# Monitoring adult Pacific lamprey *(Lampetra tridentata)* migration behavior in the lower Columbia River using radiotelemetry, 1998-99


***Fish Ecology Division***

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Seattle, Washington

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and
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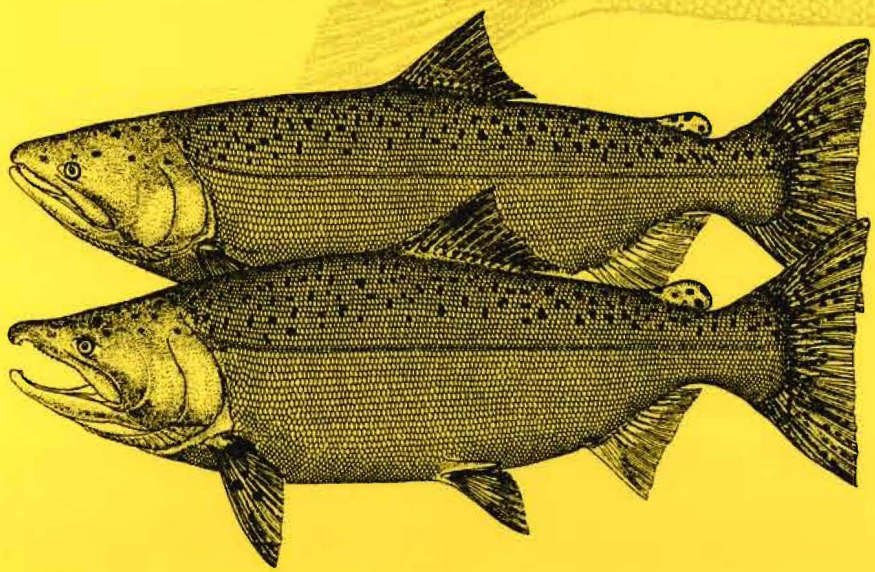
May 2001

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## EXECUTIVE SUMMARY

Pacific lamprey (*Lampetra tridentata*) abundance in the Columbia River Basin has declined significantly since the 1960s. We used radiotelemetry to document adult lamprey migration behavior at Columbia River Basin hydroelectric facilities and to identify factors affecting their successful return to spawning areas. Radiotelemetry has been used to study anadromous fish behavior for many years and has been used for lamprey research in the Columbia River for the past 4 years. In 1998 and 1999, we evaluated the behavior of radio-tagged Pacific lamprey in the lower Columbia River Basin, primarily at Bonneville Dam. Our objectives were: 1) to determine routes of passage at hydroelectric dams, 2) to identify locations in the fishways where lamprey fail to advance, and 3) to test the effects of spillway entrance modifications on lamprey entry into the fishways at Bonneville Dam.

We captured adult Pacific lamprey at Bonneville Dam using a trap designed by National Marine Fisheries Service personnel. The trap was fished from 3 May to 10 September 1998 and from 26 May to 2 September 1999, with 877 and 663 lamprey captured in each year. In 1998 and 1999, 205 and 199 fish were surgically tagged with radio transmitters and released approximately 2 km downstream from Bonneville Dam.

Of the 205 lamprey radio tagged in 1998, 182 approached Bonneville Dam (89%), 154 entered the fishways, 124 progressed to the transition areas, 105 progressed to the ladder, 99 progressed to the top of the ladder, and 71 passed the dam using the fishways. Two fish passed the dam using the navigation lock, for total passage of 73 fish (36% of 205 released, 40% of those that approached). Of the 73 fish that passed Bonneville Dam, 43 were detected near The Dalles Dam. Thirty-eight lamprey approached The Dalles Dam, 33 entered the fishway, 33 progressed to the transition area, 24 progressed to the ladder, and all of these fish passed the dam. The Dalles Dam passage efficiency was 63% of those that approached The Dalles Dam and 13% of those that migrated upstream after release below Bonneville Dam. Of the 24 fish that passed The Dalles Dam, 10 were detected at the base of John Day Dam. Of these 10, 7 entered the fishway (70%), 6 progressed to the transition area (60%), and 3 progressed to the ladder and passed the dam (30% of 10). John Day Dam passage efficiency was 30% of those that approached The Dalles Dam and 2% of those that migrated upstream after release below Bonneville Dam.

Of the 199 lamprey we radio tagged in 1999, 183 approached Bonneville Dam (92%), 161 entered the fishways, 137 progressed to the transition areas, 103 progressed to the ladder, 102 progressed to the top of the ladder, and 81 passed the dam. One lamprey passed the dam via the navigation lock for a total passage efficiency of 41% of the fish released or 45% of those that approached the dam. Fifty of the 82 fish that passed Bonneville Dam in 1999 approached The Dalles Dam (61%), and 25 passed upstream (50% of 50). Of these, 11 approached (44% of 25), and 3 passed John Day Dam (27% of 11).

At Bonneville Dam, lamprey had the most difficulty passing the transition area at Powerhouse 2 (PH2), the collection channel at PH2, and the counting window at Powerhouse 1 (PH1). At The Dalles Dam, the highest failure to pass rates occurred at entrance and transition areas of the powerhouse fishway. At John Day Dam, the highest failure to pass rates occurred at the fishway entrances and transition areas. Fish had few problems negotiating the ladders at any dam.

High failure to pass rates occurred where diffuser gratings covered the entire floor of the fishway, as was the case in collection channel and transition areas at PH2. In contrast, PH1 collection and transition areas do not have continuous sections of diffuser grates and lamprey passage success was higher in those areas. These observations indicate that lamprey need attachment areas on the floor of the fishway where they can adhere and rest. If continuous solid plates for lamprey attachment were installed on the gratings in the transition areas and in the collection channels, passage efficiency could be increased.

Stations to count fish passing the dams (counting windows) represented a second important obstacle to lamprey passage. Lamprey moved through these areas primarily at night. The counting windows are lighted to allow videotaping of anadromous fish during both day and night. Lamprey may be confused or diverted by high-intensity lighting at the windows, as negative phototaxis has been documented for other lamprey species. The lighting at the Washington shore counting window appeared to be less intense than that at the Bradford Island window in 1999, and lamprey had greater success passing at the Washington shore window than at the Bradford Island window. If the lighting regime at the counting windows proves to be an obstacle to lamprey passage, this could be easily remedied by reducing light intensity at the windows during the night.

Modifications to the fishway entrance at the north end of the spillway did not improve lamprey entrance rates. Contrary to expectation, the installation of a flat plate over I-beams on the north spillway entrance gate actually delayed passage of lamprey because the fish tended to congregate at a leaky area created by a faulty seal at this gate. In addition, lamprey were apparently unable to negotiate a lip on the edge of the plates, resulting in poor entrance success. Tests of spillway entrance velocities were inconclusive, due to the low number of fish that entered the fishways during the testing period. Future testing of both operational and structural modifications to the spillway entrances is needed to improve entrance rates.

## CONTENTS

# INTRODUCTION

Populations of Pacific lamprey in the Columbia River Basin, although variable, have declined significantly in recent years, as indicated by adult counts at Bonneville Dam that regularly exceeded 100,000 fish in the 1960s and were estimated at less than 40,000 in 1997 through 1999 (Starke and Dalen, 1995; David Close, Confederated Tribes of the Umatilla Indian Reservation, Tribal Fisheries Program, P.O. Box 638, Pendleton, Oregon, Pers. commun., August 2000). Reductions in lamprey abundance may be partly attributed to poor passage efficiency of adults at hydroelectric facilities along their upstream migration route. Radiotelemetry studies of adult salmonid migrations at hydroelectric facilities have provided insight into factors affecting successful upstream migration. Similar technology was used to assess passage efficiency of lamprey in the Columbia River starting in 1996 (Matter et al. in press). In this report we present results of telemetry work on lamprey conducted in 1998 and 1999 by personnel of the National Marine Fisheries Service (NMFS) and the Idaho Cooperative Fish and Wildlife Research Unit at the University of Idaho (UI).

The objectives of this study were: 1) to determine routes of passage at the lower Columbia River dams, 2) to identify locations in the fishways where adult lamprey fail to advance, and 3) to test the effects of spillway entrance modifications on lamprey entry into the fishways at Bonneville.

# METHODS

## Trapping

Adult Pacific lamprey were collected in the bypass ladder leading to the Adult Fish Collection and Monitoring Facility on the Washington shore of Bonneville Dam. A trap was designed by NMFS personnel to sit on the sill of an overflow weir in the ladder and intercept lamprey as they passed over the weir on the inside wall of the ladder (Fig. 1). The trap was designed not only to capture lamprey, but also to allow passage of salmonids with minimal interference. Initially, trapping was conducted only at night. However, after the peak of the lamprey migration in 1999, the trap was operated 24 hours each day in an attempt to capture sufficient numbers of fish for the study.

## Tagging

Surgical implantation is the best method for radio tagging adult lamprey (Matter et al. in press). Fish were anaesthetized using a 70-ppm bath of tricaine methane sulfonate (MS-222) for about 6 minutes, or until they offered no resistance to handling. Length (nearest cm), weight (nearest g), sex, body girth (nearest mm), and physical condition were recorded. Generally, fish larger

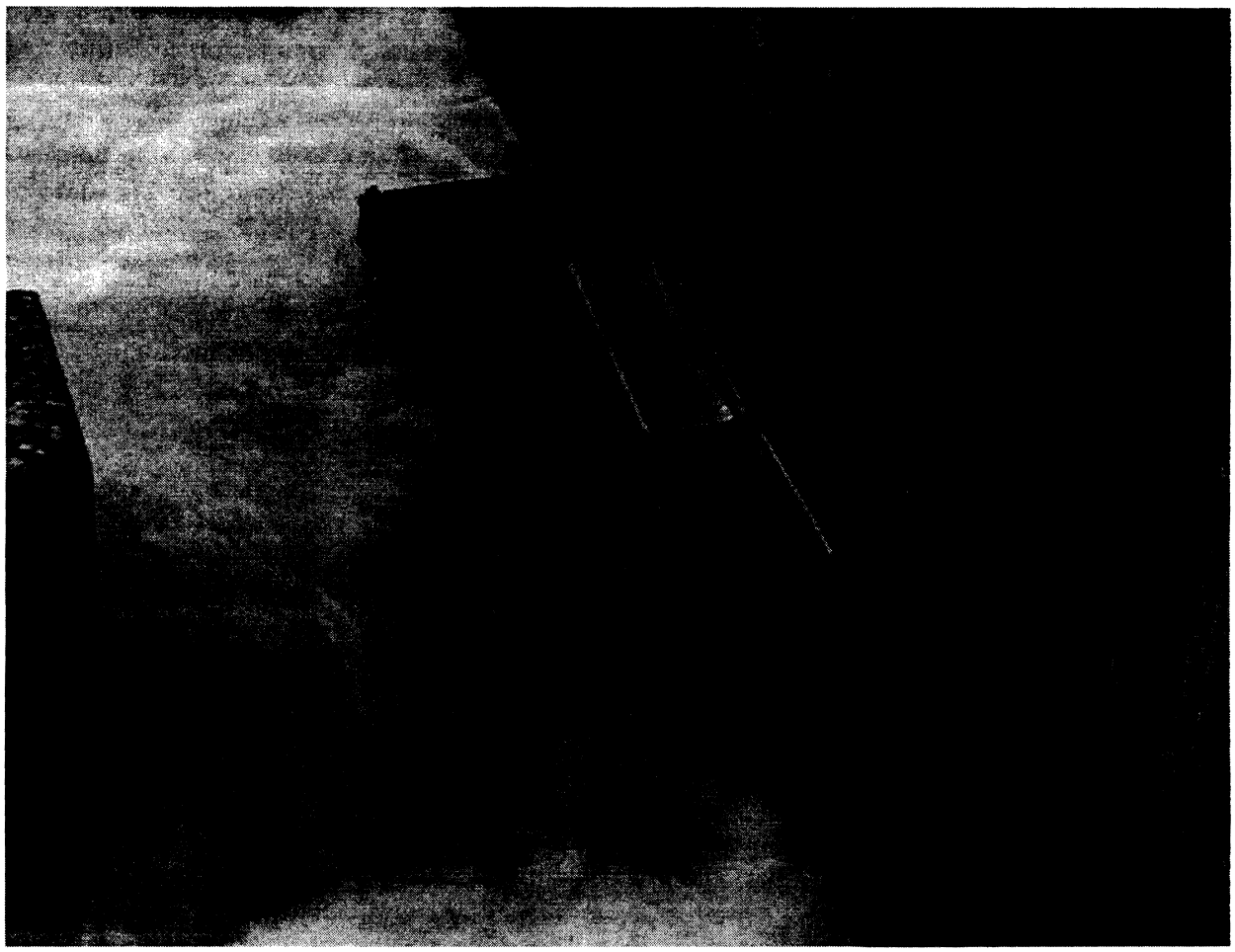

Figure 1. Lamprey trap shown in fishing position at the third overflow weir of the bypass ladder at Powerhouse 2 of Bonneville Dam.

than 500 g and/or 11.5 cm girth were tagged. Lamprey not tagged were provided to other researchers or released above Bonneville Dam. For tagging, the fish were transferred to a surgery cradle partly submerged in a 16-L bath of 50-ppm MS-222. Surgical tools and tags were sanitized in a solution of zephiran chloride and rinsed in a freshwater bath before and after each surgery. A 3-cm incision was made using a 3-mm fixed-depth disposable scalpel, approximately 1 cm off the ventral midline, 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 stitches of 3-0 absorbable surgical suture with a 19-mm CE-4 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 a bacitracin ointment as a prophylactic measure. After surgery (median time = 9 minutes), fish were placed into a holding tank supersaturated with oxygen and containing Stress Coat[1] (a product used to reduce osmotic stress). They were typically released 0.5 to 4.0 hours later in the Columbia River at one of two locations downstream from Bonneville Dam: the Hamilton Island boat launch on the Washington shore (~River Kilometer (RKm) 231) or the Tanner Creek fishing access on the Oregon shore (~RKm 232) (Fig. 2).

## Radio Transmitters

Transmitters were manufactured by LOTEK[1] Engineering Inc. of Newmarket, Ontario, Canada, and weighed 7.7 g in air and 3.7 g in water. Tags weighed less than 2% of the animal's body weight and were 4.3 cm long by 1.1 cm diameter with a 30-cm antenna wire. The tags transmitted one of 100 unique codes in the 150-MHz range at a set pulse rate. In 1998, tags transmitted at a pulse rate of 5 seconds for approximately 7 months. Two pulse rates were used in 1999: 35 tags had a 5-second pulse with a 7-month life, and 164 tags had a 10-second pulse with a 14-month life. The longer-lived tags were used to allow relocation of lamprey in the spring of 2000.

## Dam Configurations and Receiver Locations

For ease of analysis, Bonneville Dam was partitioned into four different segments that provided five different opportunities for fish passage: Segment 1) the fishway at Powerhouse 1 (PH1) on Bradford Island, Segment 2) the navigation lock, Segment 3) the fishway at Powerhouse 2 (PH2) on the Washington shore, and Segment 4) the two fish ladders that begin in the spillway tailrace between the two powerhouses (Fig. 2).

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

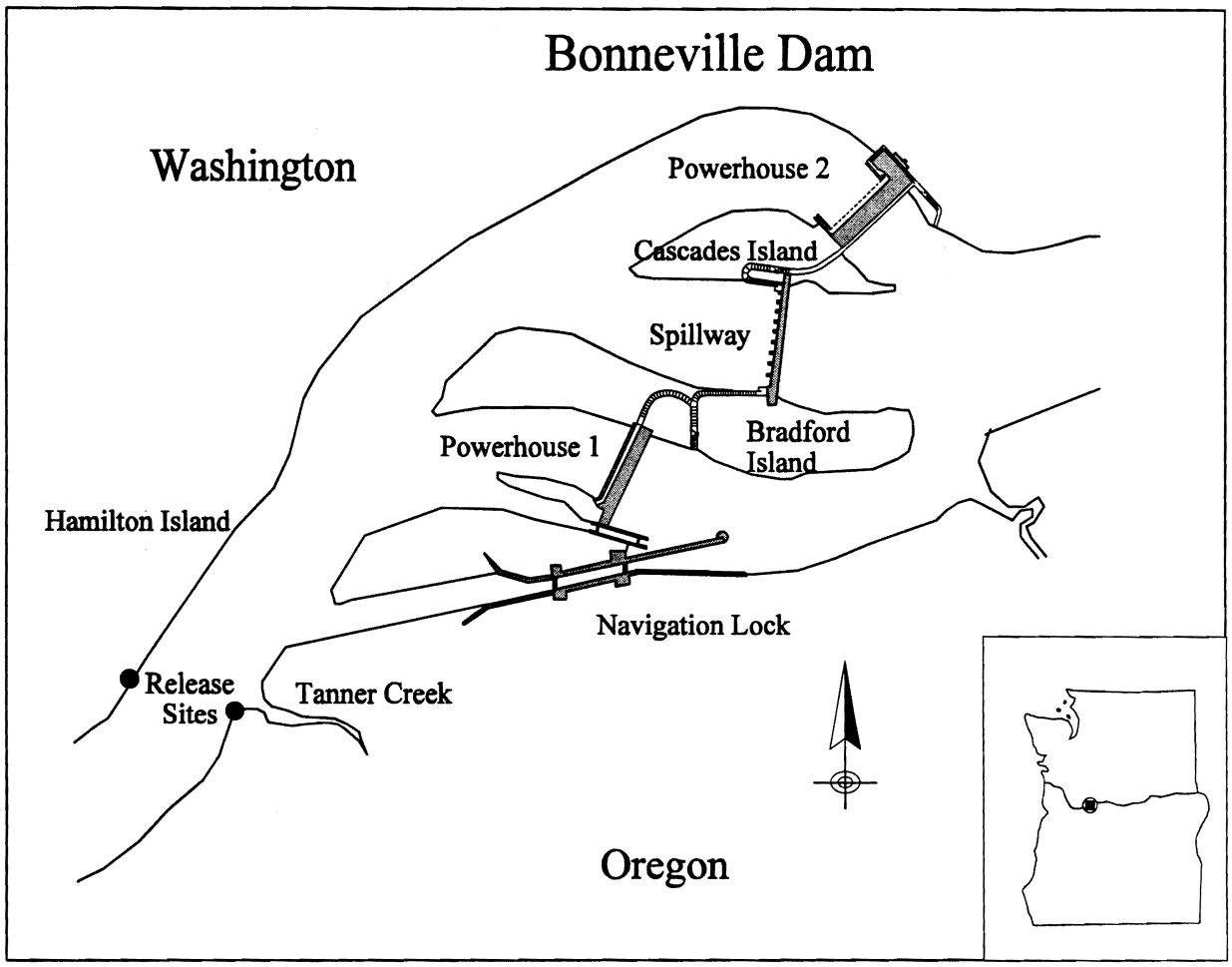


Figure 2. Overview of Bonneville Dam on the Columbia River.

Thirty-two LOTEK receivers with 105 antennae were deployed on and around Bonneville Dam. Five receivers with single (9- or 4-element) Yagi antennae were used to monitor the tailrace areas downstream from the dam. The remaining receivers located at the dam were coupled with Digital Spectrum Processors, which allow multiple channels and antennae to be monitored at the same time, and underwater antennae which monitor fishway entrances, passageways, and upstream exits.

Despite differences in construction, PH1 and PH2 have conventional fishways used throughout the Columbia River, including major entrances on each end of the powerhouses with orifice entrances along the entire face of the powerhouse. Three general entrance locations were used for analysis at PH1: 1) all orifice entrances, 2) the north main entrance, and 3) the south main entrance. For analysis at PH2, there were three general entrance locations: 1) the middle 10 floating orifices, 2) the two southern monolith entrances and southernmost orifice (south entrances), and 3) the two northern monolith entrances and northernmost orifice opening (north entrances). All entrances lead to the collection channel, transition areas, fish ladder, counting window area, and eventually to the upstream exit of the fishway.

The two ladders that start in the spillway tailrace lead directly into a transition pool and on up to the ladders on Bradford and Cascades Islands (Fig. 2). The south spillway fishway (B-branch) joins with the PH1 ladder on Bradford Island near the top weir. The north spillway ladder (Cascades Island) joins with an upstream migrant tunnel (UMT) at the upper end of the ladder. The UMT passes across the top of PH2 and joins the fishway on the Washington shore just downstream from the counting window. In the winter of 1998, flat plate was welded to the open I-beam construction of the bulkhead at the Cascades Island entrance, in an attempt to improve lamprey entrance efficiency. Tests to determine whether lowering the flow at the spillway entrances (from approximately 8 ft $s^{-1}$ to approximately 4 ft $s^{-1}$) would improve lamprey entrance performance were also conducted in 1999. Flow was decreased during the night (2100 - 0400 h) at alternating spillway entrances (Bradford Island one night, Cascades Island the next night, and so on) during the period from 2 August to 1 October 1999.

Both John Day and The Dalles Dams have two fishways at each dam, which are similar to those at Bonneville Dam: one on the north shore near the spillway and one on the powerhouse side near the south shore (Figs. 3 and 4). In 1998, these fishways were monitored for adult salmonid passage at the main entrances, inside at the junction areas, and at the top of the fishways near the exits. However, in 1999 the receivers only monitored the top of the ladders because there was no salmonid tracking that year.

To determine specific problem areas at the dams, each fishway was divided into generic sections: approach and entrance areas, the collection channel, the transition area, the ladder, and the counting window (Fig. 5). The approach and entrance area was defined as the area where a radio-tagged fish was within detection range of an antenna near a fishway entrance. The collection channel is located just inside the entrances and leads to the transition area. The transition area is where the pools and weirs begin but are inundated by tailwater. The ladder is

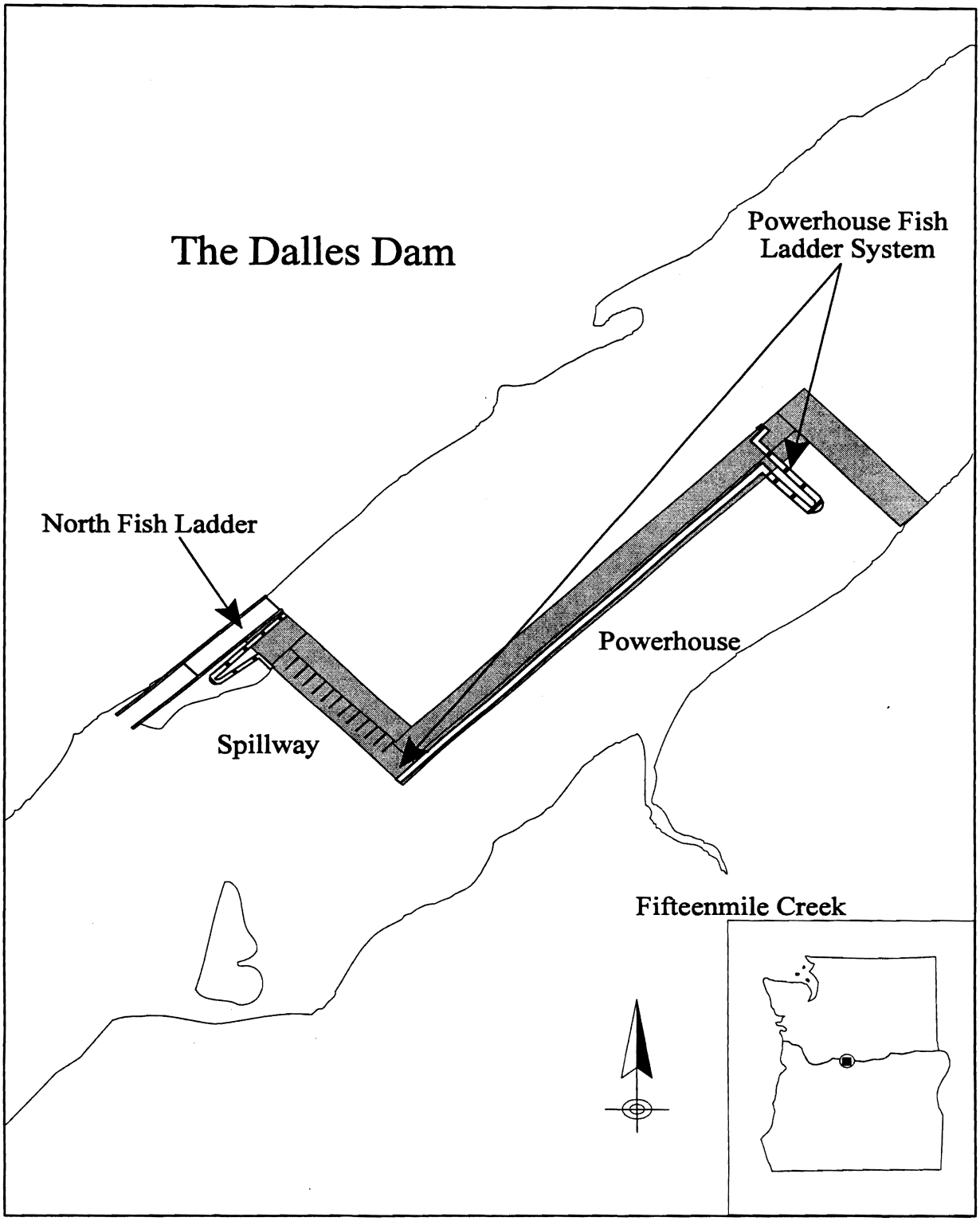


Figure 3. Overview of The Dalles Dam on the Columbia River.

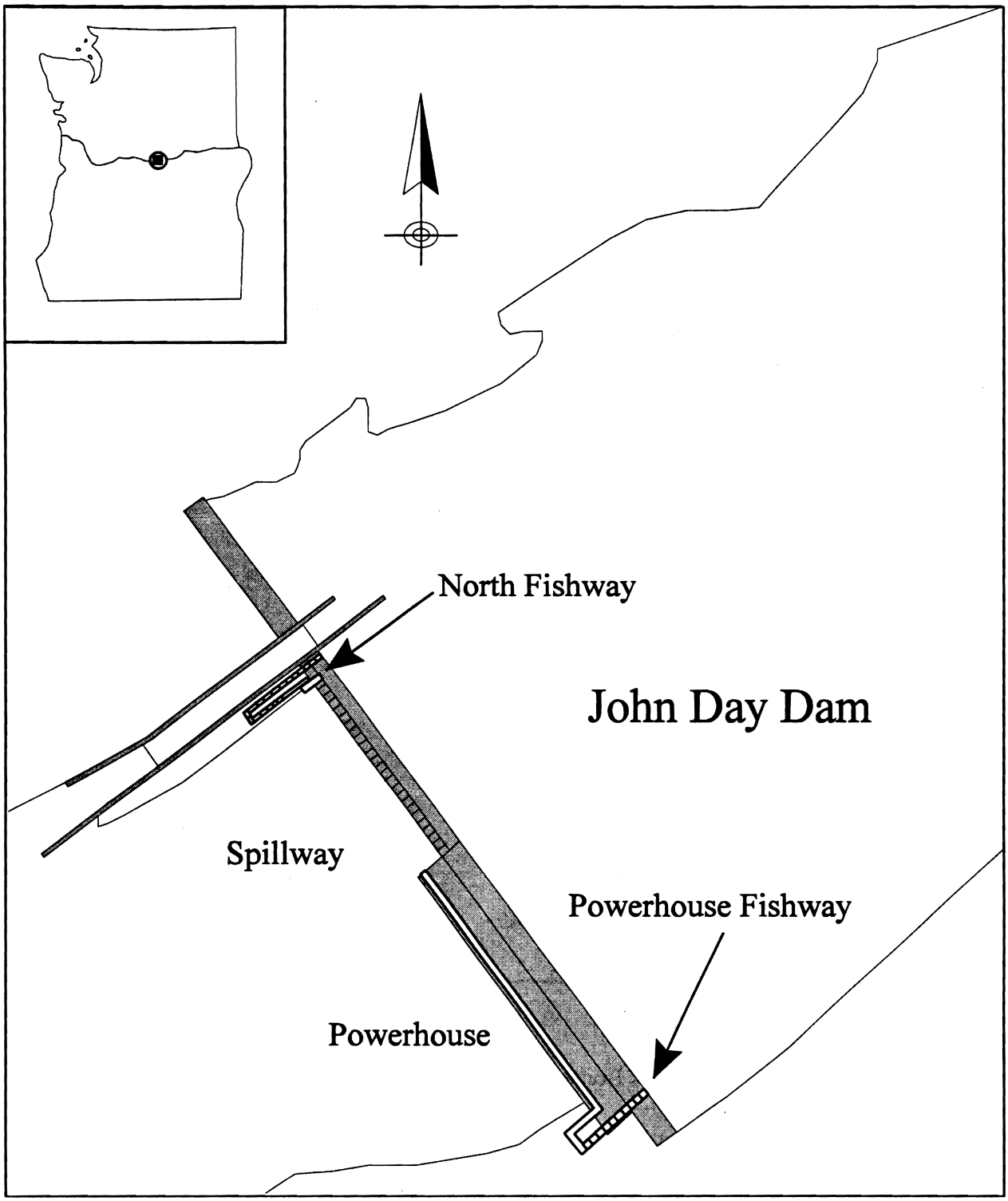


Figure 4. Overview of John Day Dam on the Columbia River.

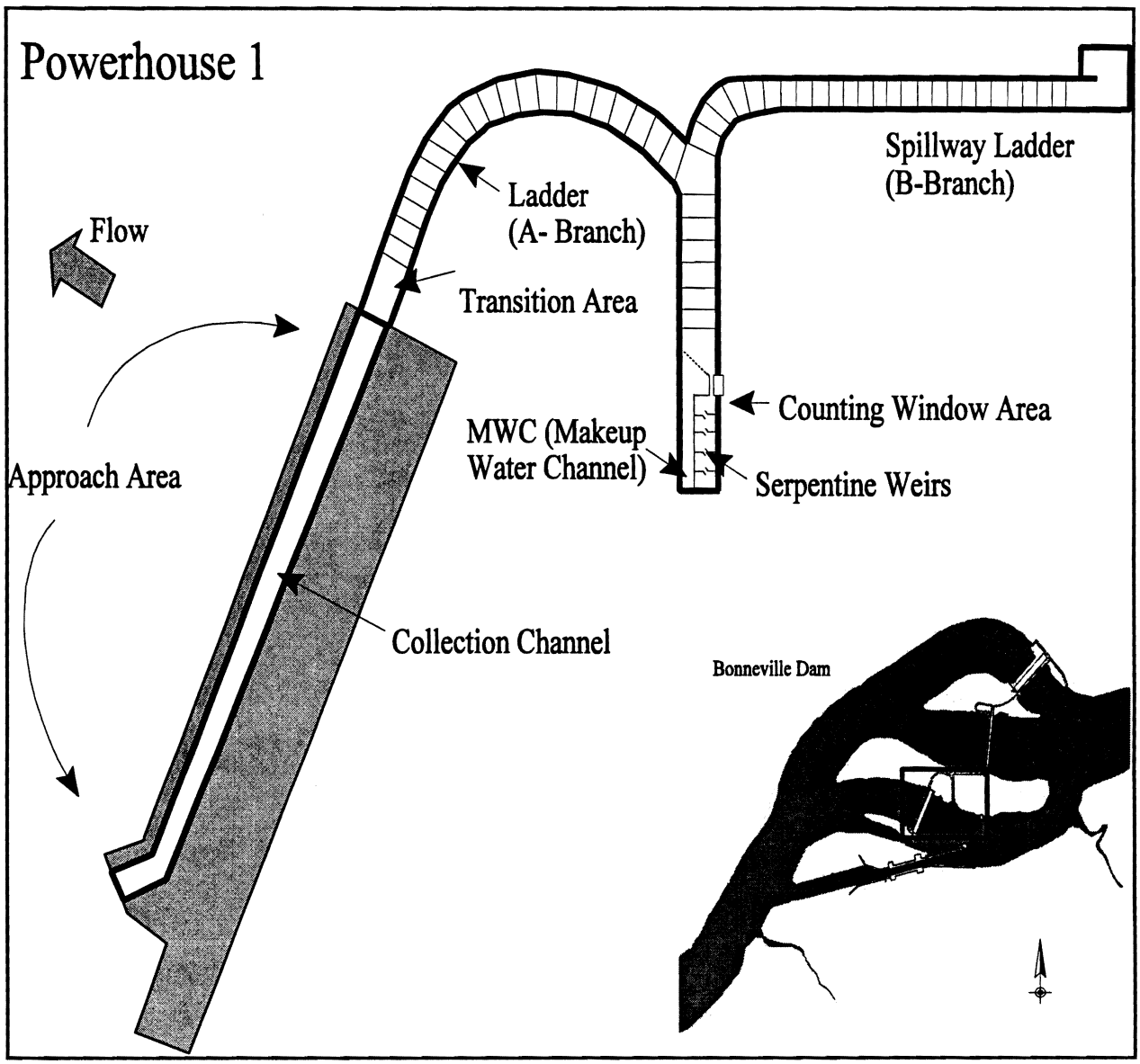


Figure 5. Overhead view of Bonneville Dam Powerhouse 1 with examples of areas used in data analysis.

defined here as the section of underwater orifices and overflow weirs not inundated by tailwater (the number inundated is variable, depending on the tailwater elevation). The counting window areas include a picketed lead, makeup water channel, counting window, and serpentine weirs leading to the ladder exit (Fig. 5).

## Data Analysis

Radio-tagged lamprey movements were analyzed from 11 May 1998 to 30 March 1999 and 27 May 1999 through 31 October 1999. The volume of data for each year was immense. Therefore, receiver data were condensed for analysis using a program written in ArcView by personnel at UI. To make the database more manageable, the following seven primary fish behavior codes were assigned to individual fish detections: approaches to entrances (defined as detection by an antenna positioned outside an entrance), entries (defined as detection by an antenna inside an entrance), movement inside the fishway (detections by antennas inside the fishways), exits from the fishway to the tailrace, exits from the top of the ladder into the forebay, mobile tracking information, and presence at remote stations positioned at tributary mouths and dam tailraces. The first approach, first entry, and first detection were also coded. If an approach, entry, or exit was unclear, a code of "unknown" was assigned to it, along with the estimated location of that behavior. This treatment of the data can lead to ostensible discrepancies (e.g., for the total number of approaches, codes of known and unknown detections were counted together but for time and duration calculations, only the known coded records were used).

Data were analyzed using four different methods. The first was to analyze records of individual fish, beginning with the first approach at Bonneville Dam and ending with the final relocation of that fish. The second method was to analyze the total number of coded behavioral activities and the duration of these events at each receiver antenna. One fish can bias results by performing multiple behaviors at a given location; therefore, duration calculation used only the first incidence of a behavior. The third approach was to examine all records of individual activities to determine the outcome of each (e.g., the passage outcome for all lamprey that used a particular set of entrances). The final approach was to calculate travel times between areas.

Passage efficiencies were calculated using the total number of fish released per year (unless otherwise indicated) and are reported as a positive percentage (i.e., the number of fish that passed an obstacle divided by the number released). Numbers/percentages of fish that failed to advance in specific areas of the ladder were calculated by using only those fish that encountered each progressive section of the ladder and are reported as negative percentages (i.e., the number of lamprey that failed to progress through an area divided by the number of lamprey that entered that area).

Hours of civil dawn, daylight, civil dusk, and dark were calculated for the areas near Bonneville, The Dalles, and John Day Dams. Civil dawn is the period of beginning twilight to sunrise,

daylight is the period from sunrise to sunset, civil dusk is the period from sunset to ending twilight, and dark is the period between ending and beginning twilight. Sunrise/sunset is defined as the instant in the morning/evening under ideal meteorological conditions, with standard refraction of the sun's rays, when the upper edge of the sun's disk is coincident with an ideal horizon. Beginning/ending of civil twilight is defined as the instant in the morning/evening when the center of the sun is at a depression angle of six degrees (6°) below an ideal horizon. The Fly-By-Day Consulting web site was used to calculate actual hours per day of each category (Toxen 2000). For Bonneville Dam, hours were calculated using the data for the Hood River Airport. At The Dalles Dam, we used The Dalles Airport data, and for John Day Dam we used the Goldendale Airport data. Estimated statistical significance for $\chi^2$ tests was set at $\alpha = 0.05$. Medians (e.g., length, weight, travel time) were compared using 95% bootstrap confidence intervals (bootstrap technique, Efron and Tibshirani 1993).

## Assumptions

Our first assumption was that lamprey that we captured were attempting to migrate upstream. In previous study years (1996 and 1997), over 80% of the lamprey released downstream migrated back to the base of Bonneville Dam (Matter et al. in press). Moreover, lamprey counts at the dams occur over fairly discrete periods (Starke and Dalen 1995), and we tagged lamprey during peak abundances at the dams (Fig. 6 and 7). Consequently, it is likely that most of the fish we tracked were actively participating in pre-spawning, upstream migration. Another assumption was that fish captured in the fishway, tagged, and released downstream would exhibit behavior similar to naive fish (e.g., fish that had not previously entered a fishway) and that the larger lamprey size classes we tagged behaved the same as all lamprey approaching the dam. The third assumption was that radio-tagged fish behaved the same as those which had not been tagged. This assumption is supported by recent swimming performance evaluations. For lamprey tagged with 7.4 g dummy transmitters (similar in all dimensions to those used in this study), the length of time tagged fish could swim at 40 cm $s^{-1}$ was compared to swim times for untagged fish (Close 2001). One hour after surgical implantation the tagged fish had significantly lower swimming times; however, 24 h after surgery there was no difference in swimming performance of the two groups. Critical swimming speed comparisons were also made for untagged lamprey and lamprey implanted with a 3.6 g transmitter that represented approximately 0.8% of the body weight of lamprey tested (Matt Mesa, U.S. Geological Survey, Biological Resources Division, Western Fisheries Research Center, Columbia River Research Laboratory, 5501A Cook-Underwood Road, Cook, WA 98605, Pers. Commun., April 10, 2001). In these experiments, critical swimming speeds of tagged fish were slightly, but significantly lower (82 cm $s^{-1}$) than critical swimming speeds of untagged fish (85 cm $s^{-1}$). The last assumption was made during data analysis. When a fish was detected on an antenna inside the fishway without being detected at an approach antenna, the approach antenna closest to the first record inside the fishway was coded as the entrance location (with a code of unknown). Timing was not calculated using these records, however, due to their ambiguous nature.

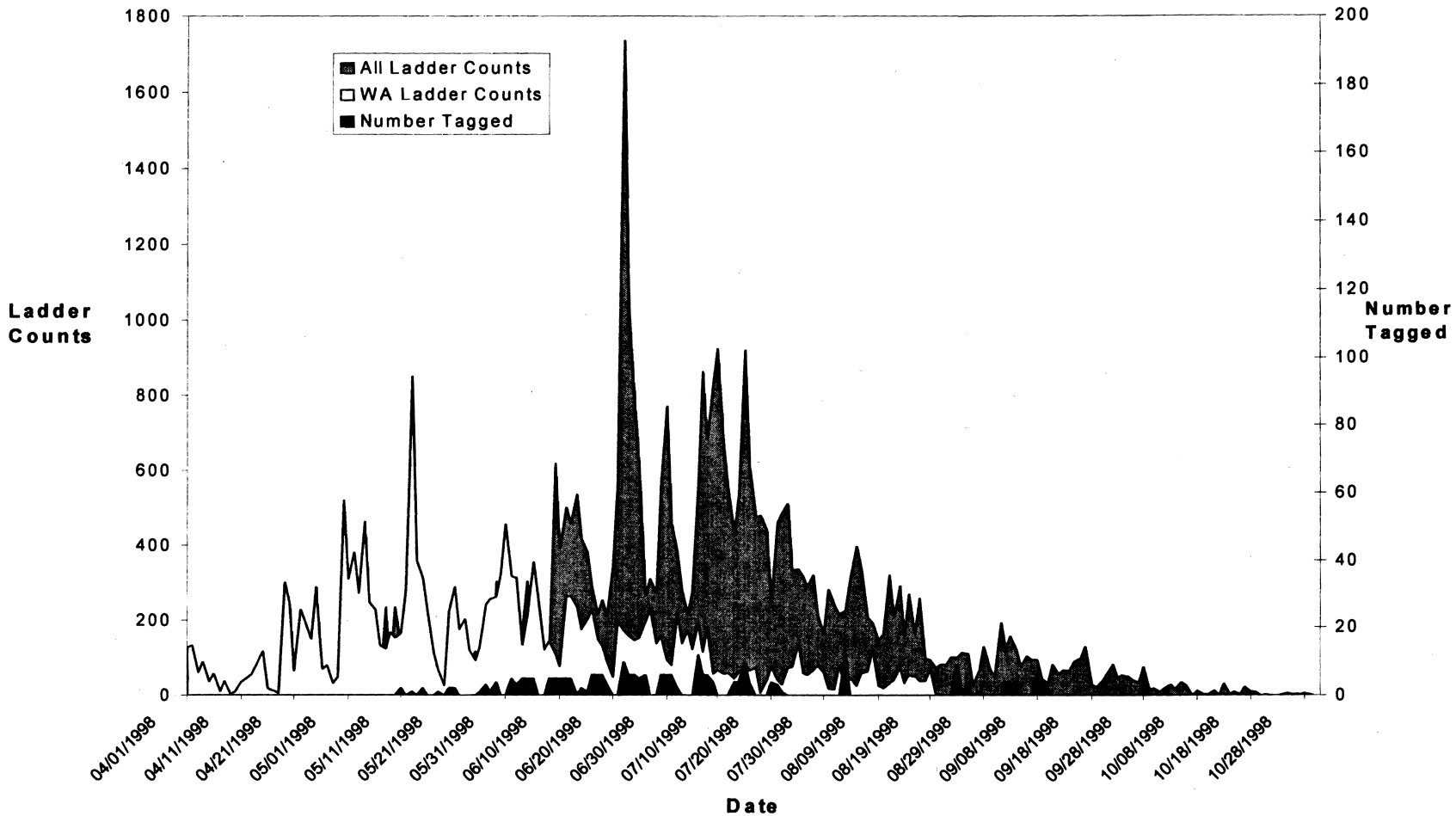


Figure 6. The number of lamprey counted at both Bonneville Dam counting windows (gray), at the Washington shore window only (white), and the number tagged each day in 1998.

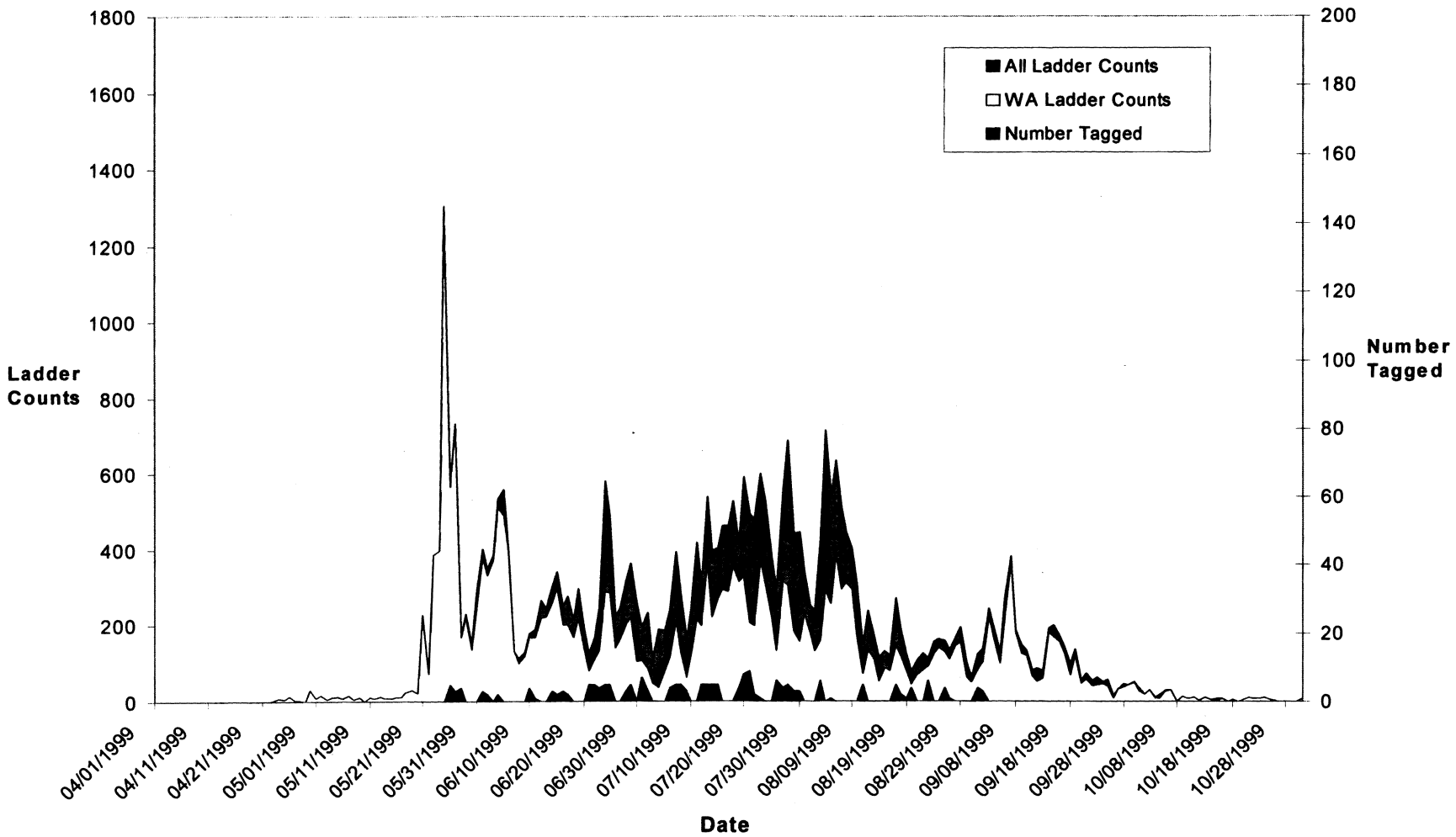


Figure 7. The number of lamprey counted at both Bonneville Dam counting windows (gray), at the Washington shore window only (white), and the number tagged each day in 1999.

## RESULTS, 1998

### Trapping and Tagging

In 1998, NMFS personnel operated the lamprey trap from 3 May to 10 September. The trap was only fished during hours of darkness, and 877 lamprey were captured during the 861 hours of trapping. Daily catch per unit effort varied from 0 to 8.2 lamprey per hour and averaged 1.0 lamprey per hour for the season. We tagged 205 lamprey having an average length of 70 cm (range = 59 to 79 cm, Fig. 8) and an average weight of 545 g (range = 420 to 530 g, Fig. 9). Of these, 101 were released on the Washington shore and 104 were released on the Oregon shore.

### Bonneville Dam

#### Upstream Progress

Of the 205 lamprey we released in 1998, 182 returned to the base of the dam (89%). There was no significant difference between release locations in the numbers of fish returning to the dam ($\chi^2 = 1.58$, $P = 0.21$, $DF = 1$), and no difference in first approach location between release locations ($\chi^2 = 2.37$, $P = 0.53$, $DF = 3$) (Table 1). There was also no significant difference in the median weight or length of fish that approached and those that did not approach the dam ($P > 0.05$). Of the 23 fish that were not detected at the dam, 15 were only detected at the release site and 8 moved upstream to within 1 km of the dam but were not recorded near any entrances. Significantly fewer lamprey ($P < 0.05$ ) approached the dam when water temperature at tagging exceeded 19.5°C in the Bonneville forebay (data from CRDART 2000). Twelve of the 42 fish we released (29%) did not approach the dam during the higher temperatures, as opposed to 11 of 163 (7%) when temperatures were lower than 19.5°C ($\chi^2 = 16.0$, $P < 0.0001$, $DF = 1$).

Of the 205 fish released, 182 approached the dam, 154 entered the collection channel, 124 progressed to the transition area, 105 progressed to the ladder, 99 progressed to the top of the ladder, and 71 passed the dam (Fig. 10). Two fish passed the dam using the navigation lock for an overall passage efficiency of 36% of released fish and 40% of those that approached the dam. Median length, median weight, date, and temperature at release had no effect on passage efficiency ($P > 0.05$). One fish was recorded in the tailrace of the dam after successfully passing over the dam (i.e., a fallback).

At PH1, 20 of the 98 fish that approached the fishway failed to enter (-20%), 15 of the 78 fish that entered the collection channel failed to reach the transition area (-19%), 2 of the 63 that were in the transition area failed to reach the ladder (-3%), 2 of the remaining 61 fish failed to ascend the ladder (-3%), and 22 of the 59 fish that ascended the ladder failed to pass the counting window area at the top of the ladder (-37%). The total percentage that failed to pass at PH1

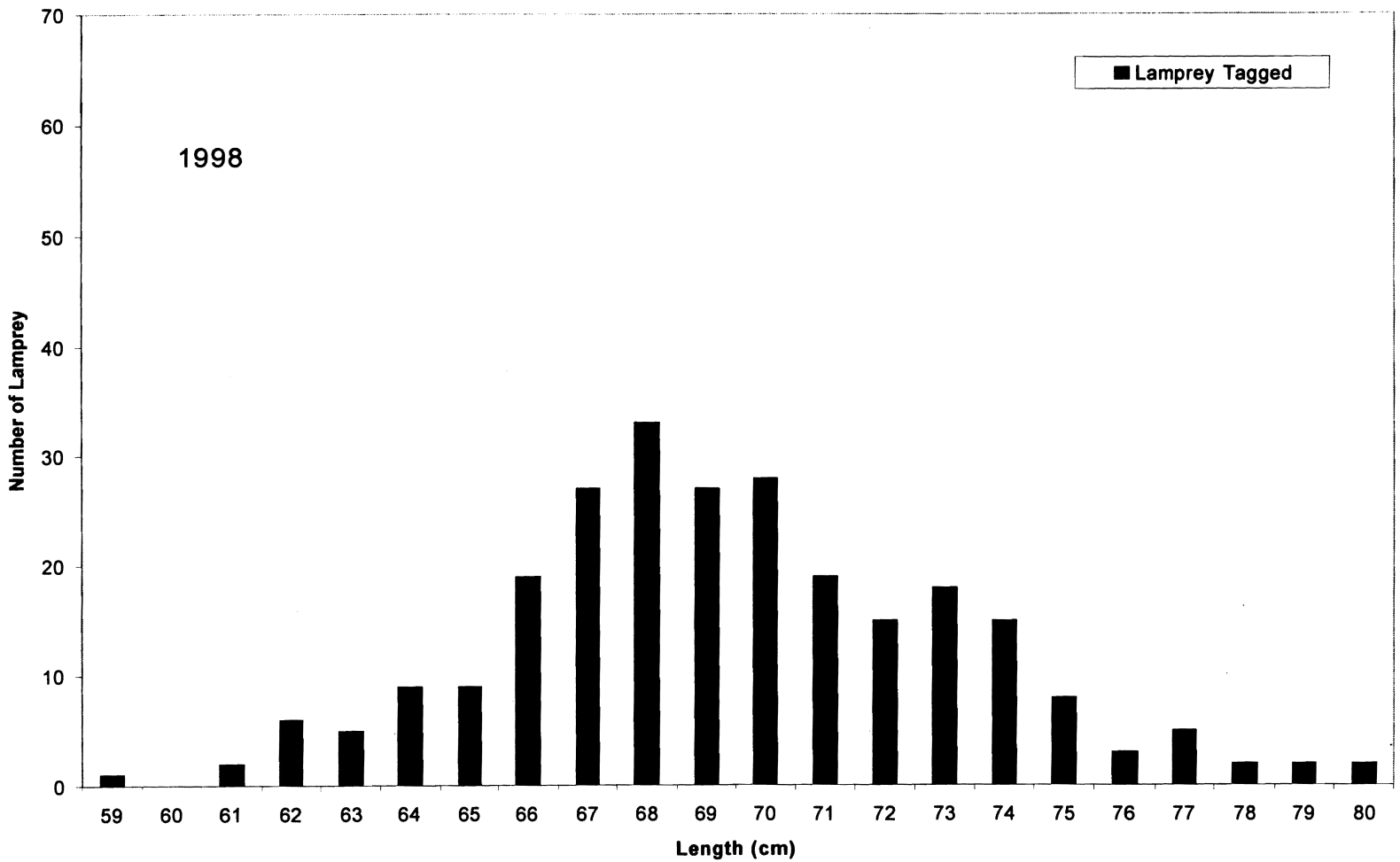


Figure 8. Length distribution (cm total length) of lamprey tagged in 1998

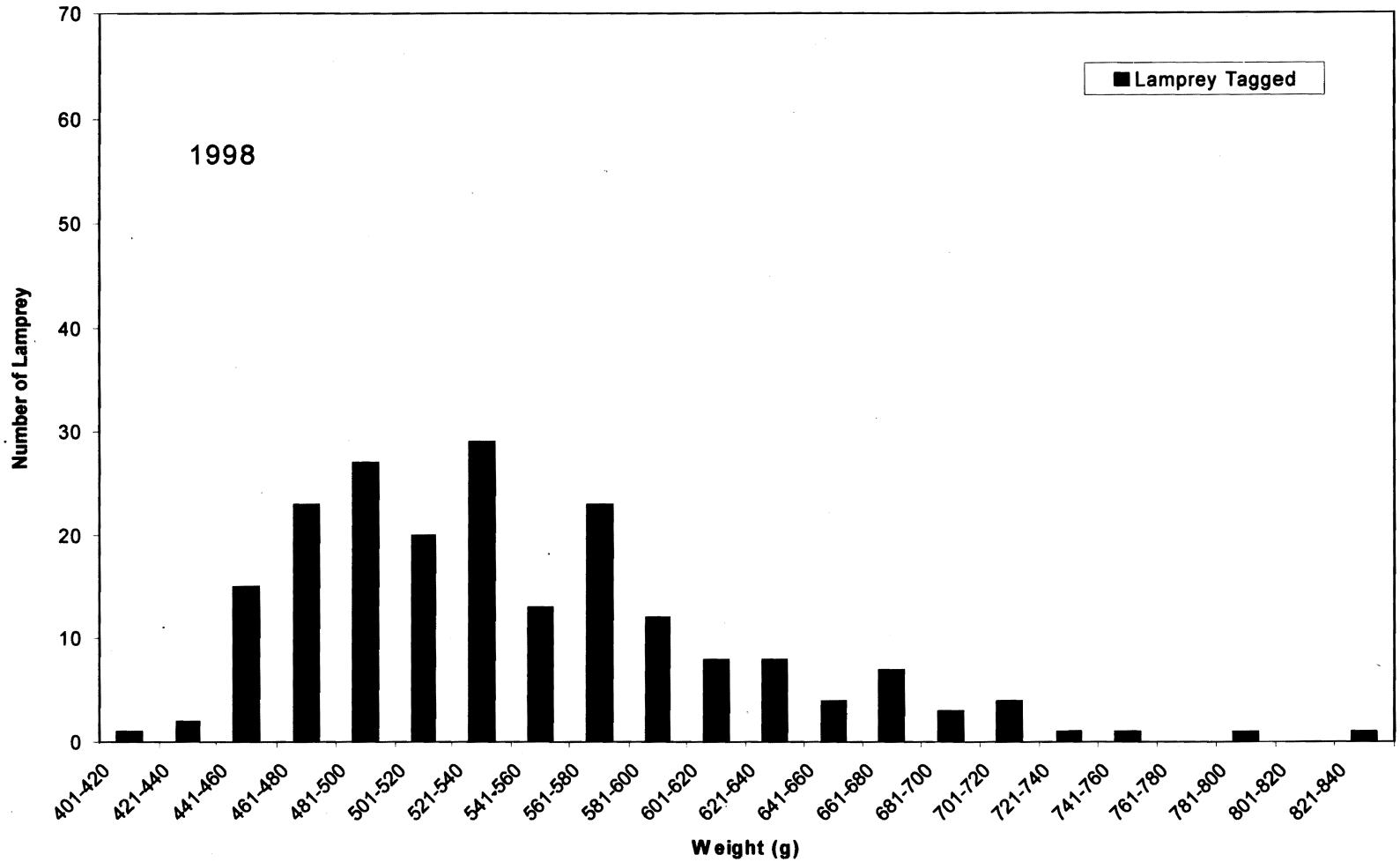


Figure 9. Weight (g) distribution of lamprey tagged in 1998.

Table 1. Numbers of lamprey released on each shore and first approach location for individual fish in 1998.

| Shore | Released | Returned | Powerhouse 1 | Powerhouse 2 | Spillway | Navigation Lock |
|---|---|---|---|---|---|---|
| Washington | 101 | 92 | 33 | 43 | 14 | 2 |
| Oregon | 104 | 90 | 42 | 36 | 11 | 1 |

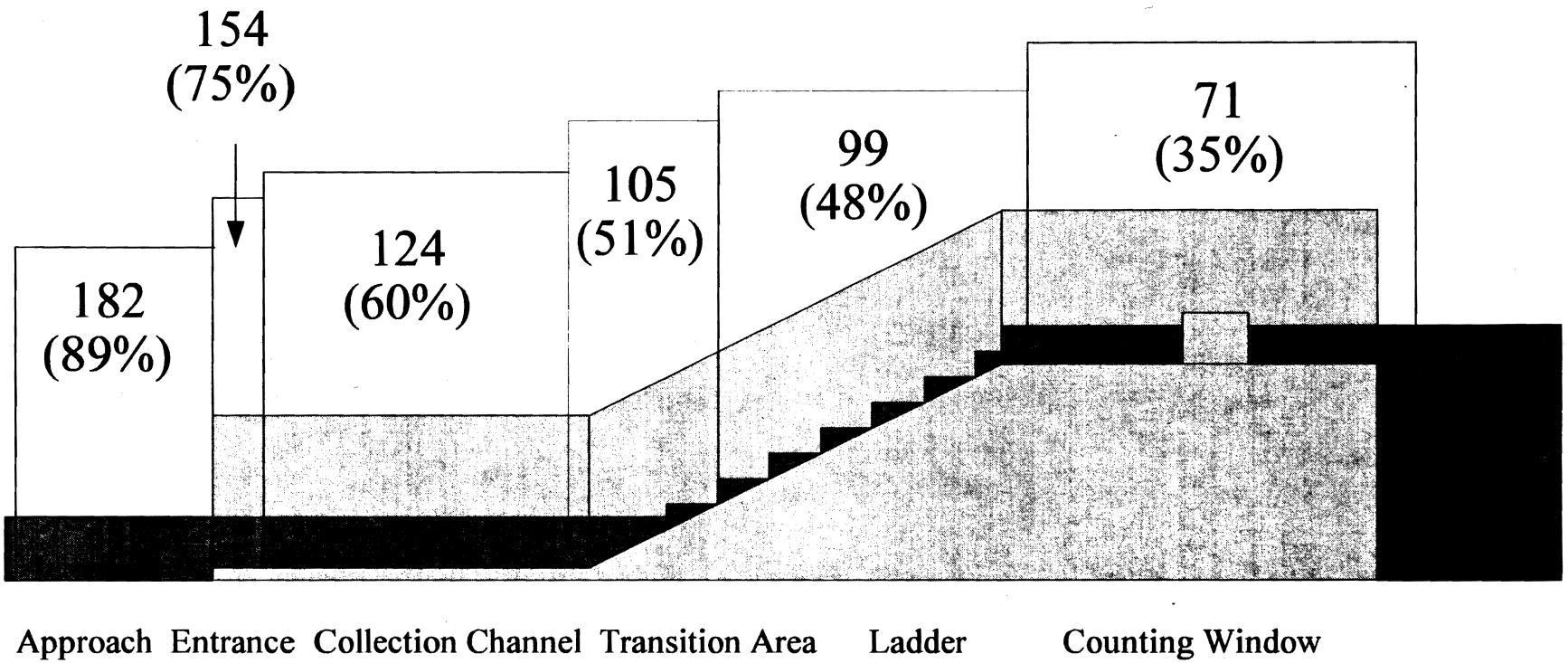


Figure 10. Overall success of lamprey released downstream from Bonneville Dam in 1998. Numbers represent the total number of fish that entered each fishway segment and percentages of the 205 fish released. Two fish passed the dam using the navigation lock, for an overall passage efficiency of 36%.

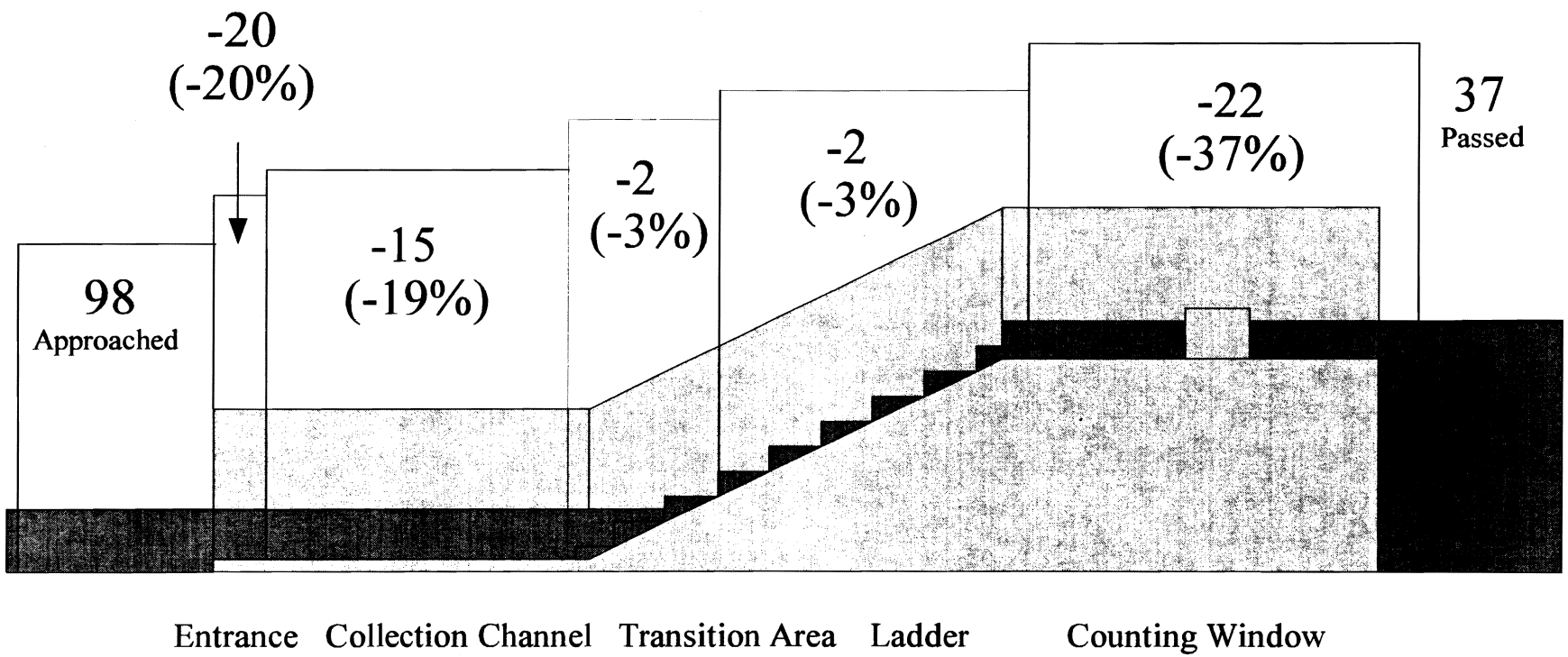


Figure 11. Overall failure to pass at each fishway section at Bonneville Dam Powerhouse 1 in 1998. The number of lamprey that failed to pass each section and percentages that failed to pass a section of those that entered that section (e.g., 59 fish reached the top of the ladder but 22 failed to pass the counting window, so 37% failed to pass the counting window) are both given.

PH1 (not including fish from the spillway ladder) was 62% (61 of the 98 fish that approached did not pass upstream). Of the 59 fish that entered at PH1 and reached the top of the ladder, 12 entered the makeup water channel (MWC). Of these, three passed by going over the upstream Tainter gate, four backed out and passed via the counting window, and five backed down the ladder and exited into the tailrace (Fig. 12).

At PH2, 18 of the 96 fish that approached failed to enter the fishway (-19%), 28 of the 78 fish that entered failed to reach the transition area (-36%), 18 of 50 failed to pass through the transition area (-36%), 3 of 32 failed to ascend the ladder (-9%), and 4 of 29 failed to pass the counting window area at the top of the ladder (-14%). The percentage of fish that failed to pass at PH2 (not including fish from the spillway ladder) was 74% (71 of the 96 that approached did not pass upstream) (Fig. 13). The MWC at PH2 was not monitored in 1998.

Forty-four of the 79 fish that approached the spillway entrances failed to enter the fishways (-56%), 14 of the 35 fish that entered failed to make it to the transition areas (-40%), 9 of 21 failed to reach the ladders (-43%), 1 of 12 failed to ascend the ladders (-8%), and 2 of 11 failed to pass the counting window area at the top of the ladders (-18%). Eighty-nine percent of the fish that approached the spillway entrances failed to pass over the dam (70 of the 79 fish that approached did not make it over the dam) (Fig. 14).

Of the 28 fish that failed to pass the counting window areas at the top of the ladders (22 at PH1, 4 at PH2, 2 from the spillway), all moved downstream in the ladder and exited, 5 re-approached the dam after exiting, but none reascended any ladder.

**Entrance Usage - Approaches, Entries, Exits, and Outcome**

**Powerhouse 1--**In 1998, 98 fish made 579 approaches at the fishway entrances (median = 4 approaches/fish, range = 1 to 22). Approaches were distributed unevenly across the powerhouse, with 96 approaches at the south entrance, 372 at the five orifice entrances, and 111 at the north entrance (Fig. 15). Of the 20 fish that approached PH1 only once, 11 reached the top of the ladder (55%). Of the 62 lamprey that approached 2-10 times, 39 reached the top of the ladder (63%), and of the 15 that made 11-20 approaches, 8 reached the top of the ladder (53%). One fish that approached 22 times reached the top of the ladder.

Entries (n = 117) into the fishway were made by 78 lamprey (median = 1 entry/fish, range = 1 to 5), with 44 at the south entrance, 42 at the five orifice entrances, and 31 at the north entrance (Fig. 15). Of the 44 entries into the fishway at the south entrance, 39% resulted in an immediate turn around and exit into the tailrace, 23% entered the collection channel area before exiting downstream, 2% entered the transition area before exiting, 11% reached the top of the ladder prior to turning around and exiting downstream, and 25% succeeded in passing the dam (Fig. 16). The result of the 42 entries by lamprey into the five orifice entrances included 48% that reached no farther than the collection channel, 5% that reached no farther than the middle of

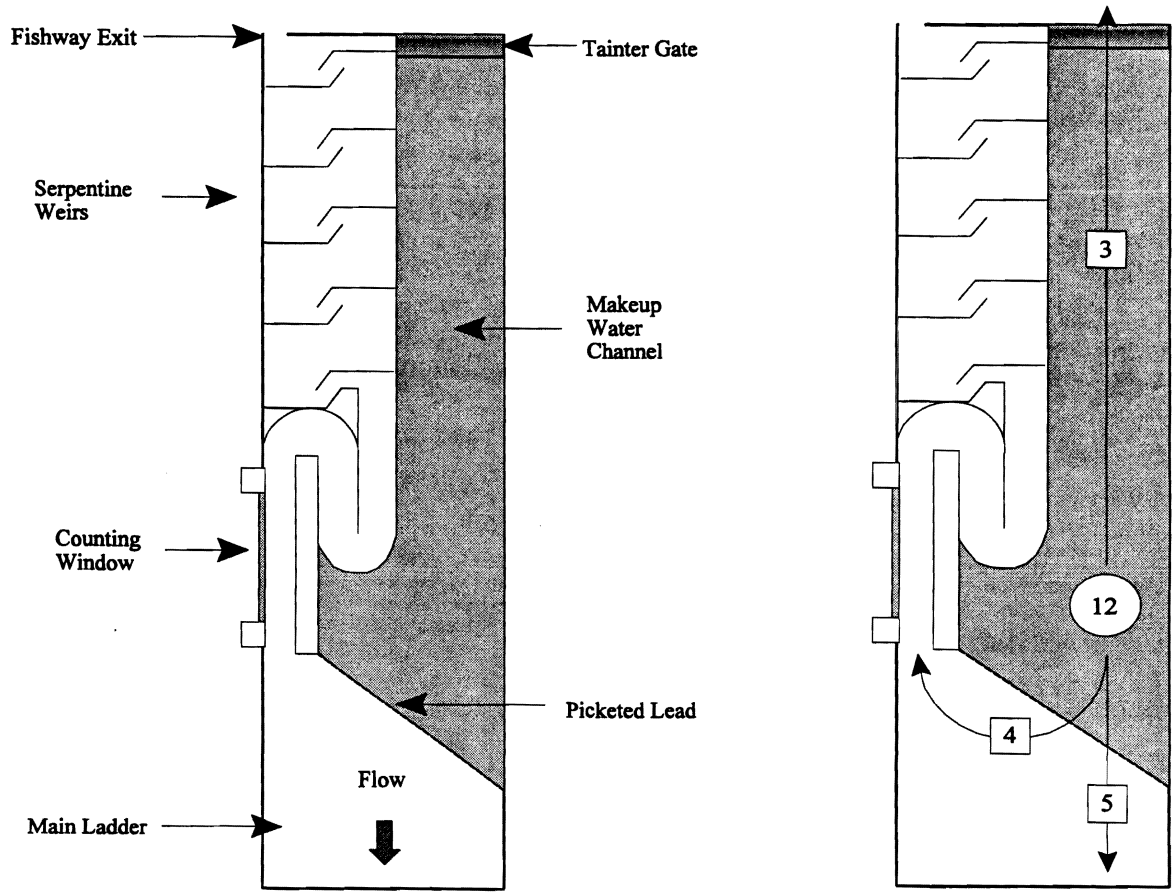


Figure 12. Overhead view of the counting window area at Powerhouse 1 and the passage outcomes for the 12 lamprey that entered the makeup water channel through the picketed lead in 1998. Twelve fish entered, 3 passed via the Tainter gate, 4 exited and passed upstream via the counting window, and 5 returned to the tailrace of the dam.

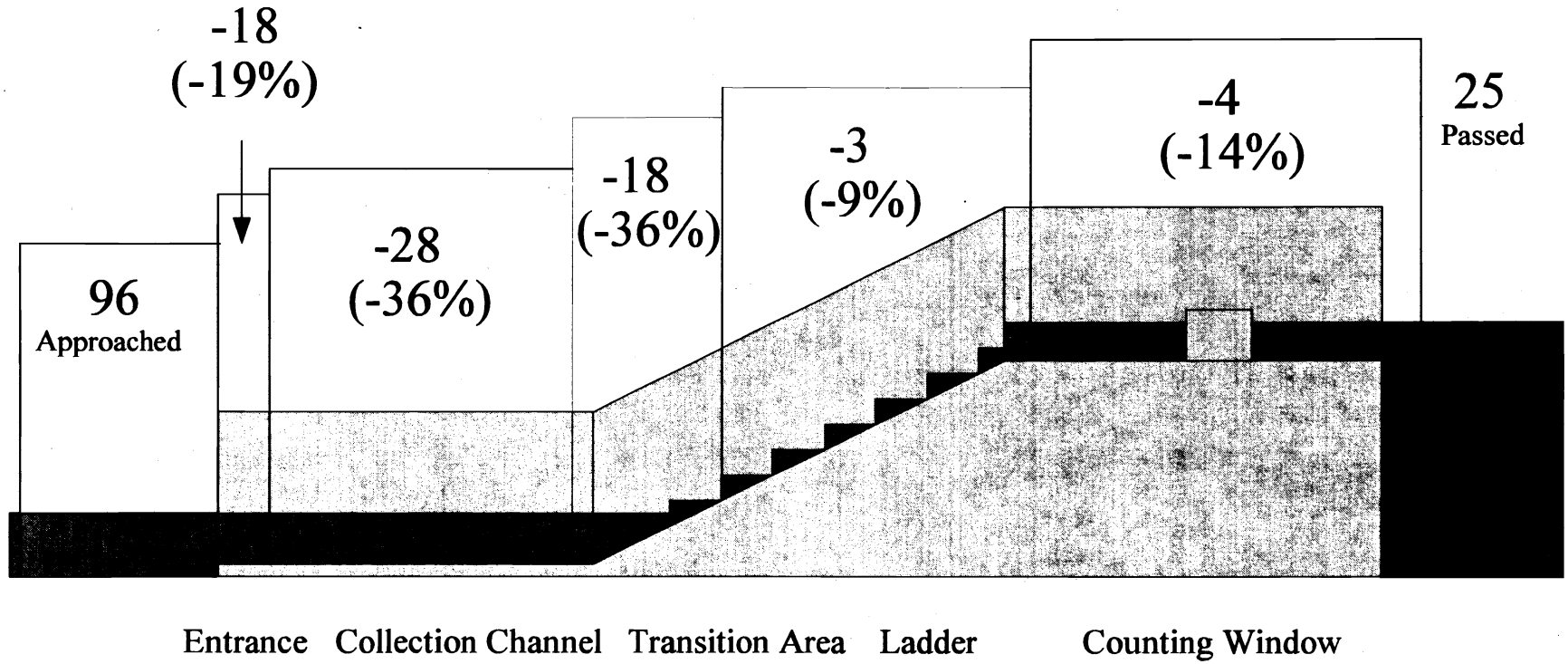


Figure 13. The number of lamprey that failed to pass at each section of the fishway at Bonneville Dam Powerhouse 2 in 1998, including the percentage of fish that failed to advance of those that entered each successive area.

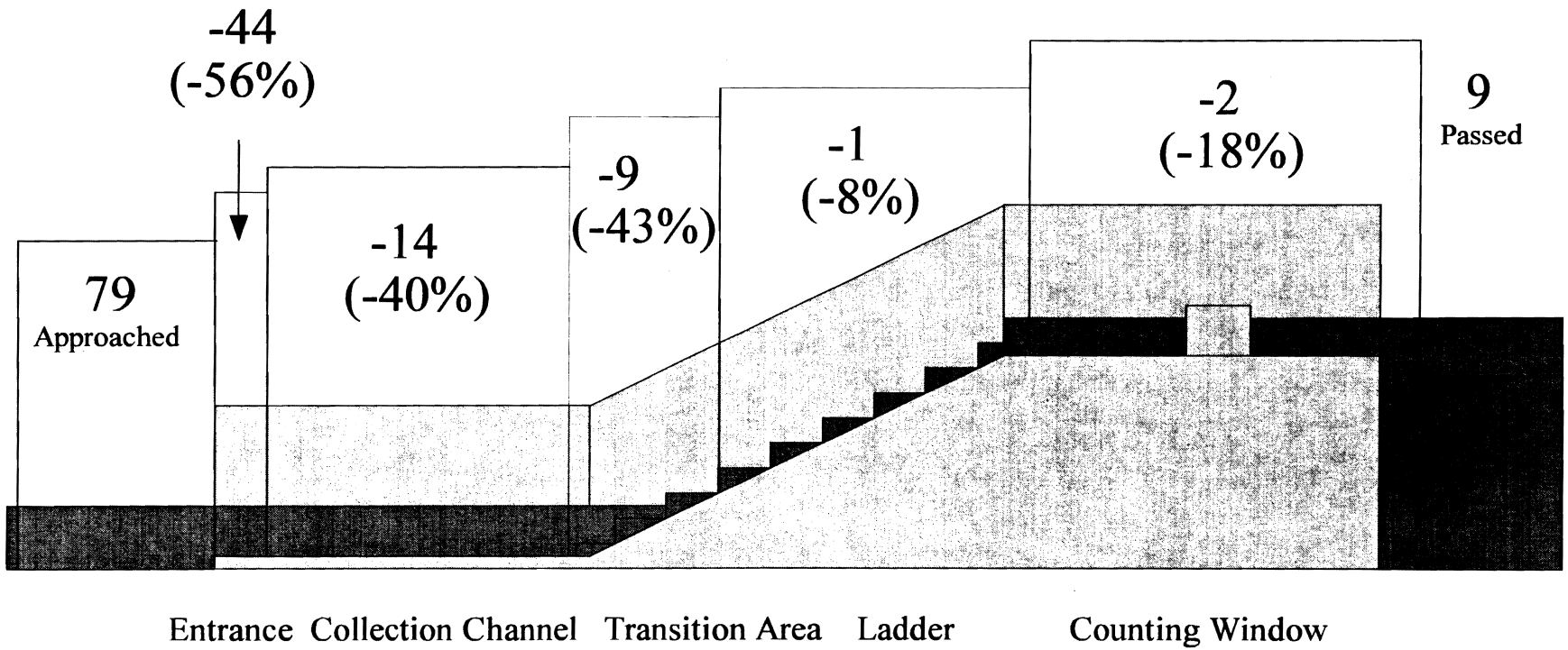


Figure 14. The number of lamprey that failed to pass at each section of the Bonneville Dam spillway fishways in 1998, including the percentage of fish that failed to advance of those that entered each successive area.

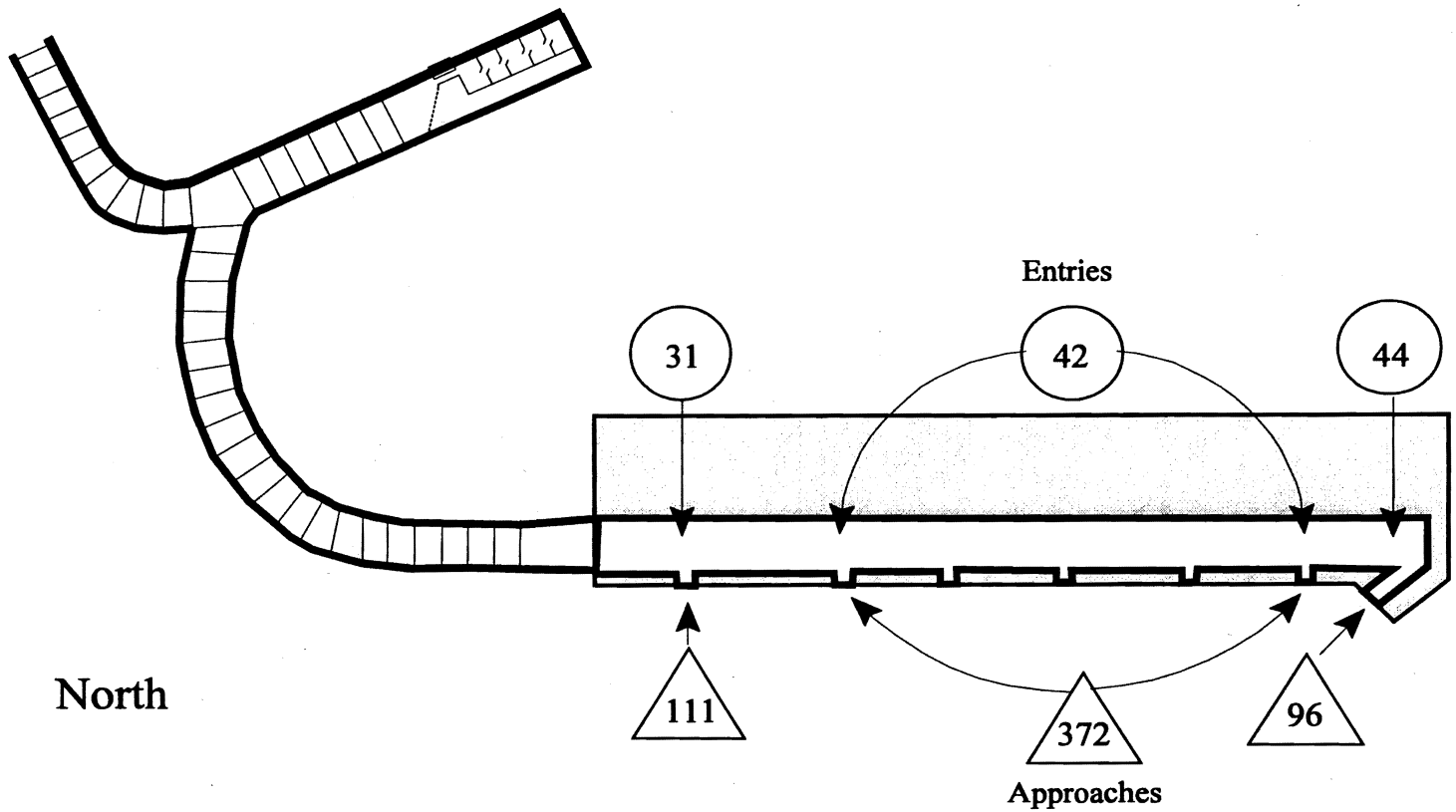


Figure 15. Overhead view looking upstream at Bonneville Powerhouse 1 with the number of approaches (triangles) and entries (circles) made by adult radio-tagged lamprey in 1998.

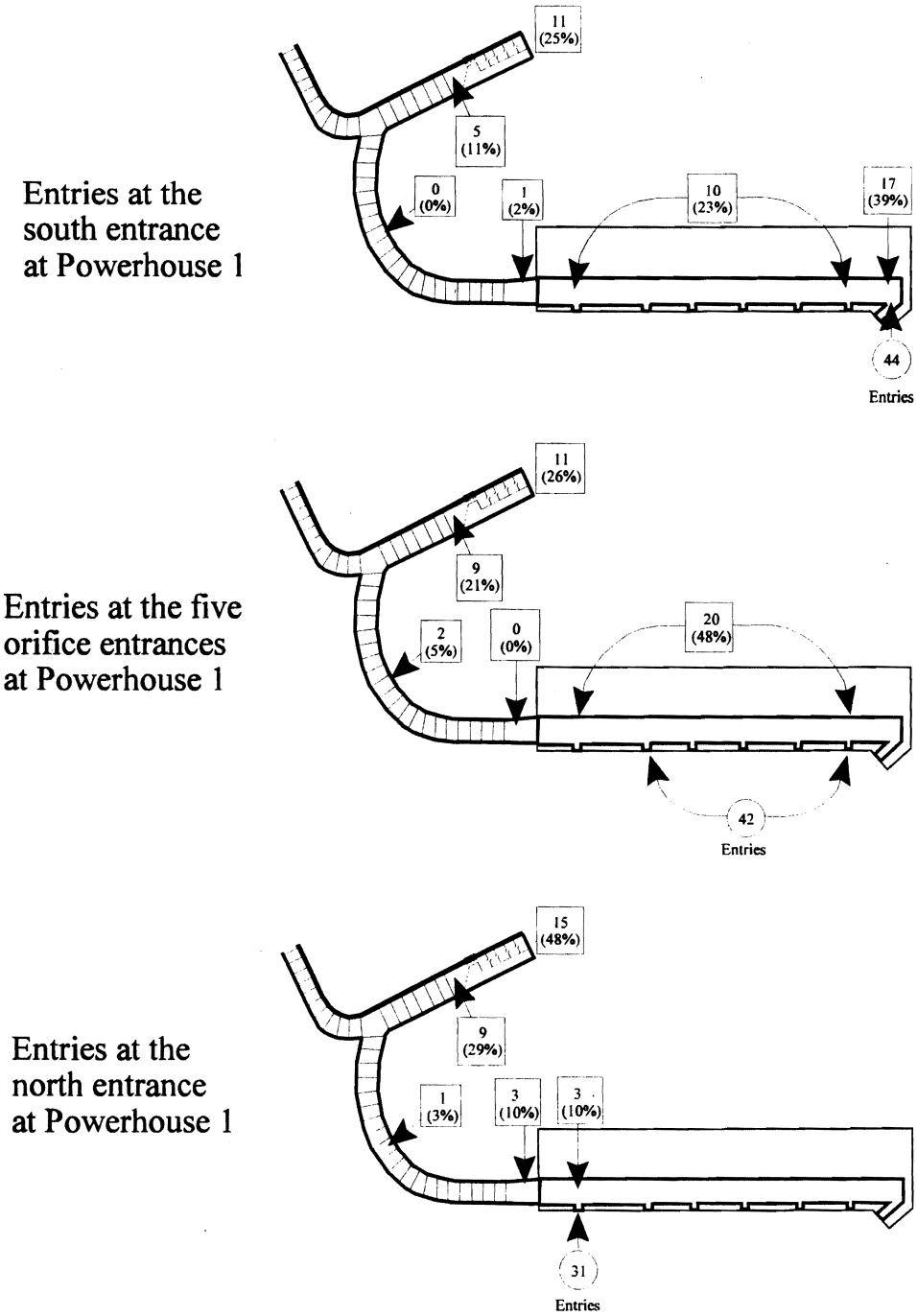


Figure 16. Highest point attained by radio-tagged lamprey (squares) for entries (circles) at the southern (top), orifice (middle), and northern (bottom) entrances at Bonneville Dam Powerhouse 1 in 1998.

the ladder, 21% that attained the top of the ladder but backed down thereafter, and 26% that passed the dam (Fig. 16). Of the 31 entries at the north end of PH1, 10% reached no farther than the collection channel, 10% reached the transition area before turning around, 3 % reached the middle of the ladder, 29% reached the top of the ladder but backed down, and 48% passed the dam (Fig. 16). For the 117 entries into the fishway at PH1, 65 exits into the tailrace occurred: 26 out the south entrance, 29 out the five orifice entrances, and 10 out the north entrance (Table 2).

**Powerhouse 2**--At PH2 in 1998, 2,592 approaches were made at fishway entrances by 96 fish, (median = 18.5 approaches/fish, range = 1 to 139). There were 930 approaches at the three south entrances, 991 across the middle ten orifice entrances, and 671 at the three north entrances (Fig. 17). Of the three fish that approached once, two attained the top of the ladder (67%). Of the 25 fish that approached 2-10 times, 9 attained the top of the ladder (36%), and of the 23 fish that approached 11-20 times, 4 attained the top of the ladder (17%). Of the 17 fish that approached 21-30 times, 2 attained the top of the ladder (12%). Of the 9 fish that approached 31-40 times, 3 attained the top of the ladder (33%), and of the 19 fish that made more than 40 approaches at PH2, 8 attained the top of the ladder (42%).

Entries into the fishway (n = 285) were made by 78 fish, (median = 3 entries/fish, range = 1 to 11). Of the 183 entries at the three south entrances of PH2, 74% immediately turned around and exited, 21% entered the collection channel before exiting, 2% entered the transition area before exiting, <1% reached the middle of the ladder before backing down, and 2% passed the dam (Fig. 18). Of the 27 entries by lamprey into the ten orifice entrances, 93% reached no farther than the collection channel, 4% entered the transition area and then exited, and 4% reached the middle of the ladder before backing down (Fig. 18). Of the 75 entrances into the three north entrances of the powerhouse, 13% reached no farther than the collection channel, 48% entered the transition area before turning around, 4% reached the middle of the ladder, 5% reached the top of the ladder before returning to the tailrace, and 29% passed the dam (Fig. 18). For the 285 entries into the fishway at PH2, 262 exits occurred with 176 exits out the three south entrances, 32 out the middle ten orifice entrances, and 54 out the three north entrances (Table 2).

**Spillway**--A total of 144 approaches were made by 79 fish at the spillway entrances to the fishways in 1998 (median = 1 approach/fish, range = 1 to 10). Approaches were distributed evenly between the two entrances, with 79 approaches at the south entrance and 65 at the north entrance (Fig. 19). Of the 45 fish that approached once, 4 attained the top of the ladders (9%), and of the 34 fish that approached 2-10 times, 7 attained the top of the ladders (21%).

Entries into the fishways (n = 51) were made by 34 lamprey (median = 1 entry/fish, range = 1 to 6). Of the 27 fish that entered at the south entrance, 52% turned around and exited after entering, 26% attained the transition area, 4% reached the middle of the ladder before exiting downstream, 4% reached the top of the ladder before returning to the tailrace, and 15% passed the dam (Fig. 20). Of the 24 fish that entered the north entrance at the spillway, 42% turned around and exited after entering, 33% entered the transition area before turning around,

Table 2. Total number of approaches, entries, and exits at Bonneville Dam fish ladder entrances by adult radio-tagged Pacific lamprey in 1998.

| | Powerhouse 1 | | | Powerhouse 2 | | | Spillway | | Navigation Lock |
|---|---|---|---|---|---|---|---|---|---|
| Entrance Location | S | Mid | N | S | Mid | N | S | N | |
| Approaches | 96 | 372 | 111 | 930 | 991 | 671 | 79 | 65 | 3 |
| Entries | 44 | 42 | 31 | 183 | 32 | 70 | 27 | 24 | 3 |
| Exit(s) | 26 | 29 | 10 | 176 | 32 | 54 | 38 | 22 | 1 |

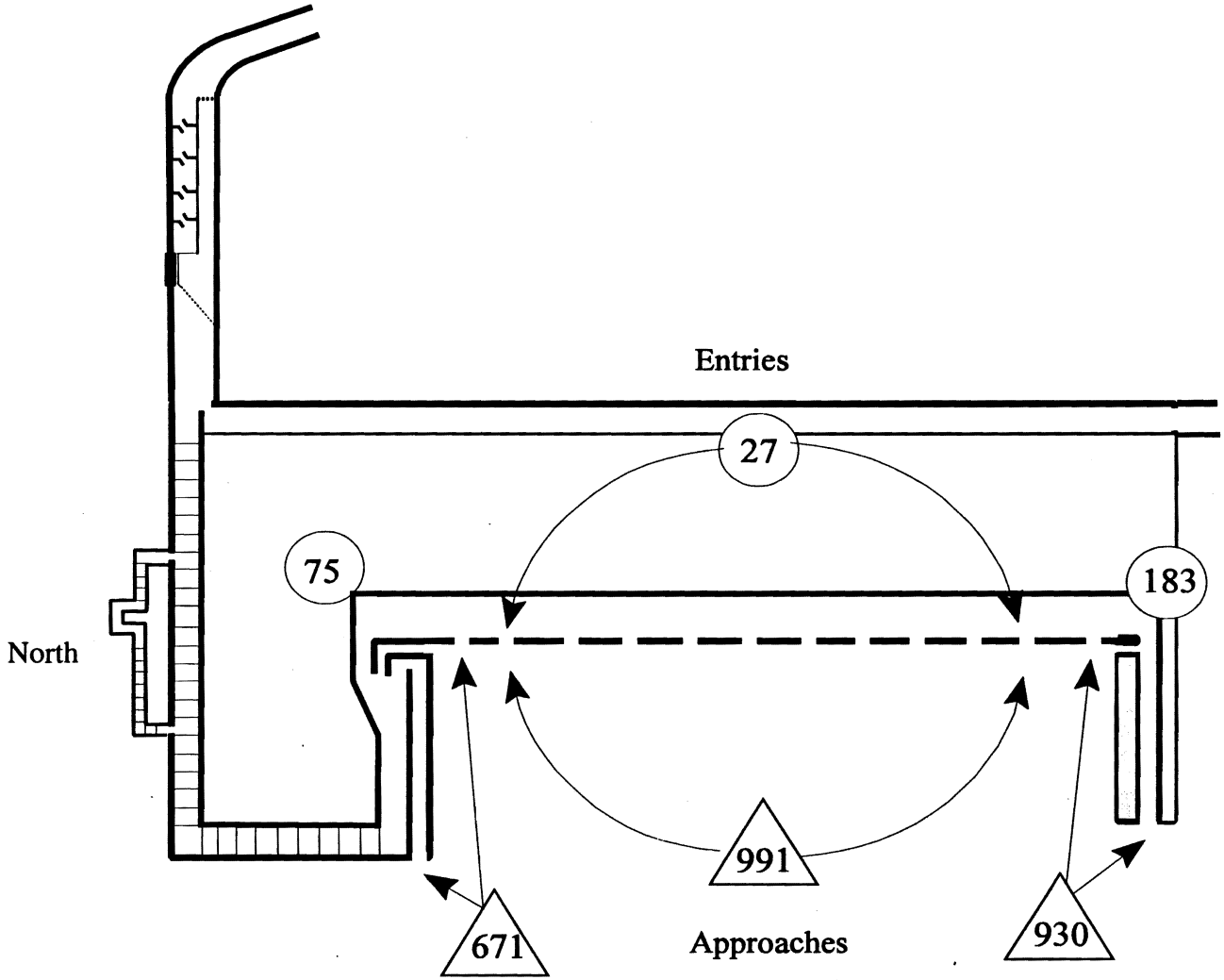


Figure 17. Approaches (triangles) and entries (circles) made by adult radio-tagged lamprey at the three northern entrances, 10 orifices, and three southern entrances at Bonneville Dam Powerhouse 2 in 1998.

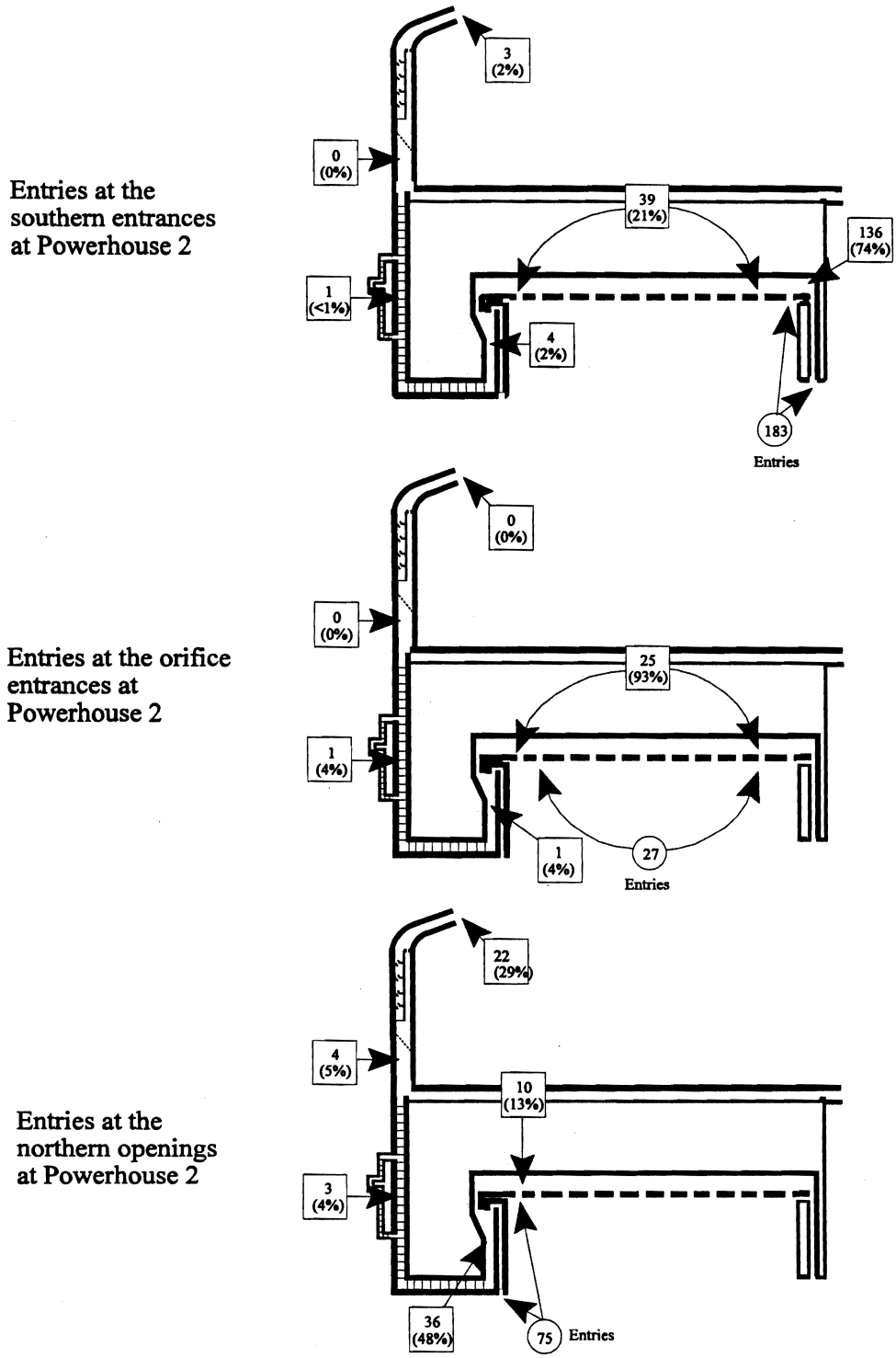


Figure 18. Highest point attained by radio-tagged lamprey (squares) that entered (circles) at the southern (top), orifice (middle), and northern entrances at Bonneville Dam Powerhouse 2 in 1998.

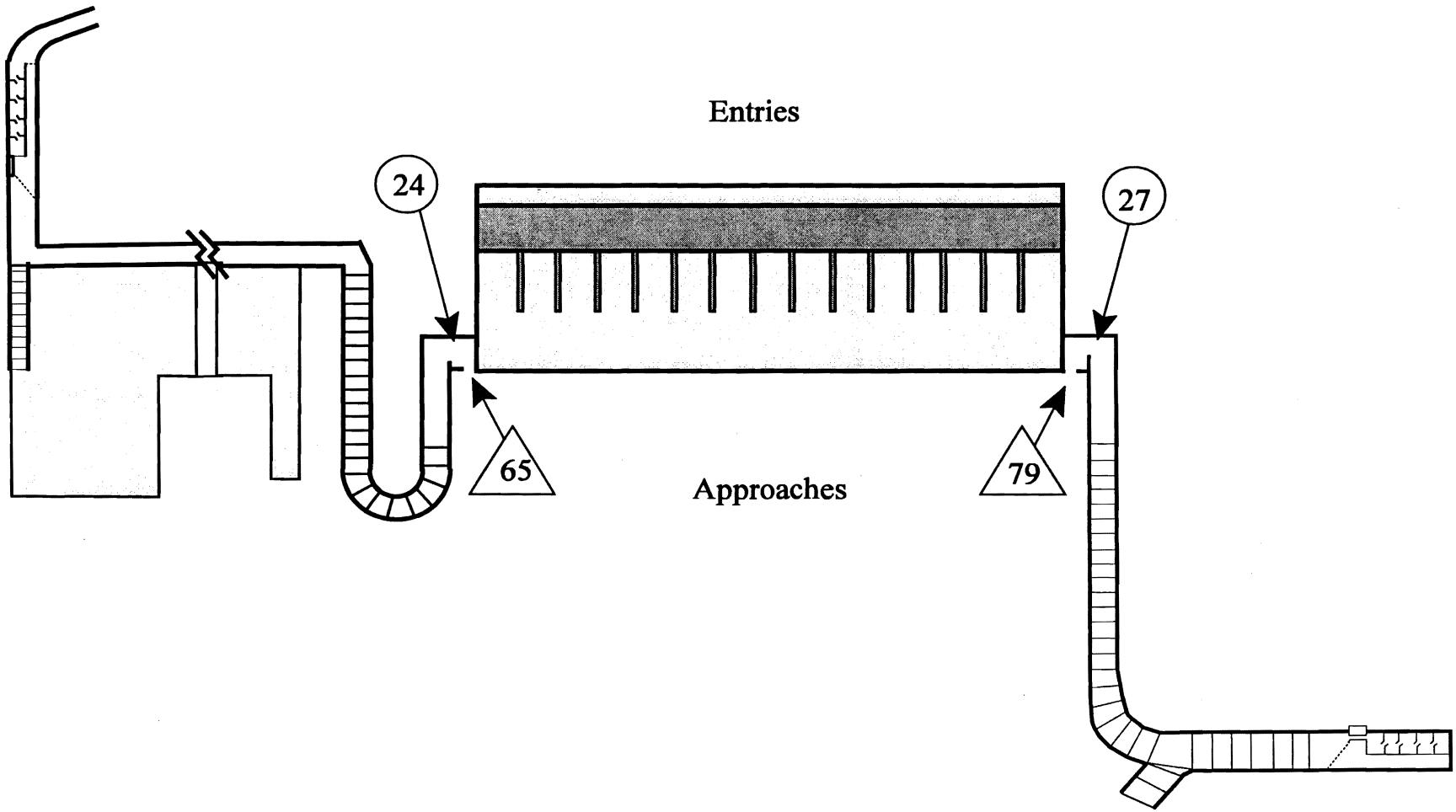


Figure 19. Approaches (triangles) and entries (circles) made by adult radio-tagged lamprey at the Bonneville Dam spillway entrances in 1998.

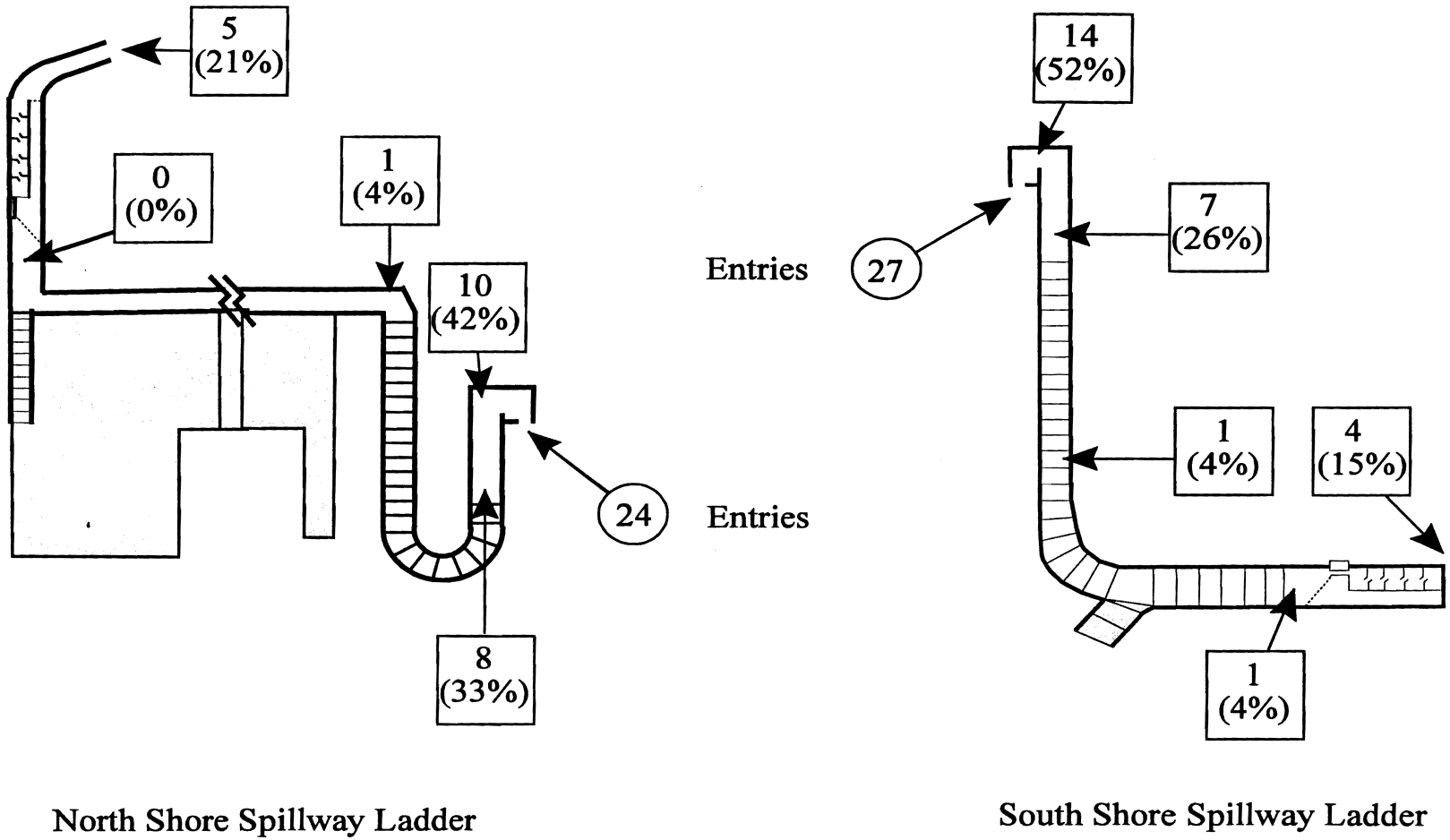


Figure 20. Highest point attained by radio-tagged lamprey (squares) for entries (circles) at the northern (left panel) and southern (right panel) Bonneville Dam spillway entrances in 1998.

4% reached the top of the ladder and upstream migrant tunnel (UMT) before returning to the tailrace, and 21% passed the dam (Fig 20).

Forty-two exits occurred at the spillway entrances, and an additional 18 exits occurred from fish backing down the spillway ladders after entering at one of the two powerhouses. Thirty-eight exits occurred out the south entrance and 22 out the north entrance (Table 2).

**Navigation Lock--**At the navigation lock in 1998, three fish approached and entered the lock chamber. One returned to the tailrace of the dam and two passed upstream when the upstream gates were opened (Table 2).

**Multiple Locations--**Of all fish that approached the dam in 1998, 105 approached only one segment (e.g., PH1, PH2, spillway, or navigation lock), 60 approached two segments, and 17 approached three segments. Numbers of fish that passed the dam for each group were 49 (47%), 18 (30%), and 6 (35%), respectively.

**Rates and Times of Passage**

In 1998, the median time between fish release and first known approach to PH1 was 87.5 hours (5.0-394.1 hours, n = 72), to PH2 was 87.4 hours (10.8-678.7 hours, n = 77), to the spillway was 164.2 hours (2.7-384.5 hours, n = 26), and to the navigation lock was 12.5 hours (n = 1)[2].

The median time between first known approach and first known entrance into the fishway (at the same segment as first approach) was 1.0 hour at PH1 (0.0-232.2 hours, n = 43), 1.0 hour at PH2 (0.0-400.2 hours, n = 58), and 0.6 hours (0.1-803.3 hours, n = 8) at the spillway entrances. The median time between first known approach and first known entrance into the fishway at a segment other than where the first approach occurred was 263.4 hours for PH1 (1.6-451.3 hours, n = 9), 87.4 hours for PH2 (20.6-273.2 hours, n = 6), and 236.1 hours (2.5-610.8 hours, n = 3) at the spillway entrances. The median time from first known entrance to passage via any ladder was 91.2 hours (7.0-620.9 hours, n = 58).

The median time for lamprey to traverse 29 weirs at PH1 was 6.0 hours (1.9-292.3 hours, n = 54) or 12.4 minutes/weir (3.8-605.0 minutes/weir). At PH2 median time to transit 34 weirs was 3.1 hours (1.9-5.3 hours, n = 26) or 5.3 minutes/weir (3.5-9.5 minutes/weir). The median time to negotiate 36 weirs at the south spillway ladder was 6.2 hours (2.9-25.9 hours, n = 4) or 10.4 minutes/weir (4.7-43.1 minutes/weirs), and at the north spillway ladder the median time required for lamprey to negotiate 38 weirs was 5.3 hours (3.4-21.6 hours, n = 6), or 8.4 minutes/weir (5.7-36.1 minutes/weir).

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[2]Numbers of individuals used for approach duration calculations and approach locations may differ due to differences in numbers of "known time" and "unknown time" approaches.

Median time for lamprey to progress up the UMT was 40.0 minutes (22.6-190.1 minutes, n = 10), and time taken to progress down the UMT was 6.6 minutes (5.4-11.0, n = 6). In computing the time to traverse any structure, we used only the first incidence of behavior for each fish to eliminate potential learning effects.

At the south spillway entrance in 1998 (first approach only), median time from approach to entry was 16.7 minutes (0.1-88.7 minutes, n = 9). Median holding time for fish that approached and did not enter was 9.5 minutes (0.4-38,083.7 minutes, n = 31). At the north spillway entrance, median time from approach to entry was 39.9 minutes (8.7-226.6 minutes, n = 11). Median holding time for fish that approached and did not enter was 20.0 minutes (0.6-4560.7 minutes, n = 26).

In 1998, there were 3,436 lamprey approaches to the fishway entrances where the exact time was recorded (known approach). Of these, 1% occurred at civil dawn, 46% occurred during daylight, 2% occurred at civil dusk, and 51% occurred in hours of darkness. Approach frequency distributions were: 0.59 $hour^{-1}$ at civil dawn, 0.77 $hour^{-1}$ during daylight, 0.92 $hour^{-1}$ at civil dusk, and 1.49 $hour^{-1}$ for hours of darkness (Fig. 21a). There were 391 entries into the fishways where exact time of entry was recorded (known entry). One percent occurred at civil dawn, 40% occurred during daylight, 3% occurred at civil dusk, and 56% occurred during hours of darkness. The entrance frequencies were 0.05 $hour^{-1}$ at civil dawn, 0.08 $hour^{-1}$ during daylight, 0.12 $hour^{-1}$ at civil dusk, and 0.19 $hour^{-1}$ for hours of darkness (Fig. 21a). Of the 1,059 records of activity in the fish ladders, 4% occurred at civil dawn, 33% occurred during daylight, 2% occurred at civil dusk, and 61% occurred during hours of darkness. Movements in the ladder occurred at a rate of 0.55 $hour^{-1}$ at civil dawn, 0.17 $hour^{-1}$ during daylight, 0.21 $hour^{-1}$ at civil dusk, and 0.54 $hour^{-1}$ for hours of darkness (Fig. 21b). Of the 73 known passage events (e.g., exits out the top of the dam), 4% occurred at civil dawn, 22% occurred during daylight, and 74% passed during hours of darkness. The frequency distributions for exits at the top of the ladder above the dam were: 0.04 $hour^{-1}$ at civil dawn, 0.01 $hour^{-1}$ during daylight, and 0.05 $hour^{-1}$ for hours of darkness (Fig. 21b).

Lamprey that passed Bonneville Dam via the PH1 Bradford Island fishway in 1998 had a median forebay travel time (from ladder exit to the Bridge of the Gods) of 21.8 hours (1.4-285.4 hours, n = 22) or 4.95 $km \cdot day^{-1}$. For fish exiting at the top of the PH2 Washington shore fishway, median forebay travel time was 19.7 hours (0.7-115.4 hours, n = 20) or 5.49 $km \cdot day^{-1}$.

## The Dalles Dam

### Upstream Progress

Of the 73 fish that passed Bonneville Dam in 1998, 1 was detected in the Klickitat River and 44 were detected near The Dalles Dam. Of the 44 fish detected near the The Dalles Dam, 6 were detected 5 km downstream from the dam and were never found any closer. Of the 38 fish that approached the dam, 33 entered the fishway (87%), 33 progressed to the transition area (87%),

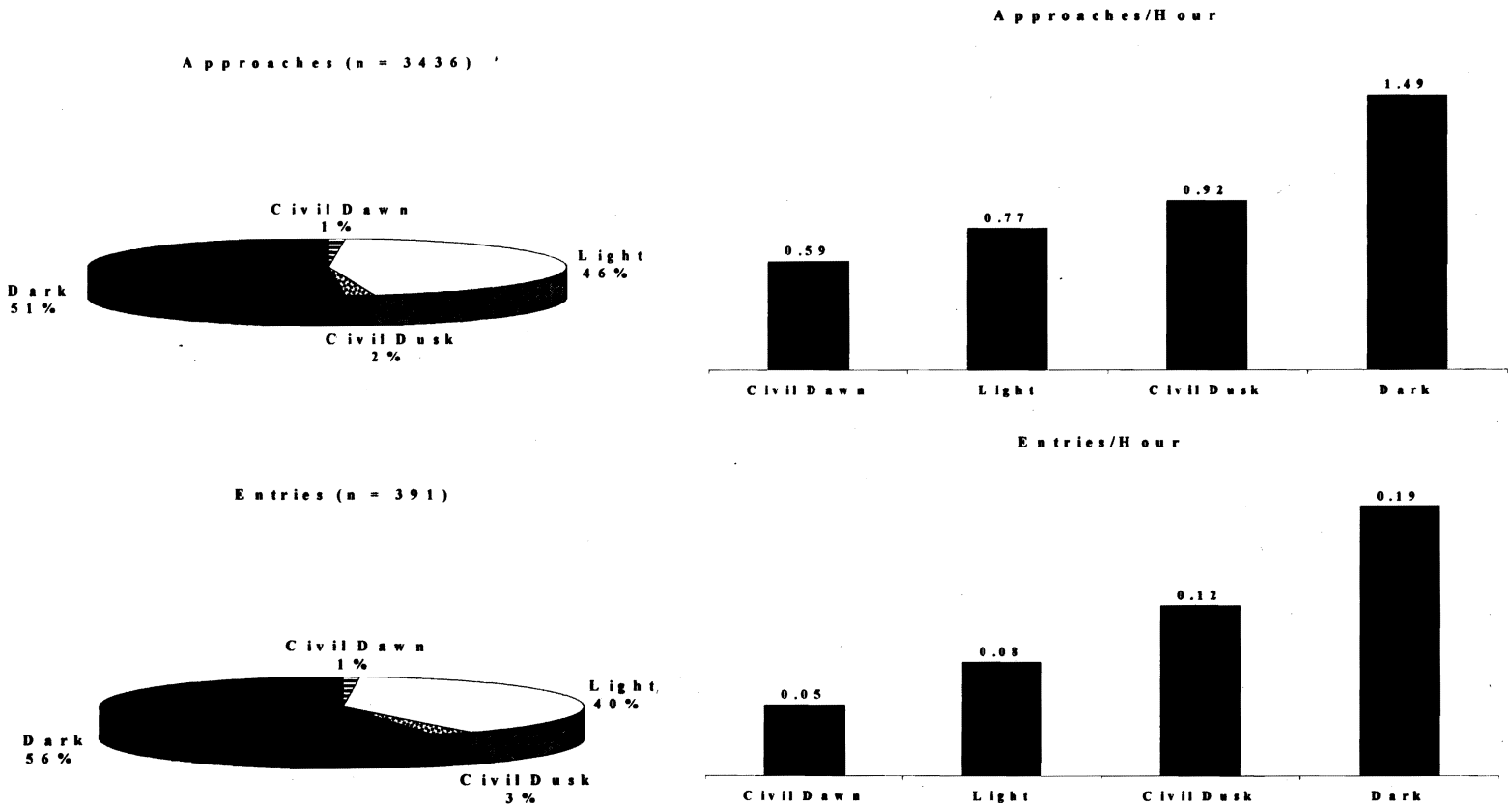


Figure 21a. The percentage of lamprey entries and approaches to Bonneville Dam during hours of darkness, light, civil dawn, and civil dusk in 1998. These data are also presented as rates (activity per hour) for each time of day.

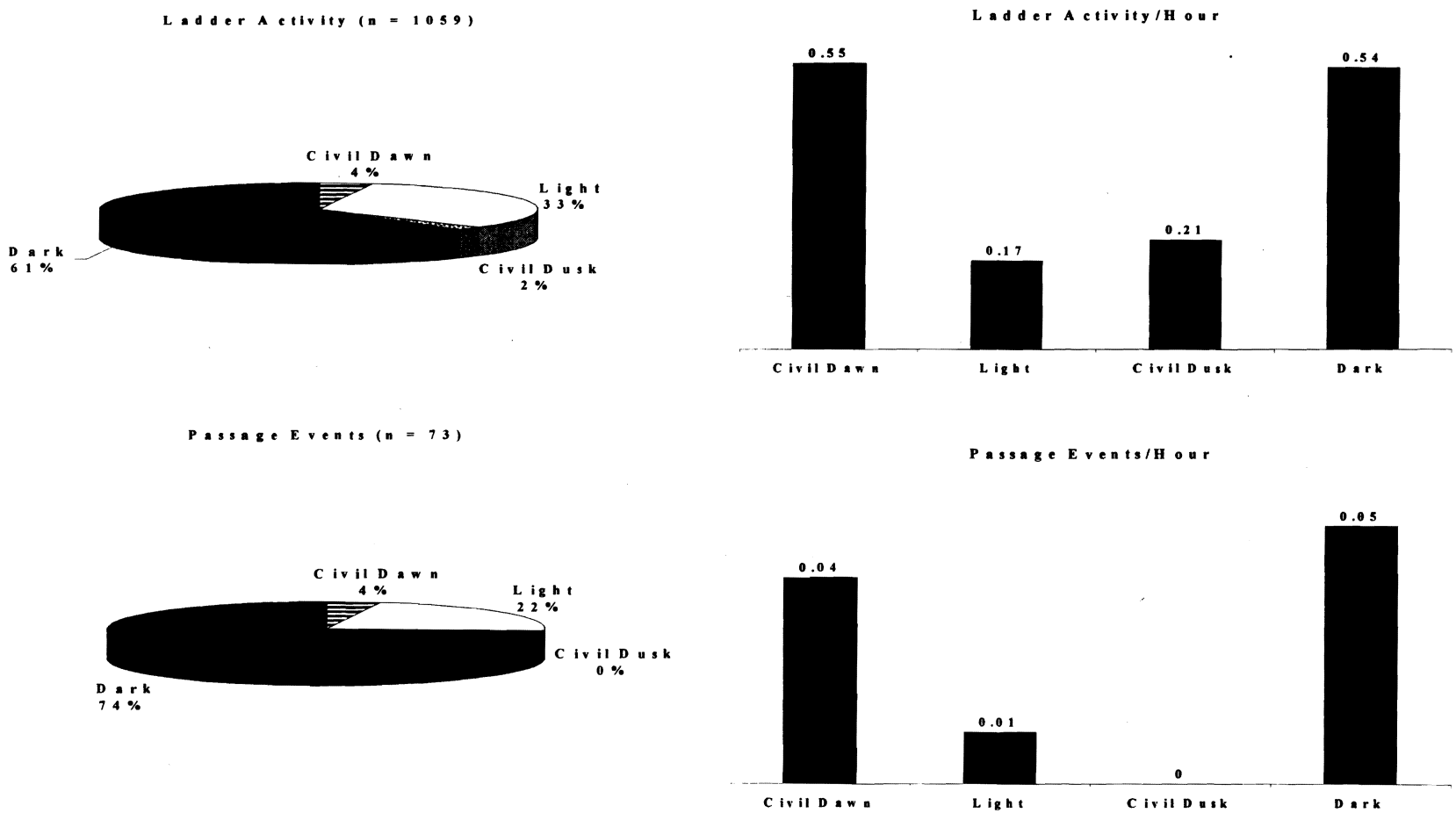


Figure 21b. The percentage of lamprey activity in the ladder and passage events at Bonneville Dam during hours of darkness, light, civil dawn and civil dusk in 1998. These data are also presented as rates (activity per hour) for each time of day.

24 progressed to the ladder (63%), 24 progressed to the top of the ladder (63%), and 24 passed the dam (63%) (Fig. 22). Fish had the most difficulty moving through the transition areas: 27% of the fish that entered those areas failed to advance to the ladder (Fig. 22). One fish fell back downstream twice after passing the north shore ladder, but in both instances it re-ascended the same ladder and eventually remained upstream of the dam. One fish that approached and entered the fishway was eventually detected in Fifteenmile Creek downstream from the dam (Fig. 3).

**Entrance Usage-Approaches, Entries, Exits, and Outcome**

In 1998, approaches (n = 102) were made at The Dalles Dam fishway entrances by 38 fish (median = 2 approaches/fish, range 1 to 9). Approaches were unevenly distributed, with 25 approaches at the north ladder entrance, 15 at the west powerhouse entrance, and 62 at the main powerhouse entrances (Fig. 3). Of the 12 fish that approached only once, 5 passed the dam (42%), and of the 25 that approached 2-10 times, 19 passed the dam (76%).

Sixty entries into the fishway were made by 33 fish (median = 1 entry/fish, range 1 to 6). Nineteen occurred at the north spillway entrance, 9 at the west powerhouse entrance, and 32 at the main powerhouse entrances (Table 3). Of the 19 fish that entered the fishway at the north spillway entrance, 2 turned around and exited after entering, 5 reached the middle of the ladder and then exited into the tailrace, and 12 passed the dam. Of the 9 entries into the west powerhouse entrance, 2 immediately turned around and exited, 4 entered the transition area before exiting downstream, and 3 passed the dam. Of the 32 entries into the main powerhouse entrances, 11 turned around and exited, 12 entered the transition area before turning around, and 9 passed the dam.

Of the 60 entries by lamprey into the fishways, 35 exits downstream occurred, with 6 from the north spillway entrance, 6 from the south spillway entrance, and 23 from the two upstream powerhouse entrances (Table 3).

**Rates and Times of Passage**

In 1998, the median lamprey travel time from an exit at Bonneville Dam to the first known approach to an entrance to a fishway at The Dalles Dam was 84.5 hours (34.6-378.5 hours, n = 37) or 21.0 $km \cdot day^{-1}$. However, median travel time from Bridge of the Gods to first known approach was 48.5 hours (30.0 - 192.0 hours, n = 25) or 34.2 $km \cdot day^{-1}$.

Median time between first known approach and first known entrance into a fishway at The Dalles Dam was 1.1 hours (0.0-150.8 hours, n = 30) and the median time from first known entrance to passage over the dam was 46.3 hours (4.6-205.4 hours, n = 23). Median time for lamprey to traverse the north ladder was 27.1 hours (4.3-124.6 hours, n = 12) and for the powerhouse ladder it was 22.8 hours (4.8-38.9 hours, n = 11).

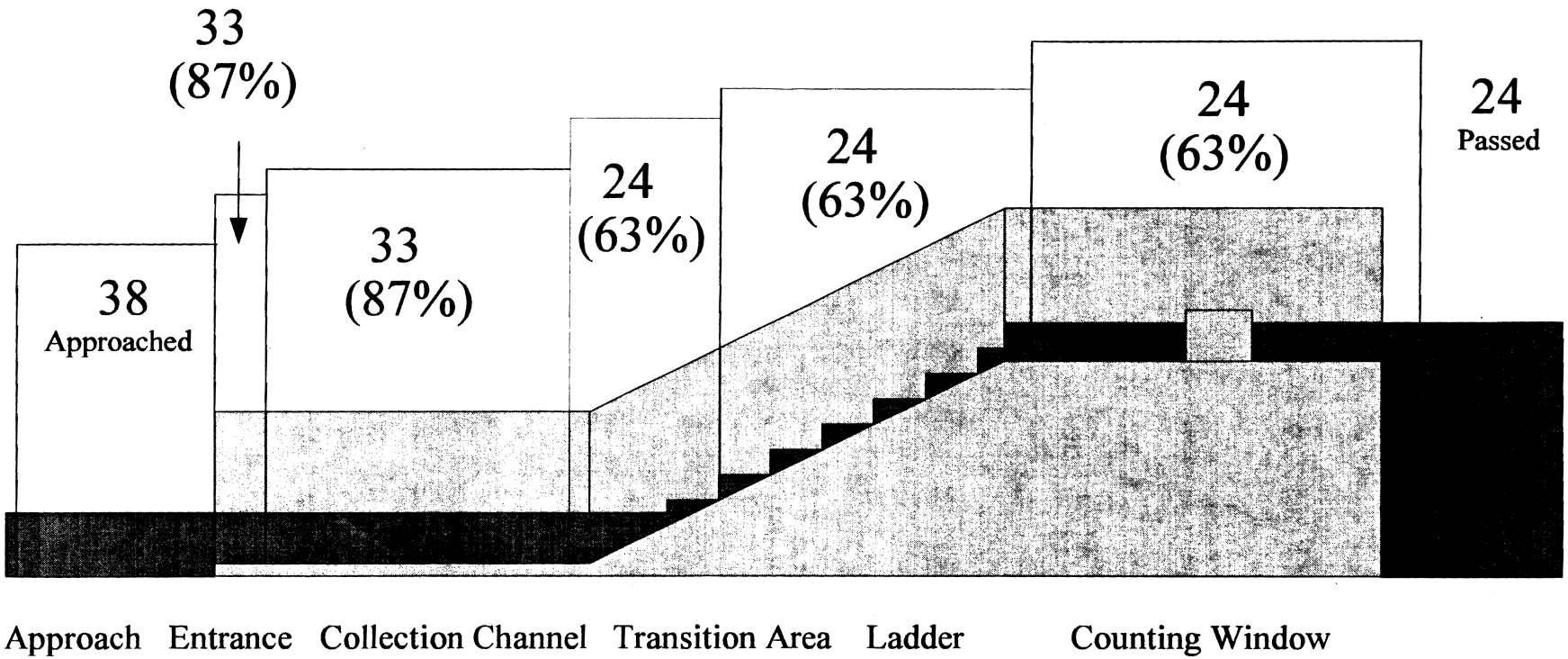


Figure 22. Overall success of lamprey that approached The Dalles Dam in 1998.

Table 3. Lamprey activity at The Dalles Dam fishway entrances in 1998.

| | North Ladder | Downstream Powerhouse | Main Powerhouse |
|---|---|---|---|
| Approaches | 25 | 15 | 62 |
| Entries | 19 | 9 | 32 |
| Exits Downstream | 6 | 6 | 23 |

Of the 100 known-time approaches at entrances to The Dalles Dam fishways in 1998, 2% occurred at civil dawn, 40% occurred during daylight, 1% occurred at civil dusk, and 57% occurred in hours of darkness. The frequency distribution of approaches was 0.04 $hour^{-1}$ at civil dawn, 0.03 $hour^{-1}$ during daylight, 0.02 $hour^{-1}$ at civil dusk, and 0.10 $hour^{-1}$ for hours of darkness. Four percent of the 55 known entries into the fishways occurred at civil dawn, 36% occurred during daylight, and 60% occurred during hours of darkness. Entry frequencies were 0.04 $hour^{-1}$ at civil dawn, 0.02 $hour^{-1}$ during daylight, and 0.06 $hour^{-1}$ for hours of darkness. Known-time records for activity inside the ladder (n = 144) occurred at the following times of day: 3% at civil dawn, 48% during daylight, 2% at civil dusk, and 47% during hours of darkness. Movements in the ladder occurred with the following frequency: 0.21 $hour^{-1}$ at civil dawn, 0.11 $hour^{-1}$ during daylight, 0.13 $hour^{-1}$ at civil dusk, and 0.24 $hour^{-1}$ for hours of darkness. Of the 26 known exits at the top of the ladder, 4% occurred at civil dawn, 27% occurred during daylight, 4% occurred at civil dusk, and 65% passed during hours of darkness. The frequency of occurrence of known-time exits were 0.04 $hour^{-1}$ at civil dawn, 0.01 $hour^{-1}$ during daylight, 0.04 $hour^{-1}$ at civil dusk, and 0.05 $hour^{-1}$ for hours of darkness.

## John Day Dam

### Upstream Progress

Of the 24 fish that passed The Dalles Dam in 1998, 8 were recorded at tributary receivers between The Dalles and John Day Dams and 10 were detected at the base of John Day Dam (1 fish reached the dam and then returned downstream to a tributary). Of the 10 fish that approached the dam, 7 entered the fishways (70%), 6 progressed to the transition areas (60%), and 3 progressed to the ladder and passed over the dam (30%) (Fig. 23).

Of the 10 fish that approached the fishway, 30% failed to enter, of those that entered, 14% did not pass through the collection channel, and half of the remaining fish failed to traverse the transition area. All of the fish that reached the ladder successfully passed over the dam. Successful passage was only documented at the powerhouse ladder, and no fish successfully negotiated the north spillway ladder. Seventy percent of the lamprey that approached John Day Dam failed to pass.

### Entrance Usage - Approaches, Entries, Exits, and Outcome

Approaches (n = 30) were made at fishway entrances by 10 fish in 1998 (median = 2.5 approaches/fish, range = 1 to 6). Approaches occurred at all entrances, with 5 approaches at the north spillway entrance, 8 at the south spillway entrance, and 17 at the south powerhouse entrance. Of the three fish that approached only once, one passed the dam (33%), and of the seven fish that approached two to ten times, two passed the dam (29%).

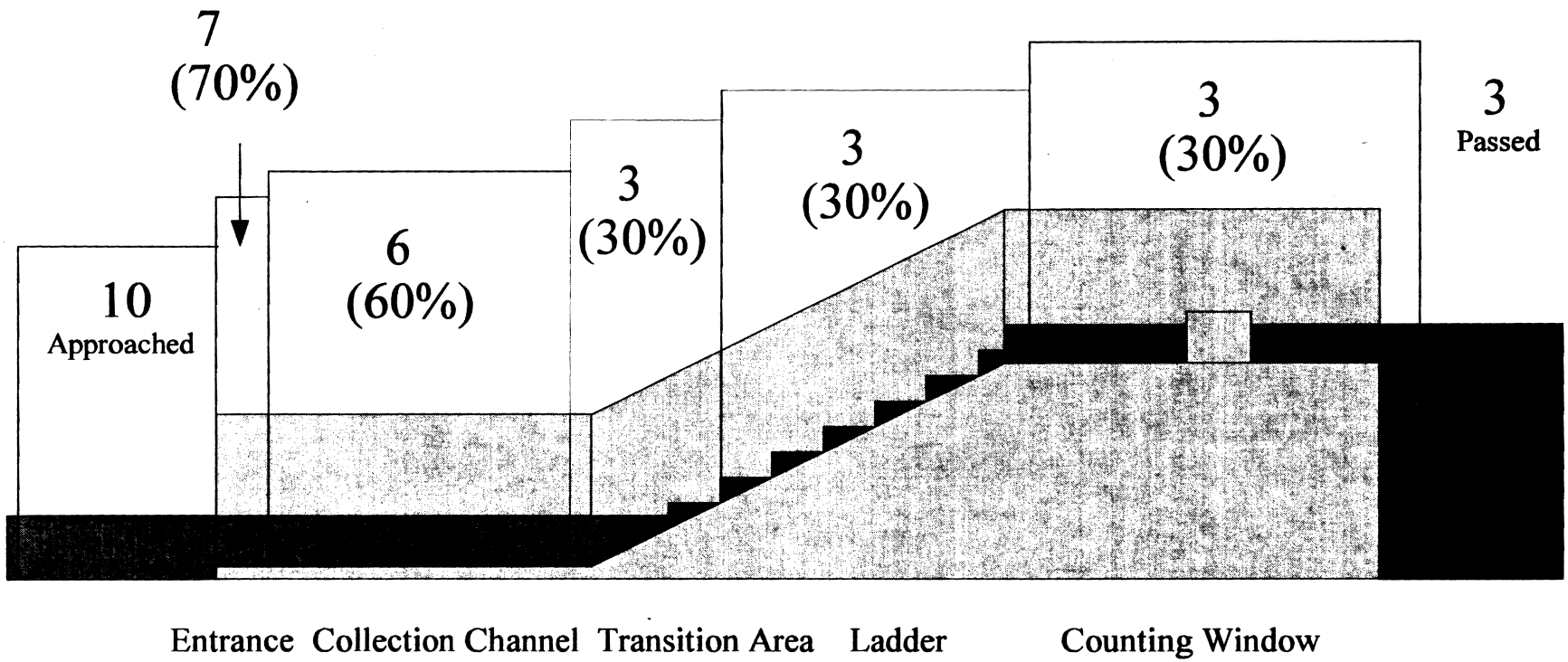


Figure 23. Overall success of lamprey that approached John Day Dam in 1998.

Twelve entries were made by seven fish (median = 1 entry/fish, range = 1 to 4), with three occurring at the north spillway entrance and nine at the south powerhouse entrance. Of the three entries into the fishway at the north spillway entrance, two immediately turned around and exited, and one attained the middle of the ladder before turning around and exiting downstream. The result of the nine entries into the south powerhouse entrance included two that immediately turned around and exited, four that reached the transition area, and three that passed the dam. Of the 12 entries into the fishway, there were 9 exits downstream, with 3 out the north spillway entrance, 2 out the south spillway entrance, and 4 out the south powerhouse entrance (Table 4).

**Rates and Times of Passage**

Median travel time from passage at The Dalles Dam to the first known approach at a John Day Dam entrance was 66.2 hours in 1998 (27.6-140.6 hours, n = 8) or 14.1 $km \cdot day^{-1}$. The median time between first known approach and first known entrance into the fishway was 1.0 hours (0.0-31.7 hours, n = 6) and the median time from first entrance to passage was 46.3 hours (range = 4.6-205.4 hours, n = 3). The median time for lamprey to traverse the south shore ladder was 9.4 hours (1.7-18.7 hours, n = 3).

Of the 30 known approaches at entrances to John Day Dam fishways in 1998, 30% occurred during daylight, 3% occurred at civil dusk, and 67% occurred in hours of darkness. Approach frequencies were 0.01 $hour^{-1}$ during daylight, 0.03 $hour^{-1}$ at civil dusk, and 0.05 $hour^{-1}$ for hours of darkness. Twenty percent of the 10 known-time entries into the fishways occurred during daylight and 80% occurred during hours of darkness. Entry rates were < 0.01 $hour^{-1}$ during daylight and 0.02 $hour^{-1}$ for hours of darkness. Sixty-nine records for activity inside the ladder were coded, of which 9% occurred at civil dawn, 33% occurred during daylight, and 58% occurred during hours of darkness. Movement in the ladder occurred with the following frequency: 0.19 $hour^{-1}$ at civil dawn, 0.03 $hour^{-1}$ during daylight, and 0.11 $hour^{-1}$ for hours of darkness. All of the known passage events occurred during the night at a rate of 0.10 $h^{-1}$.

## Tributary Use

Eight fish were tracked into the Deschutes River, two of which were recorded at Sherar's Falls, Deschutes RKm 75. One fish was detected at the mouth of the Deschutes River, three were detected in Fifteenmile Creek, and one in the Klickitat River. The fish that entered Fifteenmile Creek had previously entered The Dalles Dam fishway and one of the fish relocated in the Deschutes River had previously approached but not entered the John Day Dam fishway (see previous sections).

Table 4. Lamprey activity at John Day Dam fishway entrances in 1998.

| | North Spillway | South Spillway | South Powerhouse |
|---|---|---|---|
| Approaches | 5 | 8 | 17 |
| Entries | 3 | 0 | 9 |
| Exits Downstream | 3 | 2 | 4 |

## RESULTS, 1999

### Trapping and Tagging

In 1999, NMFS personnel operated the adult lamprey trap intermittently from 26 May to 2 September for a total of 818 hours and captured 603 lamprey. Daily catch per unit effort varied from 0 to 6.0 lamprey per hour and averaged 0.7 lamprey per hour over the entire season. In addition, 762 non-target fish were captured, primarily peamouth *Mylocheilus caurinus* and anadromous salmonids less than 30 cm.

Mean length and weight of the 199 lamprey we tagged were 71 cm (range = 65 to 78 cm, Fig. 24) and 571.1 g (range = 475 to 755 g, Fig. 25). Fish not tagged were provided to the University of Idaho, the Biological Resource Division of the U.S. Geological Service at Cook, Washington, the U.S. Fish and Wildlife Service Fish Health Laboratory, and the Columbia River Intertribal Fish Commission. The length distribution of lamprey we tagged was similar to that of most lamprey captured (i.e., those we tagged plus those provided to the University of Idaho and U.S. Geological Service; these data were not available in 1998, Fig. 24). However, the weight of lamprey we tagged represented only the upper part of the weight distribution of lamprey captured (Fig. 25). Most tagged fish appeared to be sexually immature as determined by internal examination. Of the tagged fish, 37 were males, 111 were female, and 51 were not distinguishable. The tagged fish were released at both the Washington (n = 101) and Oregon (n = 98) shore release sites.

Twelve fish were captured in January 1999 when the ladder was de-watered for routine maintenance. We intended to radio tag those fish and examine overwintering behavior in the river. However, all of the fish we captured were too small for tagging, having a median mid-body girth of 9.9 cm (range = 9.9 to 11.1 cm). Fish with a mid-body girth less than 11.5 cm were typically not tagged during 1999 unless body weight exceeded 500 g.

### Bonneville Dam

#### Upstream Progress

Of the 199 lamprey released in 1999, 183 returned to the base of Bonneville Dam. Release location did not affect either the number of lamprey that returned to the dam ($\chi^2 = 0.10$, $P = 0.75$, $DF = 1$) or the segment where they first approached the dam ($\chi^2 = 0.35$, $P = 0.84$, $DF = 2$) (Table 5). Similarly, median lengths or weights at tagging had no effect on whether fish approached the dam ($P > 0.05$).

Of the 16 fish that were not detected in the vicinity of the dam in 1999, 5 were never relocated after release, 9 were only detected at the release site, and 2 advanced to within 1 km of

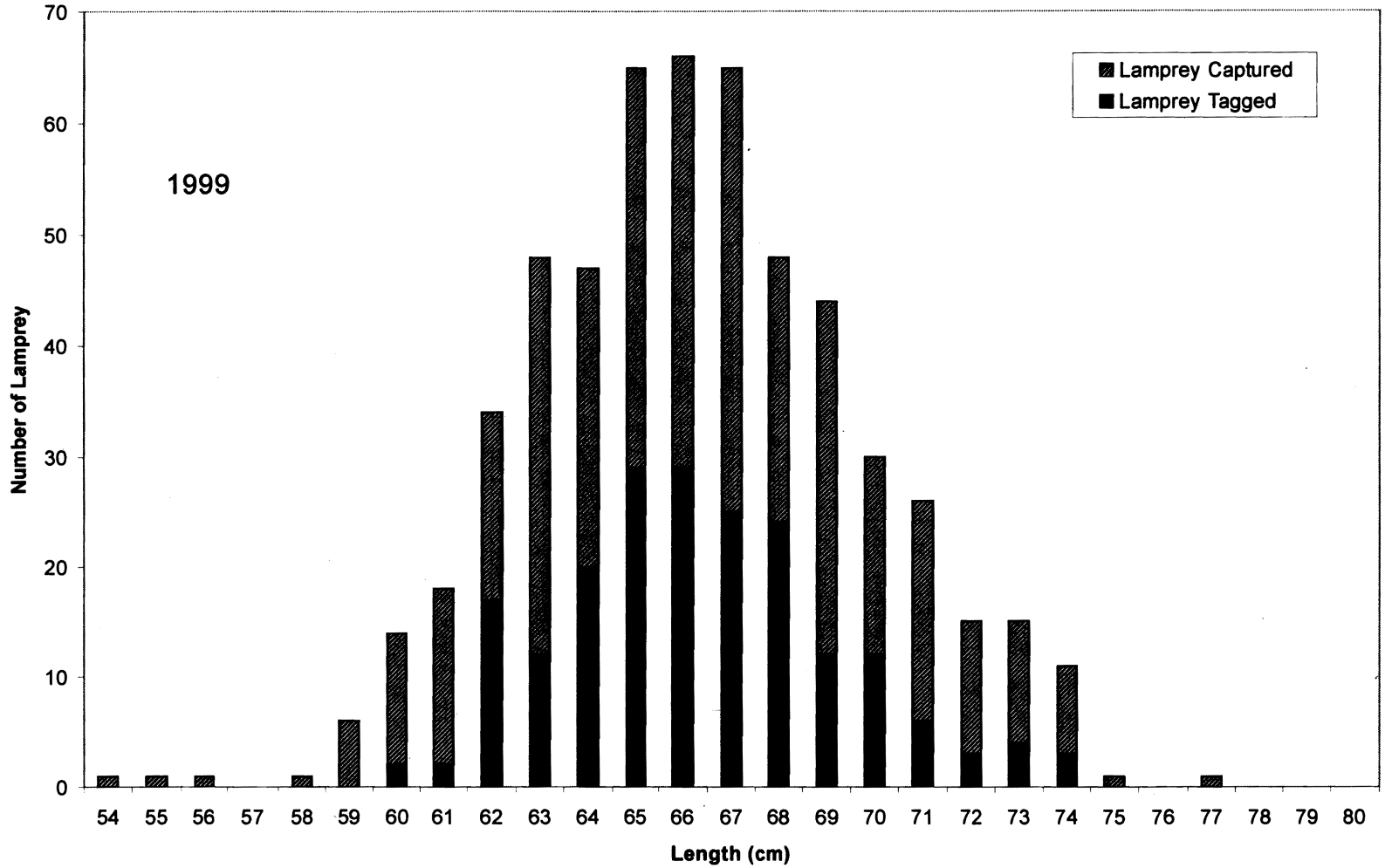


Figure 24. Length (cm total length) distributions of lamprey captured (hatched bars) and tagged (solid bars) in 1999.

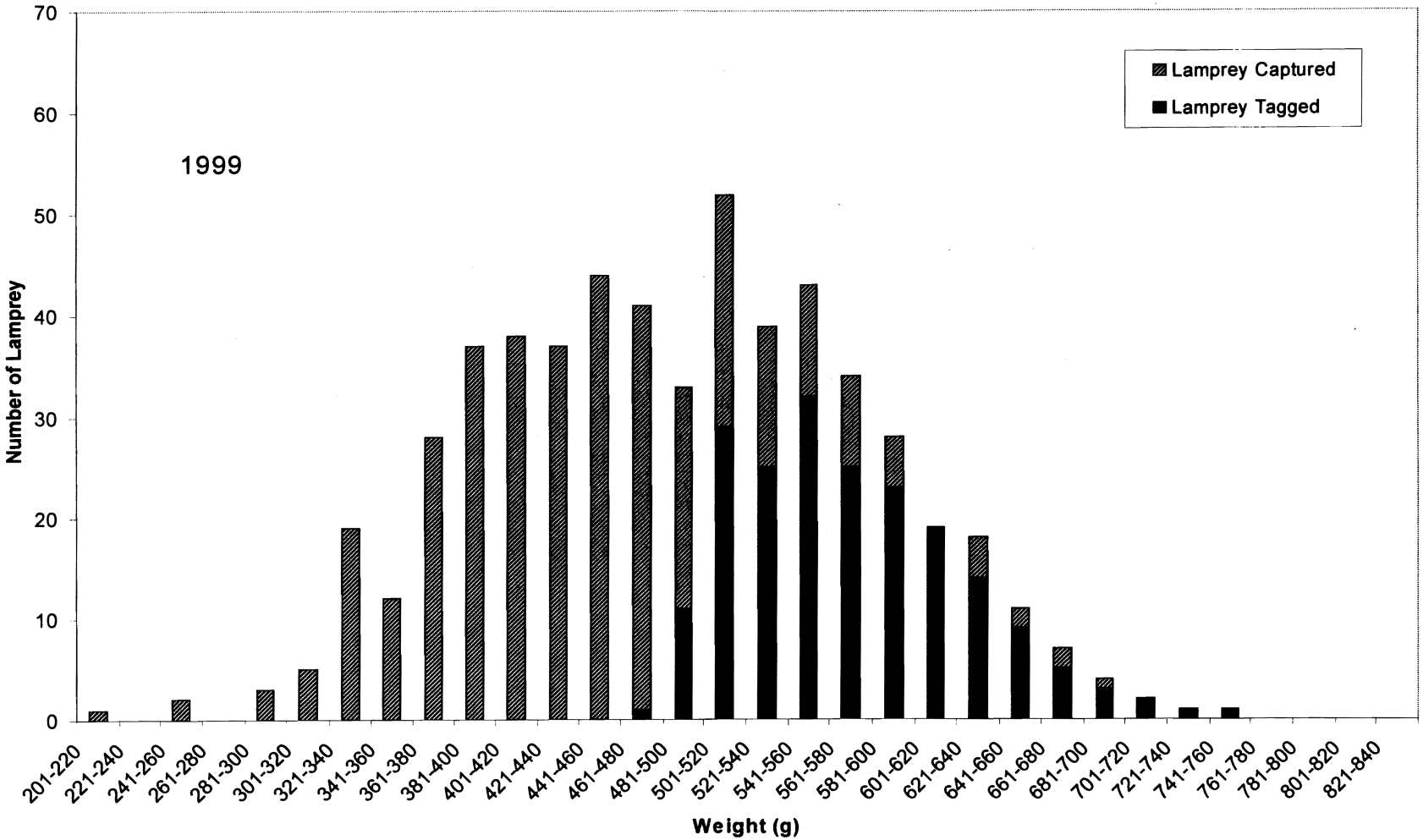


Figure 25. Weight (g) distribution of lamprey captured (hatched bars) and tagged (solid bars) in 1999.

Table 5. Numbers of lamprey that returned to the base of Bonneville Dam after release, and first approach locations for fish released on the Washington and Oregon shores in 1999.

| Shore | Released | Returned | Powerhouse 1 | Powerhouse 2 | Spillway | Navigation Lock |
|---|---|---|---|---|---|---|
| Washington | 101 | 93 | 38 | 46 | 9 | 0 |
| Oregon | 98 | 90 | 36 | 42 | 11 | 0 |

the dam but were not recorded near any entrances. Significantly fewer lamprey approached the dam when temperatures in the Bonneville forebay exceeded 19.5°C at tagging (CRDART 1998) than during periods of cooler water. Eleven of the 50 fish we released when temperatures exceeded 19.5°C (22%) were not detected at the dam, while 5 of 144 (3%) were not detected when released at temperatures lower than 19.5°C ($\chi^2 = 17.6$, $P < 0.0001$, DF = 1).

Of the 199 fish we released, 183 approached the dam (92%), 161 entered the fishways, 137 progressed to the transition areas, 103 progressed to the ladder, 102 progressed to the top of the ladder, and 81 passed the dam using the fishways (Fig. 26). One fish passed the dam using the navigation lock, for a total passage efficiency of 41% of the fish tagged, or 45% of those that approached the dam.

At PH1, 24 of the 87 fish that approached failed to enter the fishway (-28%), 8 of the 63 fish that entered failed to enter the transition area (-13%), 5 of 55 fish failed to reach the ladder (-9%), 1 of 50 fish failed to ascend the ladder (-2%), and 11 of 49 failed to pass the counting window area at the top of the ladder (-22%). Overall, 56% of the fish failed to pass PH1 (49 of the 87 that approached PH1 failed to pass upstream) (Fig. 27). Five of the 49 fish that reached the top of the ladder at PH1 entered the MWC. One passed the dam by going over the upstream Tainter gate, two backed out and passed via the counting window, and two backed down the ladder and exited into the tailrace (Fig. 28).

At PH2, 18 of the 118 fish that approached failed to enter the fishway (-15%), 21 of the 100 fish that entered failed to reach the transition area (-21%), 36 of 79 fish failed to reach the ladder (-46%), and 8 of 43 failed to pass through the counting window area at the top of the ladder (-19%). Seventy percent of the fish that approached PH2 did not pass the dam at PH2 (83 of the 118 that approached failed to pass upstream) (Fig. 29). Nine of the 50 fish that reached the top of the ladder at PH2 and the upstream end of the UMT entered the MWC. Five of these backed out of the MWC and passed the dam after moving past the counting window. The other 4 backed down the ladder and exited into the tailrace (Fig. 28).

At the spillway entrances, 31 of the 72 fish that approached failed to enter (-43%), 19 of the 41 fish that entered failed to achieve the transition areas (-46%), 11 of 22 fish failed to reach the ladders (-50%), 1 of 11 fish failed to ascend the ladders (-9%), and 2 of 10 failed to pass the counting window area at the top of the ladders (-20%). Of the fish that approached the spillway, 89% did not pass over the dam by this route (64 of the 72 fish that approached the spillway did not pass over) (Fig. 30).

Four fish fell back at the dam: three by unknown routes and one via the PH1 ladder. Eleven others may have fallen back, but this could not be confirmed. Their codes were recorded by one of the receivers downstream from the dam that used an aerial antenna which was more susceptible to recording background noise as tag hits.

Of the 21 fish that failed to pass the counting window areas at the top of the ladders, all exited downstream after backing down the ladder, 9 re-approached the dam after exiting, and none

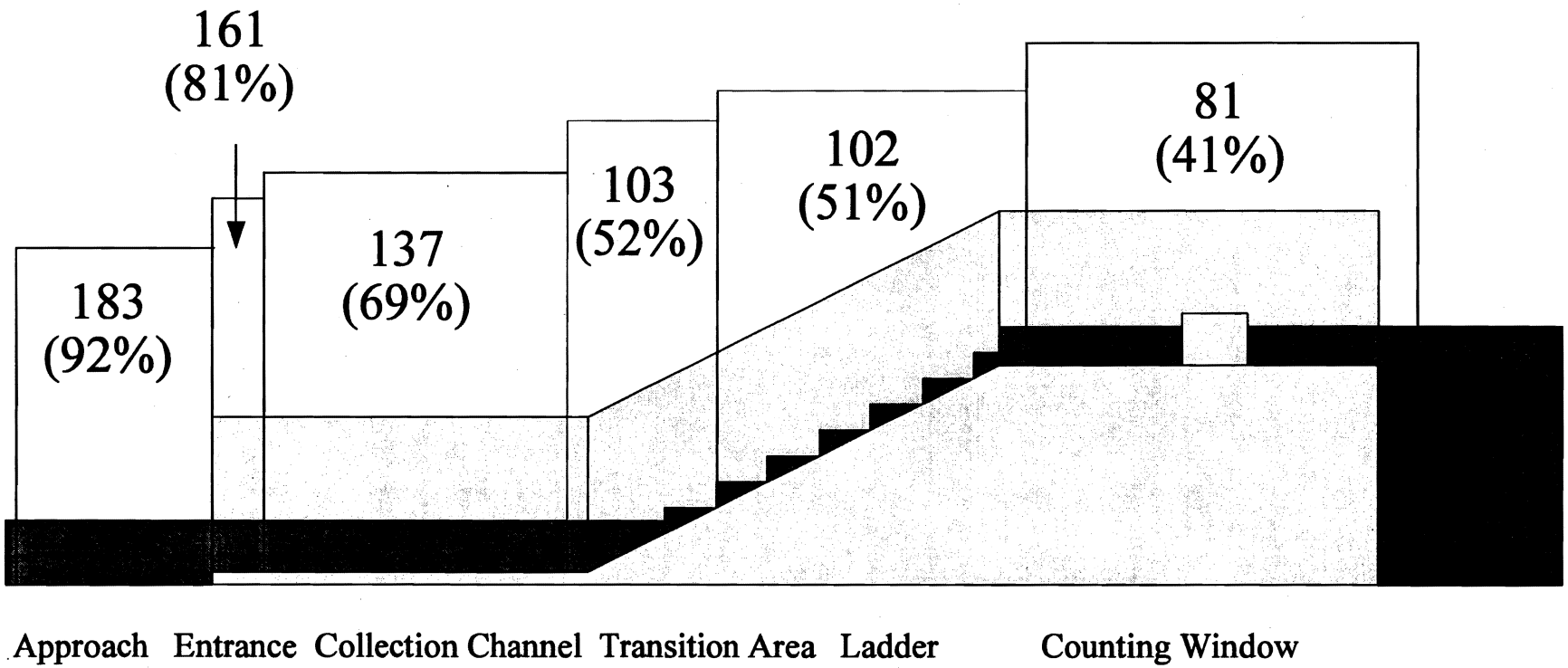


Figure 26. Overall success of the 199 lamprey released below Bonneville Dam in 1999. One fish passed upstream using the navigation lock.

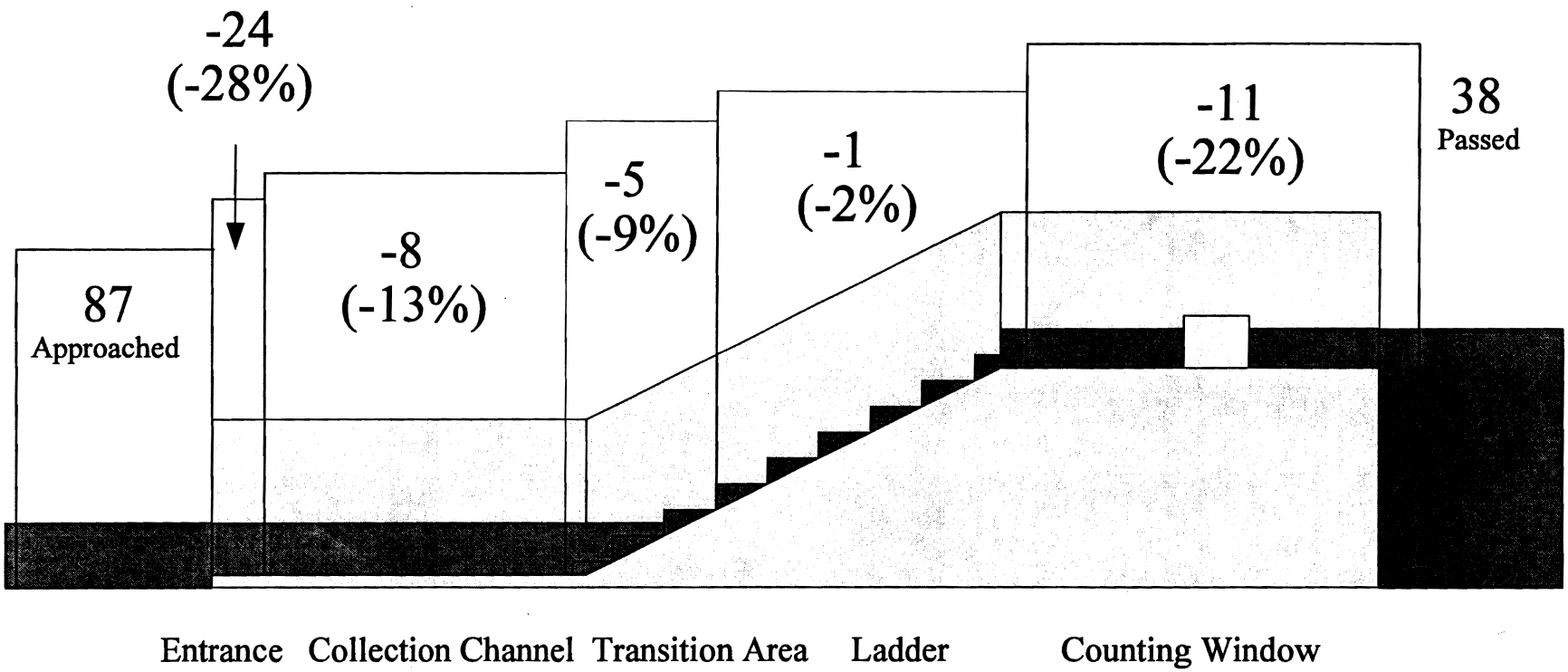


Figure 27. Failure of lamprey to pass each fishway section at Bonneville Dam Powerhouse 1 in 1999. Both the number and the percentage of fish that approached each section but failed to pass are shown.

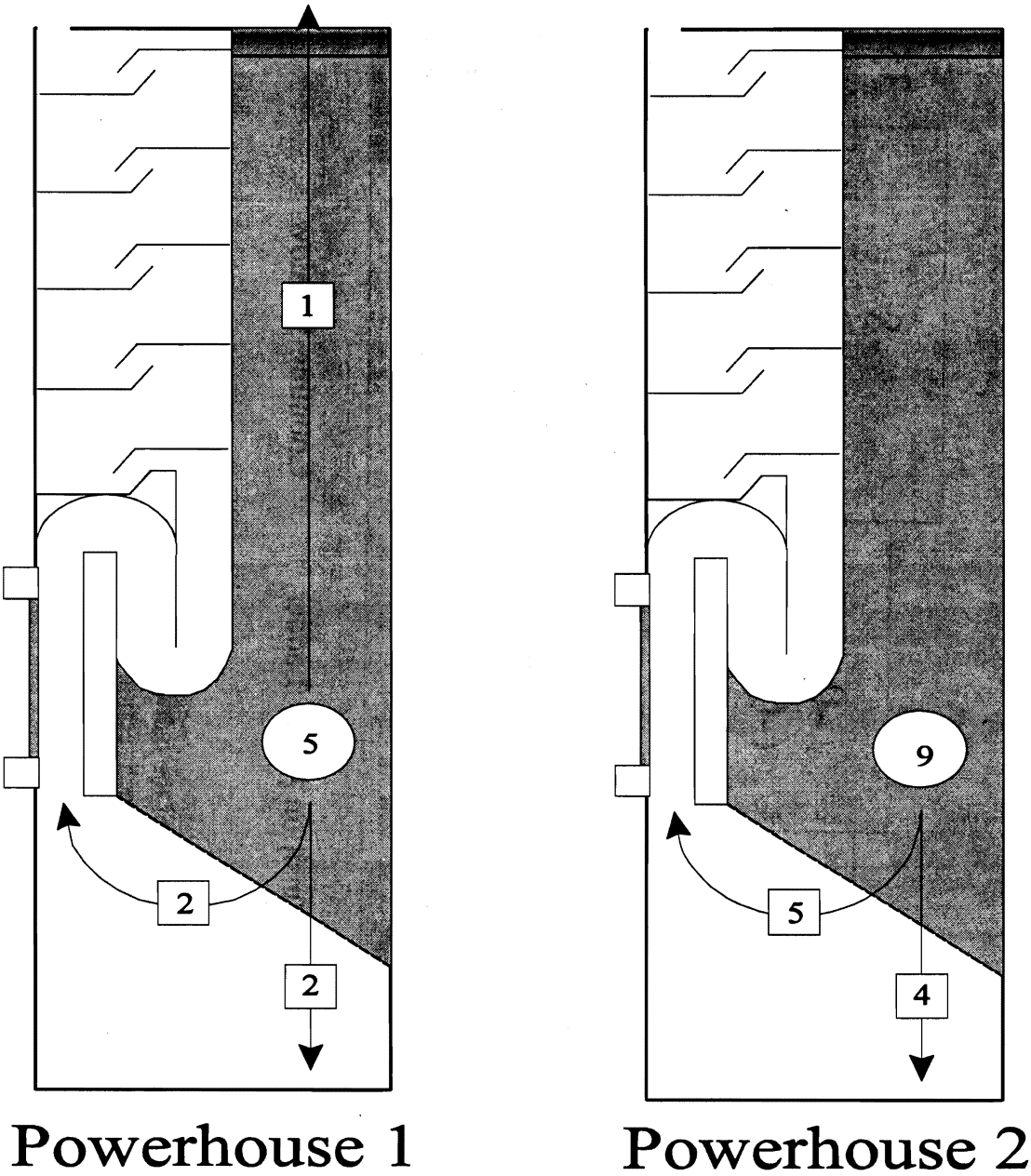


Figure 28. Overhead view of the counting window areas at Bonneville Dam with the number of fish that entered the makeup water channel (circles) and where they went (squares) at each powerhouse in 1999.

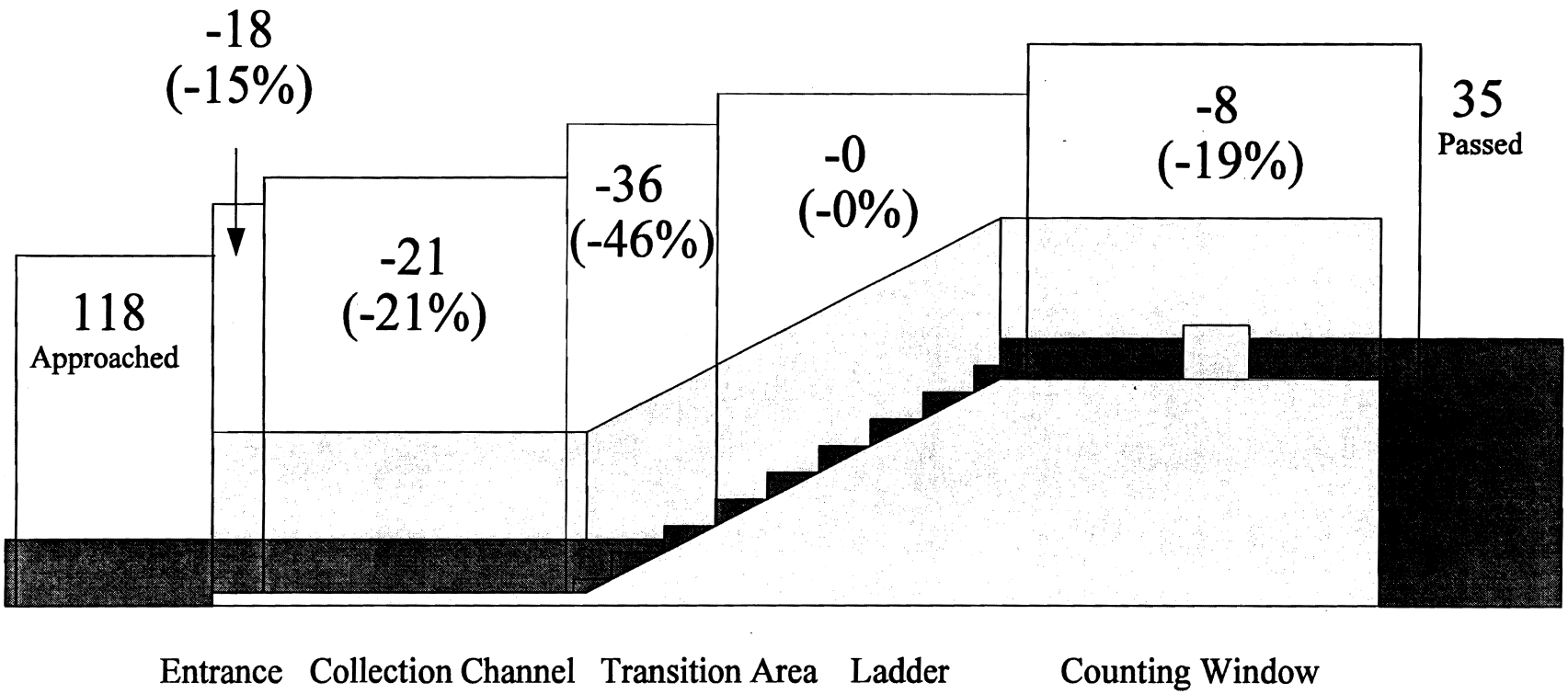


Figure 29. Failure of lamprey to pass successive sections of the fishway at Bonneville Dam Powerhouse 2 in 1999. The number and percentage of fish that approached each section but failed to pass through it are shown.

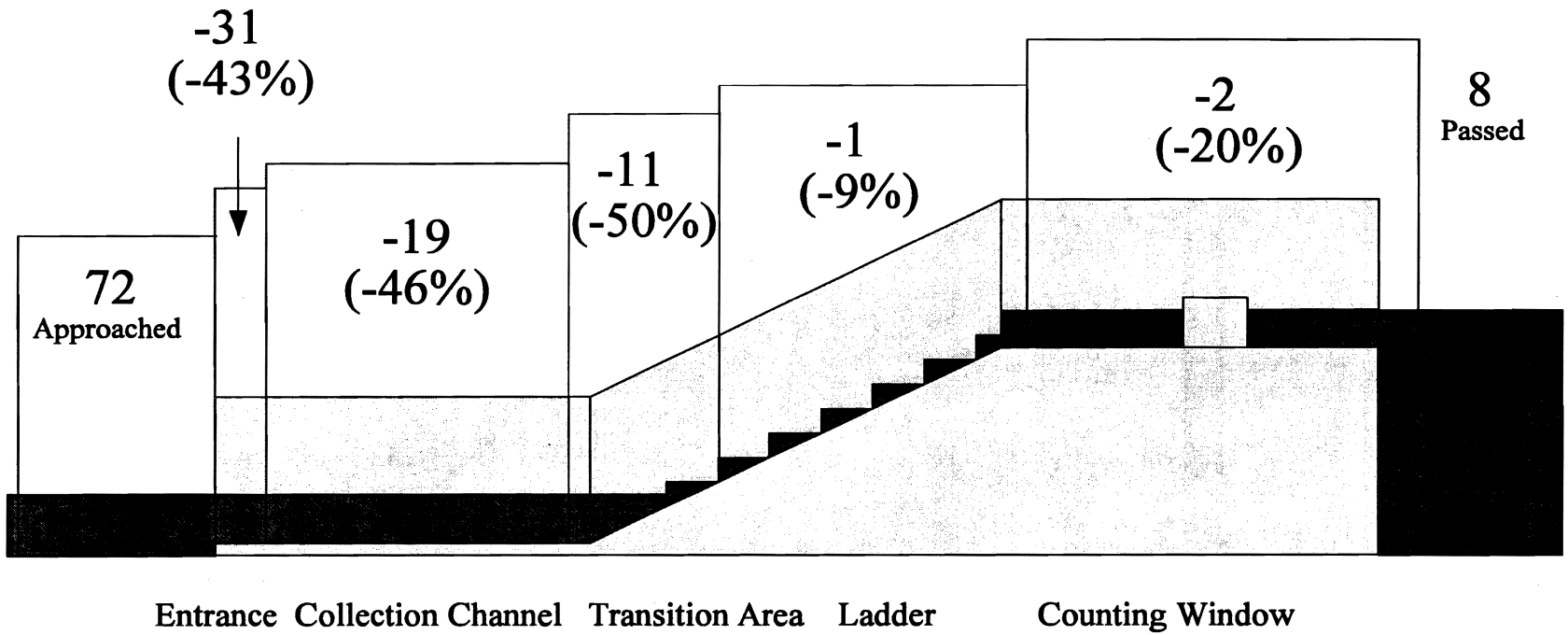


Figure 30. Failure of lamprey to pass through successive sections of the fishways at the Bonneville Dam spillway in 1999. The number and percentage of fish that approached each section but failed to pass through it are shown.

re-ascended any ladder. One radio-tagged fish attempted to overwinter in the ladder but was removed and placed upstream during de-watering of the PH2 ladder in January 2000 (Erich Gaedeke, U. S. Army Corps of Engineers, Pers. commun., January 2000).

**Entrance Usage - Approaches, Entries, Exits, and Outcome**

**Powerhouse 1--**Eighty-seven fish made 508 approaches at the fishway entrances in 1999 (median = 5 approaches/fish, range 1 to 21). Approaches were distributed unevenly across the powerhouse with 87 approaches at the south entrance, 284 at the five orifice entrances, and 137 at the north entrance (Fig. 31). Of the 9 fish that approached PH1 only once, 4 attained the top of the ladder (44%), of the 66 that approached 2-10 times, 39 attained the top of the ladder (59%), of the 11 that approached 11-20 times, 6 attained the top of the ladder (54%), and the 1 fish that approached 21 times did not attain the top of the ladder.

Ninety-nine entries into the fishway were made by 63 fish (median = 1 entry/fish, range = 1 to 5), with 29 at the south entrance, 19 at the five orifice entrances, and 51 at the north entrance (Fig. 32). Of the 29 entries at the south entrance, 28% immediately turned around and exited, 41% entered the collection channel area before exiting, 3% attained the top of the ladder prior to turning around, and 28% successfully passed the dam (Fig. 32). For the 19 entries into the five orifice entrances, 68% reached no farther than the collection channel, and 32% passed the dam. For the 51 entries into the northern entrance of the powerhouse, 27% reached no farther than the collection channel, 4% entered the transition area before turning around, 4% attained the middle of the ladder, 18% attained the top of the ladder but backed down, and 47% passed the dam (Fig. 32).

For the 99 entries into the fishway at PH1, there were 54 exits downstream, with 16 exits out the south entrance, 23 out the orifice entrances, and 15 out the north entrance (Table 6).

**Powerhouse 2--**At PH2 in 1999, 2,740 approaches were made by 118 fish (median = 16 approaches/fish, range = 1 to 120). At the three southern entrances, there were 684 approaches, 1,258 occurred across the middle ten orifice entrances, and 798 at the three northern entrances (Fig. 33). Of the five fish that approached once, none attained the top of the ladder. Of the 32 fish that approached 2-10 times, 10 attained the top of the ladder (31%), of 32 that approached 11-20 times, 12 attained the top of the ladder (38%), and of 17 that approached 21-30 times, 9 attained the top of the ladder (53%). Of the 11 fish that approached 31-40 times, 5 attained the top of the ladder (45%), and of 23 fish that made more than 40 approaches at PH2, 10 attained the top of the ladder (43%).

One hundred fish made 356 entries into the PH2 fishway (median = 2.5 entries/fish, range = 1 to 14). Of the 192 entries at the three southern entrances of PH2, 77% turned around and exited immediately, 18% entered the collection channel before exiting, 4% entered the transition area before exiting, and 2% passed the dam (Fig. 34). Of the 43 entries into the ten orifice entrances, 72% reached no farther than the collection channel, 16% attained the transition area and then

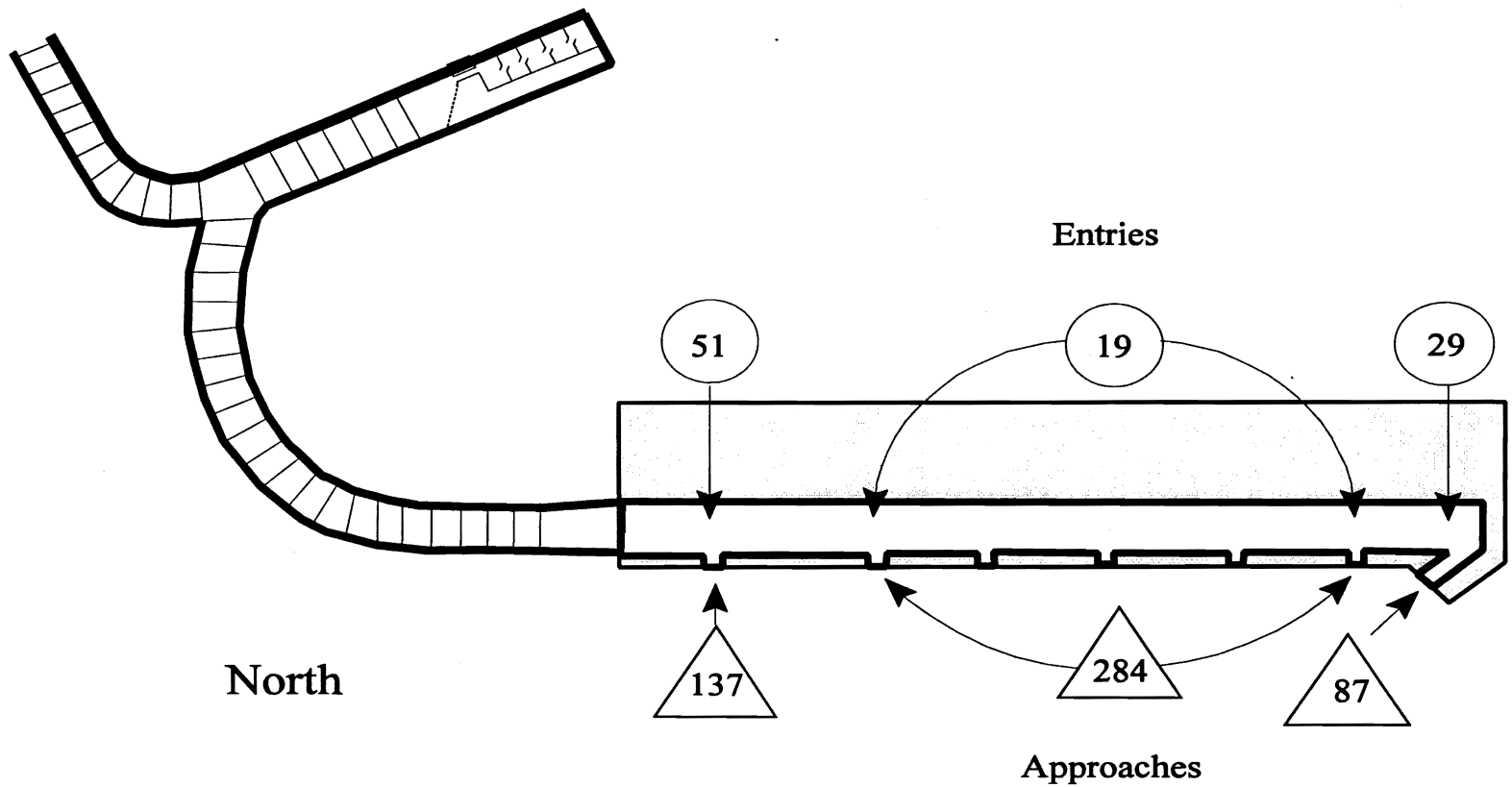


Figure 31. Approaches (triangles) and entries (circles) made by radio-tagged lamprey at Bonneville Dam Powerhouse 1 entrances in 1999.

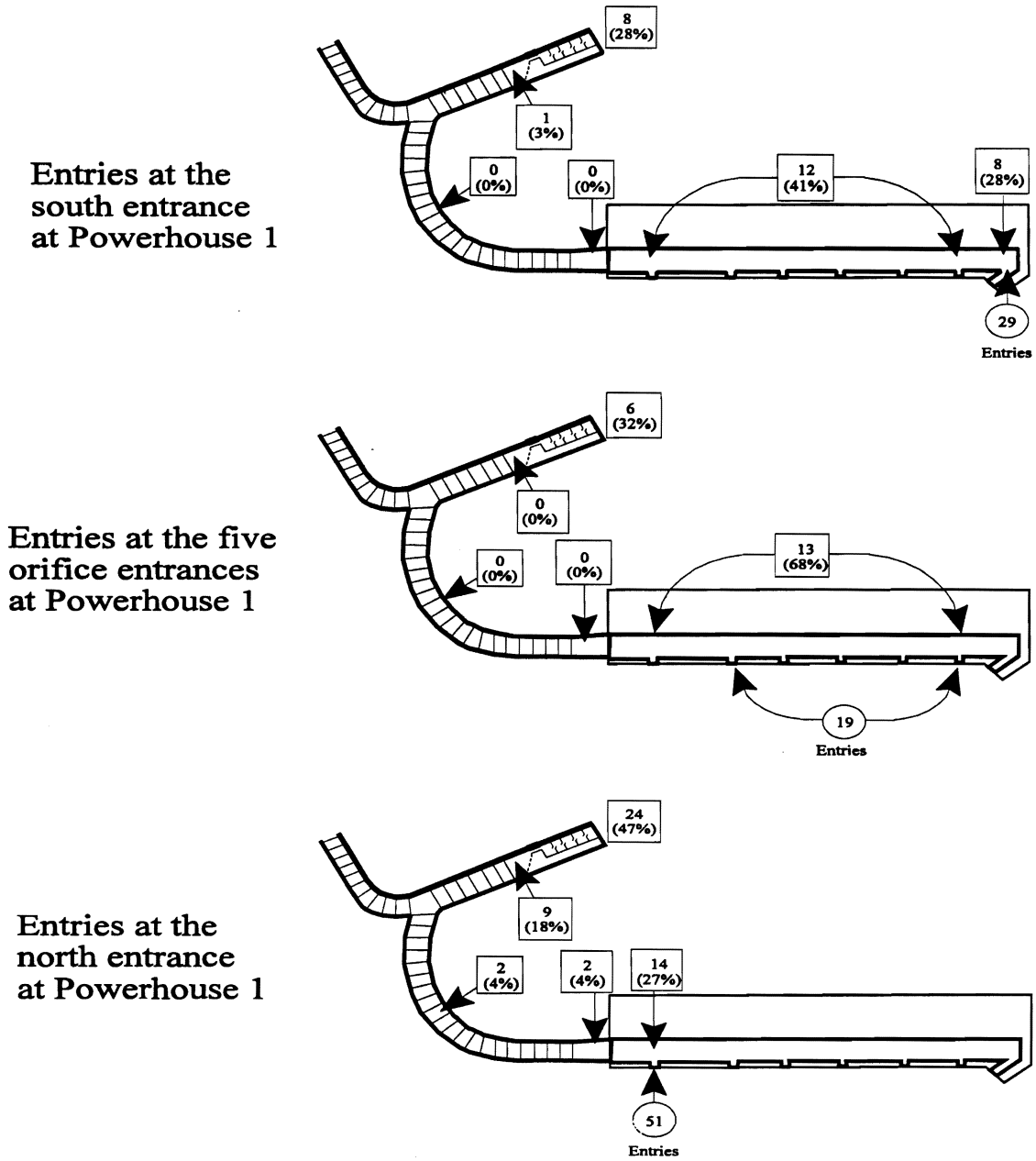


Figure 32. The highest point attained by radio-tagged lamprey (squares) that entered (circles) at the southern (top), orifice (middle), and northern (bottom) entrances at Bonneville Dam Powerhouse 1 in 1999.

Table 6. Total number of approaches, entries and exits by adult radio-tagged Pacific lamprey at Bonneville Dam fishway entrances in 1999.

| | Powerhouse 1 | | | Powerhouse 2 | | | Spillway | | Nav. Lock |
|---|---|---|---|---|---|---|---|---|---|
| Entrance Location | S | Mid | N | S | Mid | N | S | N | |
| Approaches | 87 | 284 | 137 | 684 | 1258 | 798 | 49 | 99 | 2 |
| Entries | 29 | 19 | 51 | 192 | 43 | 121 | 28 | 19 | 2 |
| Exit(s) | 16 | 23 | 15 | 194 | 29 | 92 | 33 | 19 | 1 |

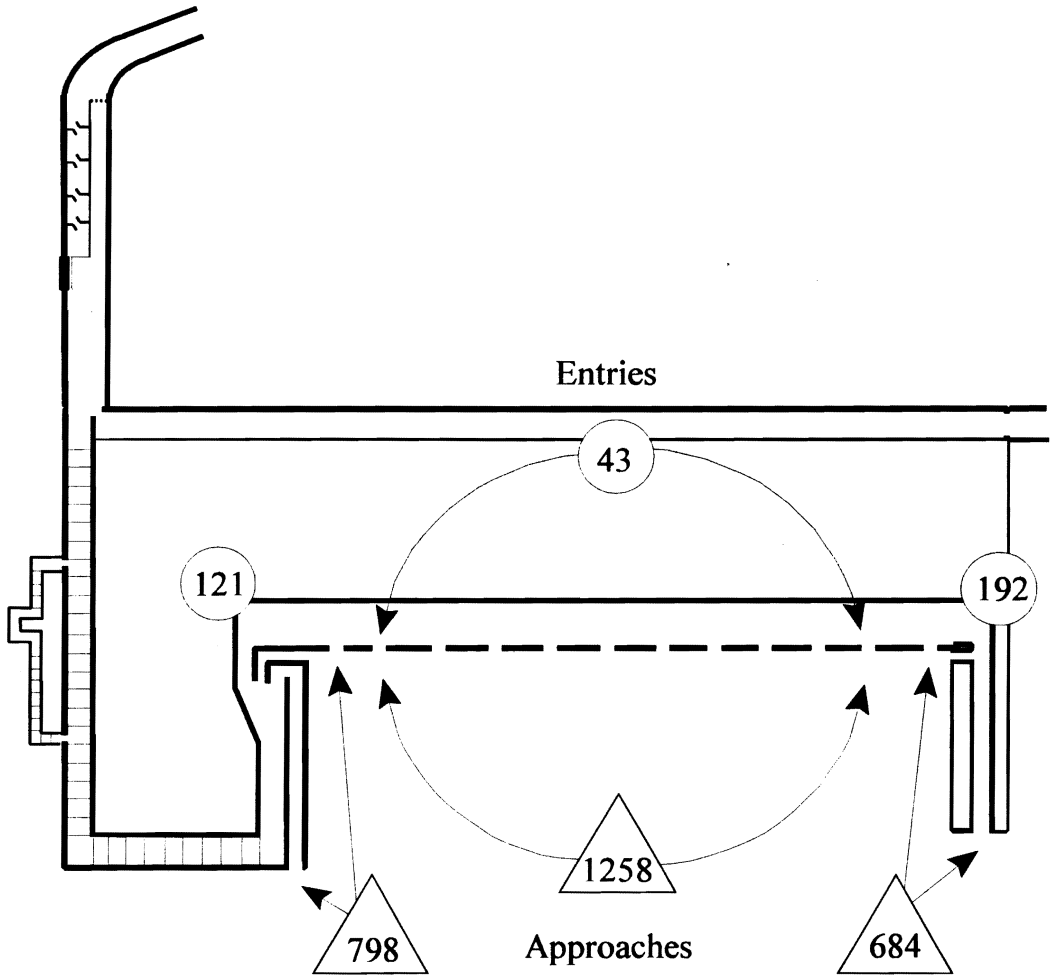


Figure 33. Approaches (triangles) and entries (circles) made by radio-tagged lamprey at Bonneville Dam Powerhouse 2 in 1999.

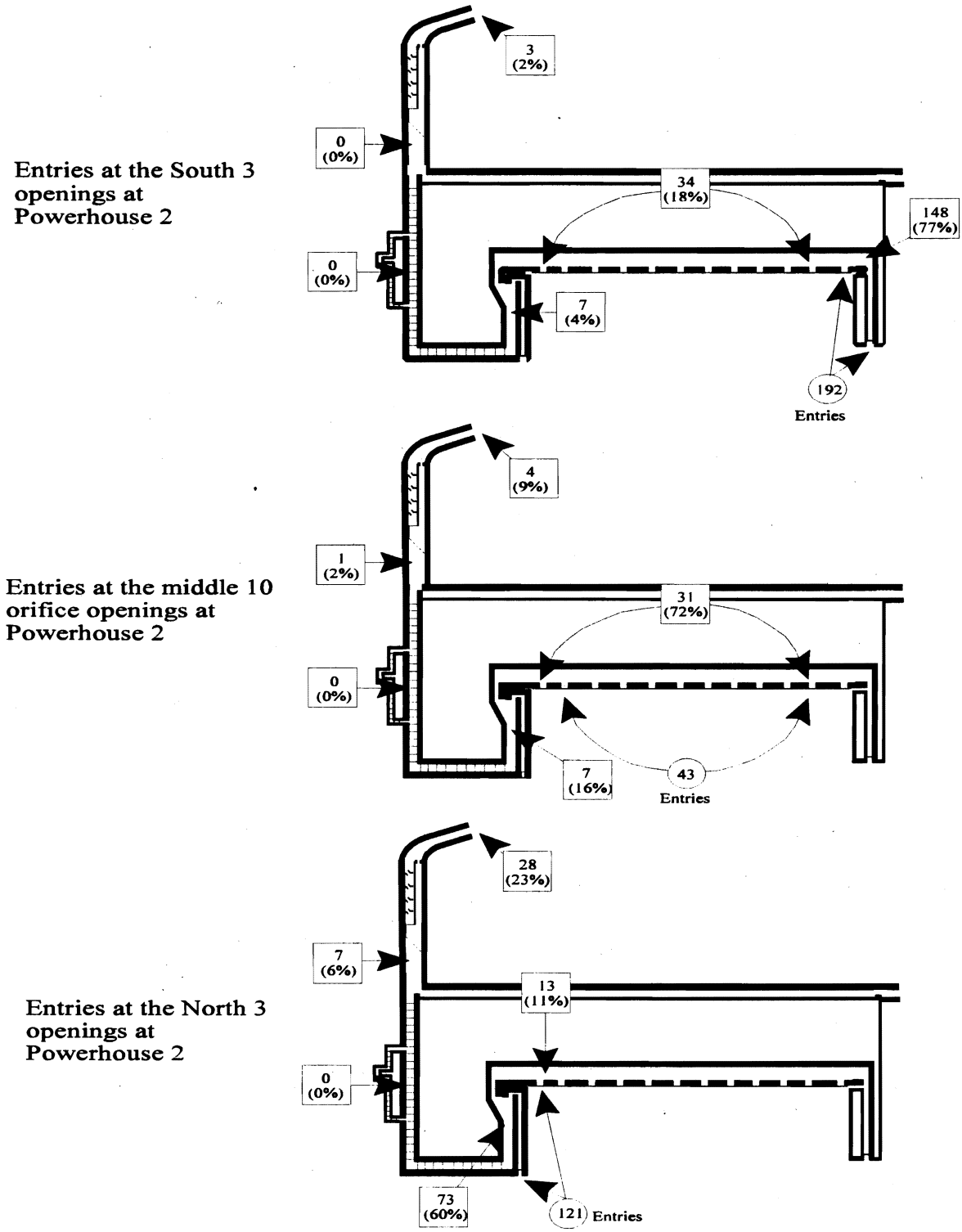


Figure 34. Highest point attained by radio-tagged lamprey (squares) for entries (circles) at the southern (top), orifice (middle), and northern (bottom) entrances at Bonneville Dam Powerhouse 2 in 1999.

exited, 2% reached the top of the ladder and then backed down, and 9% passed the dam. Of the 121 entrances into the three northern entrances at PH2, 11% reached no farther than the collection channel, 60% entered the transition area before turning around, 6% attained the top of the ladder before returning to the tailrace, and 23% passed the dam (Fig. 34).

Of the 356 entries into the fishway at PH2, there were 315 exits, with 194 out the south entrances, 29 out the middle 10 orifice entrances, and 92 out the north entrances (Table 6).

**Spillway**--At the spillway entrances in 1999, 148 approaches were made by 72 fish (median = 2 approaches/fish, range = 1 to 5). Approaches occurred at both entrances to the fishway, with 99 approaches at the south entrance and 49 at the north entrance (Fig. 35). Of the 31 lamprey that approached once, 5 attained the top of the ladders (16%), and of the 41 fish that made 2-10 approaches, 5 attained the top of the ladders (12%).

A total of 47 entries were made by 41 fish (median = 1 entry/fish, range = 1 to 2). Of the 28 fish that entered the south entrance, 64% turned around and exited after entering, 21% entered the transition area then exited downstream, 4% reached the top of the ladder before returning to the tailrace, and 11 passed the dam (Fig. 36). Of the 19 entries into the north entrance at the spillway, 37% turned around and exited, 32% entered the transition area before turning around, 5% reached the top of the ladder and UMT before returning to the tailrace, and 26% passed the dam (Fig. 36).

For the 47 entries, there were 52 exits, with 33 out the south entrance and 19 out the north entrance (more exits occurred than entries due to ladder back downs from entries made at PH1 and PH2, Table 6).

**Navigation Lock**--At the navigation lock in 1999, two fish approached and entered. One fish passed upstream when the upstream gates were opened and the other returned to the tailrace of the dam (Table 6).

**Multiple Locations**--Of all fish that approached the dam, 105 approached only one segment, 61 approached two segments, and 17 approached all segments of the dam. Numbers of fish that passed the dam for each group were 61 (58%), 15 (25%), and 6 (35%), respectively.

**Rates and Times of Passage**

The median time between fish release and first known-time approach to PH1 in 1999 was 110.4 hours (1.7-1,861.7 hours, n = 72), to PH2 was 115.7 hours (2.9-556.1 hours, n = 86), and to the spillway was 192.2 hours (2.6-1,331.5 hours, n = 26).

The median time between first known approach and first known entrance into the fishway (at the same segment) was 0.7 hours at PH1 (0.0-421.0 hours, n = 43), 1.2 hours at PH2 (0.0-607.2 hours, n = 63), and 0.7 hours at the spillway entrances (0.2-160.3 hours, n = 7). The median time

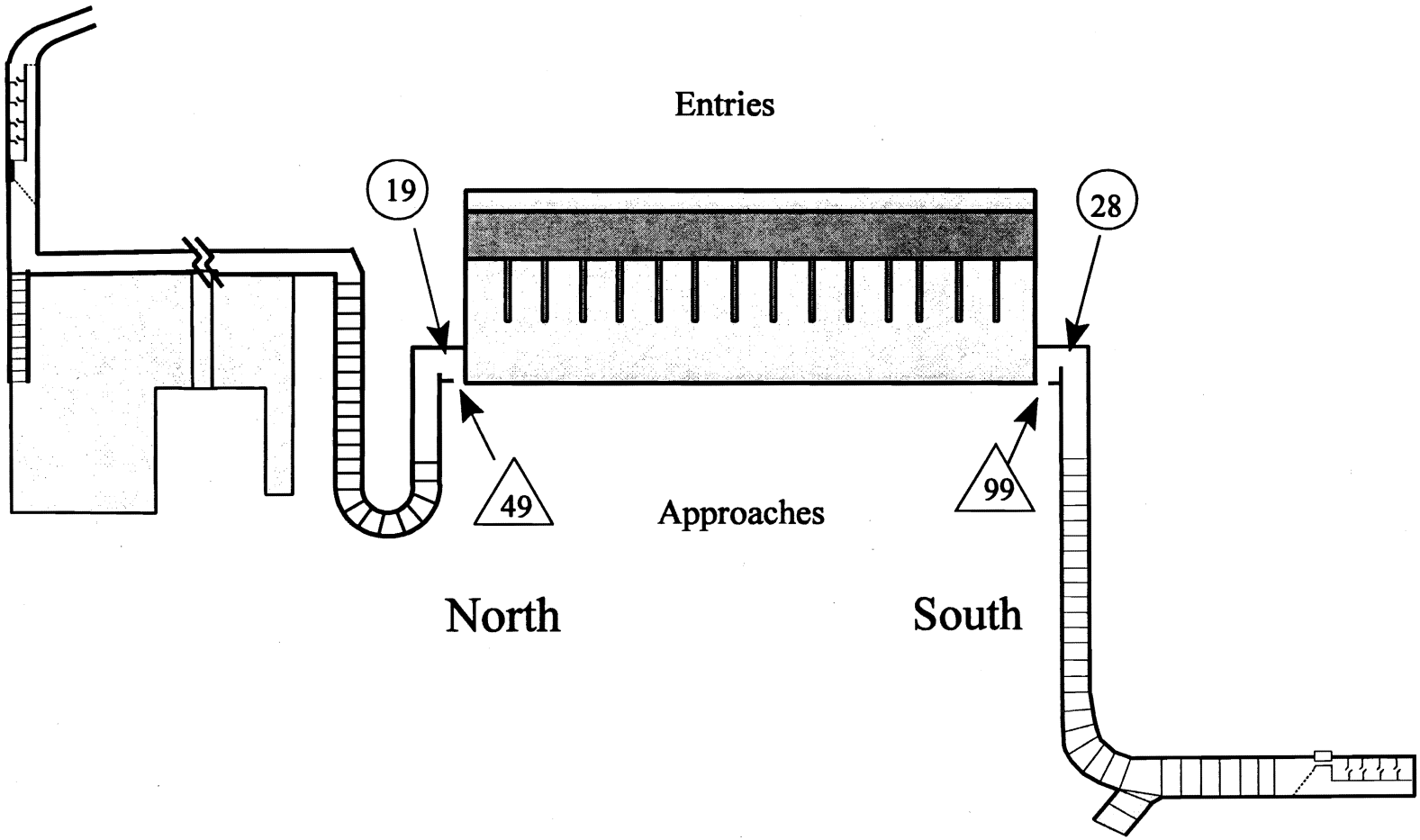


Figure 35. Approaches (triangles) and entries (circles) made by adult radio-tagged lamprey at Bonneville Dam spillway entrances in 1999.

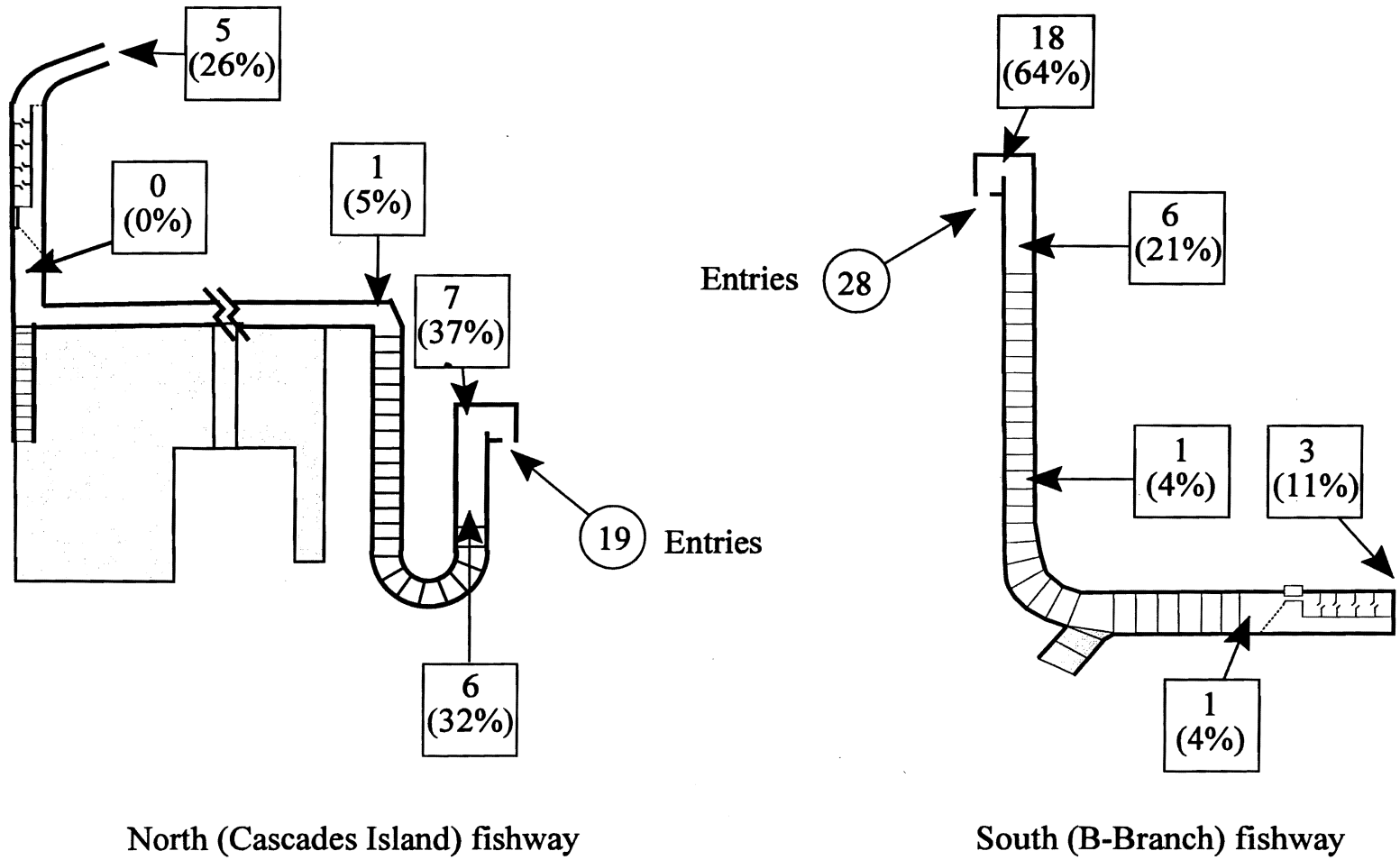


Figure 36. Highest point attained by radio-tagged lamprey (squares) that entered (circles) the northern (left) and southern (right) Bonneville Dam spillway entrances in 1999.

between first known approach and first known entrance at a segment other than where the first approach occurred was 179.5 hours for PH1 (4.1-529.4 hours, n = 15), 136.6 hours for PH2 (1.2-852.0 hours, n = 6), and 300.7 hours (108.0-594.5 hours, n = 5) for the spillway entrances.

The median time from first known entrance to lamprey passage via any ladder of the dam was 92.6 hours in 1999 (8.4-847.7 hours, n = 69). The median time for fish to traverse 29 weirs at PH1 was 9.6 hours (1.7-333.6 hours, n = 47) or 20.0 minutes/weir (3.4-690.1 minutes/weir), while at PH2 lamprey required 3.8 hours to negotiate 34 weirs (1.7-44.6 hours, n = 40) or 6.6 minutes/weir (3.2-78.8 minutes). The median time to traverse 36 weirs at the south shore spillway ladder was 3.4 hours (1.7-4.8 hours, n = 4) or 5.6 minutes/weir (2.6-8.1 minutes), and for the north shore ladder, lamprey required 5.5 hours to pass 38 weirs (3.6-149.3 hours, n = 5) or 8.5 minutes/weir (5.7-235.8 hours).

The median time required for lamprey to progress up the UMT was 249.3 minutes (21.1-2,095.0 minutes, n = 12), and the time required to progress back down the UMT was 8.5 minutes (7.0-518.7 minutes, n = 9, using only the first incidence of behavior per fish).

At the south spillway entrance in 1999 (first approach only), median time from approach to entry was 29.6 minutes (4.3-9,616.0 minutes, n = 16). Median holding time of fish that approached but did not enter was 1.4 minutes (0.0-11,290.5 minutes, n = 41). At the north spillway entrance, median time from approach to entry was 123.3 minutes (2.0-7,364.8 minutes, n = 13). Median holding time for fish that approached but did not enter was 21.2 minutes (0.0-3,824.3 minutes, n = 21).

There were 3,371 known-time approaches at entrances to the fishways in 1999. Of these, 1% occurred at civil dawn, 45% occurred during daylight, 3% occurred at civil dusk, and 51% occurred in hours of darkness. Approach rates were 0.51 $hour^{-1}$ at civil dawn, 0.70 $hour^{-1}$ during daylight, 1.16 $hour^{-1}$ at civil dusk, and 1.18 $hour^{-1}$ for hours of darkness (Fig. 37a). There were 454 known-time entries into the fishways: 2% occurred at civil dawn, 42% occurred during daylight, 1% occurred at civil dusk, and 55% occurred during hours of darkness. The entrance rates were 0.13 $hour^{-1}$ at civil dawn, 0.11 $hour^{-1}$ during daylight, 0.09 $hour^{-1}$ at civil dusk, and 0.25 $hour^{-1}$ for hours of darkness (Fig. 37a). Of the 480 known-time records for activity inside the ladder, 2% occurred at civil dawn, 29% occurred during daylight, 2% occurred at civil dusk, and 67% occurred during hours of darkness. The temporal distribution of activity in the ladder was: 0.14 $hour^{-1}$ at civil dawn, 0.07 $hour^{-1}$ during daylight, 0.14 $hour^{-1}$ at civil dusk, and 0.29 $hour^{-1}$ for hours of darkness. Of the 83 known-time exits at the top of the ladder, 7% occurred at civil dawn, 13% occurred during daylight, 2% occurred at civil dusk, and 78% passed during hours of darkness. Passage occurred at a rate of 0.08 $hour^{-1}$ at civil dawn, 0.01 $hour^{-1}$ during daylight, 0.03 $hour^{-1}$ at civil dusk, and 0.05 $hour^{-1}$ at night (Fig. 37b).

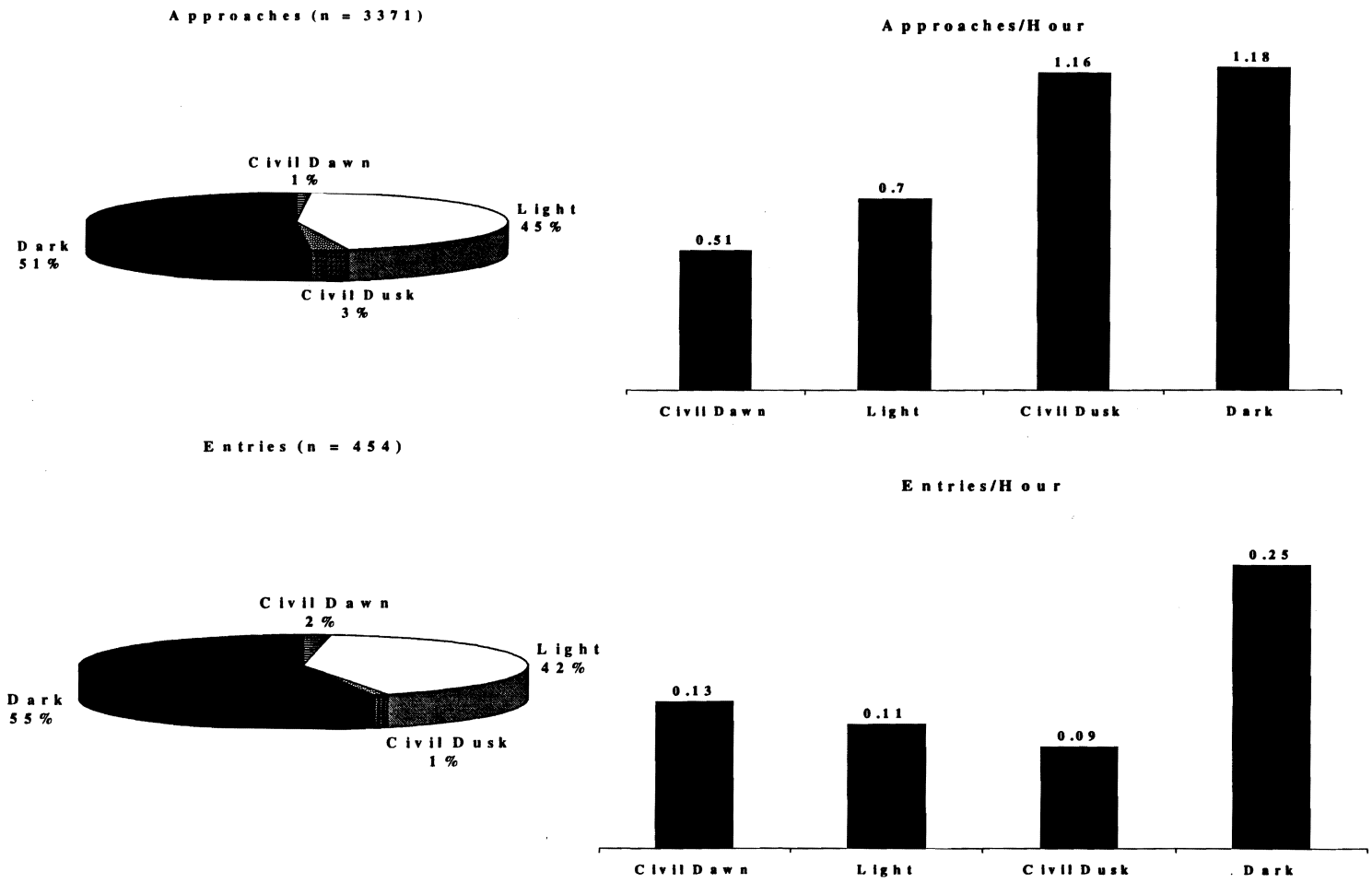


Figure 37a. The percentage of lamprey approaches and entrances at Bonneville Dam during hours of darkness, light, civil dusk, and civil dawn in 1999. These data are also presented as the rate of approach or entry per hour for each time period.

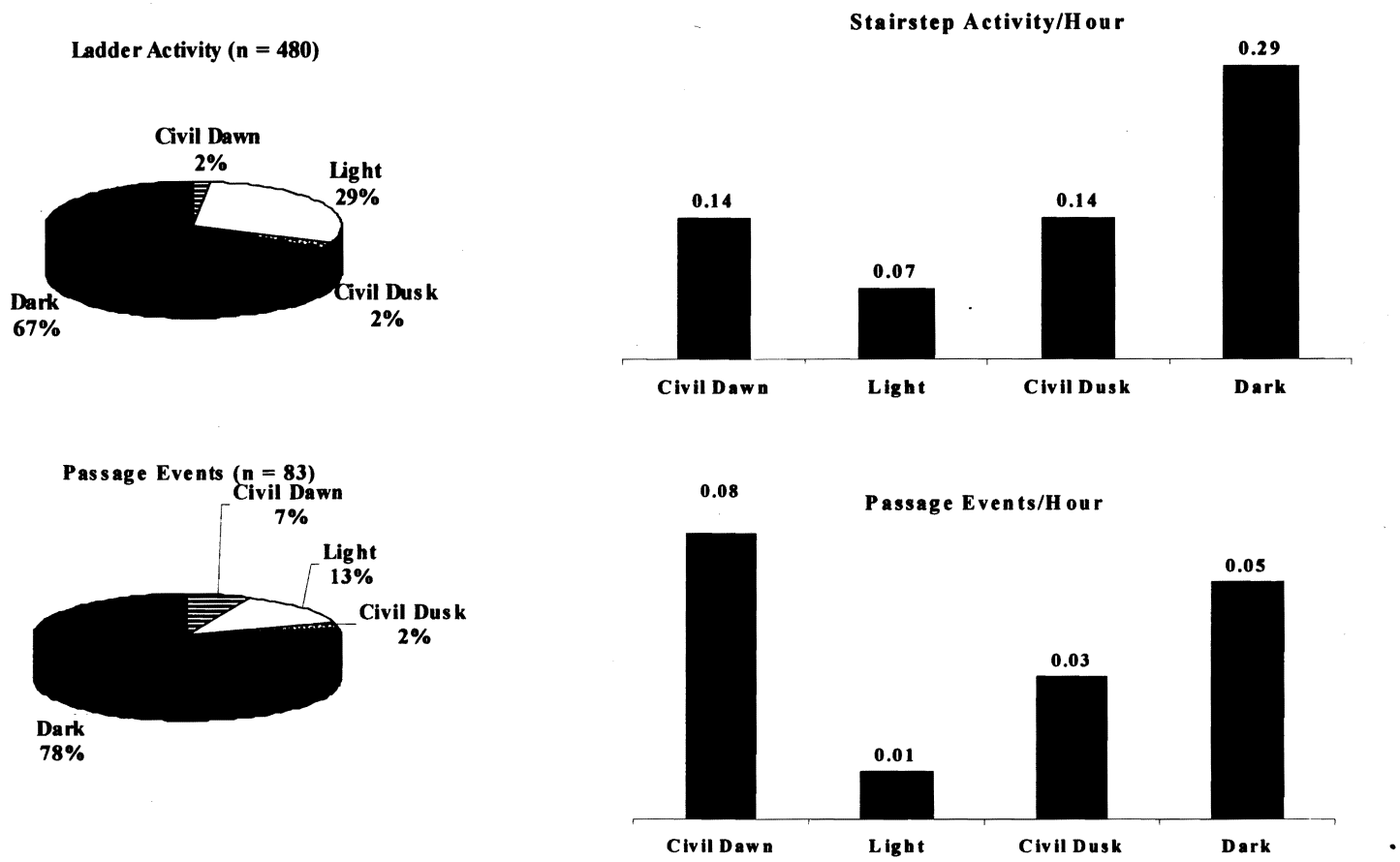


Figure 37b. The percentage of lamprey activity in the ladders and passage events at Bonneville Dam during hours of darkness, light, civil dusk, and civil dawn in 1999. These data are also presented as the incidence of activity per hour for each time period.

## The Dalles Dam

Of the 82 fish that passed Bonneville Dam in 1999, 4 fish were detected in tributaries between Bonneville and The Dalles Dams, and 50 approached The Dalles Dam[3]. Of the 50 fish detected near The Dalles Dam, 25 passed over the dam (50%). Of the 24 known-time passage events, 38% passed the top of the ladder during daylight, 12% passed at civil dusk, and 50% passed during hours of darkness. Passage rates were <0.01 $hour^{-1}$ during daylight hours, 0.06 $hour^{-1}$ at civil dusk, and 0.01 $hour^{-1}$ for hours of darkness.

## John Day Dam

Of the 25 fish that passed The Dalles Dam in 1999, 2 were detected in tributaries between The Dalles and John Day Dams and 11 approached John Day Dam. Of the 11 fish detected near John Day Dam, 3 passed the dam (27%) and all did so during hours of darkness.

## Tributary Use

In 1999, four fish were detected in Hood River (although some of these records may be deceptive, due to excessive noise at this location) and two in the Deschutes River. Two fish were detected at the mouth of the Deschutes River and one at the mouth of the Klickitat River.

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[3] Limited data are available for 1999 lamprey passage at The Dalles and John Day Dams. Only remote downstream stations and the tops of the fish ladders were monitored because there were no radio-tagged adult salmon in the river that year.

## DISCUSSION

The fish ladders used at dams on the Columbia River were not designed for Pacific lamprey passage. Nevertheless, 40% of all radio-tagged Pacific lamprey that approached Bonneville Dam in 1998 and 45% in 1999 successfully negotiated the fishways and reached the waters above the dam. Passage efficiency was higher at The Dalles Dam, with 63% of the fish that approached in 1998 and 50% in 1999 successfully negotiating the fishways there. Passage efficiency was lowest at John Day Dam: 30% in 1998 and 27% in 1999. However, very few fish were tracked at this dam, so sample sizes were low (n = 10 in 1998 and n = 11 in 1999).

### Bonneville Dam

#### Areas of High Concern

**Collection Channels and Transition Areas--**Lamprey passage success was lowest in the collection channel and transition areas where diffuser gratings covered the entire floor. The floor of the collection channel at PH1 is composed of concrete with recessed diffuser gratings, which leaves at least some areas of the floor for lamprey attachment as they swim upstream. At PH2, large sections of continuous grating cover the floor (Fig. 38) and are interspersed with areas of solid concrete flooring. This configuration leaves no area for lamprey to attach along the floor over longer lengths of the channel than at the PH1 collection channel. Fish entering near the south end of the collection channel and attempting to pass the entire length of the PH1 collection channel failed 61% of the time in 1998 (27 of 44, Fig. 16), and 69% in 1999 (20 of 29, Fig. 32). In contrast, of the entries at the south end of PH2, 96% in 1998 failed to negotiate the collection channel (175 of 183, Fig. 18) and 95% (182 of 192, Fig. 34) in 1999 were unsuccessful.

In the transition area of PH1, gratings cover less than 50% of the floor on one side of the ladder. At PH2, the gratings cover the entire floor of every other weir in the area subject to fluctuating tailwater (Fig. 38). In both 1998 and 1999, lamprey had higher passage success through the transition areas at PH1 (Fig. 16 and Fig. 18) than at PH2 (Fig. 32 and Fig. 34). Lamprey also had difficulty negotiating the transition areas at the spillway ladders (Fig. 19 and Fig. 35). Diffusers in the transition areas of both north and south spillway fishways were observed producing large, continuous emissions of entrained air and turbulent upwelling that may cause lamprey to become disoriented and may deter their upstream migration.

In sum, lamprey entering the fishways where they would encounter the fewest grating structures ascended the ladder more successfully than fish that entered at points where they would experience more gratings. Passage success for fish entering at the north entrance of PH1 was higher (48% in 1998 and 47% in 1999) than passage success of fish entering at the south end of PH1 (25% in 1998 and 28% in 1999) (Figs. 16 and 32). Similarly, passage success of lamprey entering the north three entrances at PH2 was 29% in 1998 and 23% in 1999, while fish that

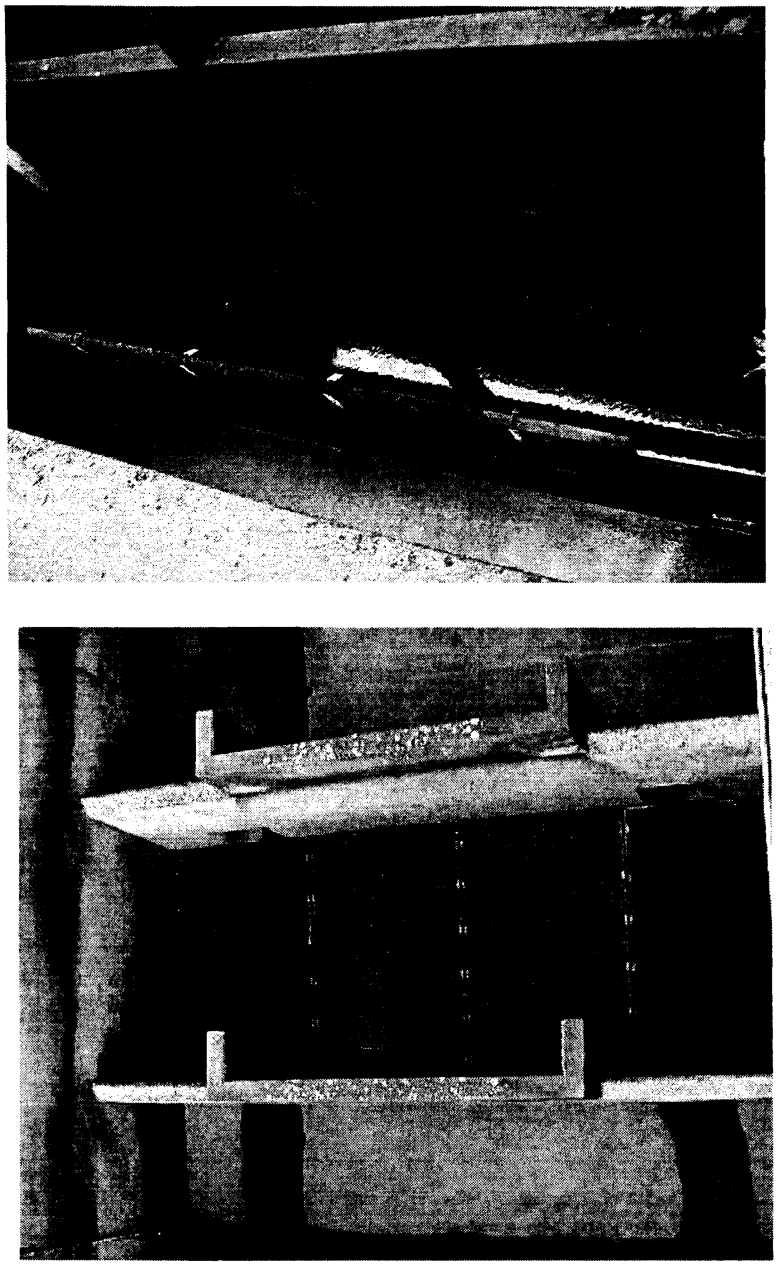

Figure 38. Overhead view of the diffuser gratings along the floor between weirs of the transition area at Powerhouse 1 (top) and Powerhouse 2 (bottom) at Bonneville Dam during dewatering in 1999. The grating structure at Powerhouse 1 allows lamprey to adhere to the floor, while the grating structure at Powerhouse 2 does not.

entered at the south three entrances at PH2 had lower overall passage success (2% in both 1998 and 1999) (Figs. 18 and 34).

**Counting Window Areas and Makeup Water Channels**--The counting window areas at Bonneville Dam consistently obstructed lamprey passage, as evidenced by the fact that 28% of the tagged lamprey in 1998 and 21% in 1999 failed to pass this area. The counting windows are brightly lit at night with white light to allow enumeration of adult salmon. Radio-tagged lamprey approached these areas primarily at night. Ullén (1996) reported a negative phototactic response for both quiescent and moving individuals of three European lamprey species. In addition, Wallén et al. (1994) reported that "In very strong illumination, an escape reaction was sometimes evoked: when entering the illuminated area, the animals (lamprey) slowed abruptly and then turned 180° - either away from or toward the illuminated side - and swam away in the opposite direction" and "stronger illumination evoked larger turning angles." We speculate that the intensity or color of light in the windows may deter passage at night.

Water movement through the picketed lead at the Makeup Water Channel (MWC) and counting window slot may also confuse the fish. In the past, lamprey have been observed in the MWC, yet their fate was not known. In 1998, 20% of the fish that reached the top of the ladder entered the MWC at PH1, and in 1999, 14% entered the MWC at both PH1 and PH2. Most fish eventually passed the dam, either by backing out of the MWC and passing the counting window, or over the top of the MWC. If the lighting situation is modified at the counting window, fewer fish may seek the MWC as a route of passage, and this area could become even less of a problem.

**Spillway Entrances**--Despite north spillway entrance modifications in the winter of 1998-99 (welding flat plate to the open I-beam construction of the gates), entrance efficiency at this location was 37% in 1998 and 39% in 1999 (Figs. 19 and 35). Median time from approach to entry at the south spillway entrance in 1998 was 16.7 minutes and the time to enter at the north spillway entrance was 39.9 minutes. In 1999, median times to entry at the south and north entrances were 29.6 and 123.3 minutes, respectively. We believe that the north entrance modifications may have functioned to increase the time fish required for entry, although no statistical significance in the median time to enter at the north entrance was detected between years ($P > 0.05$). The longer time required to enter may reflect the lower swimming velocities required to maneuver around the rounded corner. However, the delay in entry may also be attributed to a leak caused by a faulty seal on the north side of the gate. Lamprey tended to congregate in large numbers at the source of the leak (Fig. 39). In addition, the flat plate welded on the gate produced a 2-cm lip at the edge of the gate where lamprey needed to negotiate a 90° corner when entering the fishway. This also may have impeded progress.

Tests of spillway entrance velocity were inconclusive due to the low numbers of fish that approached the spillway entrances during the testing periods. Tests were not initiated until 2 August 1999 and only 10 fish approached the Bradford Island spillway entrance and 3 fish approached the Cascades Island entrance during this experiment. Future tests need to be started earlier in the season to have large enough sample sizes (numbers of lamprey approaching these entrances) for statistical comparisons.

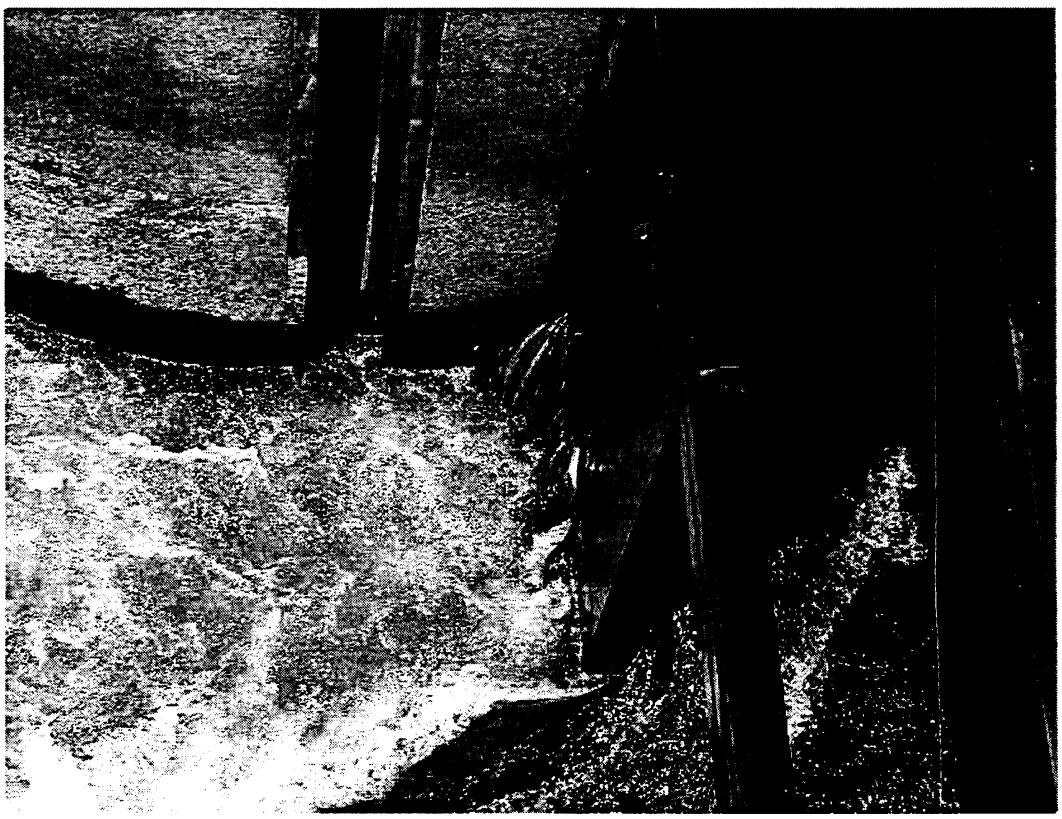

Figure 39. Lamprey were observed attached to the northern (Cascades Island) Bonneville Dam spillway entrance at the source of a leak in the gate next to the concrete, possibly increasing time spent at the entrance in 1999.

### Areas of Moderate to Low Concern

**Powerhouse Entrances**--Of the lamprey that approached Bonneville Dam, 85% in 1998 and 88% in 1999 entered a fishway. The approach-to-entry ratio was highest at the orifice entrances for both study years, an indication that lamprey seldom use this type of entrance successfully. At PH1, lamprey that entered the orifices and the north and south entrances had the highest overall passage efficiencies, while fewer lamprey that entered at the three southern entrances or via the middle ten orifice entrances at PH2 passed over the dam. We hypothesize that this poor passage success was related to the design of the diffuser gratings in the collection channel adjacent to these entrances (see previous section). However, orifice openings along the collection channel also provide more avenues for exiting the collection channel than at main entrances.

**Ladders**--The parts of the overflow weir sections of the fish ladders that did not have operating diffusers also did not impede lamprey passage. Passage efficiency in those areas was 95 and 98% in 1998 and 1999. Median duration of lamprey transit time per weir varied between years, but was consistently longer in the PH1 ladder than in other ladders. This time difference may be due to the presence of a sill at the downstream edge of underwater orifices at PH1, the Bradford B-Branch and Cascades Island ladders. There is no sill on orifices in the Washington shore ladder at PH2.

## The Dalles Dam

Radio-tagged lamprey that approached The Dalles Dam passed at a higher rate (63% in 1998 and 50% in 1999) than at Bonneville Dam. The most difficult areas for lamprey to negotiate were the transition area and the entrances to the powerhouse fishway. The diffuser grating system in the transition area of the powerhouse ladder is similar to the one at Bonneville Dam PH2, in that the diffuser grates cover the entire floor of the channel between the weirs. Failure to move through this area at The Dalles Dam (-43%) was similar to that at Bonneville Dam PH2. In addition, fewer lamprey successfully used the powerhouse entrances at The Dalles Dam, when compared to Bonneville Dam entrance use. As was the case at Bonneville Dam, the ladders were not a problem for lamprey. Interestingly, the lamprey also had no problems negotiating the fishways above the transition areas at The Dalles Dam.

## John Day Dam

Very few fish approached John Day Dam in 1998. Based on the meager data available, we believe that the transition areas, collection channels, counting windows, and entrances could all be problem areas, but that the powerhouse ladder did not obstruct passage.

## Trends and Observations

As in previous years of study, around 90% of the lamprey we tagged approached Bonneville Dam in both 1998 and 1999. The high number of returns and several tag recaptures indicated both that lamprey survival following tagging was high and that lamprey were participating in directed upstream migration. Two radio-tagged fish were recaptured and were in excellent condition. Of note was a decrease in size of the one fish that was measured on the recapture date. This male was tagged on 1 July 1999 at 69 cm and 510 g but was 66.5 cm and 455 g when recaptured on 3 August 1999. We are not sure if the smaller recapture size was a natural phenomenon related to the nonfeeding behavior of lamprey in fresh water, or if there was an effect of tagging, or both. Lamprey tagged at water temperatures greater than 19.5°C were less likely to return to the dam than those tagged at lower temperatures. Stress from handling and tagging may have contributed to the lower return of lamprey to the base of Bonneville Dam during periods of high water temperature. However, seasonal changes in flow or migrational motivation may also have produced this effect. There was no detectable difference in passage success of lamprey that approached the dam during warmer vs. cooler water conditions.

The average size of fish tagged in 1999 was 71 cm and 571.1 g. The smallest lamprey we caught in 1999 was only 35 cm long and weighed 80 g (much smaller than all of the others). Inspection of the supraoral dentition revealed three cusps, typical of Pacific lamprey (McGinnis 1984). We speculate that this fish may represent the lamprey equivalent of a precocious male (jack) salmonid.

Lamprey that accumulate at the base of Bonneville Dam may be exposed to unfavorable abiotic conditions or to increased predation risk. Travel times for lamprey from release points to the spillway entrances were longer than those to the powerhouse entrances, perhaps because lamprey find migration more difficult in the spillway tailrace, where velocities and dissolved gas levels are higher than in the tailraces of the powerhouses. Predation on lamprey near Bonneville Dam was observed only one time in 1999. An adult lamprey was seen being carried by an osprey after it was captured near the northernmost entrance at PH2. Several white sturgeon, up to 5 m in length, were observed in the transition area of PH2, primarily during the shad run. We suspect that lamprey are subject to some level of predation by these fish as well.

Lamprey migration was apparently delayed in the forebay of Bonneville Dam. Forebay travel time from Bonneville Dam to the Bridge of the Gods was calculated for 1998. Rate of travel through the forebay was slower than through the main section of the reservoir up to The Dalles Dam. The relatively slow movement through the forebay may reflect a need for recovery following exertions during ladder ascension. Lamprey may also have been slowed in this area due to swift currents, lack of attachment sites, or variable bottom topography. Interestingly, we recorded very few instances of lamprey fall-back behavior after they reached the reservoir.

## RECOMMENDATIONS

Bonneville Dam PH2, The Dalles Dam powerhouse ladder, and John Day Dam powerhouse ladder all have full-length diffuser grates in the transition areas. Plates that allow lamprey attachment along the floor of the collection channels and in transition areas between underwater orifices may aid lamprey passage. These devices should be designed, tested, and installed throughout the Columbia River hydropower system (if they are determined to be effective).

The counting window areas should be examined using radiotelemetry to determine exactly where migration delay and passage failure occurs: at the window itself, visitor center viewing windows, or through the serpentine weirs. The differences between the counting windows at Bonneville, John Day, and The Dalles Dams should be examined to determine why passage at Bonneville Dam windows was least successful. Tests to determine whether lighting alters lamprey behavior are needed to indicate whether modifications to lighting could promote passage through this area.

Modifications to the Bonneville spillway entrance gates should be continued. Emphasis should be placed on creation of smooth surfaces for lamprey attachment and lateral movement. The entrance gates should be sealed against the concrete, with no leaks (which attract lamprey). In addition, efforts should be made to reduce the volume of entrained air emitted at the spillway transition area diffusers. Efforts to reduce nighttime water velocities at all entrances should be continued.

The orifice entrances across the middle of the powerhouses contributed little to lamprey passage. However, the orifices at each end of the powerhouse were used regularly and should remain open. These entrances were probably used more because of their location at the inside corners of the face of the powerhouse near the major monolith entrances. Lamprey passage efficiency may actually increase if orifice entrances are closed, by providing fewer avenues for exiting the collection channels. Yet, fallout at the orifice entrances may be lower than that observed for salmonids because lamprey typically exhibit demersal behavior. Consequently, lamprey in the collection channel may be less affected by orifice opening than salmonids, which probably occupy more of the water column while migrating.

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