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Seattle, Washington

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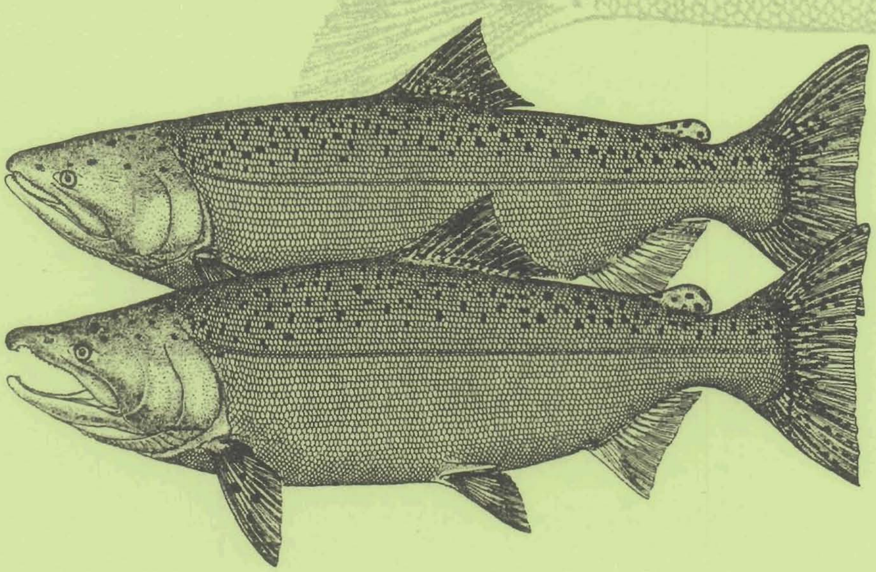

MIGRATION PATTERNS OF PACIFIC LAMPREY (*Lampetra tridentata*) IN THE LOWER COLUMBIA RIVER, 1997

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EXECUTIVE SUMMARY

Pacific lamprey (*Lampetra tridentata*) abundance, like that of other northwest anadromous fish species, has significantly declined in recent years. Study of adult migration patterns past dams and reservoirs in the Columbia River Basin may provide some insight into factors that affect or limit Pacific lamprey survival. Radiotelemetry has been used to determine migration behavior for many anadromous fish species; however, we are unaware of its use in Pacific lamprey studies. In 1997, we evaluated passage patterns of upstream-migrating radio-tagged Pacific lamprey in the lower Columbia River. Objectives of this study were to determine 1) return time from the release sites back to Bonneville Dam, 2) passage routes and behavior at the dam, and 3) migration rates through reservoirs.

Adult Pacific lamprey were captured in the entrance fishway of the Fisheries Engineering Research Laboratory (FERL) at Bonneville Dam utilizing a trap designed by the National Marine Fisheries Service. A total of 834 adult Pacific lamprey were captured, and catch per unit effort was 1.9 fish per hour. Radio tags were surgically implanted into the body cavity of 197 Pacific lamprey. A total of 147 tagged lamprey were released at two locations downstream from Bonneville Dam: Dodson, Oregon, and Skamania Landing, Washington. The remaining 50 fish were released above Bonneville Dam at either Cascade Locks, Oregon, or Stevenson, Washington. Pacific lamprey were relocated downstream from Bonneville Dam via mobile tracking from a boat, motor vehicle, or on foot. The passage of lamprey was also monitored by an extensive array of remote receivers (n = 26) equipped with either aerial or underwater antennas (n = 93).

Tracking results indicated that 130 of the 147 tagged lamprey released downstream from Bonneville Dam (88%) returned to the dam. Median travel time from the release sites to downstream monitors (6.7 km) was 5.1 days. Of the 17 fish that did not return to the dam, 8 were never relocated following their release at sites 9.5 kilometers below the dam. Median times from last detection at the downstream monitors to first approach at Bonneville Dam (a distance of approximately 2.8 km) ranged from 2 hours for fish that successfully passed over the dam to 2 days for fish that were unable to enter the fishways. Of the 130 lamprey that returned to the dam, 102 entered the fishways (78%) and one fish entered the navigation lock. Of the 102 lamprey that entered the fishways, 27 did not get past the collection channel areas (26%). Of the 75 that approached the fish ladders, 27 did not successfully negotiate the ladders (36%) and the remaining 48 fish exited at the top of the ladders. Total passage efficiency for lamprey that approached the dam was 38% (23 exits out the Bradford Island fishway, 25 exits out the Washington-shore fishway, and 1 through the navigation lock).

Of the 49 fish that passed over Bonneville Dam after release below the dam, 29 were detected at The Dalles Dam. Of these, 16 successfully passed upstream (55%). Eleven of the successful fish (69%) used the Oregon shore (powerhouse) fishway rather than the fishway adjacent to the spillway on the Washington shore. Of the 16 fish that were detected above The Dalles Dam,

8 approached John Day Dam and 3 successfully passed over (38%). All of the fish that passed over John Day Dam used the south fishway adjacent to the powerhouse on the Oregon shore.

Of the 50 lamprey released above Bonneville Dam, 41 were detected at The Dalles Dam. Nineteen (46%) of these lamprey made it over The Dalles Dam, and more of these lamprey (68%) used the powerhouse fishway than the one adjacent to the spillway on the Washington shore. Of the 19 upstream releases that passed over The Dalles Dam, 15 approached John Day Dam; however, none of these fish were able to pass over the dam.

Lamprey passage efficiency was low at the lower Columbia River dams we monitored. Of the lamprey that approached each dam, 38% passed Bonneville Dam (49 of 130), 51% passed The Dalles Dam (35 of 68), and 13% passed John Day Dam (3 of 23). Of the lamprey released below Bonneville Dam, 88% returned to the dam following release, indicating that tagging effects were low. The low number of fallbacks over Bonneville Dam (n = 1) and the fact that 82% of the fish released above Bonneville Dam migrated to the base of The Dalles Dam also indicates that the lamprey were exhibiting directed upstream migration behavior. Lamprey migration rates through the reservoirs were rapid (22.1 km d^{-1} for the Bonneville pool and 21.5 km d^{-1} for The Dalles pool). Twenty-six percent of the lamprey that successfully passed over The Dalles Dam (9 of 35) were eventually detected in the Deschutes River; however, we did not document any other use of tributaries by the radio-tagged lamprey.

CONTENTS

INTRODUCTION

Abundance of Pacific lamprey (*Lampetra tridentata*) has significantly declined in recent years (Close et al. 1995). Elucidation of adult migration patterns past dams and reservoirs in the Columbia River Basin may provide some insight into factors that affect or limit Pacific lamprey survival. Mark and recapture studies cannot provide complete descriptions of the movement of free-ranging fish; thus the development of radio transmitters for evaluation of fish behavior provides the possibility for continuous monitoring without recapture (Hart and Summerfelt 1975). Radiotelemetry has been used to determine migration behavior of many anadromous fish species; however, we are not aware of studies using radiotelemetry to determine the migration behavior of adult Pacific lamprey.

In 1996, The National Marine Fisheries Service (NMFS), the Idaho Cooperative Fish and Wildlife Research Unit (UI), and the U.S. Army Corps of Engineers (COE) initiated a study of passage behavior and passage patterns of Pacific lamprey approaching and passing Bonneville Dam. We determined return time of tagged lamprey from release sites to Bonneville Dam, passage routes at Bonneville Dam, and migration rates through reservoirs. Work in 1997 was a continuation of those studies.

The Pacific lamprey's distribution ranges from the Aleutian Islands to Baha California and Hokkaido, Japan. In the Columbia and Snake River Basins, the Pacific lamprey was once present in all waters where salmon and steelhead were found (Simpson and Wallace 1978). Currently the distribution of Pacific lamprey is limited to the waters below Chief Joseph Dam on the Columbia River and below Hells Canyon Dam on the Snake River (Close et al. 1995). Both of these dams lack adult fishways for passage. Kan (1975) suggested that access to available habitat, rather than distance from the ocean is the factor that dictates lamprey distribution. Consequently, poor passage success of lamprey at lower Columbia River dams could be limiting access to historical spawning areas and altering lamprey distribution in the drainage. In this study, we examined passage efficiency of Pacific lamprey at lower Columbia River dams using radiotelemetry.

METHODS AND MATERIALS

Trapping and Tagging

Pacific lamprey were collected from the fishway entrance at the Fisheries Engineering Research Laboratory (FERL) at Bonneville Dam. We used a trap positioned in the third plunge pool just above the third weir crest of the entrance fishway (Fig. 1). The original design of the trap was modified to avoid blocking the fishway during adult salmonid trapping operations. The trap was fished overnight and Pacific lamprey were removed and put into a 75.7-L transport bucket (25 L of water) the following morning. Fish were then placed in a 1.8- by 0.9- by 0.6-m holding tank prior to selection for tagging.

A total of 834 Pacific lamprey were caught, and 197 of these were selected for tagging. Fish not radio tagged were used in other lamprey research or were released into the Washington shore fish ladder. All fish selected for tagging were anesthetized using 0.06-g/L tricaine methanesulfonate (MS-222), examined for injuries and sexual maturity, measured, and weighed. The anesthetic tank was 0.4 by 0.4 by 1.0 m, with 45 L of anesthetic solution. Surgical procedures were similar to those used in 1996 (Vella et al. 1999). After examination and tagging, fish were placed in a recovery tank with aerated fresh water and allowed to regain equilibrium.

Radio Transmitters

Tags were manufactured by Lotek Engineering Inc. of Newmarket, Ontario, Canada. The tags were sealed in an epoxy capsule, 4.3-cm long by 0.9-cm diameter; each tag weighed 7.0 g in air and had a 20-cm-long external antenna attached to one end. The water weight of the tag did not exceed 1.25% of the fish weight, as recommended by Winter et al. (1978). Tag frequencies were in the 149 MHz range and their battery life was seven months.

Surgical Implant

Surgical techniques were similar to those described by Hart and Summerfelt (1975), Reinert and Cundall (1982), Ross (1982), and Mellas and Haynes (1985). Surgical procedures followed those developed in our initial evaluation of tagging techniques (Bjornn et al. 1996). Surgical tools and transmitters were sanitized in a solution of benzalkonium chloride. The tag was implanted into the body cavity through a 4- to 5-cm incision in the mid-ventral body wall. A cannula was used to thread the antenna of the radio-tag subcutaneously to an exit site anterior to the cloaca. Individual stitches with a 19-mm, FS-1 quarter-round cutting needle and absorbable polydioxanone monofilament suture were used to close the incision. Baciguent and Betadine were applied to the suture area and antennae exit to prevent infection.

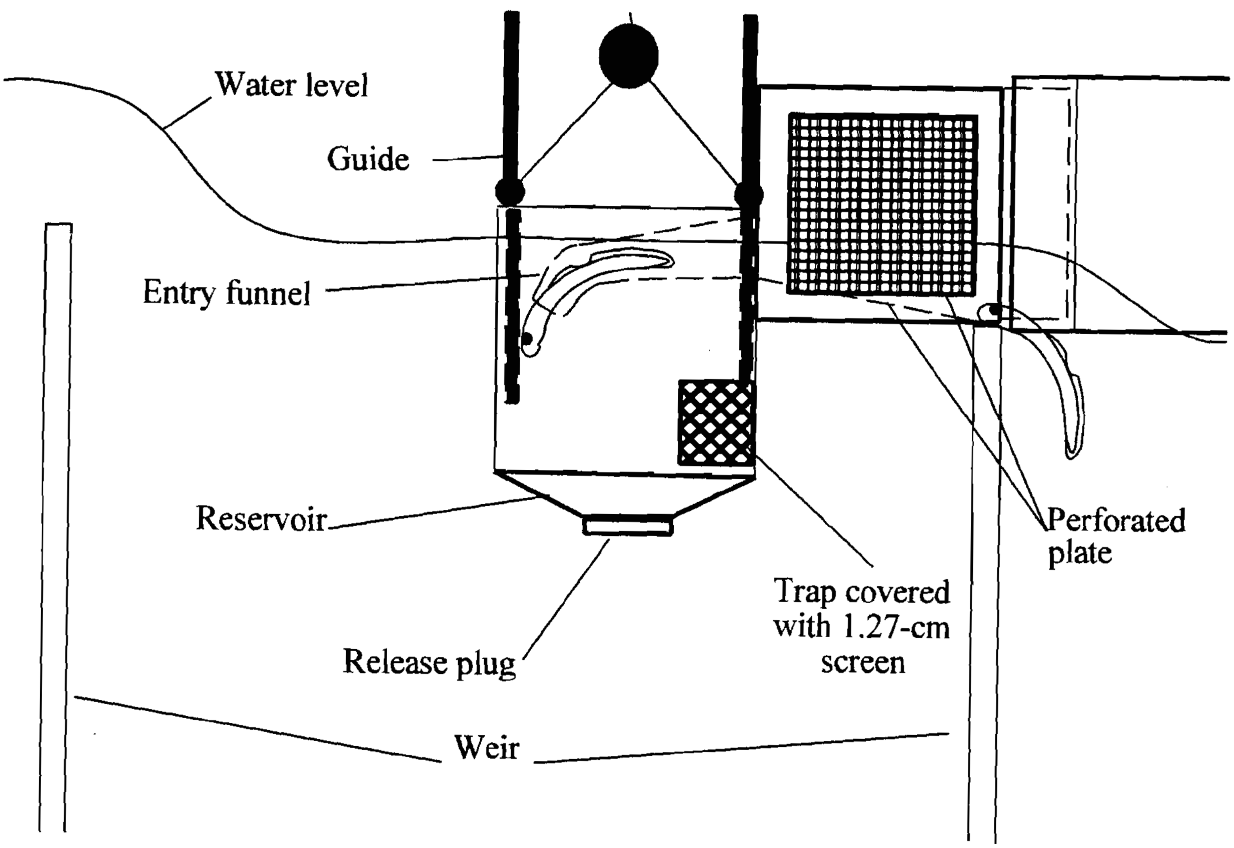

Figure 1. Side view of lamprey trap used at Bonneville Dam, 1996 and 1997.

Release Sites

Lamprey were released at four sites: two below Bonneville Dam and two above the dam. The two release sites below Bonneville Dam were on the north shore at Skamania Landing, Washington (River Kilometer (RKm) 225.7), and on the south shore at Dodson, Oregon (RKm 225.6). Release sites above the dam were at Stevenson, Washington (RKm 242.2), on the north shore and Cascade Locks, Oregon (RKm 239.1), on the south shore.

Antenna and Receiver Locations

A total of 93 antennas were installed at Bonneville Dam (Fig. 2). Nine-element air antennas were placed at two downstream fixed sites, one on the south shore at Tanner Creek (RKm 232.3) and one on the north shore at Hamilton Island boat launch (RKm 231.2). Three other air antennas were placed at Bonneville Dam, one at the entrance to the new navigation lock and two on the north and south sides of the forebay above the spillway. Air antennas were used to cover a distance of up to 0.4 kilometers on level ground but inconsistently detected tags below 9.1 m water depth. Underwater antennas were placed at all the large openings to and inside the fishways and collection channels of both Powerhouse I and Powerhouse II, at the spillway entrances, and at the exits to the fish ladders. Underwater antennas detected transmitters within approximately 9 m in all directions. Appendix A contains a detailed list of antenna locations.

The antennas were connected to 26 receivers manufactured by Lotek Engineering. Each receiver was programmable and could detect radio transmitters on 25 different frequencies and up to 150 individual codes. Two types of receivers were used. The first type of receiver, the SRX-400, scanned each tag frequency at 6-second intervals and stored up to 128 KB of data in 7 or 8 data banks (these receivers were used at single-antenna sites, such as downstream sites below the dam). The second receiver was the SRX-500 Digital Spectrum Processor (DSP), which was used in tandem with the SRX-400 and allowed multiple detections at a fixed site. The DSP was also used with the ASP-8 multiple-antenna switching unit, which allowed monitoring up to eight different antennas simultaneously. Thus, a combination of the ASP-8, SRX-500, and SRX-400 at a fixed site with multiple antennas was able to monitor up to eight different antennas and 25 separate frequencies simultaneously. In comparison, the SRX-400, with one antenna scanning 25 separate channels, would take 2.5 minutes to scan all channels given its 6-second scan interval.

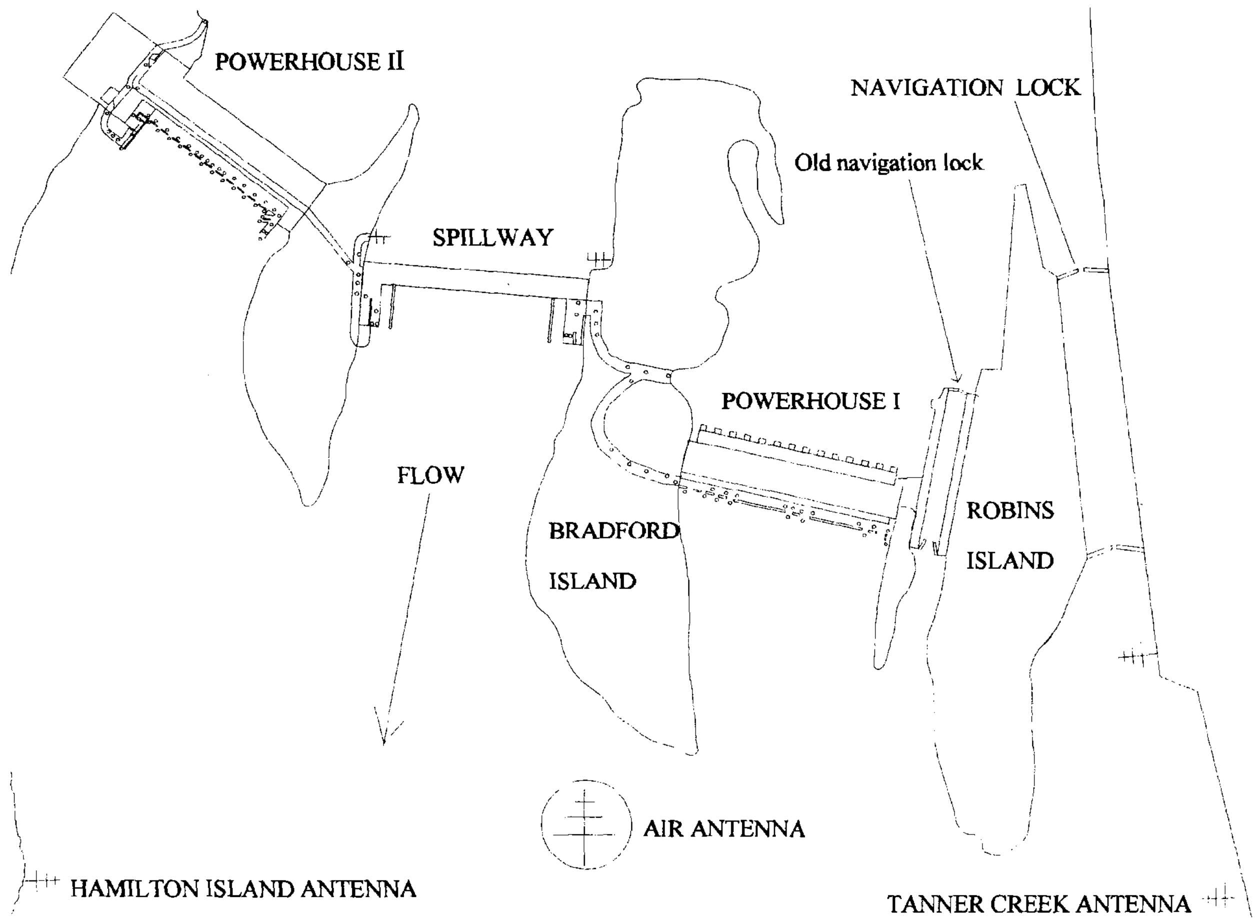

Figure 2. Bonneville Dam study area with underwater (open circles) and aerial antenna locations.

RESULTS AND DISCUSSION

We fished the lamprey trap between 2100 and 0800 hours for 44 days, from 20 May to 30 July, for a total of 429 hours. These hours of operation were chosen because trapping adult Pacific lamprey was most productive at night and this practice also reduced impacts on salmonids, which are most numerous in the fish ladder during the day. We captured 834 adult Pacific lamprey, for a catch per unit effort of 1.9 fish per hour.

A total of 197 adult Pacific lamprey > 450 g were selected and surgically implanted with radio transmitters. Of the 147 radio-tagged Pacific lamprey we released downstream from Bonneville Dam, 17 (12 %) did not return to the dam (8 of the 17 were never re-located following release). Lengths of fish we tagged ranged from 60.5 to 79.5 cm. Radio-tagged Pacific lamprey that did not return to Bonneville Dam were spread across the entire length range of tagged fish (Fig. 3). This indicated that tagging effects were similar across all size classes. Pacific lamprey released downstream that did not return to Bonneville Dam were also spread across the entire range of tagging dates, which began 20 May and ended 30 July (Fig. 4). Apparently lack of upstream movement was not related to season or temperature. The fact that half of these fish were not re-located during mobile tracking surveys below Bonneville Dam suggests that some of the tags used may have failed, that tagged lamprey were perhaps eaten by other fish, or that they may have exited downstream of our study area immediately after release. Of the fish released downstream from the dam, 48 were detected at the top of the Bonneville Dam fishways and one passed upstream via the navigation lock. Total passage efficiency was higher than passage efficiency of lamprey tagged in 1996 (Vella et al. 1999) (Table 1).

There was no difference in return rates to Bonneville Dam based on release location (chi-square = 1.43, P = 0.2311, Table 2). This indicated that the release sites were not affecting the migration behavior of radio-tagged lamprey. The distribution of lamprey as they approached Bonneville Dam for the first time was also apparently unaffected by downstream release site. Fish released at Dodson, Oregon made 33, 9, and 26 first approaches at the Powerhouse I, the spillway, and Powerhouse II, respectively. Similarly, fish released at Skamania, Washington made 31, 13, and 18, approaches at Powerhouse I, the spillway, and Powerhouse II. A chi-square analysis of these small samples indicated no difference (chi-square 2.54, P = 0.2811) in first approach locations for lamprey released at the two different sites.

We were unable to determine the sex of some fish that were released downstream from Bonneville Dam. No males were identifiable during the tagging procedure. Pacific lamprey whose sex was undetermined were grouped together, and females were grouped together based on the presence of eggs in the body cavity (Table 3). There was no indication that either group was more likely to approach the dam (chi-square = 1.02, P = 0.314), suggesting that migration behavior below Bonneville Dam was not related to identifiable sexual characteristics of these fish.

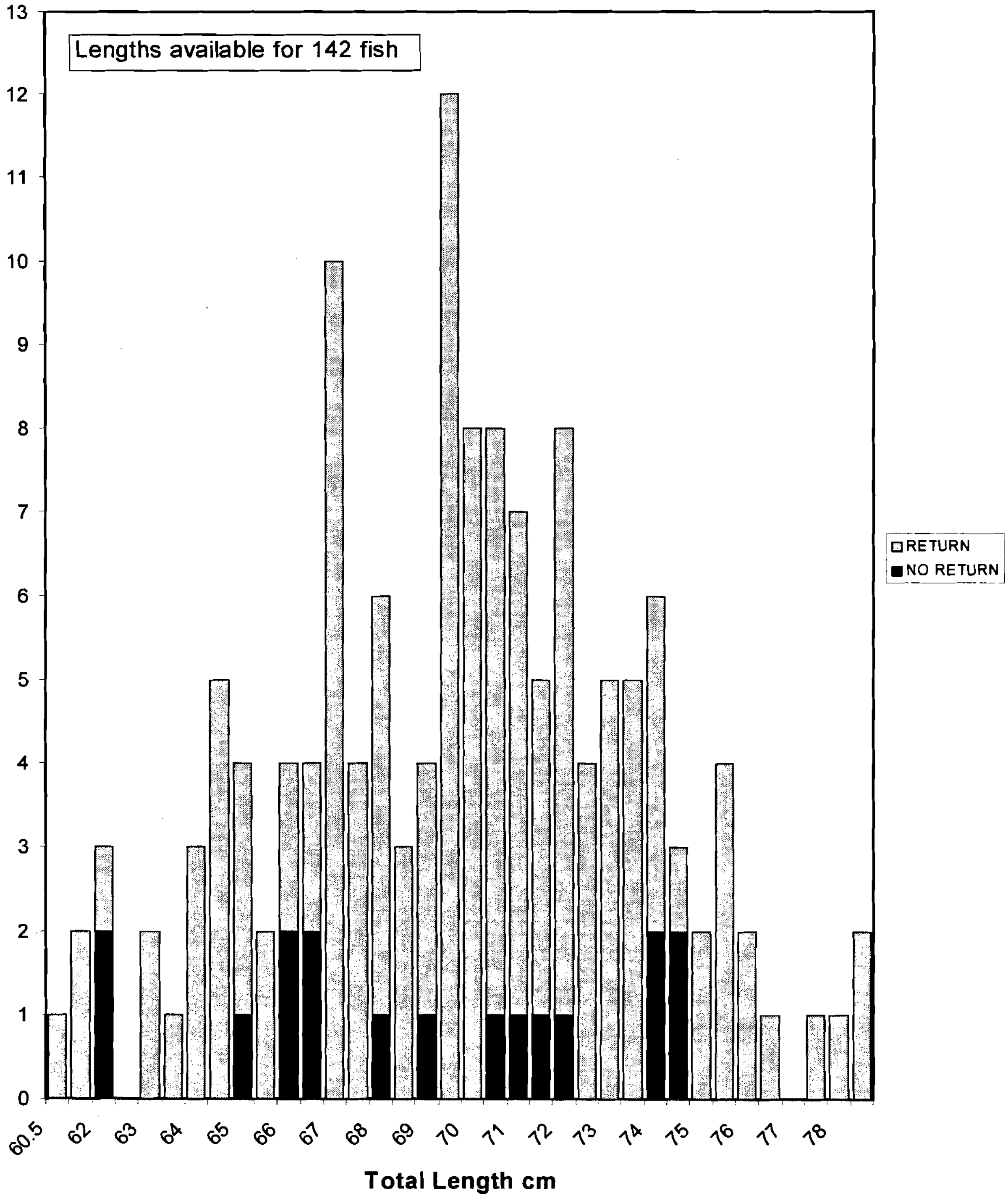

Figure 3. Number of radio-tagged Pacific lamprey that returned to Bonneville Dam (gray bars) and did not return (dark bars) based on total length.

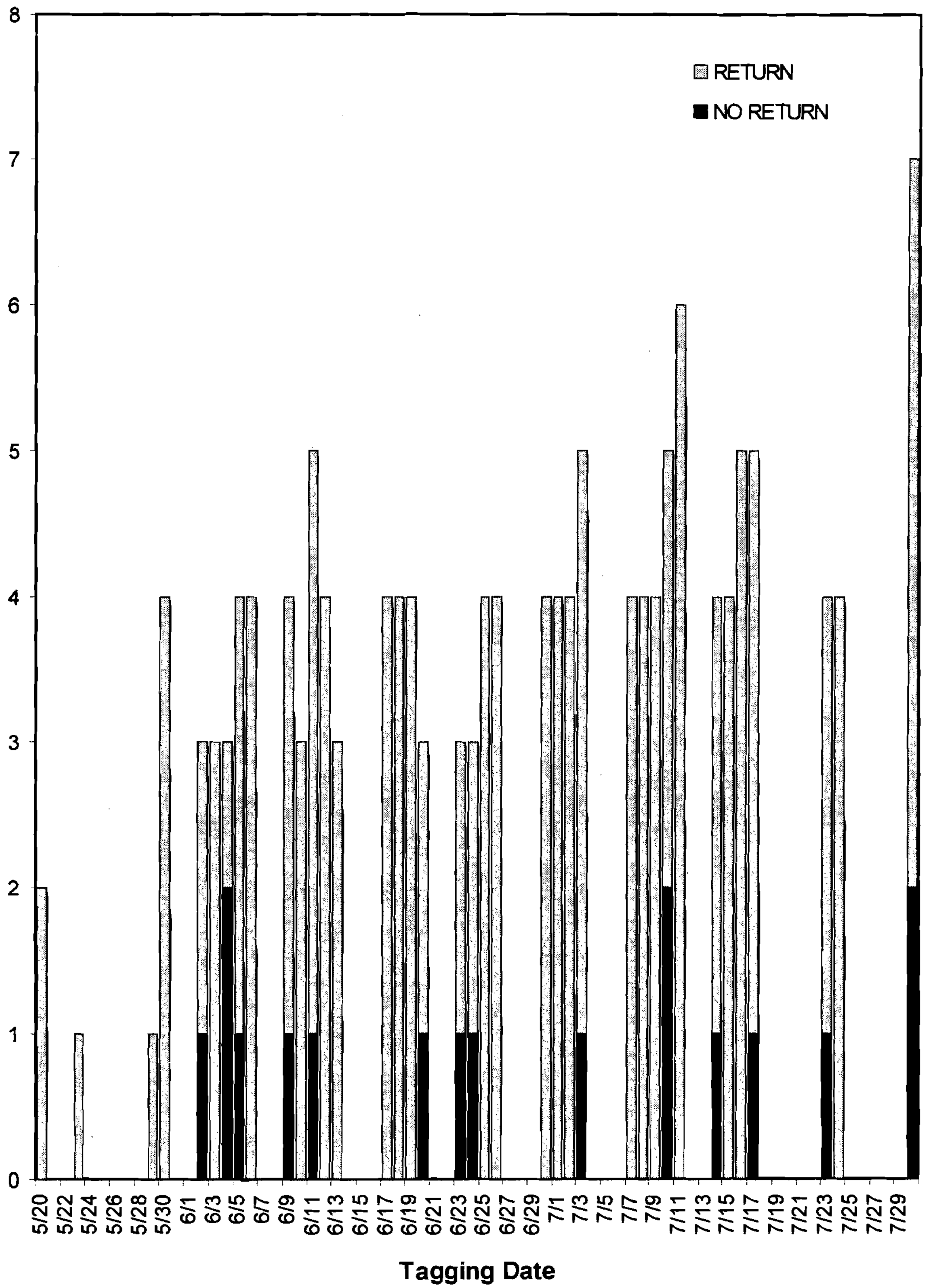

Figure 4. Number of radio-tagged Pacific lamprey that returned (gray bars) and did not return to to Bonneville Dam (dark bars) based on tagging date, 1996.

Table 1. Detections of radio-tagged Pacific lamprey at Bonneville Dam ladder exits.

Year	Total Released	Total Passed (% release)	Bradford Island	Washington shore
1996	85	18 (21 %)	9	9
1997	147	48 (33 %)	23	25

Table 2. Fate of radio-tagged Pacific lamprey released downstream from Bonneville Dam based on release site.

Fate	Dodson	Skamania
Returned to Bonneville Dam	68	62
No Return	5	12

Table 3. Fate of radio-tagged Pacific lamprey released downstream from Bonneville Dam based on sex.

Fate	Unidentifiable	Female
Returned to Bonneville Dam	65	65
No Return	12	5

The travel time from release to first arrival at the downstream monitor was available for 10 of the 18 fish that did not return to Bonneville Dam. The median travel time for these fish was 17.4 days, while median travel time for fish that did return to Bonneville Dam was 5.1 days (travel times were available for 116 of the 129 lamprey that approached Bonneville Dam). These data indicate that some of the fish were either not engaged in directed upstream migration documented for those that approached the dam, or that they did not fully recover from surgery. The first arrival of radio-tagged Pacific lamprey at Bonneville Dam was 1 June 1997, just before the flows were at their highest levels (Fig. 5). The majority of fish returned to Bonneville Dam between 28 June and 31 July 1997, during the period after high flows. The largest number of returns per day (n = 8) occurred on 29 June 1997. Flows between 1 June and 23 August 1997, the period when radio-tagged lamprey approached the dam, ranged from 175.6 to 556.7 kcfs (median flow = 286.9 kcfs).

In 1997, 130 radio-tagged Pacific lamprey were detected on monitors at Bonneville Dam (88 % of the downstream release). These fish were placed in four groups: Group 1, fish that approached Bonneville Dam but did not enter the fishways (n = 27); Group 2, fish that entered the collection channels but were not detected in the fish ladders (n = 27); Group 3, fish that were detected in the fish ladders but did not reach the top of the ladders (n = 27); and Group 4, fish that exited out the top of the fishways (n = 49, including one fish that was detected upstream of the navigation lock).

The time to first approach at Bonneville Dam varied among individuals and groups (Fig 6a). Fish in Group 1 took between 0.05 and 21.7 days to reach Bonneville Dam after their last detection at a downstream monitor (median 2.3 days). Fish in Group 2 had a median travel time from the downstream site of 0.89 days (range 0.05 to 11.7 days). Fish in Group 3 had a median travel time of 1.2 days (range 0.04 to 12.5 days), and for Group 4 it was 0.09 days (range 0.05 to 11.7 days). These data indicate that those fish that successfully passed over Bonneville Dam also migrated up from the release sites most rapidly. This may be due to physical factors such as temperature, flow, and spill conditions at the time of approach. However, reproductive readiness of an individual or its recovery time following surgery may also have dictated how long it took a fish to approach the dam after passing the downstream monitors.

The time it took for fish to enter the collection channel after approaching an entrance was less variable, with medians among groups ranging from 3.8 to 5.5 hours. The median time from first detection at the dam to first detection in the collection channel for Group 2 fish was 0.23 days (range < 0.002 to 12.0 days) (Fig. 6b). Group 3 fish took 0.19 days to pass into the collection channel (range < 0.00 to 14.4 days) after first detection at the dam, and Group 4 fish took a median of 0.16 days (range < 0.001 to 36.0 days).

Pacific lamprey that successfully migrated over the dam (Group 4) also had lower residence time in the fishways than fish that were unable to negotiate the collection channels (Group 2) or fish ladders (Group 3). Those fish that approached but did not enter the fishways (Group 1) spent a median time of 0.59 days (range < 0.0001 to155.4 days) at Bonneville Dam (Fig. 6c). Group 2 fish spent from 0.02 to 28.93 days at Bonneville Dam (median 7.7 days). Group 3 fish spent a

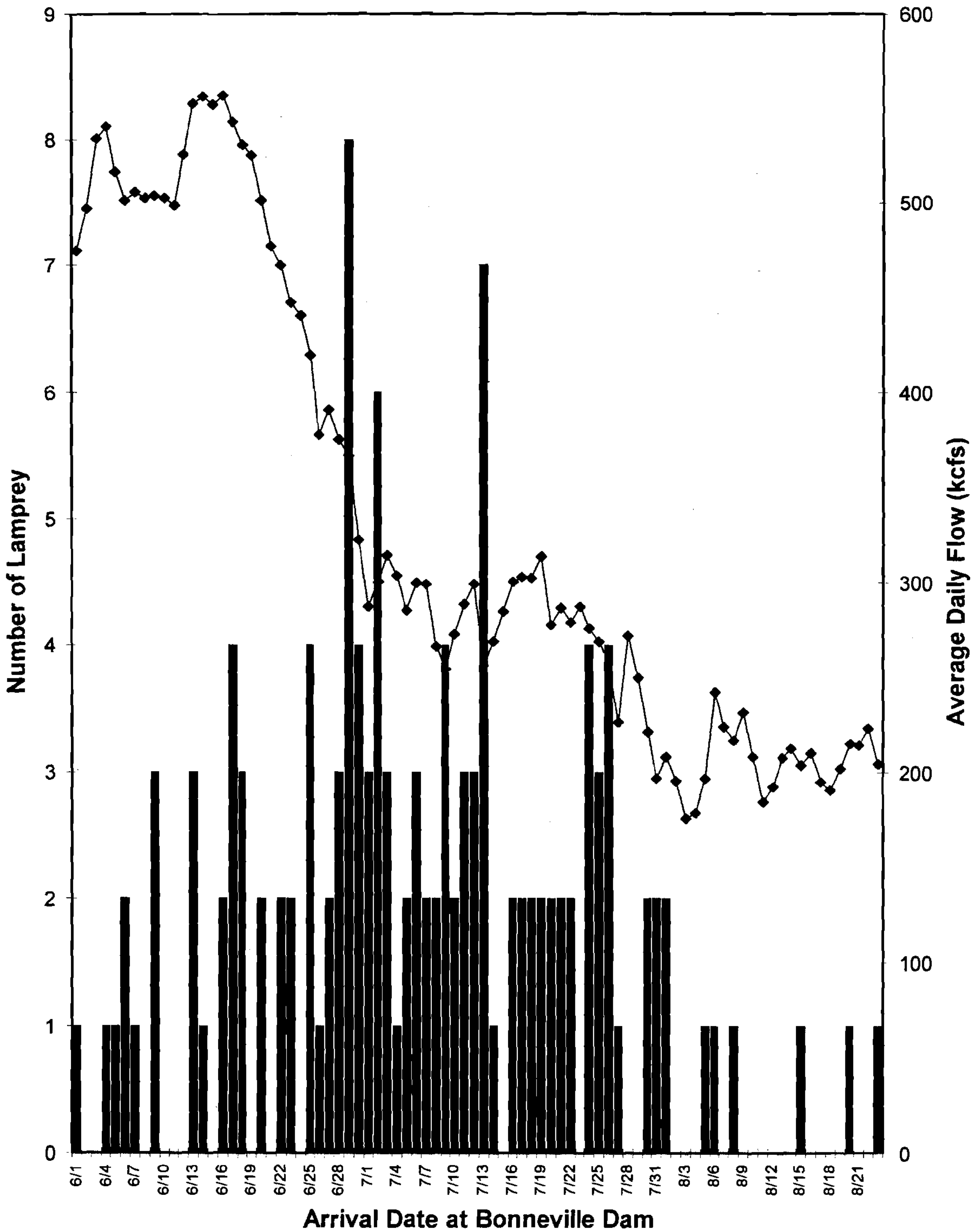

Figure 5. The number of radio-tagged Pacific lamprey that approached Bonneville Dam and the average daily flow.

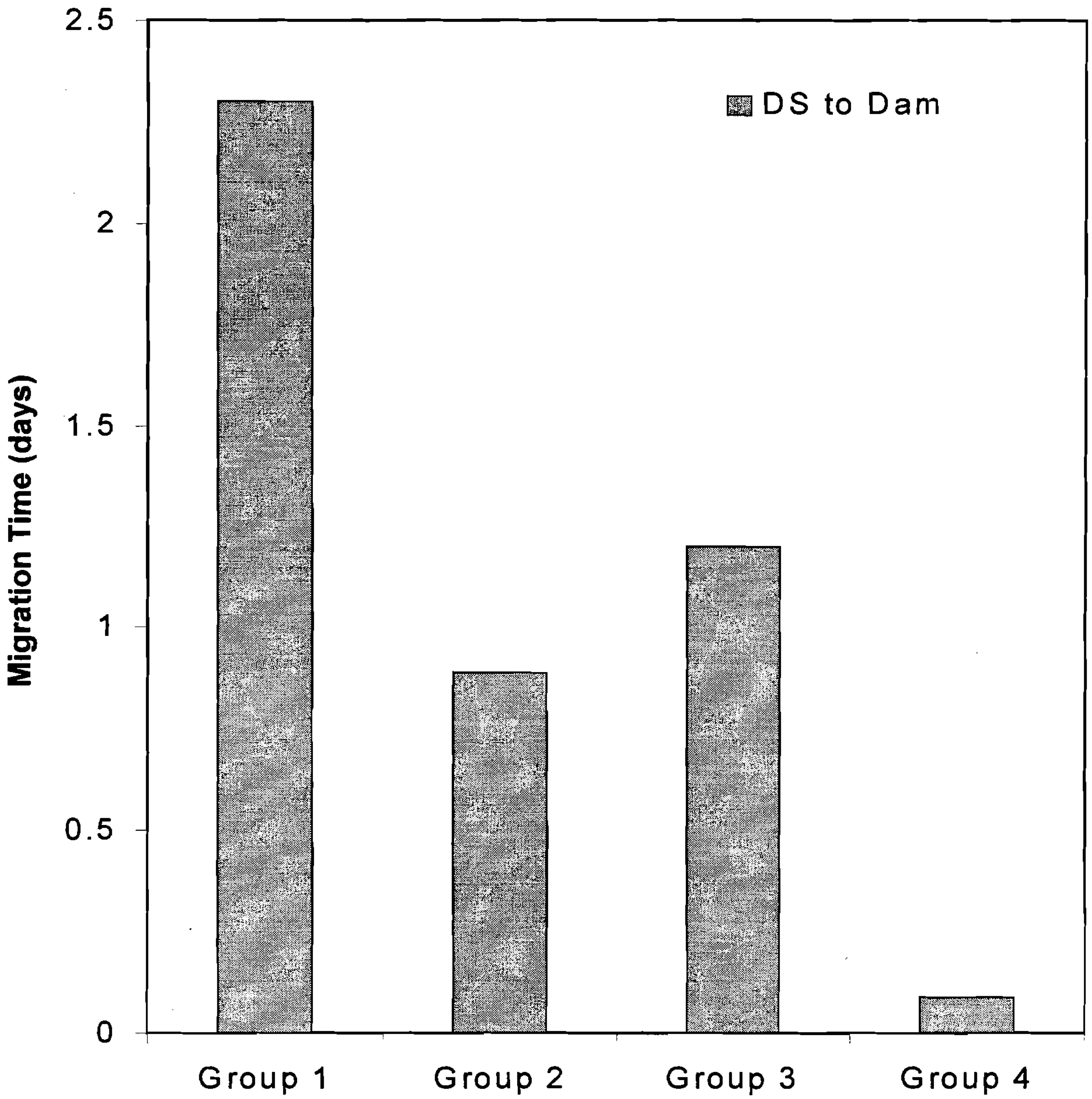

Figure 6a. Median migration times (days) for radio-tagged Pacific lamprey from last detection at downstream (DS) monitoring sites to first detection at Bonneville Dam, 1997. Group 1 fish were detected only outside the collection channel, Group 2 fish migrated as far as the collection channel, Group 3 fish migrated into the fish ladder, and Group 4 fish passed above the dam.

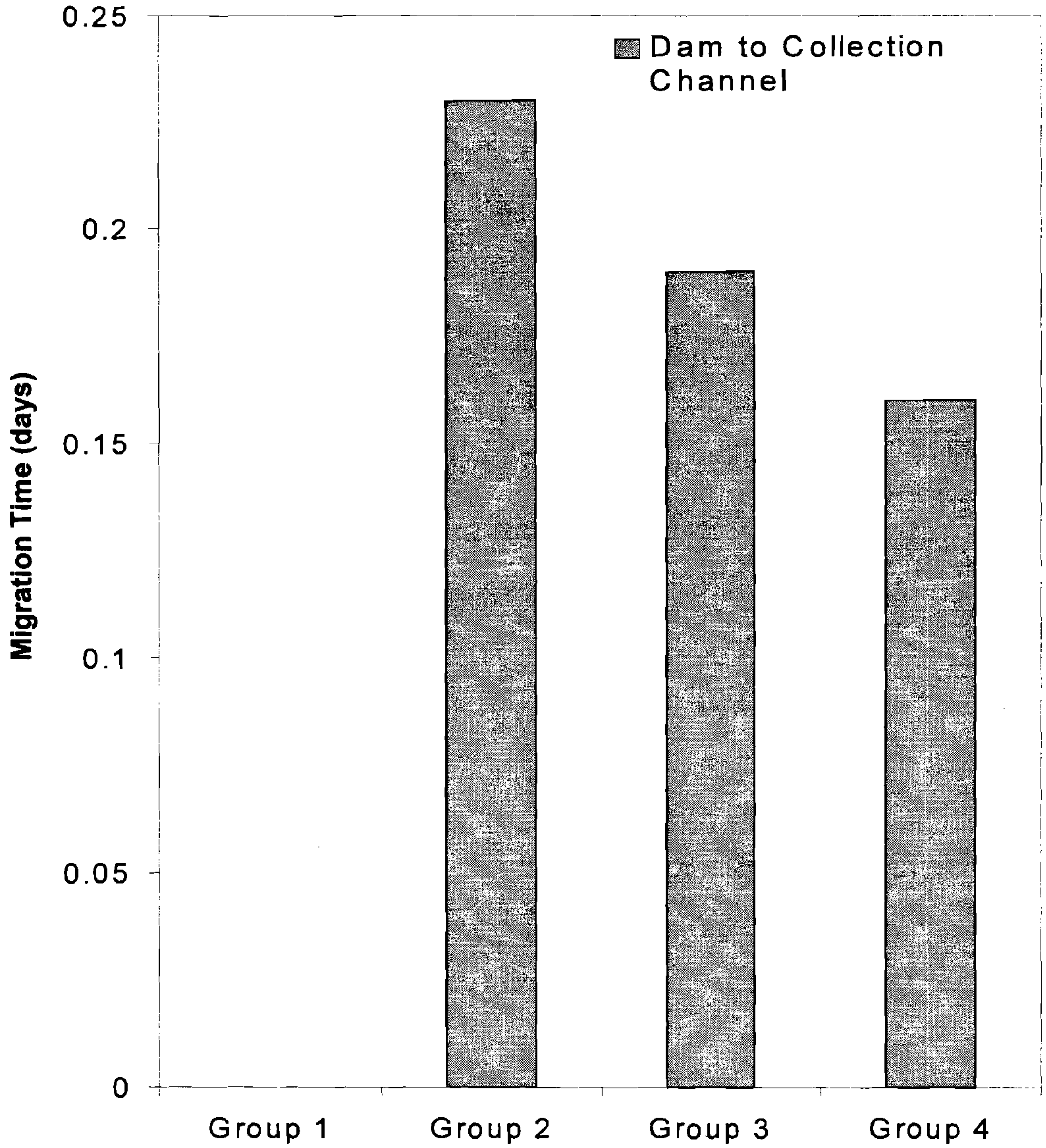

Figure 6b. Median migration times for radio-tagged Pacific lamprey from first detection on an antenna outside the collection channels to first detection inside the collection channels at Bonneville Dam, 1997. Group 1 fish were detected only outside the collection channels, Group 2 fish migrated as far as the collection channel, Group 3 fish migrated into the fish ladder, and Group 4 fish passed above the dam.

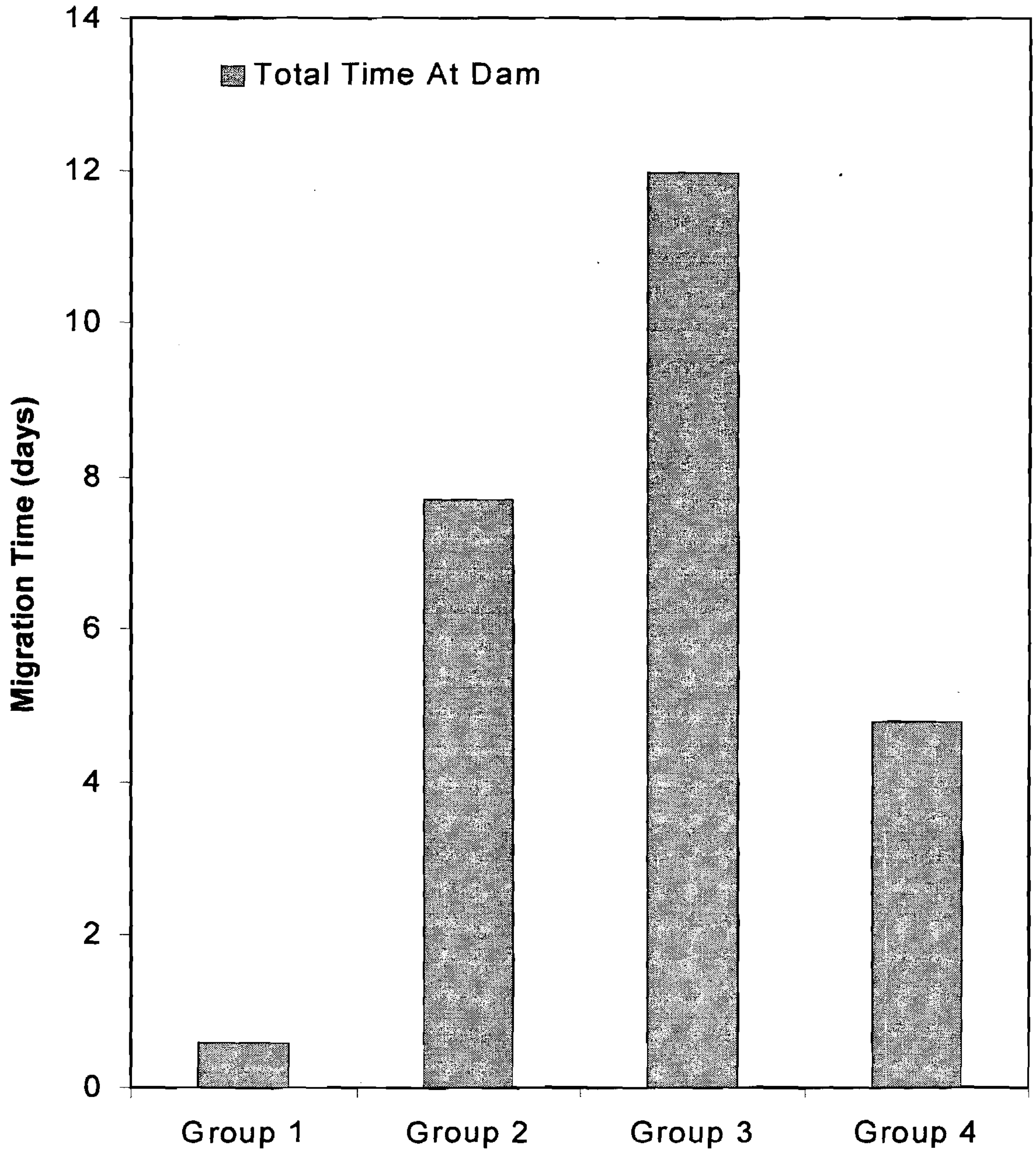

Figure 6c. Median time from the first detection of radio-tagged Pacific lamprey to last detection at Bonneville Dam, 1997. Group 1 fish were only detected outside the collection channels, Group 2 fish migrated as far as the collection channel, Group 3 fish migrated into the fish ladder, and Group 4 fish passed above the dam.

median time of 11.97 days at the dam (range 0.88 to 205.8 days). Group 4 fish spent from 0.31 to 37.23 days (median 4.83 days). Based on their swift upstream movement and rapid passage through all sections of the fishway, these data indicated that some lamprey (Group 4) either approached the dam during ideal passage conditions or were more highly motivated or able to migrate upstream. Behavior of fish that fell back inside the fishway without achieving passage was characterized by extended periods of holding and delay (as evidenced by the protracted periods spent in the fishways by Groups 2 and 3).

For analysis of Pacific lamprey activity at Bonneville Dam fishway entrances, we classified all fish detected at Bonneville Dam as either having passed the dam or not. More first approaches occurred at the Powerhouse I entrances than at the spillway or Powerhouse II (Fig. 7). However, when all approaches to the dam were included (not just the first approach by an individual), it is clear that lamprey made approaches at both powerhouse and spillway entrances (Fig. 8). While activity at the entrances occurred across both powerhouses and the spillway, there were more approaches at the south end of Powerhouse II than at any other entrance and few approaches were detected at the south end (SSE) of Powerhouse I (Fig. 8). Lamprey that successfully passed over Bonneville Dam approached entrances across both powerhouses and the spillway. This was also the case in 1996 (Vella et al. 1999).

The detection of a radio transmitter by an antenna positioned inside the collection channel was used to identify successful entrances into the collection channel. In some cases, the lamprey approached an entrance area and were later detected in the fishway, but there were not enough detections to confirm entry at a specific entrance ("unknown entrances"). Lamprey that passed over the dam entered more often at the north (NSE) and south (SSE) ends of Powerhouse II than at other entrances. However, there were also a large number of exits out of the southern end (SSE) of Powerhouse II by these fish (Fig. 10). These data indicated that lamprey use the main entrances at Powerhouse II, but are apparently unable to negotiate the collection channel.

Care should be taken in interpreting approach and entrance data. Lamprey may attach for prolonged periods in the vicinity of an entrance. This behavior can result in over-estimation of the number of approaches, particularly if the signal is periodically interrupted (resulting in large numbers of coded approaches). Moreover, due to the configuration of the various entrances, differences in turbulence, current velocity and antenna depth, the likelihood of detection at an individual entrance was variable. Therefore, we also calculated the number of fish that approached and entered each entrance (Fig. 11). These data indicated that the number of fish approaching individual entrances was less variable than the number of approaches. The fewest number of fish approached the south end (SSE) of Powerhouse I and the most different individuals were recorded approaching both ends of Powerhouse II.

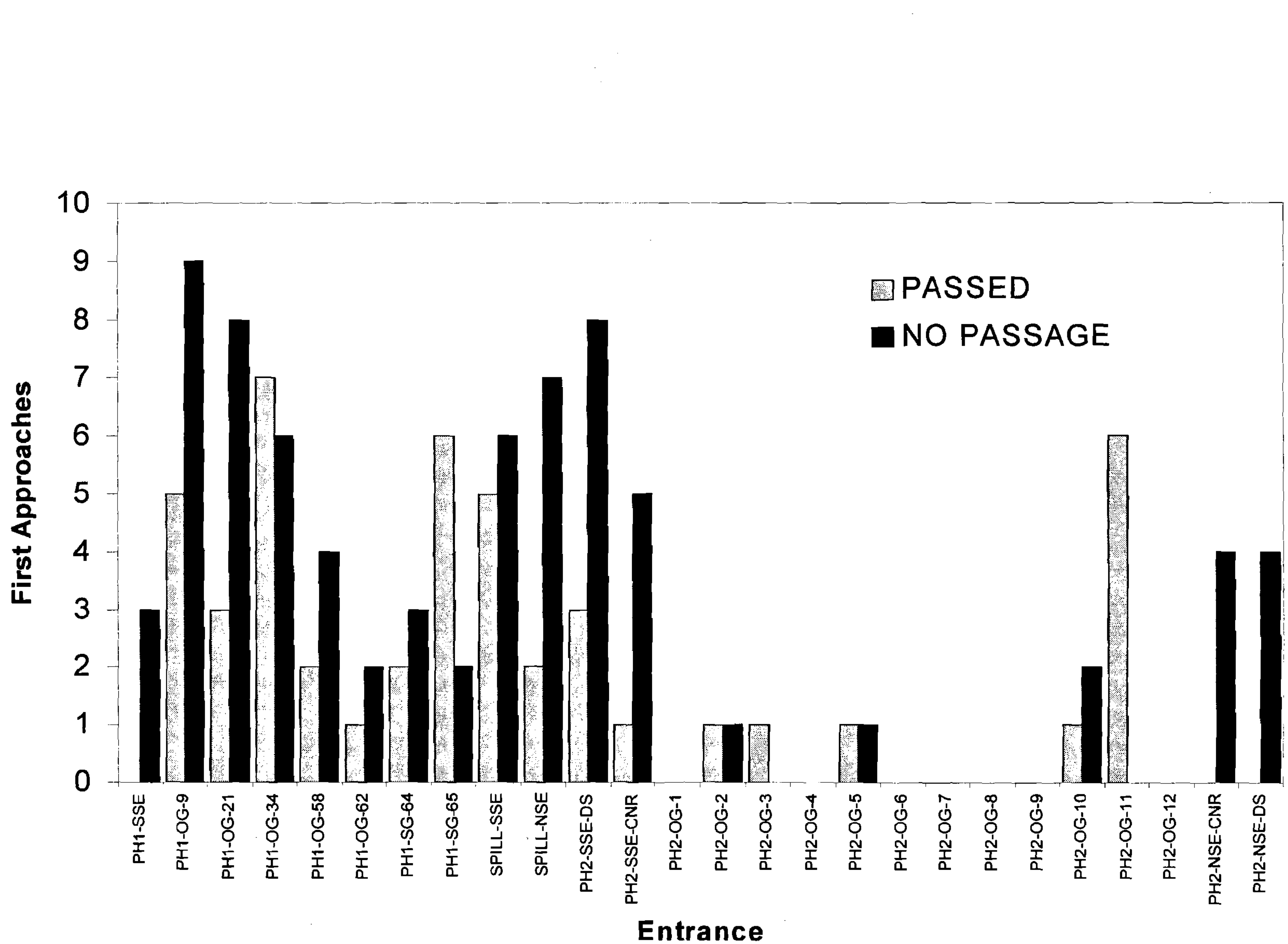

Figure 7. Number of first approaches at fishway entrances at Powerhouse I (PH1), Powerhouse II (PH2), and spillway (SPILL) made by radio-tagged Pacific lamprey that passed (light bars) and did not pass (dark bars) Bonneville Dam in 1997.

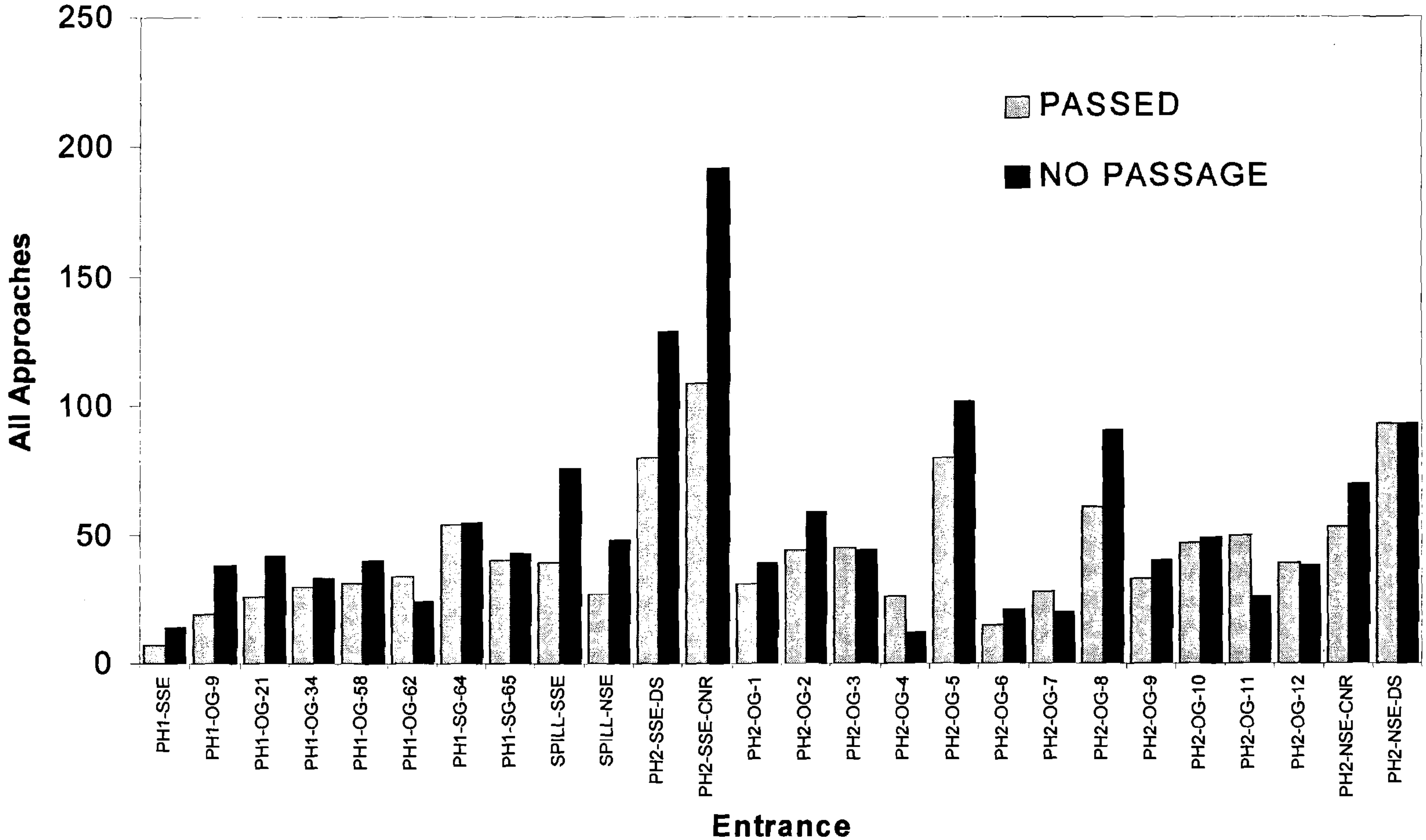

Figure 8. All approaches to Powerhouse I (PH1), Powerhouse II (PH2), and spillway (SPILL) fishway entrances made by radio-tagged Pacific lamprey that passed (light bars) and did not pass (dark bars) Bonneville Dam in 1997.

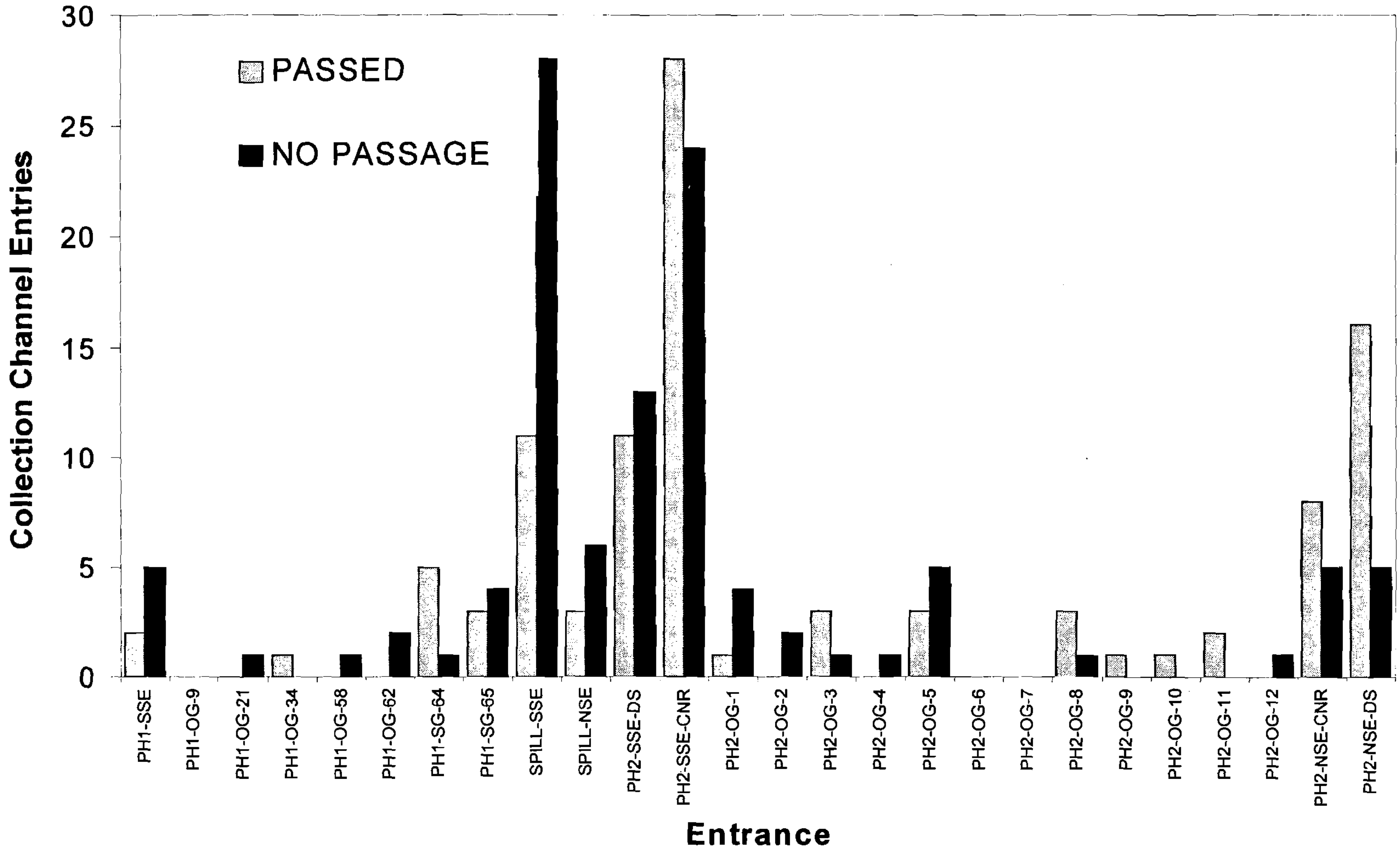

Figure 9. All entrances into the collection channels at Powerhouse I (PH1), Powerhouse II (PH2), and the spillway (SPILL) made by radio-tagged Pacific lamprey that passed (light bars) and did not pass (dark bars) Bonneville Dam in 1997.

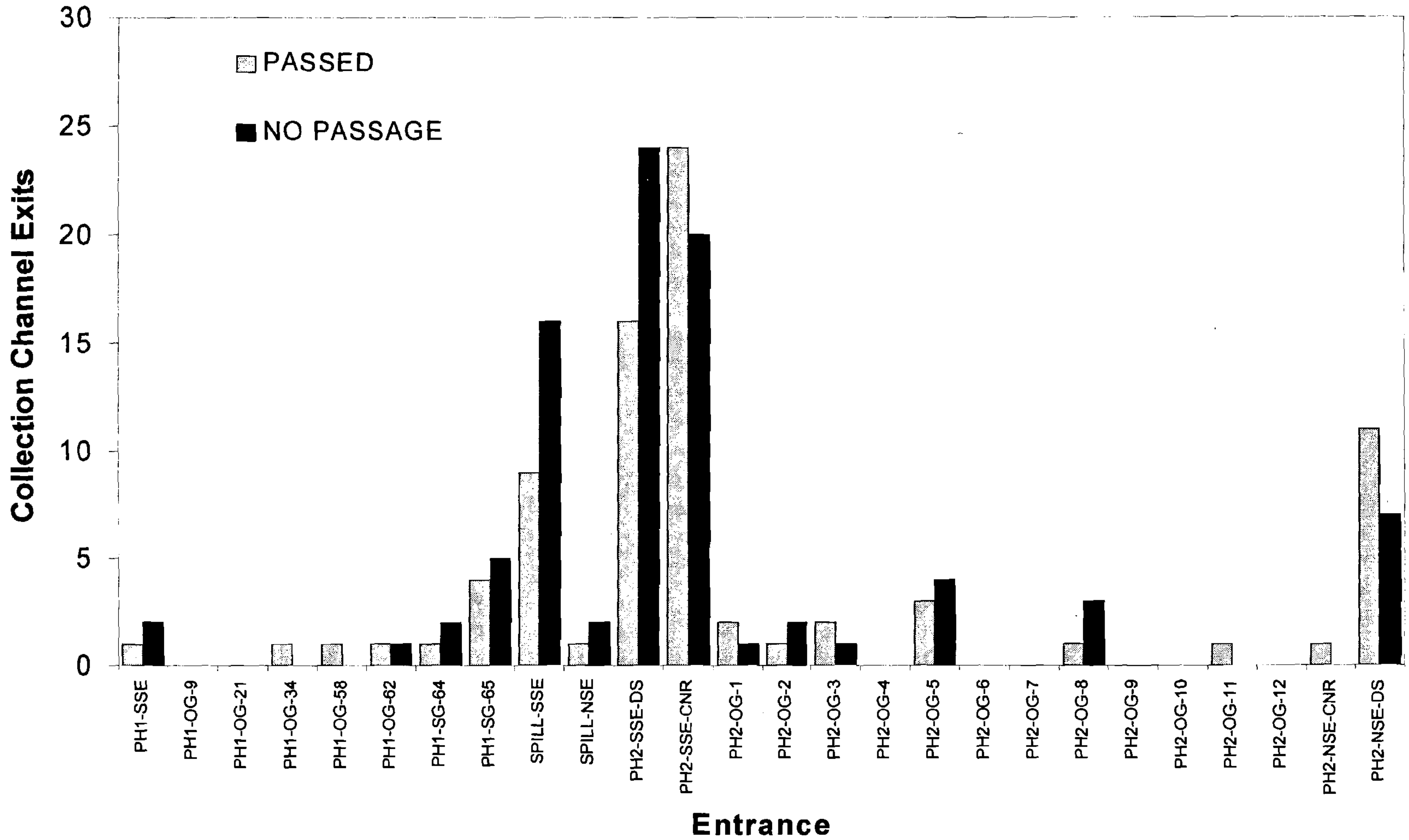

Figure 10. All exits out of the collection channels at Powerhouse I (PH1), Powerhouse II (PH2), and the spillway (SPILL) made by radio-tagged Pacific lamprey that eventually passed (light bars) or did not pass (dark bars) Bonneville Dam in 1997.

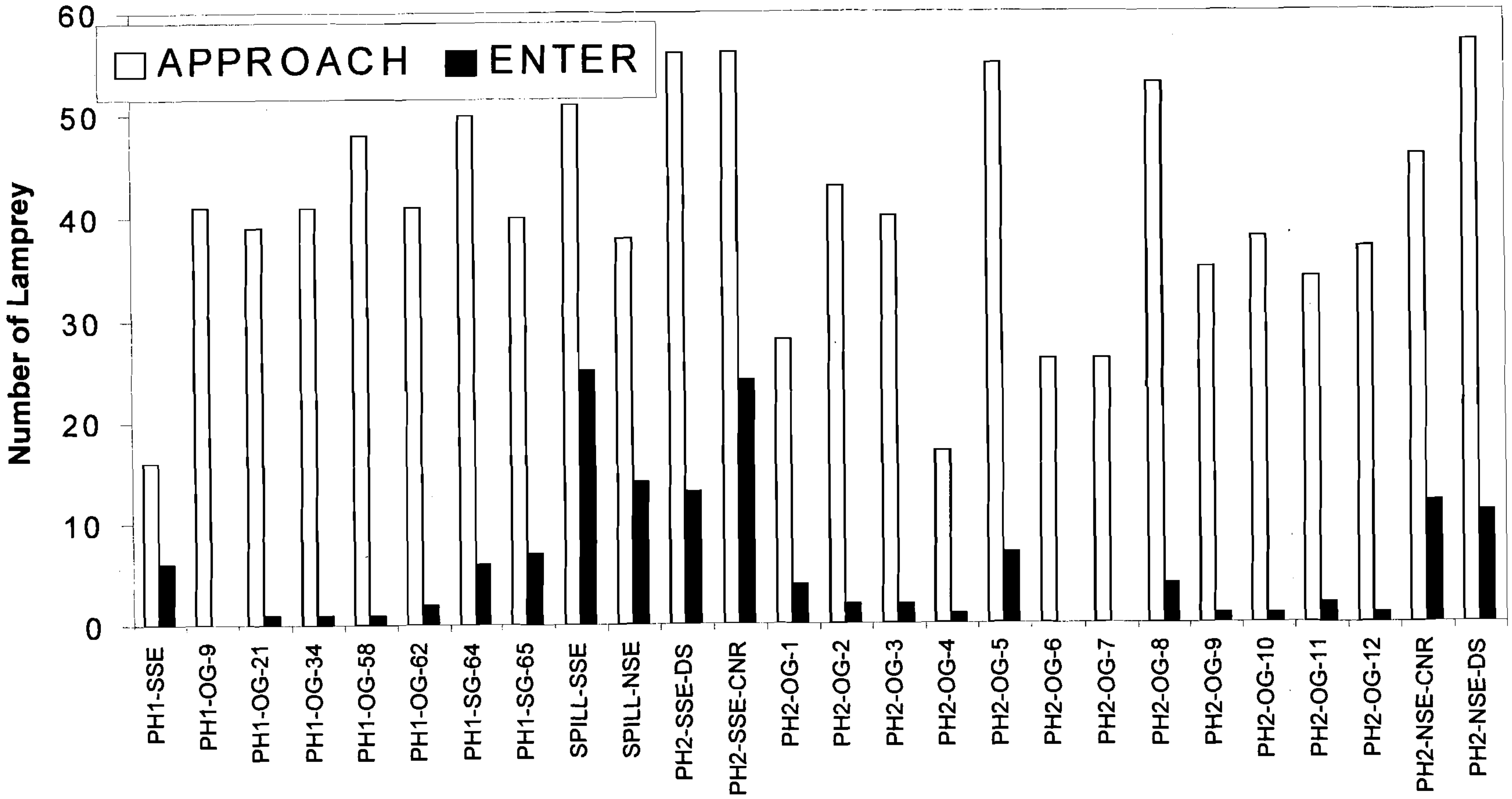

Figure 11. The number of individual lamprey that approached (open bars) and entered (dark bars) at Powerhouse I (PH1), Powerhouse II (PH2), and the spillway (SPILL) entrances at Bonneville Dam in 1997.

We divided the total number of fish that entered at a given location by the number of fish that approached at that location to obtain entrance efficiency (Fig. 12). Entrance efficiency was generally lower at the orifice gates (OG) than at the main powerhouse entrances (PH1-SSE, PH2-SSE, and PH2-NSE) and spillway entrances (Fig. 12). Entrance efficiency at the Bradford Island B-Branch entrance (SPILL-SSE) was higher than the north spillway entrance on Cascades Island (SPILL-NSE). Overall, passage was very similar for lamprey that approached either Powerhouse I or Powerhouse II, but fish that approached the spillway entrances had much lower overall passage success (Table 4). Similarly, Vella et al. (1999) found that most of the fish that entered at the spillway entrances did not ultimately pass over the dam. Overall, entrance efficiency at Powerhouse II (the total number of fish that entered at PH2 entrances divided by the total number of fish that approached PH2 entrances) was higher than overall entrance efficiency at Powerhouse I (Table 4). Although entrance efficiency was highest at the southern main powerhouse entrances, relatively few fish that entered at these locations were detected at the top of the fish ladder. In contrast, fish entering at the north end of both powerhouses were most likely to pass upstream.

These data indicated that lamprey have difficulty negotiating the collection channels. Radio-tagged lamprey dropped out of the collection channel at Powerhouse I 41 times, out of the spillway entrances 70 times, and out of the collection channel at Powerhouse II 180 times. The duration of upstream movements from one end to the other in the collection channel ranged between 9 and 79 minutes (median = 18 minutes). Downstream movement ranged from 3 to 7 minutes (median = 6 minutes). We defined passage efficiency at the collection channels and transition areas as the number of fish that successfully passed through them divided by the number that approached each area (Table 4). While passage efficiency through these areas was low at Powerhouse I (68% of the fish that entered made it through the area inundated by tailwater), even fewer fish were able to negotiate these areas at Powerhouse II (50%) and the Bradford Island B-Branch (16%). Clearly the collection and transition areas represent obstacles to lamprey passage.

Lamprey had moderate passage efficiency through pool and weir areas that were not inundated by tailwater ($\geq$ 75%), but some fish were obstructed at the top of the fishways (Table 4). Of the 30 fish that were detected above the junction of A-Branch and B-Branch of the Oregon-shore fishway, 22 passed upstream above the dam (73%). Similarly, of the 31 fish detected above the juncture of the Washington shore-ladder and the UMT, 26 were able to successfully pass (84%). One radio-tagged fish was detected in the make-up water channel at the top of the Bradford Island ladder, passed into the forebay, and was later detected at The Dalles Dam. The make-up water channel is blocked off by a picketed lead at the downstream end of the channel that was installed to guide larger fish such as salmon and steelhead past the counting window. Lamprey, however, are able to pass through the 2.3-cm-wide openings in the lead (Starke and Dalen 1995). In this area of the fishway, we observed lamprey attempting to pass the dam by climbing up the Tainter gate at the upstream end of the channel. During the peak migration period, five lamprey were observed passing over the gate while the forebay water was at an elevation that allowed water to flow down the gate. The lamprey were following the stream of water up the gate, over the other side, and presumably, into the forebay.

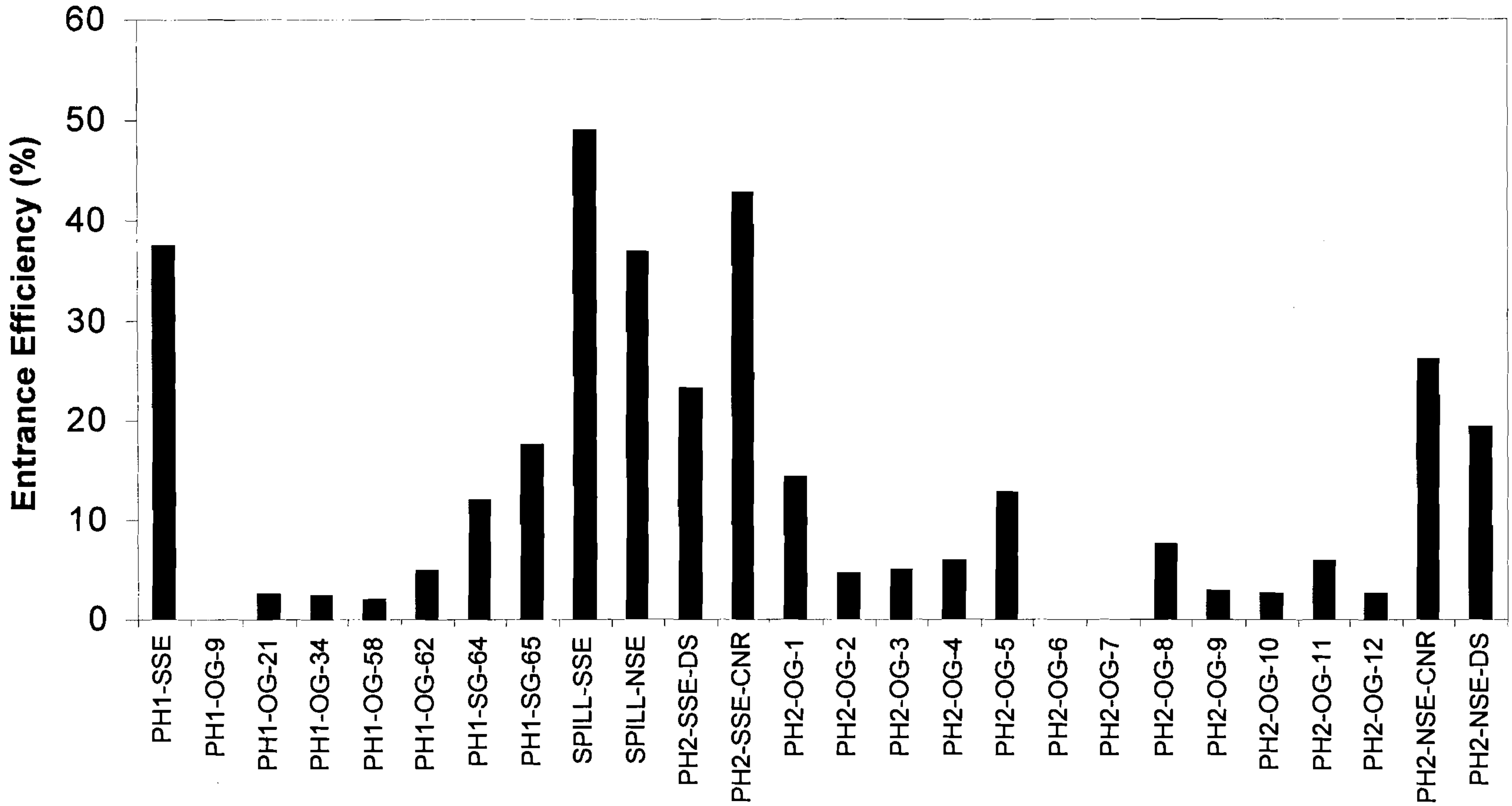

Figure 12. Entrance efficiency (the number of lamprey that entered at each location divided by the number that approached that location) at Powerhouse I (PH1), Powerhouse II (PH2), and the spillway (SPILL) entrances at Bonneville Dam in 1997.

Table 4. The number of lamprey that passed through each area of interest at least once after approaching the Bonneville Dam entrances at Powerhouse I (PH1), Powerhouse II (PH2), the south spillway entrance to B-Branch (Bradford), and the north spillway entrance on Cascades Island (Cascades Island). The approach area was defined as the area outside an entrance where a fish was within detection range of the receiver at that entrance. The collection channel was defined as the area between the entrance and the start of the pools and weirs. The transition area was defined as the section of pools and weirs that were inundated by tailwater. The ladders were defined as the pools and weirs that were not inundated by tailwater. The counting window area included the picketed lead, lighted counting and visitor window region, and the vertical slot fishway at the top of the ladder. Passage efficiency, in (), was defined as the number of fish that successfully passed through each area of interest at least one time divided by the number of fish that approached that area at least one time.

Area of Interest	PH1	PH2	Bradford	Cascades Island
Approach	78	72	51	38
Entrance	47 (60%)	50 (69%)	25 (49%)	14 (38%)
Collection Channel	36 (77%)	30 (60%)	8 (32%)	11 (79%)
Transition	32 (89%)	25 (83%)	4 (50%)	9 (82%)
Ladder	27 (75%)	24 (96%)	3 (75%)	7 (78%)
Count Window	21 (78%)	21 (88%)	1 (33%)	5 (71%)
Overall	(27%)	(29%)	(2%)	(13%)

In 1997, 48 lamprey were detected as they exited the tops of the ladders into the Bonneville Dam forebay and one lamprey was detected as it passed through the navigation lock. In addition, 50 fish were released above Bonneville Dam at Cascade Locks (n = 25) and Stevenson (n = 25) release sites. Of the 49 fish that passed over Bonneville Dam, 29 (59%) were detected in the vicinity of The Dalles Dam and one fell back downstream below Bonneville Dam. The median travel time from the Bonneville Dam forebay to first approach at The Dalles (73 km) was 3.3 days (22.1 km d^{-1}) and ranged from 1.2 to 20.1 days (n = 29). Of the 50 fish released above Bonneville Dam, 41 were detected at The Dalles Dam. Median time for fish released above Bonneville Dam to migrate to the downstream sites at The Dalles Dam was 4.8 days (range 0.3 to 17.8 days). No lamprey were detected at remote receivers located inside tributaries between Bonneville and The Dalles Dams.

Of the 70 fish that were detected in the vicinity of The Dalles Dam, 68 approached the entrances, 59 entered (87%), 48 passed through the collection channels (81%), 38 passed the transition areas (79%), and 35 passed through pools and weirs not inundated by tailwater (92%). Entrance efficiency (the number that successfully entered divided by the number that approached an entrance) was lowest at the north ladder (Washington shore, Fig. 13), but 58% of the fish that entered this fishway successfully passed over the dam and into the forebay (Table 5). In contrast, entrance efficiencies at the south and west ends of the Oregon shore fishway (Fig. 13) were high (93% and 75%) but few fish that entered at these locations successfully passed over the dam (38% and 12%). Most (73%) of the fish that gained entrance to the Oregon shore fishway at the east end of the powerhouse (Fig. 13) successfully passed upstream. These results reflect the low passage success of lamprey in extensive collection channels and transition areas (Table 5).

The overall passage efficiency at The Dalles Dam was 51% (35 passed of the 68 that approached). Median time from detection at The Dalles Dam to first detection inside the collection channel was 0.1 days (range < 0.1 to 17 days). After entering the collection channel, the median time it took lamprey to migrate to the top of The Dalles Dam fish ladder was 1.8 days (range 0.3 to 15.1 days). More fish passed through the fishway on the Oregon shore (n = 24) than on the Washington shore (n =11). This was due primarily to the larger number of approaches at the southern end of the spillway and along the powerhouse at The Dalles (Fig. 13), and the low entrance efficiency at the Washington shore fishway (Table 5). Passage over The Dalles Dam was higher for fish that had been released below Bonneville Dam (55%) and fish that were released above Bonneville Dam (46%).

Of the 35 lamprey that passed over The Dalles Dam, 7 entered the Deschutes River, and all but one of these fish remained in the Deschutes throughout the monitoring period. Three other fish were detected at the mouth of the Deschutes River but did not enter. The median travel time from the top of The Dalles fishways to the mouth of the Deschutes River (20.3 km) was 1.6 days (range = 1.0 - 3.1 d, n = 10). Six of the fish that entered the Deschutes River took between 50 and 61 minutes to travel upstream to the Deschutes River monitoring site (the one remaining fish took 495 min to cover this distance). One fish migrated an additional 70 km up to Sherar's Falls in 4.2 days. No fish were detected in other tributaries between The Dalles and John Day Dams.

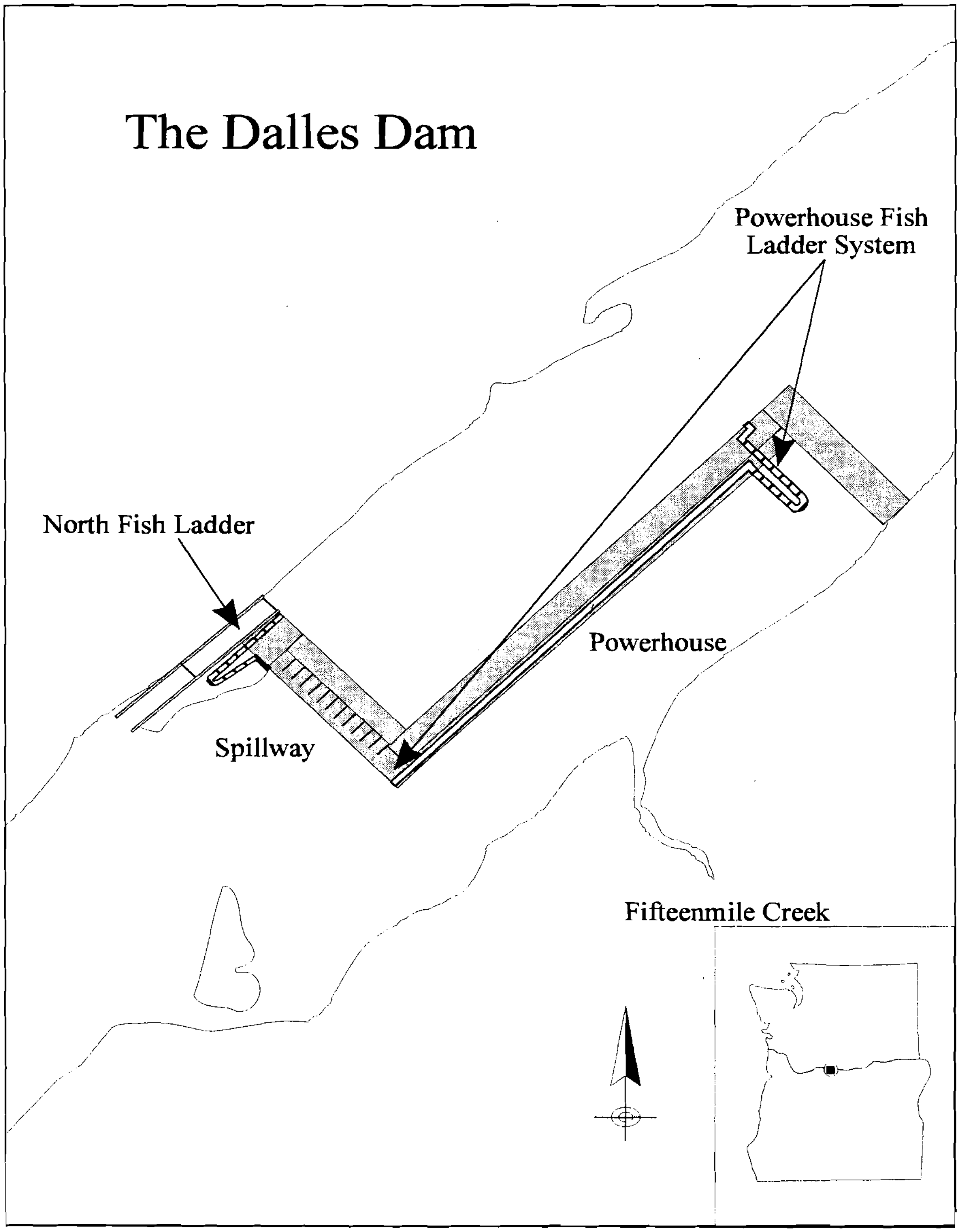

Figure 13. Study area at The Dalles Dam.

Table 5. The number of lamprey that passed through each area of interest at least once after approaching The Dalles fish ladder on the Washington shore (North) or the entrances to the Oregon shore fishway at the south end of the spillway (South), or the west (West) and east (East) ends of the powerhouse. The approach area was defined as the area outside an entrance where a fish was within detection range of the receiver at that entrance. The collection channel was defined as the area between the entrance and the start of the pools and weirs. The transition area was defined as the section of pools and weirs that were inundated by tailwater. The ladders were defined as the pools and weirs that were not inundated by tailwater. For The Dalles, the ladder area included the picketed leads, lighted counting and visitor window region, and the vertical slot fishway at the top of the ladder. Passage efficiency, in (), was defined as the number of fish that successfully passed through each area of interest at least one time divided by the number of fish that approached that area at least one time.

Area of Interest	North	South	West	East
Approach	28	14	32	26
Entrance	19 (68%)	13 (93%)	24 (75%)	22 (85%)
Collection Channel	14 (74%)	8 (62%)	7 (17%)	22 (100%)
Transition	12 (86%)	6 (75%)	5 (71%)	18 (90%)
Ladder	11 (92%)	5 (83%)	3 (60%)	16 (89%)
Overall	(39%)	(36%)	(9%)	(62%)

Of the 28 lamprey that stayed in the main stem of the Columbia River, 23 approached John Day Dam (82% of the fish that passed The Dalles Dam): 8 of the fish released below and 15 of the fish released above Bonneville Dam (Table 6). Median time for fish to migrate from the top of The Dalles fishways to first approach at entrances to the John Day fishways (38.8 km) was 1.8 days or 21.6 km d^{-1} (range = 1.0 - 9.0 days, n = 23). Twenty (87%) of the 23 fish that approached John Day Dam successfully entered the fishways. There were only 3 approaches at the north fish ladder (Washington shore, Fig. 14). All of these fish successfully entered the fishway, but they did not get any further up the fishway and eventually exited into the dam tailrace. Similarly, all fish (n = 2) that approached the north entrance at the powerhouse fishway (Oregon shore, Fig. 14) were able to enter, but none of them passed through the collection channel. In contrast, 20 of 23 fish that approached the south entrance of the Oregon shore ladder (Fig. 14) successfully entered (87%), and 13 of the 20 that entered (65%) were able to pass the collection channel and transition areas. As noted at Bonneville and The Dalles Dams, these data indicate that lamprey had difficulty negotiating the collection channel and lower sections of the fishways. While most of the fish (12 of 13, 92%) passed through the pools and weirs and got above the counting window, only 3 were able to pass through the uppermost part of the ladder and exit into the forebay (only 25% of those that passed the counting window). The cause for low passage at the top of the Oregon shore ladder at John Day Dam was not identified.

Of the three lower Columbia River dams we examined, passage efficiency was lowest at the John Day Dam (3 fish passed of the 23 that approached the dam, 13%). None of the fish released above Bonneville Dam were detected at the top of the John Day Dam ladders and only 3 of the fish released below Bonneville were detected at the top of the John Day ladders (Table 6). Of the fish that fell back out of the John Day Dam fishways below the dam, two migrated to the Deschutes River. One of these fish was detected for the remainder of the study period at Sherar's Falls and the other later returned to the main stem of the Columbia River and was never relocated. Two (67%) of the fish that successfully passed over the John Day Dam were later detected in the McNary Dam study area but did not enter the fishways at the dam (Table 6). Of the three fish that we detected in the John Day pool, two eventually fell back over the John Day Dam. One of these fish was detected near the mouth of the Deschutes River and the other fell back downstream to below Bonneville Dam.

Table 6. Detections of radio-tagged Pacific lamprey released downstream and upstream from Bonneville Dam and the number (percent) that migrated to upstream Columbia River dams.

	Released downstream (n = 147)	Released upstream (n = 50)
Approached Bonneville Dam	130 (88%)	-
Top of Bonneville Dam	49 (38%)	-
Bonneville to The Dalles Dam	29 (59%)	41 (82%)
Top of the Dalles Dam ladders	16 (55%)	19 (46%)
The Dalles Dam to John Day Dam	8 (50%)	15 (79%)
Top of John Day Dam ladder	3 (38%)	0
John Day to McNary Dam	2 (67%)	0
Top of McNary Dam ladders	0	0

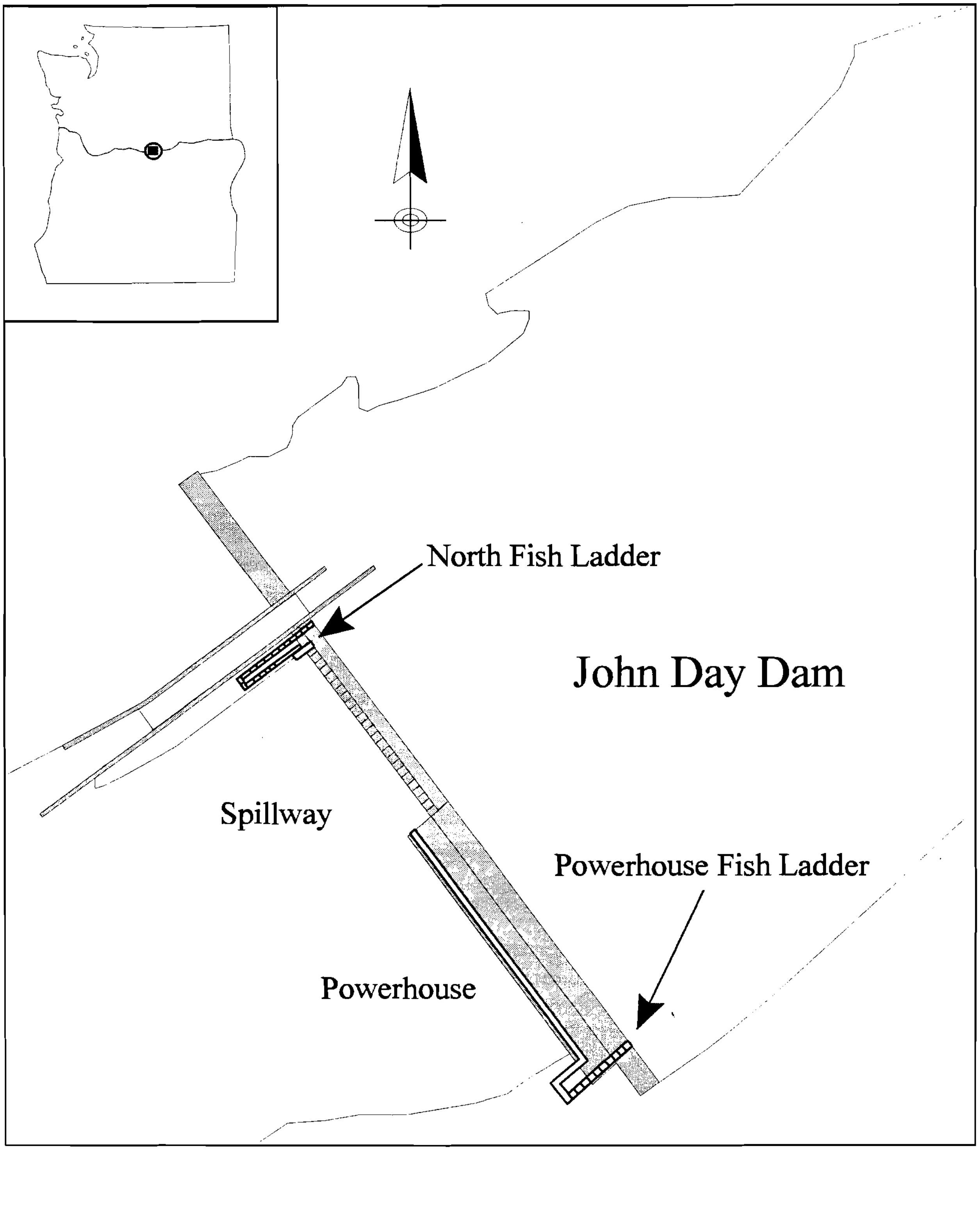

Figure 14. Study area at the John Day Dam.

SUMMARY

Lamprey passage efficiency was low at the lower Columbia River dams we monitored. Of the lamprey that approached each dam, 38% passed Bonneville Dam, 51% passed The Dalles Dam, and 13% passed John Day Dam. Of the lamprey released below Bonneville Dam, 88% returned to the dam following release, indicating that tagging effects were low. The low number of fallbacks over Bonneville Dam (n = 1) and the fact that 82% of the fish released above Bonneville Dam migrated on to the base of The Dalles Dam also indicates that the lamprey were exhibiting directed upstream migration behavior. Moreover, lamprey migration rates through the reservoirs were rapid (22.1 km d^{-1} for the Bonneville pool and 21.5 km d^{-1} for The Dalles pool). These results suggest that low lamprey passage success at the dams was probably due to their inability to negotiate the fishways and not because of tagging effects or low migrational motivation.

Lamprey swimming performance and behavior differ from that of salmonids, for which the fishways were originally constructed. Consequently, lamprey may be obstructed by some parts of the fishways that salmonids have no difficulty negotiating. At all three lower Columbia River dams, lamprey apparently had difficulty moving through collection channels and the pools and weirs inundated by tailwater. Passage was also low at the spillway entrances on Bradford and Cascades Island. Few fish that approached from the spillway at any of the dams were able to successfully pass over. We also documented apparent obstructions to lamprey movement at the top of the ladders and in the vicinity of counting stations.

RECOMMENDATIONS

Several areas in the fishways appear to obstruct lamprey movements. Entrance success and ultimate passage efficiency of lamprey at spillway entrances was low relative to passage at the powerhouses for all dams we examined. Consequently, we recommend modification of the spillway channel entrances so lamprey can better enter the fishways from the spillway. We noted that lamprey accumulate outside these entrances during peak migration periods. A flat surface rather than the current angle-iron surface on the outside of the spillway entrance may aid the passage of lamprey into the fishway by providing more attachment areas. Further study is needed to determine why lamprey fail to negotiate collection channel and transition areas, and why some areas at the tops of the fish ladder apparently obstruct upstream movement. More extensive monitoring of the make-up water channels at the top of the Bonneville Dam fish ladders is also needed. We observed entry of lamprey into this area and their attempts to exit over the Tainter gate. By preventing lamprey from entering the make-up water channel or by providing a passage device in the channels, additional lamprey could be passed into the forebay via this route.

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APPENDIX

Appendix Table A. Location and antenna configuration for fixed-site telemetry monitors at Bonneville Dam, Columbia River. Letters (BO) included with monitor number indicate Bonneville Dam study area.

Monitor Number	Monitor location	River Km	Antenna number	Antenna location
1BO	Tailrace south	234.0	1	Tanner Creek
2BO	Tailrace north	231.9	1	Hamilton Island
3BO	Navigation lock	235.1	1	Bottom of Navigation lock
4BO	PH1 SSE	235.1	1	South shore entrance outside
	PH1 SSE	235.1	2	South shore entrance inside
	PH1 SSE	235.1	3	South shore entrance pool
5BO	OG-9	235.1	1	Orifice gate 9, outside
	OG-9	235.1	2	Orifice gate 9, downstream
	OG-9	235.1	3	Orifice gate 9, upstream
6BO	OG-21, 34	235.1	1	Orifice gate 21, outside
	OG-21, 34	235.1	2	Orifice gate 21, downstream
	OG-21, 34	235.1	3	Orifice gate 21, upstream
	OG-21, 34	235.1	4	Orifice gate 34, outside
	OG-21, 34	235.1	5	Orifice gate 34, downstream
	OG-21, 34	235.1	6	Orifice gate 34, upstream
7BO	OG-58, 62	235.1	1	Orifice gate 58, outside
	OG-58, 62	235.1	2	Orifice gate 58, downstream
	OG-58, 62	235.1	3	Orifice gate 58, upstream
	OG-58, 62	235.1	4	Orifice gate 62, outside
8BO	EG-64, 65	235.1	1	SG-64, outside
	EG-64, 65	235.1	2	SG-64, downstream
	EG-64, 65	235.1	3	SG-65, outside
	EG-64, 65	235.1	4	SG-65, upstream (wall)
	EG-64, 65	235.1	5	SG-65, upstream (rope)
9BO	A/B branch junction pool	235.1	1	A-branch, top ladder (before junction pool)
	A/B branch junction pool	235.1	2	B-branch, top ladder (before junction pool)
	A/B branch junction pool	235.1	3	Upstream of A/B branch junction pool
ABO	Bradford Island	235.1	1	Bradford Island ladder exit
BBO	B-branch entrance	235.1	1	North entrance outside
	B-branch entrance	235.1	2	South entrance outside

Appendix Table A. Continued.

Monitor Number	Monitor location	River Km	Antenna number	Antenna location
BBO	B-branch entrance	235.1	3	Entrance 1,2 inside (wall)
	B-branch entrance	235.1	4	Entrance 1,2 inside (ladder)
CBO	UMT entrance	235.1	1	North entrance outside
	UMT entrance	235.1	2	South entrance outside
	UMT entrance	235.1	3	Entrance 1,2 inside (wall)
	UMT entrance	235.1	4	Entrance 1,2 inside (ladder)
DBO	PH2, SSE	235.1	1	Downstream outside
	PH2, SSE	235.1	2	Downstream inside, south side of channel
	PH2, SSE	235.1	3	Downstream inside, north side of channel
	PH2, SSE	235.1	4	Upstream outside, west side of entrance
	PH2, SSE	235.1	5	Upstream outside, east side of entrance
	PH2, SSE	235.1	6	Upstream inside, west side of entrance
	PH2, SSE	235.1	7	Upstream inside, east side of entrance
EBO	PH2 OG-1, 2	235.1	1	Orifice gate 1, outside
	PH2 OG-1, 2	235.1	2	Orifice gate 1, downstream
	PH2 OG-1, 2	235.1	3	Orifice gate 1, upstream
	PH2 OG-1, 2	235.1	4	Orifice gate 2, outside
	PH2 OG-1, 2	235.1	5	Orifice gate 2, upstream
FBO	PH2 OG-3, 4	235.1	1	Orifice gate 3, outside
	PH2 OG-3, 4	235.1	2	Orifice gate 3, upstream
	PH2 OG-3, 4	235.1	3	Orifice gate 4, outside
	PH2 OG-3, 4	235.1	4	Orifice gate 4, upstream
GBO	PH2 OG-5, 6	235.1	1	Orifice gate 5, outside
	PH2 OG-5, 6	235.1	2	Orifice gate 5, upstream
	PH2 OG-5, 6	235.1	3	Orifice gate 6, downstream
	PH2 OG-5, 6	235.1	4	Orifice gate 6, outside
	PH2 OG-5, 6	235.1	5	Orifice gate 6, upstream
HBO	PH2 OG-7, 8	235.1	1	Orifice gate 7, outside
	PH2 OG-7, 8	235.1	2	Orifice gate 7, downstream
	PH2 OG-7, 8	235.1	3	Orifice gate 7, upstream

Appendix Table A. Continued.

Monitor Number	Monitor location	River Km	Antenna number	Antenna location
HBO	PH2 OG-7, 8	235.1	4	Orifice gate 8, downstream
	PH2 OG-7, 8	235.1	5	Orifice gate 8, outside
JBO	PH2 OG-9, 10	235.1	1	Orifice gate 9, outside
	PH2 OG-9, 10	235.1	2	Orifice gate 9, downstream
	PH2 OG-9, 10	235.1	3	Orifice gate 9, upstream
	PH2 OG-9, 10	235.1	4	Orifice gate 10, outside
KBO	PH2 OG-11, 12	235.1	1	Orifice gate 11, outside
	PH2 OG-11, 12	235.1	2	Orifice gate 11, downstream
	PH2 OG-11, 12	235.1	3	Orifice gate 11, upstream
	PH2 OG-11, 12	235.1	4	Orifice gate 12 outside
	PH2 OG-11, 12	235.1	5	Orifice gate 12, upstream
LBO	PH2 NSE 1,2	235.1	1	NSE downstream outside
	PH2 NSE 1,2	235.1	2	NSE downstream inside, 1
	PH2 NSE 1,2	235.1	3	NSE downstream inside, 2
	PH2 NSE 1,2	235.1	4	NSE upstream outside, 1
	PH2 NSE 1,2	235.1	5	NSE upstream outside, 2
MBO	NSE transition pool 1	235.1	1	Exit from collection channel
	NSE transition pool 1	235.1	2	Exit from NSE upstream, inside
	NSE transition pool 1	235.1	3	Upstream transition pool
	NSE transition pool 1	235.1	4	Upstream transition pool
	NSE transition pool 1	235.1	5	Downstream channel entrance into junction pool
NBO	NSE transition pool 2	235.1	1	Upstream turnpool
	NSE transition pool 2	235.1	2	Mid section
	NSE transition pool 2	235.1	3	Downstream upper turnpool
	NSE transition pool 2	235.1	4	Downstream FERL weir
OBO	UMT/WA ladder junction	235.1	1	UMT channel exit to junction pool
	UMT/WA ladder junction	235.1	2	Washington ladder exit to junction pool
	UMT/WA ladder junction	235.1	3	Above junction pool
PBO	Washington ladder	235.1	1	Washington ladder exit
QBO	Navlock, top	235.1	1	North side

Appendix Table A. Continued.

Monitor number	Monitor location	River Km	Antenna number	Antenna location
QBO	Navlock, top	235.1	2	Middle
	Navlock, top	235.1	3	South side
RBO	Spillway	235.1	1	South, forebay
SBO	Spillway	235.1	1	North, forebay
TBO	Powerhouse I	235.1	1	Ice and trash sluiceway
UBO	Powerhouse II	235.1	1	Ice and trash sluiceway
VBO	A Branch transition pool	235.1	1	Between weirs 17 and 18 (19 ft. elevation)
	A Branch transition pool	235.1	2	Between weirs 25 and 26 (27 ft. elevation)
	A Branch transition pool	235.1	3	Between weirs 33 and 34 (35 ft. elevation)
WBO	B Branch transition pool	235.1	1	Between weirs 12 and 13 (13 ft. elevation)
	B Branch transition pool	235.1	2	Between weirs 20 and 21 (21 ft. elevation)
	B Branch transition pool	235.1	3	Between weirs 31 and 32 (32 ft. elevation)
XBO	UMT Entrance transition pool	235.1	1	Between weirs 5 and 6 (10 ft. elevation)
	UMT Entrance transition pool	235.1	2	Between weirs 11 and 12 (16 ft. elevation)
	UMT Entrance transition pool	235.1	3	Between weirs 18 and 19 (23 ft. elevation)
	UMT Entrance transition pool	235.1	4	Between weirs 30 and 31 (34 ft. elevation)