U.S. Army Corps of Engineers
Portland District

Passage Behavior of Radio-Tagged Subyearling Chinook Salmon at Bonneville Dam Associated with the Surface Bypass Program, 2000

Annual Report

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Submitted to:

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Contract No. W66QKZ00200128

Submitted:

August 2001

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Executive Summary

In 1994, the U.S. Army Corps of Engineers (COE) initiated a program to develop and evaluate surface-oriented juvenile salmonid bypass systems at hydroelectric dams on the Columbia and Snake rivers. The goal of the program was to develop juvenile bypass systems that would significantly improve the passage efficiency and survival of juvenile salmonids during their downstream migration. In 1998 a prototype surface collector (PSC) was installed at Bonneville Dam's first powerhouse. The PSC was designed not to bypass fish around the turbines but rather to examine fish behavior and hydraulics at the entrances and to determine the efficacy of surface bypass at B1 before building a full production surface bypass system.

In 1998 and 1999, our radio telemetry evaluation indicated that only 27-49% of the fish that came within 6 m of the entrances entered the PSC. We also determined that a 6 m entrance width was more efficient than a 1.5 m entrance width. In 2000, the PSC was extended to include turbines 1-6 and each of the six entrances was 6 m wide. To continue our evaluation of the PSC in 2000, we used radio telemetry to examine the movements and behavior of subyearling chinook salmon *Oncorhynchus tshawytscha* in the forebay of Bonneville Dam. The objectives of this research were to: 1) determine the behavior, distribution, and approach patterns of subyearling chinook salmon in the forebay areas of Bonneville Dam; 2) determine the time and route of dam passage of subyearling chinook salmon; 3) determine movement patterns and behavior of subyearling chinook salmon in the vicinity of the PSC; and 4) assess the efficiency and effectiveness of the PSC.

From 20 June to 21 July 2000, we radio-tagged and released 1188 subyearling chinook salmon. Fish were released from two locations upstream of Bonneville Dam: The Dalles Dam, and Hood River, Oregon. Mean river discharge at Bonneville Dam during the study period was 173.8 kcfs. Median travel rate from release to Bonneville Dam was 2.3 km/h for fish released from both The Dalles Dam and Hood River bridge, resulting in travel times of 34.6 h and 18.2 h, respectively. Of all the fish released, we detected 69% at Bonneville Dam; of the fish released at The Dalles Dam, we detected 55%; and of the fish released from Hood River, we detected 90%. Median residence time was shortest at the spillway (7.2 min) compared to 1.8 h and 2.1 h at B1 and B2, respectively.

Passage routes were determined for 88% of subyearling chinook salmon detected at Bonneville Dam. The spillway passed the most fish (69.5%), followed by B1 (30%) and B2 (0.5%). Of the fish that passed at B1, 68% passed into the sluiceway, 23% passed directly through the turbines, and 9% were guided into the downstream salmonid migration channel (DSM) via the turbine intake screens. All four fish that passed at B2 entered the turbine intakes; one was guided and three were unguided. At the spillway and B2, a higher proportion of fish passed during night compared to day. In contrast, a lower proportion of fish passed during night compared to day at B1.

Of the fish that entered the B1 forebay, 72% were detected within 6 m of the PSC and were therefore considered to have discovered the PSC. Of the fish that discovered the PSC, 67% entered the PSC. However, of the fish that entered the PSC, only 41% (59 of 143) entered via the entrance they were first detected at without meandering to one or more entrances. In relation to units 1-6, the PSC was quite efficient at collecting fish. Of

the fish that passed at units 1-6, (guided, unguided, and sluiceway) 81% entered the PSC. The PSC was also relatively effective compared to water passing into the turbines and the spillway. An effectiveness of 2.5 indicated that the percentage of fish that entered the PSC out of total passage at units 1-6 was 2.5 times the percentage of water that entered the PSC. When compared to spillway effectiveness (1.2), PSC effectiveness was over twice as high. Since fish that entered the PSC could pass through other routes, the PSC was not considered an actual passage route for purposes of calculating passage metrics such as FPE. However, if the PSC were an actual passage route, FPE would have increased from 91% to 94%.

1.0 Introduction

Years of research have been allocated to ensure the long-term survival of salmon and steelhead stocks in the Columbia River basin. Much of this research has focused on the effects of dams and reservoirs on juvenile salmonids as they migrate from their natal waters to the ocean. Raymond (1968, 1979) and Park (1969) showed migration times increased after dam construction, and suggested this may be detrimental to juvenile salmonid survival.

Reservoir drawdown, flow augmentation, spill, improved turbine bypass systems, surface collection, and transportation systems have been identified as potential management actions to improve juvenile salmonid passage and survival, thereby assisting the recovery of dwindling anadromous fish stocks in the Snake and Columbia rivers. One option being evaluated is surface collection. In 1995, the National Marine Fisheries Service (NMFS) identified development and testing of the surface bypass collection concept in the "Reasonable and Prudent Measure 11" of the Biological Opinion as a necessary measure for continued operation of the federal hydropower system (NMFS 1995). In response, the U.S. Army Corps of Engineers installed a prototype surface collector (PSC) at Bonneville Dam's first powerhouse.

Observations at several Columbia River dams have shown that migrating fish will tend to use shallow water passage structures instead of deeper turbine or spillway routes. The most successful example is at Wells Dam, where the spill bays are located above the turbines. Hydroacoustic studies of juvenile salmonid passage at Wells Dam indicated 90% of the fish passed through spillway intake baffles that use only 7% of the total discharge (Johnson et al. 1992). Research at other dams corroborates the effectiveness of near-surface flows in passing juvenile salmonids. Giorgi and Stevenson (1995) reviewed passage studies at The Dalles Dam and found that during non-spill conditions, 40 to 55% of juvenile salmonids approaching the dam passed through the ice and trash sluiceway, a surface-oriented passage route. Swan et al. (1995) discovered that even during spill conditions, about 50% of radio-tagged juvenile chinook salmon passed via the sluiceway at Ice Harbor Dam. Based on the natural tendency of out-migrating juvenile salmonids to travel near the surface of the water and the apparent success of surface collection at other dams, many have concluded that near-surface flow nets may be an effective alternative for passing juvenile salmonids.

During 2000, we used biotelemetry to evaluate the efficacy of surface bypass collection at Bonneville Dam. Our objectives were to:

- Determine the behavior, distribution, and approach patterns of juvenile salmonids in the forebay areas of Bonneville Dam.

- Determine species-specific differences in the time and route of dam passage.

- Assess species-specific differences in movement patterns and behavior in the vicinity of the PSC.

- Assess the efficiency and effectiveness of the PSC.

2.0 Methods

2.1 Study Area

Bonneville Dam is located on the Columbia River at river km 233. The dam consists of two powerhouses and a single spillway, each separated by an island. Powerhouse one (B1) consists of 10 turbine units and is located at the south side of the river, spanning from the Oregon shore to Bradford Island. Powerhouse two (B2) consists of eight turbine units and is located at the north side of the river, spanning from Cascade Island to the Washington shore. The spillway lies between Cascade and Bradford islands and has 18 spill gates. A navigation lock is located at the south end of B1 (Figure 1).

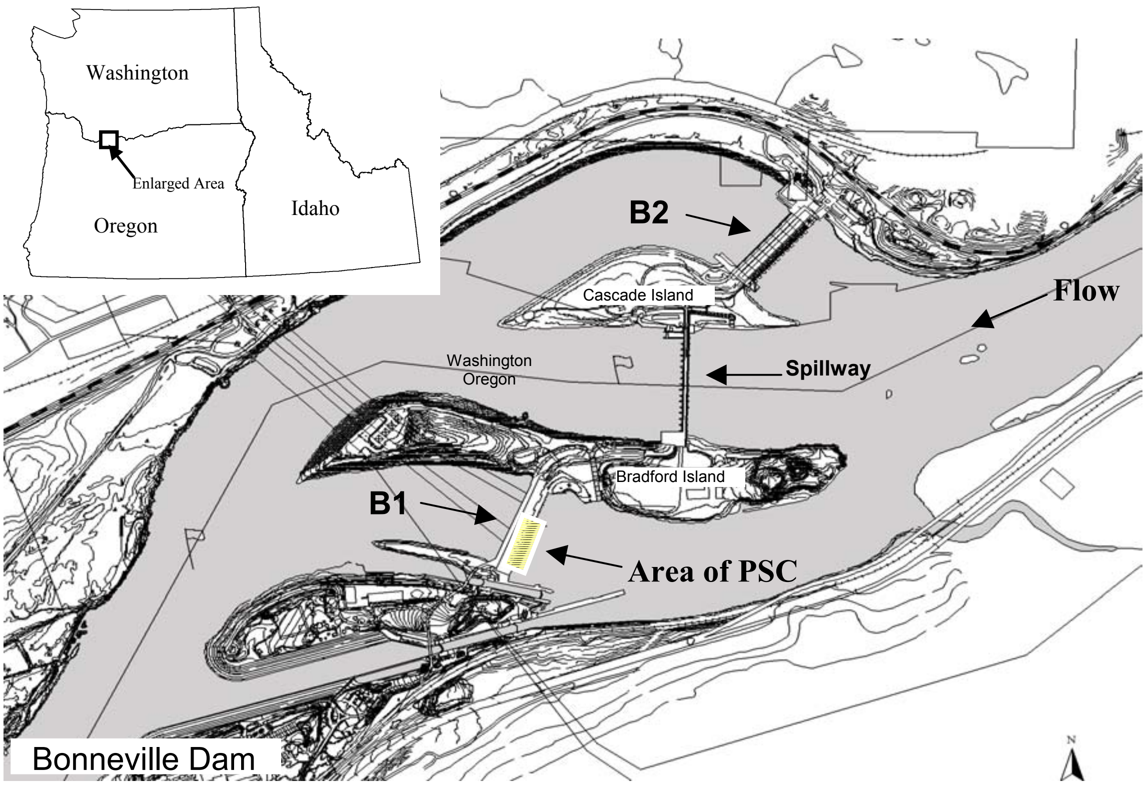


Figure 1. Plan view of Bonneville Dam on the Columbia River, showing the area of the Prototype Surface Collector (PSC) at Bonneville's first powerhouse (B1), the spillway, and Bonneville's second powerhouse (B2).

2.2 Prototype Surface Collector

The Prototype Surface Collector (PSC) was retrofitted to the upstream face of B1 at turbines 1-6. The entrances to the PSC were located in front of the middle (B) intake of each unit and consisted of vertical slots, 6 m wide x 12-14 m deep depending upon forebay level (mean forebay elevation was 22 m in 2000). Fish that entered the PSC could migrate through the structure and into the sluiceway or turbine intake. The PSC was not designed to bypass fish around the turbines. Rather, its purpose was for examining fish behavior and hydraulics at the entrances and determining the efficacy of surface bypass at B1 before building a full production surface bypass system (Figures 1 and 2). Since fish that entered the PSC could pass through other routes, the PSC was not considered an actual passage route for purposes of calculating passage metrics such as FPE. However, we did calculate $FPE_{w/PSC}$ using fish that entered the PSC to show how a fully functional collector (i.e., a collector that bypasses fish around the turbines) might affect FPE. Eventual passage routes of fish that entered the PSC were not included in estimates of $FPE_{w/PSC.}$

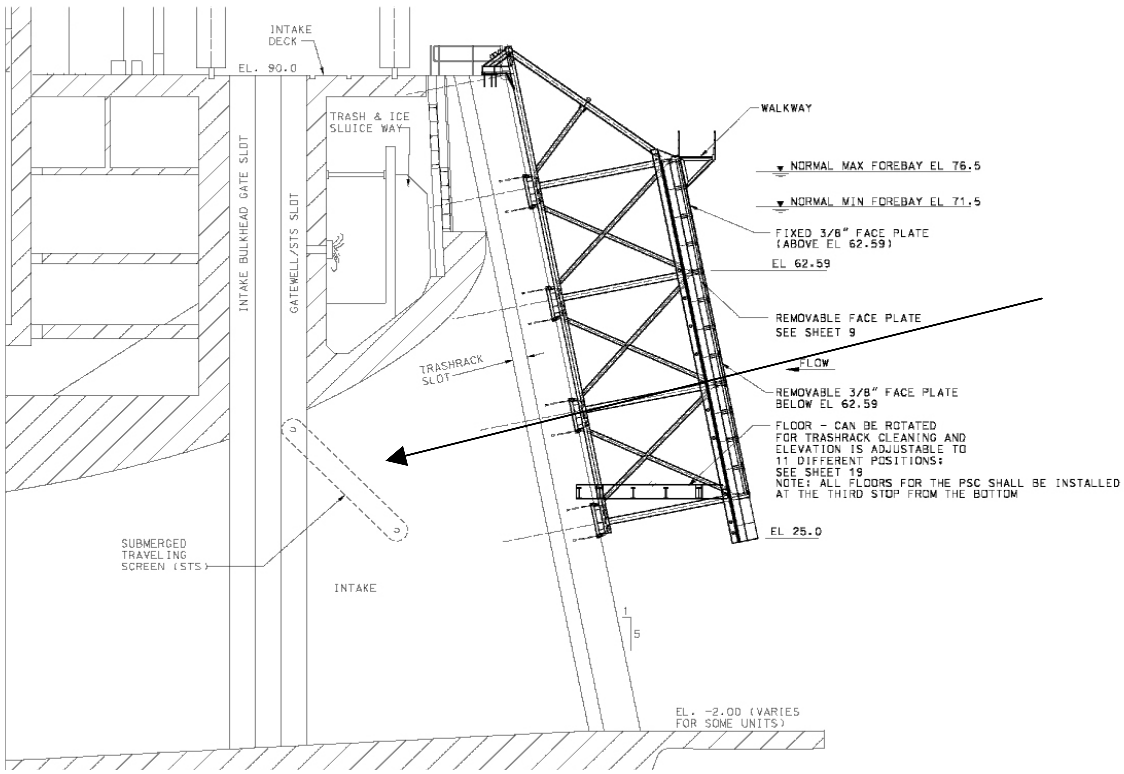


Figure 2. Side view of the PSC in front of turbine units 1-6 at B1. Arrow shows direction of flow through the PSC and into the turbine intakes.

2.3 Fixed Receiving Equipment

Fifty-four aerial antennas, and 255 underwater dipole antennas were linked to 21 Lotek SRX-400 receivers, eight Lotek DSP-500 digital spectrum processors, and two Multiprotocol Telemetry Acquisition Systems (MITAS; Grant Systems Engineering, Newmarket, Ontario). Each receiver could monitor a maximum of eight aerial antennas. Digital spectrum processor/receiver combinations, and MITAS were used to monitor underwater antennas. The combination of these technologies allowed us to monitor approach behavior and passage through Bonneville Dam.

Aerial antennas were positioned along the periphery of the forebay to detect fish within about 100 m of the dam face (Figures 3 and 4). Aerial antennas were connected to Lotek SRX-400 (Lotek Engineering, Newmarket, Ontario) data logging receivers, programmed to monitor a total of 18 frequencies. Two aerial antenna monitoring configurations were used depending on location: auxiliary/master switching or combined antennas. The auxiliary/master switching configuration was used in the forebay of both powerhouses and at entrance stations where signal acquisition time was longer, and more spatial resolution was required. Combined antenna configurations were used at the spillway and tailrace exit stations where signal acquisition time was limited and less spatial resolution was needed. In addition to combining antennas to reduce scan time, the scan time (a function of the number of frequencies being monitored) was reduced by half by using an extra receiver at each of the tailrace sites. Reducing scan time is beneficial because it increases the probability of detecting transmitters.

Underwater dipole and stripped co-ax antennas had a limited range (about 6 m) compared to aerial antennas (100 to 300 m depending on transmitter depth, receiver gain, and number of elements). Underwater antennas allowed us to obtain fine-scale fish behavior information by limiting the range of signal detection.

The six receivers monitoring the B1 sluiceway, B2 STSs, B2 DSM, and B2 sluice chute were coupled with digital spectrum processors. These receivers had essentially no scan time because DSPs acquire signals over a 1 MHz bandwidth almost instantaneously. Using DSPs was necessary to document fish passage in turbulent hydraulic environments because signal acquisition time is limited.

Four stripped co-ax antennas were positioned mid-channel in the B1 sluiceway at units 1B, 1C, 2A, and 2B to monitor sluiceway passage through B1. Two dipole antennas were mounted on the bottom frame of each STS at B2. These screen

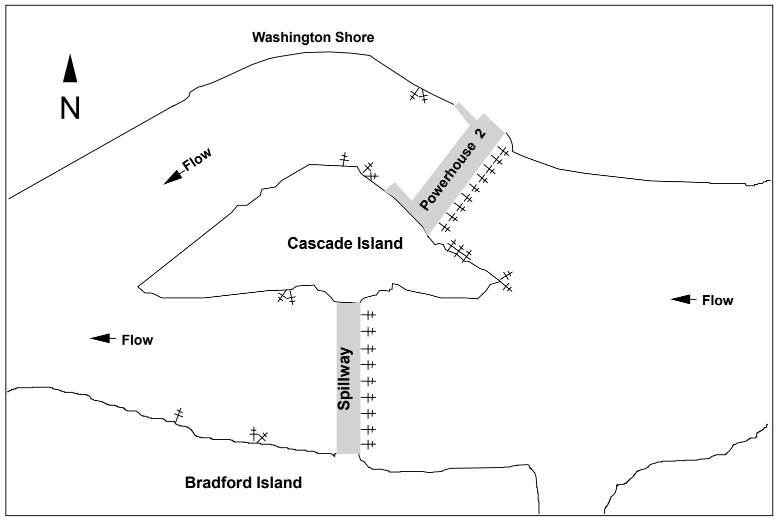


Figure 3. Plan view of aerial antenna coverage at the spillway and Bonneville's second powerhouse (B2), summer 2000.

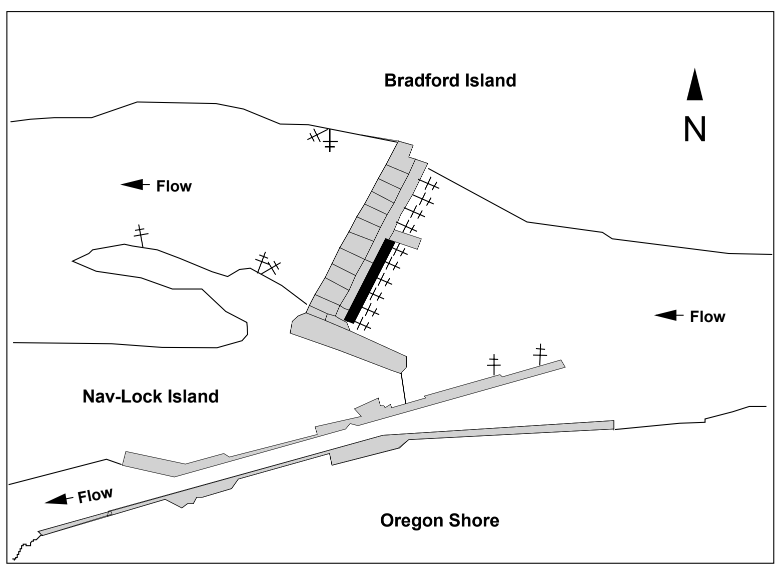


Figure 4. Plan view of aerial antenna coverage at Bonneville's first powerhouse (B1), summer 2000.

antennas were then combined to provide turbine specific passage information. Eight stripped co-ax antennas located at each "C-slot" turbine gatewell orifice monitored passage through the DSM at B2. A single aerial and stripped co-ax antenna positioned at the entrance to the B2 sluice chute measured fish passage in the chute.

Two MITASs were used at B1 to enhance monitoring at the PSC, the STSs, and the DSM. Each MITAS was capable of simultaneously monitoring up to 50 antenna inputs with greater multiple transmitter recognition than either the SRX-400 or SRX/DSP combination. Although each MITAS was limited to a maximum of 50 inputs, each input could be a horizontal or vertical combination of multiple underwater dipole or stripped co-ax antennas. In addition to its enhanced signal recognition, the MITAS's data displays and on screen diagnostics increased the robustness of the system compared to an SRX or SRX/DSP combination. These features allowed the user to identify problems in real-time and avoid potential data loss that would not be apparent until post-processing.

At B1, 42 underwater antennas linked to one MITAS monitored the PSC and an additional 20 underwater antennas linked to a second MITAS monitored the DSM and traveling screens. Underwater antennas on the PSC were located upstream of turbines 1-6 on the face (external), entrances, and inside (internal) the PSC. External and entrance underwater antennas were stratified across three depths: 4 m, 9.5 m, and 15 m and provided depth distribution information (Figure 5.). The top entrance antennas measured fish movement between 0 and 6.5 m and the middle antennas covered the 6.5 to 13 m depth range. The bottom antennas assisted in identifying fish that traveled under the PSC. Ten underwater dipole antennas per PSC unit (60 total) were deployed inside the PSC and combined vertically (across depth) to one MITAS antenna (internal array) per PSC unit (6 total). Internal PSC antennas were used to determine when fish entered and exited the PSC.

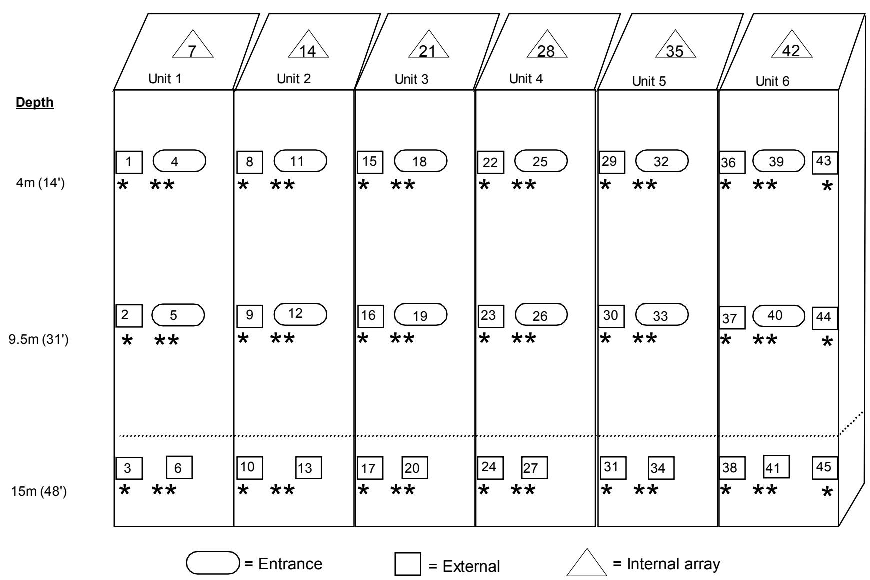


Figure 5. Front view of PSC showing location of underwater antennas. Dotted line indicates the location of the PSC's internal floor.

Ten stripped co-axial antennas were located inside the DSM at B1 (one at each "C-slot" gatewell orifice of each turbine) to measure guided fish passage (i.e., fish directed by guidance screens). Turbine passage monitoring at B1 was similar to that at B2 with the exception of the ESBSs located at unit eight. These dipole antennas were mounted on the backside of the tip of the screen rather than the bottom of the screen frame.

Regardless of the type of monitoring technology used, a standard input signal of known value was used to determine the signal strength reaching each receiver. All aerial antennas were amplified in close proximity to the receiving antenna and transmission line amplification was used as needed to insure signal quality. Underwater amplification was not used; however, underwater antenna transmission lines were amplified as soon as they reached the deck elevation. Over-amplified signals were attenuated down to a standard level. These efforts insured that all antennas within and among arrays were equally sensitive, and resulted in a balanced receiving system.

2.4 Transmitters

Pulse-coded transmitters developed by Lotek Engineering Inc., (Lotek) were implanted in subyearling chinook salmon. Newly developed transmitters called Nano tags were used in fish released from The Dalles Dam. Nano tags were 15 mm long x 6.8 mm wide x 5 mm tall and weighed 0.85 g in air. Since Lotek could supply only a limited number of Nano tags, we used a slightly larger transmitter in fish released from Hood River bridge. Those transmitters were 7.3 mm (diameter) x 18 mm and weighed 1.4 g in air. The antenna length was 30 cm and the pulse rate was 2.0 s, resulting in an estimated minimum tag life of 8 d for both transmitters.

2.5 Tagging, Fish Handling, and Release

Subyearling chinook salmon were collected at John Day Dam's Juvenile Fish Bypass Facility and Bonneville Dam's Downstream Salmonid Migrant Channel (DSM) located at B1. Fish were released into the Columbia River at The Dalles Dam and Hood River, OR.

Although fish were collected, tagged, and released at different locations, the fish handling, tagging, and release methods were standardized as much as practical. The following description is concerned only with fish collected at Bonneville Dam and released at Hood River, Oregon. A detailed description of the fish released at The Dalles Dam can be found in Beeman et al. (2000).

We collected subyearling chinook salmon from the DSM at B1. Pacific States Marine Fisheries Commission's (PSMFC) Smolt Monitoring Program operated the fish trap while USGS employees sorted and identified fish. Fish were collected between 1600 and 2400 hours. The fish trap was operated between 5 and 20 min depending on the quantity of fish that were needed. Fish were sorted and identified using methods developed by PSMFC. Fish to be radio-tagged were held 24 h in 127 L plastic holding containers at a density no greater than 30 fish/container and were supplied with flow-through river water.

All fish were gastrically implanted with a radio transmitter using procedures similar to those described in Adams et al. (1998). Fish were anesthetized using tricaine methanosulfate (MS-222) at 50 mg/L of fresh water. Once a fish started to lose equilibrium it was weighed, measured and tagged. Immediately following, fish were placed in a 19 L plastic recovery container and supplied with bottled oxygen. After about 10 min, fish were transferred into a 127 L plastic container at a density no greater than 4 fish/container and were supplied with flow-through river water. Fish were held between 18 and 24 h before release.

Before transportation to the release site, each holding container was checked for mortalities, regurgitated tags, and tag functionality. Fish were transported from the juvenile bypass facility to the Hood River Marina and loaded onto a boat. All fish were released at mid-channel just below the Hood River Bridge (rkm 273). Transportation time from the facility to the marina was about 35 minutes. Releases occurred during day (1000 – 1200 hours) and night (2200 – 2400 hours) to enable tagged fish to mix spatially and temporally with untagged fish in the river before passing the dam. The release location 40 km upstream allowed fish about 10-20 h to adjust to temperature and hydraulic conditions in the reservoir before reaching the forebay and encountering the dam.

2.6 Data Management and Analysis

Fixed receivers were typically downloaded every other day. These data and data collected by MITAS were backed up daily and imported into SAS (version 8.1; SAS Institute Inc., Cary, North Carolina, USA) for subsequent proofing and analysis. Data were manually proofed to eliminate non-valid records including: environmental noise, single records of a particular channel and code, records that were collected prior to the known release date and time, and records suspected to be fish that were predated by avian or aquatic predators. The minimum number of records required to consider a detection of a radio-tagged fish as valid was two detections within 1 min of each other.

The route and time of a fish's entrance into the near-dam area was determined by the location and time an individual fish was first detected by aerial or underwater antennas on the dam face or PSC. Similarly, the last detection of an individual fish by aerial or underwater antennas on the dam face, on the traveling screens, or within either DSM or sluiceway, was considered the route and time of passage through the dam. Data collected from tailrace exit stations were used to assign passage among dam areas (i.e., B1, B2, or spillway) for fish not detected in the forebay, but were excluded from analyses of more specific passage locations (e.g., DSM, turbine, and sluiceway).

Residence time in the near-dam area, defined as the amount of time between the first and last detections in the forebay, was calculated for each radio-tagged fish detected in the near-dam area. Residence times were not calculated for fish that were only detected at the entrance and exit stations. Calculated residence times were a minimum estimate of the actual time that radio-tagged fish spent in the near-dam area because of receiving equipment limitations and detection probabilities. In other words, fish may have been in the forebay prior to their first detection and following their last detection. Additionally, fish that approached very deep may have had limited detection histories or may have passed the dam undetected.

Following are definitions of metrics calculated to measure passage behavior of radio-tagged fish at Bonneville Dam:

- Spillway efficiency (SE) = $\dfrac{SP}{(B1 + SP + B2)}$
- Spillway effectiveness (SF) = $\dfrac{SE}{F_{sp} / F_{tot}}$
- Fish guidance efficiency (FGE) = $\dfrac{G_{tot}}{(G_{tot} + UG_{tot})}$
- Fish passage efficiency (FPE) = $\dfrac{SP + SL + G_{tot}}{TOT_{pass}}$

Where:

SP = Total number of fish passing the spillway
SL = Total number of fish passing the sluiceway or sluice chute
B1 = Total number of fish passing B1
B2 = Total number of fish passing B2
G_{tot} = Total number of guided fish
UG_{tot} = Total number of unguided fish
TOT_{pass} = Total number of fish passing the project (B1+SP+B2)
F_{sp} = Average discharge (kcfs) through the spillway during the study period.
F_{tot} = Average discharge (kcfs) through the project (B1+SP+B2) during the study period

The following are definitions of metrics used to measure behavior of radio-tagged fish relative to the PSC at Bonneville Dam:

- PSC discovery efficiency (DE) = $\dfrac{W_{1-6}}{T}$
- PSC entrance efficiency ($EE_{1\text{-}6}$) = $\dfrac{P_{1-6}}{W_{1-6}}$
- PSC collection efficiency ($CE_{1\text{-}6}$) = $\dfrac{C_{1-6}}{(C_{1-6} + U_{1-6})}$

- PSC passage effectiveness (PF) = PE / $\frac{F_{psc}}{(F_{psc} + F_u)}$

- Fish Passage Efficiency (FPE) with the PSC ($FPE_{w/PSC}$) = $\frac{SP + SL + G_{tot} + C_{1-6}}{TOT_{pass}}$

  Note: Passage routes of fish that entered the PSC are not included in calculation of $FPE_{w/PSC.}$

- Diel passage into PSC = # of fish entering PSC in day (0500-2059) vs. # of fish entering PSC at night (2100-0459).

Where:

SP = Total number of fish passing the spillway
SL = Total number of fish passing the sluiceway or sluice chute
G_{tot} = Total number of guided fish
TOT_{pass} = Total number of fish passing the project (B1+SP+B2)
T = Total number of fish entering B1 forebay
W_{1-6} = Total number of fish detected within six meters of PSC entrances 1-6
C_{1-6} = Total number of fish detected inside the PSC (units 1-6)
U_{1-6} = Total number of fish passing under the PSC (units 1-6; # Guided + # Unguided)
F_{psc} = Average discharge (kcfs) into the PSC
F_u = Average discharge (kcfs) under the PSC into units 1-6

3.0 Results

3.1 Tagging

From 20 June to 21 July 2000, we radio-tagged and released 1188 subyearling chinook salmon; 489 were released from Hood River (rkm 315) and 699 were released from The Dalles Dam (rkm 356). Fish were released throughout the central portion of the "in-river" seaward migration period (Figure 6). For fish released at Hood River, mean fork length was 125.8 mm, mean weight was 21.8 g, and the radio tag represented 3.9% of mean weight. Of the 506 subyearling chinook salmon collected at Bonneville Dam, one (0.2%) regurgitated its tag and 13 (2.6%) died during the 24-hour holding period. A tagging summary for fish released at The Dalles Dam is reported by Beeman et al. (2000).

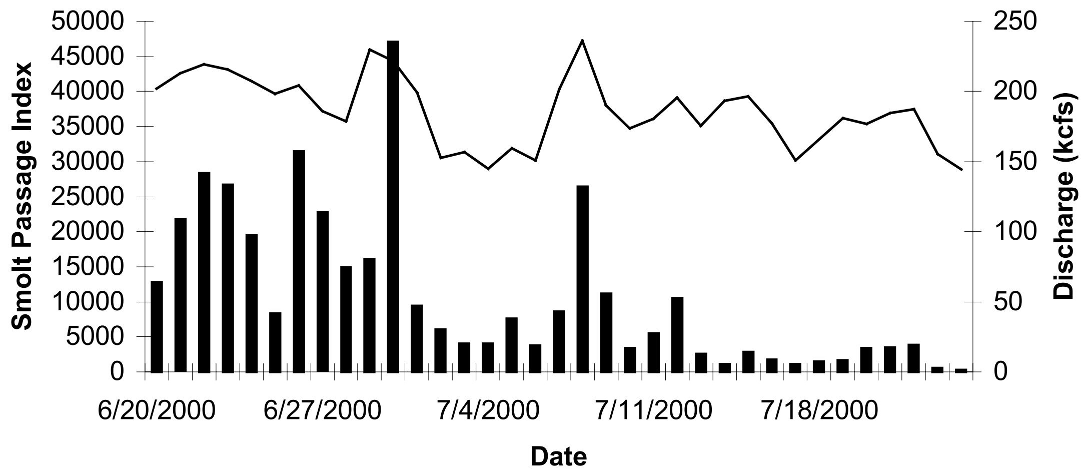


Figure 6. Mean daily river discharge through Bonneville Dam and the Smolt Passage index from Bonneville Dam's Second Powerhouse (B2) fish collection facility for subyearling chinook salmon during summer 2000. Smolt index data were acquired from the Fish Passage Center web page at www.fpc.org. Discharge data were obtained from G. Ploskey (October 26, 2000).

3.2 River Discharge and Project Operations

During summer 2000 (June 20 – July 24), mean river discharge at Bonneville Dam was 173.8 kcfs, and ranged from 133.4 kcfs to 215.5 kcfs. Over the study period, mean daily discharge fluctuated, but tended to decrease. Allocation of mean river discharge among dam areas was 54% through spill, 40% through B1, and 6% through B2 (Figure 7 and Table 1). Spill averaged 94.4 kcfs and ranged from 61.7 to 120.2 kcfs. Mean daily spill was above 80 kcfs on all but one day during the study and increased to between 100 and 120 kcfs for 2 to 6 consecutive days on 4 occasions. Spill occurred 24 h/d. Mean daily discharge at B1 (turbines 1–10) was 68.5 kcfs and ranged from 26.2 to 95.9 kcfs. Similar to spill, mean daily discharge through B1 fluctuated during the study. However, the pattern of fluctuation of discharge through B1 was nearly identical to the pattern of fluctuation of mean daily river discharge. At B2, mean daily discharge was relatively stable, with a mean of 10.9 kcfs, minimum of 3.6 kcfs and a maximum of 43.4 kcfs (Figure 8).

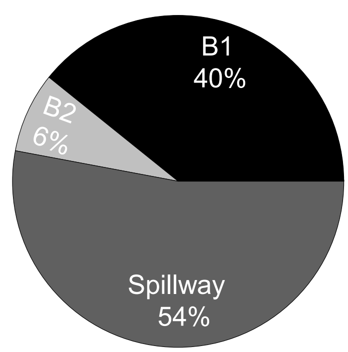


Figure 7. Discharge allocation between dam areas at Bonneville Dam during summer 2000.

Table 1. Discharge (kcfs) at Bonneville Dam from 27 April – 6 June 2000. Values have been rounded to the nearest tenth. Data obtained from G. Ploskey (October 26, 2000).

Dam Area	Mean	Median	Min	Max
B1	68.5	69.6	26.2	95.9
B2	10.9	5.9	3.6	43.4
Spillway	94.4	88.3	61.7	120.2
Total	173.8	173.8	133.4	215.5

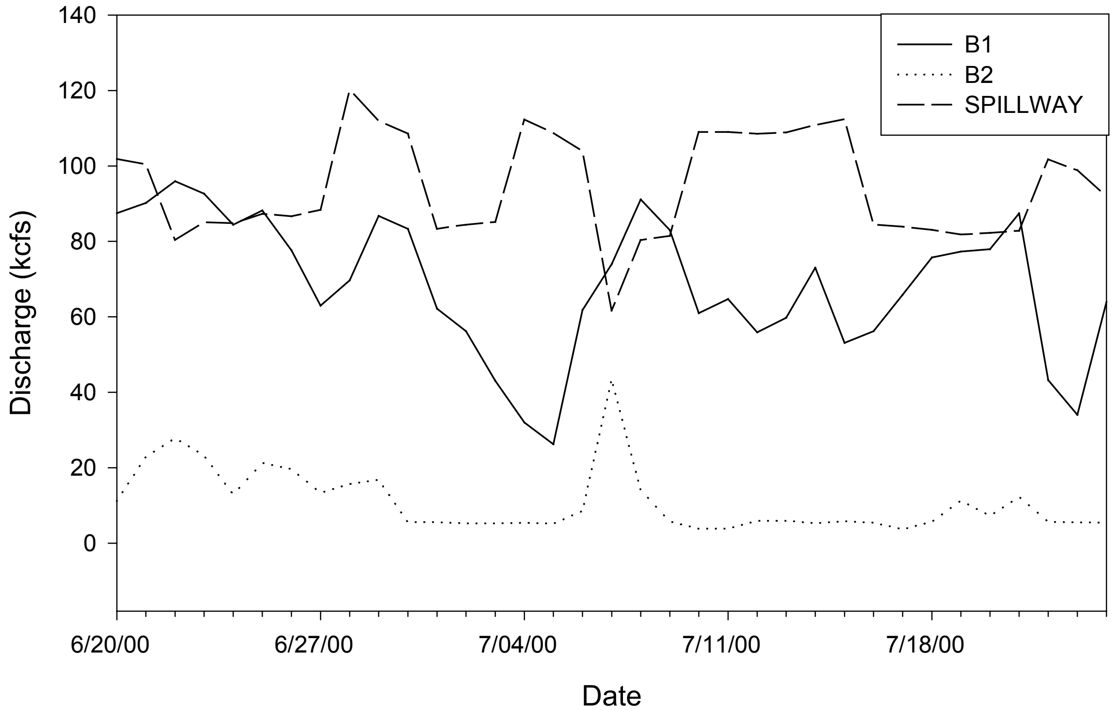


Figure 8. Mean daily discharge at Bonneville Dam, by area, from 20 June- 24 July 2000.

Turbines 1-6 represented 66% and turbines 7-10 represented 34% of the mean discharge at B1 (Figure 9). Although the fluctuations in mean daily discharge at turbines 1-6, and turbines 7-10, all corresponded with fluctuations in mean daily river discharge, mean daily discharge by turbine unit revealed considerable differences in discharge between turbine units. Differences in daily turbine discharge were observed for multiple turbines throughout the study at turbines 1-6 (at the PSC) and turbines 7-10 (Figures 10 and 11).

In relation to the PSC, we compared mean discharge through turbines 1-6 and found that about 33% (mean 15.2 kcfs) of the discharge flowed through the PSC and into turbines 1-6 and the remaining 67% (mean 31.4 kcfs) flowed under the PSC directly into turbines 1-6 (Figure 12 and Table 2). We compared mean discharge between day and night and found that discharge at B1 and B2 was slightly higher during day (from 0500 to 2159 hours) than during night (from 2200 to 0459 hours). At the spillway, discharge was 7% higher during night (Table 3).

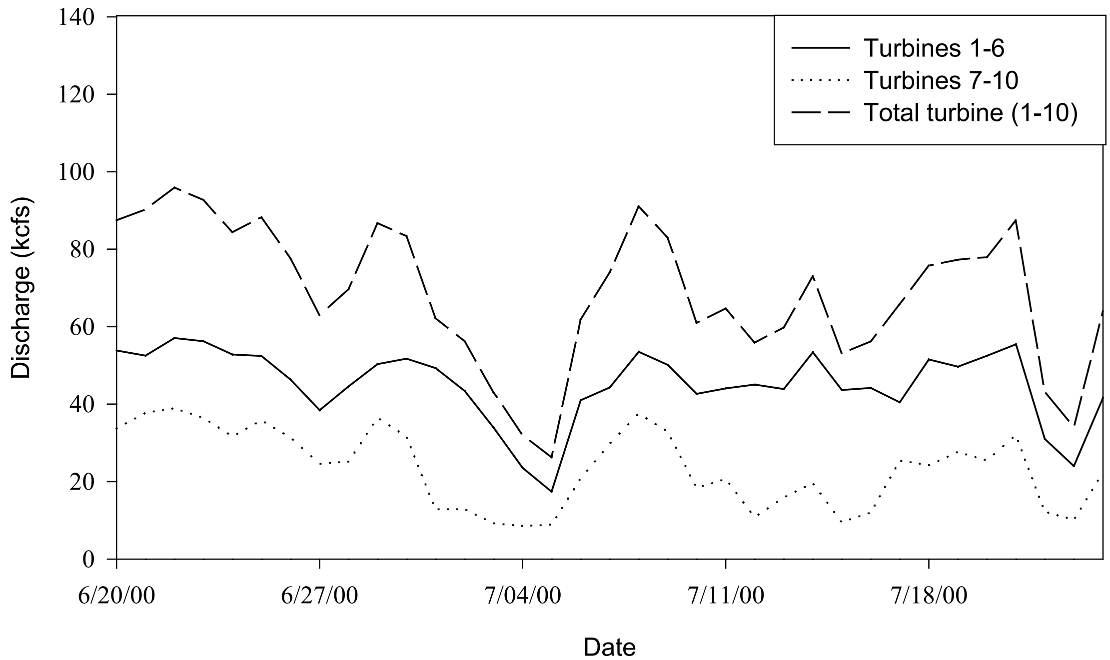


Figure 9. Mean daily discharge through turbines 1-6 and turbines 7-10 during a 35-day test period from 20 June - 24 July 2000. Data obtained from G. Ploskey (October 26, 2000).

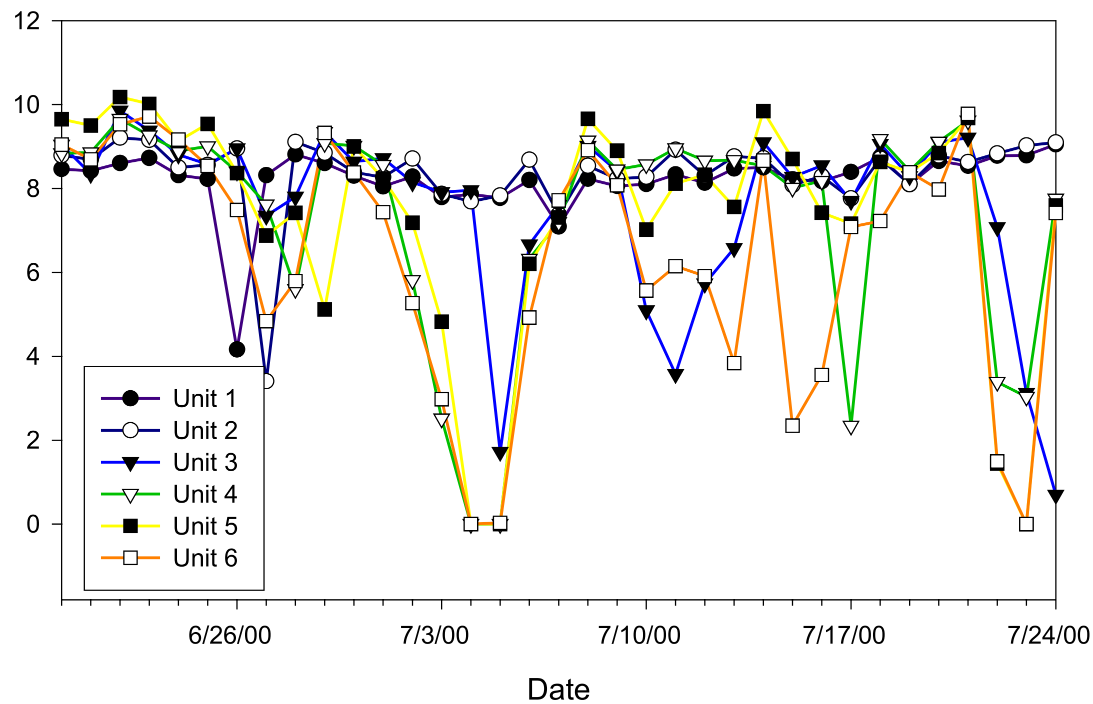


Figure 10. Mean daily discharge, by unit, for turbines 1-6 at Bonneville Dam during summer 2000.

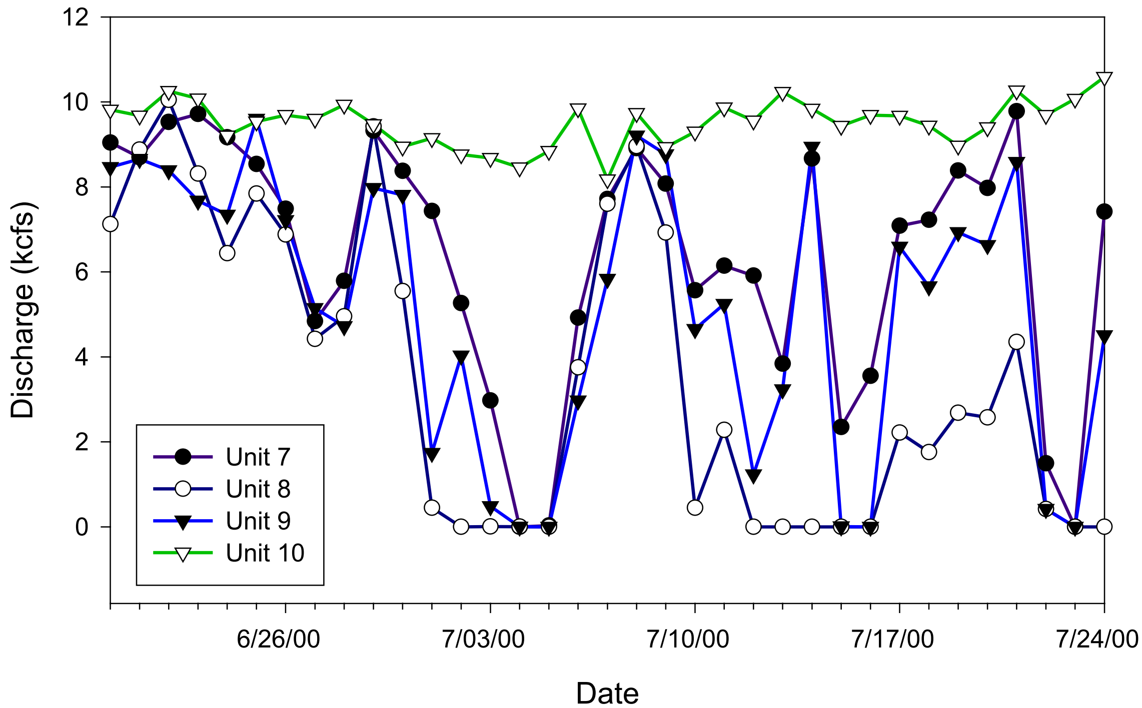


Figure 11. Mean daily discharge, by unit, for turbines 7-10 at Bonneville Dam during summer 2000.

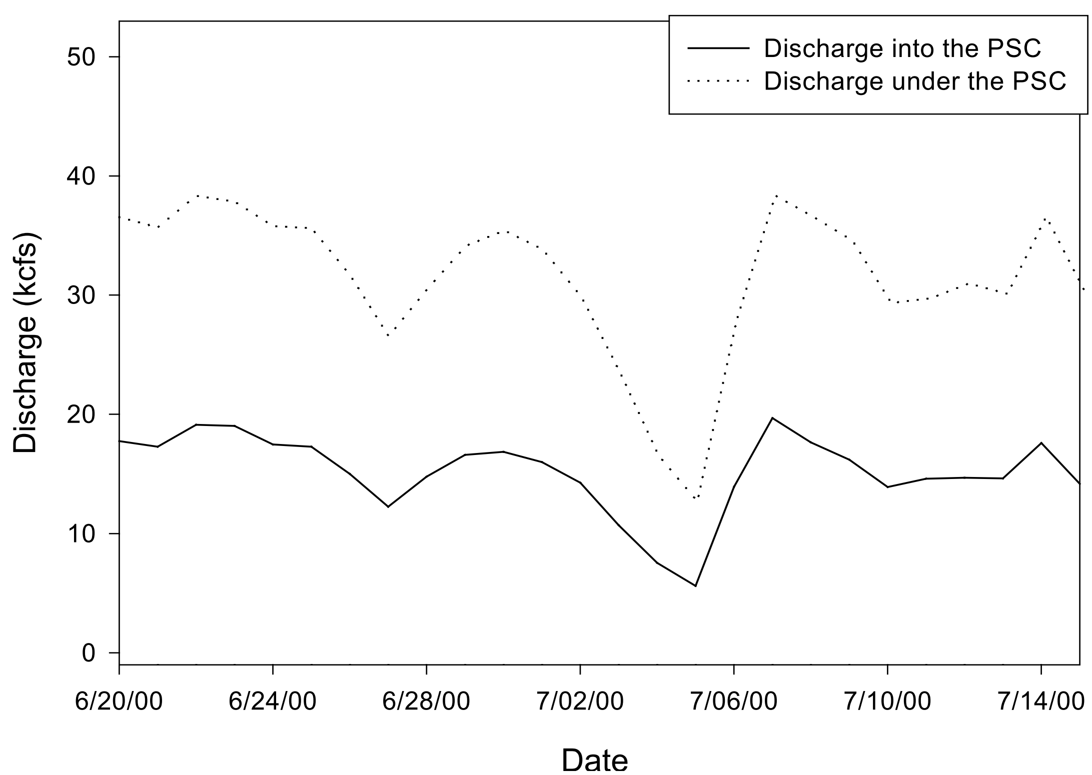


Figure 12. Mean daily discharge into and under the PSC (units 1-6) from 20 June-15 July 2000. Data obtained from G. Ploskey (October 26, 2000). PSC flow data after July 15 was unavailable.

Table 2. Mean discharge (cfs) into and under the PSC from June 20 through July 15, 2000. Data obtained from G. Ploskey (October 26, 2000). PSC flow data after July 15 was unavailable.

Into PSC at turbine unit	Mean	Median	Min	Max
Total into the PSC	15,170.0	15,500.0	5610.0	19,680.0
Unit 1	2702.3	2731.5	1323.7	3498.7
Unit 2	2769.8	2849.1	1115.8	3157.4
Unit 3	2638.4	2771.4	551.7	4029.5
Unit 4	2330.0	2676.1	0.0	3098.2
Unit 5	2658.7	2864.4	0.0	3772.1
Unit 6	2074.5	2264.9	0.0	3646.9
Under PSC at turbine unit	**Mean**	**Median**	**Min**	**Max**
Total under the PSC	31,370.0	32,690.0	12,600.0	38,300.0
Unit 1	5681.6	5745.9	2927.3	6775.4
Unit 2	5737.2	5909.9	2375.6	6312.5
Unit 3	5392.8	5810.5	1298.8	7437.5
Unit 4	4923.2	5690.4	0.0	6273.0
Unit 5	5252.9	5741.4	0.0	7116.4
Unit 6	4377.8	5012.4	0.0	6960.3

Table 3. Mean discharge (kcfs) during day (0500-2159) and night (2200-0459) by dam area from June 20 through July 24, 2000. Data obtained from G. Ploskey (October 26, 2000).

Dam Area	Period	Percent (of mean)	Mean	Median	Min	Max
B1	Day	40%	71.6	77.2	0	110.1
B2	Day	8%	13.4	5.9	0	91.4
Spillway	Day	52%	92.0	99.5	0	133.4
B1	Night	36%	64.4	65.8	0	105.9
B2	Night	5%	8.7	5.6	0	69.7
Spillway	Night	59%	107.5	109.4	0	133.4

3.3 Travel to and Arrival at Bonneville Dam

Subyearling chinook salmon traveled from release to Bonneville Dam at similar rates regardless of their release site. The median travel rate from release to first detection at Bonneville Dam was 2.3 km/h for fish released from both The Dalles Dam and Hood River. Corresponding median travel times from release to first detection at Bonneville Dam were 32.5 h for fish released from The Dalles Dam and 16.7 h for fish released from Hood River (Table 4).

Table 4. Descriptive statistics for travel time (h) and travel rate (km/h) to Bonneville Dam by release site for radio-tagged subyearling chinook salmon, during summer 2000. Travel rates are represented within parenthesis.

Release Site	Mean	Median	STD	Min	Max
The Dalles Dam	34.6 (2.3)	32.5 (2.3)	7.4 (0.5)	20.9 (1.0)	77.8 (4.9)
Hood River Bridge	18.2 (2.3)	16.7 (2.3)	6.7 (0.5)	11.3 (0.6)	67.6 (3.5)

A comparison of first detections by dam area (i.e., B1, B2, and spillway) revealed differences between the proportions of fish entering each dam area. Of the fish detected in the forebay, 38% (265 of 696) first entered B1, 2% (12 of 696) first entered B2, and 60% (419 of 696) first entered the spillway. To investigate, we compared the proportion of mean daily discharge through each dam area to the daily proportion of radio-tagged fish that entered each dam area. At B1 and the spillway, daily proportions of fish fluctuated somewhat with the proportion of daily discharge (Figure 13). The higher proportion of discharge at the spillway compared to B1 and B2 was likely the largest contributing factor to the higher number of fish entering the spillway forebay. Extremely low discharge at B2 resulted in very few fish entering that dam area.

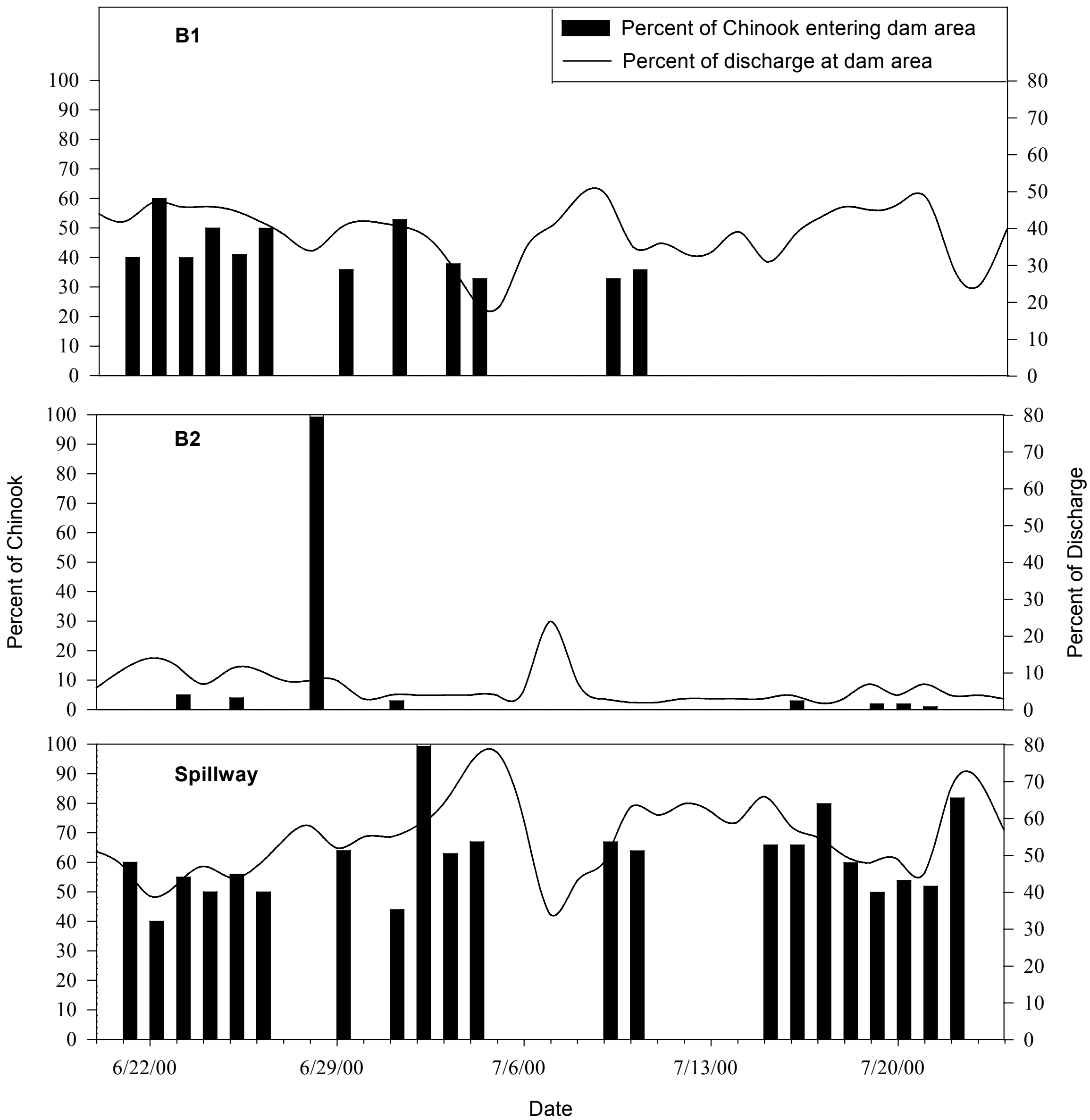


Figure 13. The percentage of subyearling chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by day during summer 2000.

Similarly, we compared the proportion of fish entering each dam area by hour to the proportion of mean discharge through each dam area by hour and found some relation. Fish entered both B1 and the spillway during all hours of the diel cycle. More fish entered the spillway due to its higher discharge. However, more fish entered B1 during midday (1100-1300 hours) even though the spillway had higher discharge than B1 during that time. Most fish entered the spillway during the crepuscular period (0500 and 2200 hours), which corresponded with increased discharge (Figure 14). These data provide an example of the influence daily patterns in dam operations had on the destination of fish in the forebay of Bonneville Dam.

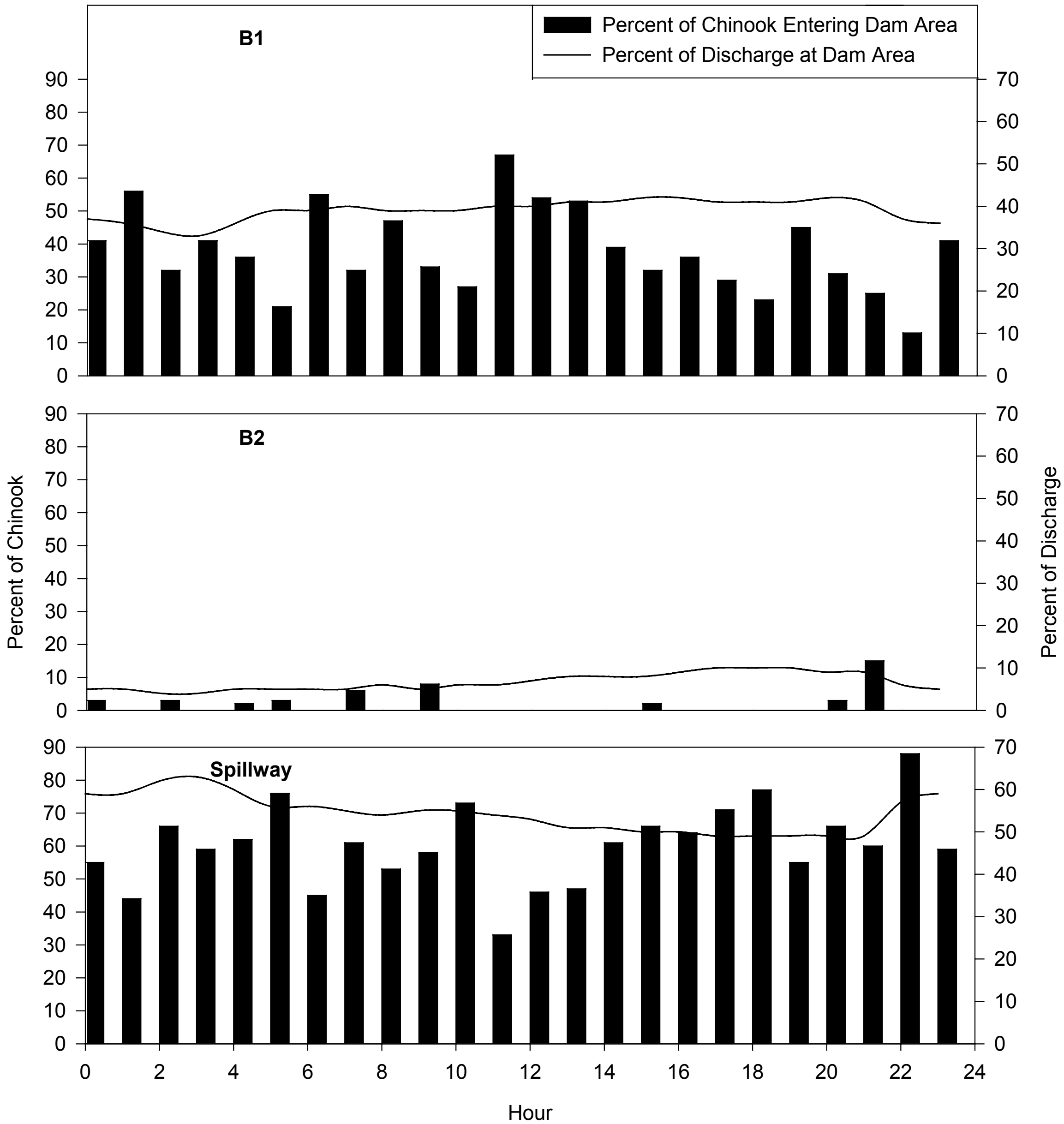


Figure 14. The percentage of subyearling chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by hour of day during summer 2000.

3.4 Detections at Bonneville Dam

At Bonneville Dam, we detected 69% (824 of 1188) of the subyearling chinook salmon that were released from The Dalles Dam and Hood River. We detected 55% (383 of 699) of the fish released at The Dalles Dam and 90% (441 of 489) of the fish released at Hood River.

3.5 Residence Time in the Forebay

Forebay residence time differed between dam areas. Subyearling chinook salmon resided considerably longer in the forebay of B1 (median = 1.8 h) than the spillway (median = 7.2 min). Median residence time at B2 (2.1 h) was slightly higher than residence time at B1; however, only four fish were detected at B2 (Table 5). We compared median forebay residence time by day of passage, by hour of passage, and by hour of arrival to mean daily discharge and found no relation (Appendix 1, 2, and 3).

Table 5. Descriptive statistics of forebay residence time (hours) for radio-tagged subyearling chinook salmon by dam area at Bonneville Dam during summer 2000. Fish that passed at a dam area different than the one they first entered were excluded from calculations of residence time.

Dam Area	N	Mean	Median	Std	Min	Max
B1	230	3.68	1.84	5.21	0.01	45.32
B2	4	3.72	2.05	3.05	1.86	7.24
Spillway	388	0.22	0.12	0.45	0.01	6.03
All areas	621	1.52	0.20	3.61	0.01	45.32

3.6 Route and Time of Passage Through Bonneville Dam

We determined the route of passage through Bonneville Dam for 88% (721 of 824) of subyearling chinook salmon detected at Bonneville Dam. Nine percent (77 of 824) passed the dam but a passage route could not be determined. Three percent (26 of 824) were not detected below Bonneville Dam. Among the three dam areas at Bonneville, the spillway passed the most (69.5%) subyearling chinook salmon, followed by B1 (30%) and B2 (0.5%; Figure 15). At B1, of the fish with known passage routes, 68% (145 of 214) passed via the sluiceway, 23% (50 of 214) passed unguided through the turbines, and 9% (20 of 214) were guided into the DSM. An additional 47 fish passed B1 through an undetermined route. Of the few fish that passed at B2, 75% (3 of 4) passed unguided through the turbines and 25% (1 of 4) were guided into the DSM (Figure 15).

Passage through Bonneville Dam occurred throughout the diel cycle (Figure 16). The greatest percentage of subyearling chinook salmon passed at sunrise (0500 hours) and the lowest percentage of fish passed between 0800 and 1100 hours. Route-specific and species-specific patterns were evident in regard to the diel cycle. At the spillway, a higher proportion of fish passed during night compared to day. In contrast, a lower proportion of fish passed during night at B1. All fish (n = 4) at B2 passed during the night (Table 6).

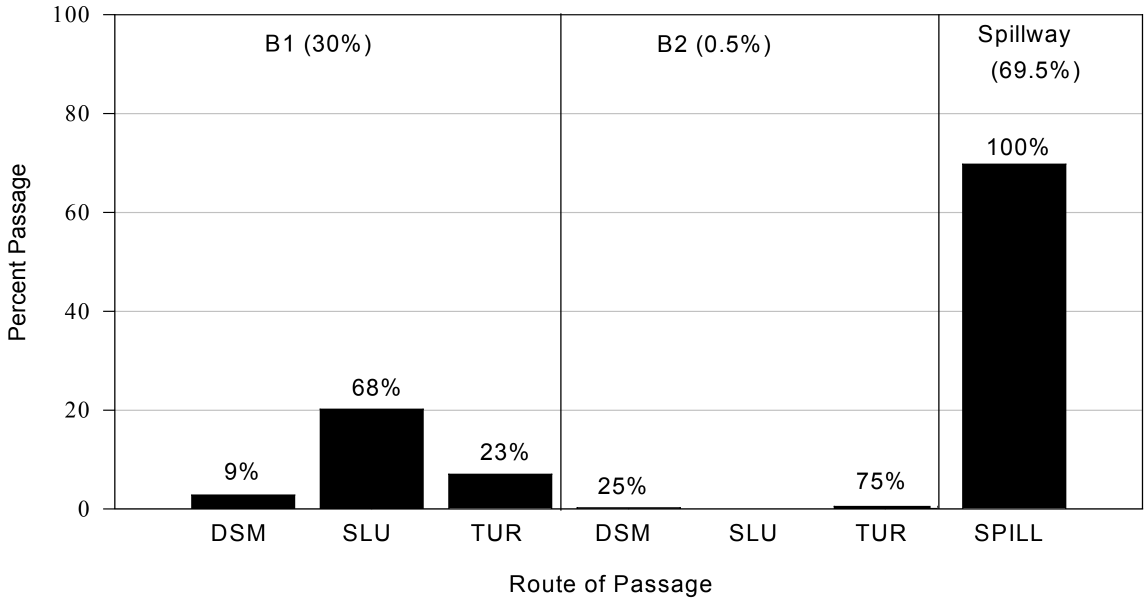


Figure 15. Percent fish passage through Bonneville Dam by dam area and route for subyearling chinook salmon during summer 2000. Percentages within parenthesis designate proportions between dam areas, percentages without perenthesis designate proportions within dam area, and the percent value of the bars represent proportions of all passage routes at the project.

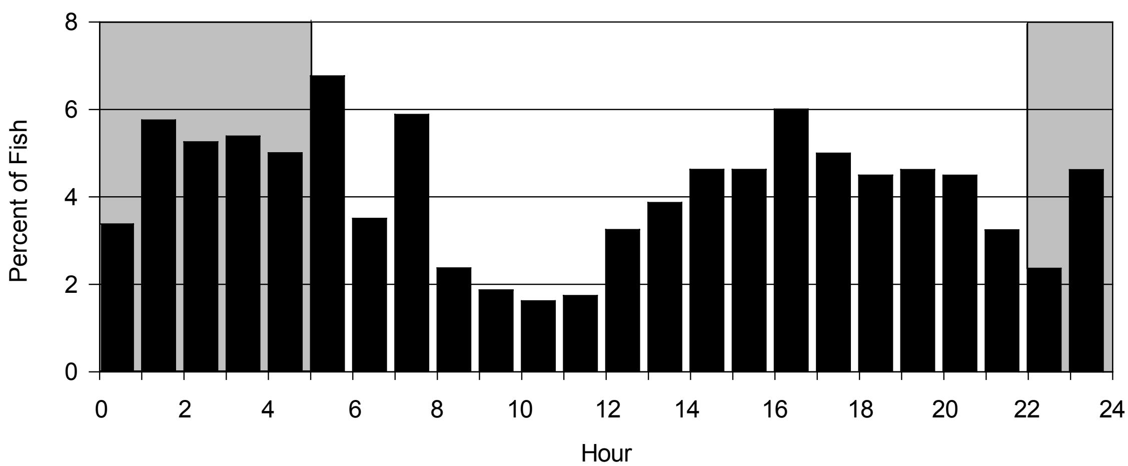


Figure 16. Percentage of subyearling chinook salmon that passed Bonneville Dam by hour of day during summer 2000. Shaded areas represent nighttime (2200 to 0459 hours) and unshaded areas represent day (0500 to 2159 hours).

Table 6. The proportion of radio-tagged subyearling chinook salmon that passed each dam area of Bonneville Dam by day (0500 to 2159 hours) versus night (2200 to 0459 hours), during summer 2000.

Period	B1 Passage	B2 Passage	Spill Passage
Day	32% (160 of 493)	0% (0 of 493)	68% (333 of 493)
Night	24% (55 of 228)	2% (4 of 228)	74% (169 of 228)

A general pattern observed was that the shallower the passage route, the more fish passed during the day. Thirty-nine percent more fish passed through the sluiceway at B1 during the day. Likewise, at B1 during daylight hours, a greater proportion of fish were guided into the DSM. At night, a greater proportion of fish passed unguided through the turbines at B1 and B2 (Figure 17).

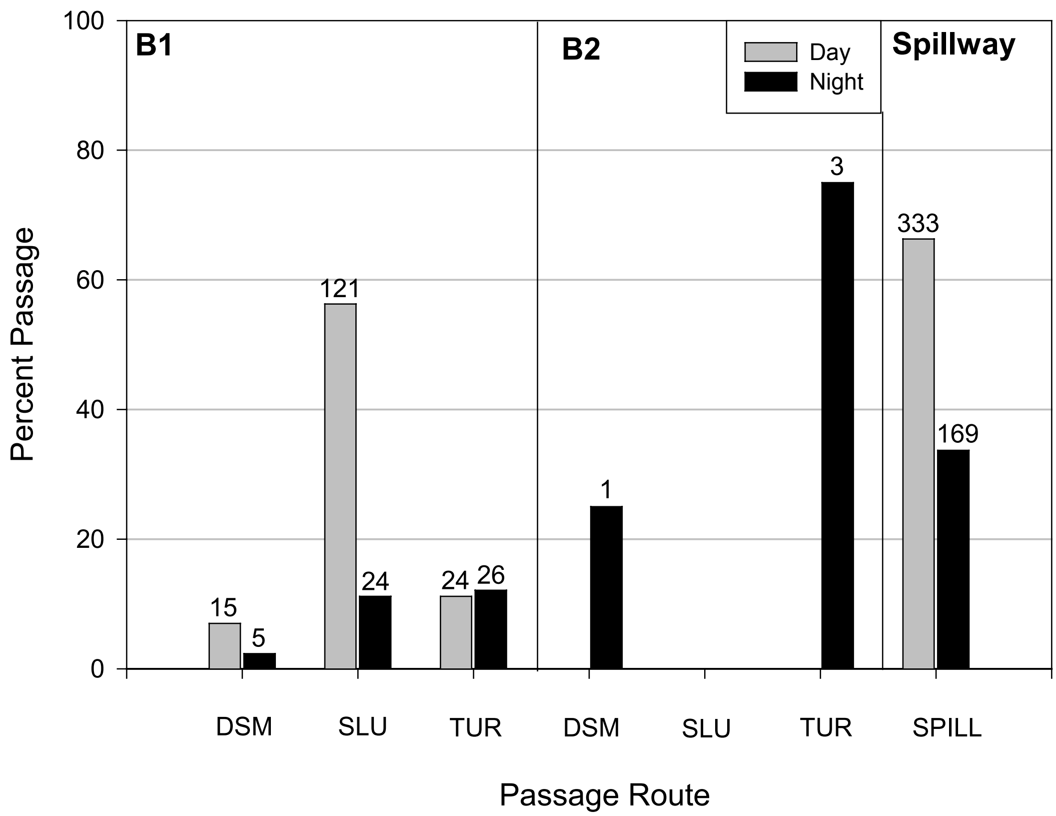


Figure 17. Percent passage by route of passage during day (0500 to 2159 hours) and night (2200 to 0459 hours) for radio-tagged subyearling chinook salmon at Bonneville Dam during summer 2000.

3.7 Passage Metrics

3.7.1 Spillway Efficiency

Spillway efficiency (SE) is the number of fish that passed through spill divided by the number of fish that passed through all routes (spill, B1 and B2). Spillway efficiency at Bonneville Dam was 65% for subyearling chinook salmon (Table 7).

Table 7. Spillway Efficiency (SE) at Bonneville Dam for subyearling chinook salmon during summer 2000. Number passed at B1 includes 49 steelhead and 70 chinook salmon that passed through unknown routes at B1.

SE	B1 Passage	B2 Passage	Spill Passage
0.65	270	4	502

3.7.2 Spillway Effectiveness

The proportion of fish that passed through spill relative to the proportion of discharge spilled (spillway effectiveness; SF) was 1.2. In other words, the percentage of fish that passed through spill out of total passage was 1.2 times greater than the percentage of water that was spilled out of total discharge (Table 8).

Table 8. Spillway Effectiveness (SF) at Bonneville Dam for subyearling chinook salmon during summer 2000.

SF	SE	F_{sp}	F_{tot}
1.2	0.65	94.4	173.8

3.7.3 Fish Guidance Efficiency

Fish guidance efficiency (FGE; number of fish guided divided by number guided plus number unguided) was slightly higher at B1 (29%) than at B2 (25%). However, sample size was small at B2. A comparison of FGE at units 1-6 (19%; location of PSC) to FGE at units 7-10 (59%) indicated that guidance was higher for subyearling chinook salmon at units 7-10 (Table 9). Turbine units 7 and 10 were most efficient at guiding fish at B1 (Table 10). At B2, sample sizes were too small (n = 4) to calculate FGE by unit.

Table 9. Estimates of Fish Guidance Efficiency (FGE) at Bonneville Dam for subyearling chinook salmon during summer 2000.

B1	Units 1-6	Units 7-10	B2
29% (20 of 70)	19% (10 of 52)	59% (10 of 17)	25% (1 of 4)

Table 10. Estimates of Fish Guidance Efficiency (FGE) by turbine unit at Bonneville's first powerhouse (B1) for radio-tagged subyearling chinook salmon during summer 2000.

Turbines at B1									
1	2	3	4	5	6	7	8	9	10
0% 0 of 1	29% 2 of 7	0% 0 of 9	17% 2 of 12	17% 2 of 12	36% 4 of 11	67% 2 of 3	50% 3 of 6	50% 2 of 4	75% 3 of 4

3.7.4 Fish Passage Efficiency

Fish passage efficiency (FPE; number through non-turbine routes divided by number through known routes at B1, B2, and spill) at Bonneville Dam was 91%. We also calculated FPE as if the PSC was an actual passage device (i.e., bypassed fish around the turbines and into the tailrace; $FPE_{w/PSC}$). Eventual passage routes of fish that entered the PSC were not included in the calculation of $FPE_{w/PSC}$. $FPE_{w/PSC}$ (94%) was 3% higher than FPE (Table 12).

Table 11. Fish Passage Efficiency (FPE) and $FPE_{w/PSC}$ for subyearling chinook salmon during summer 2000.

FPE	$FPE_{w/PSC}$
91% (564 of 617)	94% (640 of 779)

3.8 Performance of the Prototype Surface Collector

3.8.1 Discovery Efficiency

Discovery efficiency is the number of fish detected within 6 m of the PSC divided by the number of fish that entered B1. This metric was calculated to estimate the number of fish that were available to the PSC. Nearly three quarters of the fish that entered B1 eventually discovered the PSC (Table 13). Of the fish that were detected at B1, 72% (213 of 297) were detected within 6 m of the PSC. The denominator of this estimate includes 27 fish that entered B1 but were not detected passing B1. The median time from first detection in the B1 forebay to first detection at the PSC (within 6 m) was 8.4 min.

Table 12. Discovery Efficiency (DE) of the PSC for subyearling chinook salmon during summer 2000.

DE	Detected w/in 6 m of PSC	Total Fish Entering B1 Forebay
0.72	213	297

3.8.2 Entrance Efficiency

Most radio-tagged fish that apparently discovered the flownet of the PSC eventually entered the structure. Of the fish that were detected within 6 m of the PSC, 67% (143 of 213) entered the PSC (Table 14). Underwater antennas located inside the PSC at unit 2 failed early in the 2001 monitoring season. We were able to determine that 13 subyearling chinook salmon entered the PSC at unit 2 based on detections at underwater antennas located on the face of the PSC at unit 2 and subsequent detections in the sluiceway. However, this is likely an underestimate of actual fish passage into the PSC at unit 2. Of the fish that entered the PSC, 12% re-entered the PSC 1-4 more times after swimming upstream, out of the entrances of the PSC. For purposes of estimating entrance efficiency, we used only data acquired during and before a fish's first entrance to the PSC.

Table 13. Entrance Efficiency (EE) of the PSC for subyearling chinook salmon during summer 2000.

EE	Entered PSC	Detected w/in 6 m of PSC
0.67	143	213

To further investigate the efficiency of the PSC, we determined how many fish entered the PSC during their first encounter. Although 18 fish approached the PSC between two and eight times before entering, 87% (125 of 143) of subyearling chinook salmon entered the PSC during their initial encounter (Figure 18). However, of the fish that entered the PSC, only 41% (59 of 143) entered via the entrance they were first detected at without meandering to one or more entrances (hereafter referred to as direct entrance; Figure 19). Therefore, of the fish that entered the PSC, 59% (84 of 143) meandered to one or more entrances before entering. For fish that directly entered the PSC, the median time from first detection at the PSC until entering was 1.5 min (Table 15). However, for fish that meandered between multiple PSC entrances before entering, the median time from first detection at the PSC until entering was 46 min (Table 16).

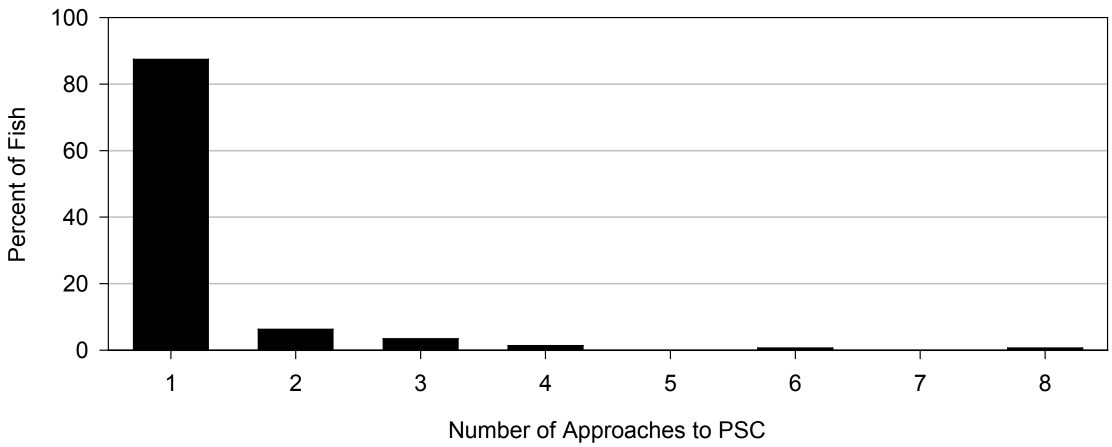


Figure 18. Percentage of fish by the number of approaches to the PSC before entering the PSC during summer 2000.

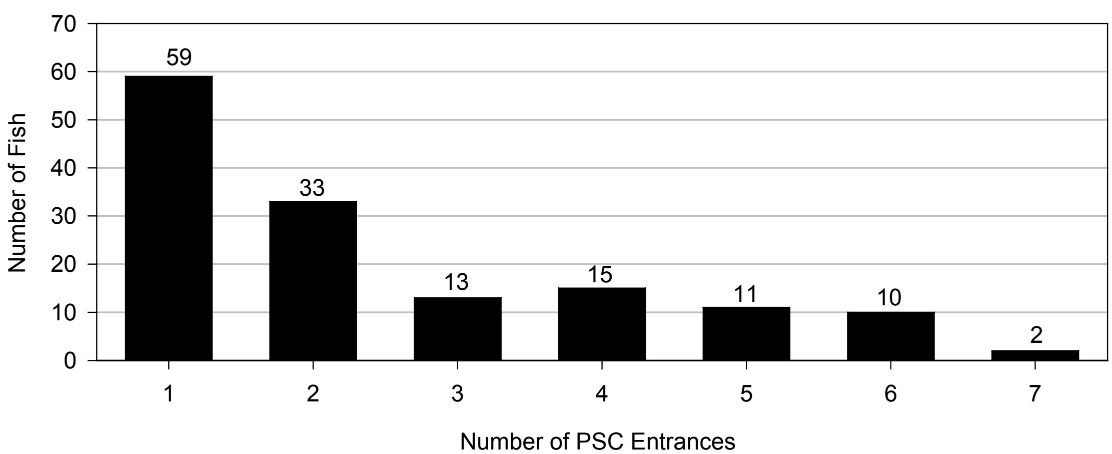


Figure 19. Number of fish that entered the PSC by the number of PSC entrances fish were detected at before entering during summer 2000. Fish that were detected at one entrance and did not travel anywhere else between first detection at the face of the PSC and first detection inside the PSC, were considered to directly enter the PSC.

Table 14. Time (h) from first external PSC detection to first Internal PSC detection for fish that directly entered the PSC during first encounter with PSC during summer 2000.

N	Mean	Median	STD	Min	Max
50	0.19	0.03	0.58	0.01	3.15

Table 15. Time (h) from first external PSC detection to first Internal PSC detection for fish that did not directly enter the PSC during first encounter with PSC during summer 2000.

N	Mean	Median	STD	Min	Max
83	1.76	0.77	2.57	0.02	13.88

To estimate entrance efficiency by unit, we divided the number of fish that directly entered a PSC entrance by the number of fish that were first detected at that entrance. The most efficient entrance to the PSC was at unit 6 for subyearling chinook salmon (44%; Figure 20; Table 17).

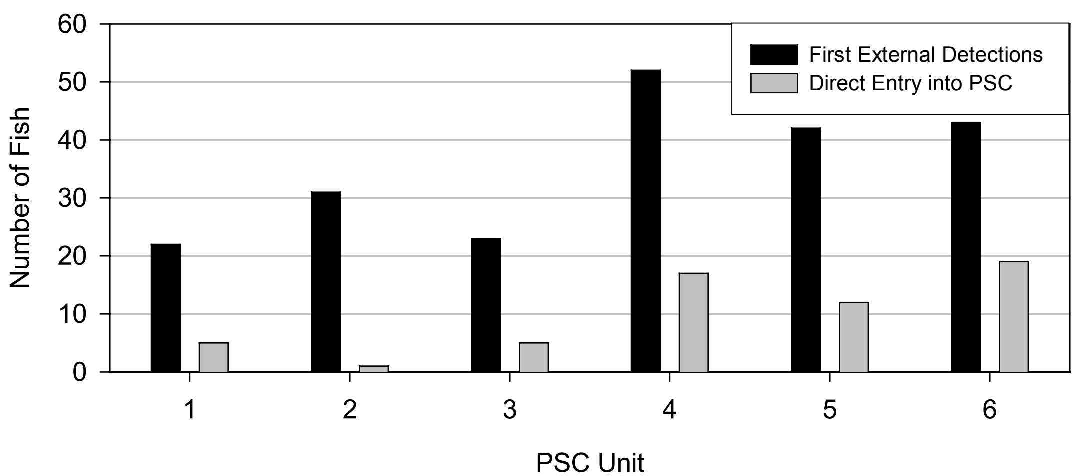


Figure 20. Number of fish first detected at the PSC and the number of fish that directly entered the PSC by unit during summer 2000. Note: Number of fish that directly entered the PSC at unit 2 may be underestimated due to equipment failure.

Table 16. Estimates of PSC Entrance Efficiency (EE) by unit for subyearling chinook salmon during summer 2000. Efficiencies are based only on fish that directly entered a PSC entrance, not all fish that entered the PSC.

1	*2	3	4	5	6
23% 5 of 22	3% 1 of 31	22% 5 of 23	33% 17 of 52	29% 12 of 42	44% 19 of 43

* Unit 2 EE may be an underestimate due to equipment failure.

3.8.3 Collection Efficiency

Collection efficiency is the number of fish that entered and passed through the PSC divided by the number of fish that entered and passed through the PSC plus the number of fish that passed under the PSC. This was calculated to estimate the efficiency of the PSC in relation to in-turbine passage routes at units 1-6. The PSC appeared to be very efficient at collecting fish that approached units 1-6 at B1. Of the fish that passed at units 1-6, including fish that entered the PSC, 81% (128 of 158) entered the PSC (Table 18). Although 143 fish entered the PSC, only 128 of those passed through the PSC and into the sluiceway or turbines intakes. The 15 fish that entered the PSC but were not detected passing B1 (3 passed at the spillway and 12 were not detected below the dam) were not included in the calculation of collection efficiency.

Table 17. Collection efficiency (CE_{1-6}) of the PSC for subyearling chinook salmon during summer 2000. Of 143 fish that entered the PSC, only 128 were detected passing through the sluiceway or turbine intake downstream of the PSC.

CE_{1-6}	Entered PSC	Passed under PSC
81%	128	30

3.8.4 Effectiveness

The effectiveness of the PSC (proportion of fish entering the PSC, i.e., PSC efficiency, divided by the proportion of discharge through the PSC) was calculated to measure the performance of the PSC in relation to the amount of water used by the PSC. PSC effectiveness was 2.5 for subyearling chinook salmon, indicating that the proportion of fish that entered the PSC out of total passage at units 1-6 was over twice as high as the proportion of discharge that entered the PSC out of total discharge into and under the PSC at units 1-6 (Table 19).

Table 18. Effectiveness (EF_{1-6}) of the PSC, and the numbers used to calculate EF_{1-6}, for subyearling chinook salmon during summer 2000.

EF_{1-6}	CE_{1-6}	F_{psc}	F_u
2.53	0.81	15.17	32.69

3.9 Fish Behavior at the Prototype Surface Collector

3.9.1 Horizontal and Vertical distribution at the PSC

Based on first detections at the underwater antennas at and near each entrance to the PSC, 64% (137 of 213) of subyearling chinook salmon detected at the face of the PSC were first detected on the north end of the PSC at units 4-6. However, nearly equal proportions of fish entered the PSC at units 1-3 (46%) compared to units 4-6 (54%; Figure 21). Likewise, although most fish first arrived at the PSC at the northern half, there were more total detections at underwater antennas located on the southern half of the PSC (Figure 22). These observations indicated that, in general, subyearling chinook salmon moved laterally from north to south along the face of the PSC before passing into it.

Subyearling chinook salmon entered the PSC throughout the diel cycle. However, fish predominantly entered the PSC during the day. Eighty-five percent of fish entered the PSC during daylight hours. Passage into the PSC peaked at sunrise (0500 hours; Figure 23).

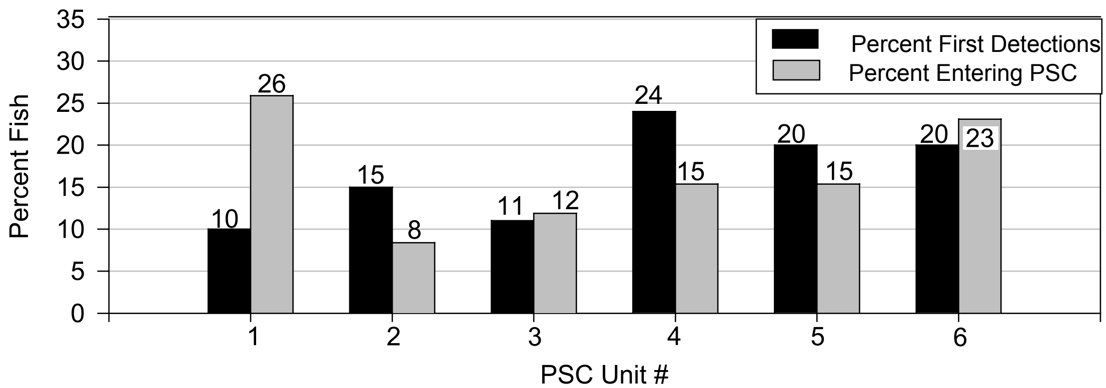


Figure 21. Percentage of fish first detected at the PSC and the percentage of fish that entered the PSC by unit during summer 2000. Percentage of fish that entered PSC at unit 2 may be underestimated due to equipment failure.

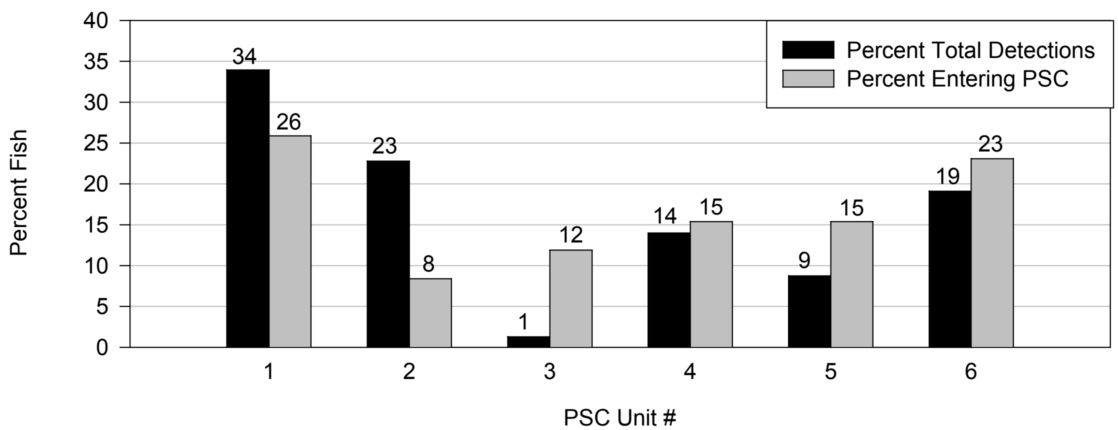


Figure 22. Percent total detections at the PSC and the percentage of fish that entered the PSC by unit during summer 2000. Percentage of fish that entered the PSC at unit 2 may be underestimated due to equipment failure.

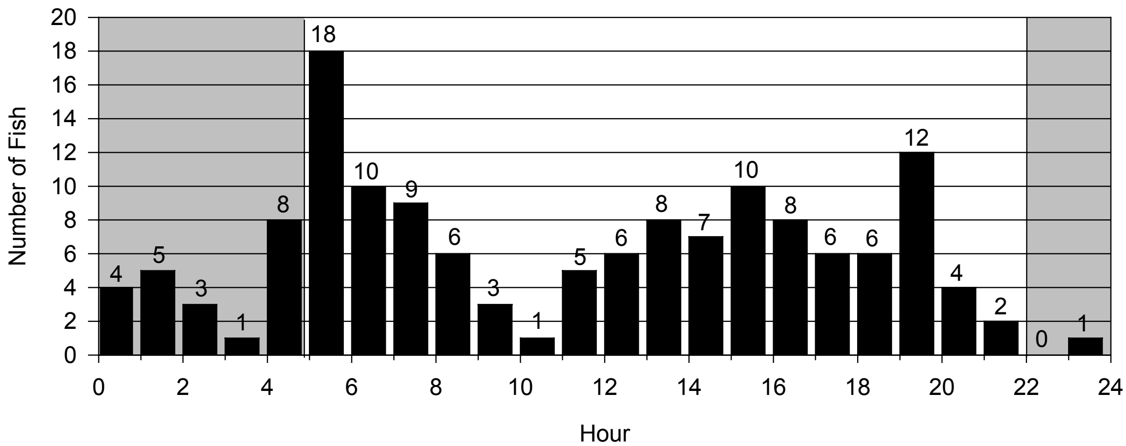


Figure 23. Number of subyearling chinook salmon that entered the PSC by hour of day during summer 2000.

Depth of approach to the PSC was determined by the first detection received by underwater antennas along the face of the PSC. Of the fish that were detected at the face of the PSC (where depth of approach could be determined), 52% (107 of 204) approached the PSC deep (between 6.5 and 13 m; Figure 24). During day, most fish approached the PSC deep (59%) and during night most fish approached the PSC shallow (69%; Figure 25). An analysis of depth of approach to the PSC by PSC unit indicated that more fish (64-65%) approached the PSC shallow at units 1 and 2 than deep. Conversely, 52-72% of first detections at units 3-6 were deep (Figure 26).

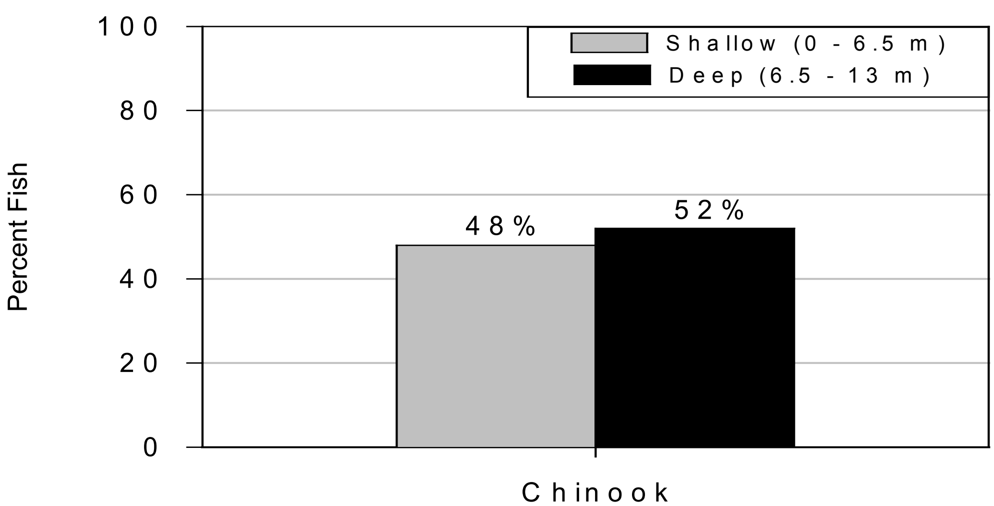


Figure 24. Percent first detections at the PSC by depth of detection for subyearling chinook salmon during summer 2000.

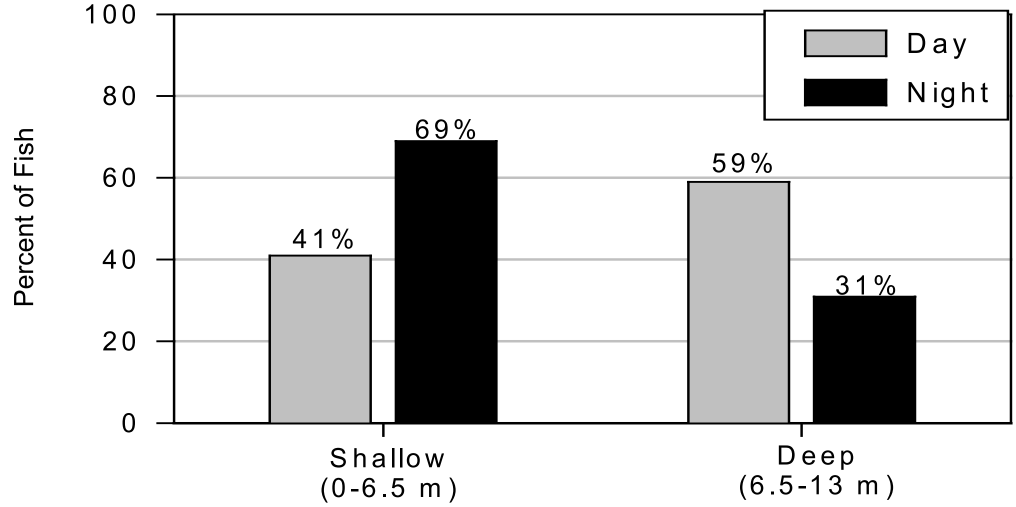


Figure 25. Percent first detections at the PSC by day, night, and depth of detection for subyearling chinook salmon during summer 2000.

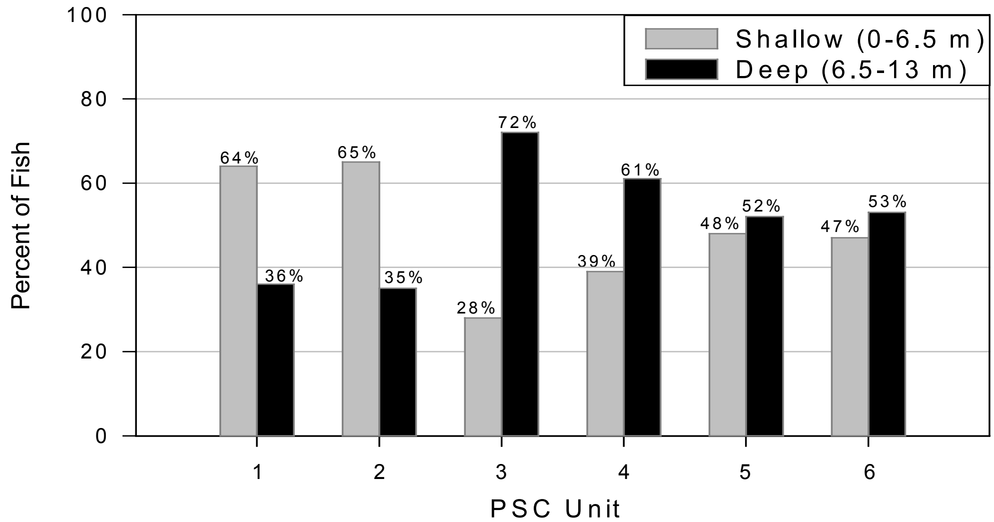


Figure 26. Percent first detections at the PSC by unit and depth of detection for subyearling chinook salmon during summer 2000.

The depth of entrance into the PSC was determined by the last detection received by underwater antennas along the face of the PSC before the first detection inside the PSC. Of the fish detected inside the PSC that were also detected at an external PSC antenna immediately before entering the PSC, 55% (74 of 134) entered the PSC shallow (Figure 27). Similar proportions of depth of entrance to the PSC were observed for fish during day. However, at night, nearly all fish entered the PSC shallow (95%; Figure 28). Depth of entrance to the PSC by unit was similar to depth of approach by unit except for unit 6 (Figure 29). Although 6% more fish were first detected deep at unit 6, 20% more fish entered shallow at unit 6.

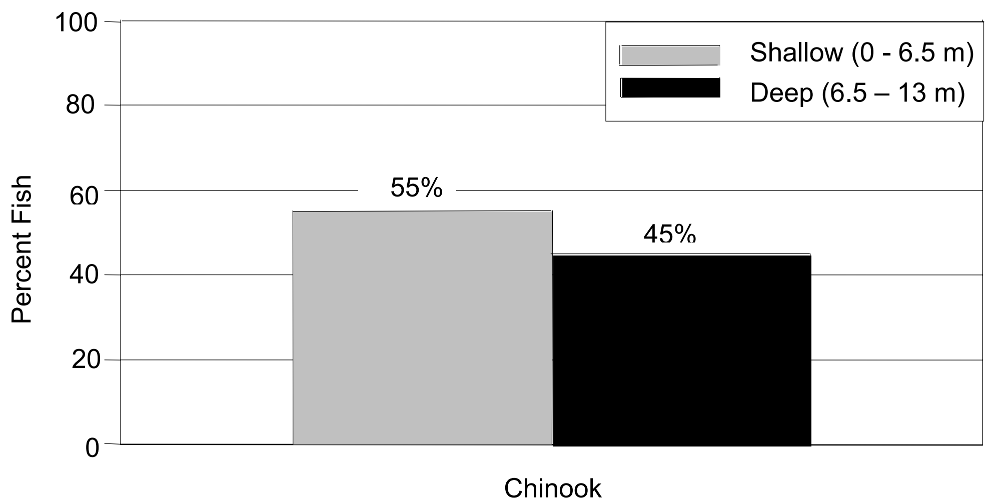


Figure 27. The percentage of subyearling chinook salmon that entered the PSC by depth of entrance during summer 2000.

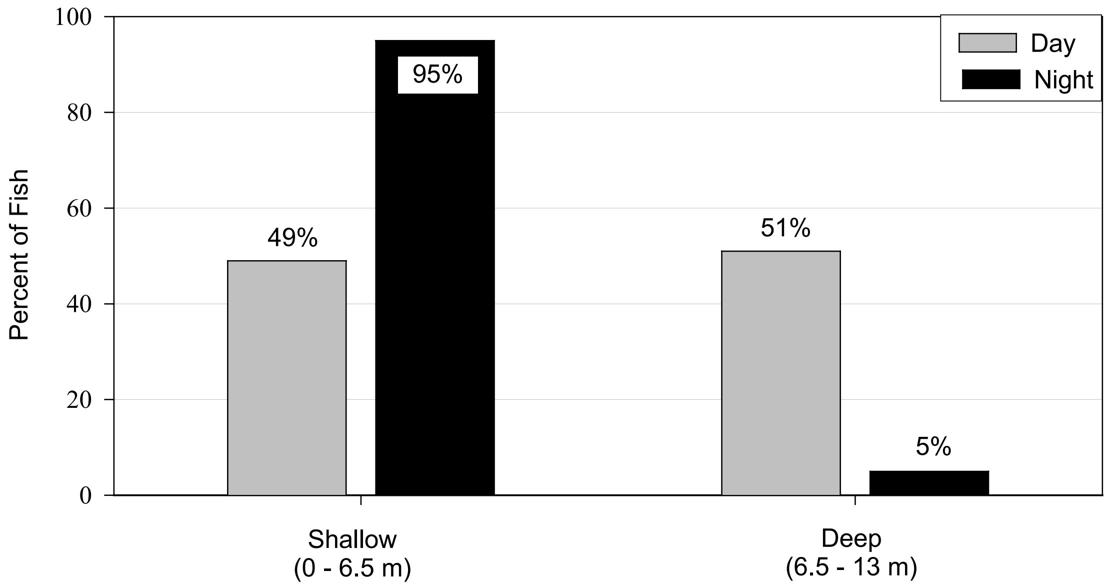


Figure 28. The percentage of subyearling chinook salmon that entered the PSC by day, night, and depth of entrance during summer 2000.

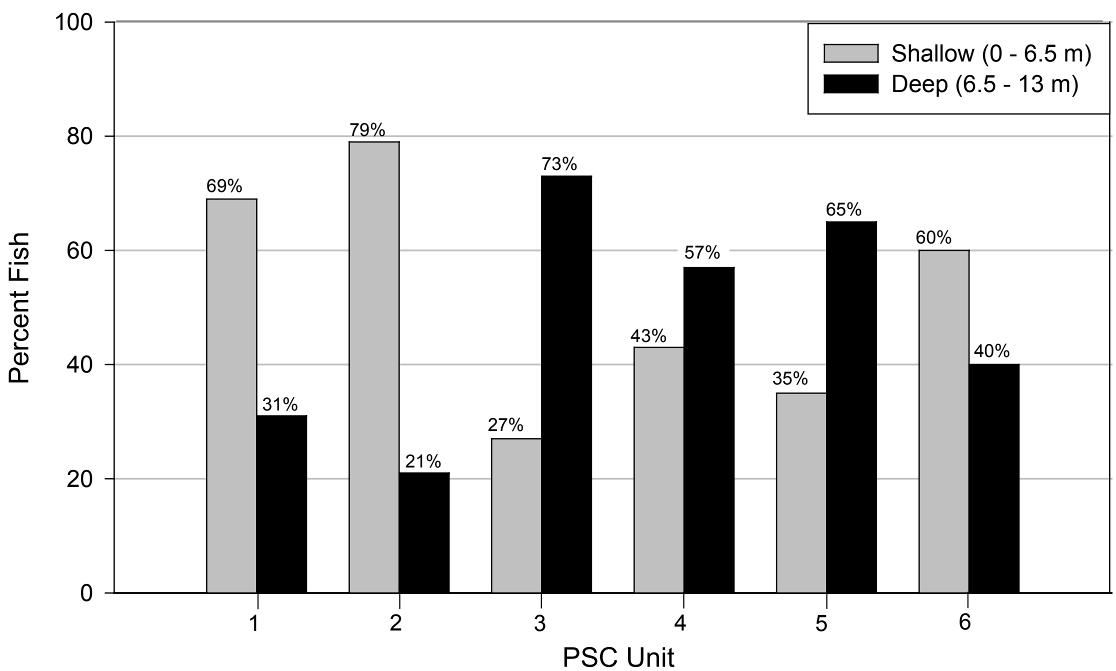


Figure 29. The percentage of subyearling chinook salmon that entered the PSC by unit and depth of entrance during summer 2000.

4.0 Discussion

4.1 Approach Paths and Forebay Residence Times

Based on first detections, the highest percentage (60%) of subyearling chinook salmon entered the spillway. The proportion of discharge at each dam area was likely the determining factor for which forebay fish entered. Based on our analysis of percent discharge per dam area by day related to percent of fish that entered each dam area, fish appeared to follow the bulk flow, entering the dam area with the highest proportion of discharge. Since the spillway discharged the most amount of water during the study (54%) most fish entered the spillway forebay. Likewise, since flows were very low at B2 (4% of project discharge), only 2% of subyearling chinook salmon entered that dam area.

Forebay residence times of subyearling chinook salmon differed considerably depending on dam area. The spillway provided the quickest route of passage as residence times there were substantially less than at B1 or B2. No relation was apparent between daily discharge patterns, hour of arrival, or hour of passage and residence time. Therefore, total discharge per dam area seemed to be the primary factor affecting residence times of subyearling chinook salmon.

4.2 Route and Time of Passage

Little movement occurred among the three dam areas (B1, B2, and the spillway) and most fish passed where they were first detected. Similar to first detections, the highest percentage (69.5%) of fish passed Bonneville Dam through the spillway. Again, project discharge was the primary factor in affecting where fish passed Bonneville Dam. Higher discharge at the spillway compared to the other dam areas resulted in most fish passing through the spillway.

At B1, the proportion of radio-tagged fish that passed through specific routes indicated that fish were generally shallow in the water column. The highest percentage (68%) of fish passed via the sluiceway. However, not all fish were shallow, since 23% passed directly through the turbines and only 9% were shallow enough to be guided by the STS and ESBS into the DSM. Although FGE was 40% higher at units 7-10 than units 1-6, a higher proportion of fish passed into the sluiceway at units 1-6 compared to units 7-10. The presence of the PSC may have been responsible for higher sluiceway passage at units 1-6. We speculate that fish that approached units 1-6 (and the PSC) at depths that would not normally result in sluiceway passage, were forced higher in the water column at the face of the PSC. This is supported by the fact that a greater percentage of fish were shallow upon entering the PSC compared to a greater percentage of fish being deep at first detection at the face of the PSC.

Passage at Bonneville Dam occurred throughout the diel cycle, however, passage was influenced differently among dam areas by day and night. At the spillway, although a higher number of fish passed during day, a higher proportion relative to B1 and B2 passed during night. In contrast, a lower proportion of fish passed during night at B1. This was likely attributed to the type of passage route fish used within each dam area.

For example, sluiceway passage (and entrance into the PSC) and turbine guidance predominantly occurred during day at B1. Since the majority of fish at B1 passed through the sluiceway, passage declined at B1 during night. At the spillway, passage increased at night, as did discharge. Therefore, time of day seemed to have the greatest effect on passage at B1, and both diel patterns and discharge, influenced passage at the spillway. No relation between route of passage and diel patterns could be found at B2. Extremely low discharge resulted in very low numbers of fish passing at B2.

4.3 Performance of the Prototype Surface Collector

Based on performance metrics calculated to measure the efficiency and effectiveness of the PSC, the PSC performed well for subyearling chinook salmon. The majority of subyearling chinook salmon (72%) that entered B1 forebay discovered the PSC (i.e., were detected within 6 m of the PSC) in a relatively short amount of time (median = 8.4 min). Likewise, most fish that apparently discovered the flownet of the PSC eventually entered the structure, resulting in an overall entrance efficiency of 67%. Entrance efficiency based on fish that entered the PSC during their first encounter (87%) was even higher than overall entrance efficiency. However, considerable meandering was observed between fish's first detection at the PSC and their time of entrance. Only 41% of juvenile chinook salmon directly entered the PSC at the same entrance they were first detected at. Further, there was a substantial difference in time from first detection at the PSC until entering the PSC for fish that meandered (median = 46 min) compared to fish that did not meander (median = 1.5 min). Based on direct entrance to the PSC, the entrance at unit 6 was most efficient for both species. This observation may indicate that entrance conditions were more favorable at unit 6, possibly because there was only one adjacent entrance to the south and the presence of the wingwall to the north. These factors may have resulted in a more defined flow field.

The PSC was quite efficient at collecting fish relative to in-turbine passage routes at units 1-6. Of the fish that passed B1 at units 1-6, 81% entered the PSC. In relation to the Bonneville complex (all three dam areas), the PSC, if it were an actual passage route, would have accounted for a 3% increase in FPE. FPE (not including fish that entered the PSC) was 91% and would have increased to 94% had the PSC been a fully functional passage device.

The PSC was also relatively effective. An effectiveness of 2.5 indicated that the percentage of fish that entered the PSC out of total passage at units 1-6 was 2.5 times the discharge through the PSC. When compared to spillway effectiveness (1.2), PSC effectiveness was over twice as high.

4.4 Fish Behavior at the Prototype Surface Collector

Approach paths of subyearling chinook salmon at B1 were predominantly toward the central portion of the powerhouse. As a result, 64% of the fish that came within 6 m of the PSC were first detected at the northern half of the PSC at units 4-6. Fish then generally moved south along the face of the PSC before entering the southern half of the

PSC (units 1-3) or moving away from the PSC and passing elsewhere. Plumb et al. (2000) and Hansel et al. (1999) also observed lateral movement of radio-tagged fish from north to south along the face of the PSC during previous evaluations of the partial PSC. Observations of horizontal distribution and movement of subyearling chinook salmon at B1 indicated that approach paths were likely determined by the bulk flow entering B1 forebay. The location of the PSC enabled the majority of fish to discover the PSC due to its proximity to the bulk flow entering B1. Fish movement from north to south along the PSC was likely due to a southerly flow component at the face of the PSC. It is this southerly flow across the entrances to the PSC that may have diminished their efficiency, or attractiveness, causing the majority of fish to meander to multiple entrances before entering the PSC or passing through another route. The PSC tests indicated that relatively high proportions of fish discovered and entered the PSC with little entrainment into turbines beneath the PSC. However, increased performance of the PSC may be realized if entrance conditions were further improved to maximize the probability that fish directly enter the PSC without meandering to multiple entrances or to other areas within the forebay.

The vertical distribution of subyearling chinook salmon during approach to the PSC was typical of summer-migrating juvenile salmonids. More fish were deep than shallow, especially during the day. Likewise, most fish that approached the PSC at night were shallow. To the contrary, during entrance to the PSC, more fish were shallow than deep. This indicates that some fish entered the PSC at a shallower depth than when first detected at the PSC; something not observed in any of the previous PSC evaluations. Our data of spring migrants indicated that fish entered the PSC at the same depth as they approached. Depth of entrance data for subyearlings in previous evaluations was not available. However, we believe project operations, rather than any species-specific difference, was responsible for subyearling chinook salmon ascending at the face of the PSC before entering. Recall that turbines at B1, including those behind the PSC, were not operated equally on a daily basis during the summer 2000 evaluation. Results at unit 6 may be the best example: unit 6 had the highest number of days of the lowest discharge among turbines at the PSC, including three days of inoperation; the PSC entrance at unit 6 had the greatest differential in depth of approach compared to depth of entrance; and finally, unit 6 was the most efficient PSC entrance. The large differences in daily turbine discharge among units behind the PSC, especially when units were not operating, may have created hydrologic conditions that either allowed or directed the movement of fish higher in the water column at the face of the PSC. Although a fish that enters the PSC shallow may not have an advantage over a fish that enters the PSC deep, a benefit may be gained in the way of less entrainment into the turbines resulting in higher collection efficiency. Varying turbine discharge among turbines at the PSC, or investigating means to improve hydrologic conditions at the face of the PSC should be included in any future testing of surface bypass at B1.

4.5 Comparison of PSC Performance Between Evaluation Tools

In addition to the radio telemetry evaluation we conducted, another research tool was utilized to effectively evaluate fish behavior at Bonneville Dam in summer 2000, especially at the PSC. Fixed location hydroacoustic methods were used by the Waterways Experiment Station of the U.S. Army Corps of Engineers (WES) to estimate fish passage rates and determine PSC performance for the run-at-large. Collection efficiency and effectiveness estimates for the PSC were similar between radio telemetry and hydroacoustics (Table 20).

Table 19. PSC performance metrics for subyearling chinook salmon at Bonneville Dam during summer 2000 as determined by radio telemetry (RT) and Hydroacoustics (HA). *HA estimate of effectiveness is an underestimate because sluiceway passage is not accounted for.

Metric	RT	HA
Discovery Efficiency (DE)	72%	n/a
Entrance Efficiency (EE_{1-6})	67%	n/a
Collection Efficiency (CE_{1-6})	81%	84%
Effectiveness (EF_{1-6})	2.5	2.2

4.6 Comparison of PSC Performance Among Evaluation Years

Discovery and entrance efficiencies for the PSC in summer 2000 were considerably higher (21-25%) than in summer 1998. Collection efficiency was higher in 1998 than in 2000, however, sample sizes were extremely low (n = 11) in 1998 and coverage was not as extensive in 1998 as in 2000. Caution should be used when comparing PSC performance among years. PSC structure and configuration, and monitoring and evaluation methods were not consistent between study years. For example the PSC extended across units 3-6 in 1998 and 1999 and across units 1-6 in 2000. Additionally, the PSC had two open entrances with two width configurations in 1998, one entrance with two width configurations in 1999 and six open entrances with one width configuration in 2000. Furthermore, sample sizes of summer migrant radio-tagged fish that entered B1 were different among years: 108 in 1998 and 297 in 2000. Since study design was more consistent and evaluation methods were more thorough in 2000, estimates of PSC performance are likely most accurate for the 2000 evaluation.

Table 20. PSC performance metrics for subyearling chinook salmon at Bonneville Dam during summer 1998, 1999, and 2000. Efficiencies for 1998 and 1999 are based only on data obtained during the 20 ft opening configuration for the partial (units 3-6) prototype surface collector. Effectiveness was not calculated (nc) for the 1998 evaluation and subyearling chinook salmon were not evaluated (ne) in 1999.

Metric	1998	1999	2000
Discovery Efficiency (DE)	48%	ne	72%
Entrance Efficiency (EE_{1-6})	46%	ne	67%
Collection Efficiency (CE_{1-6})	100%	ne	81%
Effectiveness (EF_{1-6})	nc	ne	2.5

5.0 Acknowledgements

We thank our colleagues of the U.S. Geological Survey who assisted with field operations, data analysis, and administrative support throughout the study. We thank Blaine Ebberts, Rock Peters, Jennifer Sturgill, and other COE personnel for their efforts in managing our contract and assisting in planning and executing this research. Many thanks go to Dean Ballinger and staff at the Pacific States Marine Fisheries Commission for their assistance in collecting fish for this study.

6.0 References

Adams, N.S., D.W. Rondorf, S.D. Evans, and J.E. Kelly. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of chinook salmon. Transactions of the American Fisheries Society. 127:128-136.

Beeman, J. W., H. C. Hansel, P. V. Haner, and J. Hardiman. In Review. Estimates of fish-, spill-, and sluiceway passage efficiencies of radio-tagged subyearling chinook salmon at The Dalles Dam, 2000. Draft final report of U.S. Geological Survey, Biological Resources Division (contract W66QKZ00392015) to U.S. Army Corps of Engineers, Portland Oregon.

Fish Passage Center. 2000. Smolt Passage Index data. ONLINE. Fish Passage Center, Portland, Oregon. Available: http://www.fpc.org [accessed December, 2000].

Giorgi, A.E. and J.R. Stevenson. 1995. A review of biological investigations describing smolt passage behavior at Portland District Corps of Engineers Projects: implications to surface collection systems. Report to U.S. Army Corps of Engineers, Portland, Oregon.

Hansel, H.C., R.S. Shively, J.E. Hensleigh, B.D. Liedtke, R.E. Wardell, R.H. Wertheimer, T.P. Poe. 1999. Movement, distribution, and behavior of radio-tagged juvenile chinook salmon and steelhead in the forebay of Bonneville Dam, 1998. Final report of U.S. Geological Survey, Biological Resources Division to U.S. Army Corps of Engineers, Portland, Oregon.

Johnson, G.E., C.M. Sullivan, and M. W. Erho. 1992. Hydroacoustic studies for developing a smolt bypass system at Wells Dam. Fisheries Research 14:221-237.

NMFS (National Marine Fisheries Service). 1995. Reinitiation of consultation on 1994-1998 operation of the federal Columbia River power system and juvenile transportation program in 1995 and future years. Biological Opinion, Endangered Species Act-Section 7 Consultation. March 2, 1995.

Park, D.L. 1969. Seasonal changes in downstream migration of age-group 0 chinook salmon in the upper Columbia River. Transaction of the American Fisheries Society 98:315-317.

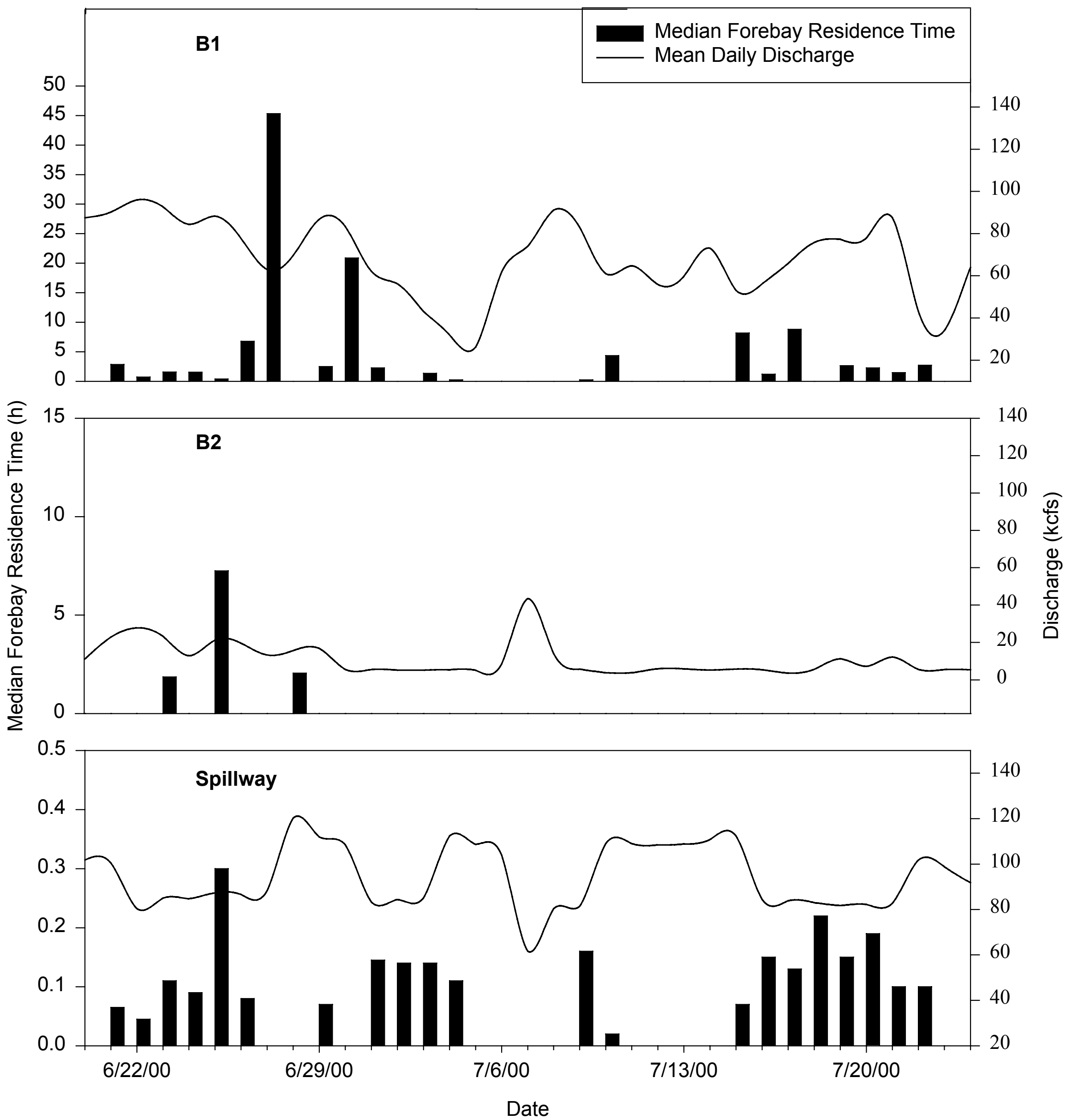
Plumb, J.M., M.S. Novick, B.D. Liedtke, N.S. Adams. 2000. Movement, distribution, and behavior of radio-tagged yearling spring chinook salmon and juvenile hatchery steelhead in the forebay of Bonneville Dam, 1999. Final report of U.S. Geological Survey, Biological Resources Division to U.S. Army Corps of Engineers, Portland, Oregon.

Raymond, H.L. 1968. Migration rates of hatchery chinook salmon in relation to flows and impoundments in the Columbia and Snake rivers. Transactions of the American Fisheries Society. 97:356-359

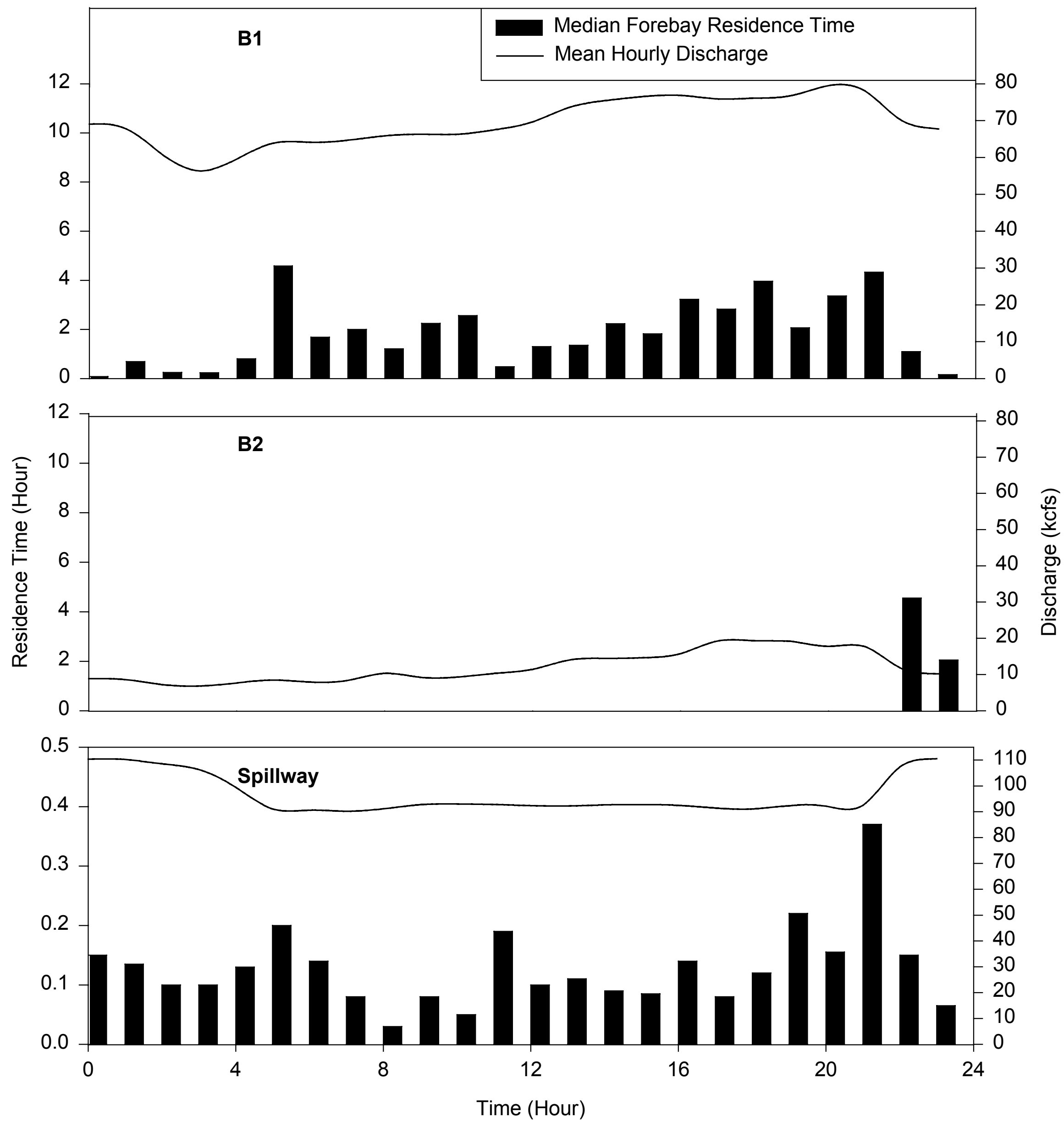
Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile chinook salmon and steelhead from the Snake River, 1966 to 1975. Transactions of the American Fisheries Society. 108:505-529.

Swan, G. A., B. L. Iverson, B. P. Sanford, and M. A. Kaminski. 1995. Radio telemetry study Ice Harbor, 1995. National Marine Fisheries Service, Seattle, Washington. Abstract for North Pacific Division, Anadromous Fish Evaluation Program, Annual Program Review, U. S. Army Corps of Engineers, Walla Walla, Washington.

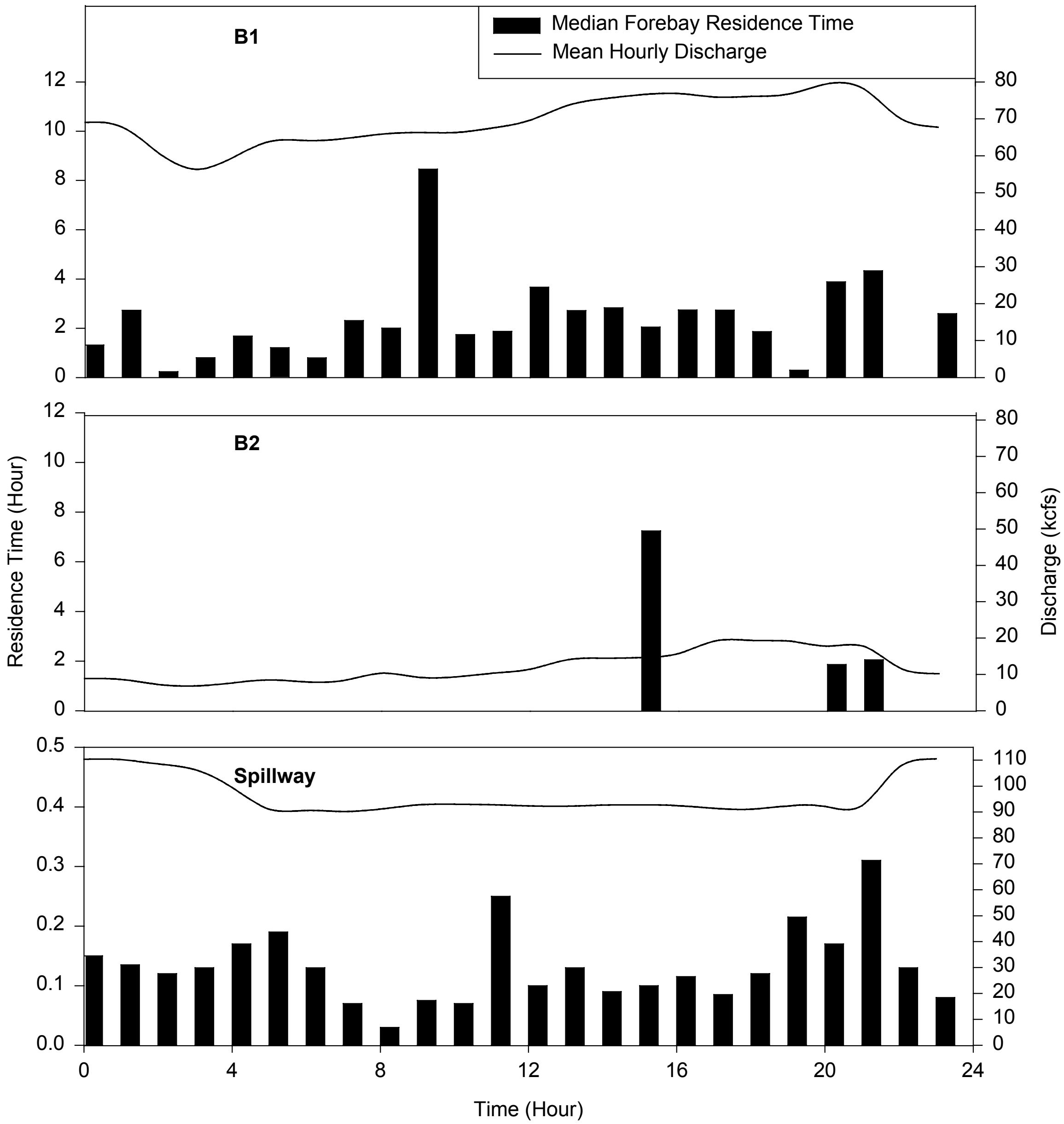
7.0 Appendices



Appendix 1. Median forebay residence time by day of passage versus mean discharge by dam area for radio-tagged subyearling chinook salmon at Bonneville Dam during summer 2000.



Appendix 2. Median forebay residence time by hour of passage versus mean discharge by dam area for radio-tagged subyearling chinook salmon at Bonneville Dam during summer 2000.



Appendix 3. Median forebay residence time by hour of arrival versus mean discharge by dam area for radio-tagged subyearling chinook salmon at Bonneville Dam during summer 2000.

Appendix 4. Passage and PSC performance metrics for radio-tagged steelhead and yearling and subyearling chinook salmon at Bonneville Dam during spring and summer 2000.

Metric	Steelhead	Yearling Chinook	Subyearling Chinook
SE	33%	44%	65%
SF	1.0	1.3	1.2
$FGE(B1)_{1\text{-}10}$	59%	50%	29%
$FGE_{1\text{-}6}$	58%	52%	19%
$FGE_{7\text{-}10}$	61%	48%	59%
FGE (B2)	55%	39%	25%
FPE	78%	73%	91%
$FPE_{w/PSC}$	85%	78%	94%
DE	74%	63%	72%
$EE_{(1\text{-}6)}$	60%	72%	67%
$CE_{(1\text{-}6)}$	83%	79%	81%
$EF_{(1\text{-}6)}$	2.5	2.4	2.5