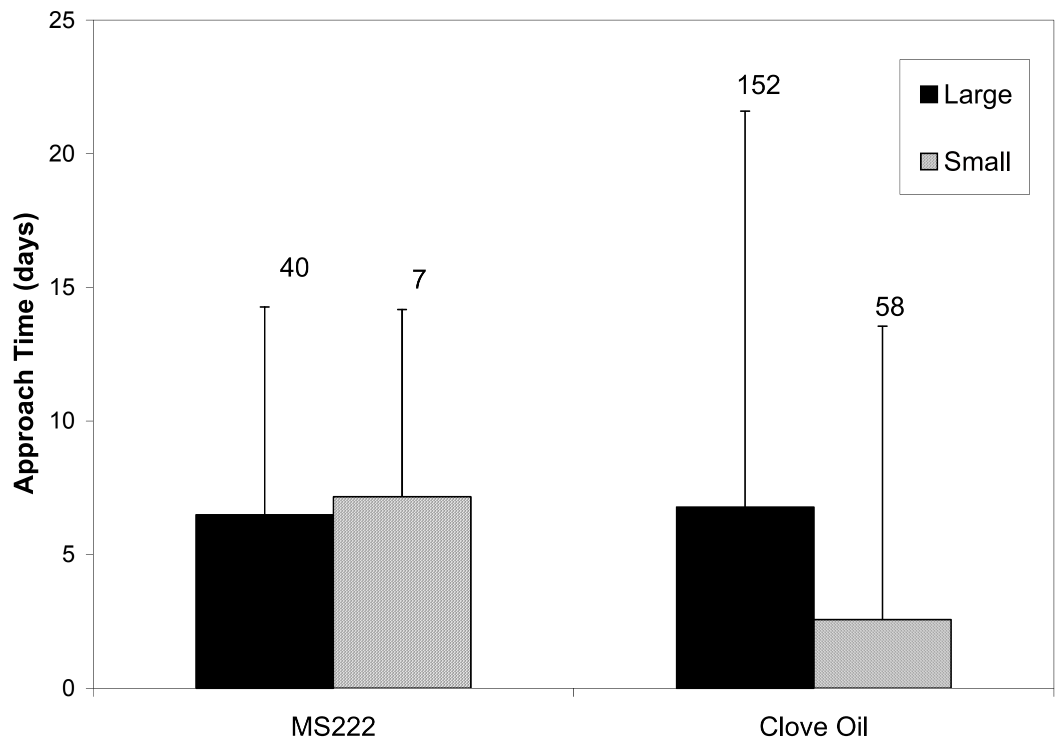


Figure 10. Median time (d) from release to the first detection outside a fishway entrance at Bonneville Dam for adult Pacific lamprey tagged with the 7.7-g (large) and 4.5-g (small) transmitters. Times are also grouped by anesthetic treatment (MS222 or clove oil).

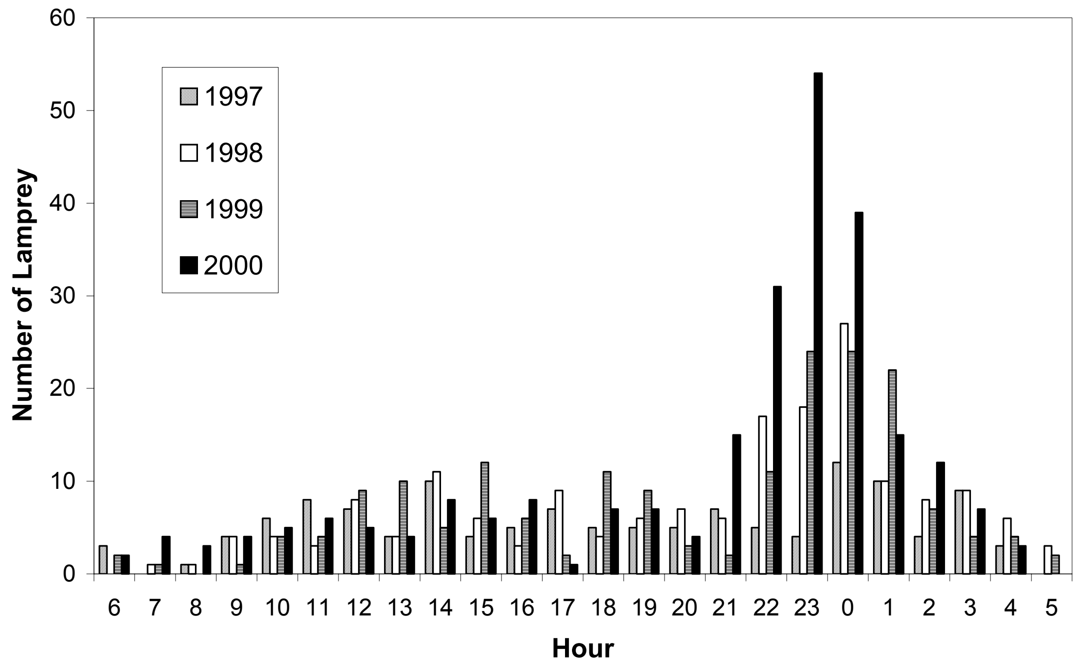


Figure 11. Frequency distribution of times of day that individual lamprey made their first approach to a Bonneville Dam fishway entrance in each year of study (1997-2000).

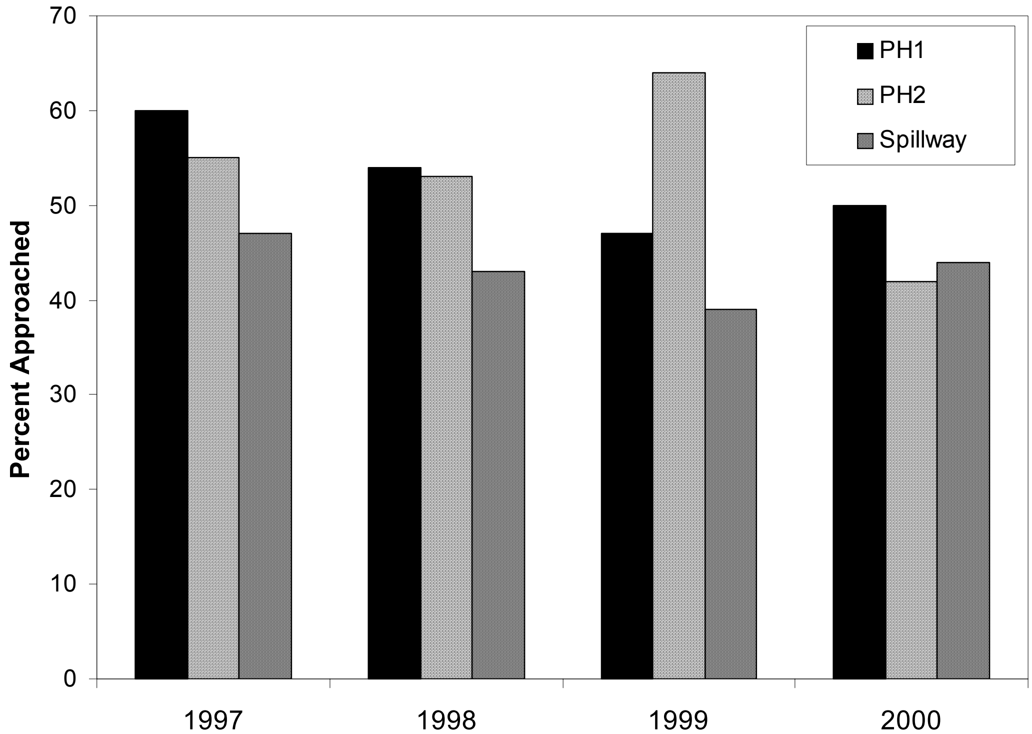


Figure 12. The percentage of all lamprey that approached Bonneville Dam fishway entrances that made at least one approach at Powerhouse 1 (PH1), Powerhouse 2 (PH2), or spillway entrances in each year of study (1997-2000).

Entrance efficiency (the number of lamprey that entered a fishway entrance divided by the number of lamprey that approached that entrance) varied among sections at Bonneville Dam (Table 1). Entrance efficiency was lowest at the spillway entrances (60%), intermediate at the PH1 entrances (74%), and highest at the PH2 entrances (80%). As in previous years, lamprey often made multiple entrances to the fishways (Fig. 13) over the course of several days (Fig. 14).

Examination of entrance efficiency at individual entrances revealed that, as in previous years, lamprey had the lowest entrance success at orifice entrances (OG = orifice gates, Fig. 15). At PH2, main entrance efficiency in 2002 was generally lower than that recorded in 1998 and 1999 (Fig. 15). Entrance efficiency at PH1 main entrances was similar to previous years, but entrance success improved at the two spillway entrances. In addition, visual observations of lamprey accumulation on the bulkheads adjacent to the spillway entrances indicated that more lamprey were visible at the Cascades Island entrance than at the Bradford B-Branch entrance (Fig. 16).

To test whether the improvement in spillway entrance efficiency was due to reduced velocity tests, we computed the entrance efficiencies of only those lamprey that approached the spillway entrances at night during the velocity tests and analyzed the resulting 2 × 2 contingency table data using the chi-square statistic (Zar 1984). During the night (2100 to 0400 h) from 25 July to 1 October 2000, 36 lamprey approached the spillway entrances. Although the entrance velocity had no significant affect on the number of successful entries ($\chi^2 = 0.93$, $P = 0.34$), entrance efficiencies were actually higher during high-velocity treatments (Fig. 17). Moreover, mean time to enter the spillway entrances was lower during high-velocity treatments (mean = 19.0 min) than during low-velocity treatments (mean = 60.3 min).

In 2000, passage efficiency of lamprey was less than 75% at the PH2 collection channel and transition area and at the spillway transition areas (Table 1). As in previous years, the percentage of lamprey that were detected moving all the way through the collection channel at PH1 was higher than through the collection channel at PH2 (Table 1).

The intermittent closure of orifice gates at PH1 did not appear to affect lamprey passage through the PH1 collection channel, as PH1 collection channel passage efficiency was similar among years: 77% in 1997, 81% in 1998, 87% in 1999, and 88% in 2000 (Table 1). Passage through transition areas in PH2 and spillway fishways was also low relative to passage through the same area at PH1. In contrast, lamprey passage efficiency through the ladders was greater than 85% in all fishways at Bonneville Dam (Table 1).

Table 1. Number of radio-tagged lamprey that passed through each area within each fishway at Bonneville Dam in 1997-2000. Passage efficiency is shown in parenthesis (number of lamprey that passed through the area/the number that approached that area × 100).

Fishway	Area	1997	1998	1999	2000
Bonneville PH1	Entrance	47 (60%)	78 (80%)	63 (72%)	97 (74%)
	Collection	36 (77%)	63 (81%)	55 (87%)	85 (88%)
	Transition	32 (89%)	61 (97%)	50 (91%)	82 (96%)
	Ladder	27 (75%)	59 (97%)	49 (98%)	71 (86%)
	Count station	21 (78%)	37 (63%)	38 (78%)	63 (89%)
Bonneville PH2	Entrance	50 (69%)	78 (81%)	100 (85%)	87 (80%)
	Collection	30 (60%)	50 (64%)	79 (79%)	63 (72%)
	Transition	25 (83%)	32 (64%)	43 (54%)	43 (68%)
	Ladder	24 (96%)	29 (91%)	43 (100%)	38 (88%)
	Count station	21 (88%)	25 (86%)	35 (81%)	32 (84%)
Spillway	Entrance	33 (54%)	35 (44%)	41 (57%)	69 (60%)
	Collection	19 (58%)	21 (60%)	22 (54%)	63 (91%)
	Transition	14 (74%)	12 (57%)	11 (50%)	37 (59%)
	Ladder	11 (79%)	11 (92%)	10 (91%)	32 (86%)
	Count station	6 (54%)	9 (82%)	8 (80%)	24 (75%)

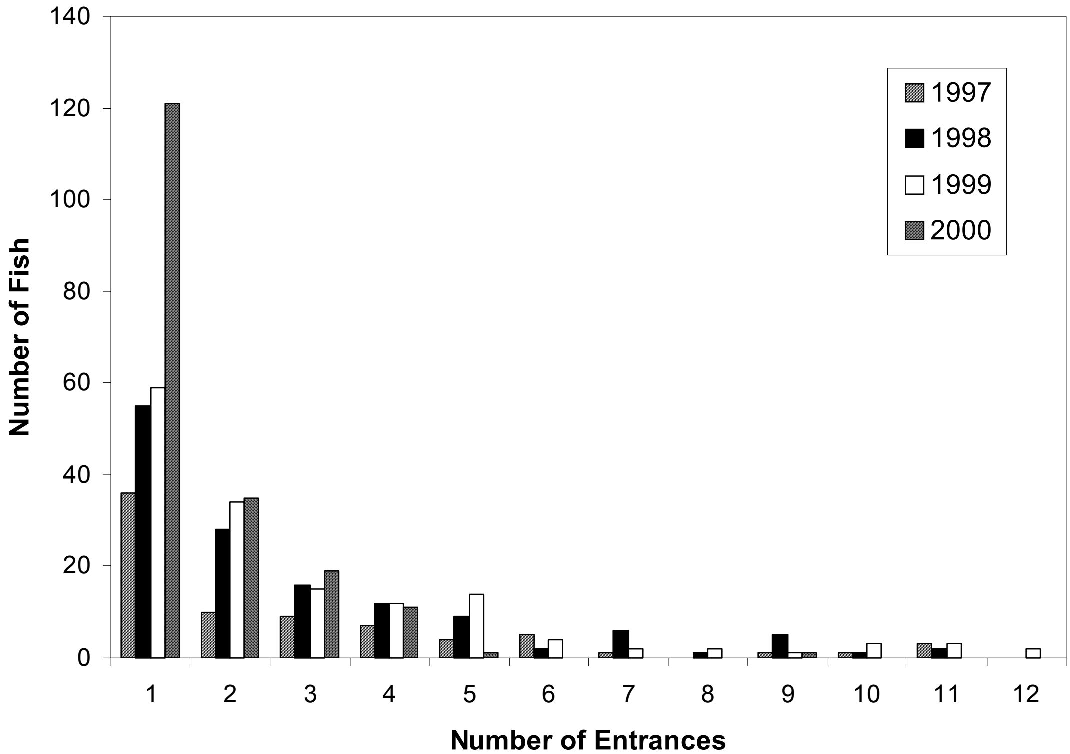


Figure 13. The number of individual radio-tagged lamprey that made one or more (up to 12) separate successful entrances at Bonneville Dam fishways in each year of study (1997-2000).

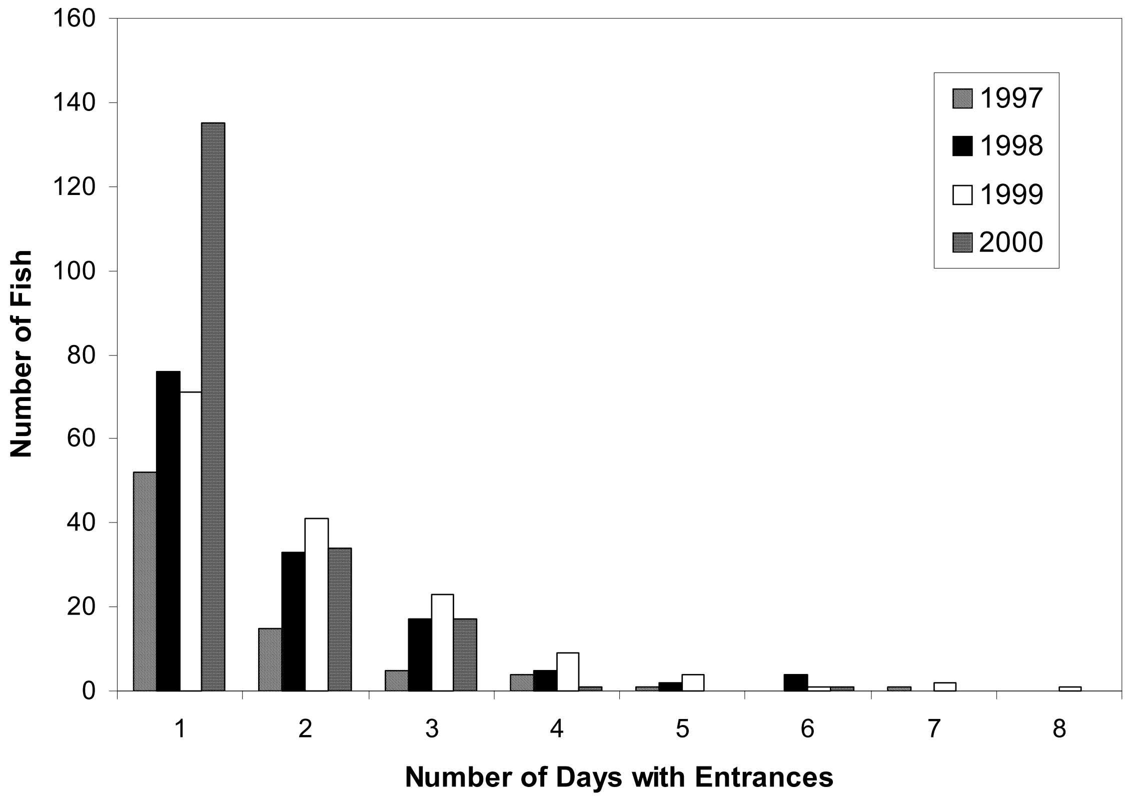


Figure 14. The number of radio-tagged lamprey that made separate successful entrances at Bonneville Dam fishways on one or more days (up to 8 days) in each year of study (1997-2000).

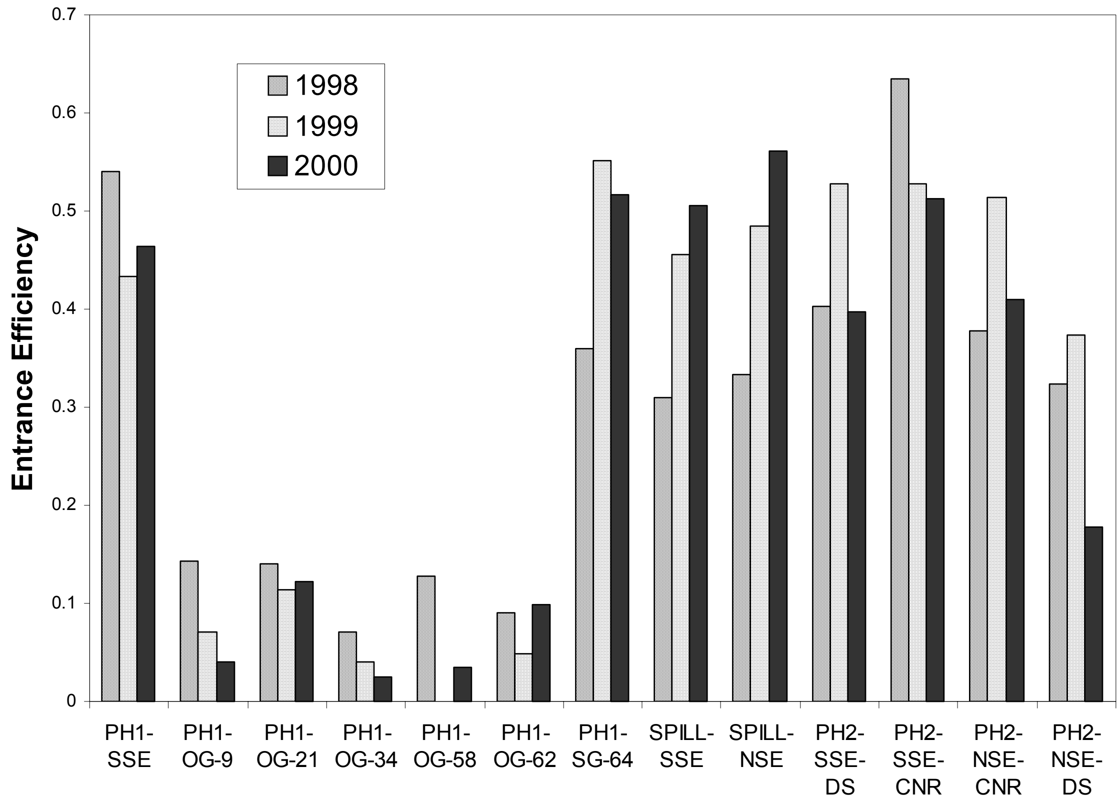


Figure 15. Entrance efficiency (percentage of lamprey that successfully entered of those that approached) at each of the Bonneville Dam fishway entrances from south to north along Powerhouse 1 (PH1), the spillway (SPILL), and Powerhouse 2 (PH2) in 1998-2000. Orifice and sluice gate entrances at PH1 are denoted by OG and SG, respectively (orifice entrances were monitored at PH2 in 2000). Main entrances at PH2 include those downstream (DS) and in the corners (CNR).

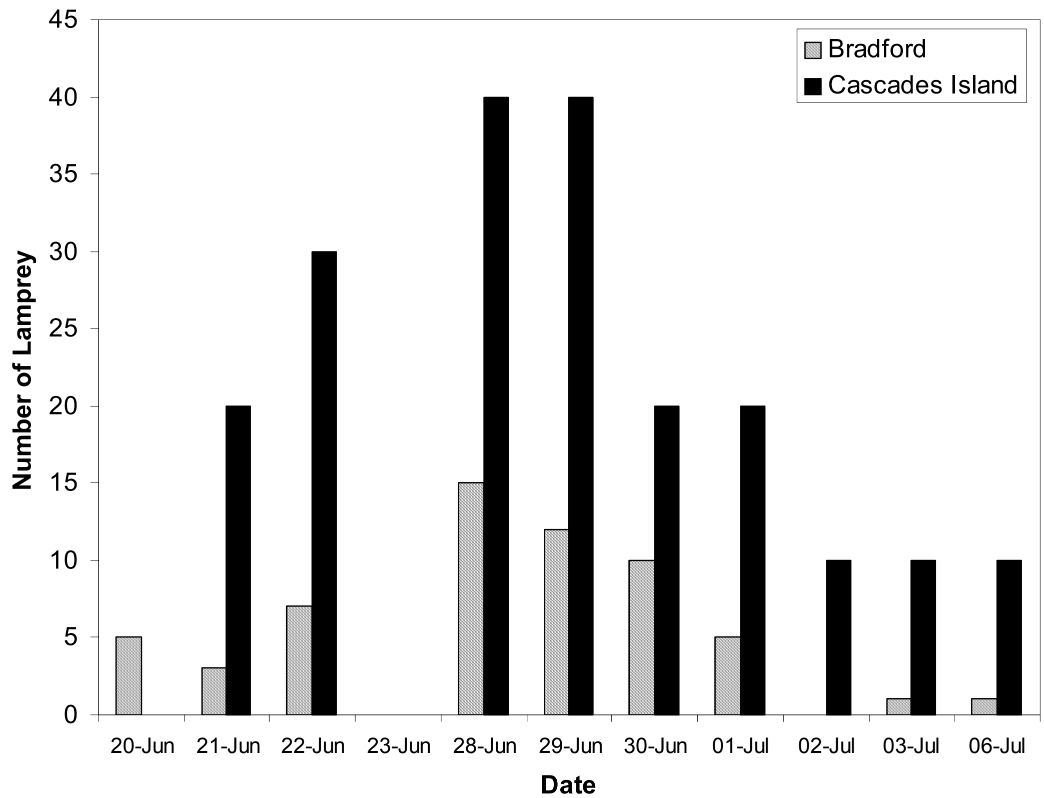


Figure 16. Counts of lamprey attached to the bulkheads adjacent to the Bradford B-Branch entrance (Bradford) and the spillway entrances on Cascades Island (Cascades Island) from 20 June to 6 July 2000.

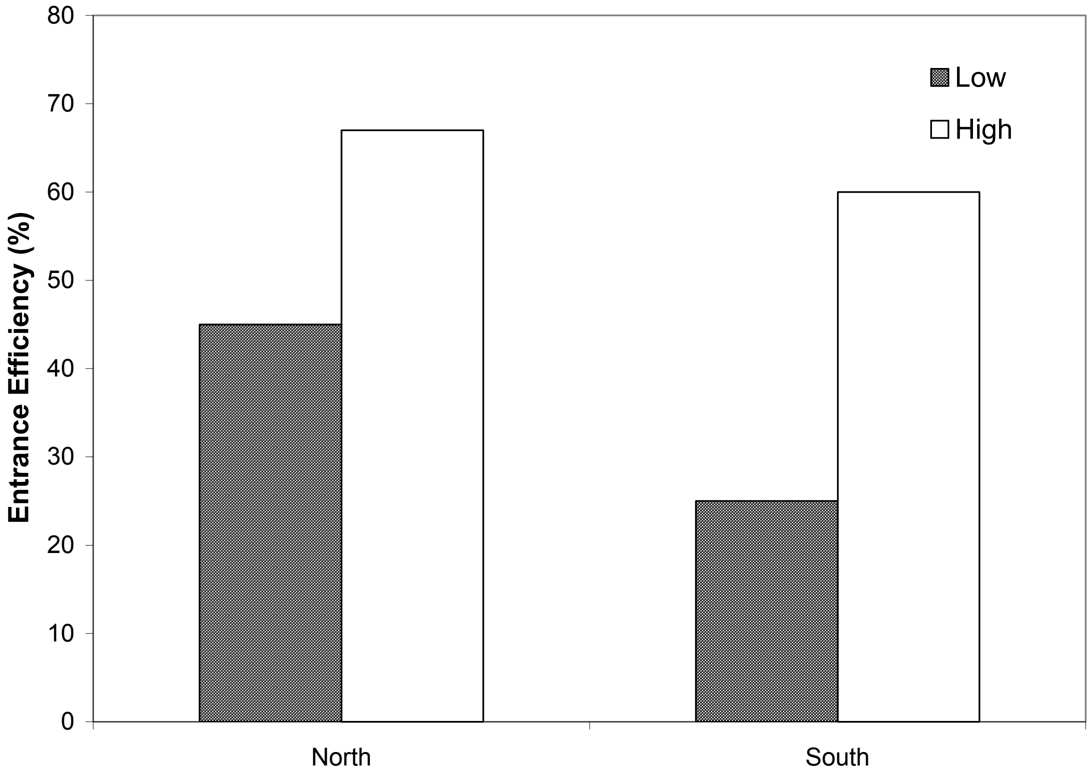


Figure 17. Entrance efficiency (percentage of lamprey that successfully entered of those that approached) at the Bradford B-Branch (South) and Cascades Island (North) spillway entrances during night-time test periods when current velocity was lowered to approximately 1.2 m/s (low) and during control conditions (approximately 2.4 m/s, high).

Passage efficiency through the counting window areas at the tops of the ladders was relatively low for lamprey that entered the Washington-shore fishway. However, fish that moved through the Bradford Island fishway exhibited higher passage through the top of the ladder than in any previous year (Table 1). However, only 68 (75%) of the 91 fish that approached the top of the Bradford Island fishway exited via the serpentine weirs. The remaining fish entered the makeup water channel that runs parallel to the serpentine weirs and then 13 exited into the forebay via the Tainter gate at the upstream end of this channel (Fig. 18).

Lamprey tended to hold for extended periods in the Bradford Island makeup water channel, compared to the highly variable, but generally lower residence times observed in the serpentine weir section (Fig. 19). On the Washington shore, only one lamprey entered the makeup water channel, and this fish fell back downstream and did not subsequently pass over the dam (Fig. 18). At both counting station areas, a higher percentage of
lamprey were delayed or obstructed at the serpentine weir areas (particularly those furthest upstream) than at the counting window (Figs. 18, 19, and 20).

Of the 260 lamprey that approached Bonneville Dam, 119 passed over the dam via the fishways and 4 passed upstream through the navigation lock, for a total passage efficiency of 47%. Median passage time from the first approach at Bonneville Dam fishway entrances to the last detection when the lamprey exited the fishway into the forebay was 4.4 d (range = 0.2-70 d, standard deviation 15.1 d). Four of the fish that passed over Bonneville Dam were subsequently detected downstream from the dam (i.e., they fell back downstream).

Analysis of variance indicated that there were no significant ($P = 0.55$) differences in passage efficiency among years, so we pooled data from 1997-2000 to test for differences among fishways and areas within each fishway. Passage efficiency for fish that used fishways at the spillway was significantly lower than for fish that used fishways at either powerhouse ($P < 0.001$).

As in previous years, lamprey passage times through the spillway fishways were longer (median = 9.5 d) than passage times through PH2 (median = 7.1 d) and PH1 (median = 3.6 d) (Fig. 21). Passage efficiencies of lamprey through discrete areas in the fishways were also significantly different (Fig. 22), with higher passage efficiency at ladders than in other areas ($P < 0.001$). Only 1% of the radio-tagged lamprey passed upstream through the navigation lock at Bonneville Dam in each year.

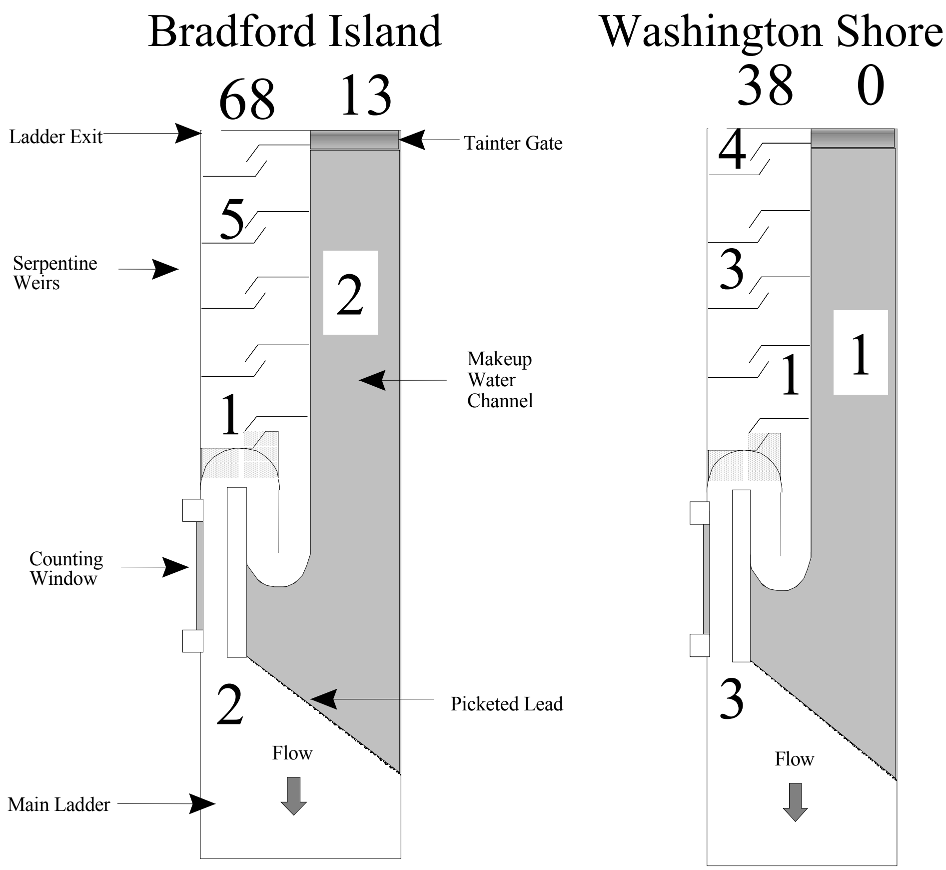


Figure 18. Diagram of the count station areas at the tops of the Bradford Island and Washington-shore fish ladders. Numbers in the fishways indicate the number of lamprey that fell back downstream at each location of the 91 fish that approached the Bradford count window and the 50 fish that approached the Washington-shore count window. Numbers above each diagram indicate the number of lamprey that successfully exited into the forebay. The shaded area represents the makeup water channel.

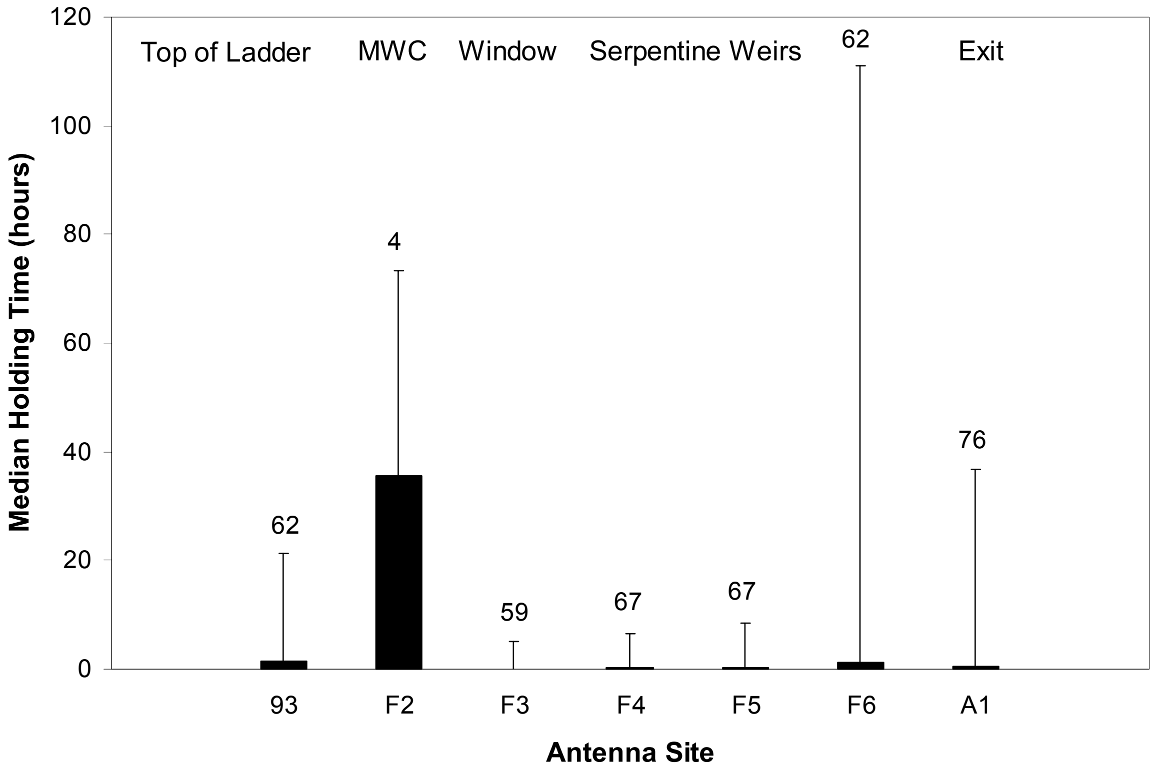


Figure 19. Median holding time at each antenna site (Fig. 5) for the Bradford Island count station area (i.e., median hours from first detection at an antenna site to the first detection at the next upstream antenna site with standard deviation denoted by error bars). Features of each site are indicated at the top of the plot (e.g., F2 is the antenna inside the makeup water channel (MWC), A1 is at the exit, etc.).

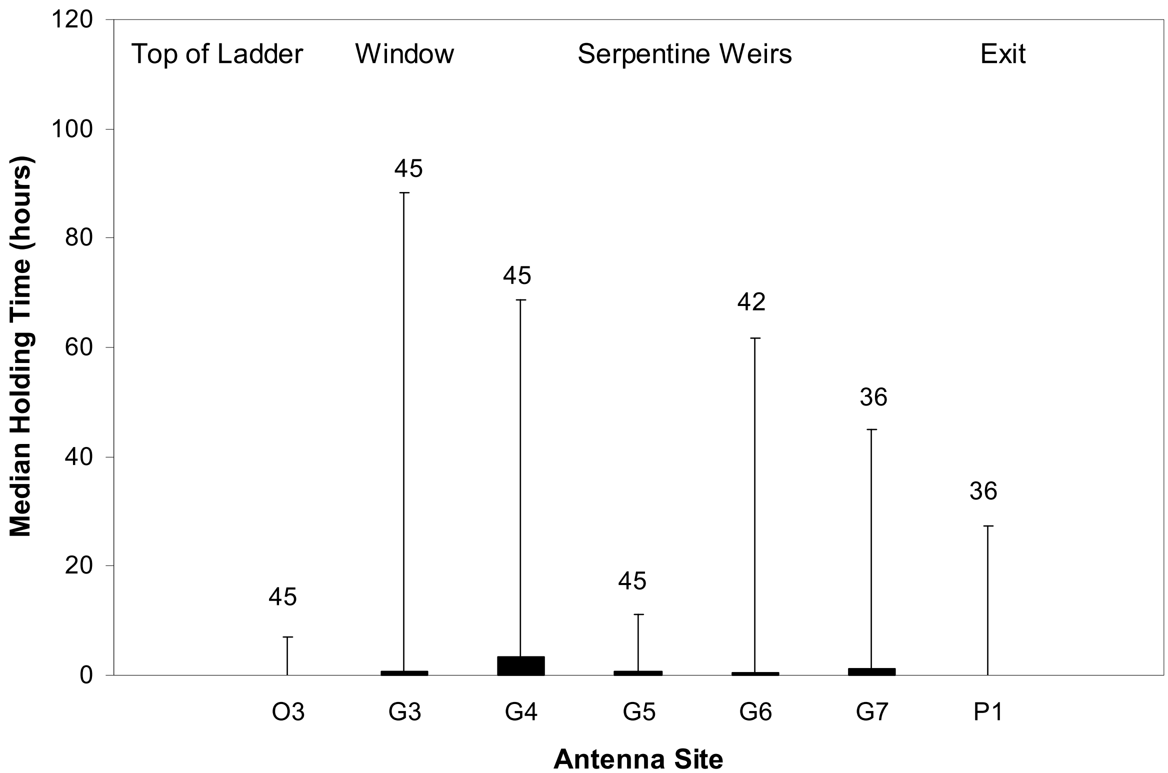


Figure 20. Median holding time at each antenna site (indicated on Fig. 6) for the Washington-shore count station area (i.e., median hours from first detection at an antenna site to the first detection at the next upstream antenna site with standard deviation denoted by error bars). Features of each site are indicated at the top of the plot (e.g., G3 is the antenna at the count station window, P1 is at the exit, etc.).

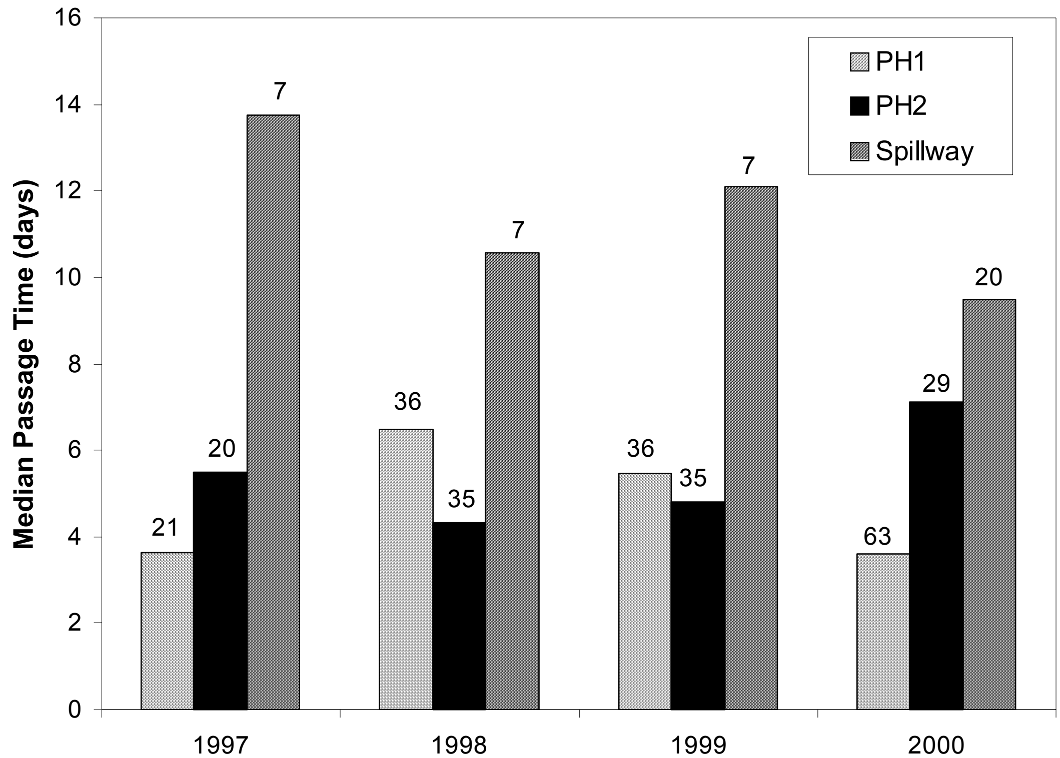


Figure 21. Median passage time (days from first detection outside a fishway entrance to last detection at the top of the fish ladder) for fish that used the fishways at Powerhouse 1 (A-Branch, PH1), the spillway (B-Branch, Cascades Island and the UMT), and Powerhouse 2 (Washington-shore ladder, PH2). Only fish with known times of first approach at an entrance and known times of exit into the forebay were used for this analysis (numbers of fish in each year for each fishway are indicated at the tops of the bars).

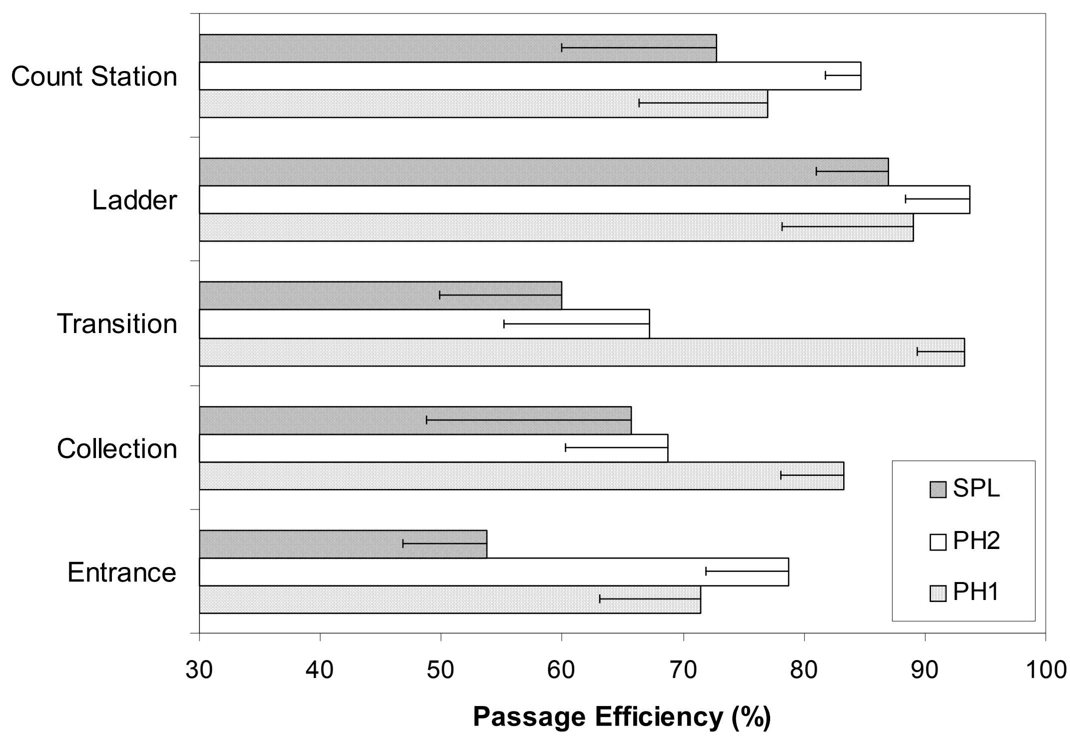


Figure 22. Mean passage efficiency (the number of lamprey that passed through each area divided by the number that approached each area) for areas of interest (entrances, collection channels, transition areas, ladders, and count stations) at Bonneville Dam Powerhouse 1 (PH1), Powerhouse 2 (PH2), and spillway (SPL) fishways in 1997-2000. Standard deviations are indicated by error bars.

The Dalles Dam

We detected 91 lamprey in the vicinity of The Dalles Dam tailrace, and 85 of these fish approached entrances to the fishways. More lamprey approached the powerhouse fishway system on the Oregon shore (East) than the fishway adjacent to the spillway on the north shore (North; Table 2). Lamprey made multiple entrances to fishways at The Dalles Dam over the course of several days in some cases (Figs. 23 and 24). As in 1998, entrance efficiency was highest at the entrances to the North Fishway (Fig. 25). Among the East fishway entrances, lamprey had highest entrance efficiency at the east end of the fishway (i.e., the entrances located closest to the fish ladder).

Passage efficiencies through the two fishways at The Dalles Dam were similar to each other and to those in previous years (Table 2). We monitored passage efficiency at discrete areas inside The Dalles Dam fishways in 1997 and 1998 (in 1999 only receivers in the tailraces and tops of fishways were operating). There were no significant differences in passage efficiency among years ($P = 0.41$), so we pooled the data to compare passage efficiencies at each fishway and the areas within each fishway. We detected no significant difference in passage efficiency between the two fishways (North and East, $P = 0.24$). However, passage time (the time from first approach at a fishway entrance to last detection at the fishway exit) was about twice as long for lamprey negotiating the East fishway (Fig. 26).

Passage efficiencies among discrete areas within The Dalles Dam fishways were significantly different from each other (Fig. 27), with highest passage success through the count stations and lowest through transition areas ($P < 0.001$). In 2000, lamprey passage through the collection channels at the East fishway was similar to passage in previous years, but passage efficiency at the transition areas (immediately upstream from the collection channel) improved in 2000 (Table 2).

Passage efficiencies at The Dalles counting stations were notably higher than those at Bonneville Dam counting stations (Tables 1 and 2, Fig. 27). Overall passage efficiency at The Dalles Dam was 82% (70 of the 85 fish that approached The Dalles Dam passed over). Median passage time for lamprey at The Dalles Dam was 2.1 d (minimum = 0.2 d, maximum = 12.7 d, standard deviation = 3.0 d).

Table 2. Number of radio-tagged lamprey that passed through each area within each fishway at The Dalles Dam in 1997, 1998, and 2000. Passage efficiency is in parenthesis (number of lamprey that passed through the area/the number that approached that area × 100).

Fishway	Area	1997	1998	1999	2000
The Dalles East	Entrance	41 (85%)	22 (73%)	-	52 (87%)
	Collection	34 (83%)	21 (95%)	-	47 (90%)
	Transition	27 (79%)	12 (57%)	-	41 (87%)
	Ladder	24 (89%)	12 (100%)	-	38 (93%)
	Count station	24 (100%)	12 (100%)	-	37 (97%)
The Dalles North	Entrance	18 (67%)	15 (94%)	-	44 (94%)
	Collection	14 (78%)	15 (100%)	-	42 (95%)
	Transition	11 (79%)	13 (87%)	-	36 (86%)
	Ladder	11 (100%)	12 (92%)	-	33 (92%)
	Count station	11 (100%)	12 (100%)	-	33 (100%)

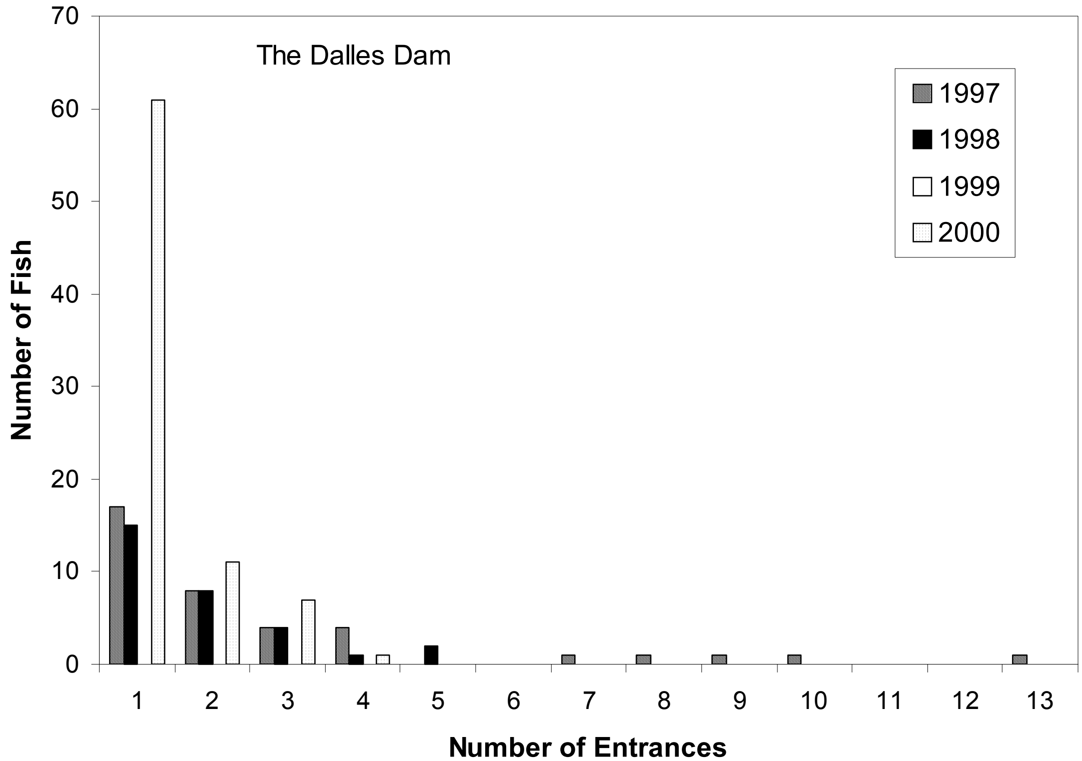


Figure 23. The number of individual radio-tagged lamprey that made one or more (up to 13) separate successful entrances at The Dalles Dam fishways in each year of study (1997, 1998, and 2000).

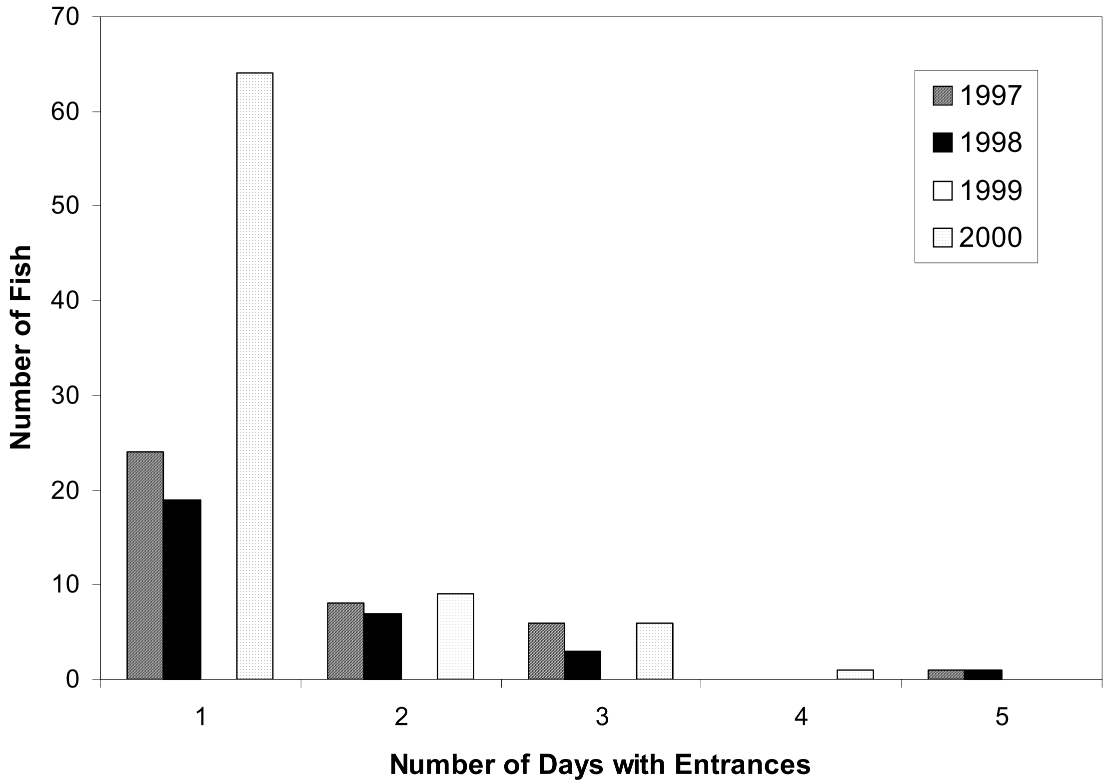


Figure 24. The number of radio-tagged lamprey that made separate successful entrances at The Dalles Dam fishways on one or more days (up to 5 days) in each year of study (1997, 1998, and 2000).

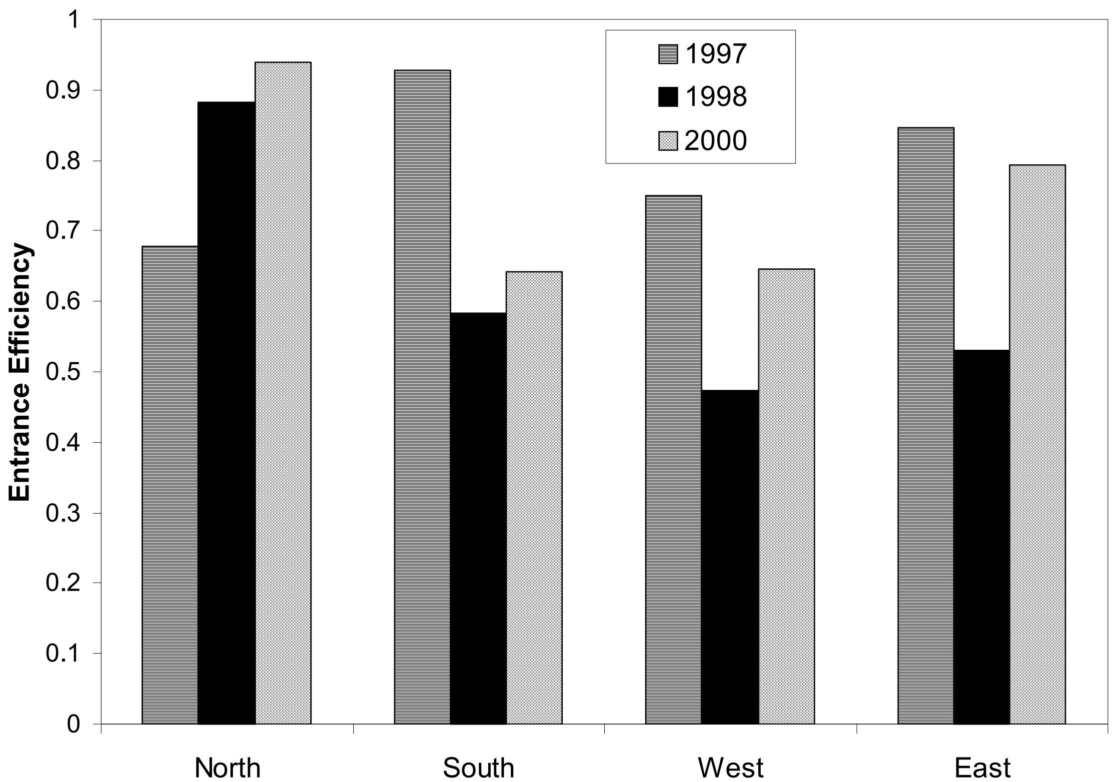


Figure 25. Entrance efficiency (proportion of lamprey that successfully entered of those that approached) at each of The Dalles Dam fishway entrances: the North Fish Ladder entrance on the Washington shore (North), the East Fish Ladder entrance at the south end of the sprillway (South), the East Fish Ladder entrance at the west end of the powerhouse (West) and the East Fish Ladder entrance at the east end of the powerhouse (East) in 1997, 1998, and 2000.

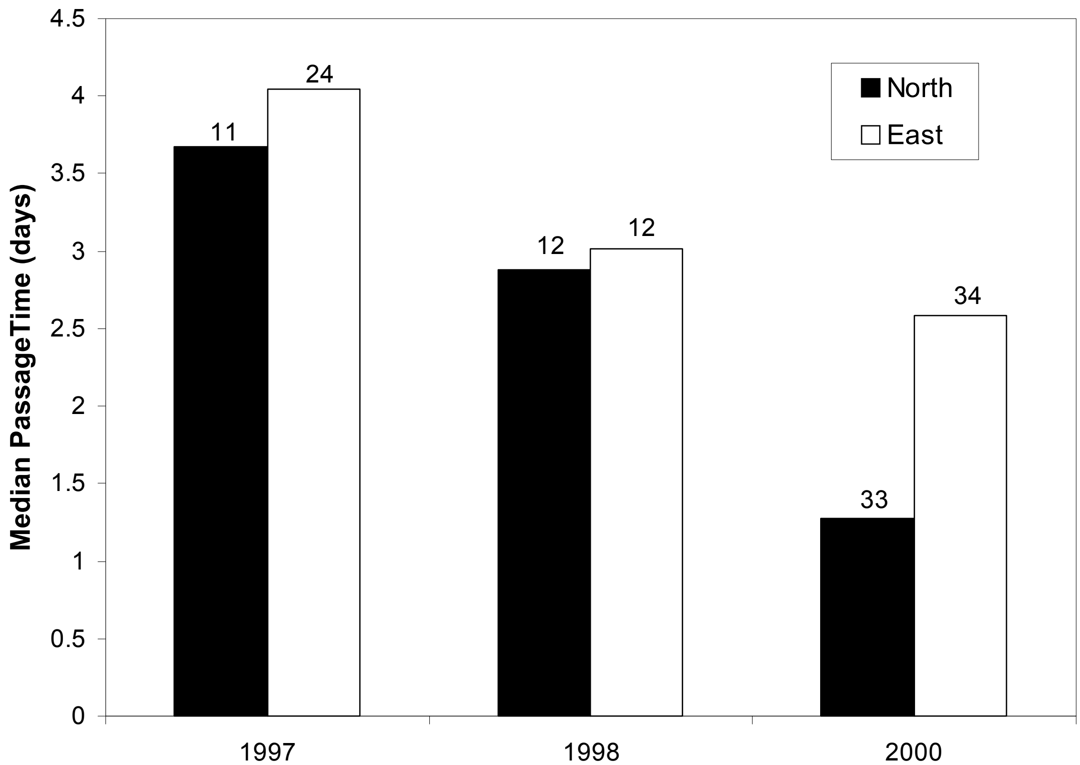


Figure 26. Median passage time (days from first detection outside a fishway entrance to last detection at the top of the fish ladder) for fish that used the North and East fishways at The Dalles Dam. Only fish with known times of first approach at an entrance and known times of exit into the forebay were used for this analysis (numbers of fish in each year for each fishway are indicated at the tops of the bars).

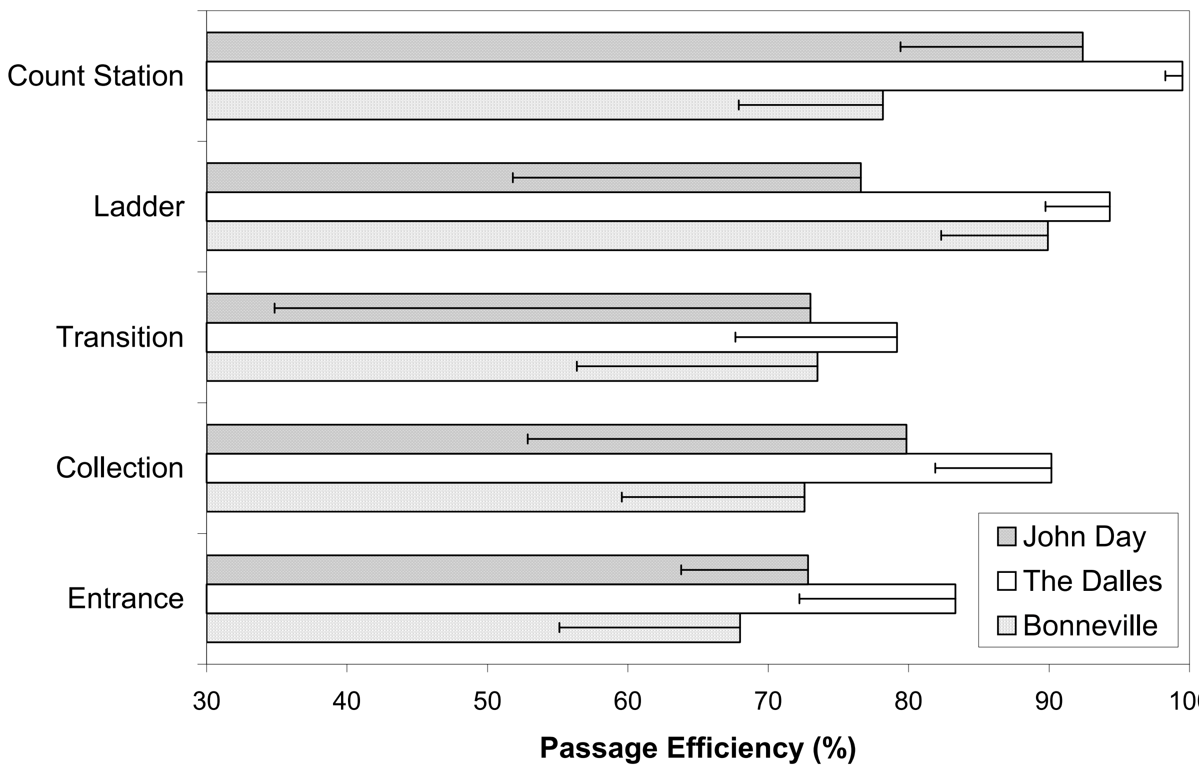


Figure 27. Mean passage efficiency (the number of lamprey that passed through each area divided by the number that approached each area) for areas of interest (entrances, collection channels, transition areas, ladders, and count stations) at Bonneville, The Dalles, and John Day Dams in 1997-2000. Standard deviations are indicated by error bars.

John Day Dam

In the vicinity of the John Day Dam tailrace we detected 42 of the radio-tagged lamprey that were originally released below Bonneville Dam. In addition, 28 of the 50 fish that we released above The Dalles Dam were detected in this area. Of the 70 fish from both release sites that were found below John Day Dam, 66 approached entrances to the fishways. Far more fish approached entrances to the powerhouse fishway system on the Oregon shore (South, n = 66 approached) than entrances to the fishway on the Washington shore (North, n = 27 approached). However, entrance efficiency was similar for the two fishways (Table 3).

Passage efficiencies differed among areas within the two fishways. Passage efficiencies through the longer and more complex collection channel and transition areas at the South fishway were lower (81 and 77%) than through the same areas of the North fishway (100 and 94%). All lamprey that entered the ladder area at the South fishway successfully passed upstream.

In contrast, 7 of 17 fish (41%) that entered the ladder area at the North fishway fell back downstream before reaching the count station. Consequently, overall passage efficiencies for the two fishways were similar. Analysis of variance indicated no significant differences in passage efficiencies among years ($P = 0.06$), fishways ($P = 0.91$) or areas within fishways ($P = 0.18$) at John Day Dam; however, these data were based on very few fish in 1997 and 1998 (Table 3).

In 2000, 28 (56%) of the 50 fish released below John Day Dam were detected at the dam, and of these 5 (18%) successfully passed over John Day Dam. In contrast, 42 of the fish released below Bonneville Dam were eventually detected at John Day Dam in 2000, and of these 23 (55%) successfully passed over the dam. The passage efficiency at John Day Dam for fish released below John Day Dam was significantly lower ($P < 0.01$) than for fish released below Bonneville Dam.

Table 3. Number of radio-tagged lamprey that passed through each area within each fishway at John Day Dam in 1997, 1998, and 2000. Passage efficiency is in parenthesis (number of lamprey that passed through the area/the number that approached that area × 100).

Fishway	Area	1997	1998	1999	2000
John Day South	Entrance	20 (87%)	6 (60%)	-	48 (73%)
	Collection	13 (65%)	6 (100%)	-	39 (81%)
	Transition	13 (100%)	6 (100%)	-	30 (77%)
	Count station	12 (92%)	6(100%)	-	21 (70%)
	Ladder	9 (75%)	4 (67%)	-	21 (100%)
John Day North	Entrance	3 (75%)	3 (75%)	-	18 (67%)
	Collection	1 (33%)	3 (100%)	-	18 (100%)
	Transition	0	2 (67%)	-	17 (94%)
	Ladder	0	2 (100%)	-	7 (41%)
	Count station	0	0-		7 (100%)

Overall Passage Patterns

Overall passage efficiency differed significantly among dams (Fig. 28). Less than 50% of the fish that approached Bonneville Dam successfully passed over it in any year. Passage efficiency at The Dalles Dam was higher than at Bonneville or John Day Dams in all years, but multiple comparison testing revealed that the only statistically significant difference was between passage efficiency at The Dalles and John Day Dams ($P < 0.01$). Passage times for lamprey also differed among dams (Fig. 29). Lamprey required more time to pass over Bonneville Dam than either The Dalles or John Day Dams. In all years except 2000, no lamprey were detected at McNary Dam.

In 2000, 13 of the 23 fish that passed over John Day Dam were detected at McNary Dam, and 11 of these (85%) successfully passed over the dam. Ten of these 11 successful fish had been released downstream from Bonneville Dam. Of the three fish that did not get over McNary Dam, one did not approach the entrances, one approached but did not enter, and the third fish entered but did not get beyond the transition area in the North fishway (located on the Washington shore). Of the 11 fish that passed over McNary Dam, 10 used the South fishway (adjacent to the powerhouse on the Oregon shore) and 1 passed through the North fishway.

Lamprey rarely fell back downstream after successfully passing over a dam. Of the fish that successfully passed over Bonneville Dam, less than 5% fell back downstream to below that dam in any year of tracking: 1 in 1997, 1 in 1998, 4 in 1999, and 4 in 2000. In 1998 and 2000, 4% of the lamprey that passed over The Dalles Dam were later detected downstream from that dam. However, in 2000, we noted that 17% of the 23 fish that passed over John Day Dam fell back downstream.

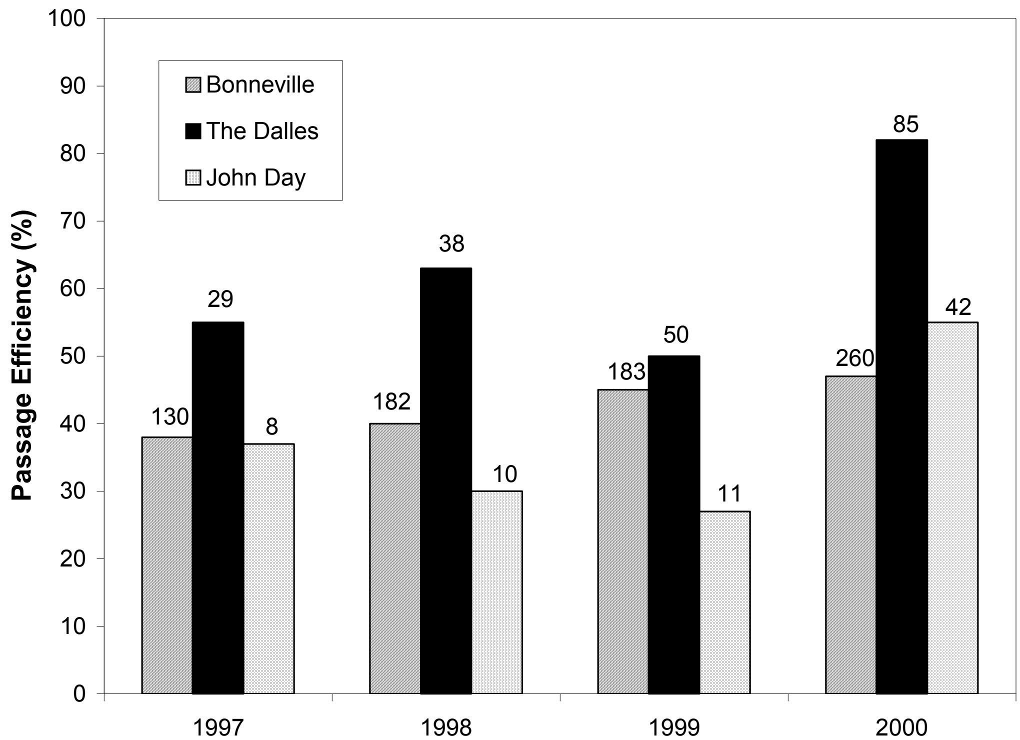


Figure 28. Overall passage efficiency (the number of lamprey that passed over each dam divided by the number that approached it) for Bonneville, The Dalles, and John Day dams in 1997-2000. The number of lamprey that approached are shown above each bar.

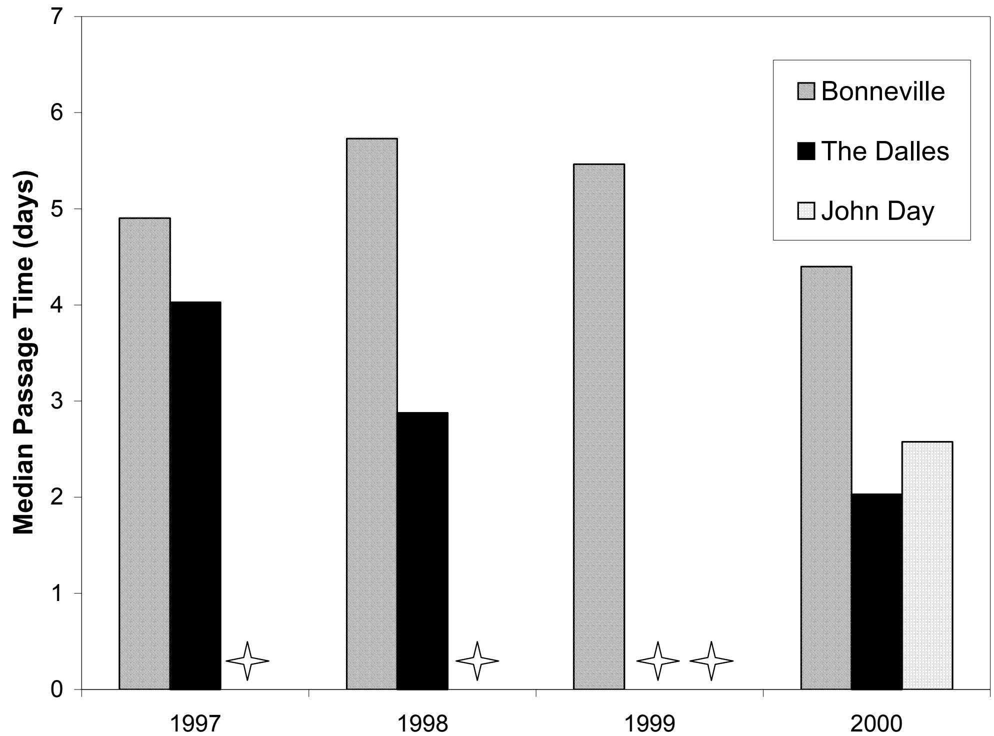


Figure 29. Median passage time (days from first detection outside a fishway entrance to last detection at the top of the fish ladder) for fish that passed Bonneville, The Dalles, and John Day Dams in 1997-2000. Only fish with known times of first approach at an entrance and known times of exit into the forebay were used for this analysis. Stars indicate years with insufficient data to compute passage times.

Tributary Use and Seasonal Distribution

We monitored the mouths of all major tributaries between Bonneville Dam and McNary Dam and were able to identify lamprey entrances into each tributary. In 2000, we detected lamprey in two Columbia River tributaries: the Deschutes and John Day Rivers.

We found 35 lamprey in the Deschutes River (which enters the Columbia River 20 km upstream from The Dalles Dam) and 10 of these fish were eventually detected on our receiving station at Shearar's Falls (396 km from the mouth of the Columbia River, 68 km from the confluence). Of the fish we located in the Deschutes River, 17 had been released below Bonneville Dam in 2000, 2 had been released below Bonneville Dam in 1999 (these fish had transmitters with a 14-month battery life), and 16 had been released above The Dalles Dam in 2000.

We detected 13 radio-tagged lamprey as they entered the John Day River (which enters the Columbia River 3 km upstream from John Day Dam). Eight of these lamprey were originally released below Bonneville Dam in 2000, and one had been released below Bonneville Dam in 1999. The remaining four (codes 6-4, 6-9, 7-17, and 8-100) had been captured and radio-tagged at the John Day River in 2000 by the U.S. Geological Survey as part of a spawning habitat study (Bayer et al. 2000). The fine-scale distribution of lamprey tagged in both studies was similar, with overwintering sites identified throughout the mainstem to river kilometer 175 (Bayer et al. 2000).

After October 1999, we detected 74 (37%) of the lamprey tagged in 1999. The mean number of days between the last detection in the 1999 tracking year (May-October) and the last detection in 2000 was 321 days with a minimum of 97 days and a maximum of 597 days (Table 4). Of these fish, 21 were found at the same location (± 0.5 km) on subsequent surveys. Sixteen of the 74 lamprey moved 1-31 km downstream from their last known position in 1999: 11 of these were downstream from Bonneville Dam, 3 were downstream from The Dalles Dam, and 2 were downstream from John Day Dam. Nineteen others were found less than 5 km upstream from their previous position (Table 4). There was evidence that at least some of these fish made short local movements between mobile tracking surveys. For example, four fish were detected on fixed site receivers as they approached either Bonneville or The Dalles Dam during the summer of 2000, but did not pass over and were subsequently found in the dam tailraces.

Table 4. Year 2000 detections of lamprey radio-tagged in 1999, including the last date and location detected in 1999. The last date and location detected in 2000, time at large (days from last 1999 detection to last 2000 detection) and the maximum distance (km) that they traveled from the1999 position are also given. Fish that passed over a dam while at large are indicated by a Y.

Channel	Code	1999 Date	1999 RKM	2000 Date	2000 RKM	Time at large (d)	Max distance (km)	Passed dam
24	1	06/19/99	232	05/08/00	347	324	115	Y
	3	07/27/99	232	04/04/00	235	252	3	N
	9	08/29/99	232	03/21/00	235	205	3	N
	10	08/03/99	235	04/18/00	235	259	0	N
	11	11/06/99	235	04/24/00	235	170	0	N
	15	09/08/99	232	04/04/00	235	209	3	N
	16	07/23/99	232	04/04/00	235	256	3	N
	17	10/31/99	232	04/04/00	235	156	3	N
	18	06/20/99	305	04/10/00	308	295	3	N
	20	07/08/99	305	03/21/00	292	257	-13	N
	25	08/21/99	232	07/14/00	247	328	15	Y
	29	08/10/99	232	03/20/00	215	223	-17	N
	30	12/08/99	305	08/16/00	305	252	0	N
	34	06/29/99	305	06/01/00	308	338	3	N
	37	08/07/99	347	08/18/00	JDR363	377	16	N
	40	09/07/99	232	09/01/00	232	360	0	N
	47	08/04/99	DES329	11/01/00	DES393	455	64	N
	55	07/27/99	235	05/23/00	232	301	-3	N
	56	08/16/99	305	06/01/00	303	290	-2	N
	58	08/06/99	235	07/25/00	235	354	0	N
	60	07/28/99	235	04/04/00	235	251	0	N
	62	09/06/99	235	09/01/00	235	361	0	N
	69	10/15/99	235	09/01/00	235	322	0	N
	71	08/22/99	233	10/20/00	212	425	-21	N
	72	08/25/99	232	10/09/00	308	411	76	Y
	73	08/18/99	DES329	11/18/00	DES385	458	56	N
	75	09/12/99	232	09/01/00	235	355	3	N
	78	08/13/99	235	10/31/00	231	445	-4	N
	79	08/24/99	232	05/08/00	347	258	115	Y
	86	12/03/99	235	10/03/00	235	305	0	N
	91	08/23/99	233	07/21/00	234	333	1	N
	92	09/04/99	232	11/17/00	226	440	-6	N
	95	12/01/99	235	04/18/00	235	139	0	N
	97	11/12/99	232	11/01/00	231	355	-1	N

Table 4. Continued.

Channel	Code	1999 Date	1999 RKM	2000 Date	2000 RKM	Time at large (d)	Max distance (km)	Passed dam
24	98	09/24/99	235	04/18/00	235	207	0	N
	100	11/27/99	235	07/21/00	235	237	0	N
25	5	07/10/99	235	08/17/00	308	404	73	Y
	7	07/23/99	345	06/01/00	324	314	-21	N
	8	07/23/99	232	09/01/00	347	406	115	Y
	12	07/20/99	235	07/12/00	234	358	-1	N
	17	10/30/99	232	09/01/00	235	307	3	N
	20	07/15/99	308	03/20/00	328	249	20	N
	21	07/28/99	232	08/07/00	224	376	-8	N
	24	08/08/99	232	07/10/00	262	337	30	Y
	25	07/28/99	235	06/08/00	235	316	0	N
	26	11/29/99	235	05/11/00	235	164	0	N
	32	08/04/99	308	07/10/00	308	341	0	N
	33	07/22/99	347	11/01/00	328	468	-19	N
	35	07/26/99	305	10/23/00	328	455	23	Y
	36	08/04/99	235	09/24/00	239	417	4	N
	40	07/19/99	235	09/01/00	235	410	0	N
	42	07/29/99	232	06/08/00	235	315	3	N
	46	08/01/99	347	03/20/01	DES389	597	80	N
	48	08/09/99	235	07/25/00	235	351	0	N
	53	08/18/99	304	06/01/00	273	288	-31	N
	54	11/27/99	232	06/10/00	235	196	3	N
	56	10/01/99	232	04/18/00	308	200	76	Y
	57	07/31/99	305	10/08/00	308	435	3	N
	64	08/17/99	232	11/22/99	235	97	3	N
	67	08/24/99	235	07/07/00	235	318	0	N
	68	08/21/99	232	06/02/00	227	286	-5	N
	69	08/05/99	235	06/01/00	228	301	-7	N
	71	09/06/99	232	10/03/00	235	393	3	N
	73	08/04/99	232	07/25/00	234	356	2	N
	74	08/14/99	235	06/17/00	235	308	0	N
	75	10/03/99	345	05/28/00	347	238	2	N
	77	08/17/99	235	08/11/00	232	360	-3	N
	79	08/21/99	308	10/11/00	328	417	20	N
	80	09/16/99	232	09/10/00	232	360	0	N
	82	10/01/99	235	06/01/00	308	244	73	Y
	83	08/04/99	235	10/31/00	308	454	73	N
	84	07/29/99	235	10/04/00	308	433	73	N
	89	10/09/99	345	06/13/00	347	248	2	Y
	99	09/30/99	235	06/08/00	235	252	0	N

Eighteen of the 74 fish we found traveled 15-115 km upstream between detections (Table 4). Of these fish, 11 successfully passed over at least one dam in their second year in the river: 5 went over Bonneville Dam only, 1 went over The Dalles Dam only, 3 went over both Bonneville and The Dalles Dams, and 1 went over John Day Dam. Two of the fish had passed over Bonneville Dam prior to 18 April, and two others passed over both Bonneville and The Dalles Dams prior to 11 May. The other fish were not detected upstream from the dams until summer, but could have migrated upstream earlier in the year. Fish that approached or passed over dams in 2001 were not included in computations of 2000 passage efficiencies.

We detected four of the 74 fish in tributaries: 3 in the Deschutes River and 1 in the John Day River. Two of the fish that entered the Deschutes River had migrated to the mouth of the Deschutes River in 1999 (the year they were tagged). One of these fish (24-47) entered the River on 12 July 2000 and was relocated at RKM 389 on 22 August 2000 and last found at RKM 393 on 1 November 2000. The other was at Shearar's Falls from 21-22 May 2000 and then was found on four occasions in the area between RKM 384-385 in August to December 2000. A third fish migrated to John Day Dam in 1999 but was found in the Deschutes River at RKM 381 on 22 August 2000 and at RKM 389 on 1 November 2000. The lamprey that entered the John Day River had passed over John Day Dam in 1999 (the year it was tagged) and was found at RKM 363 in the John Day River on 24 May 2000 and 18 August 2000.

After October 2000, we detected 125 (36%) of the lamprey tagged in 2000. The mean time at large (the number of days between the last detection in the 2000 tracking year (May-October) and the last detection in 2001) was 135 days, with a minimum of 13 days and a maximum of 325 days (Table 5). Of these fish, 47 were found at the same location (± 0.5 km) on subsequent surveys.

Fifty-five of the 125 lamprey moved 1-112 km downstream from their last known position in 2000: 30 of these were downstream from Bonneville Dam, 7 were downstream from The Dalles Dam (in the Bonneville pool), and 7 were downstream from John Day Dam (in The Dalles pool). The remaining 11 fish made downstream movements (1-93 km) in the Deschutes River. Eight lamprey moved 15-257 km upstream between 2000 and 2001: one below Bonneville Dam, one in the Bonneville pool, one above McNary Dam, one in the Klickitat River, two in the Deschutes River and two in the John Day River. No fish were detected passing over a dam between tagging years (Table 5).

Table 5. Year 2001 detections of lamprey radio-tagged in 2000, including the last date and location detected in 2000. The last date and location detected in 2001, time at large (days from last 2000 detection to last 2001 detection) and the maximum distance (km) that they traveled from the 2000 position are also given. Fish that passed over a dam while at large are indicated by a Y.

Channel	Code	2000 Date	2000 RKM	2001 Date	2001 RKM	Time at large (d)	Max distance (km)	Passed dam
6	1	06/22/00	235	02/02/01	235	225	0	N
6	2	07/24/00	235	02/02/01	235	193	0	N
6	5	10/31/00	235	11/13/00	235	13	0	N
6	7	10/21/00	DES391	12/07/00	DES393	47	2	N
6	8	07/25/00	233	01/03/01	234	162	1	N
6	13	05/26/00	232	11/13/00	234	171	2	N
6	29	09/22/00	234	02/02/01	234	133	0	N
6	34	08/15/00	235	01/04/01	217	142	-18	N
6	39	10/20/00	232	12/05/00	231	46	-1	N
6	43	07/21/00	235	01/07/01	232	170	-3	N
6	44	09/22/00	234	02/02/01	234	133	0	N
6	45	10/31/00	235	02/02/01	235	94	0	N
6	49	09/22/00	234	02/27/01	234	158	0	N
6	52	09/01/00	234	02/02/01	234	154	0	N
6	55	10/31/00	234	02/27/01	234	119	0	N
6	64	10/12/00	308	02/02/01	234	113	-74	N
6	66	10/17/00	347	02/27/01	347	133	0	N
6	75	08/05/00	347	01/09/01	329	157	-18	N
6	84	10/14/00	235	04/12/01	234	180	-1	N
6	92	10/31/00	235	02/02/01	235	94	0	N
6	93	10/21/00	DES389	04/22/01	DES389	183	0	N
6	102	09/20/00	325	11/01/00	DES397	42	72	N
6	107	10/21/00	DES415	11/18/00	DES417	28	2	N
6	112	08/22/00	308	01/03/01	234	134	-74	N
6	117	09/22/00	234	02/02/01	234	133	0	N
6	118	10/21/00	DES395	04/22/01	DES395	183	0	N
6	120	10/21/00	DES394	02/03/01	DES386	105	-8	N
6	121	10/10/00	DES395	05/15/01	DES370	217	-25	N
6	122	10/31/00	300	04/12/01	305	163	5	N
6	123	10/21/00	DES398	05/19/01	DES347	210	-51	N
6	124	08/17/00	347	02/02/01	235	169	-112	N
6	125	09/26/00	DES380	05/15/01	DES389	231	9	N
6	127	10/26/00	213	02/02/01	212	99	-1	N

Table 5. Continued.

Channel	Code	2000 Date	2000 RKM	2001 Date	2001 RKM	Time at large (d)	Max distance (km)	Passed dam
6	128	09/20/00	347	04/12/01	347	204	0	N
6	129	09/19/00	470	11/19/00	539	61	69	N
6	130	10/31/00	325	04/12/01	323	163	-2	N
6	131	08/24/00	DES329	02/02/01	235	162	-93	N
6	132	09/15/00	347	12/01/00	347	77	0	N
6	133	10/18/00	347	02/03/01	347	108	0	N
6	134	10/23/00	DES332	05/06/01	335	195	11	N
6	135	09/08/00	DES329	11/22/00	DES396	75	67	N
6	144	09/20/00	347	04/12/01	347	204	0	N
6	146	10/30/00	324	04/12/01	324	164	0	N
6	148	09/28/00	347	11/01/00	347	34	0	N
6	149	09/27/00	DES396	04/07/01	DES396	192	0	N
6	150	10/21/00	DES398	04/22/01	DES398	183	0	N
6	152	10/18/00	347	04/12/01	347	176	0	N
6	153	10/10/00	DES397	05/06/01	328	208	-69	N
6	157	10/23/00	DES330	05/19/01	DES332	208	2	N
6	159	10/16/00	347	01/03/01	342	79	-5	N
6	160	10/23/00	232	02/28/01	219	128	-13	N
6	161	10/13/00	235	04/12/01	234	181	-1	N
6	162	10/21/00	DES394	05/15/01	DES394	206	0	N
6	163	10/27/00	DES374	05/19/01	DES343	204	-31	N
6	167	10/23/00	DES366	05/19/01	DES344	208	-22	N
6	169	10/16/00	232	02/02/01	231	109	-1	N
7	3	10/16/00	229	11/13/00	227	28	-2	N
7	5	07/29/00	345	12/01/00	347	125	2	N
7	7	09/22/00	234	01/03/01	234	103	0	N
7	8	10/25/00	JDR481	01/30/01	JDR481	97	0	N
7	9	10/31/00	235	12/05/00	234	35	-1	N
7	12	06/24/00	232	01/04/01	217	194	-15	N
7	13	10/31/00	234	02/02/01	235	94	1	N
7	15	10/31/00	234	02/27/01	249	119	15	N
7	17	07/22/00	308	01/03/01	234	165	-74	N
7	20	10/21/00	DES397	02/03/01	DES389	105	-8	N
7	22	10/31/00	234	01/03/01	234	64	0	N
7	23	09/21/00	208	02/02/01	208	134	0	N
7	25	10/20/00	220	01/04/01	217	76	-3	N
7	27	07/12/00	234	04/12/01	235	274	1	N
7	36	07/16/00	325	12/06/00	310	143	-15	N

Table 5. Continued.

Channel	Code	2000 Date	2000 RKM	2001 Date	2001 RKM	Time at large (d)	Max distance (km)	Passed dam
7	38	09/22/00	217	02/02/01	205	133	-12	N
7	39	10/31/00	308	02/02/01	308	94	0	N
7	40	10/31/00	235	02/02/01	234	94	-1	N
7	41	10/30/00	293	02/02/01	293	95	0	N
7	43	08/05/00	328	04/12/01	328	250	0	N
7	45	10/31/00	235	02/02/01	235	94	0	N
7	48	10/07/00	235	02/02/01	234	118	-1	N
7	49	08/09/00	235	11/13/00	234	96	-1	N
7	50	09/01/00	234	02/27/01	234	179	0	N
7	54	10/31/00	230	02/27/01	231	119	1	N
7	55	10/31/00	234	02/02/01	234	94	0	N
7	62	10/31/00	235	02/02/01	235	94	0	N
7	66	07/20/00	235	02/02/01	233	197	-2	N
7	67	08/12/00	235	12/05/00	234	115	-1	N
7	68	08/14/00	347	07/05/01	JDR604	325	257	N
7	70	10/31/00	235	02/02/01	235	94	0	N
7	77	10/31/00	235	01/03/01	234	64	-1	N
7	78	08/22/00	235	04/12/01	234	233	-1	N
7	81	10/21/00	DES371	12/02/00	DES369	42	-2	N
7	92	10/25/00	JDR459	11/21/00	JDR460	27	1	N
7	94	10/21/00	DES368	02/03/01	DES373	105	5	N
7	105	10/20/00	230	11/17/00	229	28	-1	N
7	106	08/22/00	235	11/13/00	234	83	-1	N
7	110	08/28/00	235	05/19/01	KTR293	264	58	N
7	113	10/21/00	DES366	04/22/01	DES366	183	0	N
7	117	10/23/00	DES350	12/01/00	DES351	39	1	N
7	120	10/31/00	324	02/27/01	324	119	0	N
7	122	10/31/00	235	04/12/01	234	163	-1	N
7	123	10/06/00	235	02/02/01	234	119	-1	N
7	125	10/22/00	347	04/12/01	335	172	-12	N
8	1	10/16/00	229	11/13/00	227	28	-2	N
8	2	08/22/00	308	11/28/00	305	98	-3	N
8	5	10/31/00	235	02/27/01	234	119	-1	N
8	6	10/31/00	235	02/27/01	234	119	-1	N
8	9	10/31/00	235	01/03/01	234	64	-1	N
8	11	07/20/00	308	01/03/01	234	167	-74	N
8	12	10/20/00	232	03/25/01	232	156	0	N
8	13	10/19/00	308	02/28/01	303	132	-5	N

Table 5. Continued.

Channel	Code	2000 Date	2000 RKM	2001 Date	2001 RKM	Time at large (d)	Max distance (km)	Passed dam
8	14	10/23/00	232	03/25/01	232	153	0	N
8	16	10/26/00	196	03/22/01	232	147	36	N
8	17	10/25/00	JDR356	01/24/01	JDR356	91	0	N
8	19	08/07/00	235	03/26/01	232	231	-3	N
8	20	10/17/00	347	02/27/01	347	133	0	N
8	21	10/31/00	234	03/25/01	232	145	-2	N
8	25	09/01/00	234	12/05/00	234	95	0	N
8	27	09/01/00	234	02/02/01	234	154	0	N
8	28	10/25/00	JDR356	04/10/01	JDR496	167	140	N
8	29	08/13/00	308	12/05/00	233	114	-75	N
8	37	10/31/00	235	04/12/01	234	163	-1	N
8	39	09/08/00	232	03/22/01	232	195	0	N
8	45	10/31/00	235	02/02/01	235	94	0	N
8	49	09/01/00	346	12/05/00	234	95	-112	N
8	51	07/30/00	235	02/02/01	235	187	0	N
8	52	09/03/00	235	02/02/01	234	152	-1	N

Count Station Lighting Experiments

On 20-21 March 2000 we measured light during day and night at both the Bradford Island and Washington-shore count windows every 30 min using continuously recording light meters (Onset Stowaway LI). The light intensity at a position near the middle of the window was higher at the Bradford count station (2.7-2.8 lux) than at the count station on the Washington shore (1.6-1.9 lux; Fig. 30). At both count station windows, a light meter positioned at the upstream end of each window (within 5 cm of the window frame and 70 cm below the water surface) recorded lower light intensity than a meter positioned at the downstream end of the window (within 5 cm of the frame) at the same depth (Figs. 31). At the Bradford Island window (33 cm from the upstream edge of the window), light intensity within 3 cm of the water surface was higher than light intensity recorded at a position 1 cm from the bottom of the window (Fig. 32). However, at the Washington shore window, light intensity was higher near the bottom of the window than near the water surface (Fig. 32).

To capture daily variability in light intensity, we deployed continuously-monitoring light meters from 2 to 21 June 2000 at the Bradford Island, Washington shore, and Upstream Migrant Tunnel (UMT) count windows. At each window the two light meters were positioned 18 cm down from the surface and 23 cm up from the bottom. During the first two days, diel light intensity was unchanged at Bradford and the Washington shore ladders, but showed a moderate increase during the day at the UMT window (Fig. 33). Thereafter, a clear diel pattern of increased light during the day was recorded at all three windows (Figs. 34), although light intensity at Bradford Island was relatively low during all times of the day and night.

On 21 March 2000, we measured light during the day at the Bradford Island counting station using a spectroradiometer (LICOR 1800) fitted with a remote cosine receptor (LICOR 1800-11). This instrument measures irradiance at specific wavelengths and provides a measure of light quality. Under the normal lighting conditions used during salmon counts on Bradford Island, irradiance at a position 52 cm from the top of the window peaked at 574 nm (Fig. 35). At a deeper position (105 cm from the top of the window) irradiance peaked at 564 nm (Fig. 35). This pattern was not as apparent at the visitor's window (Fig. 35). This was likely due to the effects of the lights used during counts (overhead spotlights, and crowder lights). When we turned off the overhead spotlights the peak irradiance shifted up (566 nm), and when we turned off the crowder lights, peak irradiance shifted down (558 nm; Fig. 36).

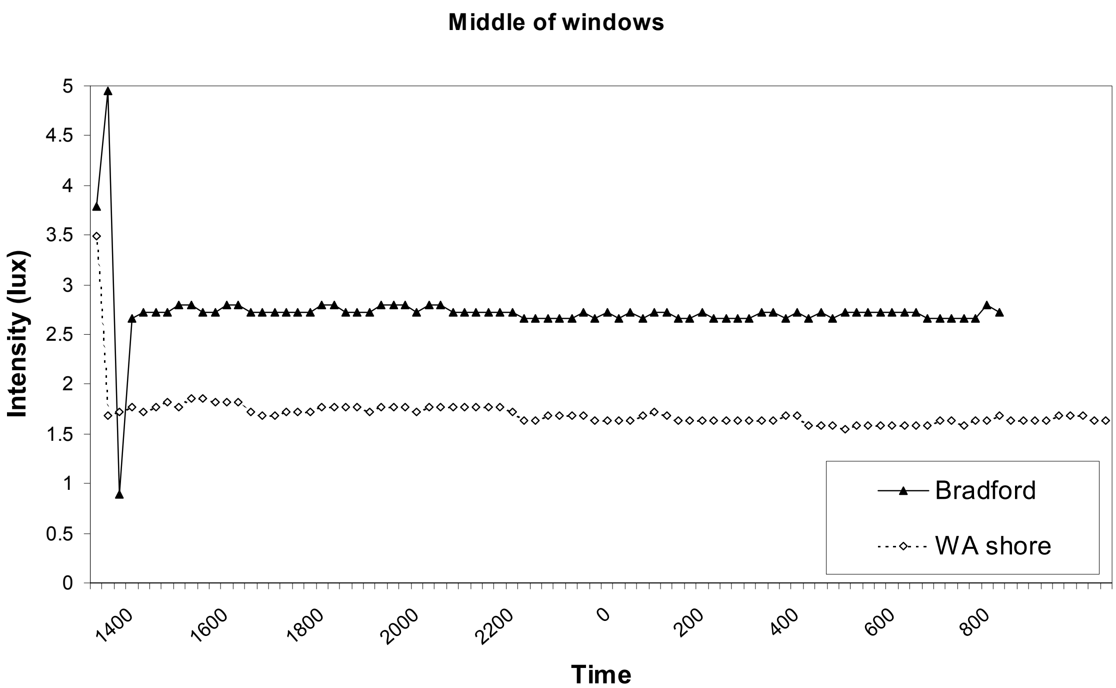
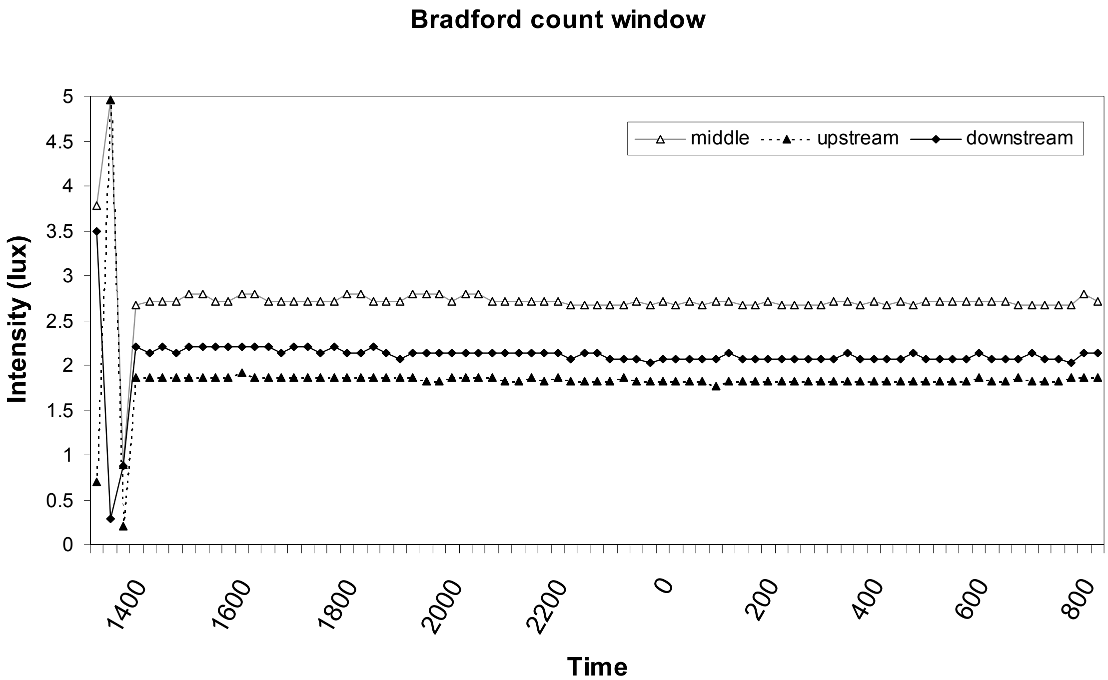


Figure 30. Light intensity (lux) recorded in the middle of the count window on Bradford Island and on the Washington shore.



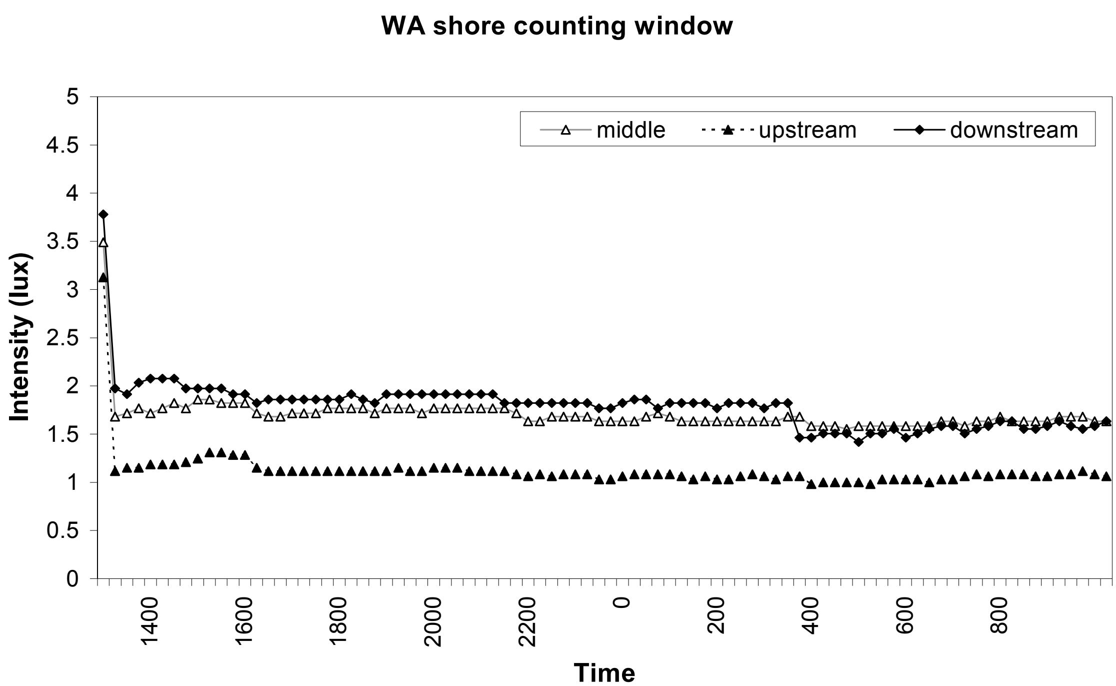
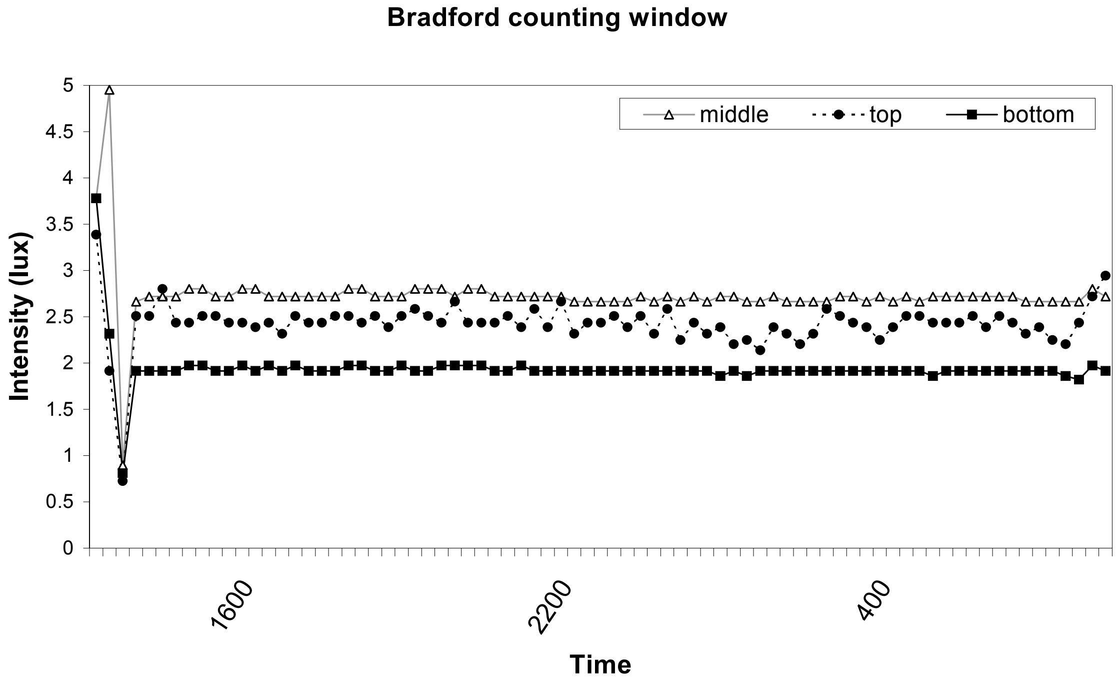


Figure 31. Light intensity (lux) recorded at positions in the middle and at the upstream and downstream ends of the count windows on Bradford Island (top) and the Washington shore (bottom).



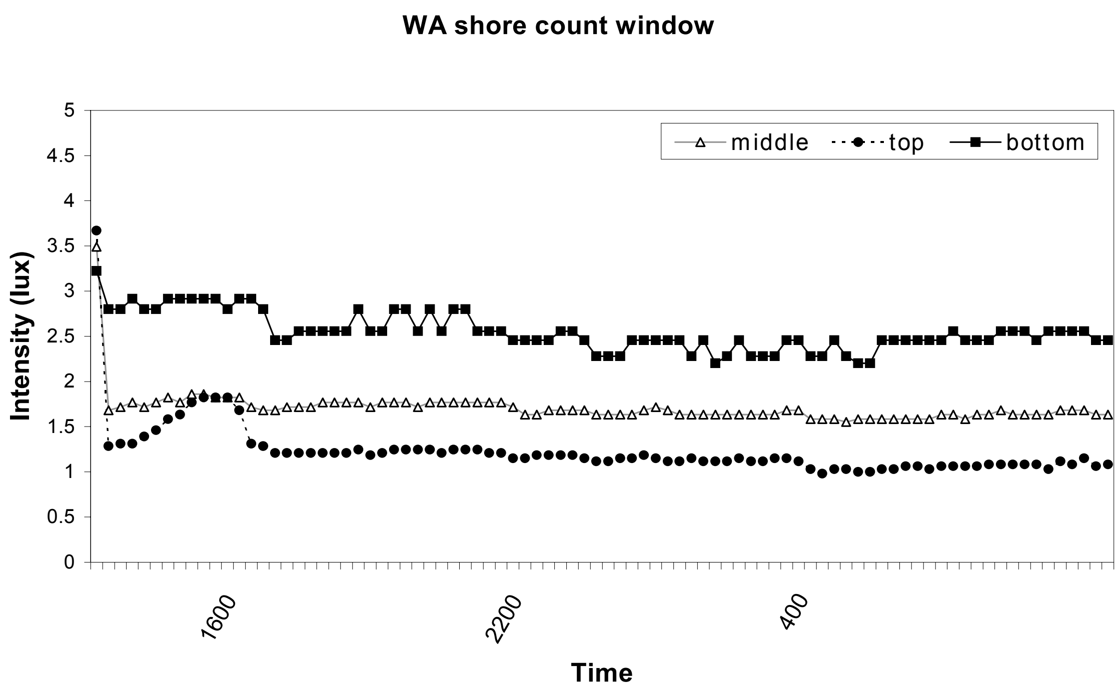


Figure 32. Light intensity (lux) recorded at positions in the middle and near the bottom and top of the count windows on Bradford Island (top) and the Washington shore (bottom).

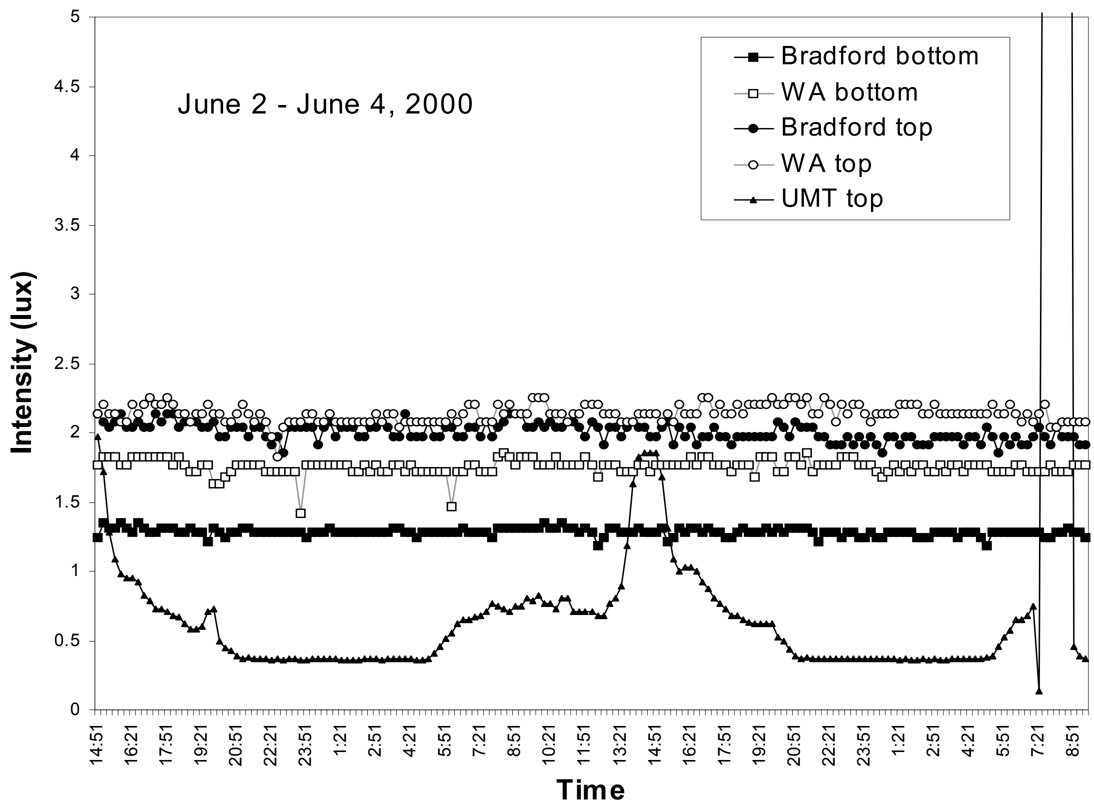


Figure 33. Light intensity (lux) recorded at the top and bottom of the Bradford Island and Washington shore count windows and at the top of the Upstream Migrant Tunnel (UMT) count window from 2 to 4 June 2000.

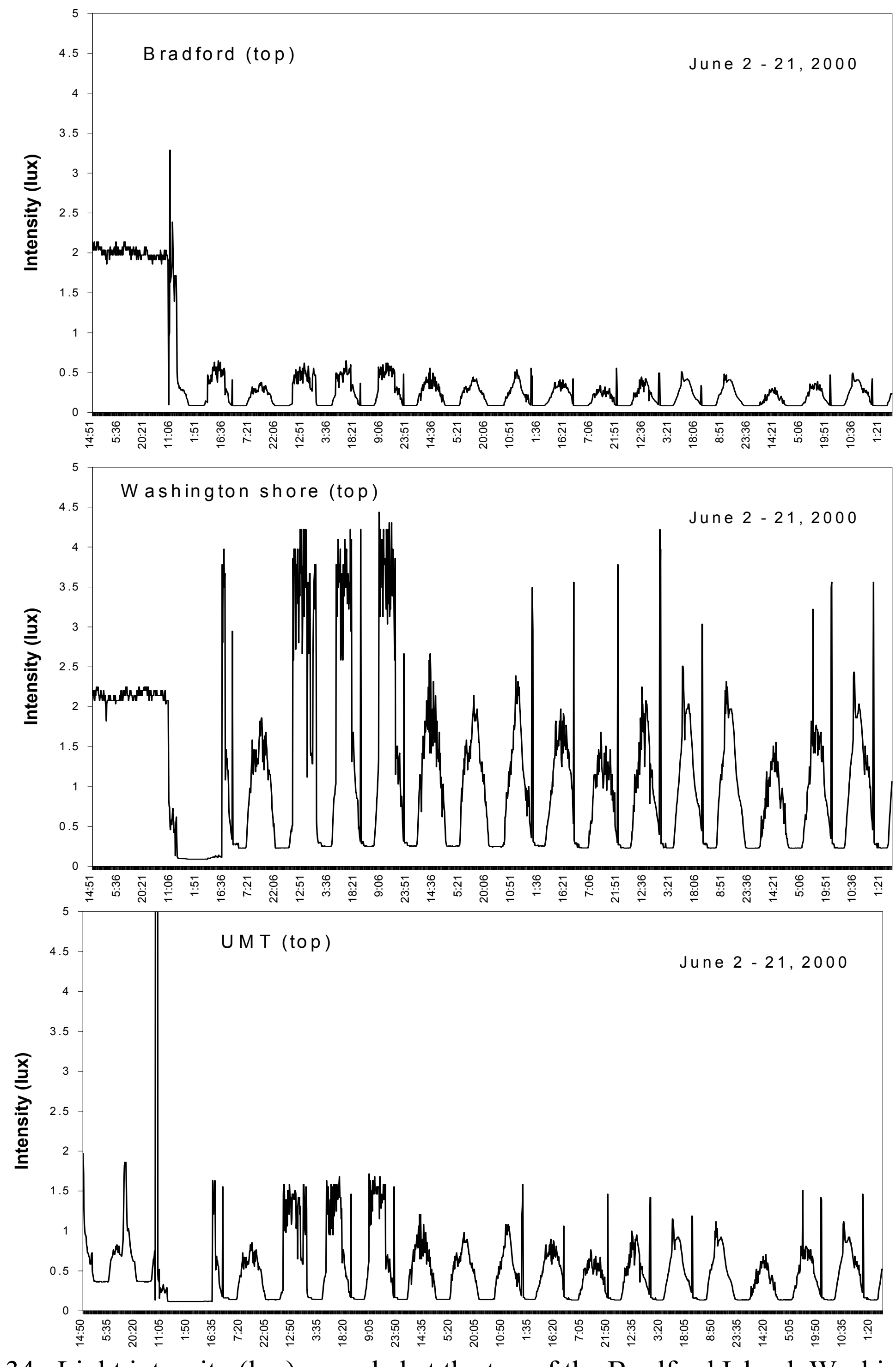


Figure 34. Light intensity (lux) recorded at the top of the Bradford Island, Washington shore and UMT count windows from 2 to 21 June 2000.

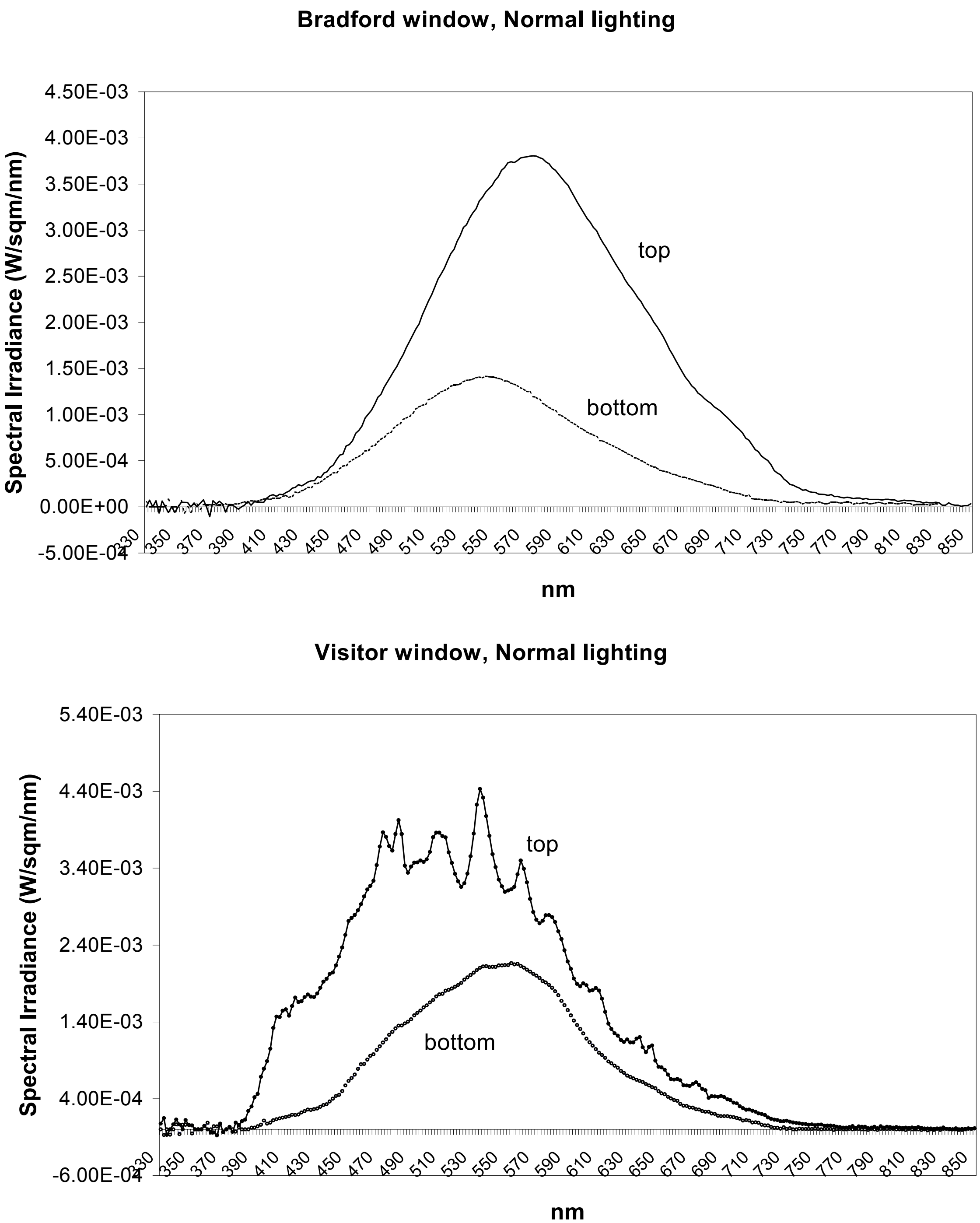


Figure 35. Spectral irradiance (W/sqm/nm) recorded near the top and bottom of the Bradford Island count (top) and visitor (bottom) windows during normal lighting conditions.

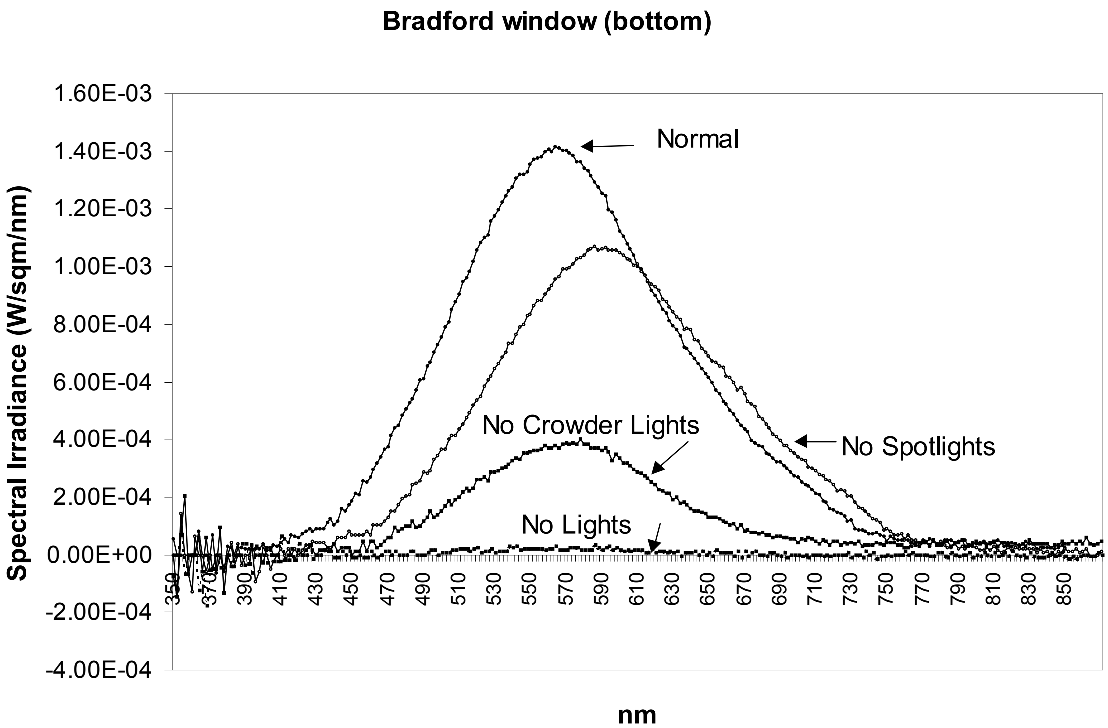


Figure 36. Spectral irradiance (W/sqm/nm) recorded near the bottom of the Bradford Island count window during normal lighting, when overhead spotlights were turned off, when crowder lights were turned off, and when all lights were turned off.

To test the effects of light quality and intensity on lamprey passage, we manipulated lighting at the experimental counting station from 17 July to 24 August 2000. On consecutive nights (2200-0500) we alternated a dark treatment (control) with a white light and a red light treatment and measured light levels at 135 cm depth and at positions 35 cm from the upstream end of the window (upstream) and 35 cm from the downstream edge of the window (downstream).

For each treatment, we computed the mean light levels each night at each position (Fig. 37) and then calculated the mean light intensity over all nights of the experiment. For the dark treatment, mean light intensity was 0.06 lux at the downstream location and 0.07 lux at the upstream location. For the red light treatment, mean light intensity was 5.18 lux at the downstream location and 3.30 lux at the upstream location. For the white light treatment, light intensity was similar to that measured during the red light treatment (5.44 downstream and 3.13 upstream).

Spectroradiometer recordings indicated that irradiance during the red light treatment was in the range from 570 to 720 nm, while irradiance during the white light treatment was over a broader range of wavelengths (440-690 nm). In spite of these differences, the catch per unit effort (CPUE) of lamprey at the trap located immediately upstream from this counting window was not significantly different among treatments ($P > 0.05$, Fig. 38).

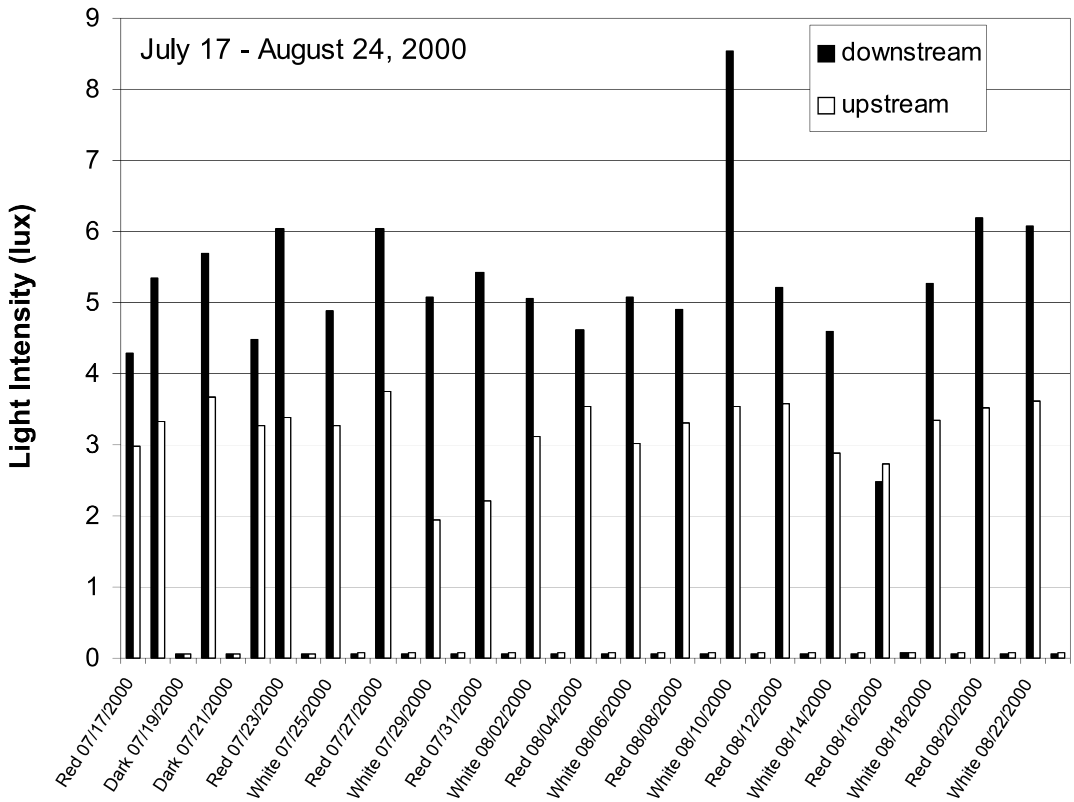


Figure 37. Mean light intensity (lux) during red, white, and dark treatments recorded at locations near the downstream and upstream ends of the experimental count window.

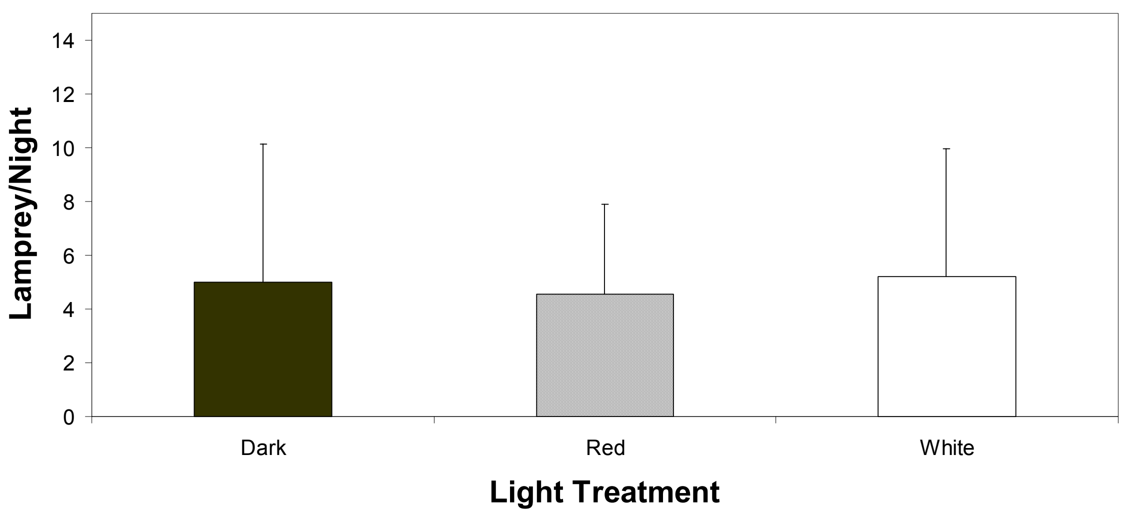


Figure 38. Mean catch per unit effort (number of lamprey captured each night) for the three light treatments conducted at the experimental count window: dark, red, and white. Error bars denote standard deviation.

DISCUSSION

Our trapping data indicated that lamprey CPUE was low in 2000 relative to previous years. In 2000 the CPUE at the downstream trap was 0.3 lamprey/h, while CPUE was 1.9 in 1997, 1.0 in 1998, and 0.7 in 1999 (Vella et al. 2001; Ocker et al. 2001). This may have been due in part to lower attraction of lamprey to the Washington-shore ladder in 2000 as a consequence of reduced discharge from PH2 in that year (Fig. 39). However, total lamprey counts at both of the Bonneville Dam counting windows also indicated that lamprey abundance was lower in 2000 than in 1998 or 1999 (Fig. 40).

The size range of lamprey tagged in 2000 was similar to that in previous years, and the median travel time to reach Bonneville Dam after release below the dam was slightly longer than in previous years (Table 6). In 2000 we used a 4.5-g transmitter, in addition to the 7.7-g transmitter used in 1997-1998. When we compared the travel times of fish tagged with the two transmitter sizes, we found that lamprey tagged with the smaller transmitter did not reach Bonneville Dam any faster after release than lamprey bearing the larger transmitter. Also, the percentage of lamprey detected at Bonneville Dam of those released was similar for the two groups (90% of the lamprey with the smaller tag and 88% of the lamprey with the larger tag).

In 2000, we experimented with the use of clove-oil-derived eugenol as an anesthetic for adult Pacific lamprey. Eugenol has been successfully used to anesthetize rainbow trout *Oncorhynchus mykiss* and a variety of other freshwater fishes (Keene et al. 1998). We found that a 60-ppm dose of eugenol generally induced anesthesia in approximately 5-7 min, which is similar to the time required to anesthetize adult lamprey using 70 ppm MS222. While we did not measure recovery time, adult lampreys appeared to revive faster (almost immediately after they were removed from the surgical bath) after exposure to eugenol than when MS222 was used. Comparisons of travel times for lamprey from the release site to a Bonneville Dam fishway entrance indicated no ill effects of the eugenol treatment. In fact, eugenol-treated animals were more likely to return to the base of the dam (90%) than those anesthetized with MS222 (81%). Consequently, we recommend the use of eugenol as an anesthetic for adult Pacific lamprey.

Radio-tagged lamprey approaching Bonneville Dam were apparently attracted to areas of highest discharge. More lamprey approached Bonneville Dam at PH1 and the spillway than PH2. This was likely due to reduced discharge emanating from PH2 during June, July, and August, when most of the lamprey were released (Fig.40).

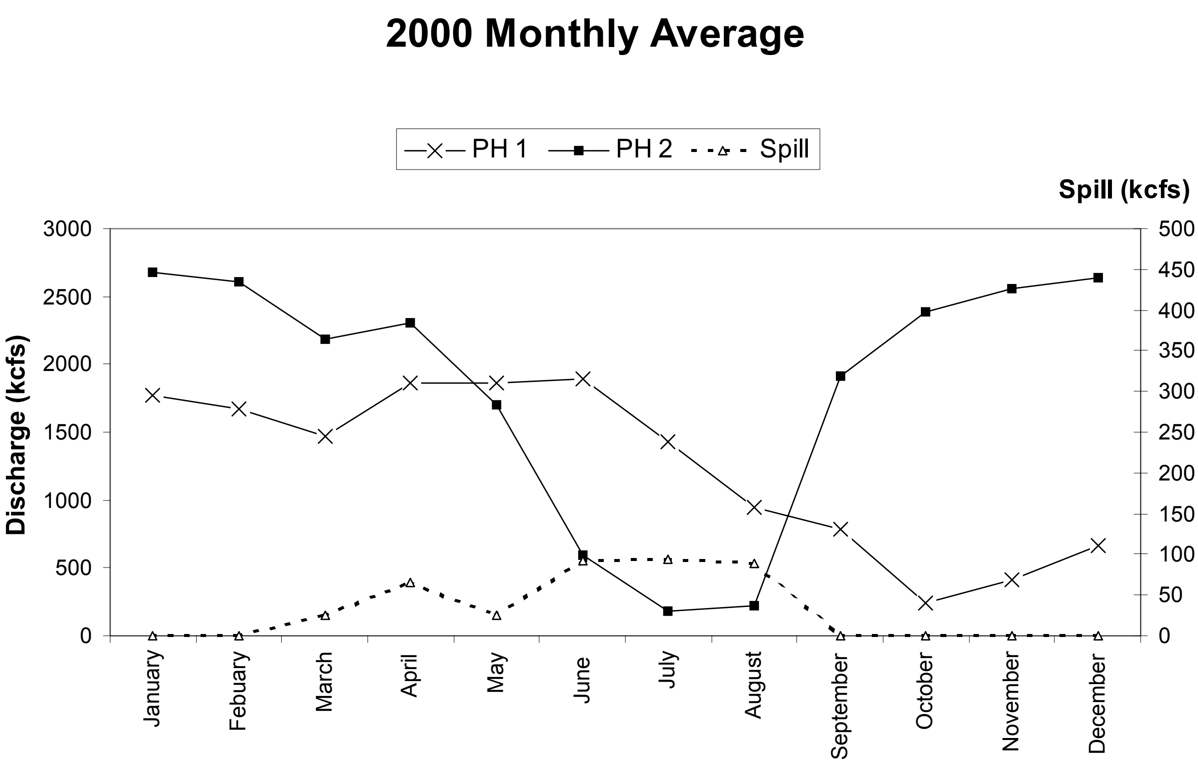


Figure 39. Mean monthly discharge (kcfs) from Powerhouse 1 (PH1), and Powerhouse 2 (PH2), and spill (kcfs) at Bonneville Dam in 2000.

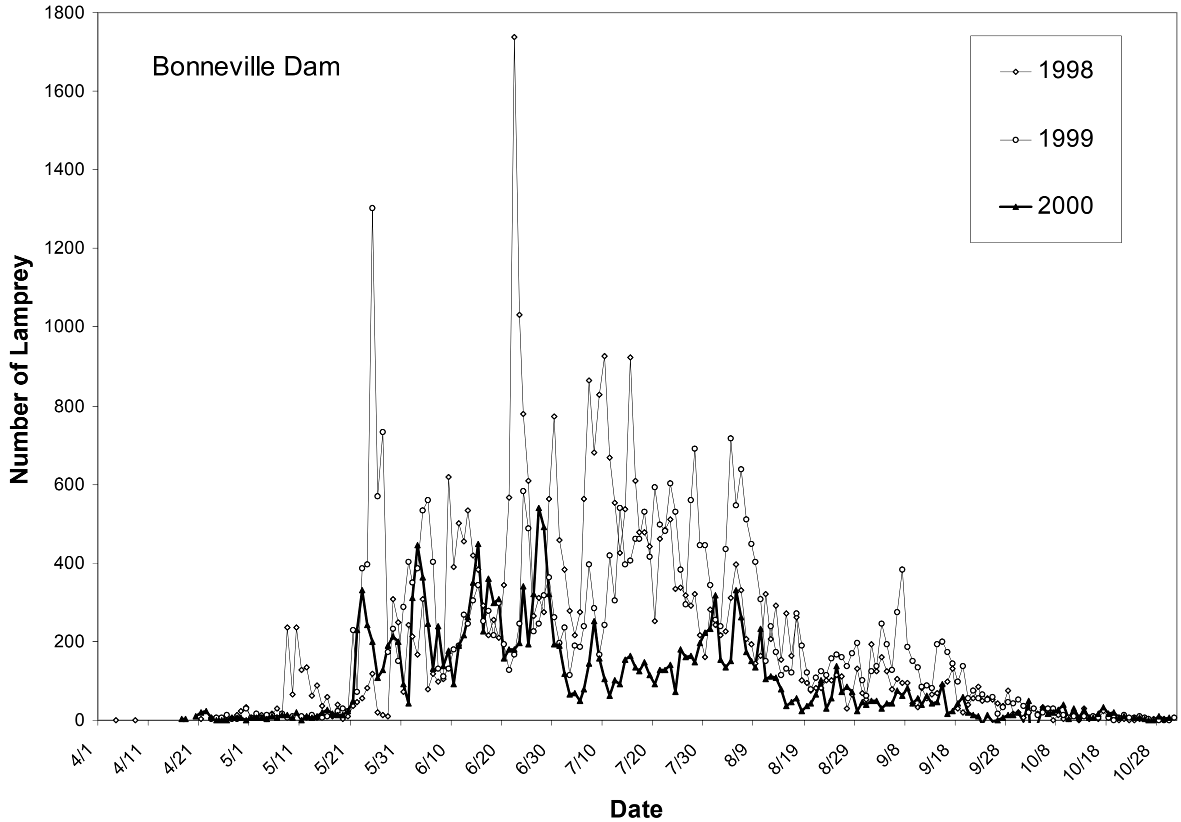


Figure 40. Daily counts of adult Pacific lamprey made at both count windows at Bonneville Dam in 1998-2000.

Table 6. Sizes and the time from release to first approach at a Bonneville Dam fishway entrance for adult Pacific lamprey radio-tagged and released below Bonneville Dam in 1997-2000.

	1997	1998	1999	2000
Number released	147	205	199	299
Mean length, cm	70	70	71	70
(range)	(60-80)	(59-79)	(65-78)	(62-80)
Mean weight, g	-	545	571	570
(range)	> 450	(420-830)	(475-755)	(405-825)
Travel time to dam				
median days	7.8	4.0	5.2	6.4
(range)	(0.5-40.5)	(0.3-11[illegible]-28.2)	(0.1-53.5)	
standard deviation	7.5	4.8	7.3	13.0

Entrance efficiency for lamprey differed among fishway entrance types at Bonneville Dam. Orifice entrance use at PH1 was low relative to entrance efficiency at all powerhouse and spillway main entrances, as was documented in 1997, 1998, and 1999 (Vella et al. 2001; Ocker et al. 2001). If lamprey are demersally-oriented when they approach the dam, it is likely that they would have difficulty locating orifice entrances, since these entrances do not span as much of the water column as main entrances (Moser et al. in press a).

The orifices at PH1 were alternately opened and closed during the period from 1 April to 31 October. This treatment did not appear to change either orifice or main entrance efficiency at PH1 relative to previous years when all orifices were open. At The Dalles Dam, orifices were also closed, and entrance efficiency at the main entrances did not differ dramatically from entrance efficiency in previous years of monitoring (Fig. 41).

Entrance efficiency at the spillway entrances in 2000 was slightly higher than at the powerhouse entrances (Fig. 42), and entrance efficiency at PH2 was generally lower than at PH1. While inter-year differences in flow emanating from the spillway and powerhouses could account for changes in approach frequency, it is less likely that they would result in differences in entrance efficiency at the main entrances. The structural and operational changes made to improve lamprey passage resulted in minor improvements in spillway entrance efficiency.

In 2000, the bulkhead at the Bradford Island B-Branch entrance was rounded to afford lamprey a better surface for attachment when entering this fishway. Entrance efficiency at this entrance (SPILL-SSE) was higher in 2000 than in 1998 or 1999; however, entrance efficiency at the unmodified Cascades Island spillway entrance (SPILL-NSE) was also improved in 2000 relative to 1998 and 1999 (Fig. 15).

The only other change at these entrances in 2000 was that water velocity was lowered on alternate nights from 25 July to 1 October. Fortunately, 58 lamprey approached the spillway entrances during this period and 36 of these fish made their approach during the velocity test period (2100-0400). Entrance efficiency was actually higher during the high-velocity treatment than during the low-velocity treatment for these fish, indicating that reducing the velocity at these entrances did not improve lamprey entrance performance.

The ability to find attachment sites is key to the success of lamprey passage through areas of high velocity, such as fishway entrances (Moser et al. in press a). We observed lamprey in the fishways and noted that, when confronted with high-velocity conditions, they typically move forward by holding fast with the suctorial oral disc and then surge ahead to re-attach.

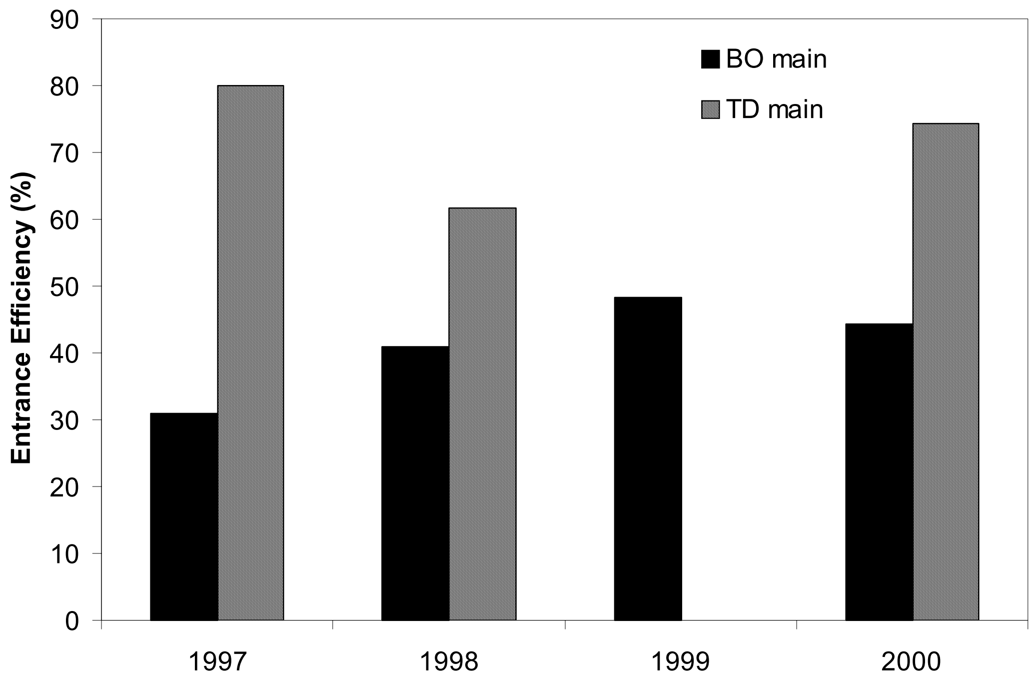


Figure 41. Entrance efficiency (the percentage of lamprey that successfully entered of those that approached) at main fishway entrances at Bonneville Dam (BO) and The Dalles Dam (TD) in 1997-2000.

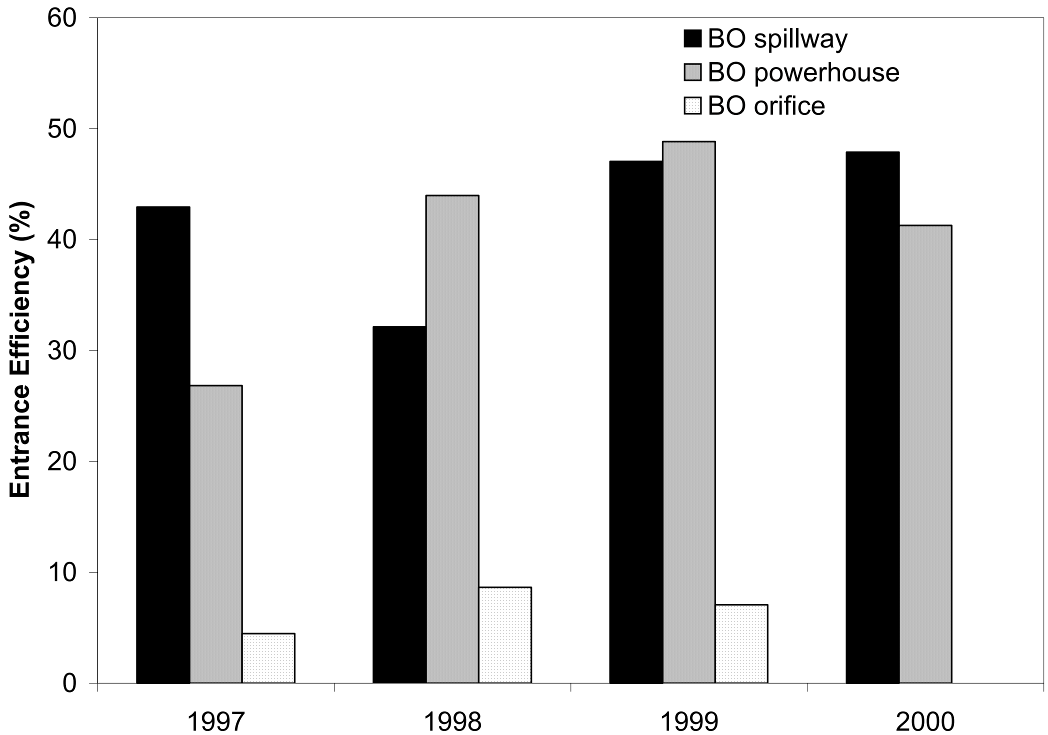


Figure 42. Entrance efficiency (the percentage of radio-tagged lamprey that successfully entered of those that approached) at Bonneville Dam (BO) main entrances at the spillway, main entrances at the powerhouses, and at orifice entrances in 1997-2000.

In all years of study, radio-tagged lamprey had relatively poor passage efficiency through collection channels and transition areas (Moser et al. in press b). It is likely that gratings on the floors and walls in these areas limit lamprey attachment and reduce passage success. For example, collection channels and transition areas at the PH1 fishway have less floor grating than at PH2 fishways, and lamprey passage success was consistently higher through these areas in PH1 fishways than through similar areas in PH2 fishways (Table 1).

Pacific lamprey also had difficulty passing through count stations at Bonneville and John Day Dams; however, they were able to pass relatively easily through these areas at The Dalles Dam. The count stations at all dams present lamprey with a complex array of physical conditions: picketed leads, narrowing channels, bright lighting, and confusing currents.

Matter et al. (2000) speculated that lamprey were able to pass through picketed leads and into areas where they became stranded or fell back downstream. Of the 15 lamprey that entered the Makeup Water Channel (MWC) on Bradford Island in 2000, 87% were able to exit into the forebay via the Tainter gate at the upstream end of the MWC. Only one lamprey was detected in the Washington-shore MWC and it fell back and did not reascend the fishway.

A second hypothesis is that negative phototaxis, which has been documented in other lamprey species, may cause lamprey to avoid passing the count stations (Ocker et al. 2001). We tested this hypotheses by intensively monitoring lamprey behavior around the count windows and by conducting controlled lighting experiments at the experimental count window.

Intensive monitoring indicated that most lamprey passed the count windows at both the Washington-shore (94%) and Bradford Island (98%) ladders. However, it is possible that lamprey did so by passing behind the crowders to avoid bright lighting. Controlled lighting experiments indicated that lamprey did not avoid experimental white light treatments that were designed to simulate lighting at the count stations. Altering light quality (to the red part of the spectrum) also did not affect the number of lamprey caught upstream from the experimental window.

Intensive monitoring documented lamprey delay and fallback in the serpentine weir area immediately upstream from the count windows at both Bonneville Dam ladders. The observation that count station passage was high at The Dalles Dam, where lamprey do not encounter serpentine weirs, is further evidence that serpentine weirs may be obstacles to lamprey. Lamprey may become disoriented in these areas of turbulent and confusing current velocity and direction. Further study is needed to determine whether (and how) serpentine weirs affect lamprey passage.

As in previous years of study, overall lamprey passage at lower Columbia River fishways was low relative to salmonid passage. In 1996, 96% of the 837 adult spring and summer chinook salmon *Oncorhynchus tshawytscha* radio-tagged by Bjornn et al. (2000a) passed over Bonneville Dam. Similar passage efficiencies for radio-tagged adult chinook salmon and steelhead trout *Oncorhynchus mykiss* have been documented in subsequent years (Bjornn et al. 2000b). In contrast, during 4 years of study we found that lamprey passage efficiency at Bonneville Dam never exceeded 50% and that on average less than 3% of the lamprey we released below Bonneville Dam passed above John Day Dam. In spite of directed fishing pressure and returns to tributaries and hatcheries along the way, 45% of the adult radio-tagged chinook salmon released below Bonneville Dam in 1996 passed above John Day Dam (Bjornn et al. 2000a).

Adult Pacific lamprey that successfully passed over the lower Columbia River dams also took longer, in general, to do so than salmonids. Median lamprey passage times at Bonneville Dam were 4-6 days, and lamprey that passed via the Bradford B-Branch or the Cascades Island ladder and UMT required even more time to get over the dam (more than 9 days in each year of study). In contrast, spring and summer chinook salmon radio-tagged by Bjornn et al. (2000a) in 1996 passed over Bonneville Dam in approximately one day. Lamprey make multiple approaches to the fishway entrances, multiple entrances, and both downstream and upstream movements in the fishways (Matter et al. 2000). These behaviors, their nocturnal activity patterns, and lower swimming performance (Beamish 1974) probably contributed to the relatively long passage times we recorded for lamprey.

Lamprey passage efficiency at the Dalles Dam was higher than at the other dams we monitored and lamprey took less time to negotiate The Dalles fishways. We hypothesized that lamprey that have passed through fishways are more successful in subsequent passage attempts than are "naive" fish. However, when Vella et al. (2001) displaced adult lamprey to sites above Bonneville Dam, they and fish released below Bonneville Dam had similar passage efficiencies at The Dalles Dam. Consequently, it is unlikely that lamprey success at the Dalles Dam was due to learning.

Moser et al. (in press a) speculated that lamprey become more motivated to migrate as they move upstream, resulting in higher entrance efficiencies at The Dalles Dam than at Bonneville Dam. However, we found that passage performance of lamprey that approached John Day Dam, which is upstream from The Dalles Dam, was relatively low. Consequently, we believe that the relatively high passage efficiencies at The Dalles

Dam were due to fishway configurations that lamprey were able to use more readily, particularly at counting stations.

Pacific lamprey adults reside in freshwater for up to a year prior to spawning, and their migratory activity during this period has never been documented (Beamish 1980). It is possible that poor passage efficiency of lamprey at lower Columbia River dams reflects low motivation to migrate, although our data do not support this idea. Nearly 90% of the fish we released below Bonneville Dam moved upstream after release and few lamprey (less than 5%) fell back downstream after passing over Bonneville Dam. Moreover, of the 50 fish displaced above Bonneville Dam in 1997, 82% migrated upstream to The Dalles Dam.

When we displaced lamprey to sites upstream from The Dalles Dam, 56% migrated to John Day Dam, and these lamprey exhibited lower overall passage efficiency than lamprey that had migrated from below Bonneville Dam. One possibility is that lamprey we transported farther upstream prior to release were more stressed, resulting in lower passage efficiency. A second possibility is that fish displaced to sites above The Dalles Dam entered tributaries below John Day Dam or lacked orienting cues needed to motivate upstream movements to John Day Dam.

The fate of Pacific lamprey that do not get above dams is unknown. It is possible that they are able to enter and successfully spawn in tributaries below the dams, thereby contributing to recruitment potential of the Columbia River population. In the winter and spring of 1999-2000 and 2000-2001, we relocated 37% and 36% of the lamprey tagged in the previous summer. From 1999 to 2000, 18 (24%) of the lamprey we relocated had moved more than 15 km upstream and 11 passed over a dam. This indicates that at least some of the lamprey overwinter in the Columbia River main stem and are able to pass over dams in their second year in freshwater. Counts of lamprey at John Day Dam in 2000, prior to the appearance of lamprey at The Dalles Dam also indicates that some fish are able to pass over the dams in their second year (Fig. 43).

In 2000-2001, we only documented upstream movements of greater than 15 km for 8 fish (0.8% of those relocated), and 5 of these fish moved upstream in tributaries. Our inability to detect upstream movements over dams in the spring of 2001 was probably due in part to the fact that transmitters used in 2000 only had a 7-month lifetime. Further study is needed to determine whether a significant percentage of the radio-tagged lamprey are able to get to spawning areas in their second year in freshwater and the fate of the large number of fish that are not relocated after making an unsuccessful attempt to pass over Bonneville Dam.

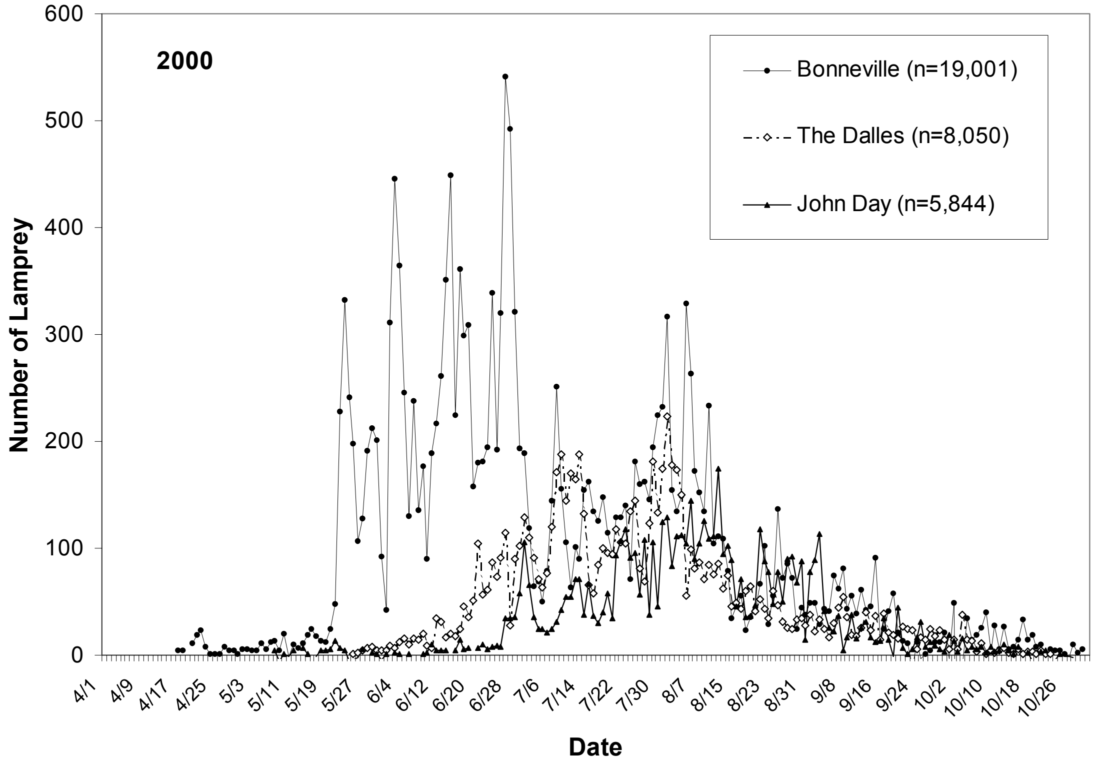


Figure 43. Daily counts of adult Pacific lamprey at Bonneville, The Dalles, and John Day Dams in 2000.

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