Technical Report 2003-6 Draft

IDAHO COOPERATIVE FISH AND WILDLIFE RESEARCH UNIT

TEMPERATURE INFLUENCED MIGRATORY BEHAVIOR AND USE OF THERMAL REFUGES BY UPRIVER BRIGHT FALL CHINOOK SALMON, 1998 AND 2000

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For

U.S. Army Corps of Engineers
Portland and Walla Walla Districts

And

Bonneville Power Administration
Portland, Oregon

2003

Abstract

Correlations between lower Columbia River water temperatures and run timing, migration behavior, and tributary use by fall chinook salmon *Oncorhynchus tshawytscha* were studied using historic counts and radio telemetry data. Over the past 70 years, mean August and September water temperatures recorded at Bonneville Dam have increased, often exceeding the estimated optimal migration temperature for fall chinook salmon. We found median run passage dates from historic fall chinook count data at Bonneville, The Dalles and McNary dams were positively correlated with mean August water temperatures at Bonneville Dam, suggesting later adult migration timing in warm years.

In 1998 and 2000, we radio-tagged and released 1,032 and 1,118 fall chinook salmon at Bonneville Dam and monitored their upstream migration. Mean water temperatures in August and September were 1.9°C warmer in 1998 than in 2000, and upriver bright (URB) fall chinook salmon migrated significantly slower in the warmer year. Lower migration rates in 1998 were due in part to temporary straying by radio-tagged fish: 30.2% of URB salmon were recorded for more than 12 h in lower Columbia River tributaries in 1998, versus 14.5% in 2000. Tagged fish were observed holding in and around the Little White Salmon, White Salmon, Klickitat, and Deschutes rivers, but not at other monitored tributaries. The four tributaries used by tagged fish had relatively high discharges, were 4 to 12°C cooler than ambient Columbia River temperatures during the migrations and entered the Columbia River at sites where cool-water plumes were likely to be encountered by migrating salmon. During both years, use of tributaries was significantly correlated with Columbia River water temperatures. URB fall chinook salmon that delayed in tributaries for longer than 12 h, and those that fell back at any of the study area dams, were significantly less likely to escape to mid-Columbia or Snake River sites.

Acknowledgements

Many people were involved in the data collection and compilation for this report. We thank Drs. James Congleton and Chris Williams for writing review and statistical support. We recognize the crew: Rudy Ringe, Steve Lee, Chuck Boggs, and Denis Queampts for radio-tagging; Eric Johnson, Brett High, George Naughton and Amy Pinson for tracking; Ken Tolotti, Kevin Trailer, and Travis Dick for downloading receivers; Megan Heinrich for tag recaptures; Mike Jepson, Mark Morasch, Dan Joosten and others for data processing; Alicia Matter from the National Marine Fisheries Service for assisting manage the Seattle database; and Tami Reischel for computer help.

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Introduction

Historically, more than 900 km of the mainstream Columbia River from The Dalles, Oregon to the Pend Oreille River, Idaho were used for spawning by fall chinook salmon *Oncorhynchus tshawytscha* (Dauble and Watson 1990; ODFW and WDFW 1991). Construction of the Columbia-Snake River hydrosystem over the past 72 years has reduced spawning grounds in the Columbia River basin by an estimated 90% (Dauble and Watson 1990). Fall chinook stocks spawn in tributaries and at mainstem sites throughout the basin (reviewed in Myers et al. 1998), but stocks are often grouped into two major spawning populations. A lower river population spawns at sites downstream from the The Dalles Dam (Liscom and Stuehrenberg 1983; Howell et al. 1985), while a second group, the upriver bright (URB) fall chinook salmon, returns to sites upstream from The Dalles Dam (Howell et al. 1985). A small population of URBs spawns in the Deschutes and Snake rivers, but since 1975 nearly 95% of fish that pass McNary Dam spawn in or upstream from the Hanford Reach, the last unimpounded section of Columbia River (Dauble and Watson 1990).

Impoundment of the lower Columbia and Snake rivers, beginning with construction of Bonneville Dam in 1938, has decreased water velocity by more than 50% throughout the system and by 64% in the Bonneville – McNary Dam segment (Quinn et al. 1997). During the last 40 years, as velocity decreased, the lower Columbia River has become warmer (Figure 1). River warming (first day above 15.5°C) occurs about 30 d earlier than historically (e.g. 1938-1940) and temperatures remain high about 12 d later in fall; maximum temperatures have increased approximately 1.8°C from 1949 to 1993 (Quinn and Adams 1996; Quinn et al. 1997). Quinn et al. (1997) showed strong correlations between increased impoundment and changes in the thermal regime of the lower river during the last 70 years. Mainstem dam construction ended with completion of Lower Granite Dam in 1975, but water temperatures have continued to increase, possibly reflecting a regional climate change. Since 1948, air temperatures have significantly increased (>1°C) in much of the Pacific Northwestern United States (Lettenmaier et al. 1994; Hamlet and Lettenmaier 1999). With a predicted rise in global temperature from 2 to 5°C over the next century (Chatters et al. 1991; Neitzel et al. 1991; Hamlet and Lettenmaier 1999), elevated Columbia River temperatures during adult fall chinook salmon migration are likely to persist.

Fall chinook salmon have evolved a freshwater migration strategy around the annual water temperature cycles of spawning rivers throughout their range (Coutant 1999). Historically, most adults migrated upstream after annual water temperatures peaked. If fall chinook salmon adjust migration to avoid warm water conditions, high temperatures during late summer and early fall may prolong or delay adult migration. Such delays may affect escapement rates and spawning success for Columbia River fall chinook salmon (Coutant 1999; McCollough 1999).

Fall chinook URB salmon begin passing Bonneville Dam in August, counts typically peak in early September and most have passed by late October (Figure 2); URB salmon spawn in the Mid-Columbia and Snake River basins in October and November (Appendix A; Dauble and Watson 1990; Myers et al.1998). Total run size and the Snake River component of the run have fluctuated greatly from year-to-year (Appendix B). Large numbers of URB fall chinook salmon continue to spawn in the Columbia mainstem between the Snake River confluence and Priest Rapids Dam, an area known as the Hanford Reach (Watson 1970; Dauble and Watson 1990). In contrast, a downward trend and critically low numbers of salmon returning to the Snake River basin in the 1980s and early 1990s prompted their listing as threatened under the Endangered Species Act on April 22, 1992 (NMFS 1992).

Mean monthly Columbia River water temperatures average 20 to 21.5°C in August and September and maximum daily temperatures reach as high as 24°C (USACE 1938-2000), well above the optimum adult chinook migration temperatures of between 10.5 and 19.5°C (Bell 1986). Average Columbia River water temperatures during August and the first half of September are within one degree of the incipient lethal range of 21 to 22°C noted for jack (precocious male) fall chinook salmon (Coutant 1970) and maximum temperatures approach 25°C, the critical thermal maximum for the species (Bell 1986). By October, Columbia River temperatures have decreased and peak spawning occurs within recommended ranges (Watson 1970; Dauble and Watson 1990). By comparison, Eagle Creek (rkm 236), Herman Creek (rkm 243), and the Wind (rkm 249), Little White Salmon (rkm 261), White Salmon (rkm 271), Hood (rkm 273), Klickitat (rkm 290), and Deschutes (rkm 328) rivers are much cooler during the period of warmest Columbia River temperatures, providing potential thermal refugia for migrating salmon.

The goal of this study was to evaluate upstream migration behavior and losses of fall chinook salmon in relation to water temperature in response to actions 107 and 118 of the final 2000 FCRPS biological opinion. Our objectives included determining peak arrival times of fall chinook salmon at Bonneville, The Dalles, John Day and McNary dams from historic fish counts and relating this measure of migration timing to water temperatures recorded at Bonneville Dam. In addition, we used radiotelemetry to evaluate relationships between water temperature, salmon migration rates, temporary straying behavior and escapement.

Study Area

The study area included the Columbia River and its tributaries from Bonneville Dam (river kilometer 235) upstream to Priest Rapids Dam (rkm 639), and the lower Snake River from its confluence with the Columbia River to Ice Harbor Dam (rkm 538) (Figure 3). The area contains six hydroelectric projects and 13 major tributary rivers, including the Snake River. Radio-tagged fall chinook salmon movements were intensively monitored at each dam, in the seven tributaries entering the Bonneville Reservoir and in the Deschutes River (Figure 3).

Methods

Tagging Procedures

Adult fall chinook salmon were intragastrically radio tagged in the Adult Fish Facility located adjacent to the Washington-shore fishway at Bonneville Dam using methods previously described by Keefer et al. (2002). Three different transmitters were used: 7-volt (8.3 cm long x 1.6 cm diameter; 13g weight in water), 3-volt (4.5 x 1.3 cm; 4.1 g in water), and 3-volt archival tags (9 x 2 cm; 20 g in water). After tagging, fish were placed in a 2,270-L aerated recovery tank and then transported to release sites. In 1998, all radio-tagged fall chinook salmon were released at sites on both sides of the Columbia River 9.5 km downstream of Bonneville Dam. In 2000, 67% of fall Chinook salmon were released at the downstream locations and 33% were released directly into the Bonneville Dam forebay. Fish were tagged between 1 August and 23 October in 2000, and from 1 September to 15 October in 1998; tagging in 1998 was delayed until September 1 due to high water temperatures (Figure 4).

Data Collection

In 1998 and 2000, approximately 189,000 and 193,000 fall chinook salmon passed Bonneville Dam, respectively. We radio tagged 1,032 (1.1%) adults in 1998 and 1,118 (0.6%) in 2000. Implanted tags emitted a unique digital code on frequencies between 149.480 – 149.800 MHz separated by 0.02 MHz increments. Movements of radio-tagged salmon were monitored using a series of radio receivers (SRX-400; Lotek Wireless, Inc.) with aerial antennas stationed in the tailraces of dams from Bonneville Dam upstream to Lower Granite and Priest Rapids dams, and at the mouths of most tributaries through this section of river. SRX receivers coupled with Digital Spectrum Processors (SRX/DSPs) were used to monitor ladder exits. SRX/DSP receivers could scan all channels simultaneously and so increased the chance that radio-tagged fish would be recorded while exiting ladders. All receivers recorded channel (frequency) and code of each transmitter plus date, time, and signal strength. Telemetry data were periodically downloaded from receivers to a portable computer and electronically transferred to the main database maintained by NOAA Fisheries personnel in Seattle, WA. All tributaries in the Bonneville Reservoir were equipped with antennas except Herman and Eagle creeks. These two creeks are smaller than the other study tributaries and were checked with frequent mobile tracking by truck and boat. All study tributaries were tracked by truck throughout the fall each year. The Hanford Reach was tracked by boat in September, October and November each year, and the entire river from Bonneville to Priest Rapids and Ice Harbor dams was tracked at the end of each field season to determine final locations of fish with tags. Additionally, the Bonneville Reservoir was tracked regularly by boat on alternating days from August through October in 2000, but not in 1998.

Historic Run Timing and Columbia River Temperatures

Fall chinook runs were defined by the dates established by USACE at each of the four lower Columbia River Dams: Bonneville (1 August to 15 November), The Dalles (4 August to 31 October), John Day (6 August to 31 October) and McNary (9 August to 31 October), except Bonneville Dam run totals were calculated from 1 August 1 to 31 October to be consistent with the three upstream dams. Run timing was defined by the date when 50% of each fall chinook run was counted passing each of the four dams, from the date of construction completion through 2001. Dam completion dates were: 1938 (Bonneville), 1957 (The Dalles), 1968 (John Day), and 1954 (McNary).

From USACE annual Fish Passage reports, daily August water temperatures recorded from the scroll case gages in powerhouse 1 at Bonneville Dam were averaged for every year from 1940 to 2001. August water temperatures were also used as an index of the river environment throughout the fall. A paired-Comparisons *T*-test ($\alpha = 0.05$) was used to determine if daily water temperatures recorded at Bonneville Dam from August 1 through September 30 were statistically different between 1998 and 2000. Potential autocorrelation errors were corrected by adjusting the standard error for both years (Ramsey and Schafer 2002).

Analysis of variance (ANOVA) was used to assess the relationships between median fall chinook salmon passage dates at the four dams and average August water temperatures at Bonneville Dam. Passage dates for each year were converted to Julian dates without correcting for leap years. Correlations between run timing and temperature were considered significant at $\alpha = 0.05$, and coefficients of determination (r^2) were used to determine how much of the variation in fall chinook arrival timing was explained by water temperature.

Migration Rates

Migration rates (km/d) of radio-tagged fish last recorded upstream from John Day Dam were calculated taking the distance traveled from Bonneville Dam to John Day Dam (109.8 km) and dividing by individual migration times. Migration time started when tagged salmon exited Bonneville Dam fish ladders or when they were released into the Bonneville forebay (Figure 5), and ended when they were first recorded at John Day Dam tailrace receiver sites, 1.9 km downstream from the dam (Figure 6). Some salmon were not recorded at the John Day tailrace sites. For those fish, we estimated Bonneville-John Day tailrace times by subtracting the mean time fish took to pass from the John Day tailrace to the John Day fishway entrances from the time fish to migrate from Bonneville Dam to the John Day fishway entrances.

The distributions of individual migration rates were calculated for 1998 and 2000 and checked for normality using the univariate procedure in SAS. A nonparametric Wilcoxon ranks sum one-tailed test ($\alpha = 0.05$) was used to test if the two populations had the same migration rates (Ott and Mendenhall 1984). A second Wilcoxon rank sum test was used on fall chinook salmon that did not enter any tributary for longer than 12 hours. This allowed for between-year comparisons of migration rates without the influence of temporary straying into tributaries.

Tributary Use

The amount of time radio-tagged URB fall chinook salmon spent migrating past tributaries in Bonneville reservoir and the Deschutes River was totaled from the fixed receiver records each year. Fish using Herman and Eagle creeks were omitted from these calculations; instead, mobile tracking records of presence/absence were used to provide a general idea of their use. Limiting analysis to salmon recorded upstream from John Day Dam concentrated study on upriver stocks and removed some uncertainty associated with downstream fisheries and straying by lower river stocks.

All URB fall chinook salmon were divided into two categories each year: fish that delayed migration (cumulative records longer than 12 hours at tributaries) and those that did not delay. The multivariate Hotelling T^2 test was used to determine if Columbia River turbidity, flow, dissolved gas percentage, and water temperature at the time each fish entered the Bonneville reservoir differed for the two groups. When the river environment was statistically different, canonical variate analysis was performed to determine which variable or variables were related to fish delay at tributaries.

Chi-squared analyses were used to compare the proportion of fish with cumulative delays longer than 12 hours between years for tributaries with fixed receivers, and for the proportions that delayed at Eagle and Herman creeks each year (Freedman et al. 1991). Use of Bonneville reservoir tributaries was also compared for Deschutes River spawners and for fish that passed John Day Dam.

To evaluate between-year differences, we compared the cumulative times fish that passed John Day Dam spent in the six tributaries with fixed receivers using a Wilcoxon rank sum test.

Escapement

All fall chinook last recorded upstream from The Dalles Dam were separated into two categories; those recorded entering spawning grounds and those that did not. All fall chinook salmon last recorded in the Yakima River, the Hanford Reach, or upstream from Ice Harbor Dam were considered escaped from the lower Columbia River. Salmon last recorded in the mainstream Columbia River upstream from the Dalles Dam but downstream from the Hanford Reach were considered to have not escaped. Fish captured in the sport and commercial fisheries and fish last recorded in the Deschutes, John Day, Umatilla and Walla Walla rivers were excluded from the analysis.

River condition variables were assigned to fish based on the day they passed The Dalles Dam. A MANOVA was run for each year with turbidity, discharge, water temperature, dam spill, length of tributary delay, dam fallback, fish fork length, fish sex, and presence of "fresh" marine mammal wounds at the time of tagging as independent variables, and escapement as the dependent variable. Length of tributary delay was transformed by natural log to conform to normality assumptions. Canonical variate analysis was used to evaluate which factors affected escapement. Chi-square and logistic regression analyses were also used to evaluate relationships between fallback, passage delay and escapement. Probability of escapement given the length of delay was determined by:

$$p(y = Escapement|x) = \frac{\exp(\beta_0 + \beta_1 x)}{1 + \exp(\beta_0 + \beta_1 x)}.\ \hat{y}$$

The Wald Statistic and Hosmer and Lemeshow test were used to interpret if regression coefficients were statistically different from zero and if predicted values accurately represented the collected data (Hosmer and Lemeshow 1989).

Results

Historic Run Timing

Annual fall chinook salmon run timing and progression upstream through the lower Columbia River was positively correlated with August water temperatures. Median passage dates at Bonneville Dam from 1938 to 2001 increased significantly (P = 0.01) as mean August water temperature increased. Median arrival dates ranged from 3 September in 1952 to September 14 in 1983 (Figure 7). Water temperature explained 10% of the total variation in arrival time at Bonneville Dam. Passage dates at The Dalles Dam were positively correlated with water temperature (P = 0.01); 50% passage dates ranged from 6 September 6 in 2000 to 19 September in 1998 (Figure 7). Water temperature explained 13% of the total variation in median arrival at The Dalles Dam. No significant relationship was detected at John Day Dam from (P = 0.33; Figure 8), but a significant positive correlation (P < 0.01) was observed at McNary Dam where 50% passage dates ranged from 3 September in 1955 to the 24 September in 1967. Water temperature explained 25% of the total variation in arrival at McNary Dam.

Plots of cumulative run passage showed relatively long migration time from Bonneville to The Dalles dams and from The Dalles to John Day dams (Figure 9). The shortest travel time between dams was in the longest reach, between John Day and McNary dams. If fish migrated through each segment at equal rates, the short The Dalles

Reservoir would have the smallest area between curves, and time spent migrating through the Bonneville Reservoir would have been intermediate.

Columbia River Temperatures

Average scrollcase water temperature at Bonneville Dam from August 1 through September 30 was 22.2°C in 1998 and 20.3°C in 2000. Daily average water temperatures in 1998 were significantly warmer than in 2000, ranging from 0.56 to 3.33°C warmer during the two months (Figure 10; $t = 9.96$, $P < 0.001$). In 1998, water temperatures were above 21.5°C, the incipient lethal limit for jack chinook salmon (Coutant 1970), for 49 of 61 d (80%); water temperatures were recorded above 21.5°C for 13 d (21%) in 2000.

Migration Rates

In 1998, 464 radio-tagged fall chinook salmon were last recorded upstream from John Day Dam. Of the 464, migration rates were calculated for 443: 341 for fish recorded at tailrace sites prior to approaching John Day Dam, and 102 for fish estimated from their fishway entrance records. In 2000, 553 fall chinook salmon were last recorded upstream from John Day Dam and migration rates were calculated for 540 fish: 258 fish had tailrace records and migration times for 282 were estimated.

Median and mean migration rates were significantly slower in 1998 than in 2000 indicating fall chinook salmon spent more time in 1998 in the Bonneville and The Dalles reservoirs than during 2000 ($Z = -4.474$, $P < 0.001$, Figure 11). In 1998 and 2000, median migration rates of radio-tagged salmon were 36.2 and 38.6 km/d, respectively. Mean migration rates were skewed to the right, but with large sample sizes a more conservative two-sample t test of the means is robust to non-normality (Ott and Longnecker 2001). The *t* test of mean migration rates agreed with the Wilcox rank sum test and further supported a difference between 1998 and 2000 ($T = -5.11$, $P < 0.001$).

After removing salmon delaying at tributary confluences longer than 12 hours, migration rates of fish migrating continuously from Bonneville to John Day Dam did not differ between years ($Z = 0.103$, $P = 0.46$). Without the influence of tributary delay, migration rates in 1998 and 2000 were not significantly different.

Tributary Use

From fixed receiver site data, we determined that some fish stopped upstream migration longer than 12 hours at the Little White Salmon, White Salmon, Klickitat, and Deschutes rivers (Table 1). No upriver salmon were recorded on fixed receiver sites at the Wind or Hood rivers either year. Only one URB fall chinook salmon was mobile tracked at Herman Creek and none were located at Eagle Creek in 1998 and 2000.

Hotelling's T^2 and canonical variate analysis showed URB fall chinook salmon that delayed at Bonneville tributaries entered the reservoir during warmer conditions than those fish that did not use tributaries (Table 2). Columbia River water temperature was responsible for nearly all the variability in tributary use between the two groups in 1998. During 2000, dissolved gas percentage and water temperature combined accounted for the greatest amount of variability associated with tributary use, indicating a difference in river environment encountered by fall chinook salmon using tributaries and those migrating continuously through the reservoirs. In 1998, the four variables tested were uncorrelated; water temperature and discharge were correlated in 2000 (Table 2).

In 1998, 30.2% of all radio tagged fall chinook salmon (n = 464) delayed over 12 hours at one or more tributaries between Bonneville and John Day dams, versus 14.5% of 553 fish in 2000 ($P < 0.001$). Significantly larger proportions ($P < 0.05$) of fall chinook salmon delayed migration at the White Salmon, Klickitat, and Deschutes rivers in 1998 than in 2000 and, although not significant, a larger proportion of fish delayed at the Little White Salmon River in 1998 as well (Table 1).

Fall chinook salmon spent up to 763 h at tributary confluences between Bonneville and John Day dams in 1998 and up to 296 hours in 2000 (Figure 12). Fish that stayed in tributaries more than 12 h in 1998 had mean delays of 152 h (median = 95 h) versus 84 h (median = 62 h) in 2000. Medians were significantly different between years (Z = -2.91, $P < 0.002$, Wilcoxon rank sum test).

Migration behavior of Deschutes River fall chinook salmon differed from that of URB stocks migrating to the Yakima, Mid-Columbia and Snake rivers and were analyzed separately. In 1998 and 2000, samples of 48 and 43 radio-tagged salmon were last recorded in the Deschutes River, respectively. As with upriver migrants, some Deschutes River salmon delayed in the Little White Salmon, White Salmon, and Klickitat rivers while migrating through the Bonneville Reservoir each year. Higher proportions of Deschutes River fish delayed in 1998 than in 2000, but differences were not significant (Table 1).

Escapement

During both study years length of tributary delay was an important factor related to escapement. In 1998, 416 of 477 (87.2%) radio-tagged fall chinook salmon escaped to spawning areas in the Mid-Columbia and Snake rivers, compared to 433 of 491 in 2000 (88.2%). Results from the MANOVA and ensuing canonical variate analyses indicated that escapement was significantly related to time in tributaries, fallback, Columbia River water temperature and discharge at The Dalles Dam in 1998 (Table 3). Length of tributary delay was the most important variable affecting escapement followed by fallback, temperature, and discharge in 1998. In 2000, fish sex, fallback, and tributary delay were most correlated with escapement.

Falling back at any of the study area dams and tributary delay significantly lowered a salmon's chance ($P < 0.002$) of successfully migrating through the lower river. In the two years, 62% (1998, $n = 21$) and 68% (2000, $n = 25$) of fall chinook salmon that fell back escaped compared to about 89% for fish that did not fall back. Similarly, in 1998, 91.5% of fish that delayed less than 12 hours escaped the lower Columbia River versus 78.3% of fall chinook salmon that delayed longer than 12 hours. The same pattern was seen during the 2000 migration when almost 90% of fish that did not delay escaped versus 80% of fish that did delay. The probability of escapement decreased with increased length of delay each year (Figure 13). From the logistic regression equation, probability of 50% escapement occurred when delay duration was longer than 635 (1998) and 253 (2000) hours. Length of delay accurately predicted almost 100% of fish that escaped but did not accurately predict fish that did not escape, indicating other factors (fallback, health, stress, etc.) are acting upon fall chinook salmon which do not escape (Figure13).

Discussion

This study directly addressed action 107 of the 2000 FCRPS Biological Opinion by specifically investigating the effect of Columbia River water temperature (including the use of cool water microhabitats) on adult migration behavior and unaccounted losses between dams. We also believe this discussion, in response to action 118, identifies possible anthropogenic stressors associated with temporary tributary straying which may lead to prespawning losses of adult URB fall chinook salmon.

Historic Run Timing

Results indicate that the fall chinook salmon run is later at Bonneville, The Dalles, and McNary dams when annual August water temperatures in the lower Columbia River are warm. The positive correlation between run timing and water temperatures at John Day was not significant, perhaps because John Day Dam was completed in 1968 and so only 34 years of passage data were available, compared to 64, 45, and 48 years for Bonneville, The Dalles and McNary dams, respectively. The earlier passage dates associated with these three dams strongly influenced each relationship, with average water temperatures prior to 1968 consistently cooler than after completion of John Day Dam (USACE 1938 – 2000).

The positive correlation between run timing and water temperature could be explained by fall chinook salmon either delaying river entry or delaying upstream migration through the estuary and lower Columbia River in warmer years. Little in the historical record has examined if fish delay entry from the ocean during years when Columbia River water temperatures were warm. However, the positive correlation between passage date and water temperature at Bonneville Dam, where the first fish counts are taken, suggests this may be the case. Delays in adult migration related to warm water temperatures in natal streams have been documented for chinook salmon

(Hallock et al. 1970), sockeye salmon *O. nerka* (Major and Mighall 1966), and steelhead *O. mykiss* (Moran et al. 1975). In those studies, fish stopped migrating due to temperature blocks or large thermal gradients at the confluences of streams until the onset of more favorable passage conditions. Complete cessation of fall chinook migration has not been reported in the lower Columbia River, but a short delay in the ocean before beginning migration upriver or delay in the mainstem or near tributaries downstream from Bonneville Dam may explain how run timing past Bonneville, The Dalles, John Day, and McNary dams is positively correlated with water temperature.

We believe the most probable reason for migration delays is the use of thermal refugia. Downstream from Bonneville Dam, NOAA Fisheries has identified several rivers that contain Evolutionarily Significant Units of fall chinook salmon (Myers et. al 1998). These lower river tributaries may be used as holding or staging areas for URBs when Columbia River water temperatures are stressful. In Bonneville and The Dalles reservoirs, eight tributaries discharge water cooler than the Columbia River throughout the fall. These tributaries provide attraction flows and cooler temperatures at their confluence areas during the warmest time of the year. A progressively larger percentage of upriver fish pausing at these tributaries during warm water years would explain the positive correlation between water temperature and arrival timing at upstream dams. Furthermore, as fall chinook salmon move upstream they continue to encounter tributaries and some may stop multiple times. The cumulative effects of such behavior could be responsible for the stronger relationship observed between median passage date and water temperature at McNary Dam compared to the other thee dams (Figure 8).

Two tributary rivers enter John Day Reservoir, the reach through which URB fall chinook salmon migrated most rapidly. Fall chinook salmon have been nearly extirpated from the John Day River because of poor spawning success as a result of warm water temperatures and compacted gravels (James 1984). Likewise, the Umatilla River historically supported a run of URBs, but because of low flow and warm temperatures (due to water diversion and damming) fall chinook were extirpated (Howell et al. 1985). We believe the warm water conditions described above provide little incentive for migrating fall chinook salmon to temporarily delay migration at the John Day or Umatilla tributaries. The difference between the number and quality of tributaries entering the Bonneville-The Dalles reservoir section and those entering John Day Reservoir may explain the difference in the time URB fall chinook salmon take to migrate through the two reaches.

Other anadromous species appear to have altered migration timing due to changes in Columbia River water temperatures. Quinn and Adams (1996) found that because spring warming has occurred progressively earlier since 1950, American shad *Alosa sapidissima* and sockeye salmon have adjusted their adult migrations to migrate past Bonneville Dam earlier than historically. Shifts in spring migration behavior have resulted in American shad migrating about 38 days earlier than in 1938 and sockeye salmon migrate about 6 days earlier since 1949 (Quinn and Adams 1996). Our data indicate that even though water temperatures are highly variable and explain less than 25% of the variation in timing over the lowest four dams, fall chinook salmon may be altering run timing to take advantage of cool water temperature benefits associated with slightly later run timing during warm water years.

Native salmonids have evolved to migrate within a time frame that accommodates delays due to unfavorable turbidity, flow, or temperature, but most stocks are accustomed to relatively predictable environments over time (Bjornn and Reiser 1991). Long-term water temperature changes in the lower Columbia River appear to force fall chinook salmon to delay migration in warmer years. Moreover the frequency of high water temperatures is increasing: seven of the 10 warmest recorded water temperature years have occurred since 1986 (USACE 1938 – 2000). In all 10 years, mainstream water temperatures exceeded 21.5 C, the incipient lethal limit for jack fall chinook salmon (Coutant 1970), during some portion of the run.

If the increasing water temperature trend of the past 65 years continues, thermal storage associated with the hydropower system, combined with an increasingly warm regional climate, may result in increasingly stressful migration conditions and/or additional changes to adult migration timing. Either result may negatively impact fall chinook salmon escapement and reproductive success. Future research is needed to compare annual timing of different stocks between years, and how those stocks are affected by water temperatures. One approach for individual stock assessment may be to mark samples of juvenile salmon leaving spawning areas in a manner easily detectable when they return as adults at dam passage facilities (e.g. with passive integrated transponder [PIT] tags). By distinguishing stock passage timing, unique behavior patterns in response to stressful water temperatures may be clarified. Further consideration may be necessary to protect ESA-listed Snake River fall chinook salmon, if their behavior differs from other stocks.

Columbia River Temperatures- comparison 1998 vs 2000

August and September water temperatures in the lower Columbia River were statistically warmer in 1998 than in 2000. In fact, 1998 was the warmest water temperature year recorded and 2000 was one of the cooler years in the last 25 (USACE 1938-2000). Bell (1986) described optimum adult fall chinook salmon migration temperature ranging from 10.5 to 19.4°C. Water temperature exceeded 19.4°C for all of August and September in 1998 and for 79% of those months in 2000. Coutant (1970) demonstrated with laboratory experiments that the incipient lethal limit for jack fall chinook salmon was between 21 and 22°C. Water temperatures exceeded 21.5°C during more than 80% of August and September in 1998 and 21% of those months in 2000.

Migration and Tributary Use

Effects of altered migration on survival are unknown, but migration timing, migration rate, and timing of egg deposition are crucial for the proper development of early life stages (Coutant 1999). Coutant (1970) found fall chinook salmon become less active when water temperatures deviate from optimal ranges, suggesting swimming speed may slow as temperatures become increasingly stressful. In this radiotelemetry study, migration rates of fall chinook salmon that did not use tributaries were not statistically different between years, suggesting other factors influenced the observed difference in run timing. The other plausible explanation is that some fall chinook salmon momentarily halted their migration in areas of more favorable environmental conditions.

During both years some fall chinook salmon delayed migration at Little White Salmon, White Salmon, Klickitat, and Deschutes rivers. Each river provides attraction flows and cool thermal plumes into the Columbia River throughout the summer and fall (Appendix C) and their confluences are located on the outside of natural bends in the Columbia River, where the channel is deeper with higher velocity. Because adult fall chinook salmon migrate upstream close to the river shoreline and probably follow bottom contours (Reischel 1999), these characteristics orient migrating fish to the outside shoreline and bring them in close contact with tributary discharge. The Deschutes, White Salmon, and Klickitat rivers have the highest mean August-September discharge among the eight tributaries monitored and therefore large areas of cool water extend into the main channel (Table 4). The Deschutes River was the tributary most frequented by migrating adult fall chinook salmon. Mean Deschutes River discharge during August and September in 1998 and 2000 was at least five times higher (4,850 cfs) than other monitored tributaries, and Deschutes River water temperatures averaged 3 to 5°C cooler then the mainstream Columbia River (Table 4). The Little White Salmon River had low discharge, but was typically 12 to 13°C cooler than ambient Columbia River summer temperatures (Table 4). The other tributaries monitored were 6 to 9°C cooler than ambient, but discharge levels were relatively low resulting in smaller cool water plumes (Table 4; Appendix C). We believe large volumes of cool discharge associated with the Deschutes, White Salmon and Klickitat rivers, very low water temperatures in the Little White Salmon River, and overall confluence locations with respect to the Columbia River channel and flow, made these areas more attractive for thermally stressed fall chinook salmon.

More than twice as many fall chinook salmon delayed upstream movement at tributaries in 1998 than in 2000 (30.3% versus 14.5%) and for longer lengths of time, probably because of unusually warm water temperatures in the Columbia River in 1998. Increased tributary use may have been a direct behavioral response to stressful water temperatures in the main river.

Movement into thermal refugia when water temperatures are high has been documented for other salmonid species. In the Firehole River in Yellowstone National

Park, rainbow *O. mykiss* and brown trout *Salmo trutta* use upwelling areas and coldwater tributaries to regulate body temperature when mainstream water temperatures become stressful (Kaya et al. 1977). Snucins and Gunn (1995) described lake trout *Salvelinus namaycush* actively moving into cool groundwater discharges along the shoreline of a shallow Ontario lake when temperatures were warm. In northern California, adult steelhead in the late summer held in thermally stratified pools prior to spawning the following spring (Nielsen et al. 1994). Likewise, spring chinook salmon have been observed seeking out "pockets" of cooler water for holding throughout the summer prior to fall spawning (Berman and Quinn 1991; Torgersen et al. 1999). Steelhead have been reported delaying migration in the cooler flows from Idaho's Clearwater River until more suitable water temperatures were available in the upper Snake River (Stabler 1981). Similar behavior has been documented for fall chinook salmon in the San Joaquin Delta, where fish cease migration when water temperatures exceed 21.1°C (Hallock et al. 1970; State of California 1988).

Not all tributaries in the lower Columbia River were recorded being used by adult fall chinook salmon migrating upstream. At the Wind River, fall chinook salmon could have delayed in the cooler thermal plume without actually entering the stream. Some fish could have held downstream from Highway 14 and gone undetected (Appendix C). In 1998 and 2000, two and three upriver fall chinook salmon were mobile tracked near the Wind River at least once on 9 and 33 tracking occasions, respectively. If radio tagged fish were frequently holding in the thermal plume downstream from Highway 14, more fish would have been recorded by mobile tracking efforts. The low numbers of salmon detected while mobile tracking and on the fixed-site receiver suggests that most salmon migrated outside the Wind River's influence.

The Hood River was another tributary rarely used by adult migrants. The river enters the Columbia River from the Oregon shore almost directly across from the White Salmon River on the inside of a large bend in the river (Appendix C). Before entering the Columbia, water from the Hood River flows over a shallow shelf covered with aquatic macrophytes. In respsonse, we believe most fall chinook salmon migrate in the main Columbia River channel and away from the mouth of Hood River.

Mobile tracking data from Eagle and Herman creeks suggests these two streams were not intensively used by upriver salmon. These tributaries were tracked five times in 1998, and 35 (Eagle) and 46 (Herman) times in 2000. Both creeks have relatively low discharge and probably smaller thermal plumes compared to tributaries where fall chinook salmon delayed (Table 4). Eagle Creek enters the Columbia River from the Oregon shore 300 m upstream from Bonneville Dam (Appendix C). Salmon that exit the Bradford Island fish ladder must immediately cross the river to locate the tributary. During both years numerous steelhead and lower river stocks of fall chinook salmon were observed at Herman Creek, but URB fall chinook salmon were not. However, Zone 6 tribal fishery gill nets placed across the mouth blocked entry and exit during the fishery and may have influenced URB fall chinook behavior.

Escapement

Fall chinook salmon that delayed in tributaries had a lower rate of escapement than fish that continuously migrated upstream. This impact of tributary use on escapement seems counterintuitive. In both years logistic regression indicated that, as the duration of time spent in tributaries increased, probability of escapement declined (Figure 13). Delaying migration significantly decreased the probability that an adult URB fall chinook salmon would successfully reach spawning areas. However, short delays may have produced survival benefits as a strategy used to conserve metabolic energy and enhance survival by reducing thermal stress. Successful escapement of salmon delaying in tributaries short amounts of time was evident during both years. Records of salmon using tributaries longer and continuing to successfully migrate in 1998 indicate thermal benefits associated with delay are extended during warmer years. It is possible that short delays during stressful conditions are beneficial, while extended delays may decrease a fish's chance of escapement due to other factors.

One variable measured and shown to negatively impact escapement both years was fallback at any of the study area dams. In 1998, eight of 21 (38%) fall chinook salmon that fell back did not escape; eight of 25 (32%) fall chinook salmon that fell back in 2000 did not escape. Seven of these fish delayed less than 253 hours in tributaries. We hypothesize that 13 of the 119 fish that did not escape the Columbia River, failed as a result of lowered fitness associated with fallback events rather than short tributary delays.

Significant sport and commercial fisheries concentrated at the mouths of tributaries to Bonneville Reservoir, the Deschutes River and throughout the study area remove several thousand fall chinook salmon annually (ODFW and WDFW 2000). Angling- or gillnet-related stress associated with delay in tributaries may negatively affect escapement. Although no known estimates have been conducted in the Columbia River, hooking mortality of chinook salmon caught in Alaska's Kenai River averaged 7.6% and was as high as 10.6% (Bendock and Alexandersdottir 1993). Gillnet fisheries upstream and downstream from confluences may also affect fall chinook salmon entering or exiting tributaries. The Zone 6 tribal fishery has removed 22,800 to 145,000 fall chinook adults annually since 1970 and in 1998 and 2000 the nets were in for 15 and 17 days, respectively (ODFW and WDFW 2000, ODFW and WDFW 2002). Stress, energy expenditure, and possible cuts, scratches, or descaling associated with a gillnet encounter may negatively impact escapement.

Some migrating salmon undoubtedly experience natural mortality unrelated to anthropogenic changes in the river environment, from disease, low energy reserves, or other natural phenomena. Researchers have evaluated swimming speeds and energy use during migration (e.g. Hinch and Rand 1998), but few have attempted to estimate natural mortality in pristine systems. Separation of natural and human-caused mortality was beyond the scope of this project, but should be further investigated.

The between-year difference in fall chinook salmon tagging schedules at Bonneville Dam may have influenced our statistical tests. Tagging started on 1 August in 2000, but not until 1 September in 1998 due to high water temperatures. As a result, no early-run stocks were tagged in 1998. In 2000, salmon migrating in August were the most likely to delay at tributaries. Because water temperatures were very high in August, 1998, we suspect that a relatively high proportion of the untagged August portion of the 1998 run delayed at tributaries. Median passage dates for all fish counted at Bonneville and The Dalles dams support this conclusion: the lag between median dates at the two dams was much higher in 1998 than in 2000, suggesting extensive delay behavior in the Bonneville reservoir or its tributaries in 1998. August 2000 was the only month during the study years when spill occurred at any lower Columbia River dams. This may explain why the Hotelling *T* test for 2000 showed dissolved gas as the most important factor contributing to tributary use while not a factor in 1998. However, with the two concerns acknowledged above, the majority of fall chinook salmon (100%-1998; 76%-2000) were tagged after September 1 in both study years and since the main difference between the years was water temperature. We believe tributary delay was primarily related to high water temperatures.

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Table 1. Number and percent of URB and Deschutes River fall chinook salmon that delayed migration longer than 12 hours at tributaries to the Bonneville and Dalles reservoirs in 1998 and 2000, with results of Chi-squared tests comparing the two years.

Upriver Stocks

	1998 (N = 464)		2000 (N = 553)		Difference	
	N	Percent	N	Percent	❹2	*P*
Total using tributaries	140	30.2	80	14.5	36.66	<0.0001
Fixed receiver sites						
Little White Salmon R.	31	6.7	26	4.7	1.87	0.171
White Salmon R.	51	11.0	12	2.2	33.93	<0.001
Klickitat R.	7	1.5	0	0.0	8.37	0.004
Wind R.	0	0.0	0	0.0	NA	NA
Hood R.	0	0.0	0	0.0	NA	NA
Deschutes R	72	15.5	48	8.6	11.40	<0.001
Mobile Tracking						
Herman Cr.	1	0.2	0	0.0	1.03	0.278
Eagle Cr.	0	0.0	0	0.0	NA	NA
Cumulative Delay						
2 tribs > 12 hours each	12	2.6	7	1.3	2.35	0.125
3 tribs > 12 hours each	5	1.1	0	0.0	5.90	0.015
4 tribs > 12 hours each	0	0.0	0	0.0	NA	NA

Deschutes River Stock

	1998 (N = 48)		2000 (N = 43)		Difference	
	N	Percent	N	Percent	❹2	*P*
Total Using Tributaries	12	25.0	8	18.6	0.58	0.447
Fixed Receiver Sites						
Little White Salmon R.	6	12.5	2	4.7	1.78	0.182
White Salmon R.	5	10.4	6	14.0	0.27	0.606
Klickitat R.	4	8.3	1	2.3	1.66	0.197
Wind R.	0	0.0	0	0.0	NA	NA
Hood R.	0	0.0	0	0.0	NA	NA
Mobile Tracking						
Herman Cr.	1	2.1	0	0.0	1.01	0.315
Eagle Cr.	0	0.0	1	2.3	1.01	0.315

Table 2. Hotelling T^2 and canonical variate analysis testing tributary use for URB fall chinook salmon that did (>12 hours) and did not (<12 hours) delay in the lower Columbia River as a function of river environment variables in 1998 and 2000.

Sample size and river environment

	1998		2000	
	> 12 h	< 12 h	> 12 h	< 12 h
Number of fish (N)	140	324	80	471
Mean Discharge (kcfs)	114.5	112.5	126.7	121.8
Mean Turbidity (ft)	6.05	6.45	6.49	6.43
Mean Water Temperature (C)	70.9	68.8	68	67.1
Mean Dissolved Gas (%)	99.8	98.5	102.0	100.7

Correlation Matrix - 1998

	Discharge	Turbidity	Temperature	Dissolved Gas	CAN1
Discharge	1	0.1630	0.1095	0.2914	**0.1276**
Turbidity	0.1630	1	-0.3685	0.0593	**-0.4380**
Water Temperature	0.1095	-0.3685	1	0.5681	**0.9871**
Dissolved Gas	0.2913	0.0593	0.5681	1	**0.6443**
CAN1	0.1276	-0.4480	0.9871	0.6443	**1**

Correlation Matrix - 2000

Discharge	1	-0.0878	0.2862	0.1515	**0.4799**
Turbidity	-0.0878	1	0.2620	0.1027	**0.1315**
Water Temperature	0.2862	0.2620	1	0.4792	**0.7024**
Dissolved Gas	0.1515	0.1027	0.4792	1	**0.9109**
CAN1	0.4799	0.1315	0.7024	0.9109	**1**

Canonical Analyses

	Within Can1 (rank)		Standardized Can1 (rank)	
	1998	2000	1998	2000
Discharge	0.1291 **(4)**	0.4799 **(3)**	0.0080 **(4)**	0.2954 **(2)**
Turbidity	-0.4290 **(3)**	0.1315 **(4)**	-0.1353 **(3)**	0.0132 **(4)**
Water Temperature	0.9881 **(1)**	0.7024 **(2)**	0.9250 **(1)**	0.2618 **(3)**
Dissolved Gas	0.6454 **(2)**	0.9109 **(1)**	0.1814 **(2)**	0.7504 **(1)**

Table 3. Results from MANOVA (Wilks' lambda statistic) and canonical variate analysis comparing fall chinook that escaped and those that did not, based on behavioral and environmental variables.

Manova Results

Year	F-Value	Num DF	Den DF	Pr > F
1998	7.21	8	468	< 0.0001
2000	3.96	9	481	< 0.0001

Canonical Variate Analysis Results

Variable	Within Can1 (rank)		Standardized Can1 (rank)	
	1998	2000	1998	2000
Tributary Time	0.5915 **(1)**	0.5091 **(3)**	0.6729 **(1)**	0.4838 **(2)**
Fall Back	0.4694 **(2)**	0.5380 **(2)**	0.4641 **(3)**	0.4568 **(3)**
Temperature	-0.3665 **(3)**	-0.2708 **(4)**	-0.5937 **(2)**	-0.1890 **(4)**
Discharge	0.2800 **(4)**	-0.1364 **(7)**	0.3608 **(4)**	-0.1115 **(6)**
Length	0.2302 **(5)**	0.2198 **(5)**	0.0991 **(7)**	0.1003 **(7)**
Turbidity	-0.1769 **(6)**	0.1338 **(8)**	-0.1506 **(5)**	0.0253 **(8)**
Sex	-0.1736 **(7)**	-0.5913 **(1)**	-0.1498 **(6)**	-0.6662 **(1)**
Marine Mammal	0.0644 **(8)**	0.1719 **(6)**	0.0416 **(8)**	0.1870 **(5)**
Spill	. **(-)**	-0.1110 **(9)**	. **(-)**	0.0071 **(9)**

Table 4. Characteristics of monitored Columbia River tributaries during 1998 and 2000 including: discharge and difference in water temperature between tributary and Columbia River.

	Discharge (cfs)	Temperature Difference (ºC)			
Tributary	Aug-Oct	Aug	Sep	Oct	Aug-Oct
1998					
Deschutes	4,822	4.2	4.7	5.4	4.8
Klickitat	877	2.6	5.8	7.8	5.4
White Salmon	744	10.6	11.2	9.3	10.4
Hood	358	5.4	7.1	8.4	7.0
Wind	<200	6.2	7.7	7.8	7.2
Little White Salmon	<100	13.7	13.5	10.4	12.5
Eagle Creek	<100	5.4	6.8	7.2	6.5
Herman Creek	<100		9.1[1]		
2000					
Deschutes	4,862	3.1	3.4	3.8	3.4
Klickitat	876	2.6	5.1	7.2	5.0
White Salmon	731	10.7	9.8	8.5	9.7
Hood	437	5.5	6.2	7.8	6.5
Wind	<200	6.3	6.7	7.2	6.7
Little White Salmon	<100	13.9	11.8	9.6	11.8
Eagle Creek	<100	5.5	5.9	6.6	6.0
Herman Creek	<100		8.2[1]		

[1] Temperature loggers were only deployed from 30 August to 17 September

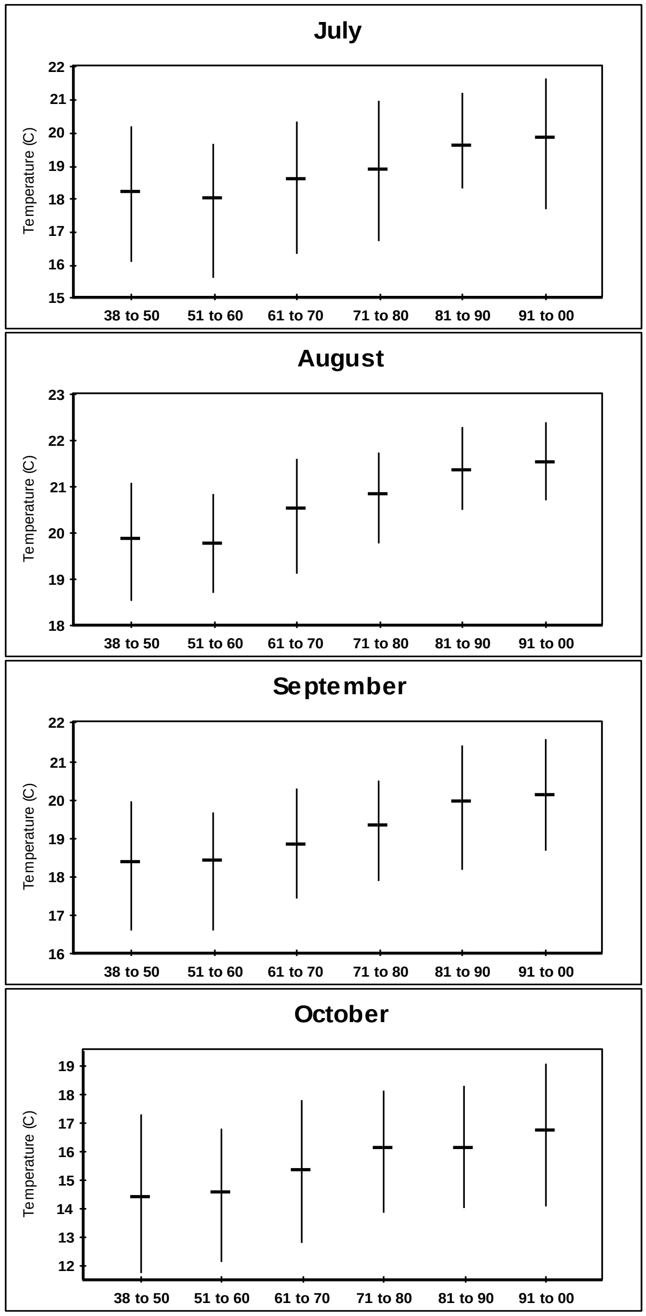


Figure 1. Average monthly water temperatures and average maximums and minimums for the forebay of Bonneville Dam in July, August, September, and October from 1938 to 2000 (USACE 1938-2000).

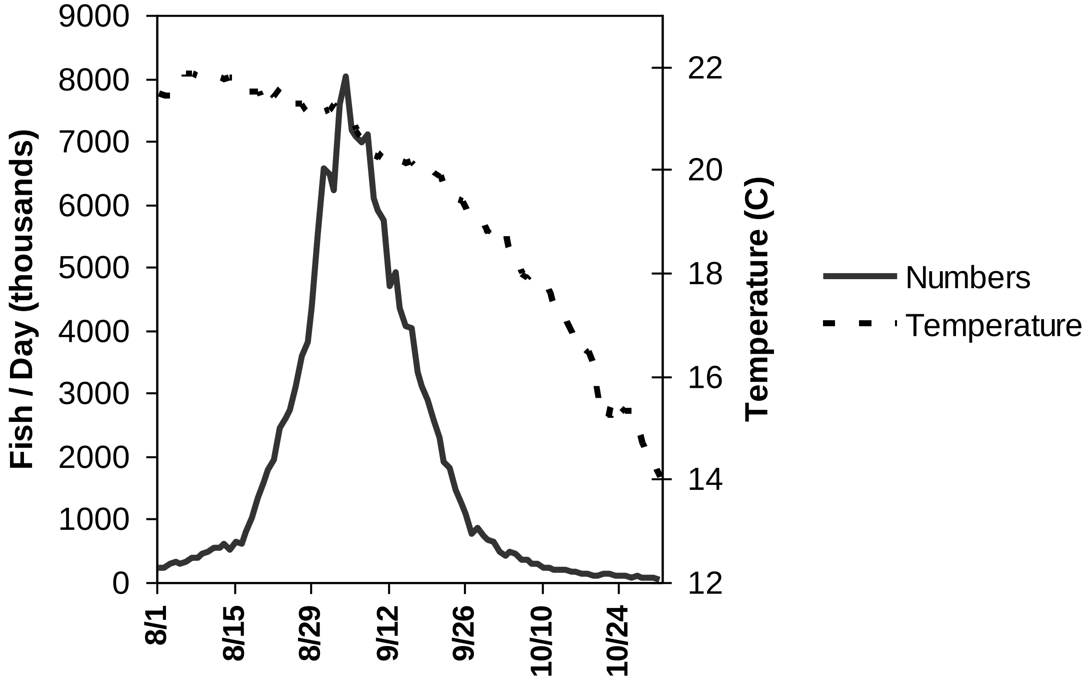


Figure 2. Average daily counts of adult fall chinook passage and mean water temperatures at Bonneville Dam from 1990 to 2000.

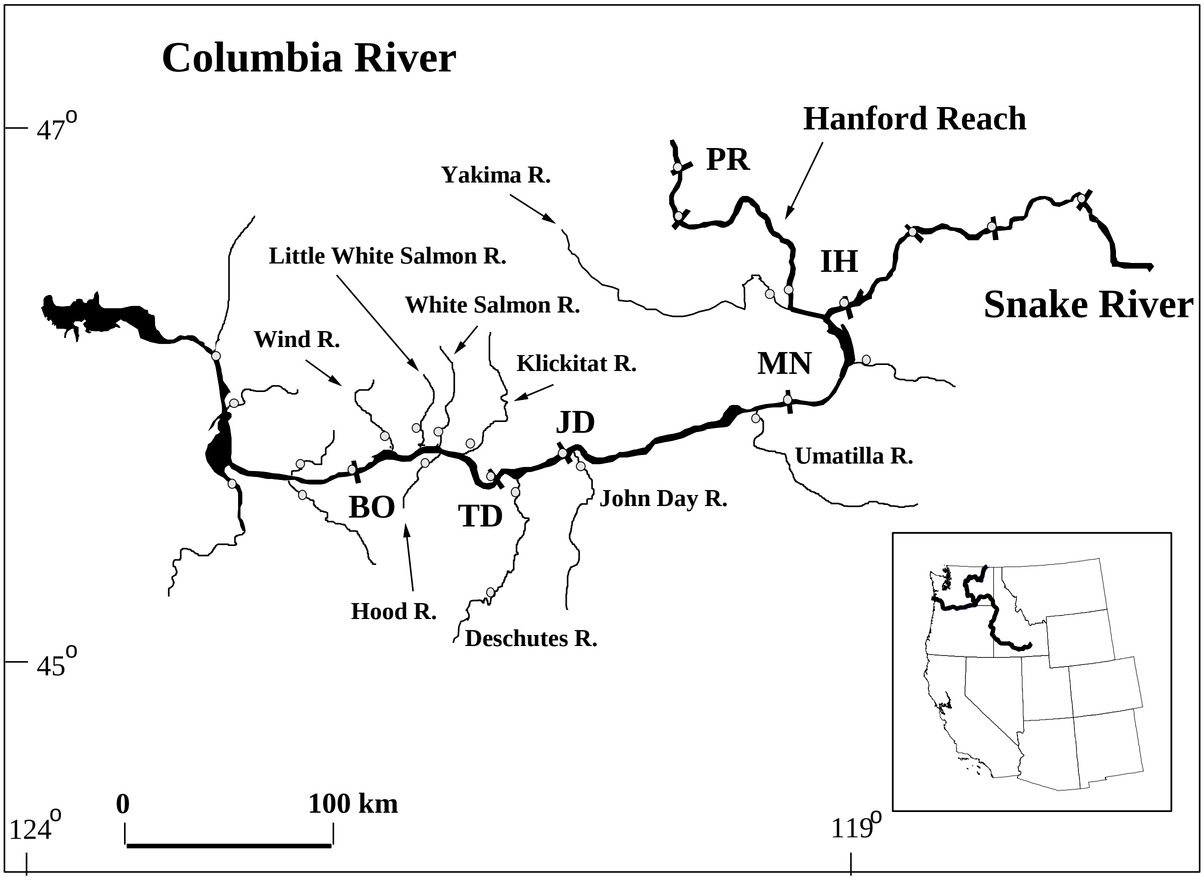


Figure 3. The Columbia River study area where radio-tagged fall chinook salmon were monitored at dams and around tributary confluences in 1998 and 2000. Gray circles indicate locations of one or more telemetry receivers.

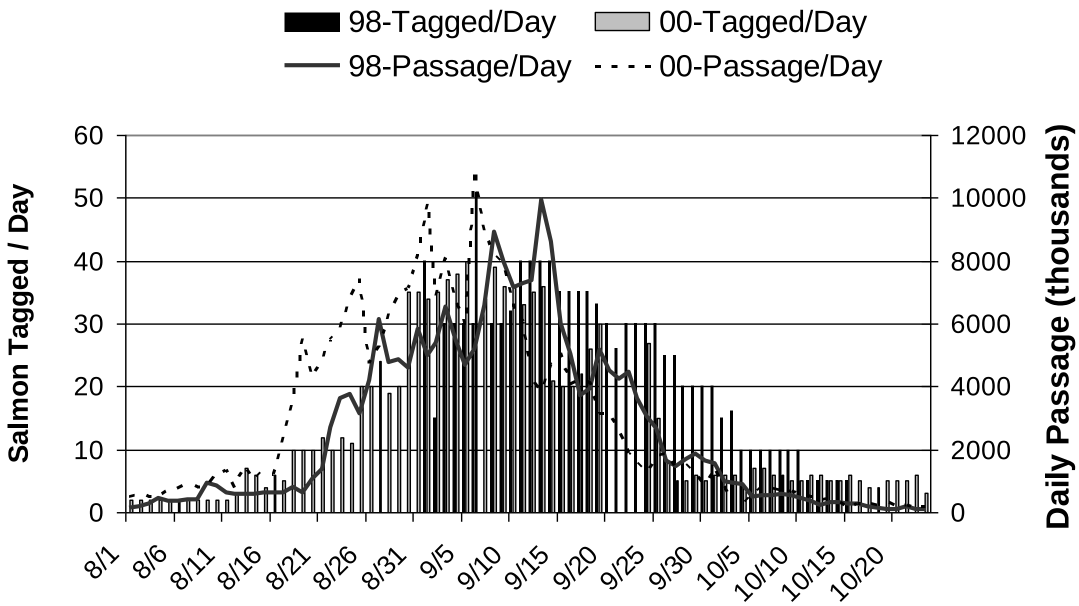


Figure 4. The number of adult fall chinook salmon radio tagged and run counts per day at Bonneville Dam in 1998 and 2000.

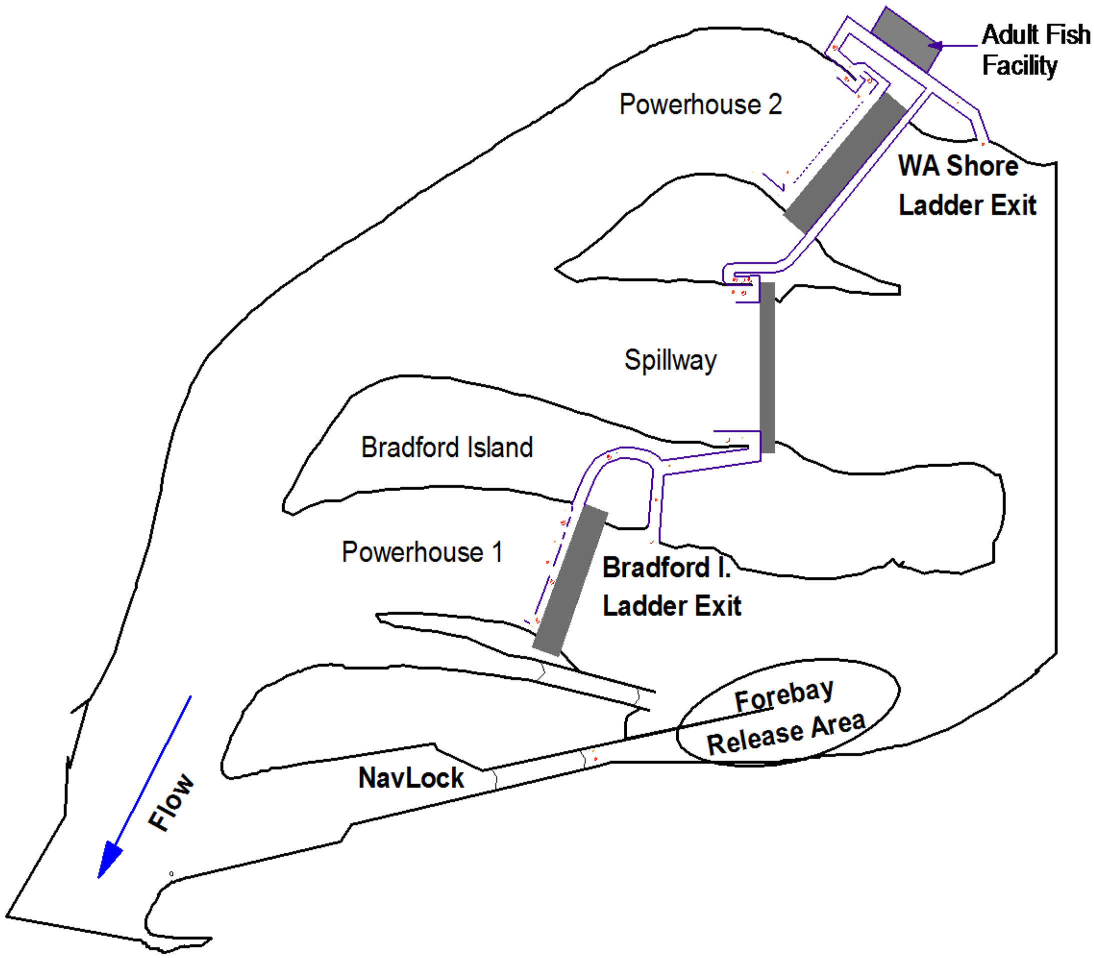


Figure 5. Diagram of Bonneville Lock and Dam with the two fishway exits, navigation lock, and forebay release area used as the starting points for calculating migration times in 1998 and 2000.

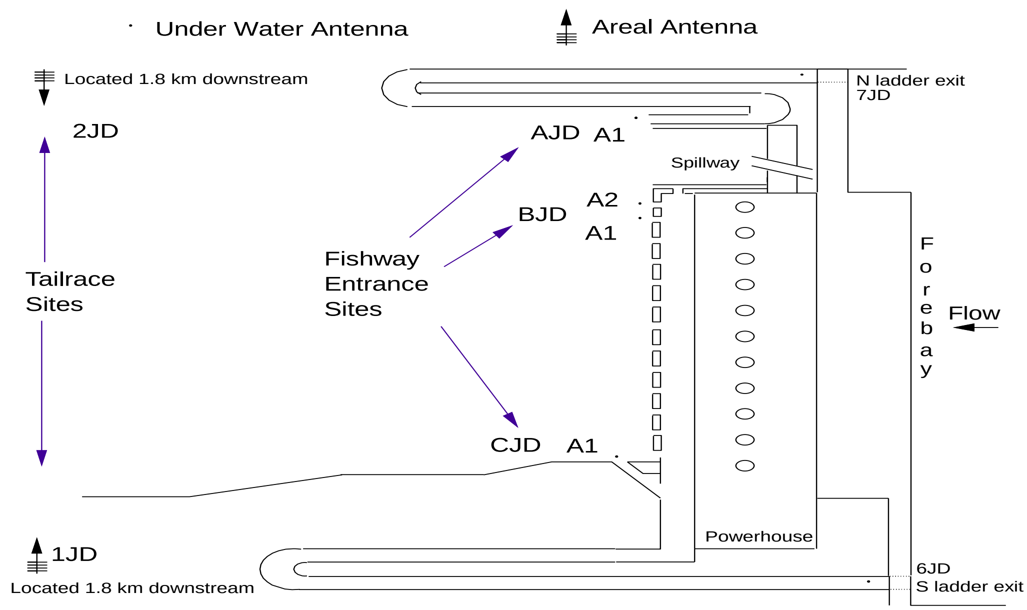
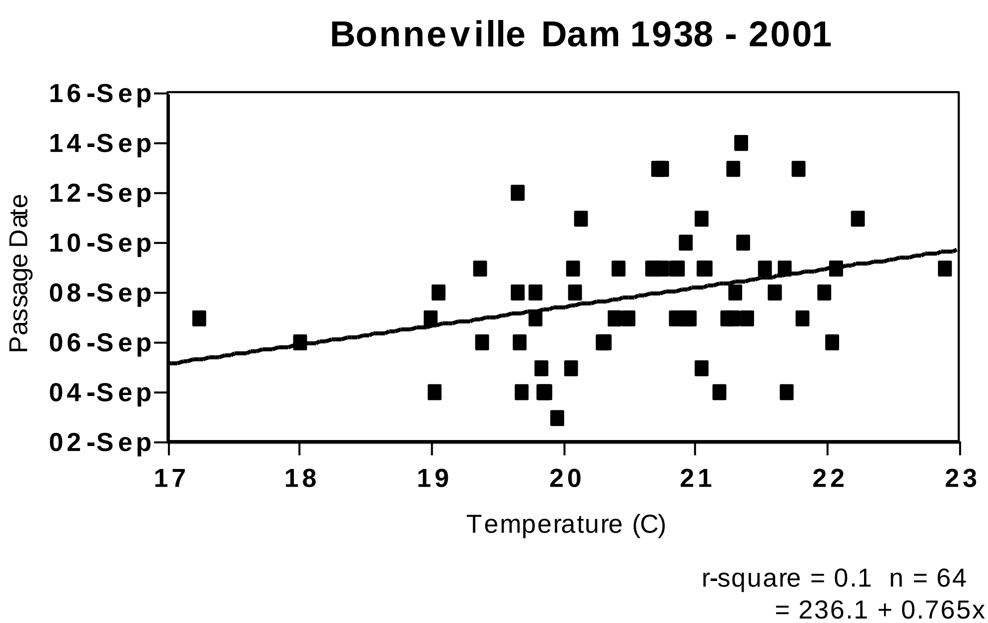


Figure 6. Diagram of John Day Dam and antenna configuration for the tailrace and fishway entrance sites used as the end points for calculating migration rates.



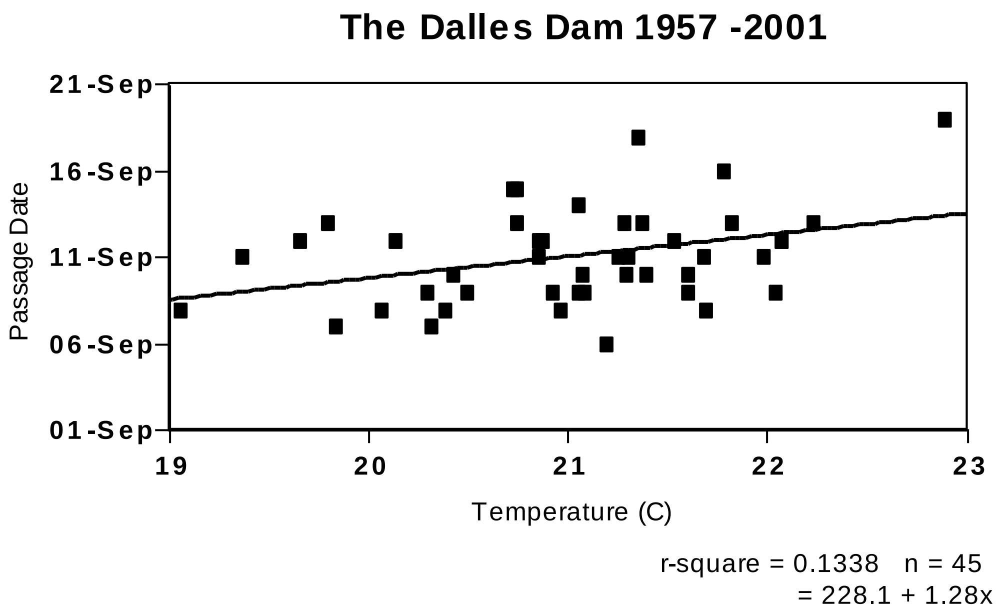


Figure 7. The date 50% of the fall chinook salmon run passed Bonneville and The Dalles dams as a function of mean August water temperature.

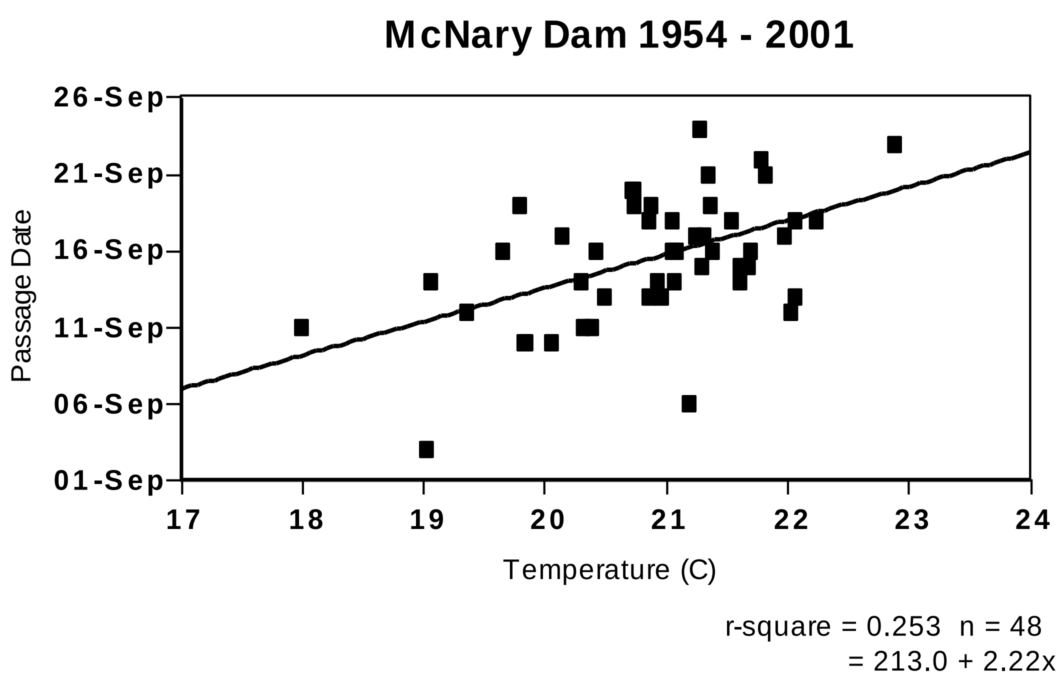


Figure 8. The date 50% of the fall chinook salmon run passed John Day and McNary dams as a function of mean August water temperature.

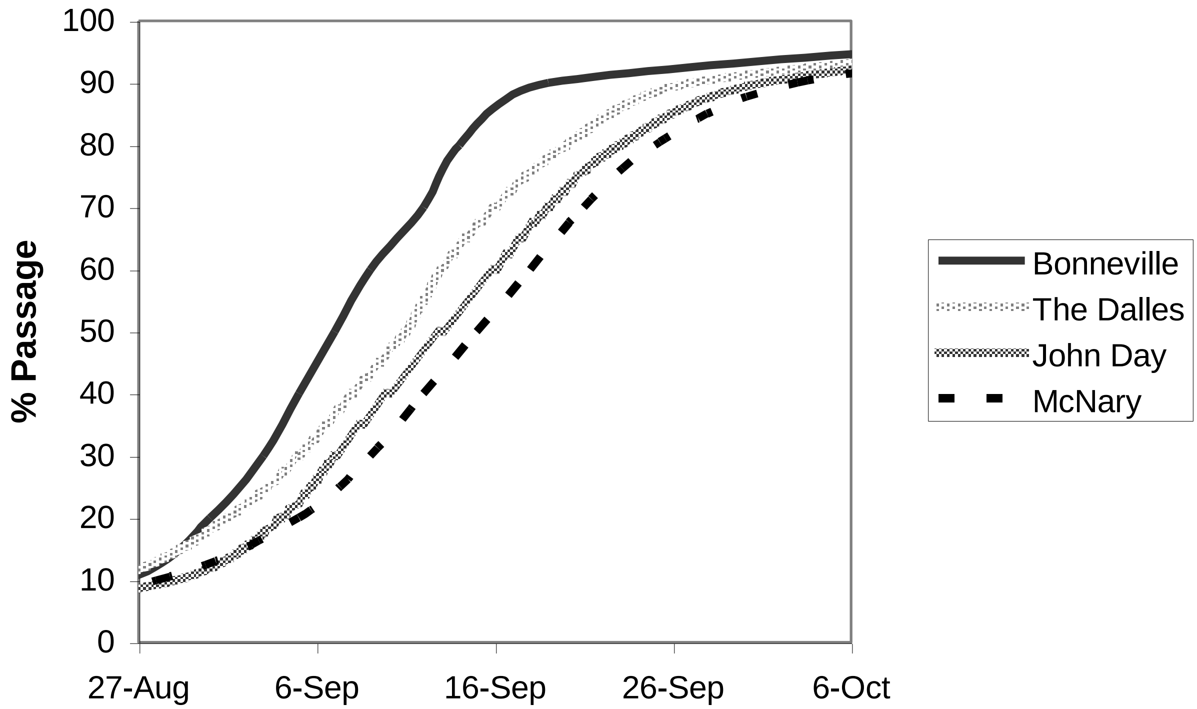


Figure 9. The average timing of historical run progression past the four dams in the lower Columbia River.

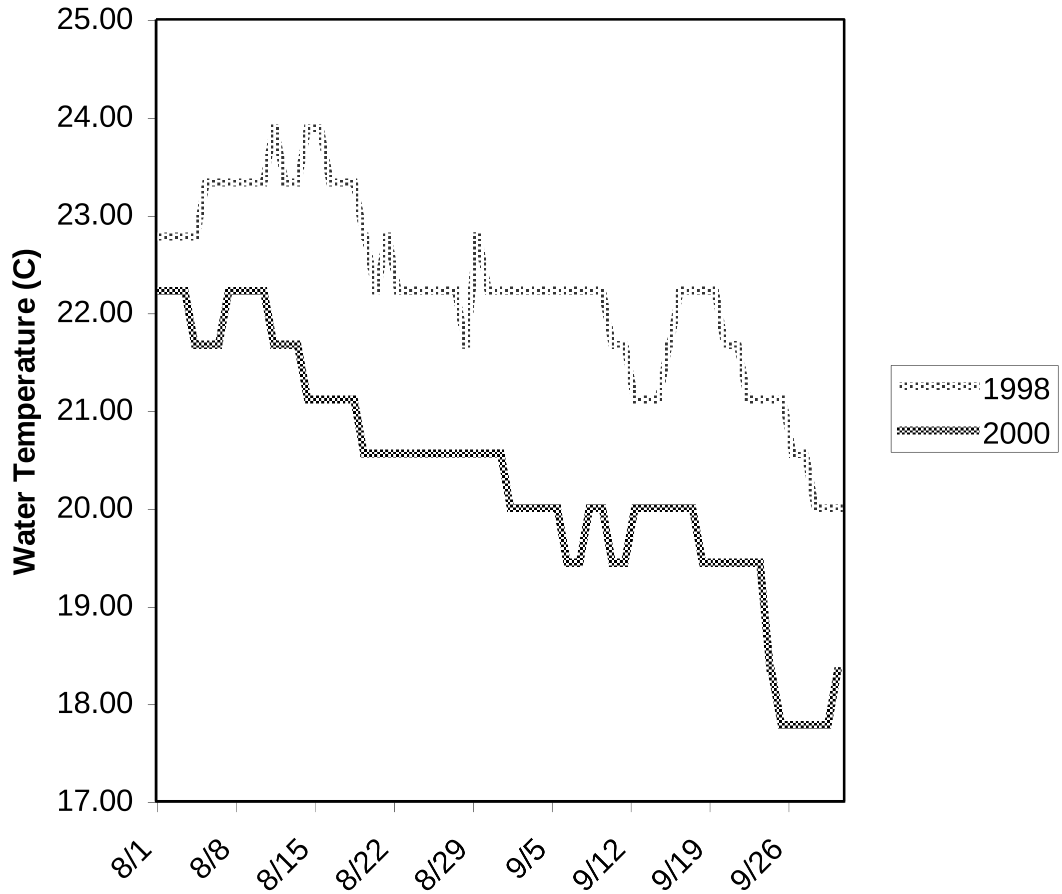


Figure 10. Daily water temperatures in the lower Columbia River as recorded at Bonneville Dam in 1998 and 2000.

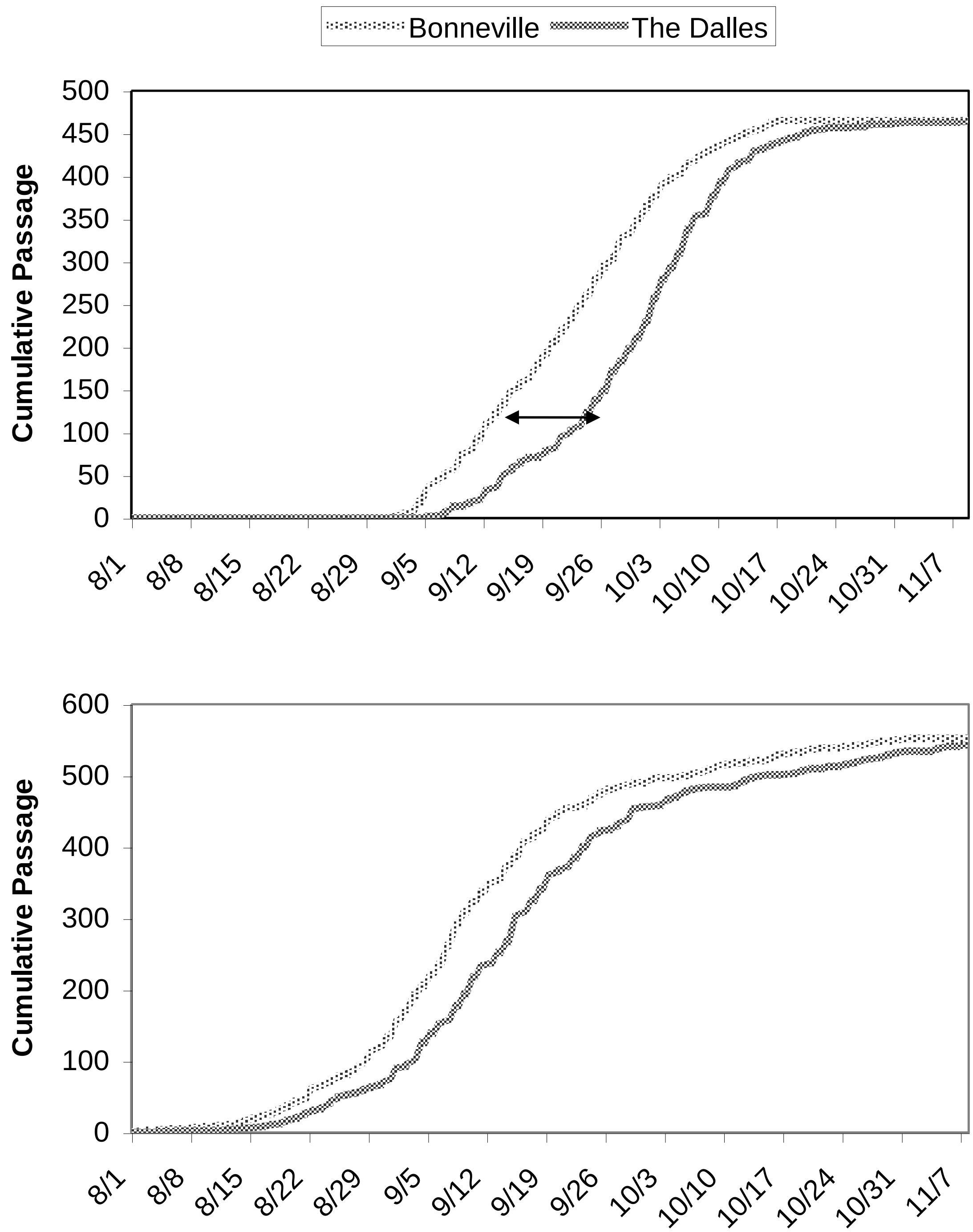


Figure 11. The cumulative passage at Bonneville and The Dalles dams of radio-tagged URB fall chinook salmon in 1998 (top) and 2000 (bottom). Arrow length indicates travel time between dams.

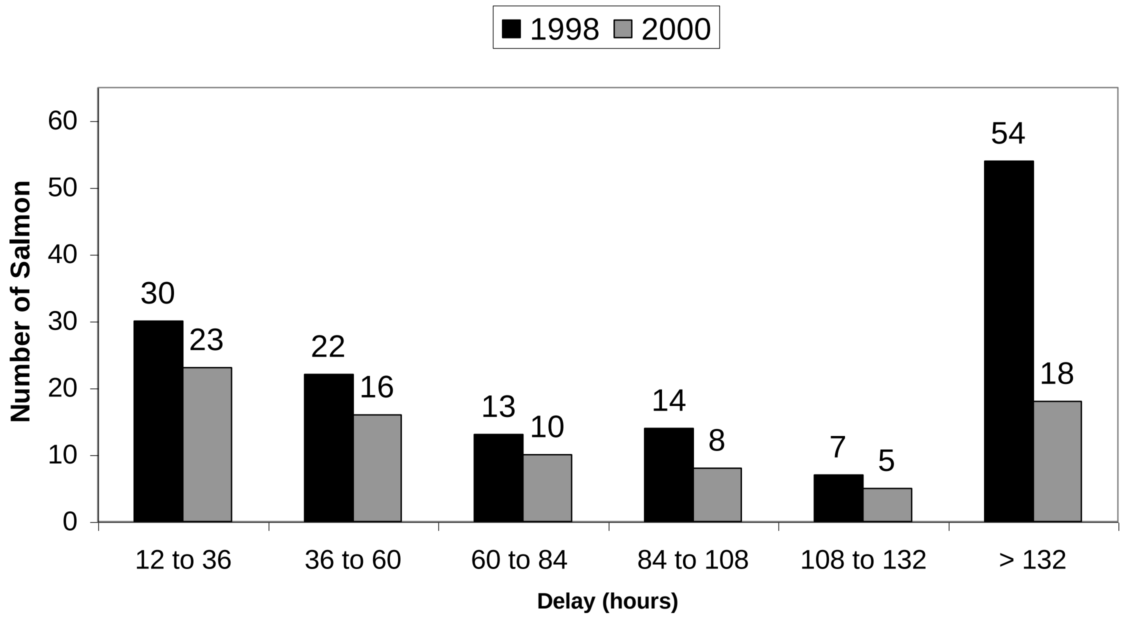
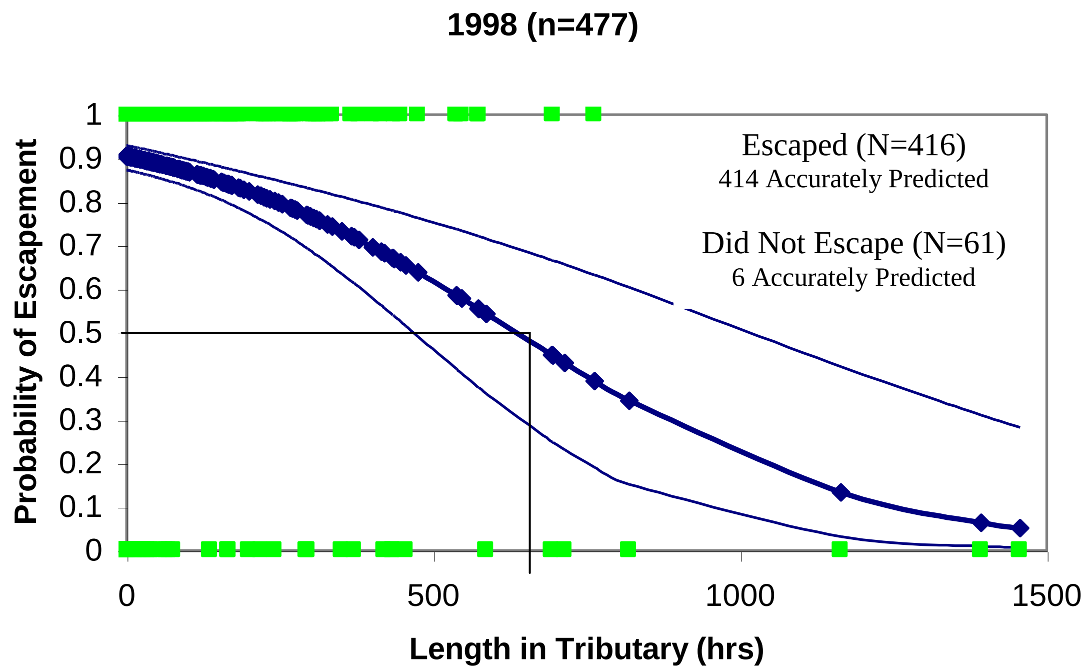


Figure 12. Cumulative length of delay at tributary confluences by chinook salmon last recorded above John Day Dam in 1998 and 2000. Fish that delayed less than 12 hours were excluded.



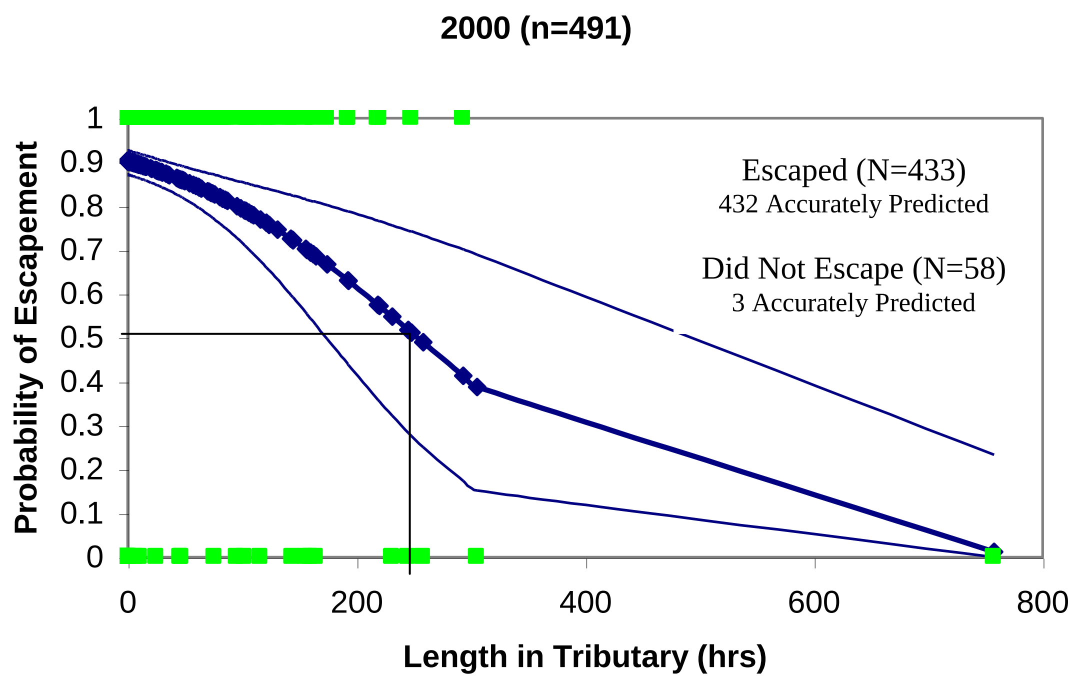
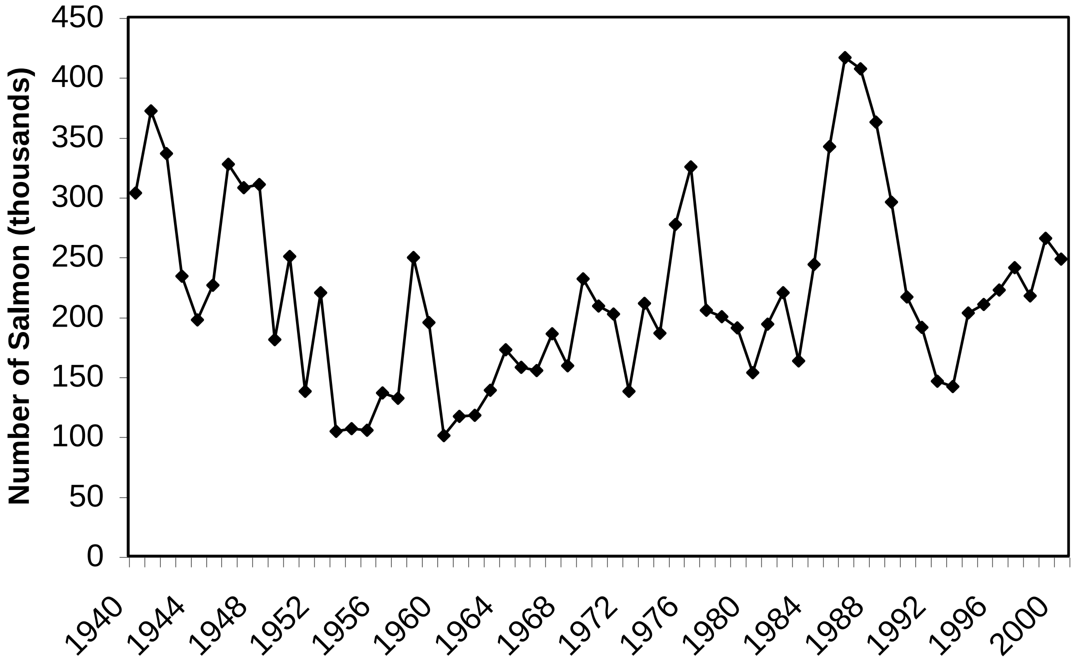


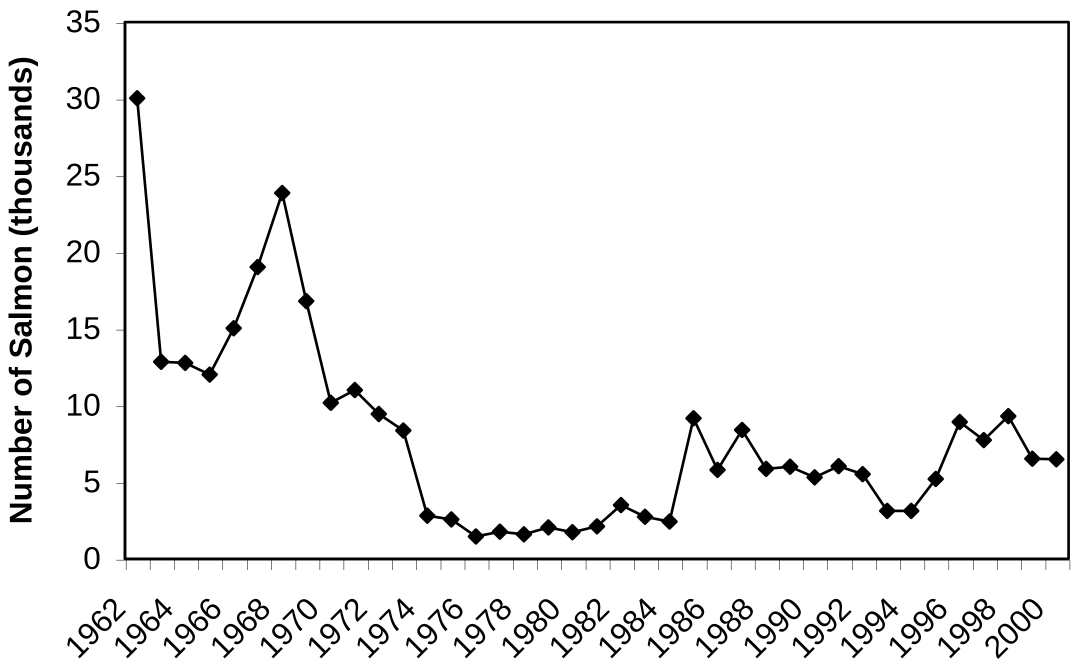
Figure 13. Logistic plots including 50% estimates and prediction success of escapement with 95% confidence intervals as a function of length of delay.

Appendix A. The timing of freshwater migration (light gray), spawning (dark gray), and peak spawning (black) of different stocks of fall chinook salmon in the Columbia River basin (from Myers et al. 1998).

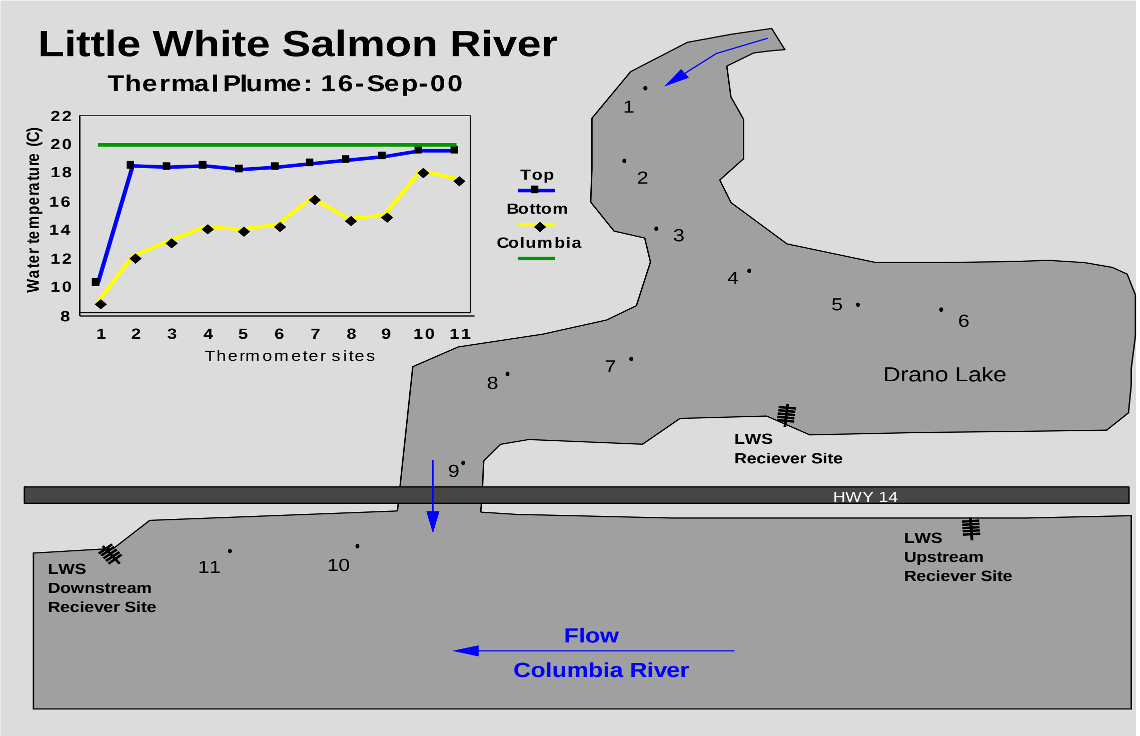
Stock	July	August	September	October	November	December	January	Reference
1) Lower Columbia River Basin								
Lower Col R.								Howell et al. 1985, WDF et al. 1993
Kalama R.								Howell et al. 1985, WDF et al. 1993
Lewis R								WDF et al.1993, WDFW 1995
Washougal R.								Howell et al. 1985, WDF et al. 1993
Deschutes R.								Jonasson and Lindsay 1988
2) Middle Columbia River Basin								
Hanford Reach								Howell et al. 1993, WDFW 1995
Marion Drain								WDF et al.1993, WDFW 1995
Yakima R.								WDF et al.1993, WDFW 1995
3) Snake River Basin								
Grande Ronde R.								Olsen et al.1992
Snake R.								Chapman et al. 1991, Garcia et al. 1996

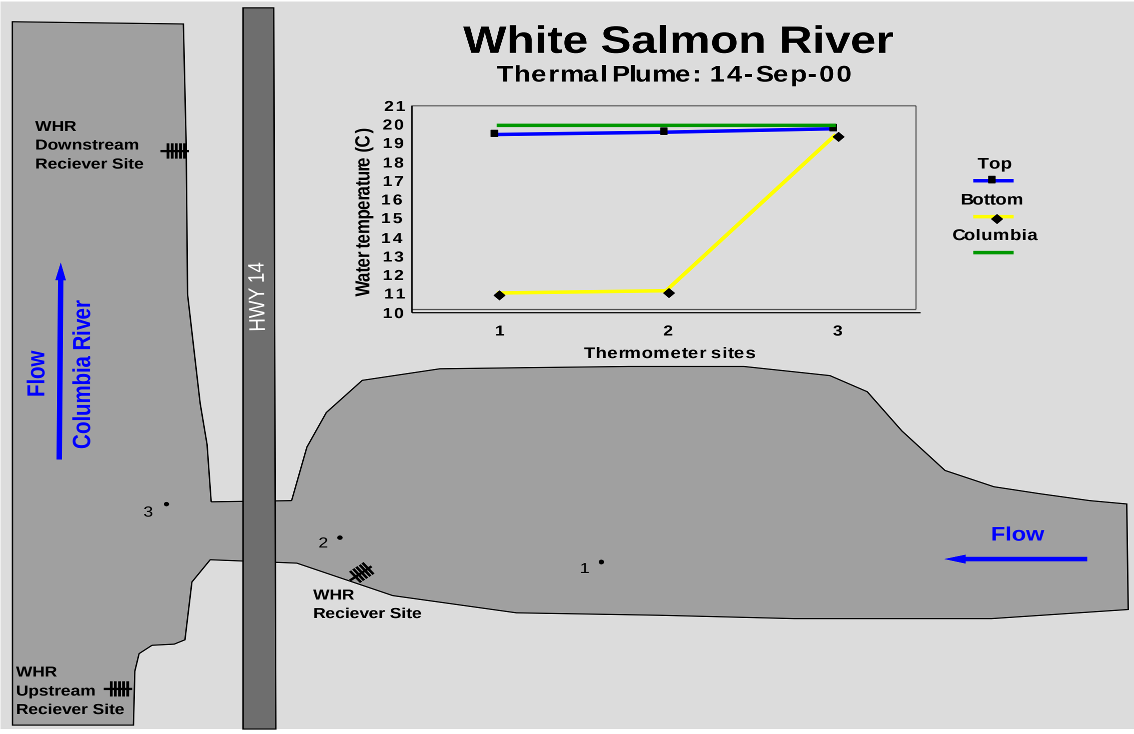
Appendix B. Annual total numbers of fall chinook salmon over Bonneville (top) and Ice Harbor (bottom) dams since 1940 and 1962, respectively (USACE 1940-2000).

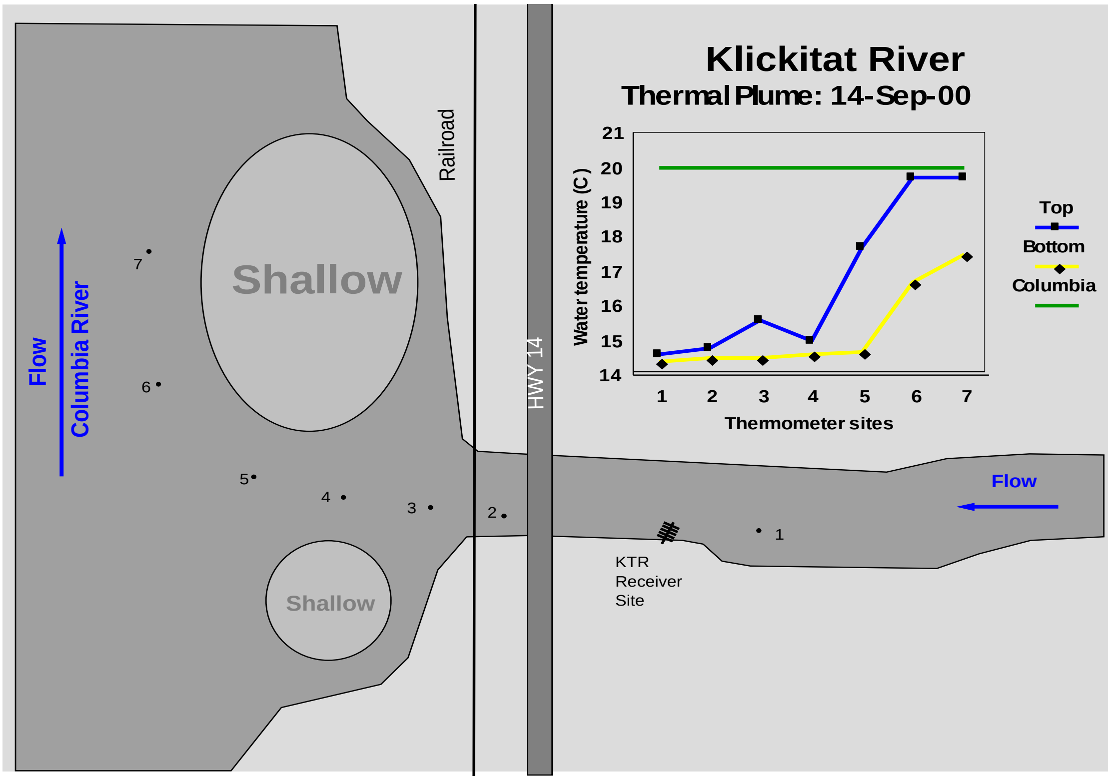


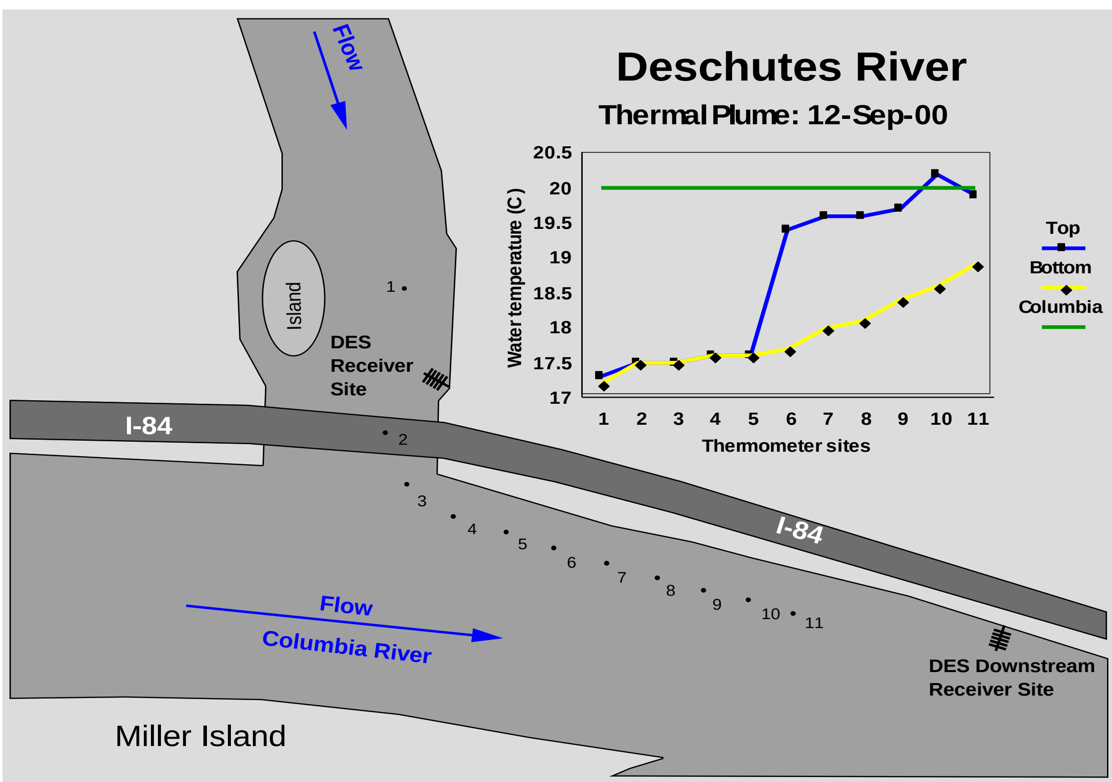


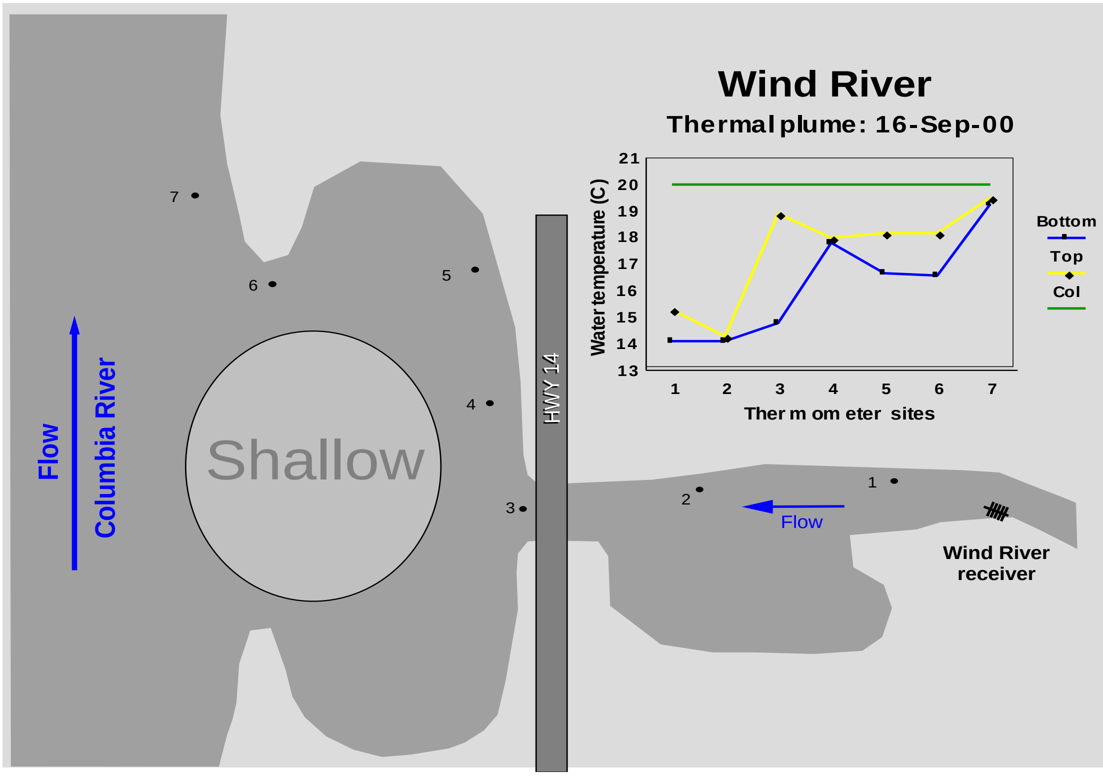
Appendix C. Maps of the eight study tributary confluence features, fixed receiver sites and locations where temperatures were taken at the top and bottom of the water column depicting the thermal plumes.

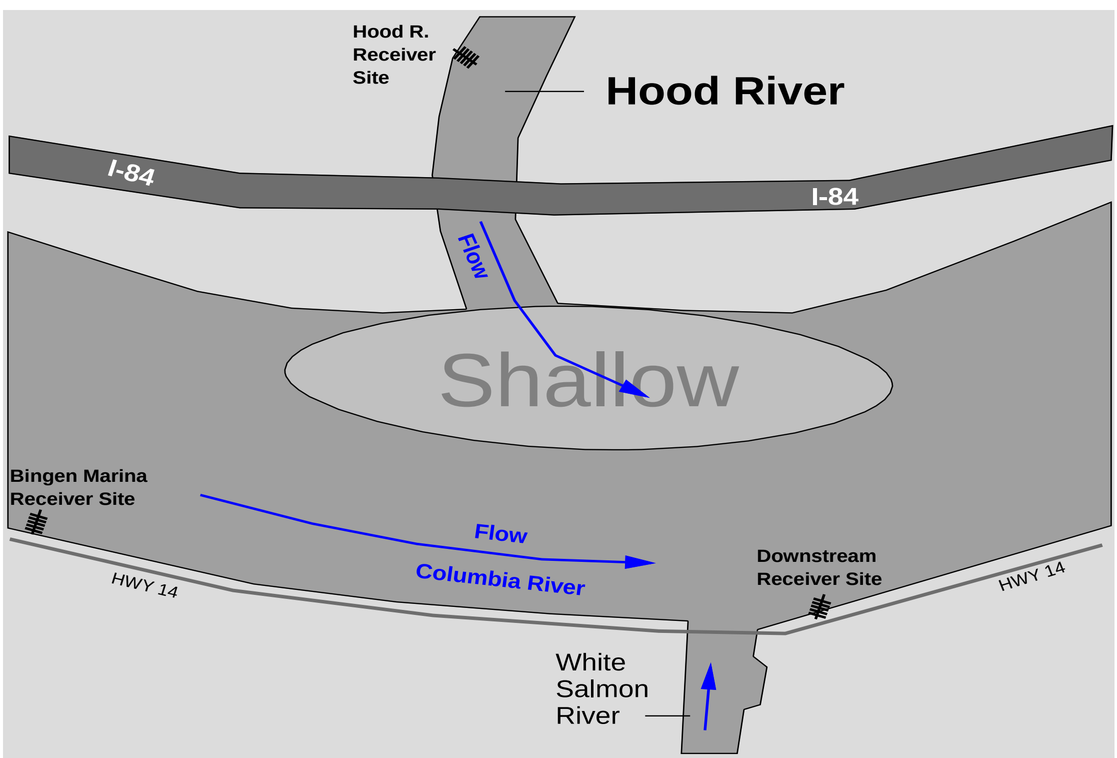


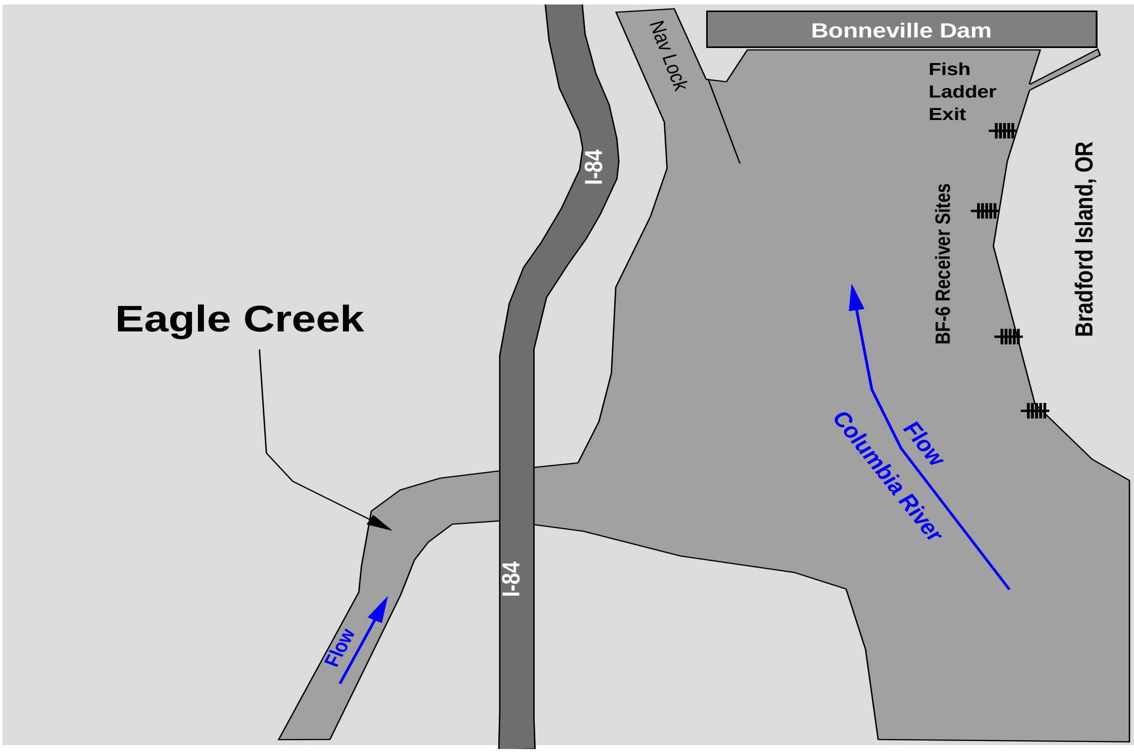


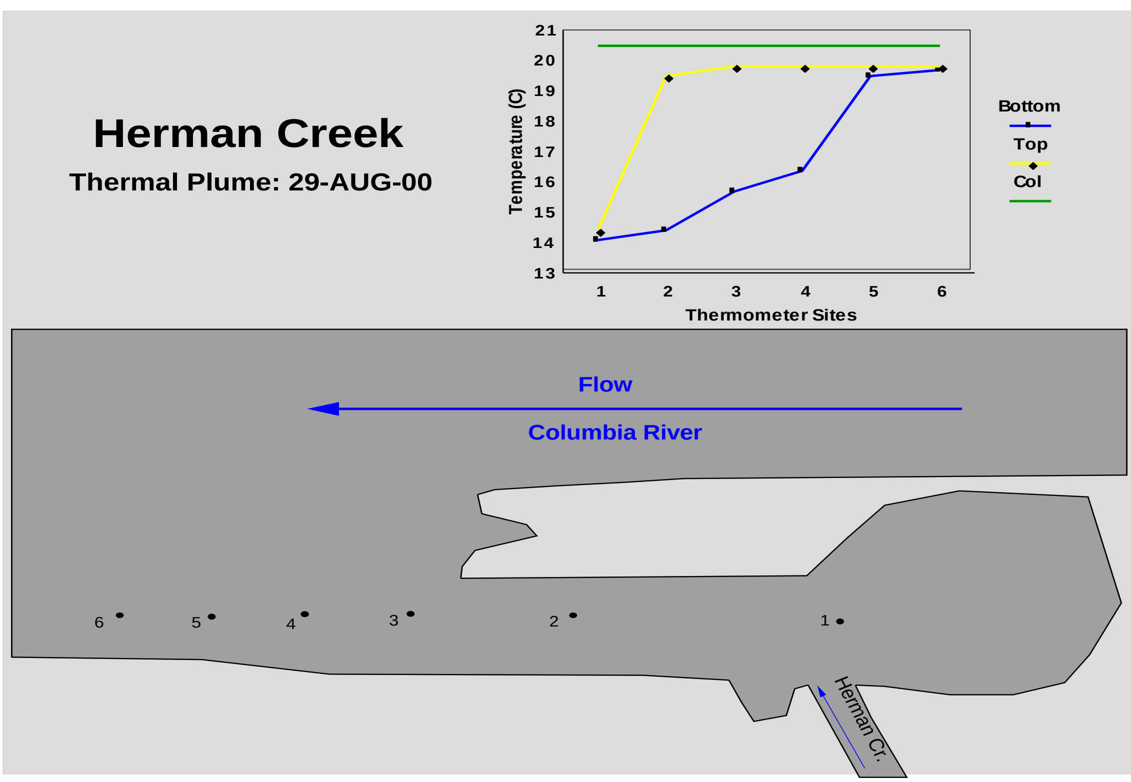

Klickitat River
Thermal Plume: 14-Sep-00
Water temperature (C)
Thermometer sites
Top
Bottom
Columbia
Shallow
Shallow
Railroad
HWY 14
Flow
Columbia River
Flow
KTR
Receiver
Site


Deschutes River
Thermal Plume: 12-Sep-00
Water temperature (C)
Thermometer sites
Top
Bottom
Columbia
Flow
Island
DES
Receiver
Site
I-84
I-84
Flow
Columbia River
DES Downstream
Receiver Site
Miller Island


Wind River
Thermal plume: 16-Sep-00
Water temperature (C)
21
20
19
18
17
16
15
14
13
1
2
3
4
5
6
7
Thermometer sites
Bottom
Top
Col
Flow
Columbia River
Shallow
HWY 14
Flow
Wind River receiver


Hood R. Receiver Site
Hood River
I-84
I-84
Flow
Shallow
Bingen Marina Receiver Site
Flow
Columbia River
Downstream Receiver Site
HWY 14
HWY 14
White Salmon River


Bonneville Dam
Nav Lock
Fish Ladder Exit
I-84
BF-6 Receiver Sites
Bradford Island, OR
Eagle Creek
Flow
Columbia River
Flow
I-84


Herman Creek
Thermal Plume: 29-AUG-00
Temperature (C)
Thermometer Sites
Bottom
Top
Col
Flow
Columbia River
Herman Cr.
1
2
3
4
5
6