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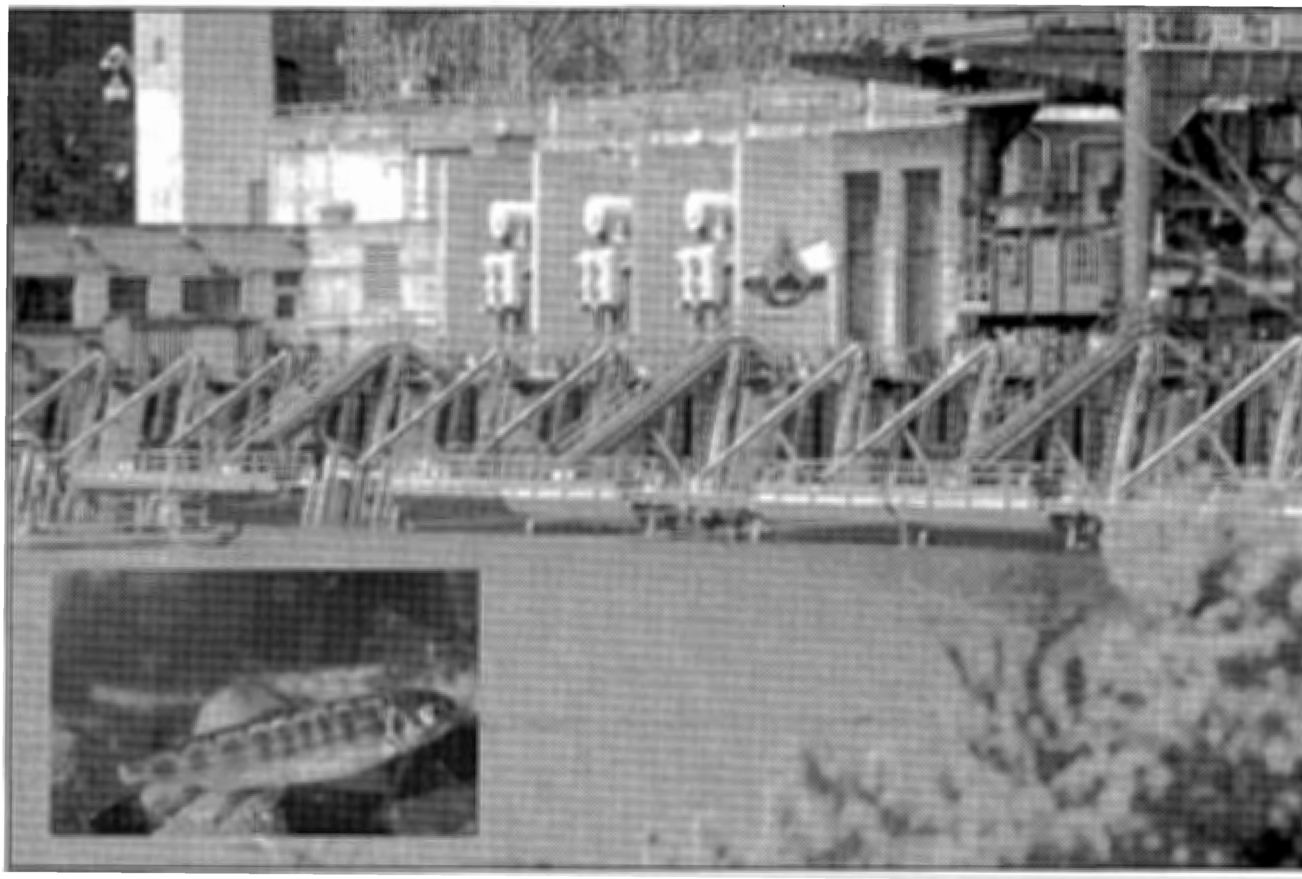
Passage Behavior of Radio-Tagged Yearling Chinook Salmon and Steelhead at Bonneville Dam Associated with The Surface Bypass Program, 2000



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

Annual Report

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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 25 April to 1 June 2000, we radio-tagged and released 1,193 juvenile hatchery steelhead and 2,075 yearling chinook salmon. These fish were released from four locations upstream of Bonneville Dam: Rock Creek, John Day Dam, The Dalles Dam, and Hood River, Oregon. Median travel times from release to Bonneville Dam ranged from 14 h to 76 h, depending on species and the location of release. Of all the fish released, we detected 80% of steelhead and 82% of chinook salmon at Bonneville Dam. Of the fish released at Hood River, we detected 95% of steelhead and 94% of chinook salmon. Median residence time in the forebay areas of Bonneville Dam ranged from 8 min to 9.7 h, depending on species and forebay area. Discharge rates and diel periods effected residence times of both species.

Passage routes were determined for 91% of steelhead and 92% of chinook salmon detected at Bonneville Dam. Nearly half (49%) of steelhead passed at powerhouse one (B1), and the largest proportion (44%) of chinook salmon passed through the spillway. Thirty-four percent of steelhead detected at Bonneville Dam passed through the spillway. Of the steelhead that passed at B1, 44% passed into the sluiceway, 33% were guided into the downstream migration channel (DSM) via the standard-length submersible traveling screens (STS) or extended-length submersible bar screens (ESBS), and 23% were unguided and passed directly through the turbines. Of the chinook salmon that passed at B1, 29% passed into the sluiceway, 36% were guided into the DSM, and 35% were unguided and passed directly through the turbines. Of the fish that passed at B2, 55% of steelhead and 39% of chinook salmon were guided into the DSM by the STS and 45% of steelhead and 60% of chinook salmon passed through the turbines unguided. No steelhead and 1% of chinook salmon were detected passing through the sluice chute at

B2, which was minimally operated during spring 2000. Passage rates were highest for both species during the day at the spillway and B1. However, passage rates were highest for both species during the night at B2.

Of the fish that entered the B1 forebay, 74% of steelhead and 63% of chinook salmon were detected within 6 m of the PSC and were therefore considered to have discovered the PSC. Of the fish that discovered the PSC, 60% of steelhead and 72% of chinook salmon entered the PSC. However, of the fish that entered the PSC, only 29% (61 of 214) of steelhead and 41% (100 of 246) of chinook salmon entered the PSC via the entrance they were first detected at without meandering to one or more entrances. Therefore, of the fish that entered the PSC, 71% (153 of 214) of steelhead and 59% (146 of 246) of chinook salmon meandered to one or more entrances before entering the PSC. In relation to units 1-6 at B1, the PSC was quite efficient at collecting fish. Of the fish that passed at units 1-6 (guided and unguided) 83% of steelhead and 78% of chinook salmon entered the PSC. The PSC was also relatively effective compared to water passing into the turbines and the spillway. An effectiveness of 2.5 for steelhead and 2.4 for chinook salmon indicated 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. When compared to spillway effectiveness (1.0 for steelhead and 1.3 for chinook salmon), PSC effectiveness was about 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 78% to 85% for steelhead and from 73% to 78% for chinook salmon.

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).

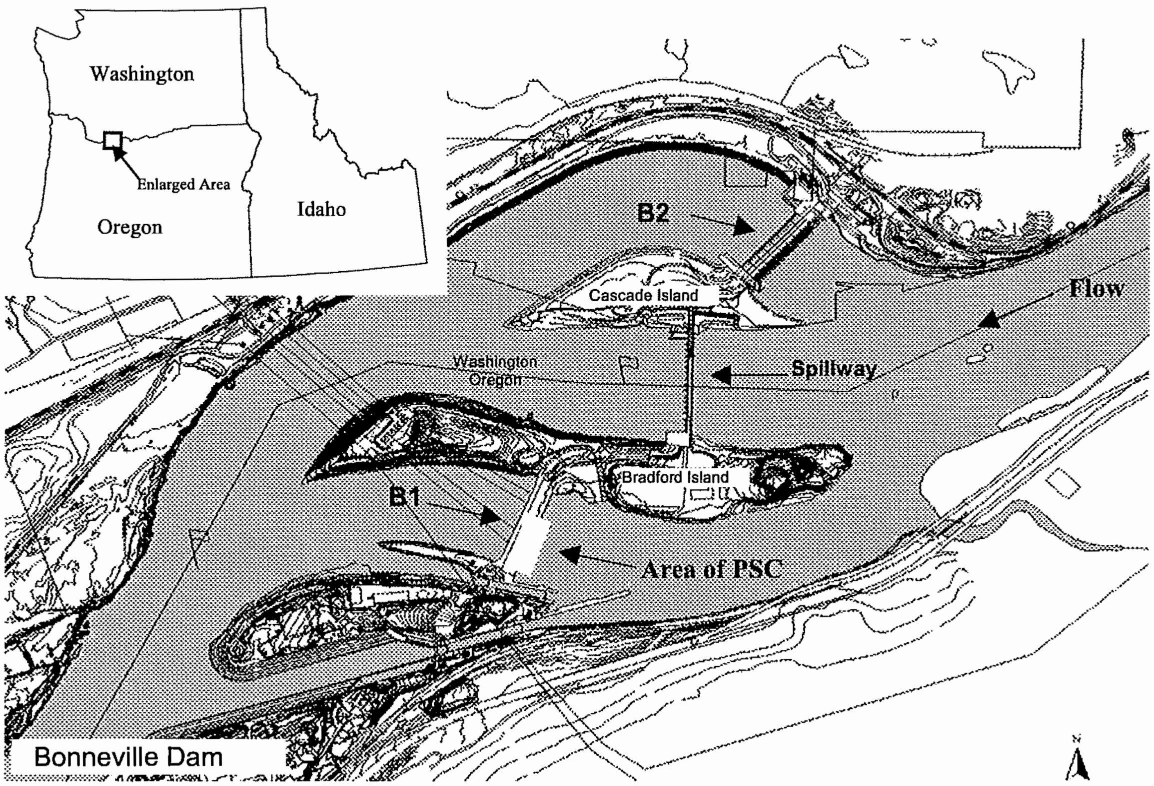

Figure 1. Plan view of Bonneville Dam on the Columbia River showing the second powerhouse (B2), the spillway, and the area of the Prototype Surface Collector (PSC) at Bonneville's first powerhouse (B1).

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 $FPE_{w/PSC}$.

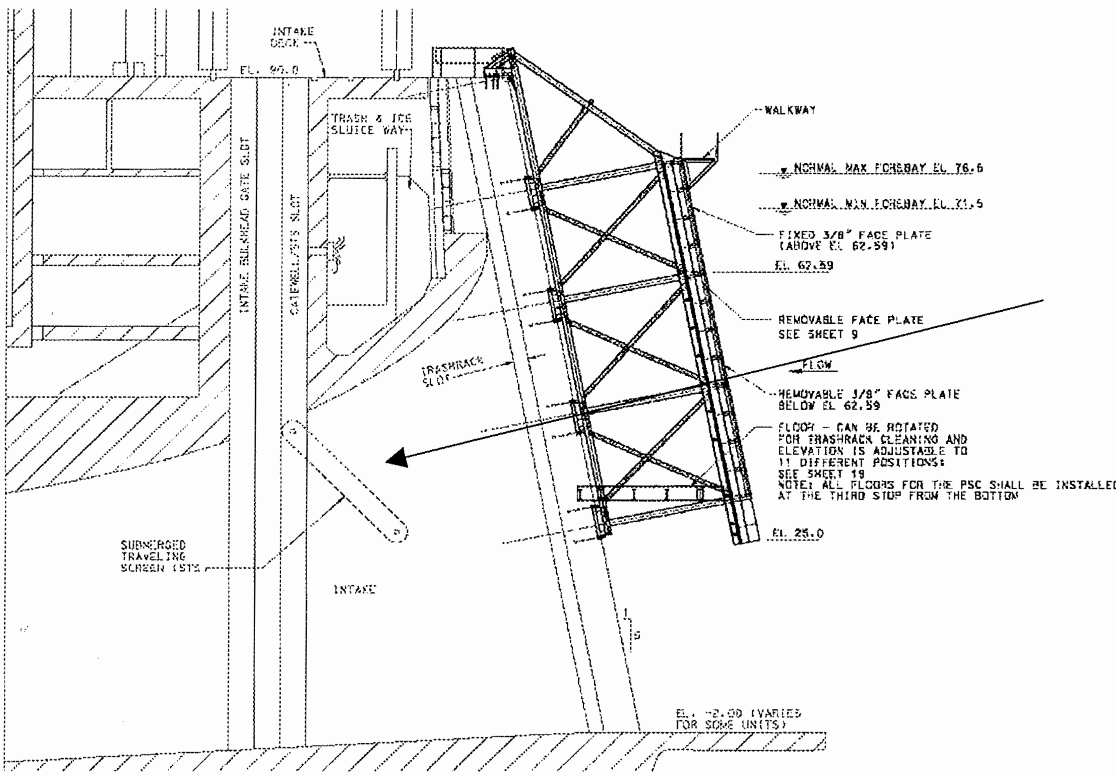

Figure 2. Side view of the PSC in front of turbine units 1-6 at B1. Arrow shows direction of flow through the PSC and into the turbine intakes.

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.

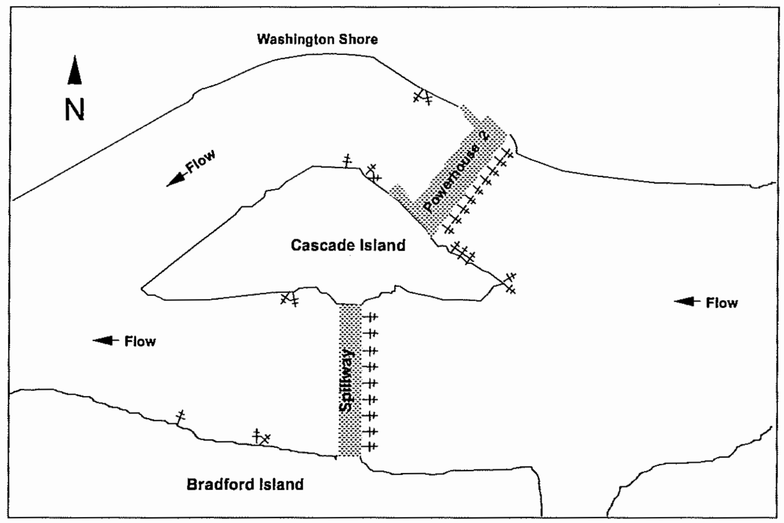

Figure 3. Plan view of aerial antenna coverage at the spillway and Bonneville's second powerhouse (B2) during spring 2000.

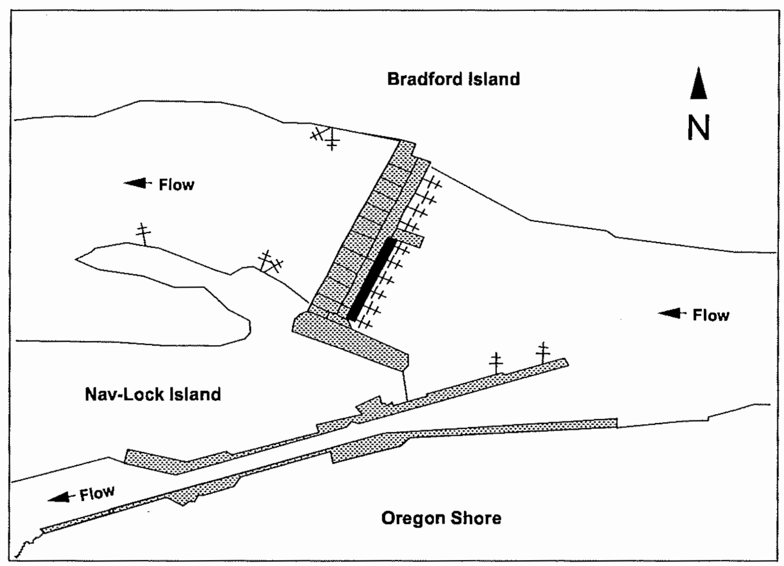

Figure 4. Plan view of aerial antenna coverage at Bonneville's first powerhouse (B1) during spring 2000.

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 standard-length submersible traveling screens (STS), B2 downstream migration channel (DSM), and B2 sluice chute, were coupled with digital spectrum processors. These receivers had essentially no scan time because a DSP acquires 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. Screen antennas were then combined to provide turbine unit-specific passage information. Eight stripped co-ax antennas located at each "C-slot" turbine gatewell orifice monitored passage through the DSM at B2. One aerial antenna and one 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 otherwise would not be apparent until post-processing.

At B1, 42 underwater antennas monitored the PSC and were coupled to a single MITAS. Twenty underwater antennas linked to a second MITAS monitored the DSM and turbine intake 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 documented 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.

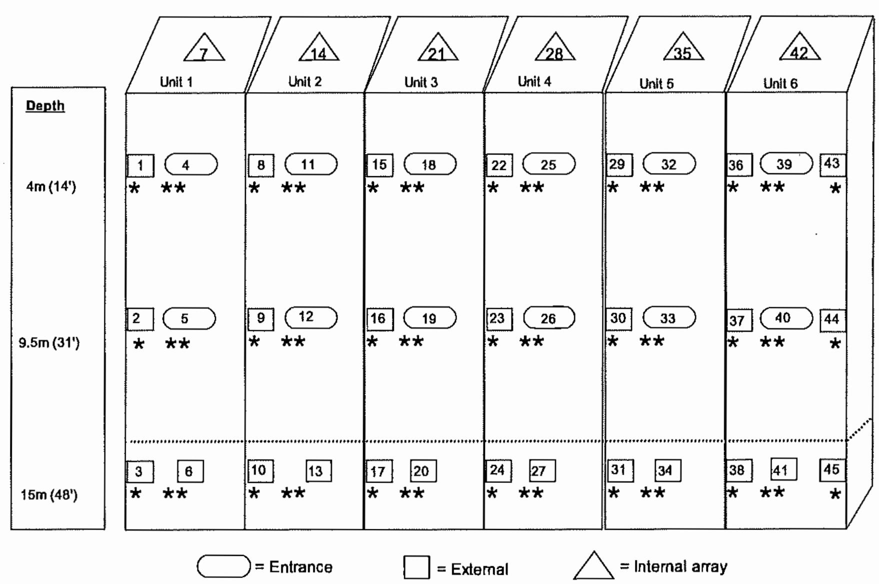

Figure 5. Front view of PSC showing location of underwater antennas. Dotted line indicates the location of the PSC's internal floor.

Ten stripped co-axial antennas were located inside the DSM at B1 (one at each "C-slot" gatewell orifice of each turbine) to document 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 (Lotek) were implanted in steelhead and chinook salmon. Two transmitter sizes were used to accommodate the different sizes of the two species. Transmitters implanted in steelhead were 8.2 mm (diameter) x 18.9 mm and weighed 1.75 g in air, while the transmitters implanted in chinook salmon were 7.3 mm (diameter) x 18 mm and weighed 1.4 g in air. The antenna length was 30 cm for both transmitters. The pulse rate was 2.0 s, resulting in an estimated minimum tag life of 15 d for steelhead transmitters and 8 d for chinook salmon transmitters.

2.5 Tagging, Fish Handling, and Release

Juvenile salmon and steelhead 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 Rock Creek, John Day Juvenile Fish Bypass Facility, 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 above Hood River can be found in Allen et al. (2000), Beeman et al. (2000), and Duran et al. (2000).

We collected juvenile hatchery steelhead and juvenile hatchery spring 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 min. 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 prior to 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. All data was 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 collected prior to a 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 duration 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 are a minimum estimate of the actual time that radio-tagged fish spend in the near-dam area because of receiver limitations and detection probabilities. For example, fish may enter the forebay before they are first detected and may remain following their last detection. Additionally, fish that approach very deep may have a low probability of detection, and thus pass the dam undetected.

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

- Spillway efficiency (SE) = $\frac{SP}{(B1 + SP + B2)}$

- Spillway effectiveness (SF) = $\frac{SE}{F_{sp} / F_{tot}}$

- Fish guidance efficiency (FGE) = $\frac{G_{tot}}{(G_{tot} + UG_{tot})}$

- Fish passage efficiency (FPE) = $\frac{SP + SL + G_{tot}}{TOT_{pass}}$

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) = $\frac{W_{1-6}}{T}$

- PSC entrance efficiency ($EE_{1\text{-}6}$) = $\frac{P_{1-6}}{W_{1-6}}$

- PSC collection efficiency ($CE_{1\text{-}6}$) = $\frac{C_{1-6}}{(C_{1-6} + U_{1-6})}$

- 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 13 April to 1 June 2000, we radio-tagged and released 1,193 steelhead and 2,075 chinook salmon. Of the steelhead, 252 were released from Hood River, 454 were released from John Day Dam, and 487 were released from Rock Creek. Of the chinook salmon, 252 were released from Hood River (rkm 315), 882 were released from The Dalles Dam (rkm 356), 457 were released from John Day Dam (rkm 400), and 484 were released from Rock Creek (rkm 426). Fish releases occurred throughout the central portion of the "in-river" seaward migration period (Figure 6). For steelhead released at Hood River, mean fork length was 222.0 mm, mean weight was 100 g, and the radio tag represented 1.8% of mean weight. For chinook salmon released at Hood River, mean fork length was 155.1 mm, mean weight was 41.5 g, and the radio tag represented 3.3% of mean weight. Mortality before release into the reservoir at Hood River was no steelhead and one (0.4%) chinook salmon. Fifteen (5.6%) steelhead and 21 (7.6%) chinook salmon regurgitated their tags during the 24-hour holding period. Tagging summaries for fish released upstream of Hood River are reported by Allen et al. (2000), Beeman et al. (2000), and Duran et al. (2000).

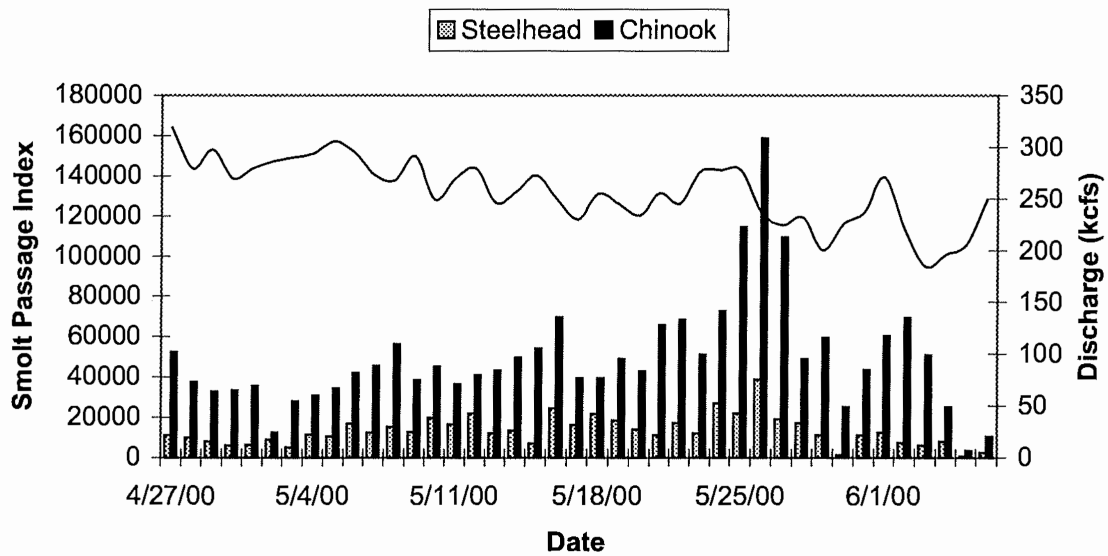

Figure 6. Mean daily river discharge through Bonneville Dam and the Smolt Passage index from Bonneville Dam's Second Powerhouse (B2) fish collection facility for steelhead and chinook salmon during spring 2000. Smolt index data were acquired from the Fish Passage Center web page at www.fpc.org. Discharge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

3.2 River Discharge and Project Operations

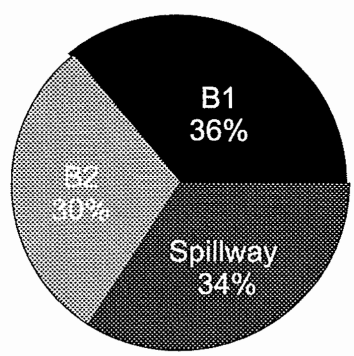

Figure 7. Discharge allocation between dam areas of Bonneville Dam during spring 2000.

During spring 2000 (April 27- June 6), mean river discharge was 257.4 kcfs, with a minimum mean daily discharge of 184.4 kcfs and a maximum mean daily discharge of 318.6 kcfs. Over the study period, mean daily discharge fluctuated but tended to decrease. Allocation of mean river discharge among dam areas was 34% through spill, 36% through B1, and 30% through B2 (Figure 7 and Table 1). Spill averaged 88.6 kcfs and ranged from 78.6 to 119.2 kcfs. Mean daily spill remained stable throughout the study period, and usually occurred 24 h/d. Mean discharge at B1 (turbines 1–10) was 92.4 kcfs and mean daily discharge ranged from 80.0 to 106.9 kcfs. Similar to spill, mean daily discharge through B1 remained uniform throughout the study. At B2, mean discharge was 76.4 kcfs and mean daily discharge ranged from 2.1 to 129.8 kcfs (Figure 8). Mean daily discharge at B2 had an identical fluctuation and decrease to that of the mean daily river discharge.

Table 1. Mean project discharge (kcfs) for Bonneville Dam during spring 2000. Values have been rounded to the nearest tenth. Data obtained from G. Ploskey (October 26, 2000).

Dam Area	Mean	Median	Min	Max
B1	92.4	92.8	80.0	106.9
B2	76.4	82.0	2.1	129.8
Spillway	88.6	87.3	78.6	119.2
Total	257.4	256.4	184.4	318.6

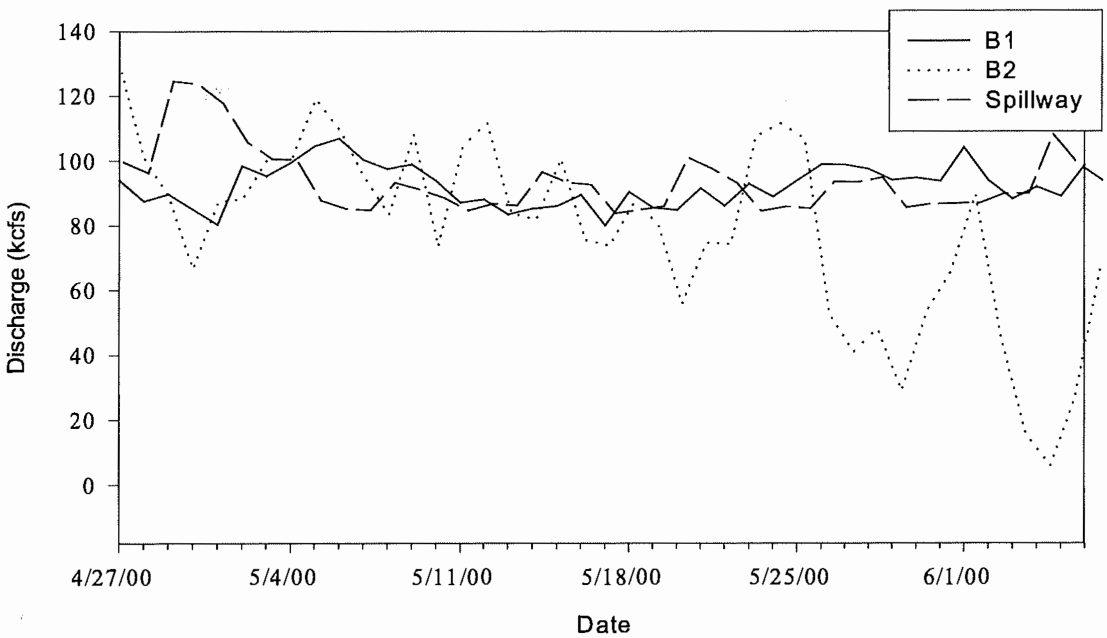

Figure 8. Mean daily discharge by dam area at Bonneville Dam during spring 2000. Data obtained from G. Ploskey (October 26, 2000).

Turbines 1-6 represented 60% and turbines 7-10 represented 40% of the mean discharge at B1. Additionally, from May 11 to May 25, turbine unit 10 was not operated which resulted in a mean discharge through turbines 7-10 of about 30 kcfs during this period. Mean daily discharge through turbines 1-6 fluctuated, but remained relatively uniform over the study period (Figure 9).

In relation to the PSC, we compared mean discharge through turbines 1-6 and found that about 33% (mean 18.3 kcfs) of the discharge flowed through the PSC and the remaining 67% (mean 37.0 kcfs) flowed under the PSC, directly into turbines 1-6 (Figure 10 and Table 2). We compared mean discharge between day and night and found that discharge at B1 was relatively equal during day (from 0500 to 1900 hours) and night (from 2000 to 0400 hours). At B2, discharge was higher during the day and at the spillway, discharge was higher during night (Table 3).

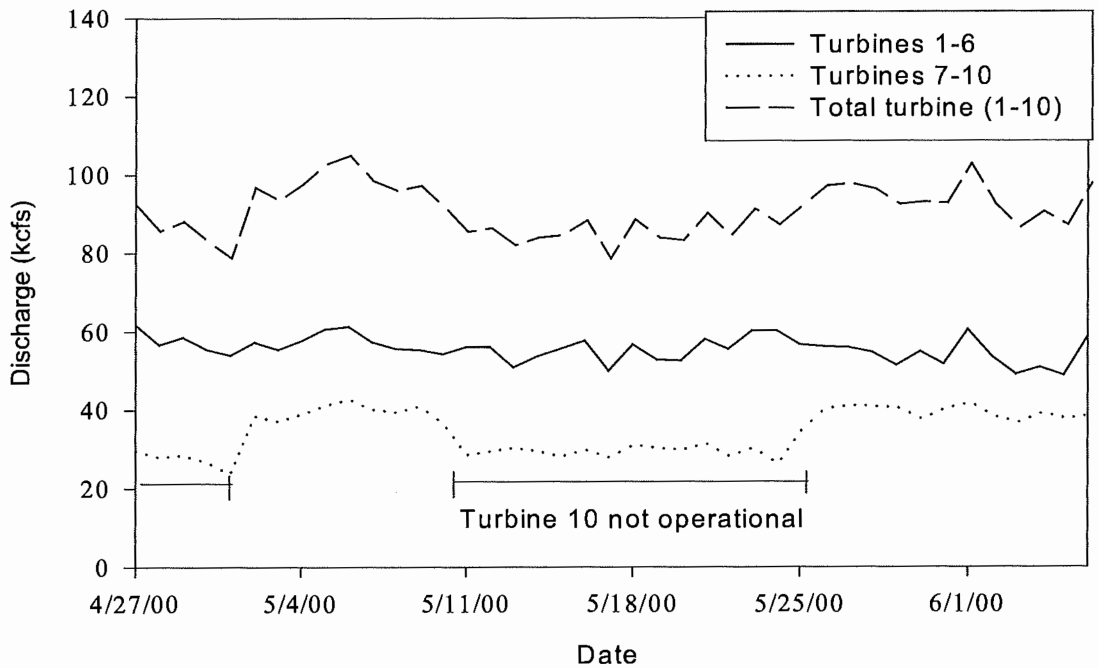

Figure 9. Mean daily discharge through turbines 1-6 and turbines 7-10 during spring 2000. Data obtained from G. Ploskey (October 26, 2000).

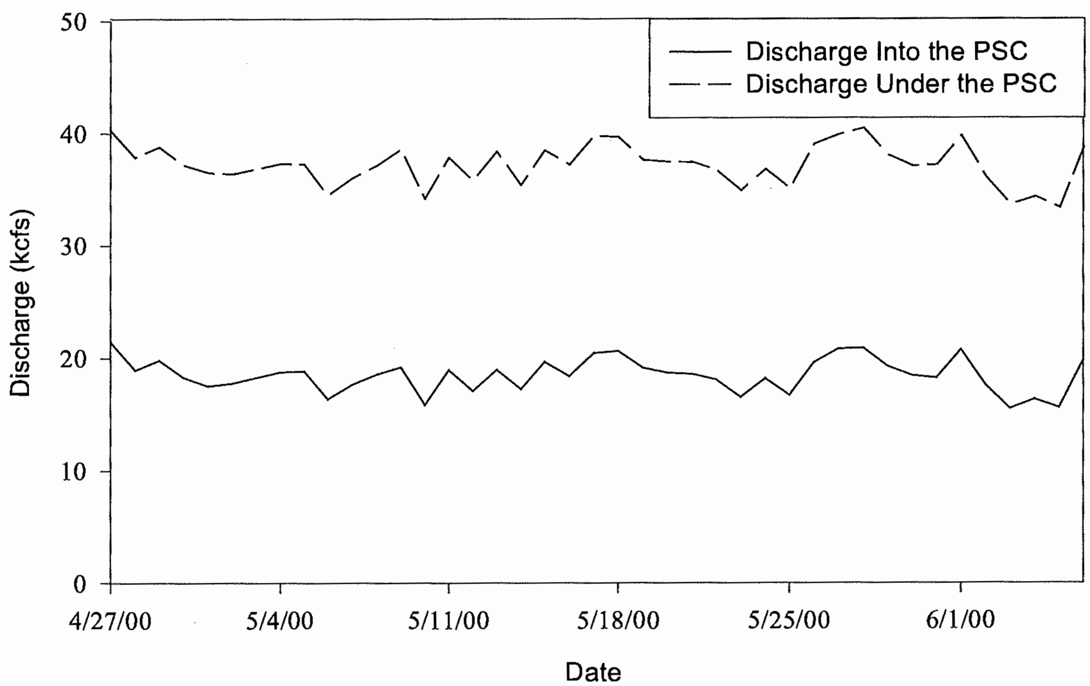

Figure 10. Mean daily discharge into and under the PSC at B1 (turbine units 1 through 6) during spring 2000. Data obtained from G. Ploskey (October 26, 2000).

Table 2. Mean discharge (cfs) into and under the PSC during spring 2000. Data obtained from G. Ploskey (October 26, 2000).

Into PSC at turbine unit	Mean	Median	Min	Max
Total into the PSC	18,750.0	18,730.0	15,490.0	22,440.0
Unit 1	3094.6	3069.0	2123.5	2344.3
Unit 2	3180.3	3156.8	2684.5	3782.9
Unit 3	3176.0	3265.8	1206.9	3812.7
Unit 4	3041.0	3040.0	2348.7	3705.0
Unit 5	3157.2	3172.5	2087.5	3815.4
Unit 6	3100.1	3188.4	1161.6	3681.7
Under PSC at turbine unit	**Mean**	**Median**	**Min**	**Max**
Total under the PSC	37,510.0	37,330.0	33,330.0	41,750.0
Unit 1	6213.5	6164.0	4985.5	6838.4
Unit 2	6320.4	6281.1	5673.5	7011.3
Unit 3	6315.1	6375.8	3818.8	7079.3
Unit 4	6146.6	6139.2	5330.1	6914.1
Unit 5	6291.6	6296.9	4953.7	7080.1
Unit 6	6220.4	6321.9	3816.2	6

Table 3. Mean discharge (kcfs) during day (0500- 2059) and night (2100- 0459) by dam area during spring 2000. Data obtained from G. Ploskey (October 26, 2000).

Dam Area	Period	Percent (of mean)	Mean	Median	Min	Max
B1	Day	36%	92.8	93.1	3.0	114.6
B2	Day	31%	78.8	79.8	2.2	140.8
Spillway	Day	33%	84.7	84.5	0	123.2
B1	Night	35%	91.1	90.6	42.5	110.6
B2	Night	28%	71.6	76.0	0	139.0
Spillway	Night	37%	95.3	94.7	0	121.3

3.3 Travel to and Arrival at Bonneville Dam

The median travel time to Bonneville Dam increased as the distance from the release site to the dam increased. Of the fish released from Rock Creek, median travel time to Bonneville Dam was 75.7 h for steelhead and 67.7 h for chinook salmon. The median time to travel to Bonneville Dam from John Day Dam was 41.1 h for steelhead and 45.5 h for chinook salmon. The median travel time for chinook salmon released at The Dalles Dam was 31.2 h (no steelhead were released from The Dalles Dam). Of the fish released from Hood River, median travel time was 13.9 h for steelhead and 14.3 h for chinook salmon (Table 4). We compared median travel rates by release site and found that rates were highest for steelhead (2.79 km/h) and chinook salmon (2.73 km/h) released from Hood River. The lowest median travel rates were observed for fish released at Rock Creek (Table 4).

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

Steelhead					
Release Site	**Mean**	**Median**	**STD**	**Min**	**Max**
Hood River Bridge	15.7 (2.7)	13.9 (2.8)	8.8 (0.6)	9.5 (0.3)	123.3 (4.1)
John Day Dam	45.2 (2.7)	41.1 (2.8)	15.5 (0.5)	29.7 (0.7)	159.9 (3.9)
Rock Creek	86.4 (1.8)	75.7 (1.9)	40.1 (0.5)	41.5 (0.4)	313.4 (3.3)
Chinook salmon					
Release Site	**Mean**	**Median**	**STD**	**Min**	**Max**
Hood River Bridge	17.7 (2.7)	14.3 (2.7)	10.4 (0.8)	9.7 (0.4)	92.3 (4.0)
The Dalles Dam	32.8 (2.4)	31.2 (2.4)	8.2 (0.5)	19.8 (0.9)	84.9 (3.8)
John Day Dam	49.4 (2.4)	45.5 (2.5)	13.7 (0.5)	32.6 (0.9)	129.7 (3.5)
Rock Creek	73.5 (2.0)	67.7 (2.0)	24.4 (0.5)	32.7 (0.5)	256.8 (4.2)

A comparison of first detections by dam area (i.e., B1, B2, and Spillway) revealed differences between the proportions of each species entering each dam area. Of the steelhead, 45% (338 of 757) first entered B1, 36% (272 of 757) first entered the spillway, and 19% (147 of 757) first entered B2. The proportion of chinook salmon that entered each area of the dam was 29% (384 of 1,298) at B1, 48% (620 of 1,298) at the spillway, and 23% (294 of 1,298) at B2. 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 B2 and the spillway, daily proportions of steelhead fluctuated with the proportion of daily discharge. The relation between the daily proportion of steelhead entering B1 and the proportion of discharge allocated to B1 was not as apparent as the other two dam areas (Figure 11). Similar results were observed when the daily proportions of chinook salmon were compared to daily discharge allocation (Figure 12). Although each species exhibited a "preference" for a particular dam area (B1 for steelhead and the spillway for chinook salmon), the proportion of discharge to each dam area did influence the proportion of fish that entered a dam area.

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 a relation. The most apparent relation was the hourly proportion of steelhead that entered B2 versus the hourly proportion of discharge allocated to B2 (Figure 13). Only a slight increase was observed in the hourly proportion of chinook salmon that entered B2 and the spillway with an increase in the hourly proportion of discharge at these locations (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.

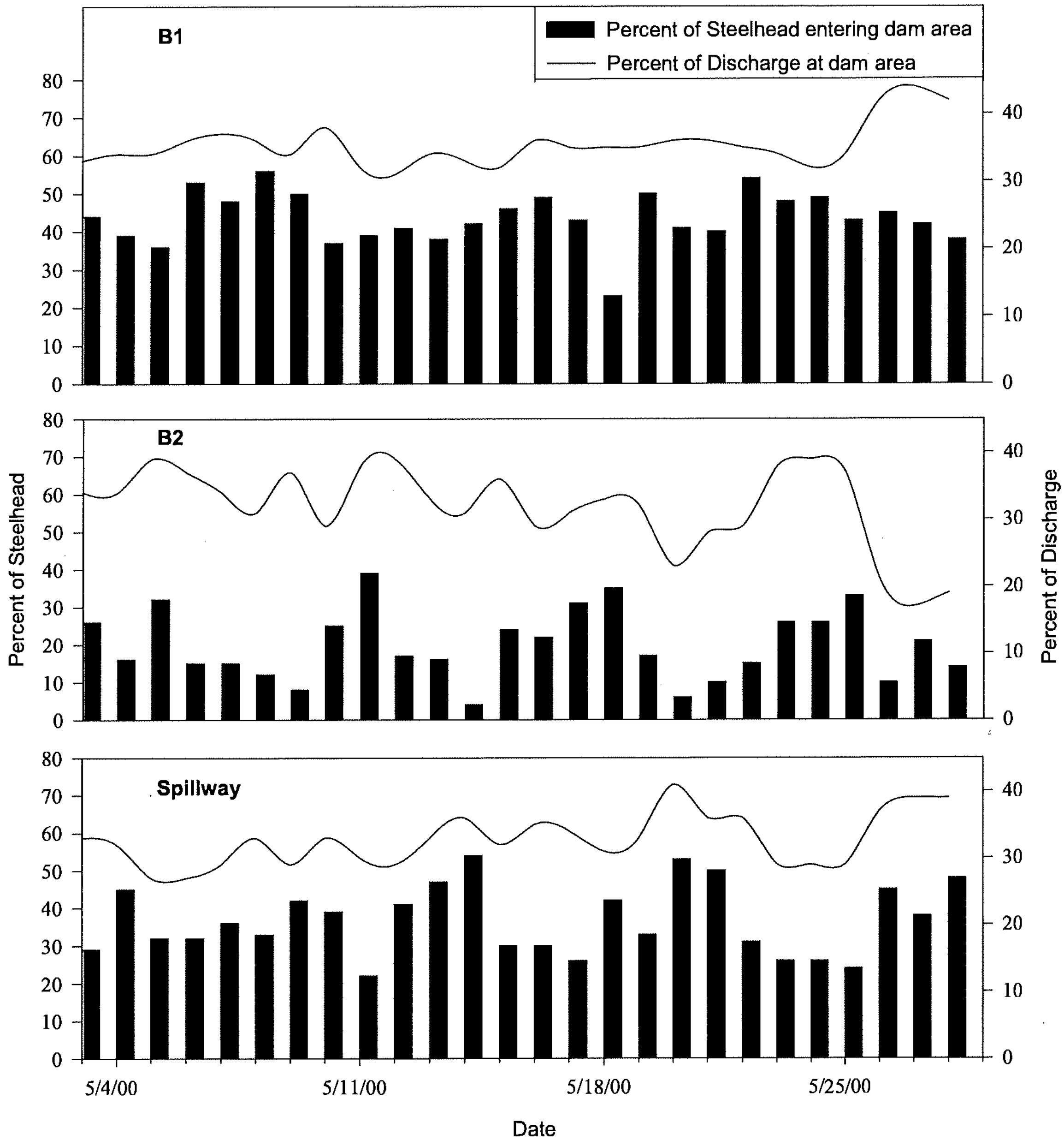

Figure 11. The percentage of steelhead that entered each dam area versus the percentage of mean discharge at each dam area by day during spring 2000.

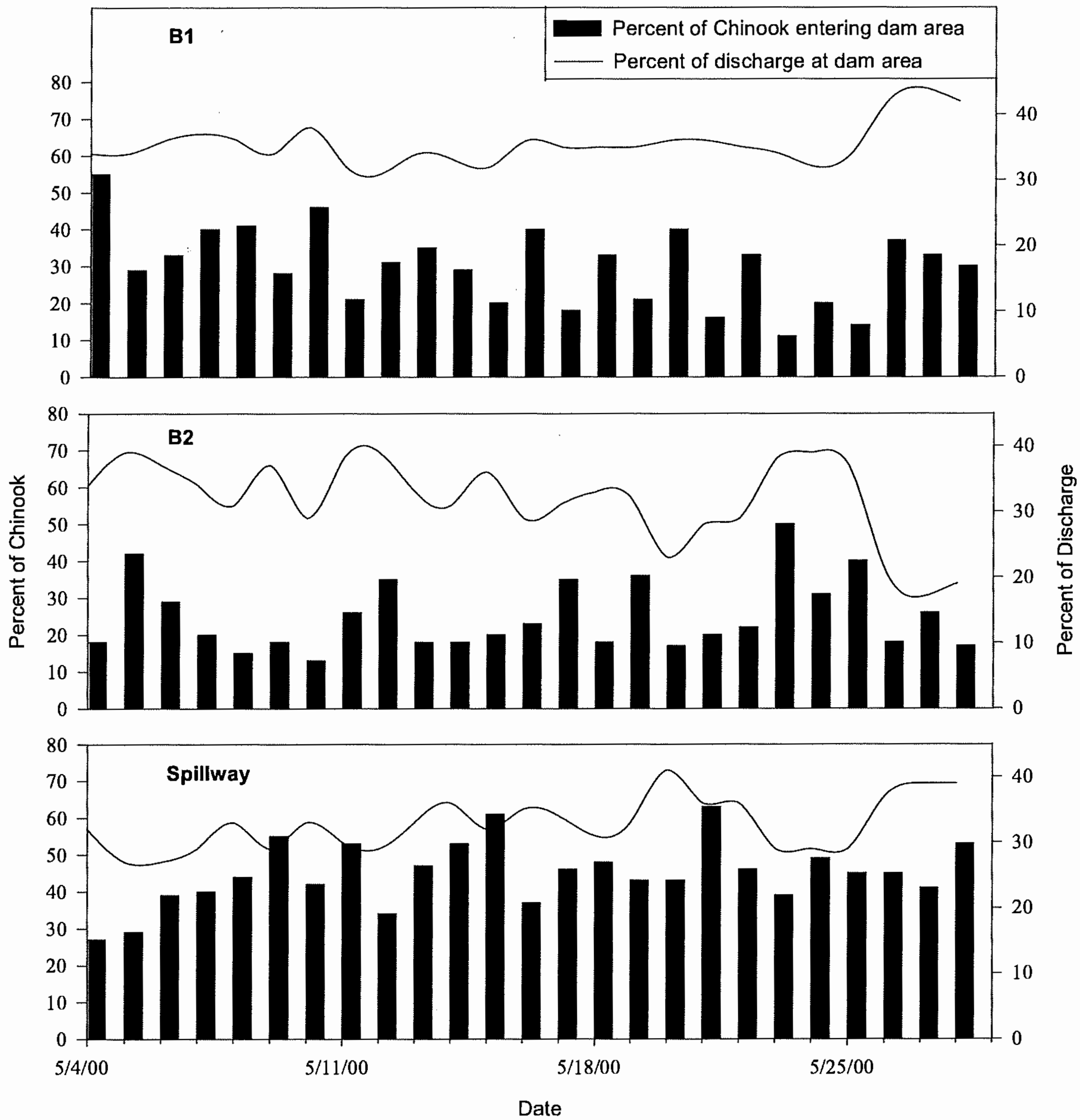

Figure 12. The percentage of chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by day during spring 2000.

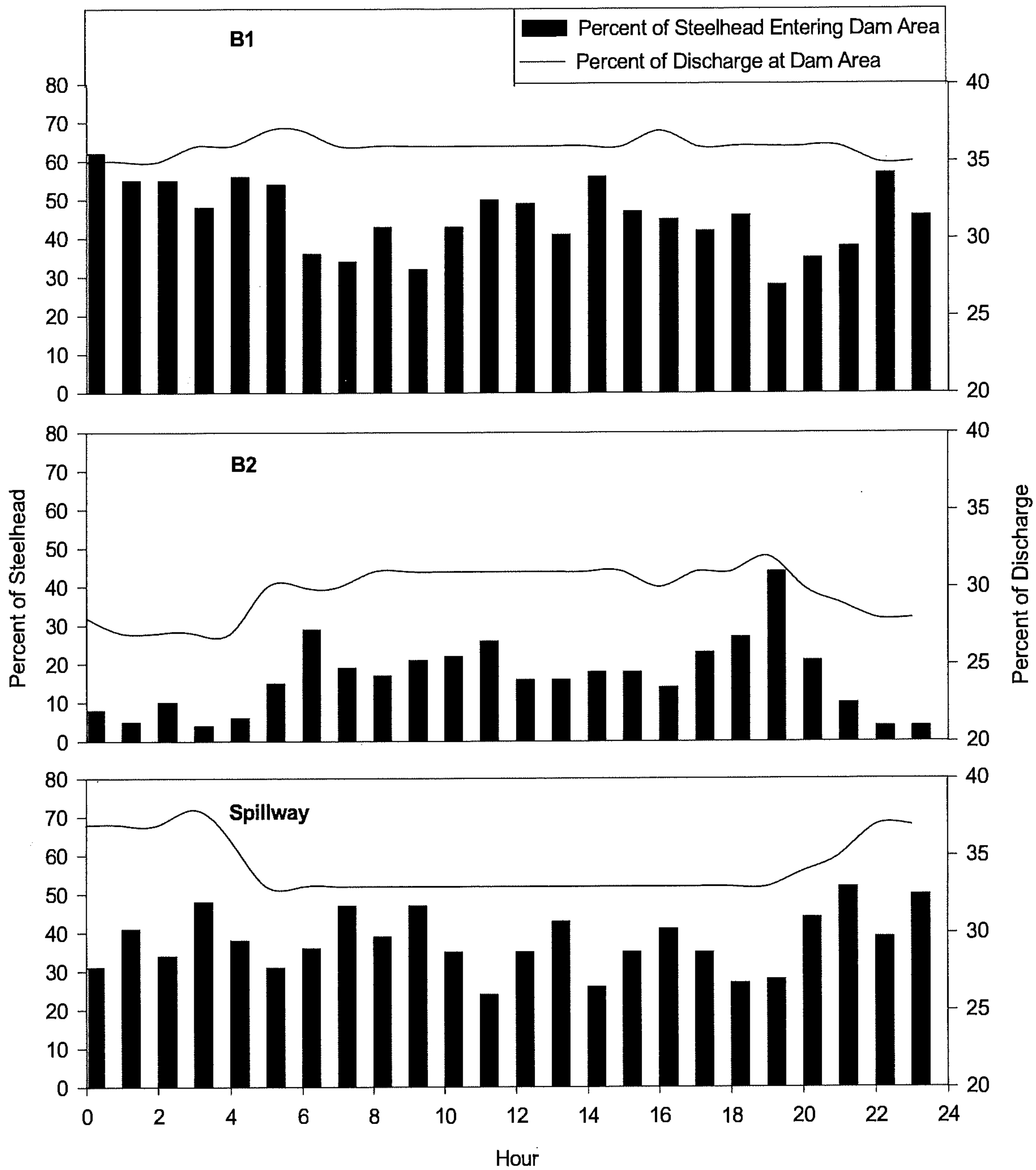

Figure 13. The percentage of steelhead that entered each dam area versus the percentage of mean discharge at each dam area by hour of day during spring 2000.

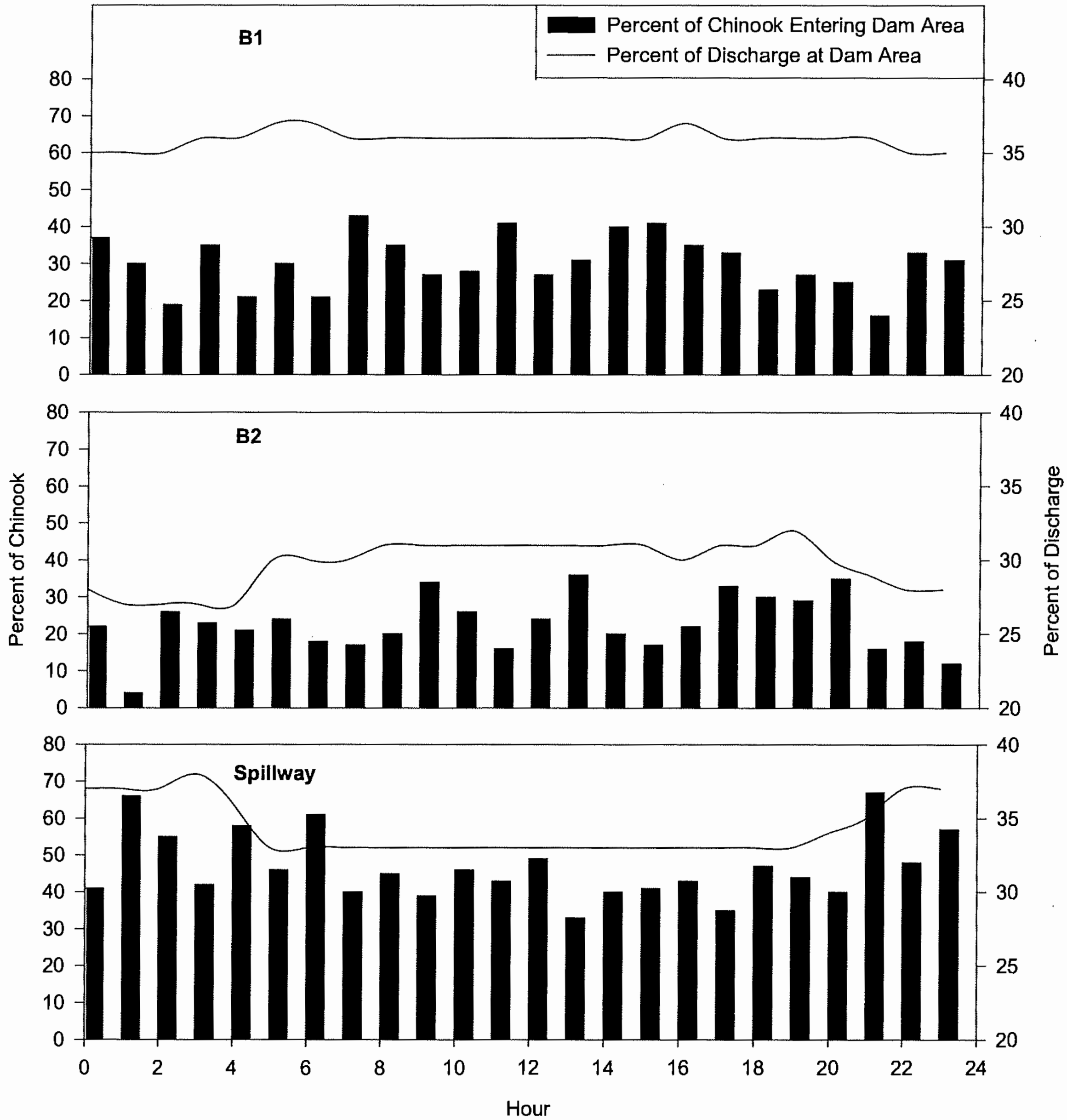

Figure 14. The percentage of chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by hour of day during spring 2000.

3.4 Detections at Bonneville Dam

At Bonneville Dam, we detected 80% (957 of 1193) of steelhead and 82% (1703 of 2075) of chinook salmon that were released from Rock Creek, John Day Dam, The Dalles Dam, and Hood River Bridge. Of the fish released at Rock Creek, we detected 75% (365 of 487) of the steelhead and 74% (360 of 484) of the chinook salmon. Of the fish released at the John Day Juvenile Fish Bypass Facility, we detected 78% (352 of 454) of the steelhead and 75% (341 of 457) of the chinook salmon. Eighty-seven percent (764 of 882) of the chinook salmon released from the The Dalles Dam were detected at Bonneville Dam. Of the fish released just below Hood River Bridge, 95% (240 of 252) of steelhead and 94% (238 of 252) of chinook salmon were detected at Bonneville Dam.

3.5 Residence Time in the Forebay

Forebay residence time differed between dam areas. For both species, the greatest median time spent in the forebay was observed at B1 and the shortest median time spent in the forebay was observed at the spillway (Table 5). The median forebay residence time for steelhead was greater than that observed for chinook salmon.

Table 5. Descriptive statistics of forebay residence time (h) for radio-tagged steelhead and chinook salmon by dam area of Bonneville Dam during spring 2000. Note: If fish passed at a dam area different than the one they first entered, they were excluded from calculations of forebay residence time.

Species	Dam Area	N	Mean	Median	Std	Min	Max
Steelhead	B1	335	19.67	9.65	31.46	0.01	258.34
Steelhead	B2	147	9.36	6.40	13.37	0.01	125.01
Steelhead	Spillway	272	1.62	0.48	3.21	0.01	24.52
Steelhead	All areas	754	11.15	3.22	23.30	0.01	258.34
Chinook	B1	382	9.84	3.43	16.06	0.01	103.87
Chinook	B2	294	6.15	1.33	11.51	0.01	95.51
Chinook	Spillway	619	0.36	0.13	0.94	0.02	9.34
Chinook	All areas	1,295	4.70	0.25	11.12	0.01	103.87

We compared median forebay residence time by day to mean daily discharge and found no relation (Appendix 1 and 2). In addition, we calculated the median forebay residence time by the hour fish entered a dam area and compared this to the mean hourly discharge. This comparison demonstrated a relation between forebay residence time, discharge, and day and night behavioral responses, particularly for steelhead. For instance, during daylight hours, steelhead that arrived during periods of lower discharge had a greater forebay residence time than steelhead that arrived during a higher discharge. However, despite a lower discharge at B1 and B2 during night, forebay residence time remained relatively short during hours of darkness. At the spillway, discharge increased through the night and forebay residence time for both species was least during night (Figures 15 and 16).

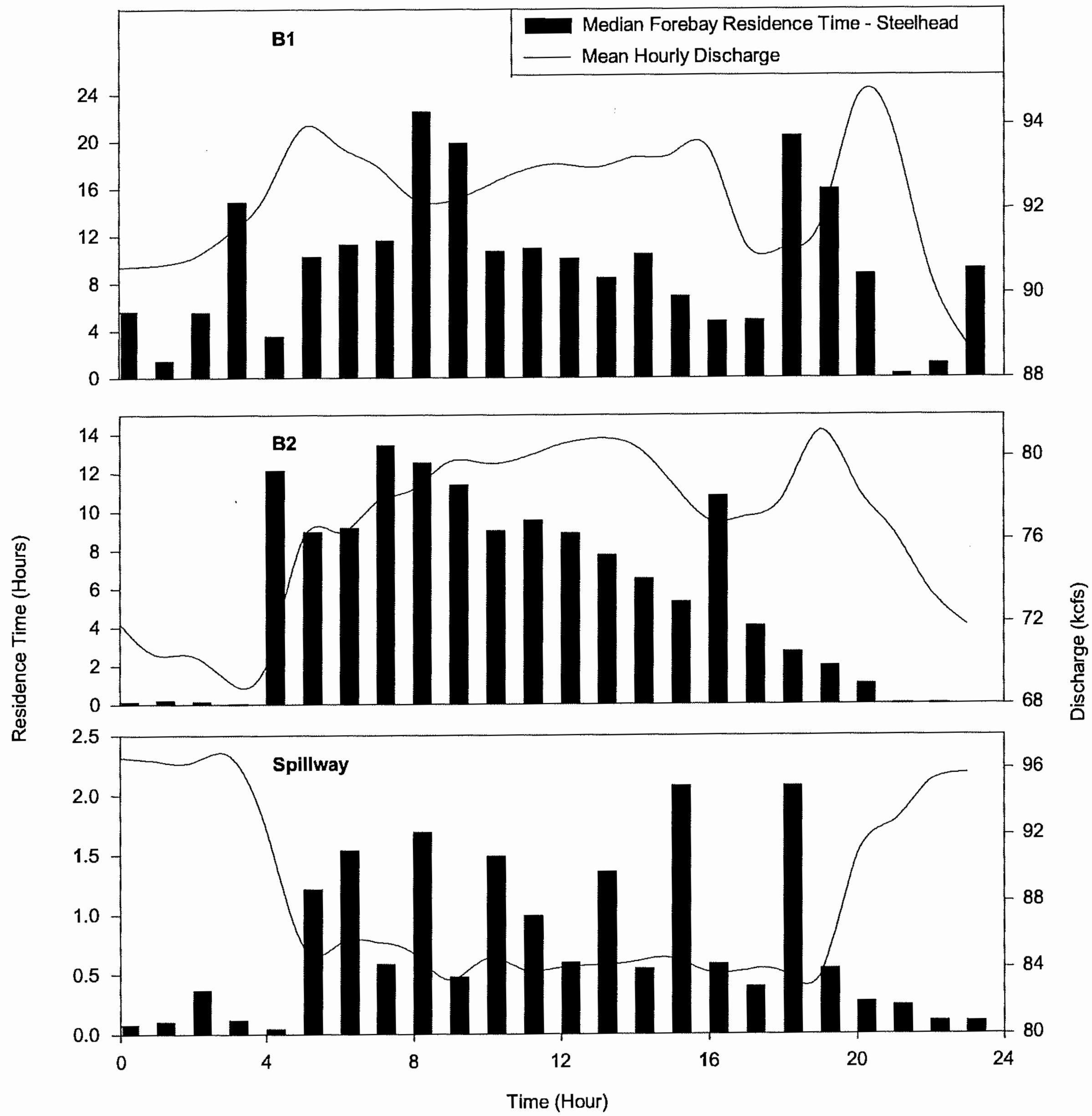

Figure 15. Median forebay residence time by the hour steelhead entered a dam area versus mean daily discharge through each dam area during spring 2000.

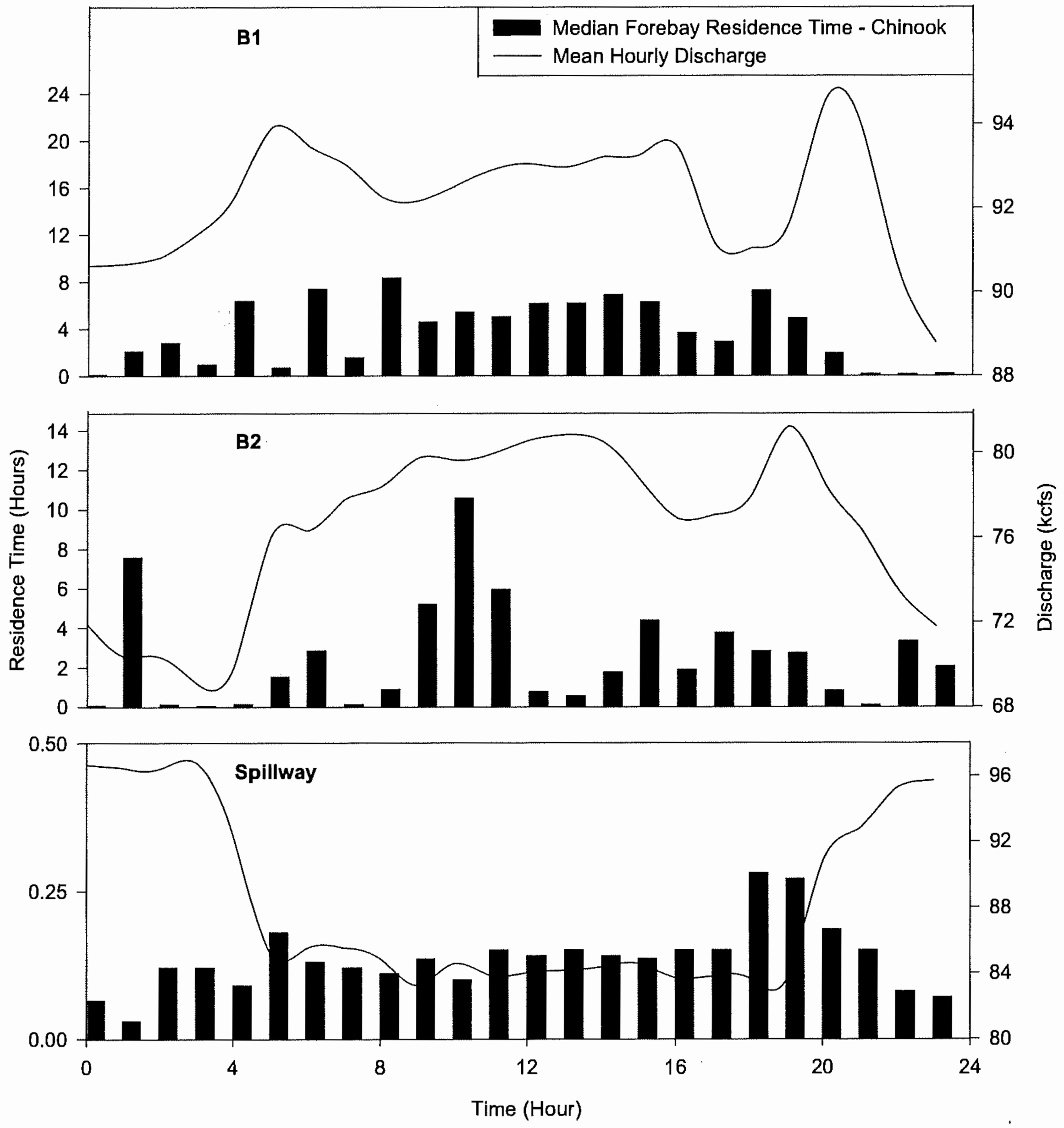

Figure 16. Median forebay residence time by the hour chinook salmon entered a dam area versus mean daily discharge through each dam area during spring 2000.

3.6 Route and Time of Passage Through Bonneville Dam

We determined the route of passage through Bonneville Dam for 91% (868 of 957) of steelhead and 92% (1569 of 1703) of chinook salmon. Seven percent (67 of 957) of steelhead and 6% (94 of 1703) of chinook salmon passed the dam but a passage route could not be determined. Two percent (22 of 957 for steelhead and 40 of 1703 for chinook salmon) of both species were not detected below Bonneville Dam.

Nearly half of steelhead passed at B1 and the majority of chinook salmon passed through the spillway. Of the steelhead detected passing the dam, 49% (459 of 935) passed through B1, 33% (306 of 935) passed via the spillway, 17% (164 of 935) passed through B2, and 1% (6 of 935) passed through an unknown route of passage. Of the chinook salmon detected passing the dam, 31% (515 of 1663) passed through B1, 44% (736 of 1663) passed via the spillway, 24% (402 of 1663) passed through B2, and 1% (10 of 1663) passed through an unknown route of passage (Figure 17).

At B1, of the steelhead with known passage routes, 44% (176 of 399) passed via the sluiceway, 33% (131 of 399) were guided into the DSM and 23% (92 of 399) were unguided through the turbines. An additional 60 steelhead passed B1 through an undetermined route. Equal numbers of chinook salmon were guided (153; 36%) and unguided (152; 35%) at B1 and 29% (126 of 431) passed via the sluiceway (Figure 17). A passage route could not be determined for 84 chinook salmon that passed at B1. Slightly more steelhead (55%) were guided through the DSM at B2 than went unguided through the turbines (45%). The opposite was true for chinook salmon at B2 where 60% passed unguided through the turbines and 39% were guided into the DSM. Four (1%) chinook salmon were detected passing B2 through the sluice chute, which was operated minimally during spring 2000 (Figure 17).

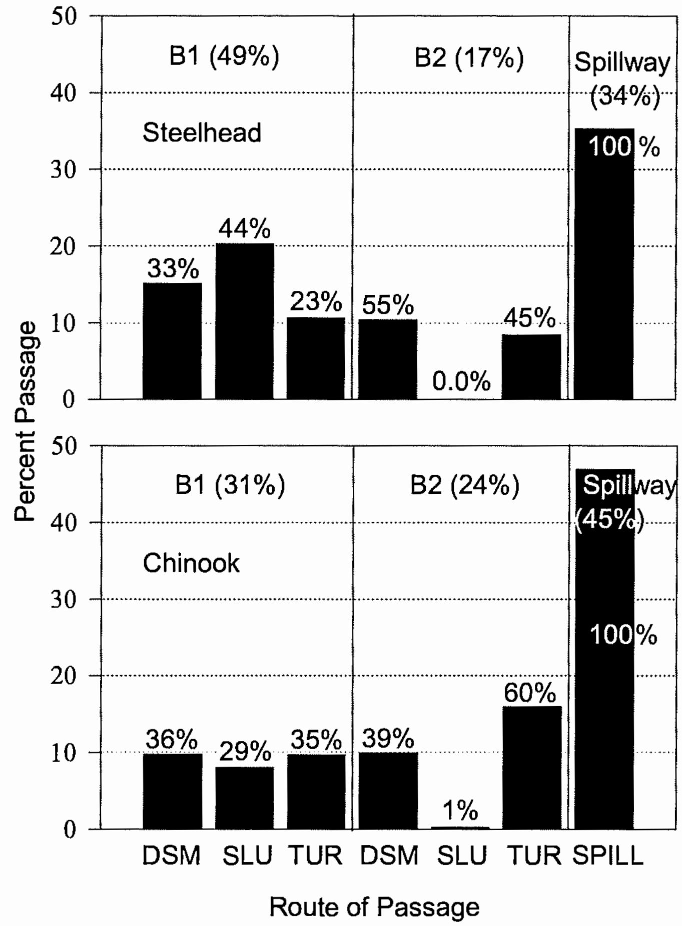

Figure 17. Percent fish passage by dam area and route of passage through Bonneville Dam for radio-tagged steelhead and chinook salmon, during spring 2000. Note: percentages within parenthesis designate proportions between dam areas, percentages without parenthesis designate proportions within dam area, and the percent value of the bars represent proportions of all passage routes.

Passage through Bonneville Dam occurred throughout the diel cycle with a peak observed at 2100 hours for both species (Figure 18). Route-specific and species-specific patterns were evident in regard to the diel cycle. At the spillway, a lower proportion of both species passed during night as compared to day. Likewise, a lower proportion of both species passed during night at B1. However, at B2, a higher proportion of steelhead and chinook salmon passed during the night (Table 6).

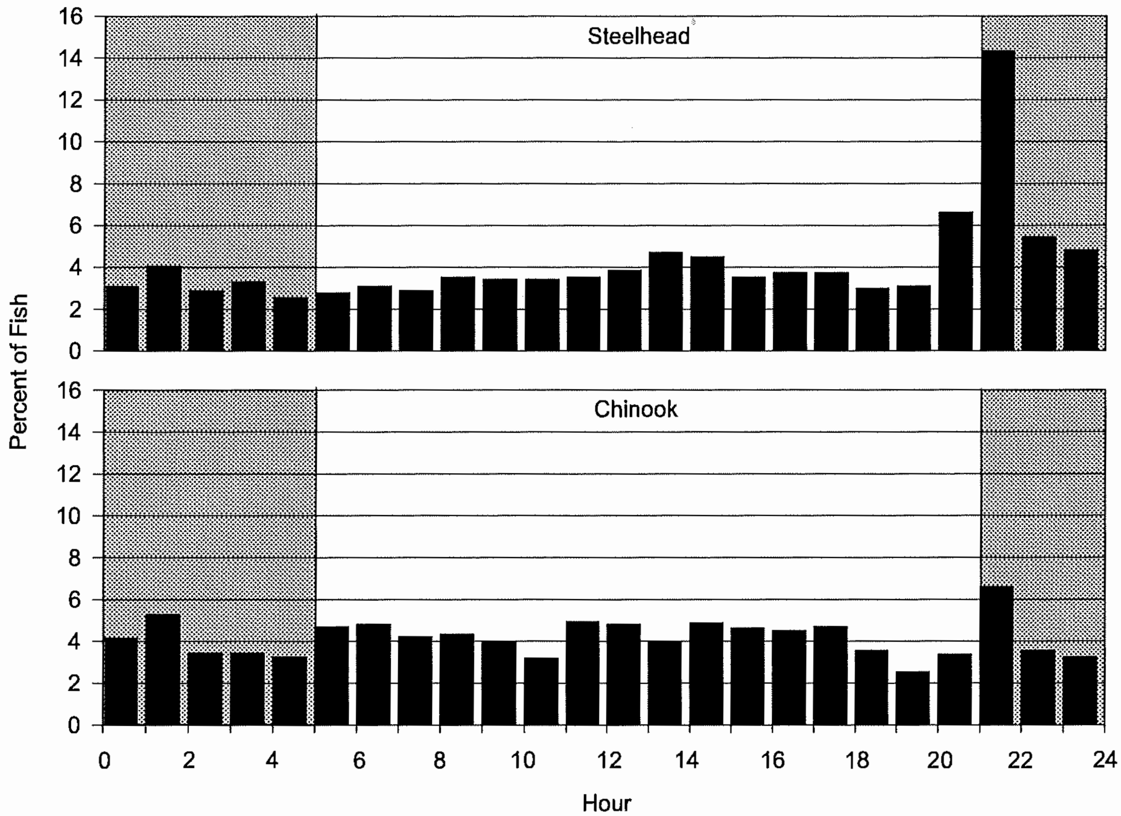

Figure 18. Percentage of steelhead and chinook salmon that passed Bonneville Dam by hour of day during spring 2000. Shaded areas represent night (2100 to 0459 hours) and unshaded areas represent day (0500 to 2059 hours).

Table 6. The proportion of radio-tagged steelhead and chinook salmon that passed each dam area of Bonneville Dam by day (0500 to 2059 hours) versus night (2100 to 0459 hours) during spring 2000.

Species	Period	B1 Passage	B2 Passage	Spill Passage
Steelhead	Day	50% (254 of 514)	11% (59 of 514)	39% (201 of 514)
Steelhead	Night	41% (145 of 354)	29% (104 of 354)	30% (105 of 354)
Chinook	Day	29% (310 of 1,055)	22% (233 of 1,055)	49% (512 of 1,055)
Chinook	Night	24% (121 of 514)	33% (169 of 514)	44% (224 of 514)

A general pattern observed, for both species, was that the shallower the passage route, the more fish passed during the day. Nineteen percent more steelhead and 8% more chinook salmon passed through the sluiceway at B1 during the day compared to night. Likewise, at B1 during daylight hours, a greater proportion of chinook salmon were guided into the DSM. At night, a greater proportion of steelhead and chinook salmon passed unguided through the turbines at B1 and B2 (Figure 19).

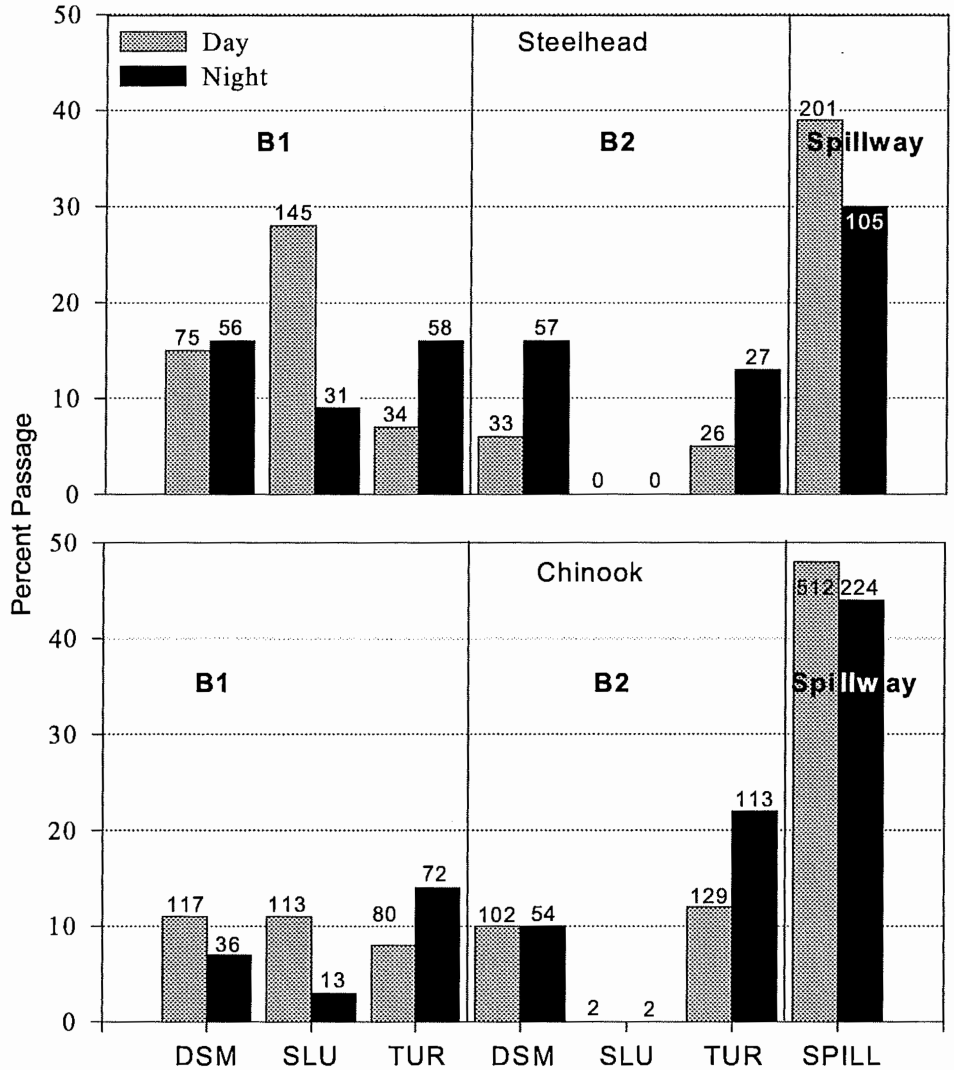

Figure 19. Percent passage by route of passage during day (0500 to 2059 hours) and night (2100 to 0459 hours) for radio-tagged steelhead and chinook salmon at Bonneville Dam during spring 2000.

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 spill, B1 and B2. Spillway efficiency at Bonneville Dam was 33% for steelhead and 44% for chinook salmon (Table 7).

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

Species	SE	B1 Passage	B2 Passage	Spill Passage
Steelhead	0.33	501	408	722
Chinook	0.44	448	164	301

3.7.2 Spillway Effectiveness

The proportion of fish that passed through spill relative to the proportion of discharge spilled (spillway effectiveness; SF) was 1.0 for steelhead and 1.3 for chinook salmon. In other words, the proportion of steelhead that passed through spill was equal to the proportion of water discharged as spill and the proportion of chinook salmon that passed through spill was one third greater than the proportion of water discharged as spill (Table 8).

Table 8. Spillway Effectiveness (SF) at Bonneville Dam for steelhead and chinook salmon during spring 2000.

Species	SF	SE	F_{sp}	F_{tot}
Steelhead	1.0	0.33	88.6	257.4
Chinook	1.3	0.44	88.6	257.4

3.7.3 Fish Guidance Efficiency

Fish guidance efficiency (FGE; number of fish guided divided by number guided plus number unguided) was higher at B1 (59% for steelhead, 50% for chinook salmon) than at B2 (55% for steelhead, 39% for chinook salmon). A comparison of FGE at units 1-6 (52%; location of PSC) to FGE at units 7-10 (48%) indicated that guidance was slightly higher for chinook salmon at units 1-6. However, steelhead had a slightly higher FGE at units 7-10 (61%) than at units 1-6 (58%; Table 9). Turbine units 8 (ESBS) and 3 were most efficient at guiding both species at B1 (Table 10). At B2, units 13 and 16 were most efficient for steelhead and unit 11 was most efficient for chinook salmon (Table 11).

Table 9. Estimates of Fish Guidance Efficiency (FGE) at Bonneville Dam for steelhead and chinook salmon during spring 2000.

Species	B1	Units 1-6	Units 7-10	B2
Steelhead	59% (131of 223*)	58% (70 of 121)	61% (61 of 100)	55% (90 of 163)
Chinook Salmon	50% (153 of 305**)	52% (91 of 174)	48% (62 of 128)	39% (156 of 398)

* Two steelhead were unguided at an undetermined unit.

** Three chinook salmon were unguided at an undetermined unit.

Table 10. Estimates of Fish Guidance Efficiency (FGE) by turbine unit at Bonneville's first powerhouse (B1) for steelhead and chinook salmon during spring 2000.

Turbines at B1									
1	2	3	4	5	6	7	8	9	10
Steelhead									
36% 5 of 14	29% 20 of 34	62% 13 of 21	64% 9 of 14	65% 11 of 17	57% 12 of 21	54% 15 of 28	83% 15 of 18	58% 18 of 31	57% 13 of 23
Chinook Salmon									
33% 3 of 9	64% 21 of 33	68% 23 of 34	43% 12 of 28	49% 21 of 43	41% 11 of 27	40% 16 of 40	66% 18 of 27	25% 6 of 24	59% 22 of 37

Table 11. Estimates of Fish Guidance Efficiency (FGE) by turbine unit at Bonneville's second powerhouse (B2) for radio-tagged steelhead and chinook salmon during spring 2000.

Turbines at B2							
11	12	13	14	15	16	17	18
Steelhead							
56% 28 of 50	59% 13 of 22	75% 15 of 20	64% 7 of 11	43% 3 of 7	75% 12 of 16	44% 7 of 16	25% 2 of 8
Chinook Salmon							
55% 40 of 73	39% 16 of 41	47% 26 of 55	38% 11 of 29	52% 12 of 23	37% 16 of 43	34% 20 of 59	35% 11 of 31

3.7.4 Fish Passage Efficiency

Fish passage efficiency (FPE; number of fish through non-turbine routes divided by number passed through known routes at B1, B2, and spill) at Bonneville Dam was 78% for steelhead and 73% for chinook salmon. 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 $FPE_{w/PSC}$. $FPE_{w/PSC}$ was 7% higher than FPE for steelhead and 5% higher than FPE for chinook salmon (Table 12).

Table 12. Fish Passage Efficiency (FPE) and $FPE_{w/PSC}$ for steelhead and chinook salmon during spring, 2000.

Species	FPE	$FPE_{w/PSC}$
Steelhead	78% (580 of 745)	85% (746 of 880)
Chinook	73% (1069 of 1463)	78% (1247 of 1599)

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. Over half of the fish that entered B1 eventually discovered the PSC (Table 13). Of the fish that were detected at B1, 74% (356 of 481) of steelhead and 63% (341 of 545) of chinook salmon were detected within 6 m of the PSC.

The denominator of these estimates include fish that entered B1 but were not detected passing B1 (33 steelhead and 44 chinook salmon). The median time from first detection in the B1 forebay to first detection at the PSC (within 6 m) was 31.8 min for steelhead and 7.2 min for chinook salmon.

Table 13. Discovery Efficiency (DE) of the PSC for steelhead and chinook salmon during spring 2000.

Species	DE	Detected w/in 6 m of PSC	Total Fish Entering B1 Forebay
Steelhead	0.74	356	481
Chinook	0.63	341	545

3.8.2 Entrance Efficiency

Most radio-tagged fish that apparently discovered the flownet of the PSC eventually entered the structure. Of the fish detected within 6 m of the PSC, 60% (214 of 356) of steelhead and 72% (246 of 341) of chinook salmon 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 32 steelhead and 12 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, these are likely an underestimate of actual fish passage into the PSC at unit 2. Of the fish that entered the PSC, 7% of steelhead and 15% of chinook salmon re-entered the PSC from one to seven 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 14. Entrance Efficiency (EE) of the PSC for steelhead and chinook salmon during spring 2000.

Species	EE	Entered PSC	Detected w/in 6 m of PSC
Steelhead	0.60	214	356
Chinook	0.72	246	341

To further investigate the efficiency of the PSC, we determined the number of fish that entered the PSC during their first encounter with the PSC. Similar to entrance efficiency, 55% (118 of 214) of steelhead and 73% (180 of 246) of chinook salmon entered the PSC during their initial encounter with the PSC (Figure 20). However, of the fish that entered the PSC, only 29% (61 of 214) of steelhead and 41% (100 of 246) of chinook salmon entered the PSC via the entrance they were first detected at without meandering to one or more entrances (hereafter referred to as direct entrance; Figure 21). Therefore, of the fish that entered the PSC, 71% (153 of 214) of steelhead and 59% (146 of 246) of chinook salmon meandered to one or more entrances before entering the PSC. For fish that directly entered the PSC, the median time from first detection at the PSC until entering was 1.2 min for both steelhead and chinook salmon (Table 15). However, for fish that meandered between multiple entrances before entering the PSC, the median time from first detection at the PSC until entering was 4.0 h for steelhead and 1.4 h for chinook salmon (Table 16).

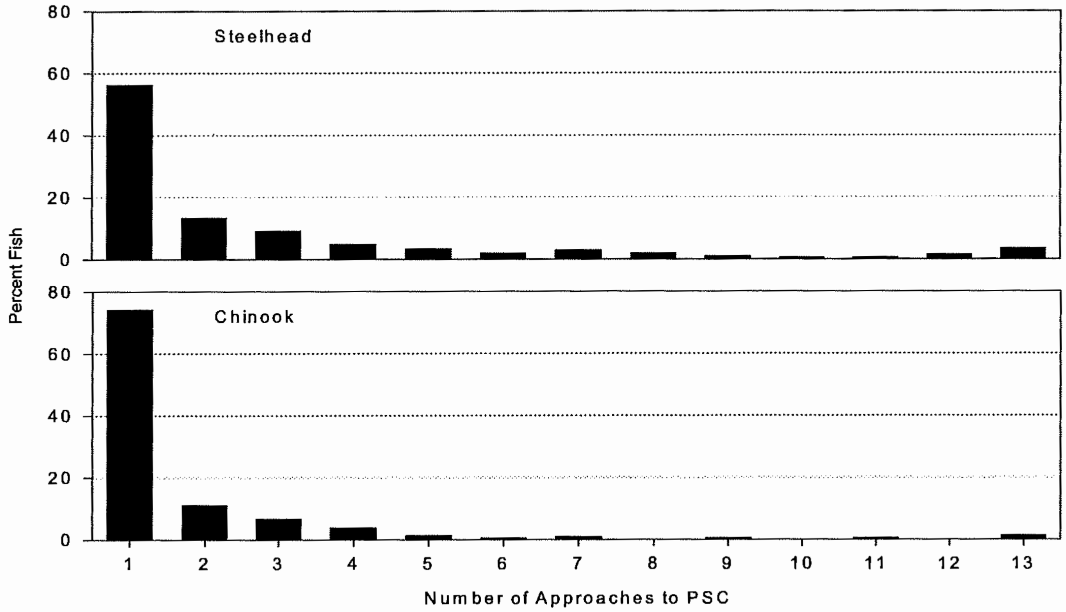

Figure 20. Percentage of fish by the number of approaches to the PSC before entering the PSC during spring 2000.

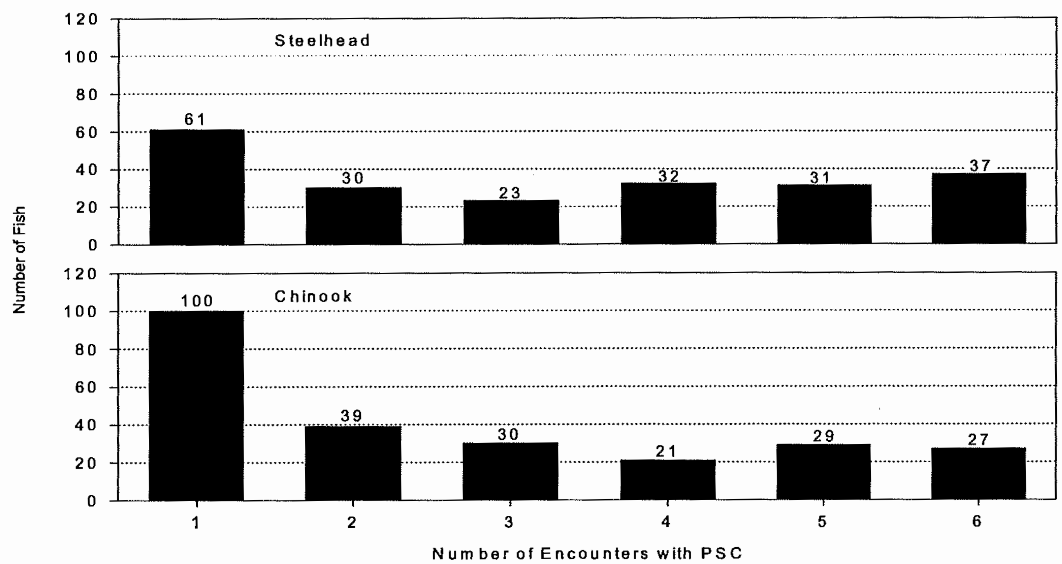

Figure 21. Number of fish that entered the PSC by number of encounters with the PSC before entering during spring 2000. Fish that entered the same PSC entrance as they approached, without traveling anywhere else between first detection at face of PSC and first detection inside the PSC, had one encounter with the PSC and were considered to directly enter the PSC.

Table15. Time (h) from first external PSC detection to first Internal PSC detection for fish that directly entered PSC on first encounter with PSC during spring 2000.

Species	N	Mean	Median	STD	Min	Max
Chinook	63	0.49	0.02	0.03	0.01	23.72
Steelhead	40	0.29	0.02	1.61	0.01	10.22

Table16. Time (h) from first external PSC detection to first Internal PSC detection for fish that did not directly enter the PSC on first encounter with PSC during spring 2000.

Species	N	Mean	Median	STD	Min	Max
Chinook	134	6.73	1.43	16.09	0.01	127.46
Steelhead	144	14.28	4.04	28.04	0.03	166.74

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 entrance to the PSC at unit 1 was most efficient for both steelhead (33%) and chinook salmon (41%; Figure 22; Table 17). The PSC entrance at unit 6 was nearly as efficient as the entrance at unit 1 for both species.

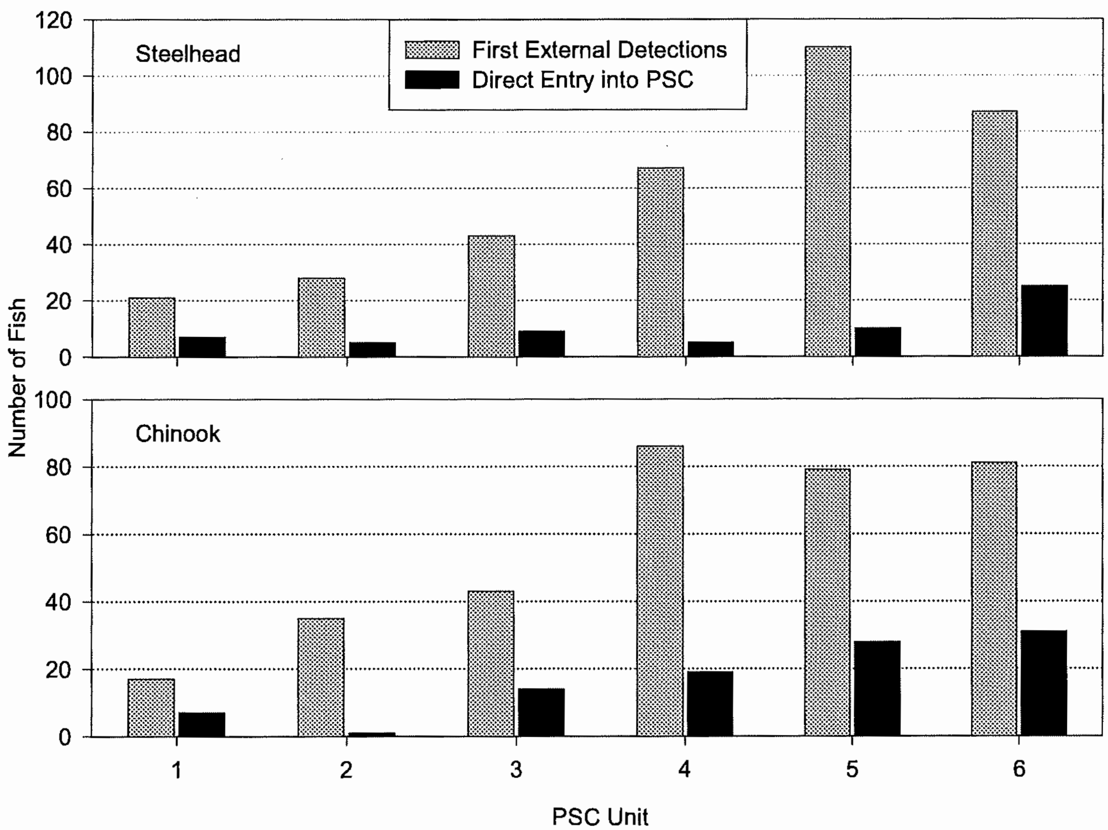

Figure 22. Number of fish first detected at the PSC and the number of fish that directly entered the PSC by unit during spring 2000. Note: Number of fish that directly entered the PSC at unit 2 may be underestimated due to equipment failure.

Table 17. Estimates of PSC Entrance Efficiency (EE) by unit for steelhead and chinook salmon during spring 2000. Efficiencies are based only on fish that directly entered a PSC entrance, not all fish that entered the PSC.

	PSC Unit					
Species	1	*2	3	4	5	6
Steelhead	33% 7 of 21	18% 5 of 28	21% 9 of 43	8% 5 of 67	9% 10 of 110	29% 25 of 87
Chinook	41% 7 of 17	3% 1 of 35	33% 14 of 43	22% 19 of 86	35% 28 of 79	38% 31 of 81

*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, 83% (208 of 252) of steelhead and 78% (235 of 301) of chinook salmon entered the PSC (Table 18). Although 214 steelhead and 246 chinook salmon entered the PSC, only 208 steelhead and 235 chinook salmon passed through the PSC and into the sluiceway or turbines intakes. Six steelhead and 11 chinook salmon that entered the PSC but were not detected passing B1 were not included in the calculation of collection efficiency.

Table 18. Collection efficiency (CE_{1-6}) of the PSC for steelhead and chinook salmon during spring 2000.

Species	CE_{1-6}	Entered PSC	Passed under PSC
Steelhead	83%	208	44
Chinook	78%	235	66

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 discharged through the PSC. PSC effectiveness was 2.5 for hatchery steelhead and 2.4 for 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 19. Effectiveness (EF_{1-6}) of the PSC for steelhead and chinook salmon during spring 2000.

Species	EF_{1-6}	CE_{1-6}	F_{psc}	F_u
Steelhead	2.52	0.83	3.07	6.18
Chinook	2.36	0.78	3.07	6.18

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, 74% (262 of 354) of hatchery steelhead detected at the face of the PSC were first detected on the north end of the PSC at units 4-6. Likewise, 71% (244 of 338) of chinook salmon were first detected at PSC units 4-6. However, slightly more fish, regardless of species, first entered the PSC at units 1-3 compared to units 4-6. Fifty-five percent of hatchery steelhead and 56% of chinook salmon entered the southern half of the PSC (Figure 23). 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 24). These observations indicated that, in general, both steelhead and chinook salmon moved laterally from north to south along the face of the PSC before passing into it.

Steelhead and chinook salmon entered the PSC throughout the diel cycle. However, both steelhead and chinook salmon predominantly entered the PSC during the day. Sixty-nine percent of steelhead entered the PSC during daylight hours and passage of

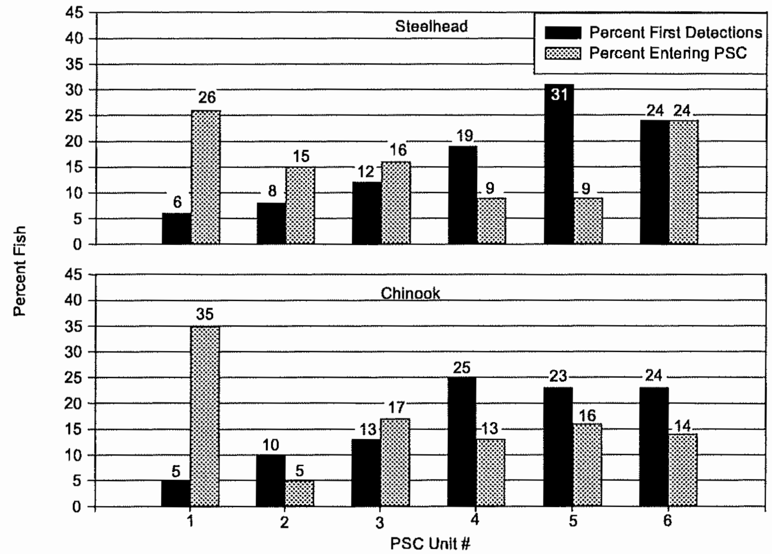

Figure 23. Percentage of fish first detected at the PSC and the percentage of fish that entered the PSC by unit during spring 2000. Percentage of fish that entered PSC at unit 2 may be underestimated due to equipment failure.

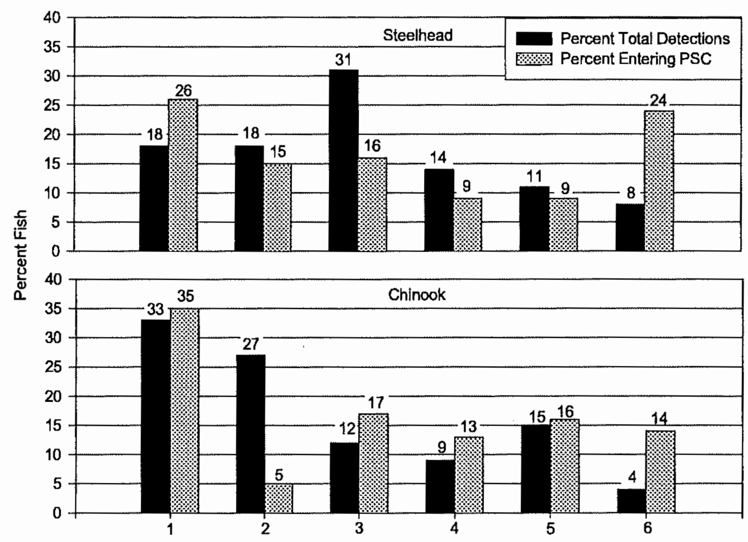

Figure 24. Percent total detections at PSC and the percentage of fish that entered the PSC by unit during spring 2000. Percentage of fish that entered PSC at unit 2 may be underestimated due to equipment failure.

steelhead into the PSC peaked during the crepuscular period. Likewise, 83% of chinook salmon entered the PSC during daylight hours. However, passage of chinook salmon into the PSC peaked during midday (Figure 25).

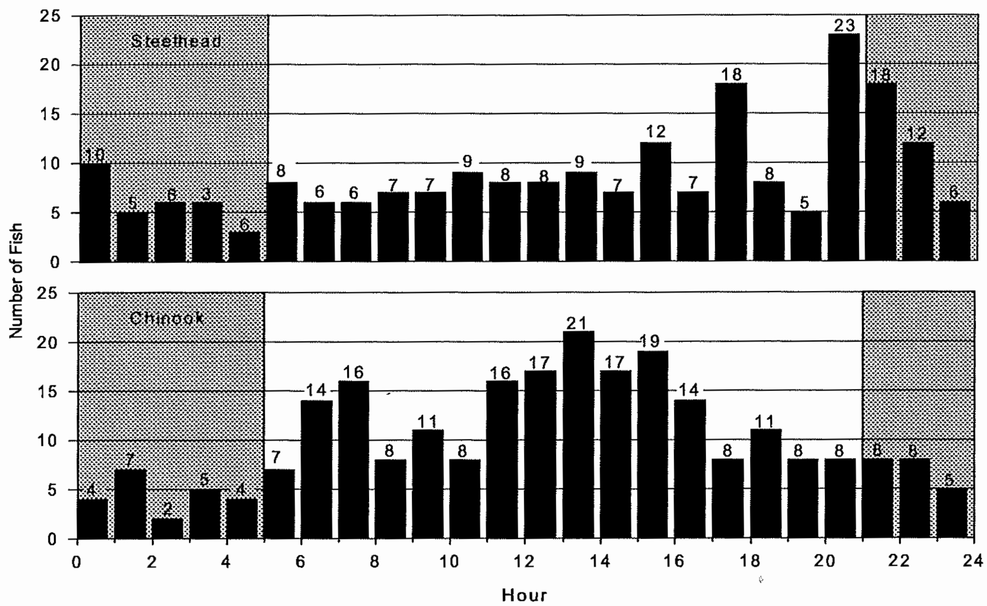

Figure 25. Number of steelhead and chinook salmon that entered the PSC by hour of day during spring 2000.

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), 76% (268 of 354) of hatchery steelhead and 53% (180 of 338) of chinook salmon approached the PSC relatively shallow (Figure 26). During day, we observed a similar percentage of chinook salmon approach the PSC shallow (54%) and deep (46%). In contrast, 82% of steelhead approached the PSC shallow during the day. During night, however, the majority of both species approached the PSC deep (Figure 27).

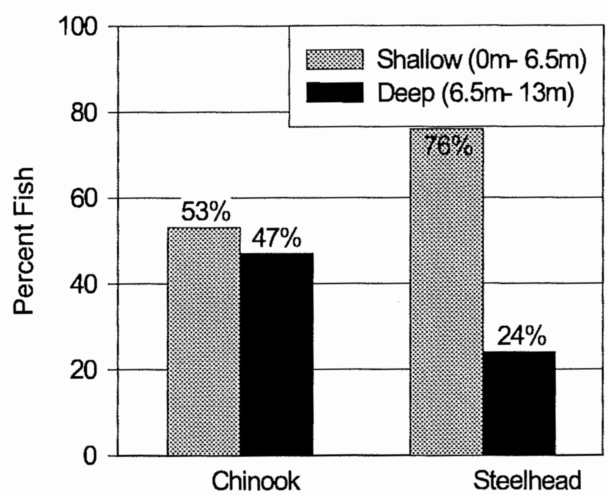

Figure 26. Percent first detections by depth of detection for steelhead and chinook salmon during spring 2000.

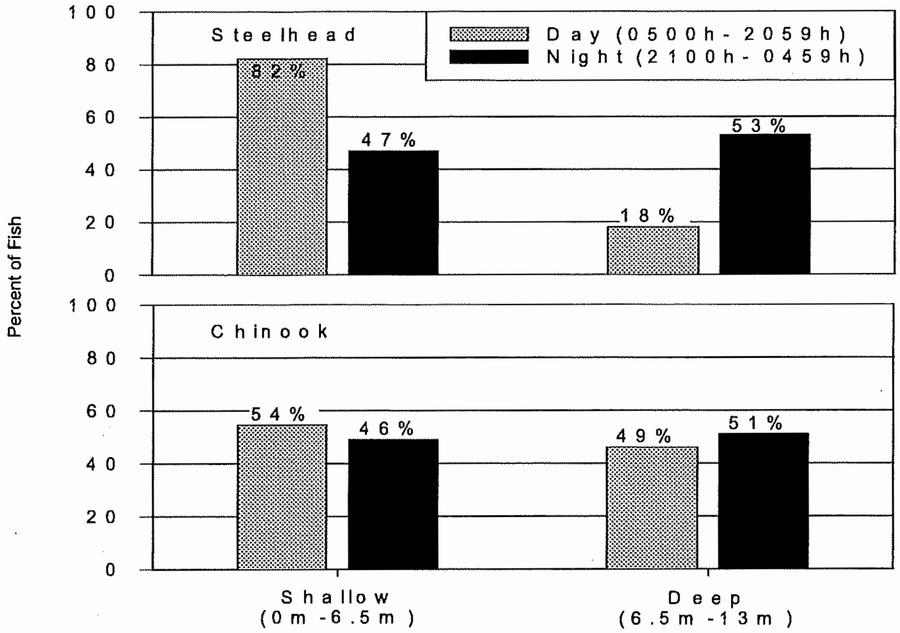

Figure 27. Percent first detections by day, night, and depth of detection for steelhead and chinook salmon during spring 2000.

An analysis of depth of approach to the PSC by PSC unit indicated that more steelhead (63-90%) approached the PSC shallow at units 2-6 than deep (between 6.5 and 13 m). Conversely, 62% of first detections of steelhead at unit 1 were deep. First detections of chinook salmon at PSC units 1-3 and unit 5 were fairly equally distributed between shallow and deep. Sixty-four percent of chinook salmon approached unit 4 shallow and 60% of chinook salmon approached unit 6 deep (Figure 28).

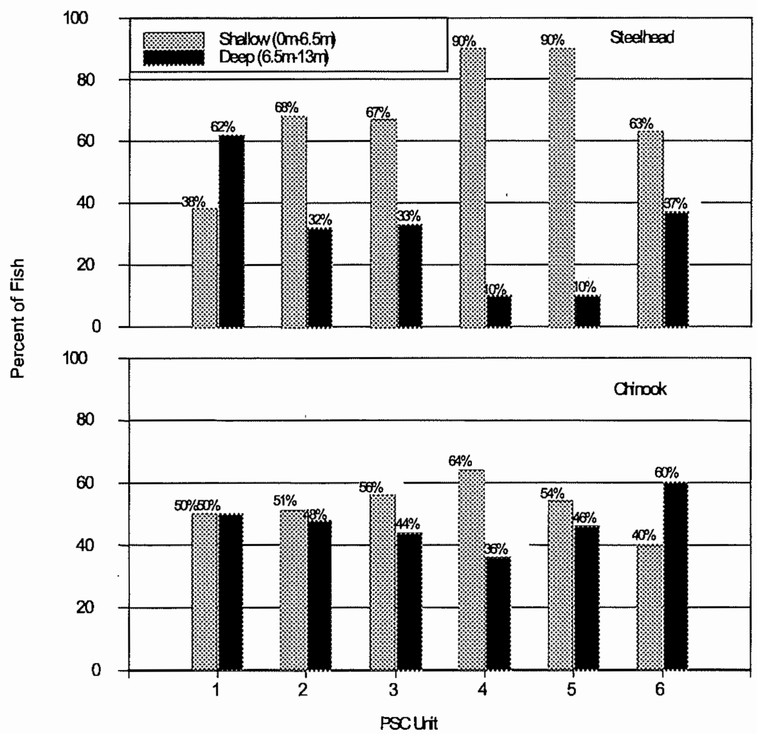

Figure 28. Percent first detections at the PSC by unit and depth of detection for steelhead and chinook salmon during spring 2000.

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, 73% (154 of 211) of hatchery steelhead entered the PSC shallow. However, chinook salmon entered the PSC deeper than steelhead. Fifty-five percent (134 of 243) of chinook salmon entered the PSC between 6.5 and 13 m deep (Figure 29).

During the day, 84% of steelhead entered the PSC shallow and only 48% of chinook salmon entered the PSC shallow. At night, the majority of both species entered the PSC deep (Figure 30). Analysis of entrance depth to the PSC by unit also indicated that 68% to 80% of steelhead entered the PSC shallow at all PSC entrances. However, for chinook salmon, most fish entered the PSC at unit 2 shallow, and most fish entered the PSC at units 3 and 6 deep (Figure 31).

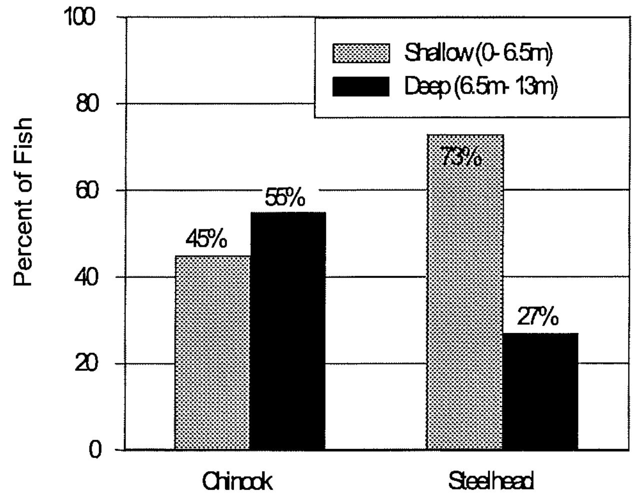

Figure 29. The percentage of steelhead and chinook salmon that entered the PSC by depth of entrance during spring 2000.

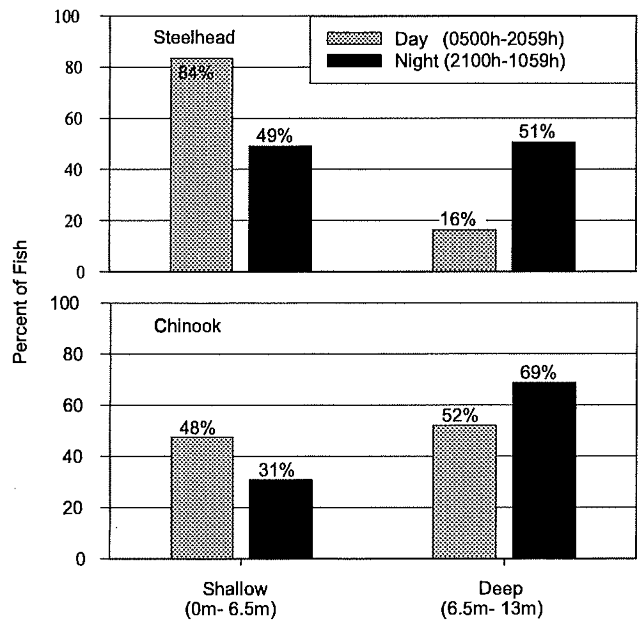

Figure 30. The percentage of steelhead and chinook salmon that entered the PSC by day, night, and depth of entrance during spring 2000.

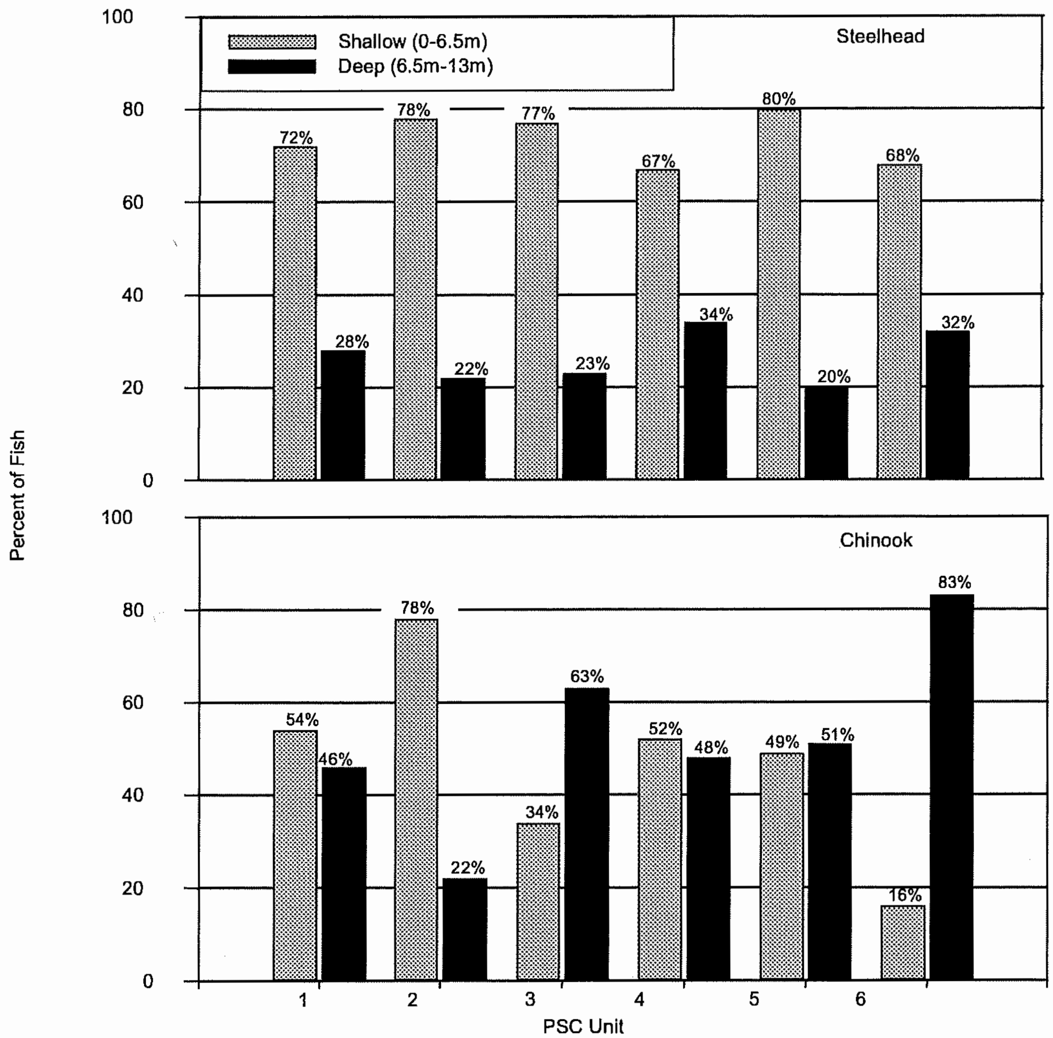

Figure 31. The percentage of steelhead and chinook salmon that entered the PSC by unit and depth of entrance during spring 2000.

4.0 Discussion

4.1 Approach Paths and Forebay Residence Times

Based on first detections, most steelhead (45%) entered B1 and most chinook salmon (48%) entered the spillway. Although species-specific approach paths at Bonneville were observed, the proportion of discharge at each dam area likely determined 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. This pattern was most evident for steelhead at B2 and the spillway. Both species seemed to consistently enter B1 forebay with little influence from fluctuating discharge at B1.

Forebay residence times of juvenile salmonids differed considerably depending on species and dam area. The overall median forebay residence time for steelhead was nearly 13 times that for chinook salmon. The spillway provided the quickest route of passage as residence times there were substantially less for both species than at B1 or B2. Fish that entered B1 had much longer residence times than juvenile salmonids that entered B2 or the spillway. Although no relation was apparent between daily discharge patterns and residence time, hourly discharge patterns at a particular dam area did seem to influence the residence time of fish in the forebay. Residence times usually decreased during periods of increased discharge, especially for steelhead at B1 and both species at the spillway. However, shorter residence times at the spillway during increased discharge were confounded because increased discharge always occurred at night. Time of day likely had the most influence on residence times. Regardless of discharge, both species had shorter residence times during hours of darkness at all three forebays.

The difference between the residence times of the two species may be due to inherent differences in the life history and migration patterns of the two species. However, the forebay that fish entered likely affected residence time as well. Most steelhead entered B1, and B1 was where fish resided the longest. Likewise, most chinook salmon entered the spillway, where residence times were shortest.

These observations indicated that project operations and the resulting discharge per dam area affect approach paths of migrating juvenile salmonids and may determine which dam area they enter. Discharge, the time of day that fish arrive, and species-specific migration behavior all affected how long fish resided in the forebay of Bonneville Dam before passing.

4.2 Route and Time of Passage

Little movement occurred between the three dam areas (B1, B2, and the spillway) and most fish passed where they were first detected. The highest percentage (49%) of steelhead passed Bonneville Dam at B1 and the highest percentage (44%) of chinook salmon passed through the spillway. The same pattern was observed for first detections; most (45%) steelhead entered B1 and most (48%) chinook salmon entered the spillway.

The proportion of radio-tagged fish that passed through the various routes indicated that steelhead were higher in the water column than chinook salmon. At B1, the highest percentage (44%) of steelhead passed via the sluiceway and relatively equal proportions of chinook salmon were guided (36%), unguided (35%) and sluiced (29%). A predisposition for steelhead to migrate shallow in the water column was the likely cause for most steelhead passing into the sluiceway at B1. Guided passage was about 10% higher than unguided passage at B1. Likewise, 10% more steelhead were guided than unguided at B2. However, 21% more chinook salmon were unguided than guided at B2. Higher FGE for steelhead at B1 (59%) and B2 (55%) compared to chinook salmon at B1 (50%) and B2 (39%) also indicated that steelhead were likely higher in the water column than chinook salmon.

Passage occurred throughout the diel cycle, however, passage rates were influenced differently among dam areas by day and night. At B1 and the spillway, steelhead and chinook salmon passage was lower at night than at B2. This was likely attributed to the type of passage route fish used within each dam area. For example, sluiceway passage and turbine guidance predominantly occurred during day for both species. Since the majority of both species at B1 were guided or sluiced, passage rates declined at B1 during night. Likewise, since the majority of chinook salmon and nearly equal numbers of steelhead at B2 were unguided, passage rates increased at B2 during night. At the spillway, despite increased discharge at night, passage was highest for both species during day, indicating time of day may have had the largest effect on spillway passage for both species.

4.3 Performance of the Prototype Surface Collector

The majority of steelhead (74%) and chinook salmon (63%) that entered B1 forebay discovered the PSC (i.e., were detected within 6 m of the PSC) and did so in a relatively short amount of time. Steelhead took longer to discover the PSC (31.8 min) than chinook salmon (7.2 min) based on median time from first detection in the forebay to first detection (within 6 m) at the PSC. Although a higher percentage of steelhead discovered the PSC, overall entrance efficiency (number that entered PSC divided by number within 6 m of PSC) was higher for chinook salmon (72%) than steelhead (60%). Entrance efficiency, based on fish that entered the PSC during their first encounter with the PSC (73% for chinook salmon and 55% for steelhead), was similar to overall entrance efficiency. However, considerable meandering was observed for both species. Only 29% of steelhead and 41% of 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 (4.0 h for steelhead and 1.4 h for chinook salmon) compared to fish that did not meander (1.2 min for both species). Based on direct entrance to the PSC, the southern most (unit 1) and the northern most (unit 6) entrances were most efficient for both species. This relation may have indicated that entrance conditions were more favorable at units 1 and 6, possibly because there was only one adjacent entrance, which 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, 83% of steelhead and 78% of chinook salmon 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 5-7% increase in FPE. FPE (not including fish that entered the PSC) was 78% for steelhead and 73% for chinook salmon. These values would have increased to 85% for steelhead and 78% for chinook salmon, had the PSC been a fully functional passage device.

The PSC was also relatively effective. An effectiveness of 2.5 for steelhead and 2.4 for chinook salmon indicated that the percentage of fish that entered the PSC out of total passage at units 1-6 was about 2.5 times the proportion of discharge through the PSC. When compared to spillway effectiveness (1.0 for steelhead and 1.3 for chinook salmon), PSC effectiveness was over twice as high for both species.

4.4 Fish Behavior at the Prototype Surface Collector

Approach paths of both species at B1 were predominantly toward the central portion of the powerhouse. As a result, 74% of steelhead and 71% of chinook salmon were first detected at the northern half of the PSC at units 4-6. Both species 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 a lateral movement from north to south along the face of the PSC during previous evaluations of the partial PSC. Observations of horizontal distribution and movement at B1 indicated that both species approach paths were likely determined by the bulk flow entering B1 forebay. The location of the PSC enabled the majority of juvenile salmonids 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 both species 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 steelhead and chinook salmon at the PSC was similar to that observed in the forebays of B1, B2, and the spillway. Seventy-six percent of steelhead approached the PSC shallow compared to only 53% of chinook salmon. Most juvenile salmonids approached the PSC shallow during the day. At night however, the majority of both species approached the PSC deep. Vertical distributions of juvenile salmonids during entrance to the PSC were nearly identical to vertical distributions during approach to the PSC for both species. Therefore, for at least the majority of fish that entered the PSC, vertical distribution did not change from approach to entrance to the PSC. Species-specific behavior like migration depth, as well as response to the diel cycle, are important factors to consider during the design of surface flow bypass systems, especially when considering entrance design.

4.5 Comparison of PSC Performance Among Evaluation Tools

In addition to the radio telemetry evaluation we conducted, other research tools were utilized to effectively evaluate fish behavior at Bonneville Dam in 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. Acoustic telemetry was conducted by Battelle, USGS, and WES to determine three-dimensional fish movement patterns and PSC performance on a species-specific basis. Collection efficiency and effectiveness estimates for the PSC were similar between radio telemetry, acoustic telemetry, and hydroacoustics (Table 20). However, acoustic telemetry estimates for discovery and entrance efficiencies for both species and entrance efficiency for chinook salmon were considerably higher (7-35%) than radio telemetry estimates. The differences in PSC performance metrics as determined by radio telemetry and acoustic telemetry may be attributable to a smaller sample size of tagged fish for acoustic telemetry.

Table 20. PSC performance metrics for chinook salmon and steelhead at Bonneville Dam during spring 2000 as determined by radio telemetry (RT), acoustic telemetry (AT) and Hydroacoustics (HA). *HA estimate of effectiveness is an underestimate because sluiceway passage is not accounted for.

Metric	Chinook Salmon		Steelhead		Run-at-large
	RT	AT	RT	AT	HA
Discovery Efficiency (DE)	63%	82%	74%	67%	n/a
Entrance Efficiency (EE_{1-6})	72%	96%	60%	95%	n/a
Collection Efficiency (CE_{1-6})	78%	96%	83%	88%	83%
Effectiveness (EF_{1-6})	2.4	2.9	2.5	2.6	2.2*

4.6 Comparison of PSC Performance Among Evaluation Years

Discovery and entrance efficiencies for the PSC in 2000 were considerably higher (~30-40%) than those during 1998 and 1999. Collection efficiency was higher in 2000 than in 1999 but lower than collection efficiency in 1998 (Table 21). Caution should be used however, 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 spring migrant radio-tagged fish that entered B1 were different among years: 340 in 1998, 330 in 1999, and 1026 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 21. PSC performance metrics for chinook salmon and steelhead at Bonneville Dam during spring 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 and 1999 evaluations.

Metric	Chinook Salmon			Steelhead		
	1998	1999	2000	1998	1999	2000
Discovery Efficiency (DE)	36%	26%	63%	44%	29%	74%
Entrance Efficiency (EE_{1-6})	46%	33%	72%	49%	21%	60%
Collection Efficiency (CE_{1-6})	93%	55%	78%	89%	75%	83%
Effectiveness (EF_{1-6})	nc	nc	2.4	nc	nc	2.5

5.0 Acknowledgements

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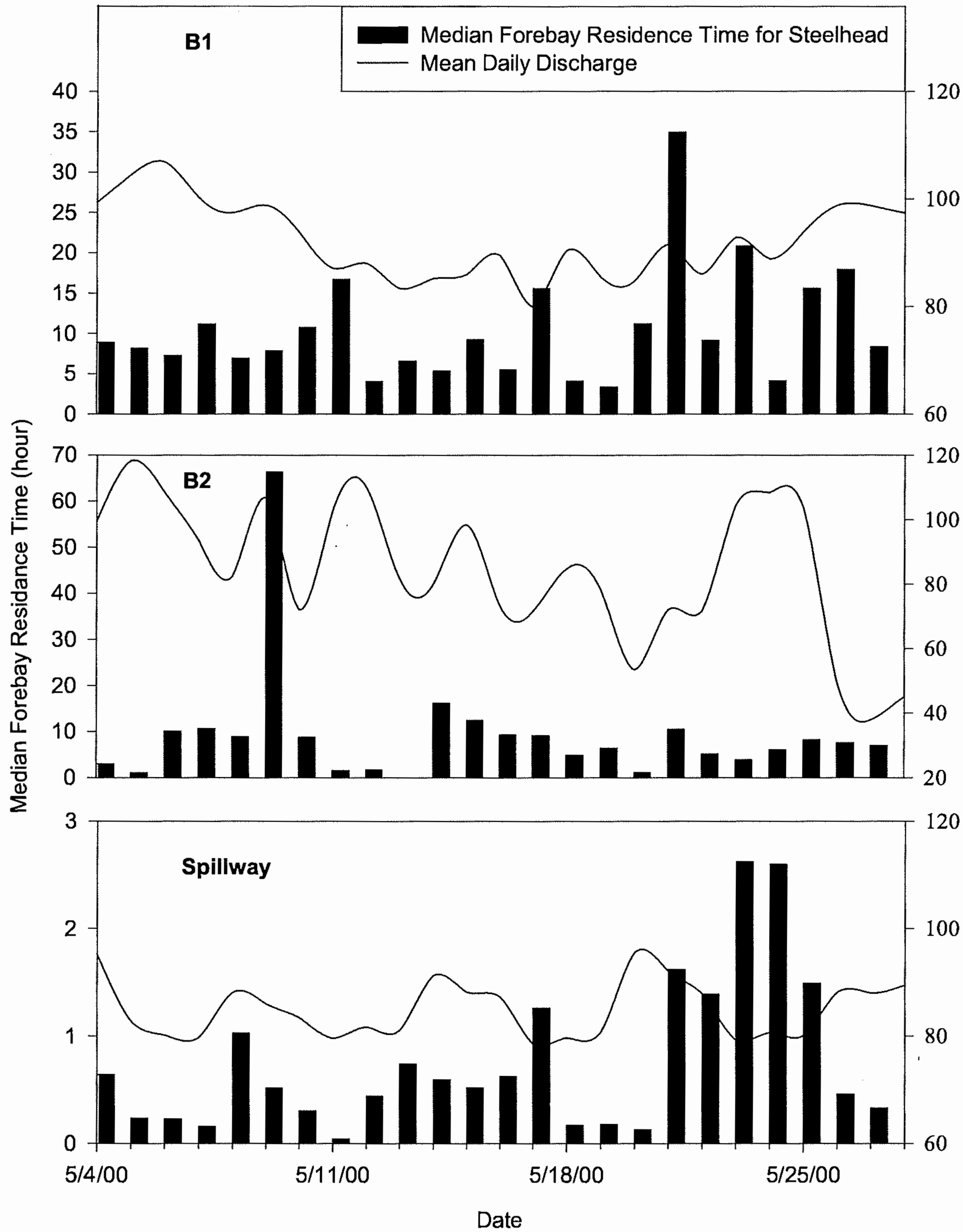
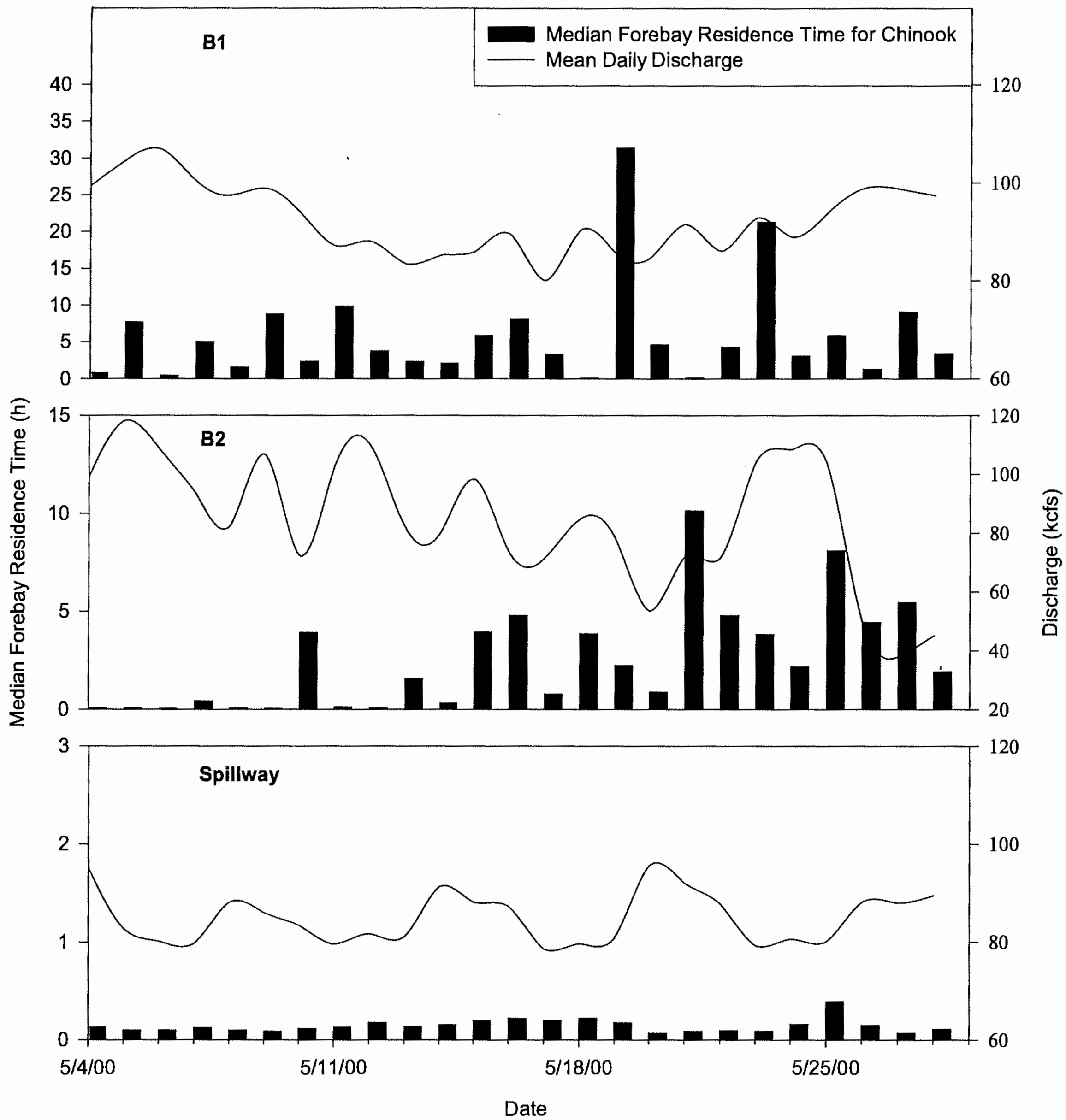
7.0 Appendices



Appendix 1. Median forebay residence time versus mean discharge by day and dam area for radio-tagged steelhead at Bonneville Dam during spring 2000.



Appendix 2. Median forebay residence time versus mean discharge by day and dam area for radio-tagged chinook salmon at Bonneville Dam during spring 2000.

Appendix 3. Passage and PSC performance metrics for radio-tagged chinook salmon and steelhead at Bonneville Dam during spring 2000.

Metric	**Chinook**	**Steelhead**
	Passage Metrics	
SE	44%	33%
SF	1.3	1.0
$FGE(B1)_{1\text{-}10}$	50%	59%
$FGE_{1\text{-}6}$	52%	58%
$FGE_{7\text{-}10}$	48%	61%
FGE (B2)	39%	55%
FPE	73%	78%
$FPE_{w/PSC}$	78%	85%
	PSC Performance Metrics	
DE	63%	74%
$EE_{(1\text{-}6)}$	72%	60%
$CE_{(1\text{-}6)}$	78%	83%
$EF_{(1\text{-}6)}$	2.4	2.5