U.S. Army Corps of Engineers
Portland District

Passage Behavior of Radio-Tagged Yearling Chinook Salmon at Bonneville Dam, 2001

Annual Report

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Submitted to:

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Contract No. W66QKZ10442576

Submitted:

September 2001

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Executive Summary

Flow augmentation, spill, surface collection, and improved turbine guidance systems have been identified as potential management actions to improve passage efficiency and survival of outmigrating juvenile salmonids. The U.S. Army Corps of Engineers (COE), along with regional, state, and federal resource agencies, has designed and implemented studies to determine which management actions would provide significant biological benefits to juvenile salmonids. From 1994 to 2001, the COE contracted the U.S. Geological Survey to evaluate juvenile salmonid behavior in relation to passage improvement tests at Lower Granite, John Day, The Dalles, and Bonneville Dams.

In 2001, we used radio telemetry to examine the movements and behavior of yearling 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 fish in the forebay areas of Bonneville Dam, 2) determine the timing and route of dam passage of fish, 3) estimate fish passage efficiency for the entire Bonneville Dam complex, fish guidance efficiency for powerhouses I and II, and spillway efficiency and effectiveness, and 4) provide data to estimate survival of radio tagged fish released above Bonneville Dam (reported by Counihan et al. *in prep).*

From 1 May to 2 June 2001, we radio-tagged and released 1211 yearling chinook salmon upstream of Bonneville Dam near Hood River, Oregon. We detected our last radio-tagged fish on June 9, 2001. Mean river discharge at Bonneville Dam during the study period was 134.9 kcfs, with 72% of flow discharged at powerhouse II (B2), 22% at the spillway, and 6% at powerhouse I (B1). From May 1-15 and during three 5 h blocks on May 24-25, 1.2 kcfs of spill was discharged through each of spillbays 1 and 18 and represented 1.7% of total discharge (hereafter referred to as 2% spill). From May 16 to June 9, a mean 50 kcfs was discharged through 10 spillbays and represented 37% of total discharge (hereafter referred to as 37% spill). Median travel rate of radio-tagged fish from release to Bonneville Dam was 1.8 km/h, resulting in a median travel time of 22.1 h. Of the fish released, we detected 97% at Bonneville Dam. Median forebay residence time was shortest at B2 (0.2 h) compared to 2.7 h at B1 and 0.3 h at the spillway.

Passage routes were determined for 98% of fish detected at Bonneville Dam. B2 passed the most fish (80%), followed by the spillway (16%) and B1 (4%). Of the fish that passed at B1, 76% passed into the sluiceway, 13% passed through the turbines (unguided), and 11% were diverted into the turbine bypass system by turbine intake screens (guided). All fish that passed at B2 entered the turbine intakes; 54% were unguided and 46% were guided. At all dam areas, a higher proportion of fish passed during night compared to day.

Fish passage efficiency (FPE; the proportion of total fish that passed through non-turbine routes) at Bonneville Dam in spring 2001 was 56%. During hours of 37% spill, FPE was 64%, and during hours of 2% spill, FPE was 47%. At B1, FPE was 87% overall, 100% during 37% spill, and 86% during 2% spill. At B2, FPE was 46% overall, 49% during 37% spill, and 43% during 2% spill. Fish guidance efficiency (FGE; the proportion of powerhouse-entrained fish that are guided by screens into bypass systems) was nearly identical at B1 (45%) and B2 (46%). At B1 during 37% spill, no fish passed through the turbine intakes so FGE could not be calculated for B1. During 2% spill at

B1, FGE was 45%, equal to overall FGE at B1. At B2 during 37% and 2% spill levels, FGEs were equal to FPEs since all fish passed guided or unguided through the turbine intakes. Spillway efficiency (SE), which is the proportion of total fish that passed the project that passed through the spillway, was 16% overall, 30% during 37% spill, and 1% during 2% spill. Spillway effectiveness (SF; SE divided by the proportion of total discharge through the spillway) was 0.70 overall, 0.86 during 37% spill, and 0.53 during 2% spill.

The proportion of discharge allocated at B1, B2, and the spillway affected which dam area fish entered and passed, as well as the time spent in the forebay before passing. All passage metrics except FGE at B2 were lower in 2001 than 2000, largely due to low river flows experienced in 2001. Although low discharge negatively affected passage metrics in general, at B1, it was likely responsible for fewer fish becoming entrained in turbine flow, thereby increasing the number of fish available to the surface-oriented sluiceway. All passage metrics were higher during periods of 37% spill than during periods of 2% spill. Our results indicate that, during a low flow year, the current intake screen guidance systems at B1 and B2 do not divert sufficient numbers of yearling chinook salmon to meet the project FPE goal of 80%.

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 effort 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.

Flow augmentation, spill, surface collection, and improved turbine intake guidance systems have been identified as potential management actions to improve juvenile salmonid passage and survival, thereby assisting the recovery of anadromous fish stocks in the Snake and Columbia rivers. One option being evaluated is the improvement of turbine intake guidance systems. The National Marine Fisheries Service and the Northwest Power Planning Council have established goals of 80% fish passage efficiency (FPE) for Columbia and Snake River dams (Whitney et al. 1997). To achieve this goal, migrant salmonids are diverted from turbines via intake screen guidance systems. However, at Bonneville Dam, the present intake screen guidance systems do not divert enough fish to meet the 80% FPE goal.

In 2000, we conducted the first evaluation of species-specific FPE for the entire Bonneville Dam project and estimated that FPE was between 73% and 91%, depending on species (Evans et. al. 2001). The draft Biological Opinion, July 27, 2000 states " The dam passage survival rate at Bonneville Dam is currently one of the lowest of any Corps FCRPS project, and is therefore the highest priority relative to the need for improvements", and that the Corps should "continue intake screen guidance improvement investigations and implement as warranted". To address these concerns, in 2001, the COE field-tested a prototype screen system at unit 15 at powerhouse II (Monk et al. *in prep*). In 2002, tests will be conducted on a new minimum gap runner turbine at Powerhouse I and on new and old flow deflector bays at the spillway. To determine whether these management actions are effective, it is necessary to estimate passage efficiency metrics such as FPE, fish guidance efficiency (FGE), spillway efficiency (SE) and effectiveness (SF) and survival.

During spring 2001, we used radio telemetry to examine the movements and behavior of yearling chinook salmon *Oncorhynchus tshawytscha* in the forebay of Bonneville Dam. Our objectives were to:

- Determine the behavior, distribution, and approach patterns of yearling chinook salmon in the forebay areas of Bonneville Dam.
- Determine the time and route of dam passage of yearling chinook salmon.
- Estimate fish passage efficiency for the entire Bonneville Dam complex, fish guidance efficiency for powerhouses I and II, and spillway efficiency and effectiveness.
- Provide data to estimate survival of radio tagged fish released above Bonneville Dam (reported by Counihan et al. *in prep*).

2.0 Methods

2.1 Study Area

Bonneville Dam is located on the Columbia River at rkm 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 Cascades Island to the Washington shore. The spillway lies between Cascades and Bradford islands and has 18 spill gates. A navigation lock is located at the south end of B1 (Figure 1).

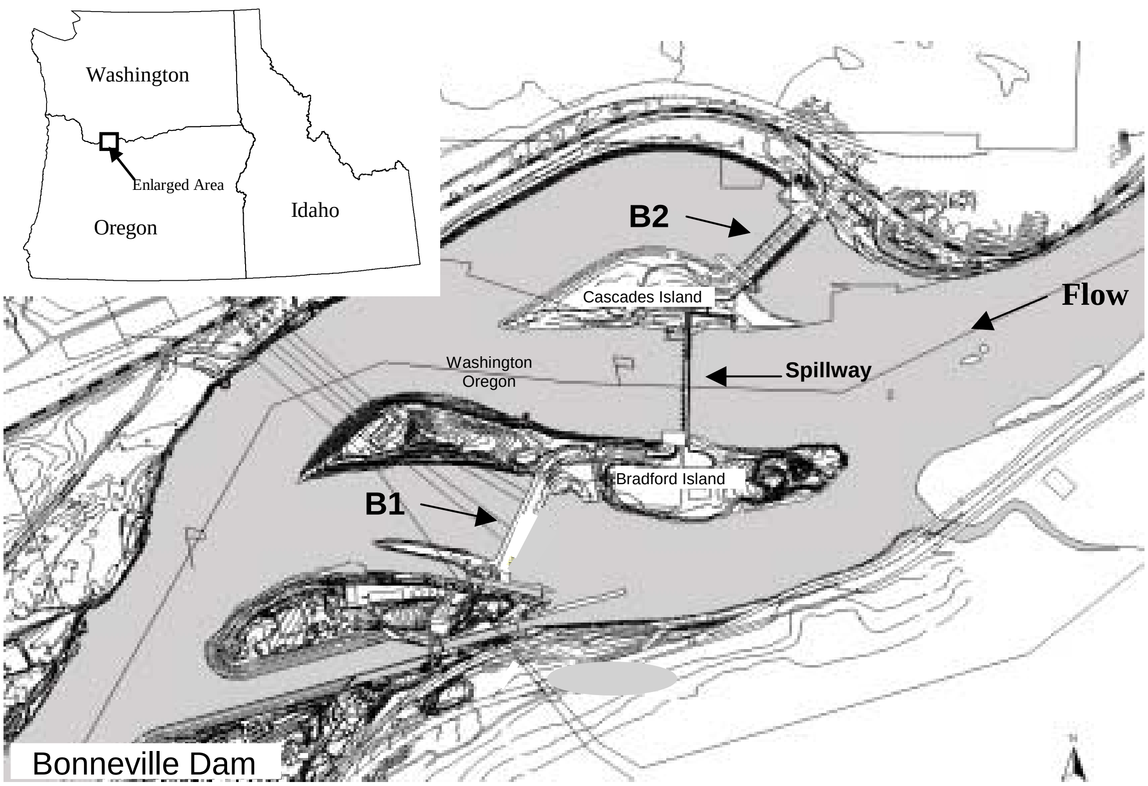

Figure 1. Plan view of Bonneville Dam on the Columbia River, showing the first powerhouse (B1), spillway, and second powerhouse (B2).

2.2 Fixed Receiving Equipment

Sixty-four aerial antennas, 45 stripped co-ax antennas, 32 balanced loop-vee antennas, and 180 underwater dipole antennas were linked to 31 Lotek SRX-400 receivers (SRX; Lotek Engineering, Newmarket, Ontario), three Lotek DSP-500 digital spectrum processors (DSP; Lotek Engineering, Newmarket, Ontario), and three Multiprotocol Integrated Telemetry Acquisition Systems (MITAS; Grant Systems Engineering, Newmarket, Ontario, Canada). Each receiver monitored 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 all routes at Bonneville Dam.

Aerial antennas were positioned along the periphery of the forebay to detect fish within about 100 m of the dam face (Figures 2 and 3). Aerial antennas were connected to Lotek SRX-400 data logging receivers, programmed to monitor 23 frequencies split between two receivers. 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 aerial sites. Reducing scan time is beneficial because it increases the probability of detecting transmitters. Underwater dipole, stripped co-ax, and loop-vee antennas had limited ranges (about 6, 6, and 15 m, respectively) compared to aerial antennas (100 to 300 m depending on transmitter depth, receiver gain, and number of antenna elements). Underwater antennas allowed us to obtain fine scale fish behavior information by limiting the range of signal detection.

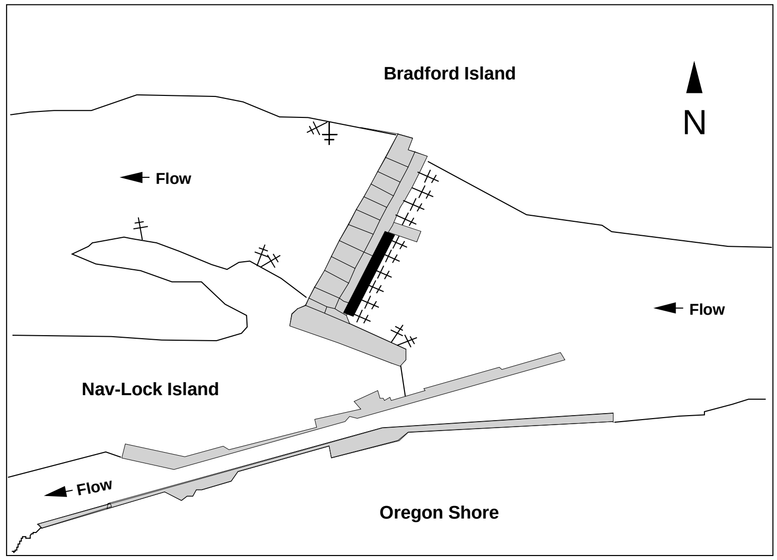

Figure 2. Plan view of aerial antenna coverage at Bonneville's first powerhouse (B1) during spring 2001.

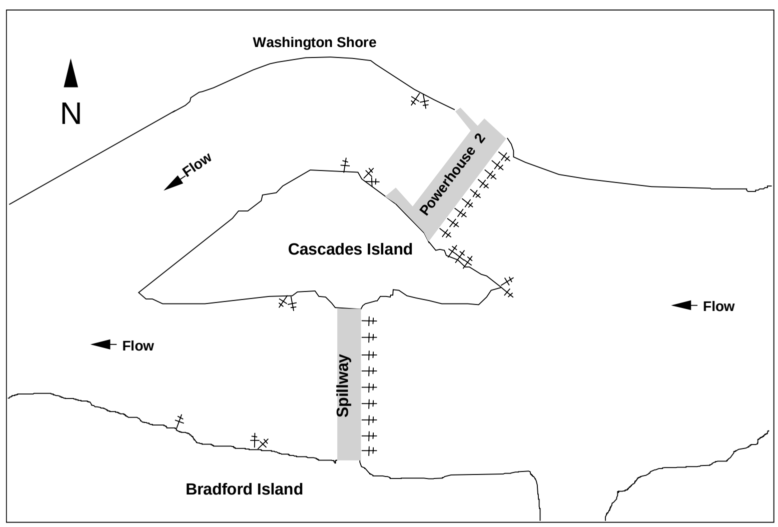

Figure 3. Plan view of aerial antenna coverage at Bonneville's second powerhouse (B2) and spillway during spring 2001.

Two receivers in the B2 tailrace and one receiver at the B2 sampling facility 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. Although antennas monitored by DSPs could have been monitored by a MITAS, we chose to use DSPs due to wiring logistics. Using DSPs was necessary to document fish passage in turbulent hydraulic environments because signal acquisition time is limited.

Three MITASs were incorporated at B1, B2, and the spillway. Each MITAS was capable of simultaneously monitoring up to 50 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. These features allowed the user to identify problems in real-time and avoid potential data loss that otherwise would not have been apparent until post-processing.

The MITAS at B1 was comprised of 90 underwater antennas. Sixty dipole underwater antennas monitored turbine passage and were attached to the standard length traveling screens (STS) at units 1-7, and units 9 and 10, as well as the extended submerged bar screens (ESBS) at unit 8. Two dipole antennas were mounted on the bottom frame of each STS and the backside of the lower portion of the extended screen on each ESBS. Screen antennas were then combined to provide turbine unit-specific passage information. Twenty stripped co-axial antennas were positioned mid-channel in the sluiceway, two at each unit, to monitor unit-specific sluiceway passage. Ten stripped co-axial antennas were located inside the DSM (one at each "C-slot" gatewell orifice) to measure guided fish passage (i.e., fish directed by guidance screens).

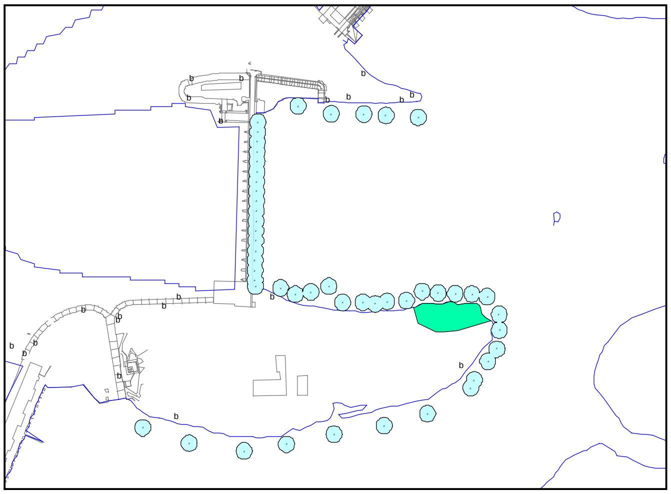

Figure 4. Plan view of underwater antenna coverage at the Bonneville spillway and Cascades and Bradford Islands during spring 2001.

The MITAS located at B2 was comprised of 59 underwater antennas and one aerial antenna. Forty-eight dipole underwater antennas monitored turbine passage and were attached to the standard length traveling screens. Eight stripped co-ax antennas located at each "C-slot" turbine gatewell orifice and one additional stripped co-ax antenna located at the terminus of the DSM, monitored guided fish passage through the DSM. A single aerial and two stripped co-ax antennas positioned at the entrance to the sluice chute measured fish passage in the chute. Although aerial antennas are not typically used with a MITAS due to noise sensitivity, the quiet environment of the sluice chute enabled the successful use of an aerial antenna with the MITAS at B2.

The spillway MITAS consisted of 104 underwater antennas. Seventy-two dipole underwater antennas monitored spillway passage and were attached to the forebay pier noses about 4.5 and 10.5 m below mean pool level. Four antennas in each of the 18 spillbays were combined to one per spillbay to monitor spillbay-specific passage. We used balanced loop-vee underwater antennas at Cascades Island (n = 5) and Bradford Island (n = 27) to monitor fish approach behavior (Figure 4). Antennas at Cascades and Bradford Islands were deployed as part of an adult salmonid study conducted by USGS and Battelle. Although they were intended for another study, the loop-vee antennas provided valuable information regarding juvenile salmonid behavior in the forebay of Bonneville Dam.

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 antennas on Cascades and Bradford Islands were amplified within a waterproof antenna housing. Underwater amplification was not used on the B1 or B2 MITAS; 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.

2.3 Transmitters

Pulse-coded transmitters developed by Lotek Engineering Inc., (Lotek) were implanted in yearling chinook salmon. The transmitters were 7.3 mm (diameter) x 18.9 mm and weighed 1.4 g in air and 0.8g in water. The antenna length was 30 cm and the pulse rate was 2.0 s, resulting in an estimated minimum tag life of 9 d.

2.4 Tagging, Handling, and Release of Fish

Yearling chinook salmon *Oncorhynchus tshawytscha* were collected from the Bonneville Dam's Juvenile Bypass System (JBS) located downstream of B2. Employees form the Pacific States Marine Fisheries Commission's (PSMFC) Smolt Monitoring Program sorted and identified fish. Fish were collected 24 hours per day at a collection rate between 0.8 and 3.3 percent depending on the quantity of fish that were needed. Fish were sorted and identified using methods developed by PSMFC. Fish were held 24 h before tagging in 127 L plastic holding cans. Fish were held 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 per one-liter 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 recovery bucket and supplied with bottled oxygen. After about 10 min, fish were transferred into a 127 L plastic recovery 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 (1000-1100 hours) and night (2200-2300 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 12-36 h to adjust to temperature and hydraulic conditions in the reservoir before reaching the forebay and encountering the dam.

2.5 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 had been predated by avian or aquatic predators. To consider a detection of a radio-tagged fish as valid, we required at least two detections within 1 min of each other.

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. Similarly, the last detection of a fish by aerial or underwater antennas on the dam face, on the traveling screens, or within either DSM or sluiceway, was considered to be the route and time of passage through the dam. If a fish was not detected in the forebay or within the dam, the tailrace exit stations were used to determine which dam area fish passed (i.e., B1, B2, or spillway). However, exit stations were excluded when identifying more specific passage locations (e.g., DSM, turbine, and sluiceway). If a fish was detected in the DSM it was identified as being guided. Guided fish are powerhouse-entrained fish that are diverted by turbine intake screens. If a fish was detected at the turbine guidance screens and subsequently in the tailrace, it was identified as an unguided fish. Unguided fish are powerhouse-entrained fish that are not diverted by turbine intake screens. If a fish was detected in the sluiceway and subsequently in the tailrace, it was identified as passing through the 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.

The following are definitions of metrics used 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) = $\frac{Non-turbine\ passage}{TOT_{pass}}$

Where:

SP = Total number of fish passing spillway
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

3.0 Results

3.1 Tagging

From 1 May to 2 June 2001, we radio-tagged and released 1211 yearling chinook salmon. The release period coincided with the central portion of the "in river" seaward migration of chinook smolts (Figure 5). Fifty-two percent (634 of 1211) were released during the day (1000-1100 hours) and 48% were released at night (2200-2300 hours). Mean fork length was 157 mm and the mean weight was 41 g. The radio tag represented 3.4% of mean fish body weight. Fish size increased slightly over the course of study (Appendix 1). Of the 1250 yearling chinook salmon collected, 32 (2.6%) regurgitated their tags and 4 (0.3%) died during the 24 h holding period.

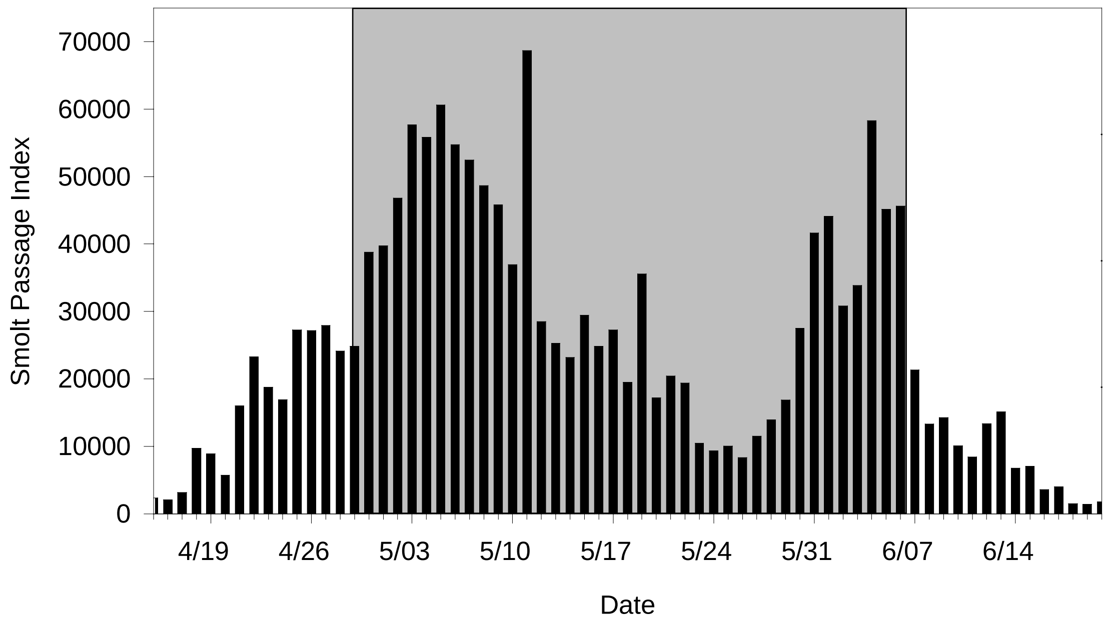

Figure 5. Smolt Passage index for yearling chinook salmon at Bonneville Dam's Second Powerhouse (B2) fish collection facility during spring 2001. Shaded area represents study period. Smolt index data were acquired from the Fish Passage Center web page at www.fpc.org.

3.2 River Discharge and Project Operations

During spring 2001 (May 1 – June 9), mean river discharge at Bonneville Dam was 134.9 kcfs, and ranged from 99.7 kcfs to169.9 kcfs. Allocation of mean river discharge among dam areas (i.e., B1, B2, and spillway) during the study period was 6% through B1, 72% through B2, and 22% through spill (Figure 6 and Table 1). Mean daily discharge at B1 (turbines 1–10) was 8.0 kcfs and ranged from 0 to 38.0 kcfs. B2 displayed the greatest fluctuation in mean daily discharge with a mean of 96.9 kcfs, minimum of 57.3 kcfs and a maximum of 120.3 kcfs. Spill averaged 29.0 kcfs and ranged from 2.4 to 50.0 kcfs. Mean daily spill was above 48 kcfs on all but two days following the initiation of spill (through 10 spill bays) on 16 May 2001, and occurred 24 h/d with the exception of three 5 h blocks on May 24-25 (Figure 7). During the three 5 h blocks on May 24-25 and from May 1-15, 1.2 kcfs of spill was discharged through each of spillbays 1 and 18 and represented 1.7% of total discharge. Periods when spill occurred only through bays 1 and 18 will hereafter be referred to as 2% spill. When 48-50 kcfs of spill was discharged through a total of 10 spillbays, spill represented 37% of total discharge and will hereafter be referred to as 37% spill.

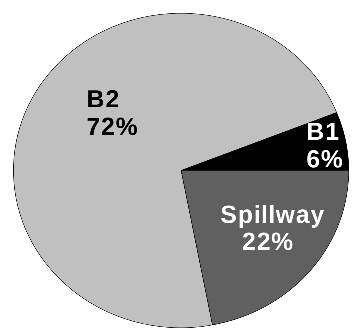

Figure 6. Discharge allocation between dam areas at Bonneville Dam during spring 2001.

Table 1. Mean project discharge (kcfs) for Bonneville Dam during spring 2001. Values have been rounded to the nearest tenth

Dam Area	Mean	Median	Min	Max
B1	8.0	3.3	0.0	38.0
B2	96.9	102.5	57.3	120.3
Spillway	29.0	48.9	2.4	50.0
Total	134.9	133.6	99.7	169.9

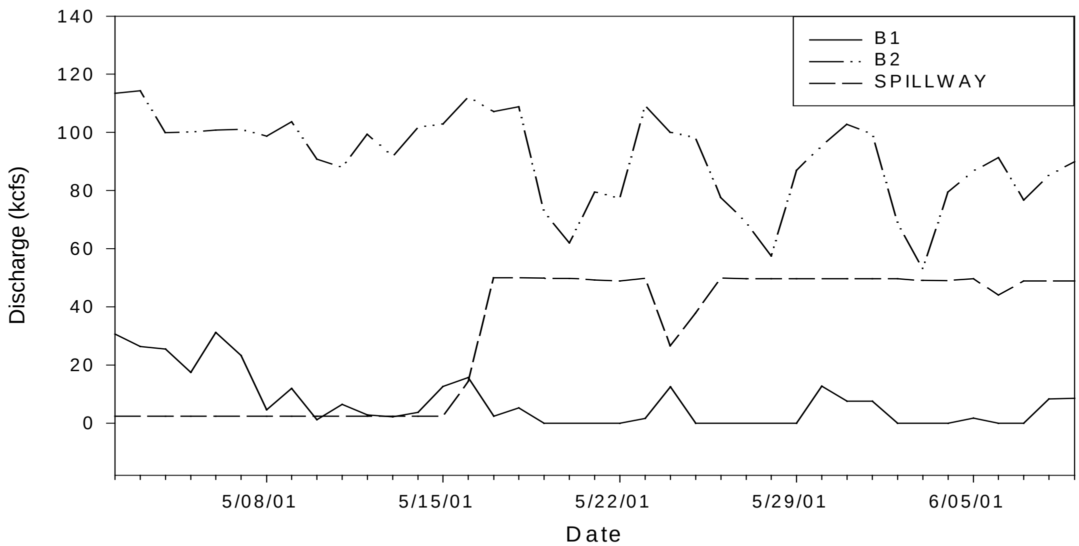

Figure 7. Mean daily discharge at Bonneville Dam by dam area during spring 2001.

Turbines 1-6 represented 25% and turbines 7-10 represented 75% of mean discharge at B1 (Figure 8). Turbines 11-14 represented 53% and turbines 15-18 represented 47% of mean discharge at B2 (Figure 9). There were considerable differences in discharge between turbine units, although fluctuations in mean daily discharge of turbines 11-18, 11-14, and 15-18, corresponded with mean daily river discharge. Differences in daily turbine discharge were observed for multiple turbines throughout the study (Figures 10, 11, 12, and 13). We found that discharge at B1, B2, and the spillway were essentially the same during day (0500 to 2059 hours) and night (2100 to 0459 hours; Table 2).

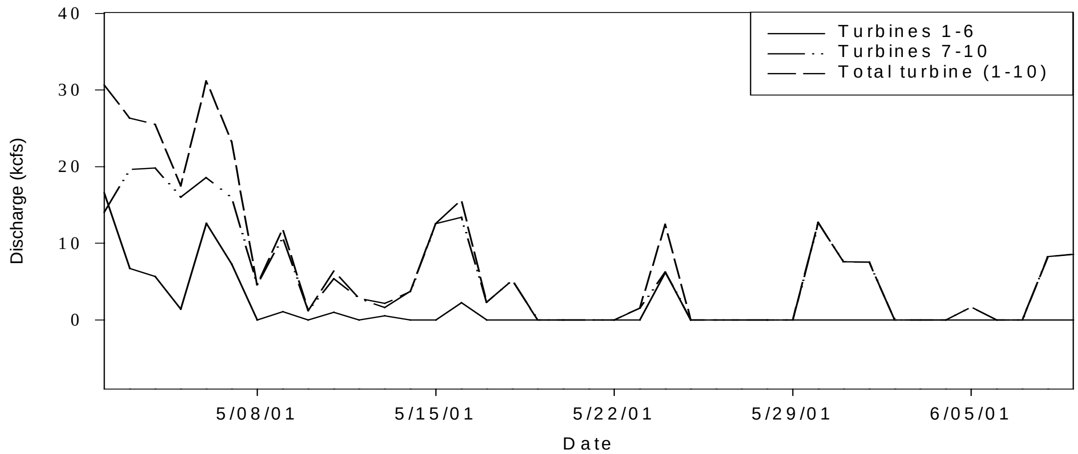

Figure 8. Mean daily discharge through turbines 1-6 and turbines 7-10 during spring 2001.

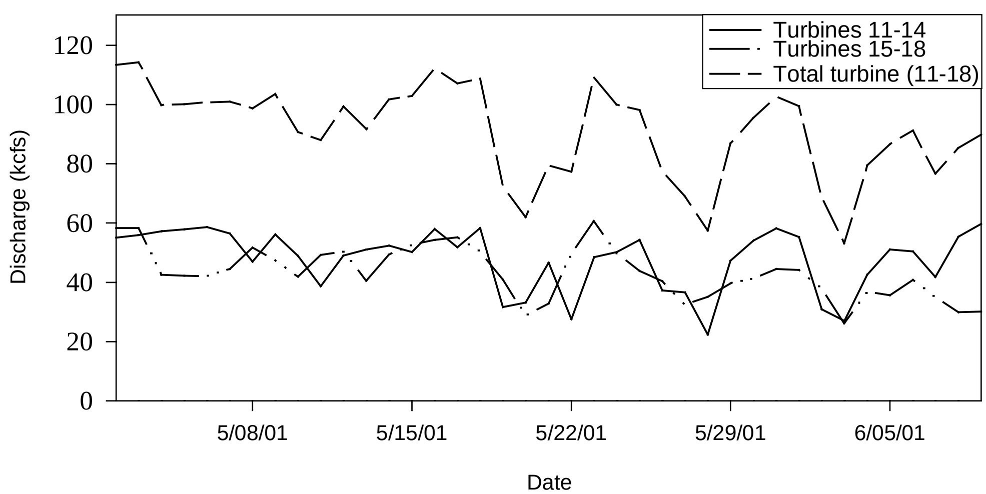

Figure 9. Mean daily discharge through turbines 11-14 and turbines 15-18 during spring 2001.

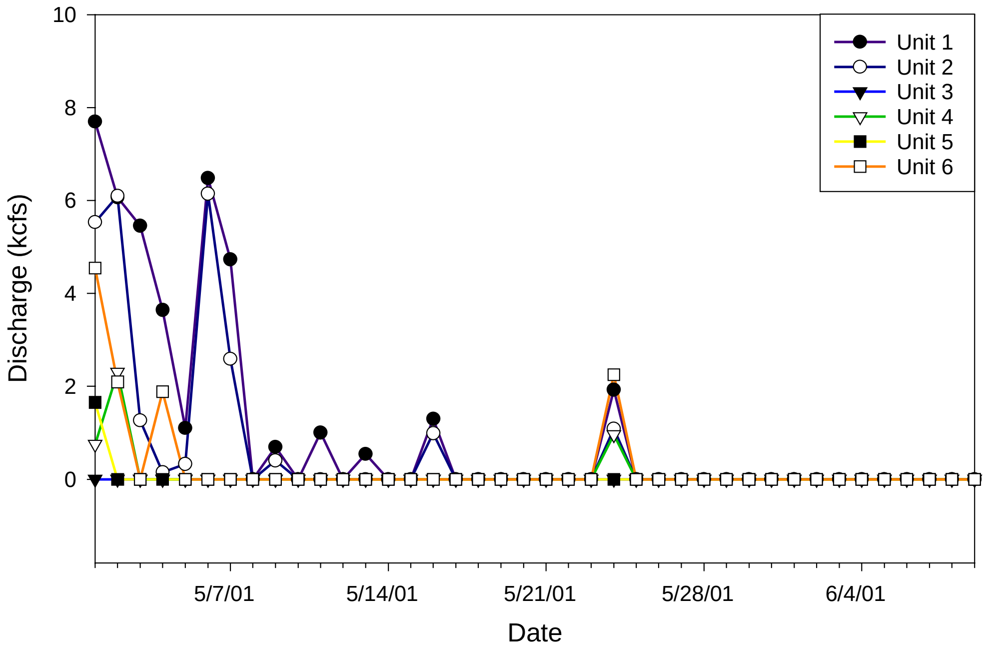

Figure 10. Mean daily discharge by unit for units 1-6 at Bonneville Dam during spring 2001.

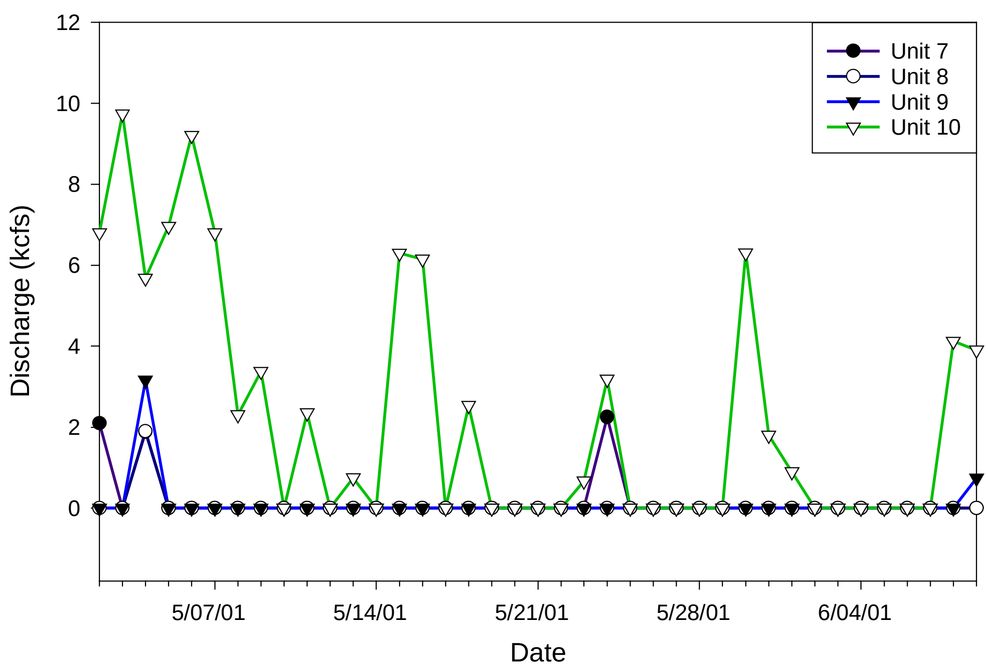

Figure 11. Mean daily discharge by unit for units 7-10 at Bonneville Dam during spring 2001.

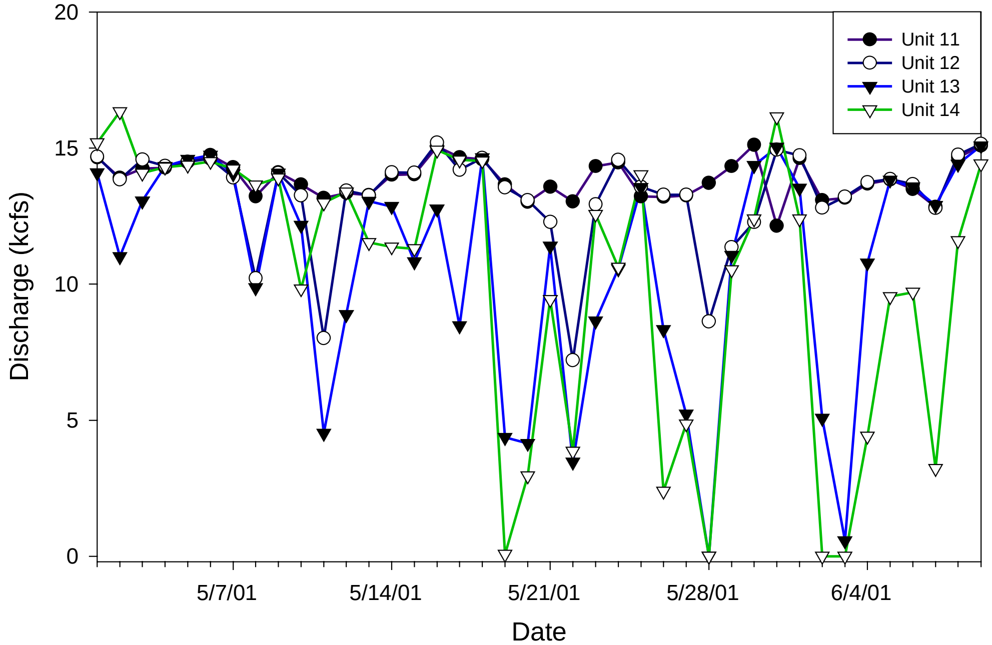

Figure 12. Mean daily discharge by unit for units 11-14 at Bonneville Dam during spring 2001.

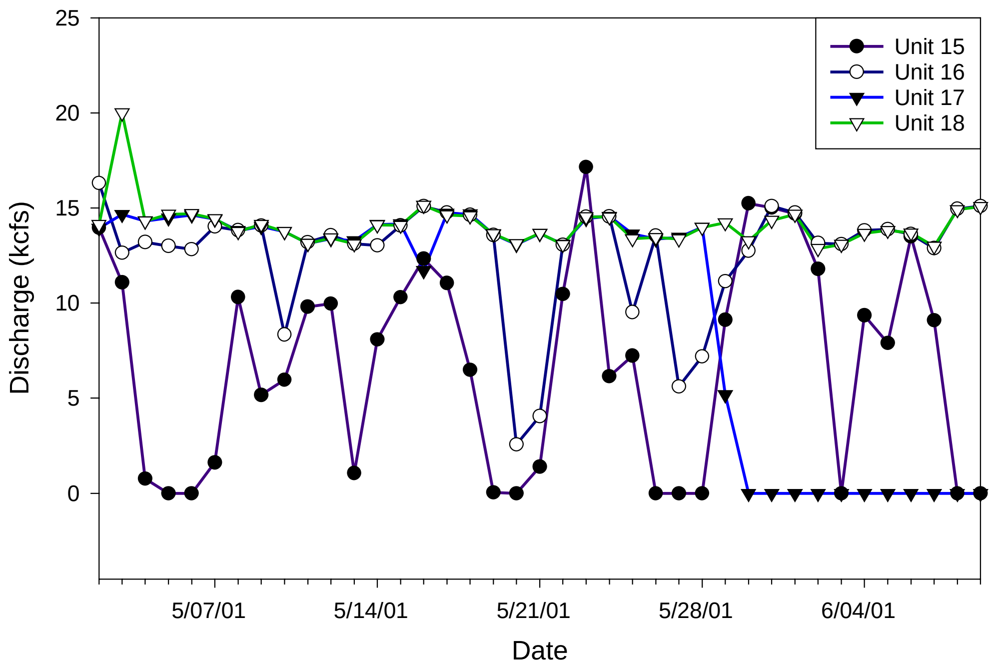

Figure 13. Mean daily discharge by unit for units 15-18 at Bonneville Dam during spring 2001.

Table 2. Mean discharge (kcfs) during day (0500-2059 hours) and night (2100-0459 hours) by dam area during spring 2001.

Dam Area	Period	Percent (of mean)	Mean	Median	Min	Max
B1	Day	6%	8.6	0	0	58.1
B2	Day	72%	98.6	100.9	41.6	275.5
Spillway	Day	22%	30.0	48.9	2.4	50.7
B1	Night	5%	6.9	0	0	48.5
B2	Night	72%	93.6	96.4	44.7	236.0
Spillway	Night	23%	29.9	48.9	2.4	50.0

3.3 Travel to and Arrival at Bonneville Dam

At Bonneville Dam, we detected 97% (1171 of 1211) of the yearling chinook salmon that were released near the Hood River Bridge. The median travel rate from release at Hood River to first detection at Bonneville Dam was 1.8 km/h. The corresponding median travel time from release to first detection at Bonneville Dam was 22.1 h (Table 3).

Table 3. Descriptive statistics for travel time (h) and travel rate (km/h) to Bonneville Dam for radio-tagged yearling chinook salmon during spring 2001. Travel rates are represented within parenthesis.

Release Site	Mean	Median	STD	Min	Max
Hood River Bridge	24.4 (1.8)	22.1 (1.8)	11.1 (0.5)	11.7 (0.2)	178.3 (3.3)

Fish did not enter dam areas (i.e., B1, B2, and spillway) in equal proportions. Of the fish detected at Bonneville Dam, 6% (66 of 1171) first entered B1 forebay, 71% (834 of 1171) first entered B2 forebay, and 23% (271 of 1171) first entered the spillway forebay. Differences in the number of fish entering the forebay of each dam area appeared to be strongly related to allocation of river discharge among dam areas. B1, B2, and the spillway represented 6%, 72%, and 22%, respectively, of mean river discharge. To further investigate this relation, 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 fish fluctuated somewhat with the proportion of daily discharge (Figure 14). The higher proportion of discharge at B2 compared to B1 and the spillway was likely the largest contributing factor to the higher number of fish that entered the B2 forebay. Extremely low discharge at B1 resulted in very few fish entering that dam area.

Similarly, we compared the hourly proportion of fish entering each dam area to the hourly proportion of mean discharge through each dam area but found no relation. Fish entered B1, B2 and the spillway during all hours of the diel cycle and hourly discharge was fairly constant at each dam area. More fish entered B2 due to its higher discharge (Figure 15).

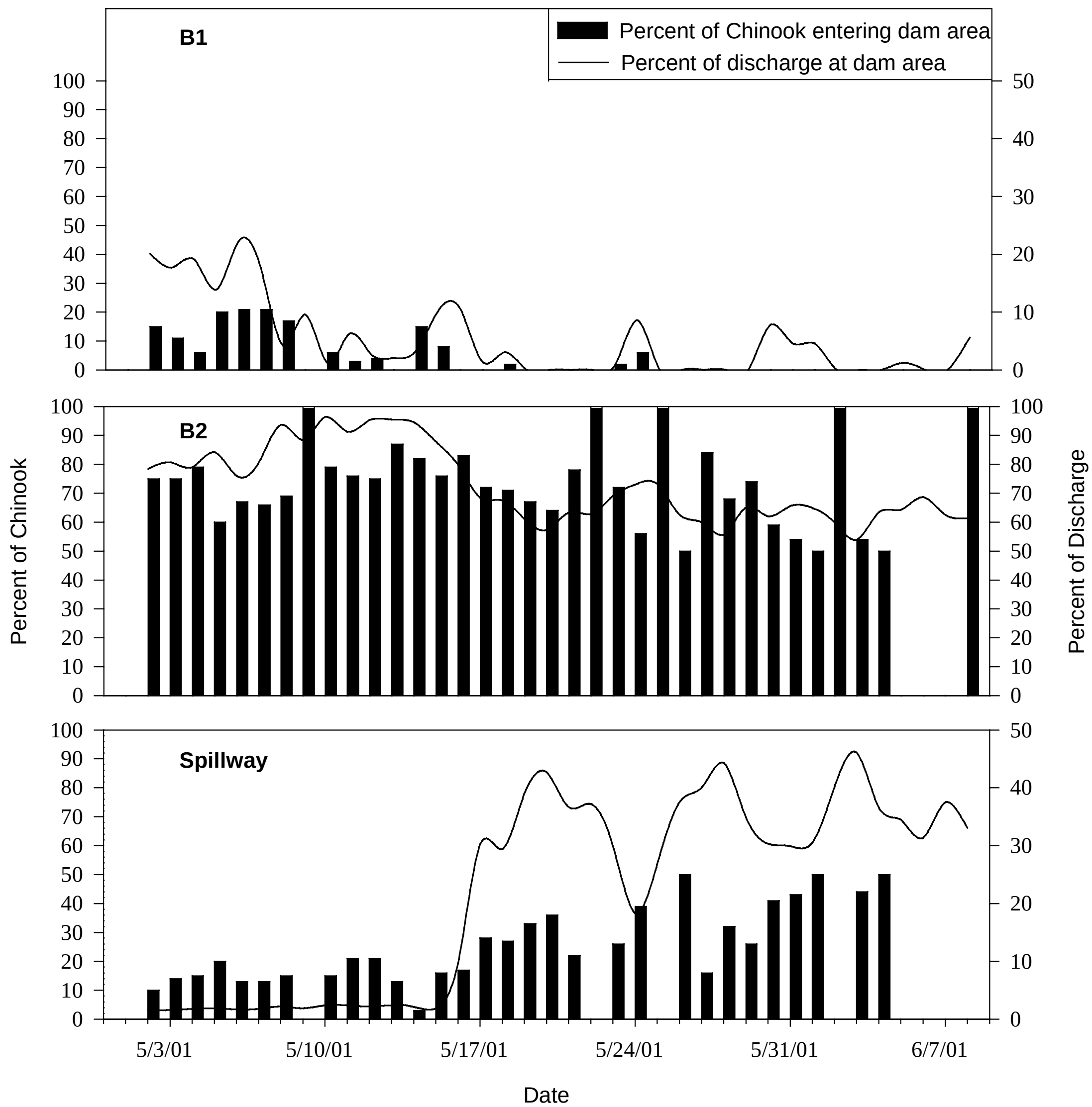

Figure 14. The percentage of yearling chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by day during spring 2001.

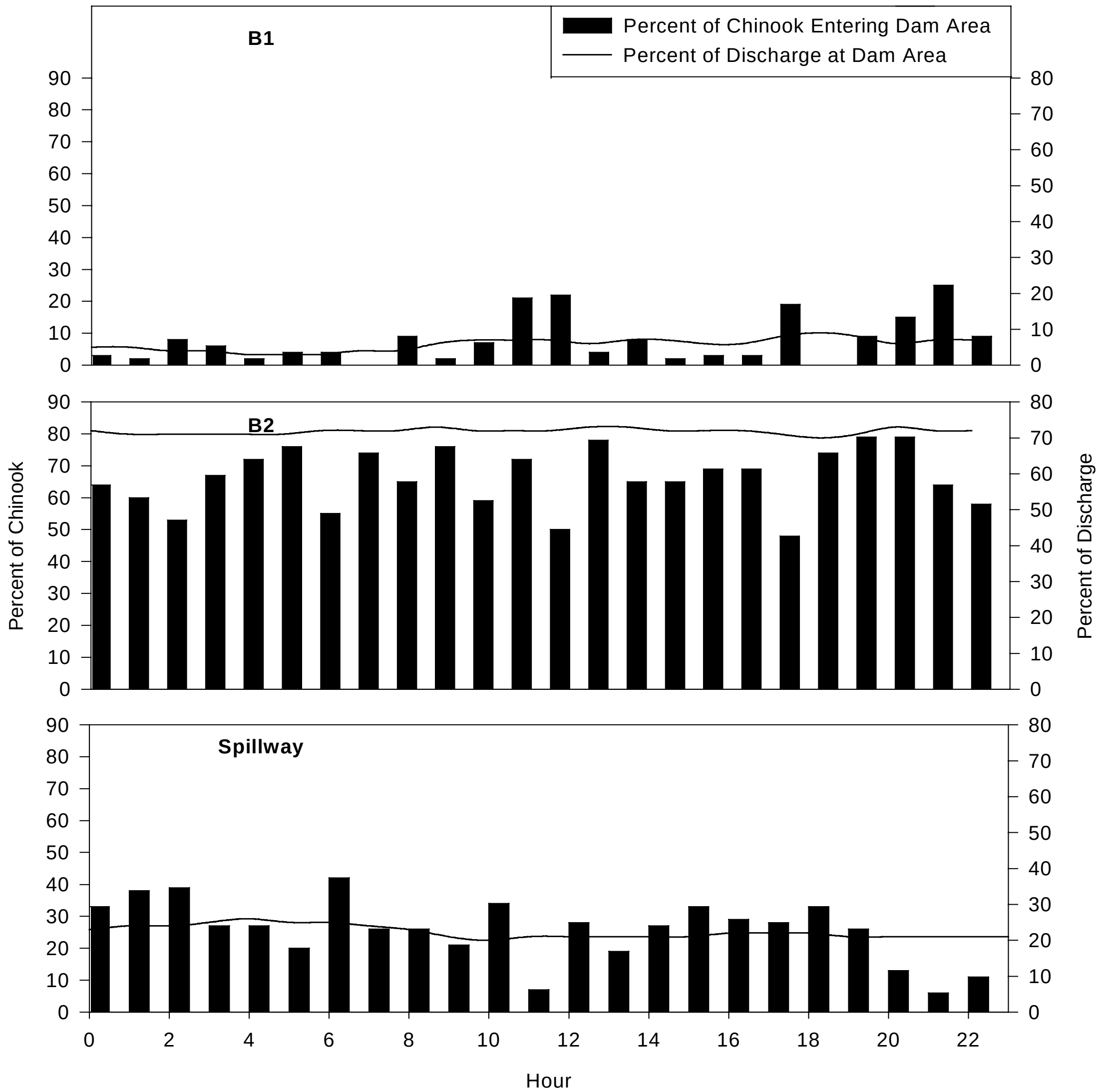

Figure 15. The percentage of yearling chinook salmon that entered each dam area versus the percentage of mean discharge at each dam area by hour of day during spring 2001.

3.4 Residence Time in the Forebay

Forebay residence time (time from first detection until time of passage) differed between dam areas. Yearling chinook salmon resided considerably longer in the forebay of B1 (median = 2.7 h) than the forebay of B2 (median = 0.2 h). The median time spent in the forebay of the spillway (0.3 h) was slightly higher than residence time at B2 (Table 4). 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 2, 3, and 4).

Table 4. Descriptive statistics of forebay residence time (h) for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001. Note 82 fish that passed at a dam area different than the one they first entered and 341 fish not detected in the forebay were excluded from calculations of forebay residence time.

Dam Area	N	Mean	Median	Std	Min	Max
B1	53	6.6	2.7	10.1	0.03	50.8
B2	488	1.8	0.2	4.5	0.01	56.6
Spillway	179	0.7	0.3	1.6	0.01	20.0
All areas	720	1.9	0.3	4.9	0.01	56.6

3.5 Route and Time of Passage Through Bonneville Dam

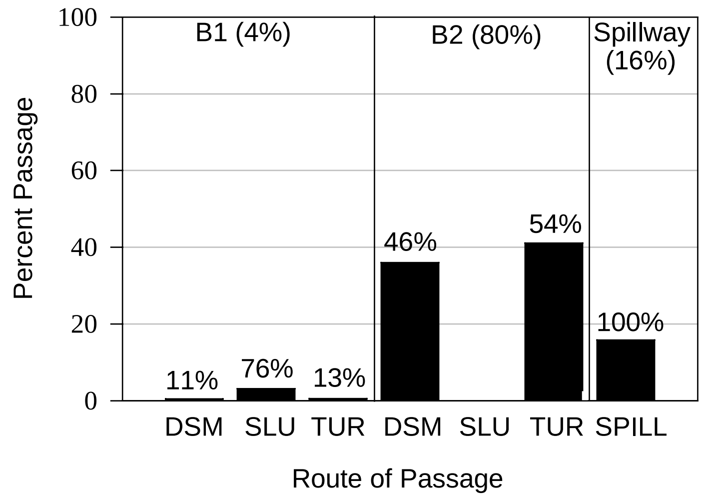

Figure 16. Percent fish passage by dam area and route of passage through Bonneville Dam for radio-tagged yearling chinook salmon during spring 2001. Percentages in parenthesis designate proportions between dam areas, percentages without parenthesis designate proportions within dam area, and the percent value of the bars represent proportions of all routes.

We determined the route of passage through Bonneville Dam for 98% (1143 of 1171) of yearling chinook salmon detected at Bonneville Dam. One percent (18 of 1171) passed the dam but a passage route could not be determined and 1% (10 of 1171) were not detected below Bonneville Dam. Among the three dam areas, B2 passed the most (80%; 915 of 1143) fish, followed by the spillway (16%; 181 of 1143) and B1 (4%; 47 of 1143; Figure 16). These percentages differ slightly from percentages of fish that first entered each dam area: 71% at B2, 23% at the spillway, and 6% at B1. Therefore, of the fish that first entered the spillway (23%), 7% eventually passed at B2. Similarly, of the fish that first entered B1 forebay (4%), 2% eventually passed at B2.

At B1, of the fish with known passage routes, 76% (36 of 47) passed via the sluiceway, 13% (6 of 47) passed unguided through the turbines, and 11% (5 of 47) were guided into the DSM. An additional 18 fish passed B1 through undetermined routes. At B2, of the fish with known passage routes, 54% (498 of 915) passed unguided through the turbines and 46% (417 of 915) were guided into the DSM (Figure 16).

Project passage of yearling chinook salmon peaked at sunset (2100 hours) and was lowest between 1000 and 1300 hours (Figure 17). Diurnal passage of yearling chinook salmon varied depending on the dam area and route of passage (Appendix 5). At all dam areas, a higher number of fish passed during day (652) compared to night

(491; Table 5). However, based on the number of hours in each diel period (16 for day, 8 for night), a higher proportion of fish passed at night. At all three dam areas, passage rates were higher during night than during day (Table 6).

Route-specific passage in regard to the diel cycle also indicated the majority of fish passed during day. At B1, 51% (24 of 47) of fish passed via the sluiceway during the day. Likewise, 65% (117 of 181) of fish that passed through the spillway did so during day. At B2, 60% (249 of 417) of fish were guided during day and 52% (257 of 498) were unguided during day (Figure 18). But again, based on the number of hours in each diel period, a higher proportion of fish passed at night, regardless of route.

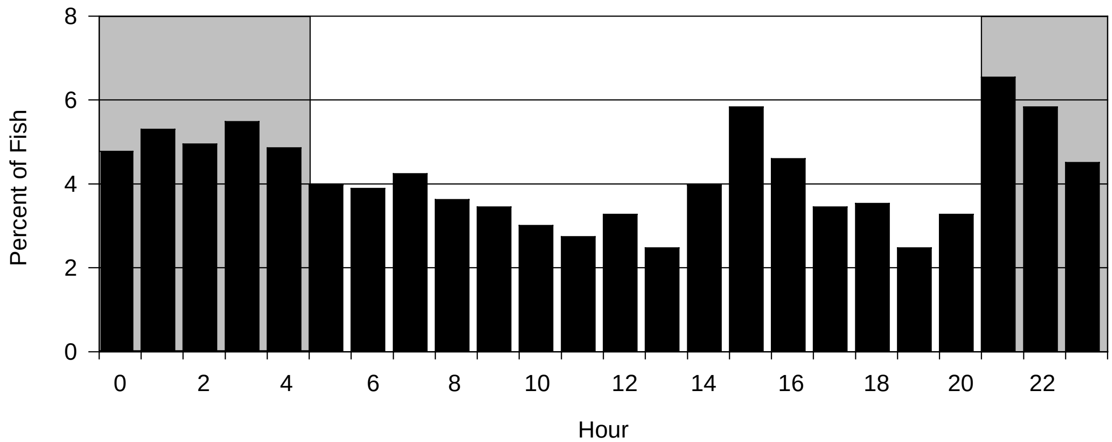

Figure 17. Percentage of yearling chinook salmon that passed Bonneville Dam by hour of day during spring 2001. Shaded areas represent night (2100-0459 hours) and unshaded areas represent day (0500-2059 hours).

Table 5. The proportion of radio-tagged yearling chinook salmon that passed each dam area of Bonneville Dam during day (0500-2059 hours) and night (2100-0459 hours) during spring 2001.

Period	B1 Passage	B2 Passage	Spill Passage
Day	4% (29 of 652)	78% (506 of 652)	18% (117of 652)
Night	4% (18 of 491)	83% (409 of 491)	13% (64 of 491)

Table 6. Passage rates for radio-tagged yearling chinook salmon at each dam area of Bonneville Dam during day (0500-2059 hours) and night (2100-0459 hours) during a 40 day test period in spring 2001.

Dam Area	Day	Night
B1	$29 \text{ fish} \div (16\text{h/d} \times 40\text{d}) = 0.05 \text{ fish/h}$	$18 \text{ fish} \div (8\text{h/d} \times 40\text{d}) = 0.06 \text{ fish/h}$
B2	$506 \text{ fish} \div (16\text{h/d} \times 40\text{d}) = 0.79 \text{ fish/h}$	$409 \text{ fish} \div (8\text{h/d} \times 40\text{d}) = 1.28 \text{ fish/h}$
Spillway	$117 \text{ fish} \div (16\text{h/d} \times 40\text{d}) = 0.18 \text{ fish/h}$	$64 \text{ fish} \div (8\text{h/d} \times 40\text{d}) = 0.20 \text{ fish/h}$

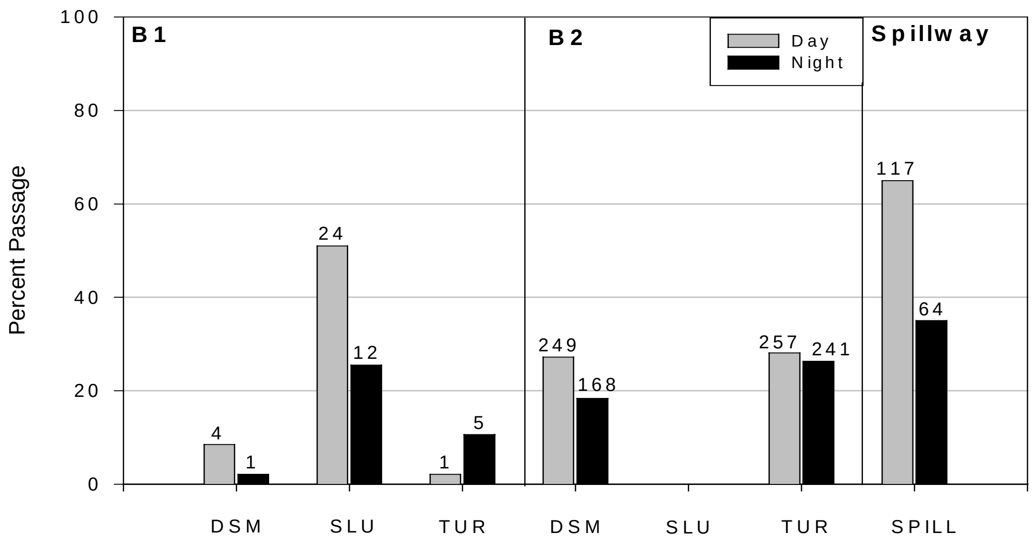

Figure 18. Percent passage by route of passage during day (0500-2059 hours) and night (2100-0459 hours) for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001.

3.6 Passage Metrics

3.6.1 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 for yearling chinook salmon at Bonneville Dam was 16% overall, 30% during 37% spill, and 1% during 2% spill (Table 7).

Table 7. Spillway Efficiency (SE) at Bonneville Dam for yearling chinook salmon during spring 2001. B1 passage includes fish that passed through unknown routes at B1: 18 overall, 2 during 37% spill, and 16 during 2% spill.

Period	SE	B1 Passage	B2 Passage	Spill Passage
Overall	0.16	65	915	181
37% spill	0.30	6	408	175
2% spill	0.01	59	507	6

3.6.2 Spillway Effectiveness

The proportion of fish that passed through spill relative to the proportion of discharge spilled (spillway effectiveness; SF) was 0.70 overall, 0.86 during 37% spill, and 0.53 during 2% spill. These values for spillway effectiveness indicate that the percentage of fish that passed through spill was less than the percentage of discharge spilled (Table 8).

Table 8. Spillway Effectiveness (SF) at Bonneville Dam for yearling chinook salmon during spring 2001.

Period	SF	SE	F_{sp}	F_{tot}
Overall	0.70	0.16	29.0	133.9
37% spill	0.86	0.30	49.3	141.7
2% spill	0.53	0.01	2.4	127.1

3.6.3 Fish Guidance Efficiency

Fish guidance efficiency (FGE; number of fish guided divided by number guided plus number unguided) at B1 (45%) and B2 (46%) was nearly the same. However, sample size was small at B1 (n = 11). FGE at B2 increased slightly during 37% spill and decreased slightly during 2% spill. Spill did not affect FGE at B1. FGE at units 11-14 was nearly identical to FGE at units 15-18, regardless of spill level (Table 9). Turbine unit 17 was the most efficient at guiding fish at B2; 64% of fish were guided at unit 17 overall and 70% were guided during 2% spill (Table 10). At B1, sample sizes were too small (n = 11) to calculate FGE by unit.

Table 9. Estimates of Fish Guidance Efficiency (FGE) at Bonneville Dam for yearling chinook salmon during spring 2001. Estimates for units 11-14 and units 15-18 do not include 143 unguided fish and 78 guided fish that passed through an unknown unit.

Period	B1	B2	Units 11-14	Units 15-18
Overall	45% (5 of 11)	46% (417 of 915)	49% (227 of 462)	48% (112 of 232)
37% spill	n/a (0 of 0)	49% (199 of 408)	51% (113 of 220)	49% (46 of 93)
2% spill	45% (5 of 11)	43% (218 of 507)	47% (114 of 242)	48% (66 of 139)

Table 10. Estimates of Fish Guidance Efficiency (FGE) by turbine unit at Bonneville's second powerhouse (B2) for radio-tagged yearling chinook salmon during spring 2001. These estimates do not include 143 unguided fish and 78 guided fish that passed through an unknown unit.

Turbines at B2 - Overall

11	12	13	14	15	16	17	18
51% (63 of 124)	40% (36 of 90)	58% (79 of 136)	44% (49 of 112)	39% (20 of 51)	48% (46 of 96)	64% (35 of 55)	37% (11 of 30)

Turbines at B2 – 37% spill

11	12	13	14	15	16	17	18
58% (37 of 64)	37% (22 of 59)	59% (41 of 69)	46% (13 of 28)	45% (13 of 29)	60% (21 of 35)	47% (7 of 15)	36% (5 of 14)

Turbines at B2 – 2% spill

11	12	13	14	15	16	17	18
43% (26 of 60)	45% (14 of 31)	57% (38 of 67)	43% (36 of 84)	32% (7 of 22)	41% (25 of 61)	70% (28 of 40)	38% (6 of 16)

3.6.4 Fish Passage Efficiency

Fish passage efficiency (FPE; number guided, sluiced, and spilled divided by total number passed B1, B2 and spill) at Bonneville Dam was 56% overall, 64% during 37% spill, and 47% during 2% spill (Table 11). At B1, FPE was 87% overall, 100% during 37% spill (4 of 4 fish passed through spill), and 86% during 2% spill. At B2, FPE was identical to FGE since no fish could pass through the closed sluice chute (46% overall, 49% during 37% spill, and 43% during 2% spill).

Table 11. Numbers used to calculate Fish Passage Efficiency (FPE) at Bonneville Dam for radio-tagged yearling chinook salmon during spring 2001.

	Non-Turbine Routes				Turbine Routes	
Period	B1 Guided	B1 Sluiceway	B2 Guided	Spillway	B1 Unguided	B2 Unguided
Overall	5	36	417	181	6	498
37% spill	0	4	199	175	0	209
2% spill	5	32	218	6	6	289

3.7 Comparison of Passage Performance Metrics as Measured by RadioTelemetry and Hydroacoustics

In addition to the radio telemetry evaluation we conducted, the Waterways Experiment Station of the U.S. Army Corps of Engineers (WES) used fixed hydroacoustics to monitor fish passage and estimate passage performance metrics for the run-at-large. Although the hydroacoustic spring monitoring period started earlier than did radio telemetry, passage metrics were calculated for each research tool using data from overlapping time periods (May 1–June 9) to facilitate comparison of the two techniques. Spillway effectiveness was 0.27 to 0.51 higher for hydroacoustics than for radio telemetry, depending on spill levels, and all other passage metrics were 2–14% higher for hydroacoustics than for radio telemetry (Table 12). However, differences in passage metrics were under 10% except for overall project FPE (10%) and B2 FGE during 2% spill (14%). For both hydroacoustics and radio telemetry, project FPE, spillway efficiency, and spillway effectiveness were all higher during periods of 37% spill than during periods of 2% spill.

A comparison of unit-specific estimates of FGE for B2 (units 11-18), as measured by radio telemetry and hydroacoustics, revealed further disparity: 1-32% (Table 13). Except at units 11, 17, and 18, estimates of FGE by unit were higher for hydroacoustics than for radio telemetry. Differences in FGE between hydroacoustics and radio telemetry were under 10% for only two units (units 11 and 13). Radio telemetry estimates of unit 11 FGE may have been overestimated due to unit 15 FGE tests during which fish were sampled out of unit 15 and then returned to unit 11. Any unreported radio-tagged fish returned to unit 11 could have been counted as a guided fish at unit 11.

We also compared diurnal passage results between radio telemetry and hydroacoustics. Diurnal trends in project passage were similar for both research methods except that radio telemetry data indicated a peak in passage from 1400–1600 hours and hydroacoustics data did not (Figures 19 and 20). A peak in passage from 1400-1600 hours for radio-telemetry was observed at both B2 and the spillway, and somewhat at B1, however, sample size was small at B1 (Appendix 5).

Table 12. Comparison of passage performance metrics for yearling chinook salmon, as measured by radio telemetry (RT), and the run-at-large, as measured by hydroacoustics (HA), at Bonneville Dam during spring (overlapping period of May 1-June 9) 2001. Hydroacoustic data were provided by Carl Schilt, Waterways Experiment Station (January 9, 2001).

Metric	RT Overall	HA Overall	RT 37% spill	HA 37% spill	RT 2% spill	HA 2% spill
SE	16%	26%	30%	38%	1%	n/a[a]
SF	0.70	1.21%	0.86	1.13	0.53	n/a[a]
FGE_{B1}	45%	47%	n/a	39%	45%	50%
FGE_{B2}	46%	56%	49%	55%	43%	58%
FPE	56%	67%	64%	71%	47%	56%
FPE_{B1}	87%	n/a[b]	100%[c]	n/a[b]	86%	n/a[b]
FPE_{B2}[d]	46%	56%	49%	55%	43%	58%

[a]Spillbays 1 and 18 were not monitored by hydroacoustics so SE and SF during 2% spill could not be estimated.
[b]The sluiceway at B1 was not monitored by hydroacoustics so FPE_{B1} could not be estimated.
[c]0 fish were guided, 0 fish were unguided, and 4 fish were sluiced.
[d]FPE_{B2}= FGE_{B2} since no fish could pass through closed sluice chute at B2.

Table 13. Estimates of Fish Guidance Efficiency (FGE), by turbine unit, at Bonneville's second powerhouse (B2) for yearling chinook salmon, as measured by radio telemetry (RT), and for the run-at-large, as measured by hydroacoustics (HA), during spring (overlapping period of May 1-June 9) 2001. Hydroacoustic data were provided by Carl Schilt, Waterways Experiment Station (January 9, 2001).

Location	RT FGE	HA FGE	Difference
Unit 11	51%	50%	1% (RT>HA)
Unit 12	40%	59%	19% (HA>RT)
Unit 13	58%	67%	9% (HA>RT)
Unit 14	43%	62%	19% (HA>RT)
Units 11-14	49%	58%	9% (HA>RT)
Unit 15	38%	70%	32% (HA>RT)
Unit 16	48%	60%	12% (HA>RT)
Unit 17	64%	48%	16% (RT>HA)
Unit 18	42%	32%	10% (RT>HA)
Units 15-18	49%	51%	2% (HA>RT)
Units 11-18	46%	56%	10% (HA>RT)

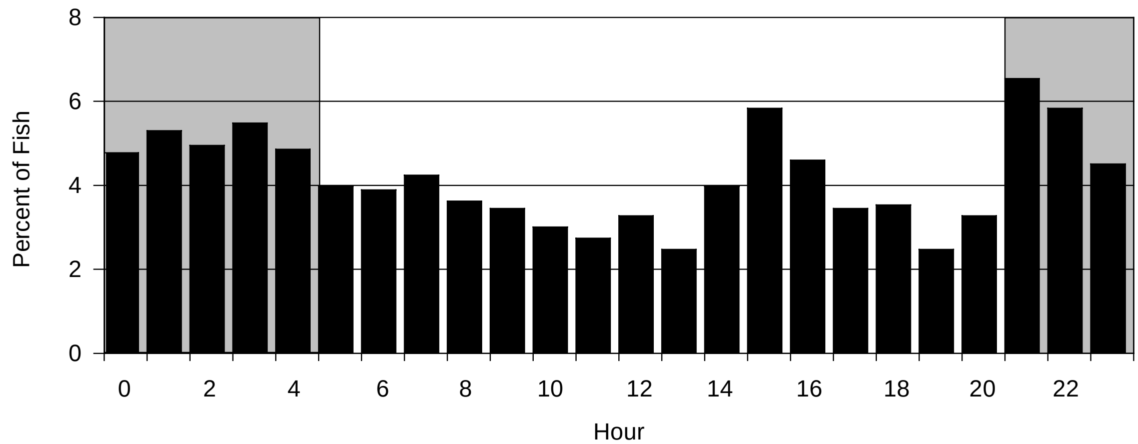

Figure 19. Percentage of yearling chinook salmon that passed Bonneville Dam by hour of day during spring (5/1-6/9) 2001. Shaded areas represent night (2100-0459 hours) and unshaded areas represent day (0500-2059 hours).

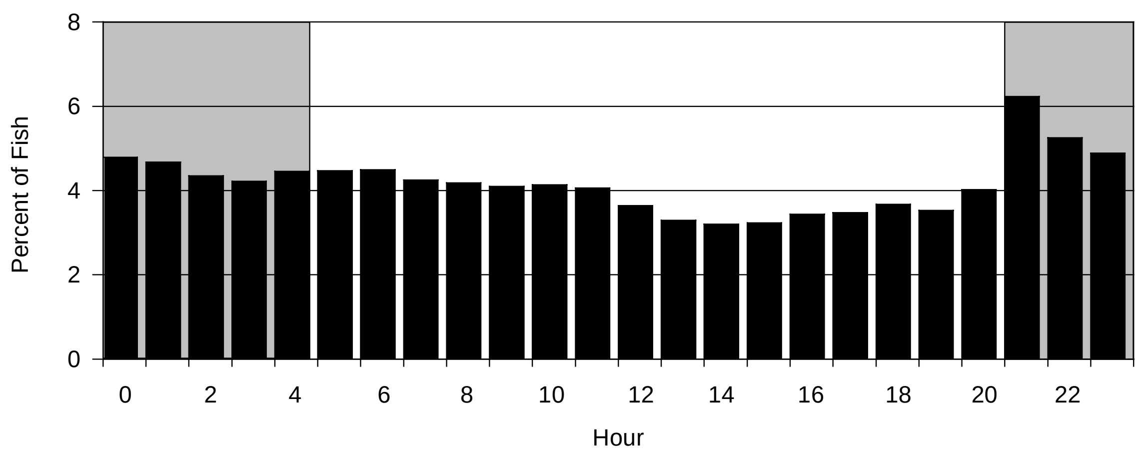

Figure 20. Percentage of run-of-river fish that passed Bonneville Dam by hour of day as measured by hydroacoustics during spring (5/1-6/9) 2001. Shaded areas represent night (2100-0459 hours) and unshaded areas represent day (0500-2059 hours). Data were provided by Carl Schilt, Waterways Experiment Station (January 9, 2002).

4.0 Discussion

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 B2 discharged the most amount of water during the study (72%) most fish entered the B2 forebay (71%). Likewise, since flows were very low at B1 (6% of project discharge), only 6% of yearling chinook salmon entered that dam area.

Forebay residence times of yearling chinook salmon differed considerably depending on dam area. B2 and the spillway provided the quickest routes of passage as residence times there were substantially less than at B1. 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 yearling chinook salmon. These observations indicate that project operations and the resulting discharge per dam area influence approach paths of migrating yearling chinook salmon and may determine which dam area they enter. Likewise, discharge per dam area affected how long fish resided in the forebay of Bonneville Dam before passing.

Although some movement occurred between the three dam areas (B1, B2, and the spillway), most fish passed through the dam area they first entered. Nine percent of the fish that first entered B1 and the spillway, eventually passed at B2. Therefore, project discharge was the primary factor in affecting not only approach behavior but also which dam area fish ultimately passed.

At B1, the proportions of radio-tagged fish that passed through specific routes indicated that fish were generally shallow in the water column. The greatest percentage (76%) of fish passed through the shallow, weir-type entrances of the sluiceway, followed by the deeper unguided (13%) and guided (11%) routes of passage. At B2, where a shallow, surface-oriented route of passage was unavailable because of the closure of the sluice chute, slightly more fish passed directly through the turbines (54%) than were guided into the DSM (46%). The unprecedented high rate of passage through the sluiceway at B1 was likely due to the low amount of discharge at B1. Since few turbines were operated at B1 due to low river flow and priority of turbines at B2, less fish were entrained into turbine intakes at B1 and thus were available to the shallow entrances of the sluiceway.

Passage distributions during day and night did not appear to be influenced by discharge, which was nearly equal during day and night at all dam areas. The higher proportion of fish that passed at night (based on the number of hours in each diel period) concurs with the findings of numerous studies regarding juvenile salmonid behavior at hydroelectric projects. Coutant and Whitney (2000) reported in a review of literature on fish behavior relative to passage of fish through hydropower turbines, that emigrating salmonids descend, mostly at night, to pass the dam through the turbines or turbine intake bypass system.

All passage metrics in 2001 were lower than in 2000 with the exception of FGE (and therefore FPE) at B2, and FPE at B1 (Table 14). Decreased passage metric values in 2001 can be attributed to low river flows. Due to B2 FGE tests, turbine operation at B2 was prioritized over turbine operation at B1. Additionally, spill occurred for only two thirds of the study and was limited in quantity. The resulting high discharge at B2, compared to the other dam areas, attracted and passed a majority of the fish. Since fewer fish entered B1 and the spillway, fewer fish passed at those locations, resulting in low passage metrics. Low discharge at B1, although it may have produced low FGE, likely was responsible for increasing project FPE compared to what it might have been if discharge were higher at B1. Low discharge at B1 minimized the number of turbine-entrained fish, thereby increasing passage into the sluiceway, which in turn increased FPE.

Table 14. Passage performance metrics for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2000 and spring 2001.

Metric	Yearling Chinook		Steelhead
	2000	2001	2000
Spillway Efficiency	44%	16%	33%
Spillway Effectiveness	1.3	0.7	1.0
FGE_{B1}	50%	45%	59%
FGE_{B2}	39%	46%	55%
FPE	73%	56%	78%
FPE_{B1}	65%	87%	77%
FPE_{B2}	40%	46%	55%

The comparison of our estimates of passage metrics with those obtained with hydroacoustics, demonstrates the importance of having more than one independent estimate of passage performance. Although each research tool has its strengths, each tool also has its weaknesses. Radio telemetry is useful because it enables the investigator to obtain information on a species-specific basis and it has a relatively wide range of spatial resolution in terms of coverage area. However, radio telemetry sample size is often restricted by costs of tags and the number of radio-tagged fish that can be tracked concurrently. Hydroacoustic sampling is an effective means of obtaining information on numerous fish, but deciphering fish species or obtaining information on individual fish is not currently possible. Therefore it can be advantageous to utilize both technologies to overcome the limitations of each method. We do not have a clear explanation of why differences in passage metric estimates for radio telemetry and hydroacoustics were, in some instances, so great (>10%). The smaller sample sizes utilized by radio telemetry may have contributed to these differences. Equally plausible is that, because hydroacoustics sampled the run-at-large, passage estimates may have been based on a mixture of species with different passage behavior than yearling chinook salmon. Radio telemetry examined the passage behavior of a single species; yearling chinook salmon.

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 U.S. Army Corps of Engineers personnel for their efforts in managing our contract and assisting in planning and executing this research. Many thanks go to Dean Ballinger, Bruce Mills, John Barton and Rick Martinson at the Pacific States Marine Fisheries Commission for their assistance in collecting fish for this study. We would also like to thank Gene Ploskey and Carl Schilt, of the U.S. Army Corps of Engineer's Waterways Experiment Station, for providing hydroacoustic data and information that enabled our comparison of radio telemetry and hydroacoustic results.

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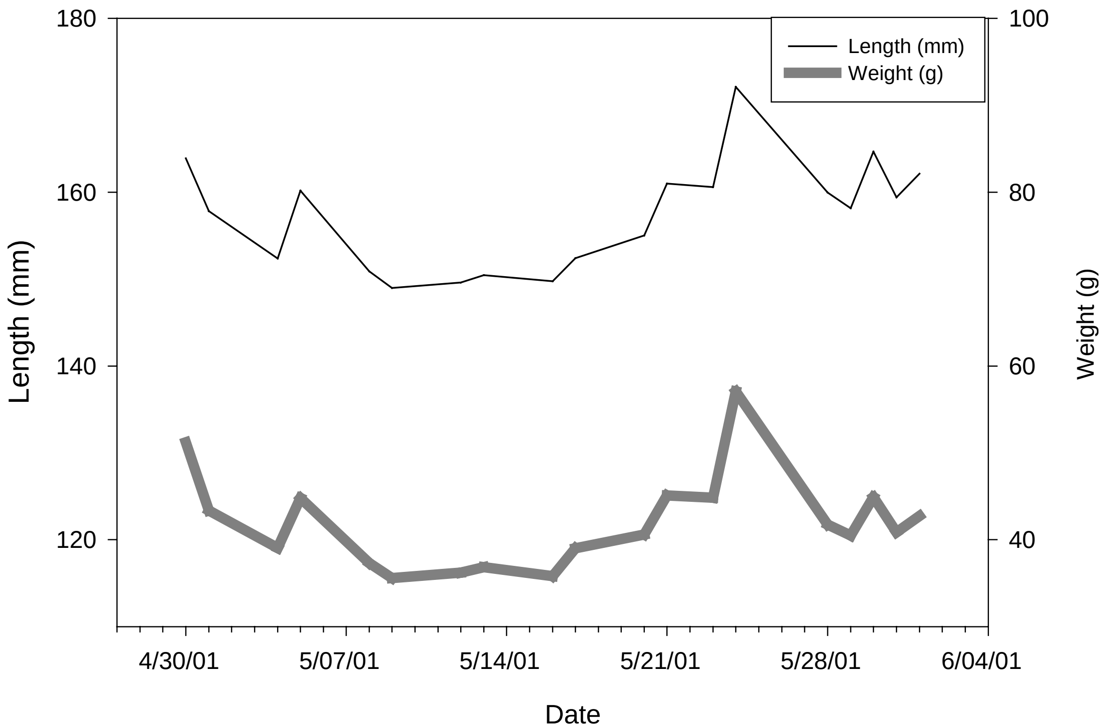
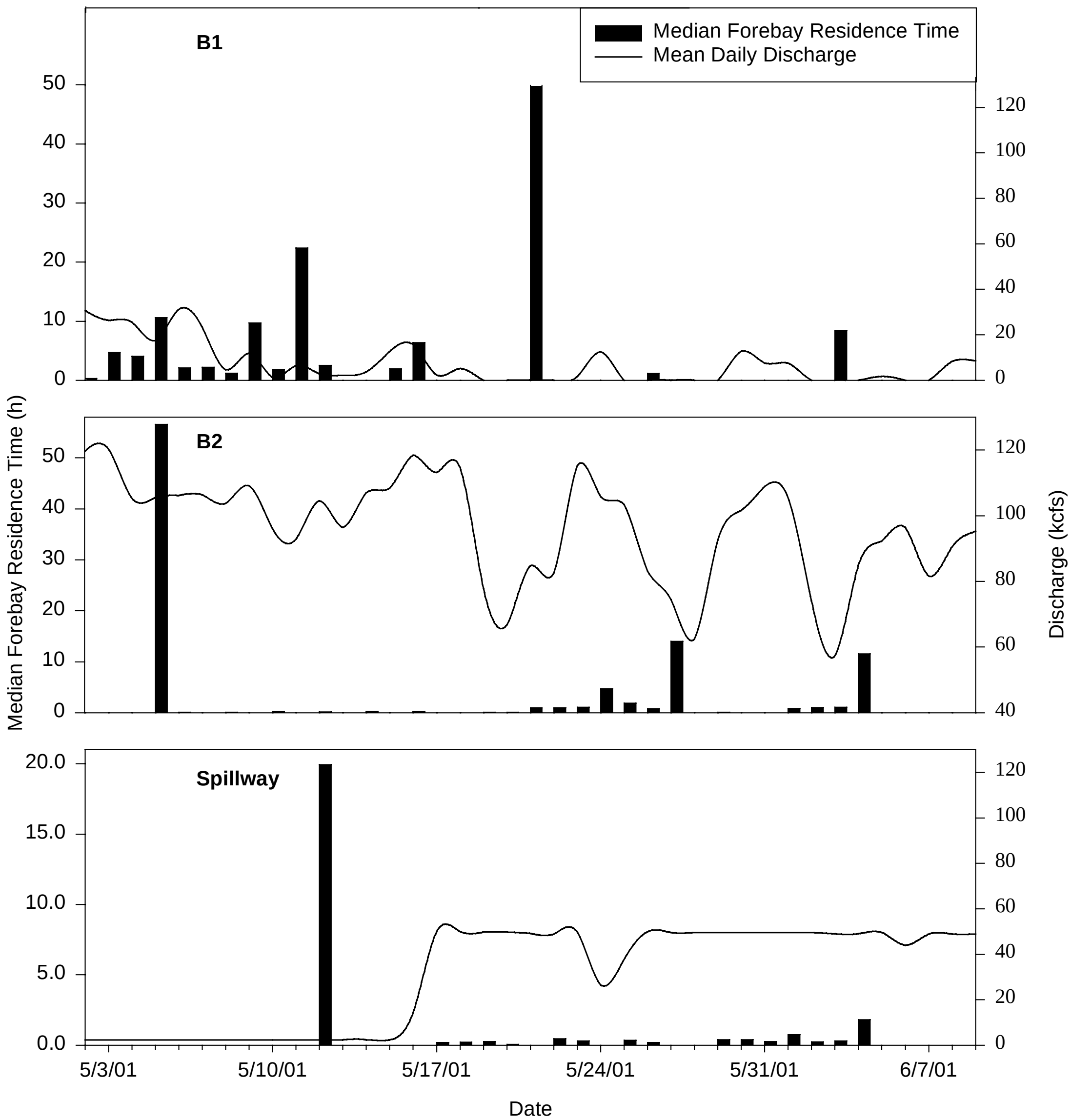
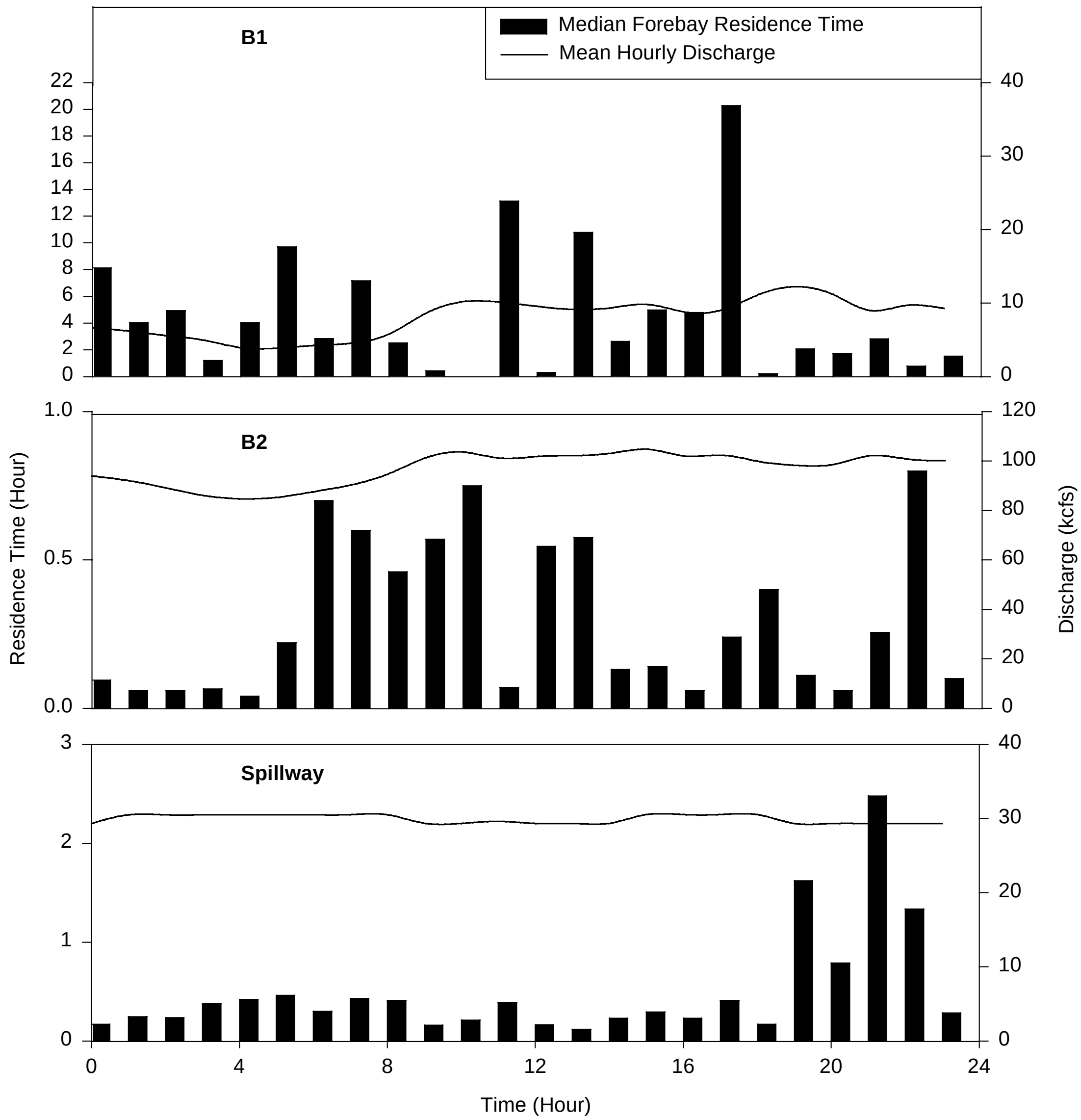
7.0 Appendices



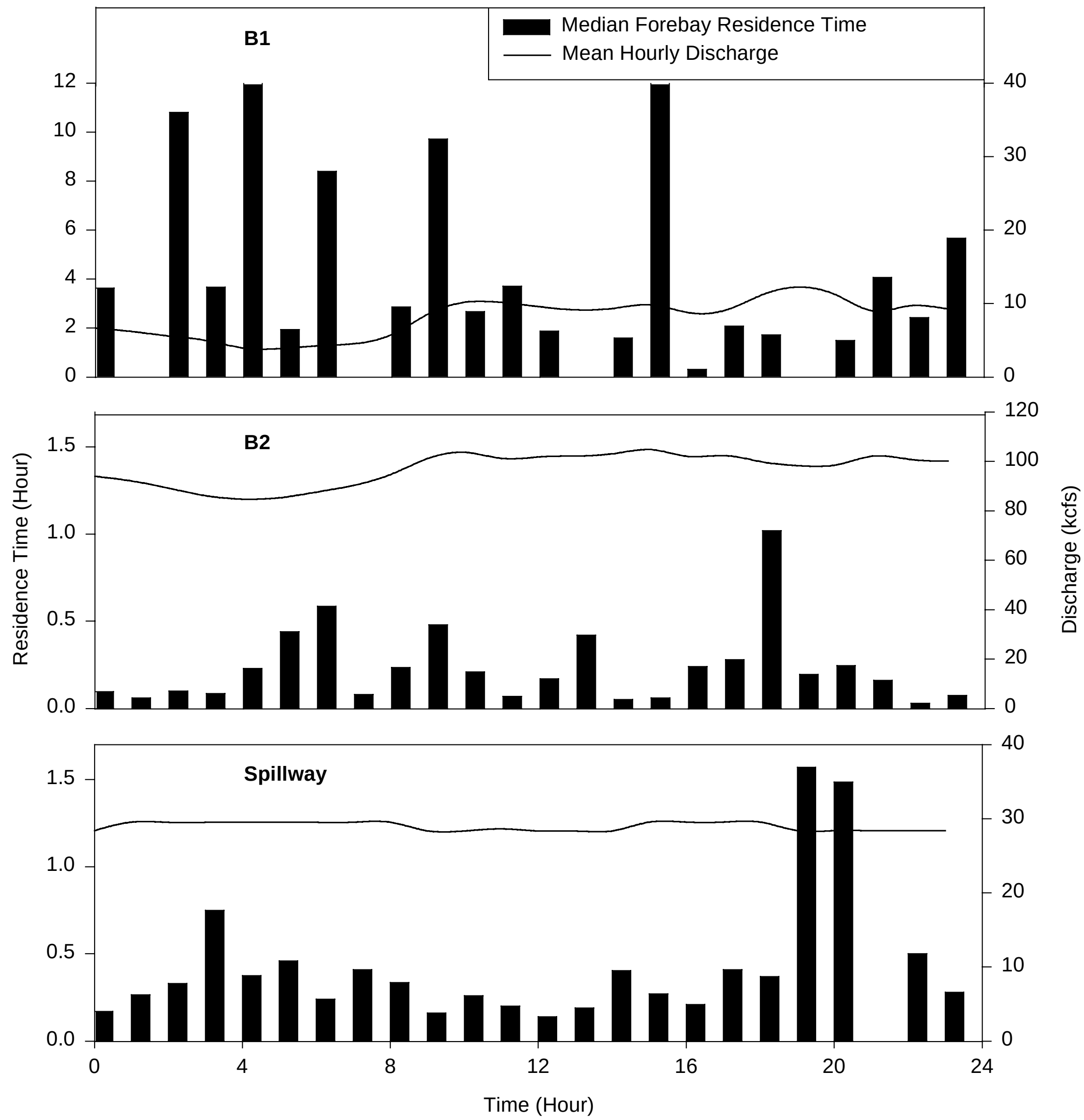
Appendix 1. Mean length and weight by date for yearling chinook salmon collected at Bonneville Dam before radio tag implantation during spring 2001.



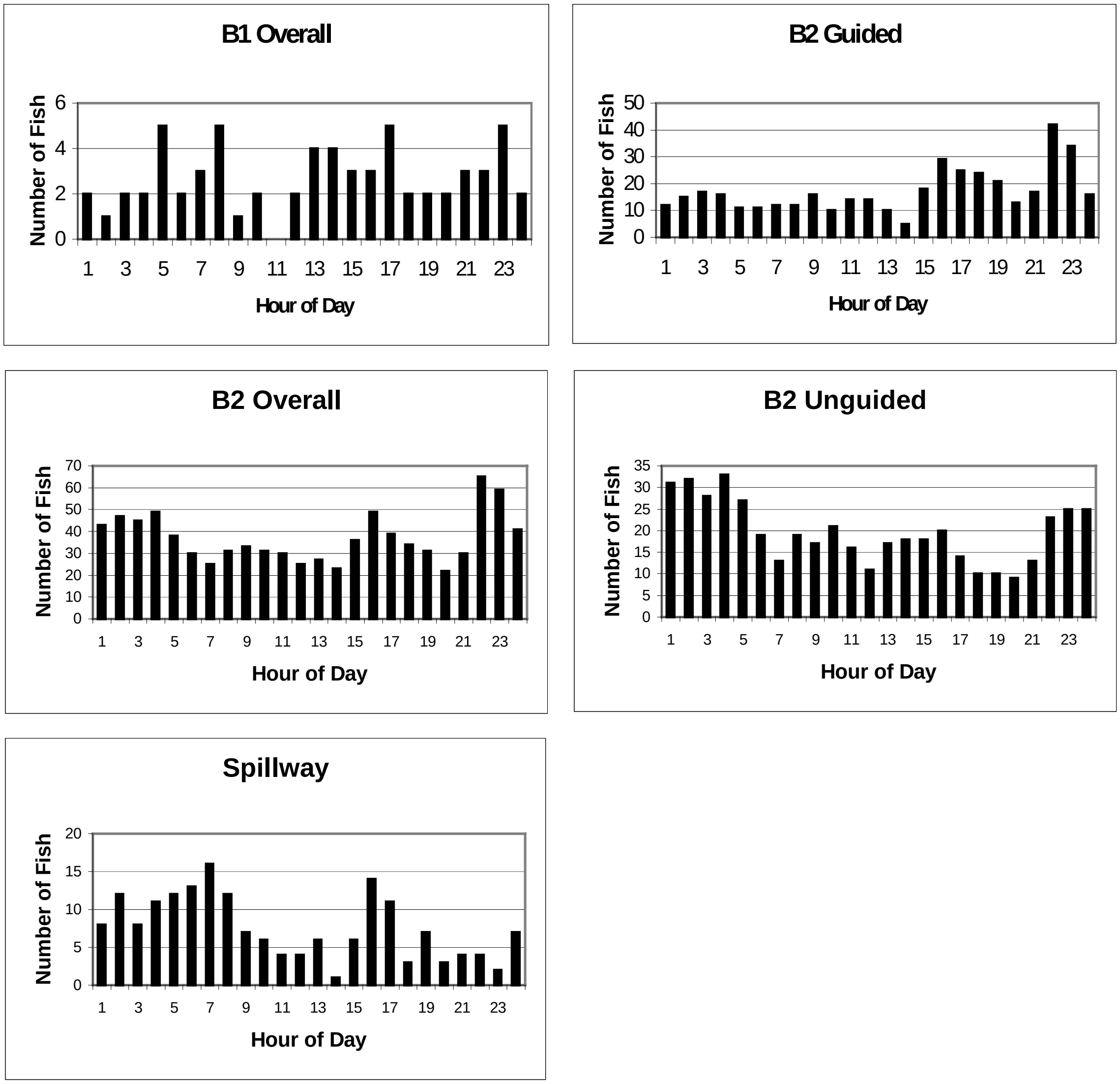
Appendix 2. Median forebay residence time by day of passage versus mean discharge by dam area for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001.



Appendix 3. Median forebay residence time by hour of passage versus mean discharge by dam area for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001.



Appendix 4. Median forebay residence time by hour of arrival versus mean discharge by dam area for radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001.



Appendix 5. Diurnal passage of radio-tagged yearling chinook salmon at Bonneville Dam during spring 2001. Note the y-axis scales differ among graphs.