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**WATER TEMPERATURES AND PASSAGE OF ADULT SALMON AND STEELHEAD
IN THE LOWER SNAKE RIVER**

by

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Abstract

We used recently collected and historic data to evaluate effects of water temperatures on passage of adult salmon and steelhead in the lower Snake River, especially in relation to temperature exposures in fishways. Similar to the findings of others, we found little evidence that water temperatures have increased over time at the mouth of the Snake River (downstream from Ice Harbor Dam) but temperatures in the forebay of Ice Harbor Dam have trended upwards in the fall (September and October) since 1962. The latter trend can be explained at least in part by an increase in air temperatures during August and September in the region since 1948.

Water temperatures collected in and near fishways at Ice Harbor and Lower Granite dams for the four years 1995 to 1998 routinely exceeded 20°C. Warmest water temperatures typically occurred during July and August during the nadir between the summer and fall chinook salmon runs and before onset of the bulk of the steelhead run. However, during warm years, such as occurred in 1998, warm water conditions can persist at the dams into October. Another potential problem was a temperature discontinuity that typically occurred at the base of fishways where water flowing down the ladder from the forebay surface met potentially cooler water pumped into the fishway from the tailrace, most notably at Lower Granite Dam when flows were released from Dworshak reservoir. Water released from Dworshak reservoir was effective at cooling summertime water temperatures near the forebay surface and in fishways by an estimated 1 to 3°C at Lower Granite Dam. Cooling effects from Dworshak releases were diminished at Ice Harbor Dam because of warming and degree of mixing that occurred as water masses moved downstream, and were difficult to quantify. Best results through the lower Snake River appeared to occur when Dworshak flows were set at 20 kcfs or more, or 50 to 60% of the Snake River flow as measured at Lower Granite Dam.

There was evidence from monitoring radio-tagged adult salmon and steelhead that some fish had longer travel times into the lower Snake River, and some fish took longer to travel between Ice Harbor and Lower Granite dams, during unfavorable water temperature conditions. There was a significant trend for later arrival of salmon and steelhead at Ice Harbor Dam during years with warm summertime water temperatures.

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Introduction

Impounding the Columbia River through construction of large hydroelectric dams has altered the flow dynamics of the system. Typical of this region, flows in the Columbia River peaked in spring with snowmelt runoff, and were lowest in winter. But storage of water at upstream reservoirs during spring for release in the summer for irrigation and in winter for power generation has flattened the hydrograph so that springtime peak flows are lower and summer flows are higher than historic levels. Lower springtime flows, longer hydraulic residence times, and larger surface areas exposed to solar input have resulted in earlier warming, later cooling and higher maximum water temperatures in the lower Columbia River (Quinn and Adams 1996; Quinn et al. 1997). Impoundment of the Snake River by a series of dams has caused warm water temperatures to persist longer in the fall over the period 1962-94 at Ice Harbor Dam (Quinn et al. 1997). As a result, adult fall chinook salmon and steelhead migrating through the lower Columbia and Snake rivers during late summer and early fall may be exposed to water temperatures higher on average than those experienced during pre-impoundment periods. Migrating adult salmon and steelhead can theoretically avoid the warmest surface waters in reservoirs by moving deeper in the water column. But to pass dams, adult migrants must use the relatively shallow (6-8 ft depth) fishways which receive water from the surface of the dam's forebay, potentially the warmest water in the system.

Water in fishways initially flows in from the surface of the forebay and is augmented by water primarily pumped in from near the surface (intakes approximately 5 m depth) in the forebays and tailraces at dams. There is concern that warm surface water in the forebays and warming of water as it passes down fishways during summer could produce conditions that delay or halt passage of adult salmon and steelhead at the lower Snake River dams. Excessively warm water temperatures at dams and in reservoirs could also have indirect effects on migrating adult salmon and steelhead by increasing their susceptibility to disease and the amount of energy expended to reach spawning areas, resulting in lower reproductive fitness overall for Snake River populations. The goal of this study was to monitor summer water temperatures in the forebays, tailraces, and fishways at Ice Harbor and Lower Granite dams on the lower Snake River, and assess effects of warm water temperatures on passage of adult chinook salmon and steelhead.

How does water temperature affect fish? Salmon, like most fish, are poikilothermic vertebrates and, as such, their physiology is directly affected by the temperature of the surrounding water. For adult salmon there should exist a range of temperatures within which energy use and swimming efficiency is optimal. Above the optimal range swimming performance declines and energy use increases, and at excessively high temperatures death occurs. Lethal temperature limits (the temperature at which a fish can no longer survive indefinite exposure) have been reported to be 26-27°C for adult salmon (Trefethen 1968) and 23-25°C for adult chinook salmon (Baker et al. 1995). Sub lethal effects of warm water temperatures on fish include increased osmotic stress, caused in part by the lower dissolved oxygen content of warm water, increased metabolism and energetic costs, increased susceptibility to diseases, and possibly

premature maturation and underdevelopment of gametes. Delays at dams as fish avoid warm temperatures could extend migration times. In general, excessively warm water temperatures during migration could reduce the overall reproductive potential for adult salmon and steelhead migrating through the system.

Before we can evaluate water temperatures, we first need to define what constitutes warm water for adult salmon and steelhead. There has been little research to determine the optimal or preferred water temperature for adult salmonids in freshwater. Brett and Glass (1973) suggested that 15°C was the optimal temperature for adult sockeye salmon, based mostly on research they completed with juvenile sockeye salmon. Brett et al. (1958; 1969) found that optimal growth and sustained swimming speeds for sockeye salmon fingerlings (mean length = 69 mm) occurred at 15°C. But coho salmon juveniles (54 mm mean length) performed best at 20°C (Brett et al. 1958), and chinook salmon juveniles raised in the laboratory had their highest weight gain at 19-20°C (Brett et al. 1982). Oregon has adopted the water quality guideline that a 7-d moving mean of maximum daily water temperatures should not exceed 17.8°C (64°F) in streams where salmonids rear, and 20°C (68°F) in the migration corridors in the lower Columbia and Willamette rivers. Idaho's criteria calls for maximum daily temperatures of 22°C or a daily mean temperature of 19°C in salmonid streams. If optimal temperatures for adult chinook salmon lay somewhere in the range of 15-20°C, we assumed that sub lethal effects from warm water temperature occur when temperatures exceeded 20°C. We chose to use number of days when mean temperatures were \geq 20°C as a measure of warm water conditions for adult salmon and steelhead passing lower Snake River dams.

Study Area

The Snake River converges with the Columbia River at river kilometer (rkm) 522 (Figure 1). For purposes of this report, the lower Snake River was defined as the section from the mouth upstream 236.2 km to the upstream limit of Lower Granite Reservoir. This section of the Snake River is impounded by a series of four reservoirs. Lake Sacajawea, created by Ice Harbor Dam (rkm 15.6), extends 51.3 km upstream to Lower Monumental Dam (rkm 66.9). Lake Herbert G. West, created by Lower Monumental Dam, extends 46.2 km upstream to Little Goose Dam (rkm 113.1), which creates Lake Bryant with a length of 59.9 km. Lower Granite Lake is created by Lower Granite Dam (rkm 173.0) and extends upstream 63.2 km on the Snake River to near the town of Asotin, WA, and 7.4 km up the Clearwater River. These four reservoirs have a combined surface area of about 13,556 ha (33,890 acres) at maximum pool levels (<http://www.cqs.washington.edu/crisp/hydro/index.html>). Volumes of the reservoirs are in the range of 400 to 700 million cubic meters each, or combined volume about 2.24 billion cubic meters for the four lower Snake River reservoirs (at full pools). With a mean flow of 1,132 m³/s (40 kcfs, mean daily flow during July and August during 1990's), hydraulic residence times would be about 5 to 7 d for each reservoir, or about 23 d for the four lower Snake River reservoirs. Flows in the lower Snake River are also influenced by operation of Dworshak Dam on the North Fork of the Clearwater River and by the Hells Canyon Complex (Hells Canyon, Oxbow, and Brownlee dams) which

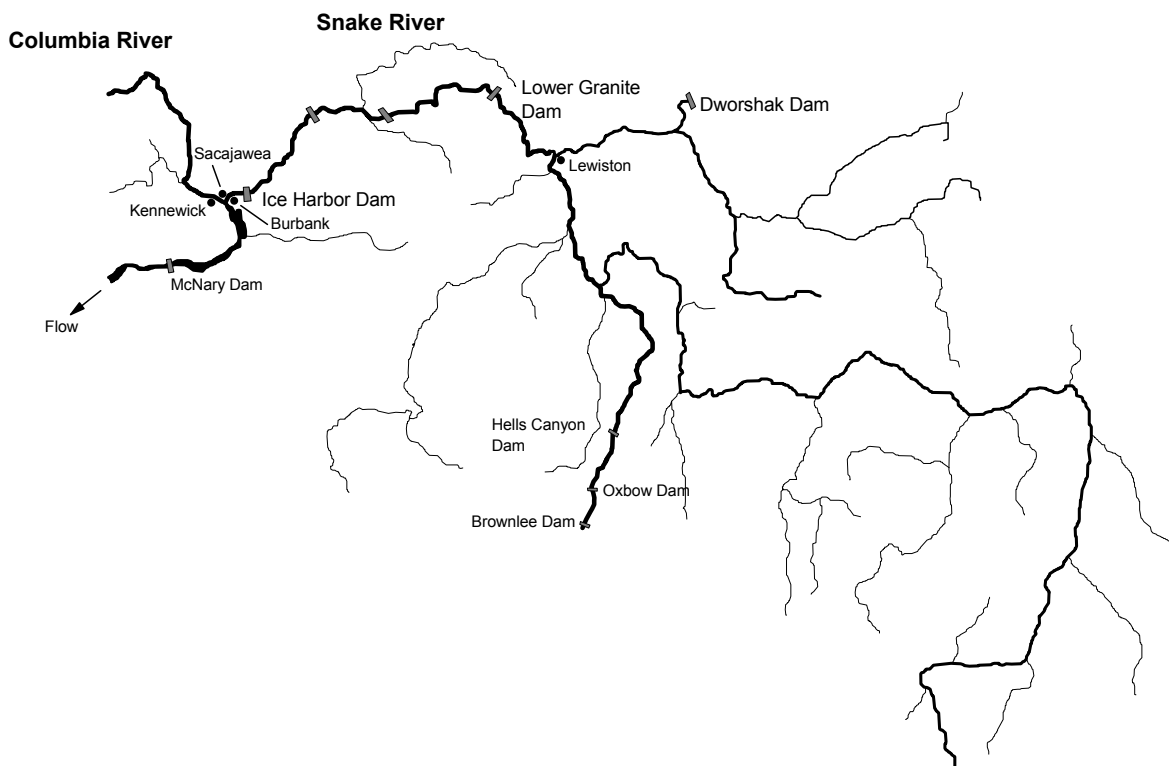


Figure 1. Map of Lower Snake River study area.

start at rkm 397 on the Snake River. The focus of this study was to characterize water temperatures in the lower Snake River in general and in and near the fishways at Ice Harbor and Lower Granite dams in specific, and to determine how those temperatures affect passage of adult salmon and steelhead at the two dams.

Methods

Historic flow and temperature data

Ice Harbor Dam was the first mainstem dam constructed on the lower Snake River, completed in 1962. Prior to that, Brownlee Reservoir and Dam was completed in 1959. The remaining dam completion dates were; Oxbow Dam, 1961; Hells Canyon, 1967; Lower Monumental, 1969; Little Goose, 1970; Dworshak, 1973; and Lower Granite, 1975. Minimal data is available on water temperature and flow conditions in the lower Snake River prior to construction of the dams. Sylvester (1958) conducted a study in the mid 1950's, funded by U.S. Fish and Wildlife Service, to assess water quality conditions throughout the Columbia River basin. As part of that study some water temperatures were collected near the mouth of the Snake River (Sacajawea, WA), downstream from the current location of Ice Harbor Dam. Sylvester (1958) reported mean monthly water temperatures and flows for the study period, 1954-55. Water temperatures were collected during the day by boat from water samples collected from a depth of 10 ft. USFWS collected temperature data at the Sacajawea, WA, site during

the summers from 1945 until 1958 (Pacific Northwest River Basins Commission 1967). However, it appears that data has been lost. Temperatures from the last four years (1955-58) at that site were illustrated in a figure from a 1963 proceedings for a water pollution research symposium (Eldridge 1963; Figure 3). The same data was reproduced in a figure by Bennett et al. (1997a; Figure 1). We estimated water temperatures for those four years from the figures using visual methods. Some water temperatures were collected by EPA personnel, at the mouth of the Snake River near Pasco, WA during 1960-64. However, only a single reading was taken each month and are of limit value for comparison purposes. USGS operated a water temperature monitor at the mouth of the Snake River, near Burbank, WA, from 1973 until 1981 (USGS station 13353200, data downloaded from; <http://water.usgs.gov/pubs/dds/wqn96cd/html/wqn/wq/region17.htm>). Daily river flow readings for the three years 1913-15 were available from historical USGS data at the mouth of the Snake River (USGS station 13353000, data downloaded from: <http://water.usgs.gov/nwis-w/>). Since 1962, water temperatures and river flow have been routinely collected at Ice Harbor Dam (data downloaded from http://www.cqs.washington.edu/dart/river_det.html for daily mean values, and http://www.nwd-wc.usace.army.mil/TMT/tdg_data/months.html for hourly data since 1995). From 1962 until 1974 water temperatures at Ice Harbor Dam were probably collected from the fish ladder or forebay. Since 1974, water temperatures have been collected from the scrollcase of turbine 1 at the dam. Initially a single scrollcase reading was taken at 2400 hrs. Since 1993, temperatures have been measured twice a day, at 0700 and 2400 hrs and averaged. Turbine scrollcase temperatures are of water pulled from depths from 14 to 36 m below the surface. Scrollcase readings are generally considered to be less than ideal for characterizing river conditions, but were the only continuous source of water temperatures available from that period. Starting in 1988, hourly temperature readings have been collected in forebay at Ice Harbor Dam, and since 1994 hourly temperatures have been collected in the tailrace, 5.8 km downstream from the dam. Forebay and tailrace temperatures were collected from a depth of about 4.6 m. The National Oceanic and Atmospheric Administration (NOAA) has collected daily mean air temperatures at Kennewick, WA, and Lewiston, ID, since 1948 (data downloaded from <http://www.ncdc.noaa.gov/ol/climate/stationlocator.html>). We used air temperatures from those two cities because they are situated immediately east and west of the lower Snake River.

We used linear regression to look for trends in mean monthly water temperatures at the mouth of the Snake River and in the forebay of Ice Harbor Dam, Snake River flows, and air temperatures at Kennewick and Lewiston over time. Plots of residual error values versus predicted values were used to check for normality for the regression analysis. We looked for autocorrelation errors in time series data using the Durbin-Watson test. When autocorrelations were present we used autoregressive error corrections (Proc Autoreg, SAS Inc.) to determine if trends were significant. We specifically looked at the period from June through September to determine if summer temperature and flow conditions have changed with impoundment of the lower Snake River.

Fishway and Forebay Water Temperatures at Ice Harbor and Lower Granite Dams

OmniData EPROM Series thermal recorders with S-060 probes were used to collect

hourly water temperatures in the tailraces, fishways, and forebays at Ice Harbor and Lower Granite dams during summers of 1991-1998 (Figures 2 and 3). Temperature probes were placed in the tailraces and forebays near intakes for water pumped into diffusers near base and tops of ladders (approximately depth of 5 m), and 1 m below the surface outside the major fishway entrances and exits. In fishways, temperatures were collected at 1 m depths just inside and outside the main entrances and exits, and at locations upstream and downstream from the diffusers at the base and tops of ladders. The temperature recorders were downloaded about every two weeks, at which time a precision thermometer was used check probe accuracies. Thermal recorders measured temperature in 0.1°C increments and were rated at $\pm 0.25^\circ\text{C}$ accuracy. We generally found the probes to be within 0 to 0.5°C of the true temperature. Measured deviations were used to correct recorded temperatures prior to analysis. Occasionally it was noted that a probe was drifting (temperature bias increasing over time). In those instances the probe was replaced and linear relationship was used to adjust the affected temperatures.

Hourly temperatures at any one location were found to vary about 0.5°C diurnally, and were averaged to produce one temperature per day at each recording site. Additionally, daily mean temperatures were combined and averaged for comparable locations at a dam to describe typical temperatures experienced by adult migrants at different stages of its passage. The resulting eight locations described were;

- (1) tailrace (lower fishway diffuser intakes),
- (2) outside fishway entrances,
- (3) inside fishway entrances,
- (4) bottom of ladders (upstream from lower diffusers),
- (5) top of ladders (downstream from upper diffusers),
- (6) inside exits,
- (7) outside exits, and
- (8) forebay (diffuser intakes).

Because Lower Granite Dam has a single ladder, temperatures from six of the eight locations (tailrace, ladder bottom, ladder top, inside and outside ladder exits, and the forebay) were from a single recording site while temperatures at all eight locations at Ice Harbor Dam were averaged from at least two recording sites.

The highest mean value measured at a dam on any given day (maximum daily temperature) was used to characterize water conditions in fishways each day since it represented the most extreme conditions an adult migrant would experience while crossing a dam. Warm water conditions were considered to exist if the maximum daily temperature exceeded 20°C at any location at the dam. The difference between the highest and lowest temperatures (maximum temperature difference) was used to determine the greatest differential in temperatures a fish would experience while crossing a dam on any given day.

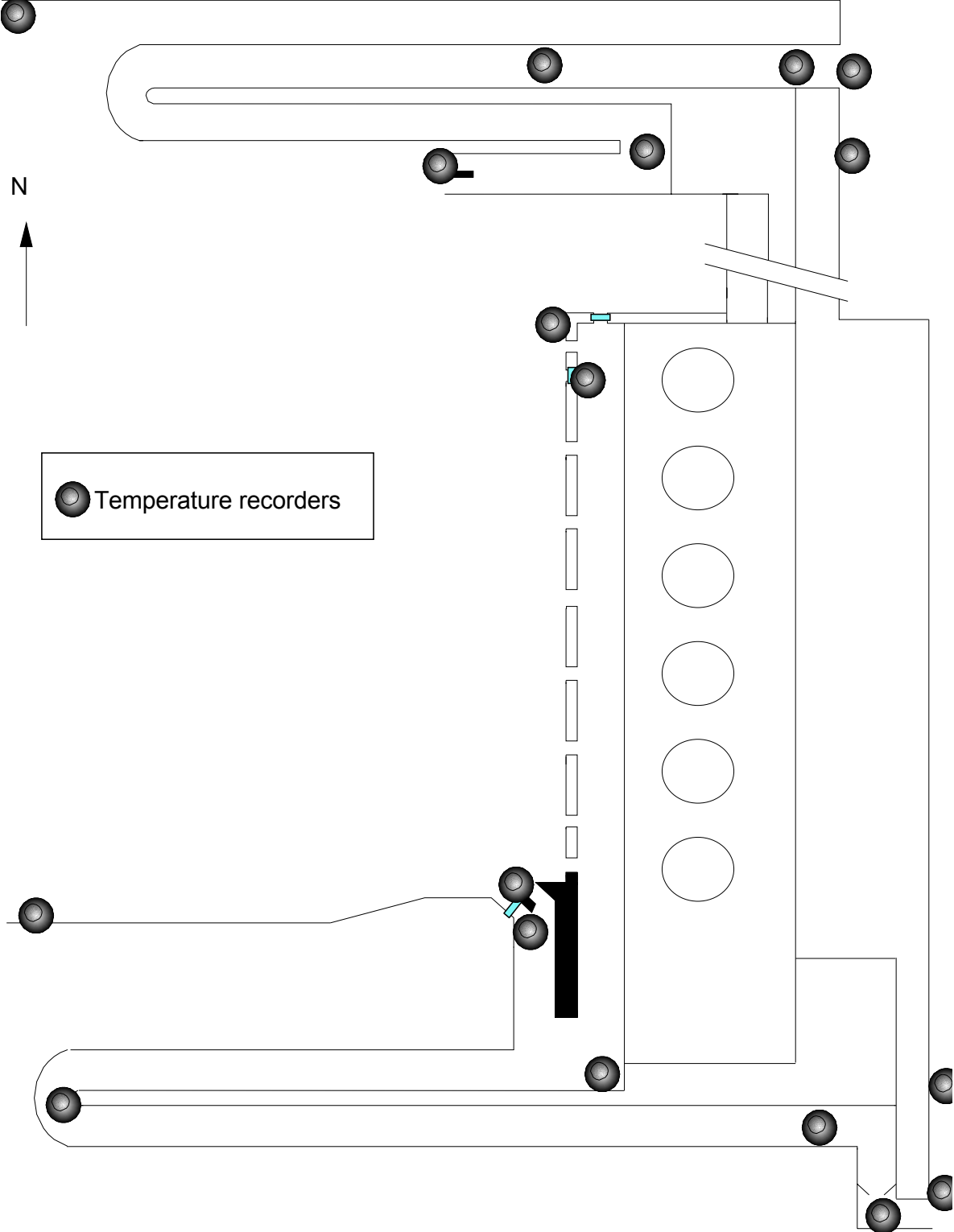


Figure 2. Location of temperature recorders used during 1995-98 at Ice Harbor Dam.

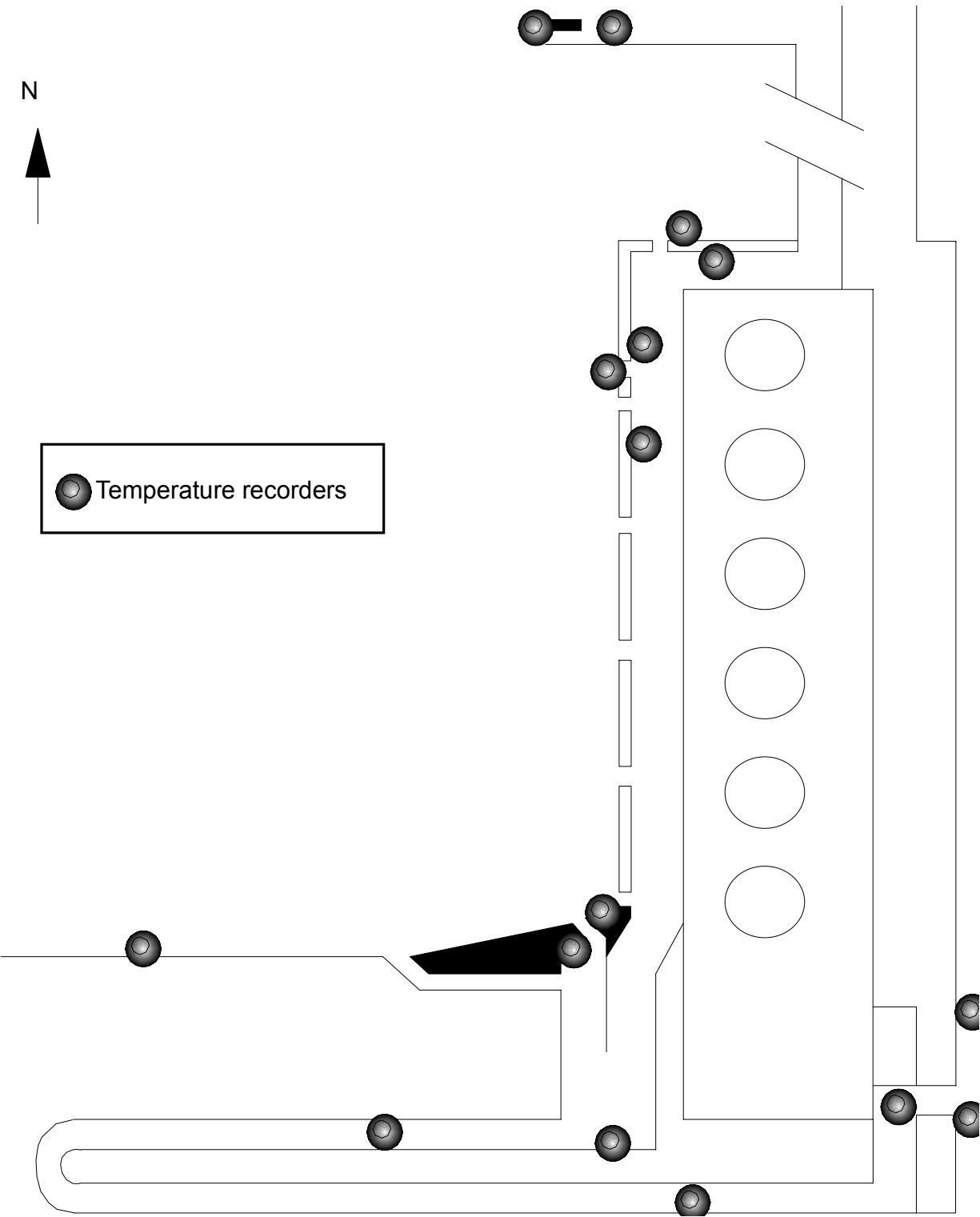


Figure 3. Location of temperature recorders used during 1995-98 at Lower Granite Dam.

Temperature-at-depth data were collected in the forebays at both dams. Temperatures were measured to the nearest 0.1°C from a boat using a YSI Multimeter. Readings were made at transects about 600 m upstream from the face of each dam at seven sites evenly spaced across the width of the forebay. At each site, temperatures were recorded at depths of 0.1, 1.5, 3.0 m, and then at 3 m intervals down to the bottom (max depth = 36 m). Temperatures were collected at those transects at both dams at roughly 2 week intervals during July, August, and September for the four years 1995-98. Temperatures at the seven sites across the forebay width were averaged across depths to produce a mean temperature profile for the forebays at the two dams for each date. Temperature profiles were used to determine degree of stratification that occurred and effects of releasing water from Dworshak Reservoir on temperatures in the forebays at the two dams.

Multiple regression analysis was used to determine relative effect of releasing water from Dworshak on daily maximum fishway water temperatures at Lower Granite Dam. We selected 8 years of data for this analysis, the 4 years during this study in the 1990's (1995-98) with higher levels of summer flow from Dworshak, and 4 years from the early 1980's (1980, 1982, 1983, and 1984) when relatively little water was released from Dworshak during summer. The measure of water temperature used was the mean daily forebay temperatures recorded by USACE personnel at Lower Granite Dam at their water quality station (recorded hourly, mid-channel at the navigational lock exit, 4.6 m depth), from June through October during the 8 years, which was similar to the maximum daily fishway temperatures we measured during the 1995-98 period. Six variables regressed on Lower Granite Dam water temperature were Snake River flow, air temperature, and the proportion of Snake River flow coming from Dworshak reservoir and the squares of these variables. Snake River flow was the mean flow (USACE readings) at Lower Granite Dam on the day water temperatures were recorded. Air temperatures were a three-day mean of temperatures recorded at Lewiston, Idaho (NOAA data), 6, 7, and 8 d prior to the day water temperatures were recorded at Lower Granite Dam. Using a three-day mean dampened the effect of day-to-day variations in air temperatures that occurred in the data while preserving the pattern of air temperatures that occurred in the region. The proportion of flow from Dworshak reservoir was calculated from the amount of flow released from Dworsak Dam (USACE data) 6 d prior to the day water temperatures were recorded at Lower Granite Dam. The 7 and 6 d lags applied to air temperatures and Dworshak flows in analysis were determined from visual inspection of plots of the three variables for all years combined and represent an estimated mean for the dataset as a whole, although it may not be the best fit for any individual year. Regression analysis (PROC REG, SAS Institute Inc. 1990) was used to develop a model that best represented the temperature data using the adjusted r-square selection method. Analyses for each year (all months combined) and for each month (all years combined) were compared to determine which model best fit the summer temperature conditions. Data were checked for autocorrelations and plots of residual errors versus predicted values were used to determine the appropriateness of models to fit the data. Data simulations were developed to determine relative affect of releasing water from Dworshak reservoir on summer fishway water temperatures at Lower Granite Dam at various river flow and air temperature values.

Analyses of chinook salmon and steelhead radio telemetry and count data

Temperatures were correlated to passage indices of adult chinook salmon and steelhead at Ice Harbor and Lower Granite dams to determine if there were any general trends in how fish runs responded to warm water temperatures. We used radio telemetry data to characterize behavior of individual fish migrating through the Snake River during summer and fall when warm water conditions were likely to occur. Two years of telemetry data were available for summer and fall chinook salmon (1997 and 1998) and steelhead (1996 and 1997) during the period that we measured water temperatures at Ice Harbor and Lower Granite dams. All fish were outfitted with transmitters and released at Bonneville Dam and monitored using a series of fixed receivers as they passed McNary, Ice Harbor, and Lower Granite dams. Radio receivers connected to aerial antennas located approximately 1 km downstream from each dam were used to determine when fish with transmitters first entered the tailrace at dams. Receivers connected to underwater antennas in the forebay just outside fishway ladder exits were used to determine when fish left dams and continued migrating upstream. We used first tailrace records and last records from the tops of ladders to calculate times for fish to travel between McNary and Ice Harbor dams, to pass Ice Harbor Dam, to travel between Ice Harbor and Lower Granite dams, and to pass Lower Granite Dam. Travel and passage times were plotted against various measures of water temperatures to determine if there were general patterns to fish behavior with respect to temperature patterns. Regression analysis was also used to evaluate general trends in passage times. Travel times between McNary and Ice Harbor dams were compared to the forebay temperatures at McNary Dam (collected by the USACE) at the time fish left McNary Dam, the maximum water temperature we measured at Ice Harbor Dam on the day fish left McNary Dam (see above), and the difference between the two temperatures. Travel times between Ice Harbor and Lower Granite dams were compared to the maximum water temperatures on the days fish left and arrived at the respective dams. Passage times at Ice Harbor and Lower Granite dams were compared to the maximum water temperature we measured at the dam on the day fish arrived, the maximum water temperature on the day they left the dam heading upstream, and to the daily maximum difference in water temperatures we measured at the dam on the day fish arrived (greatest difference between coolest and warmest temperatures measured at the dam, see above). Each water-temperature variable was regressed separately on passage or travel times because they were highly correlated to each other. It is common in telemetry data to find some fish that take much longer to migrate upstream or pass a dam than the bulk of the run. We were concerned that these outliers would bias results of regression analysis, so at times analyses was performed with outliers (greater than 2 standard deviations from the mean) removed to determine their effect on results.

In our second analysis of fish data, we used fish counts and water temperatures collected at Ice Harbor and Lower Granite dams to evaluate if fish runs passed later during years with warmer water temperatures. The passage index used was date at which the first 25% of the run had been counted at the two dams for each year of operation (1962 to 2000 for Ice Harbor Dam; 1975 to 2000 for Lower Granite Dam). Fall chinook salmon are counted from 12 August to 31 October at Ice Harbor Dam, and from 18 August to 31 October at Lower Granite Dam. For steelhead, we used counts from 1

June until fish were no longer counted (31 October at Ice Harbor Dam and 15 December at Lower Granite Dam). Mean daily forebay temperatures were again used as measure of warmest fishway water conditions at the dam. We regressed date of 25% passage on year and mean forebay water temperatures for the six-week period 1 August-15 September of each year.

Results

Historic Temperatures and Flows.

“The Snake River reaches a temperature in excess of 72°F. in August and less than 35°F. in the winter. In August, it is 8.5°F. warmer than the Columbia River at its confluence and in December it is 8°F. colder. In late July of 1956 (a warm summer), afternoon water temperatures exceeded 77°F.” (Sylvester 1958, p. 44).

Sylvester (1958) reported that water temperatures near the mouth of the Snake River averaged 15.9, 20.2, 21.4, and 19.3°C (converted from °F) for June, July, August, and September during 1954-56 (Figure 4). From Eldridge (1963; Figure 3), and the similar data in Bennett et al. (1997a; in Figure 1), we determined that water temperatures at the mouth of the Snake River during the four years 1955-58, were consistently over 20°C from early July until mid-September (Figure 5). The number of days during which the mean water temperature exceeded 20°C averaged 70.5 d for the four years, ranging from 61 d in 1955 to 86 d in 1958. Monthly water temperatures during June, July, August, and September during 1955-58 averaged 17.2, 22.0, 23.3, and 20.3°C, respectively. These mean temperatures were about 2°C higher than reported by Sylvester (1958) for the 1954-56 period, probably because of the warmer temperatures that occurred in 1957 and 1958.

During 1973-81, water temperatures at the mouth of the river averaged 14.5, 19.0, 21.9, and 20.1°C from June through September (USGS monitoring site) and 14.6, 19.5, 21.1, and 19.2°C for the four months during 1995-2000 (USACE Ice Harbor Dam tailrace site) (Figure 6). Mean daily water temperatures in the tailrace of Ice Harbor Dam were 20°C or higher a mean of 39 d (range 26 to 55 d) per year during the period 1995-2000. Temperatures in the Snake River near the mouth trend for lower mean monthly temperatures in June (regression $P = 0.0232$, $r^2 = 0.467$, corrected for autocorrelation), July (corrected $P = 0.006$, $r^2 = 0.5185$), August ($P = 0.0002$, $r^2 = 0.517$), with no pattern for September ($P = 0.859$) (Figure 6). Insufficient data was available from October to make a determination.

Temperatures were available from the forebay of Ice Harbor Dam since 1962. By 1962 Brownlee and Oxbow dams were in place. Between 1962 and 1973, five mainstem dams were constructed on the Snake River (Hells Canyon, Lower Monumental, Little Goose, Dworshak, and Lower Granite). Following impoundment of

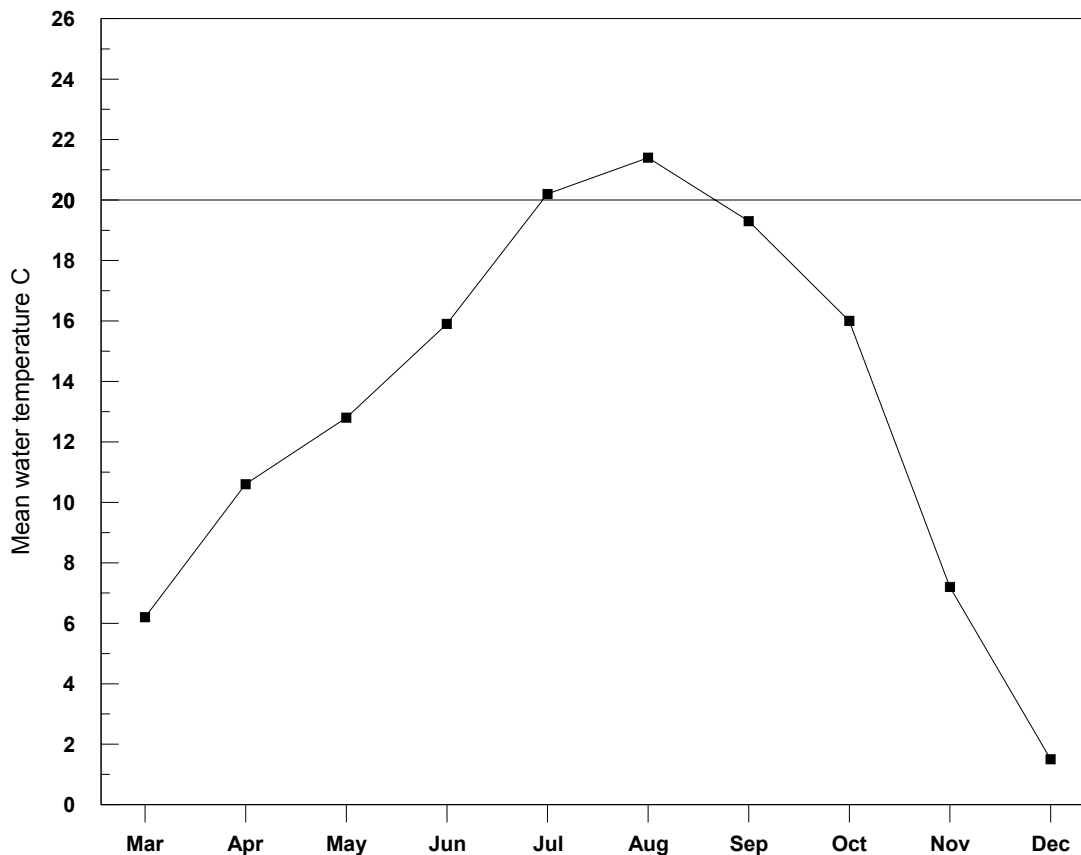


Figure 4. Mean monthly water temperatures near mouth of the Snake River during 1954-56 (Sacajawea, WA). Taken from Sylvester (1958).

the lower Snake River by Ice Harbor Dam, mean monthly water temperatures in the forebay generally increased during October ($P = 0.006$, $r^2 = 0.193$) and were unchanged during June ($P = 0.082$), July (corrected $P = 0.560$), August (corrected $P = 0.145$), and September ($P = 0.372$) during the period 1962-2001 (Figure 7). The monthly maximum temperature (highest daily mean for each month) was unchanged for June (corrected $P > 0.6$), July (corrected $P > 0.7$), August (corrected $P > 0.3$), September ($P > 0.9$), and October ($P > 0.2$) since 1962. The variability in temperature data for each month (standard deviation of daily mean temperatures) has declined over time during June ($P < 0.04$, slope = -0.012 , $r^2 = 0.11$) and July ($P < 0.04$, slope = -0.016 , $r^2 = 0.11$) but was unchanged during August, September and October since 1962. The date of maximum daily mean temperature in the forebay of Ice Harbor Dam for each year has not changed ($P > 0.7$), being about 23°C in the middle of August (median 15 August) since 1962. However, during the 1955-58 sampling, maximum water temperatures appeared to have occurred closer to the end of July (Figure 5).

Quinn et al. (1997) found that Snake River temperatures were inversely related to river flows. Snake River flows can vary greatly between years (Figure 8) but generally, mean monthly flows have not changed over time during June (corrected $P = 0.254$),

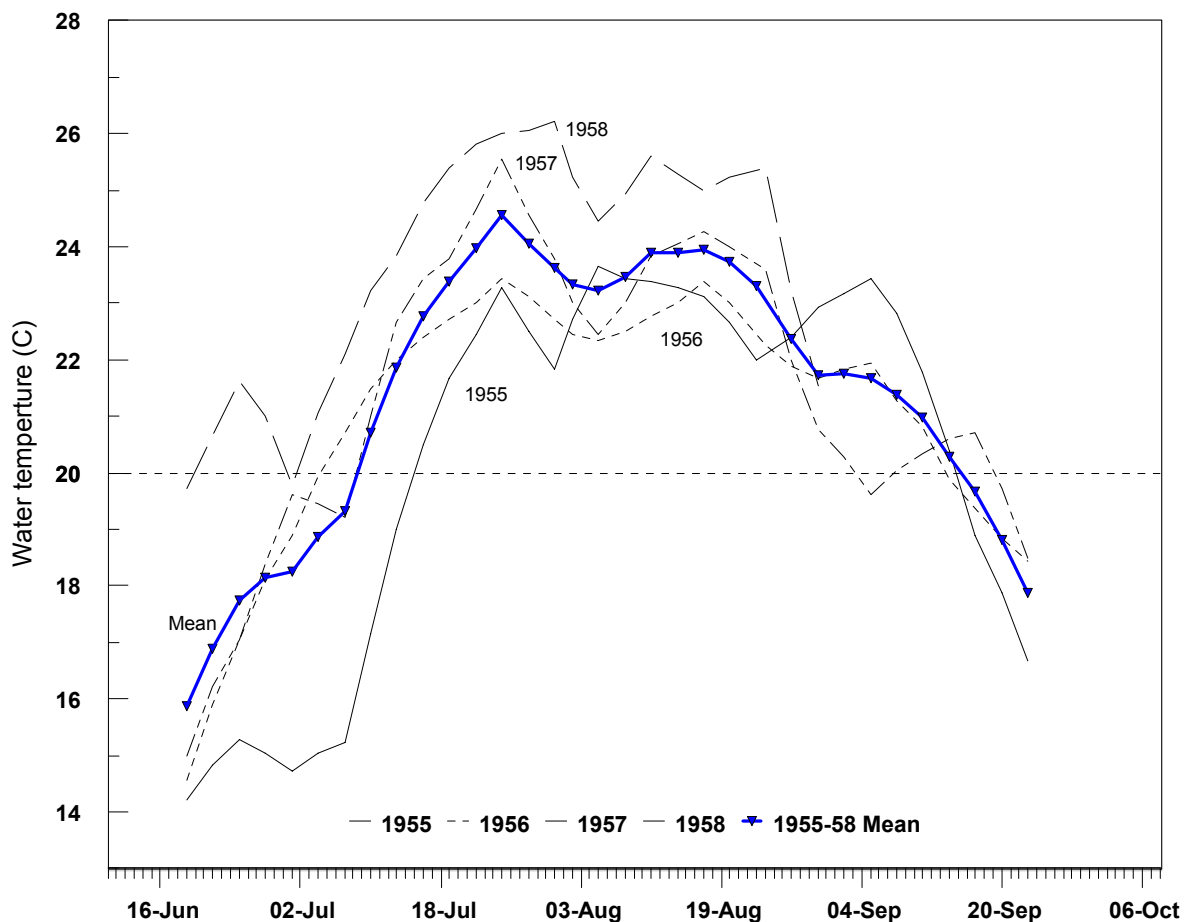


Figure 5. Water temperatures recorded at mouth of the Snake River (Sacajawea, WA) during 1955-58, and mean water temperatures for the four years. Taken from Eldridge (1963) and Bennett et al. (1997).

July (corrected $P = 0.606$) and October (corrected $P = 0.582$) and have increased during August (corrected $P < 0.002$, $r^2 = 0.396$) and September (corrected $P < 0.001$, $r^2 = 0.401$) (Figure 8). Since 1962, when Ice Harbor Dam came into operation, the trend has been for increased flows during August over time (corrected $P < 0.042$, $r^2 = 0.108$) but no pattern of change for other four months. Prior to impoundment of the Snake River, flows appeared highest (> 100 cfs) in April, May and June and generally low (< 50 cfs) the remainder of the year. Peak spring runoff usually occurred late May and early June and lowest flows were usually around 1 September and that pattern does not appeared to have changed appreciably over time (e.g. Figure 9).

Mean monthly air temperatures have increased significantly during August at Lewiston, ID ($P < 0.01$, $r^2 = 0.129$) and Kennewick, WA ($P < 0.01$, $r^2 = 0.163$), and during September at Kennewick ($P < 0.04$, $r^2 = 0.0866$) (Figure 10). Air temperatures during the remaining months at the two locations have not changed significantly ($P >$

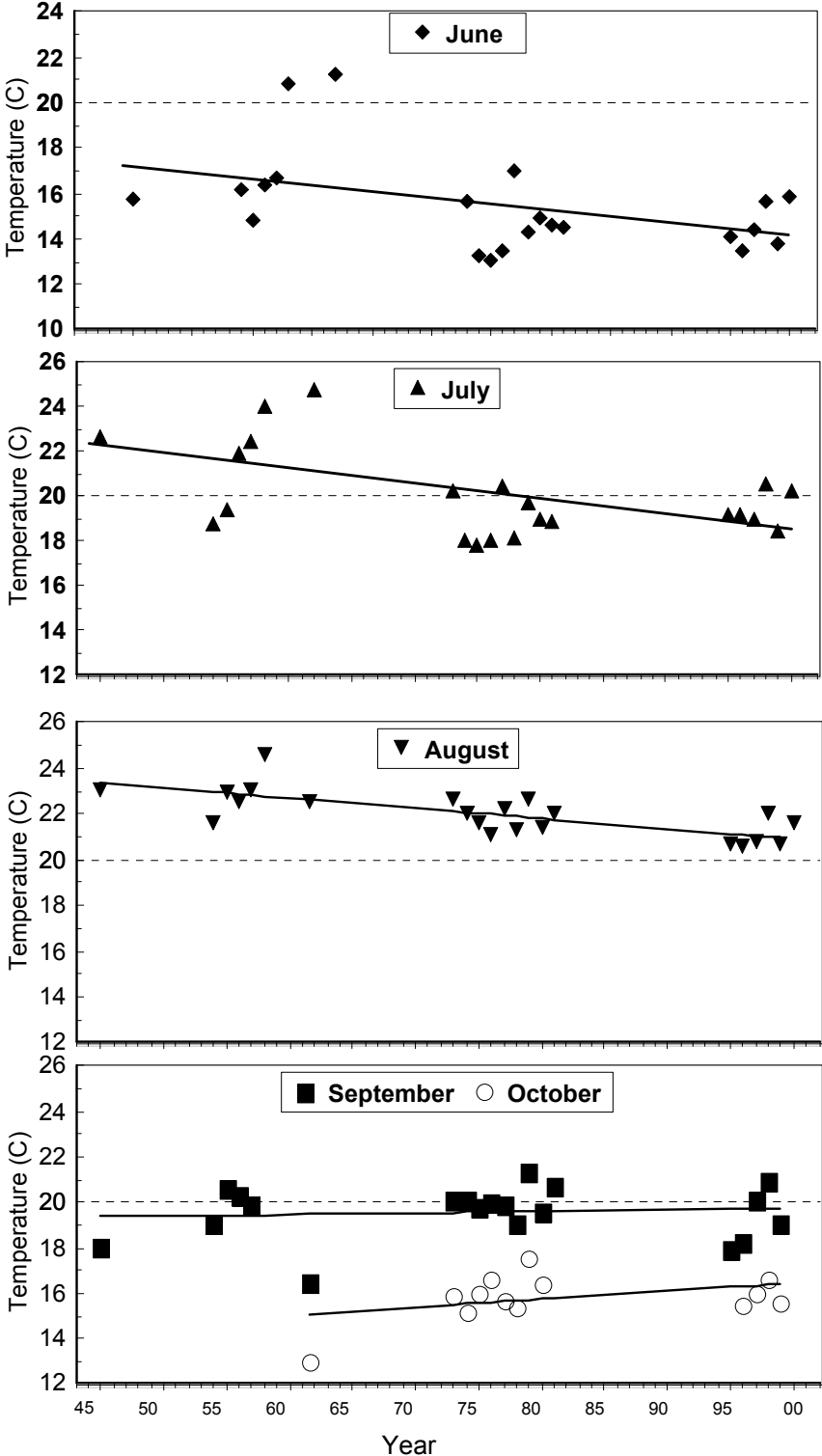


Figure 6. Mean monthly temperatures near mouth of Snake River. Temperatures from 1990's collected at USACE site 5.8 km downstream from Ice Harbor Dam. Earlier data were from USGS sites at the mouth of the Snake River, 16 km downstream from the dam.

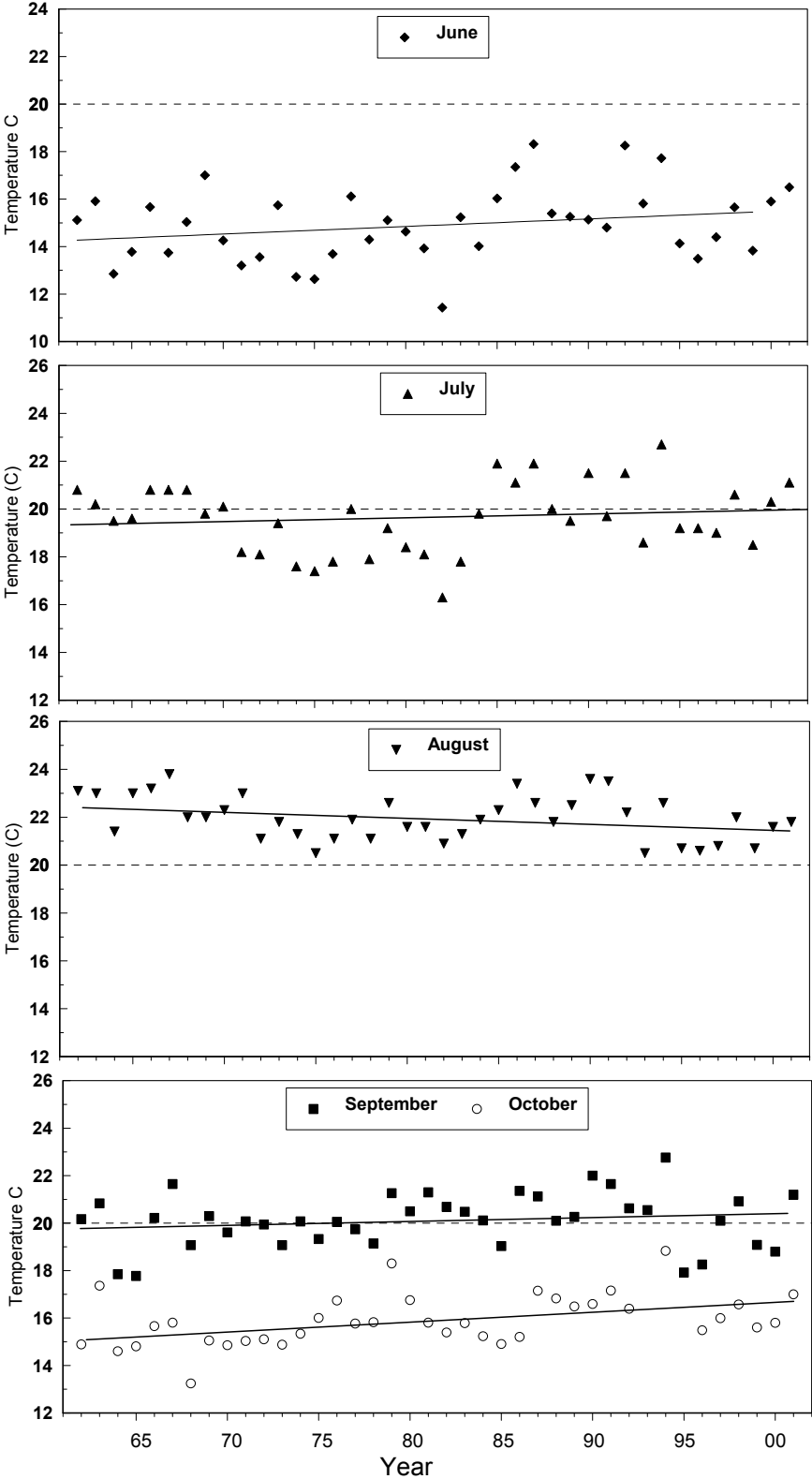


Figure 7. Mean monthly temperatures in forebay of Ice Harbor Dam. Forebay temperatures collected hourly at depth of 5 m since May 1983. Daily scrollcase temperatures used prior to 1983.

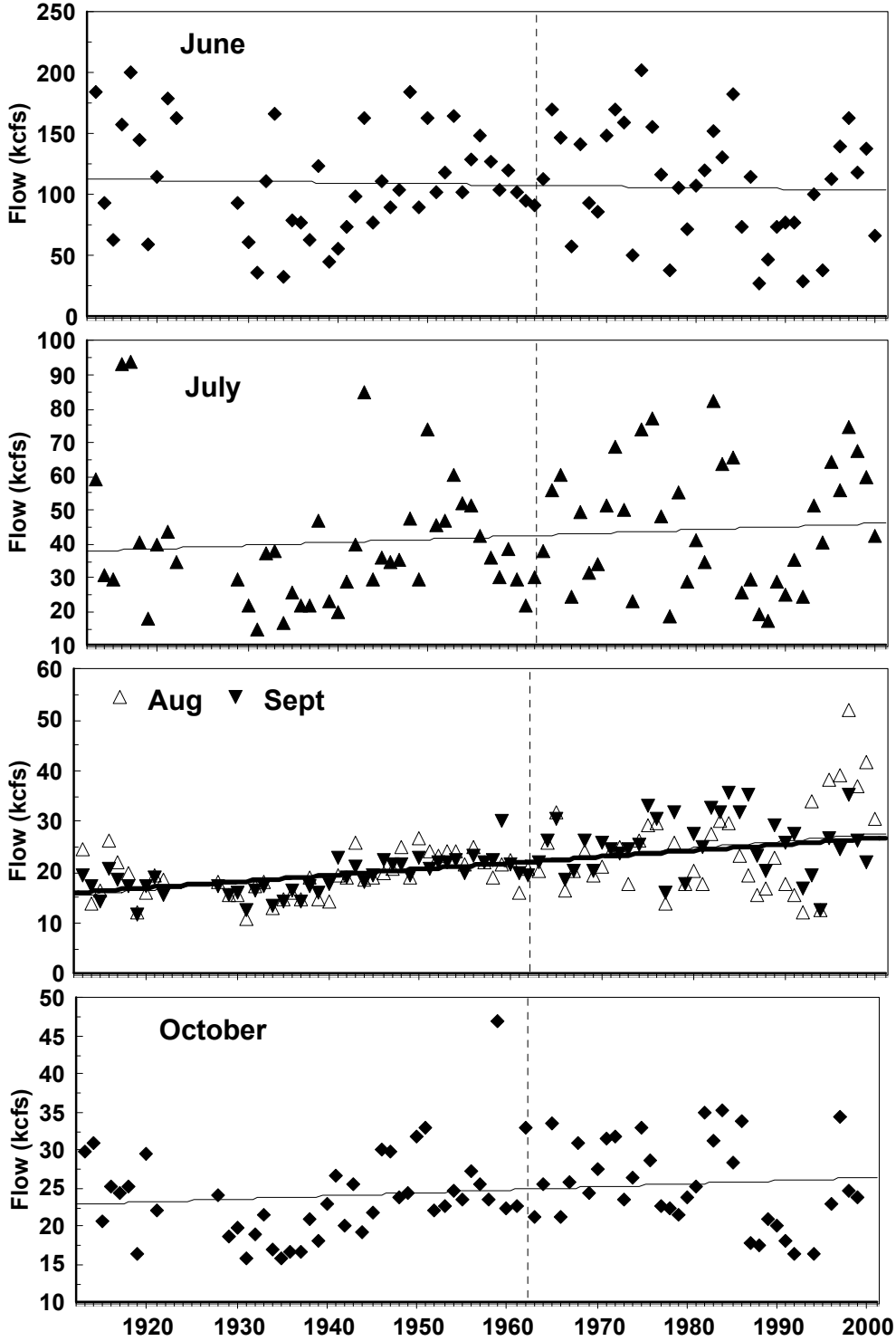


Figure 8. Mean monthly flows near mouth of the Snake River. Flows from 1913-15 are from USGS gauging station at Snake River mouth. Flows from 1916 to 1961 are from USGS gauging station at Clarkston, WA, and would not account for inputs from Palouse and Tucannon rivers. Flows during 1962-99 were collected by USACE at Ice Harbor Dam.

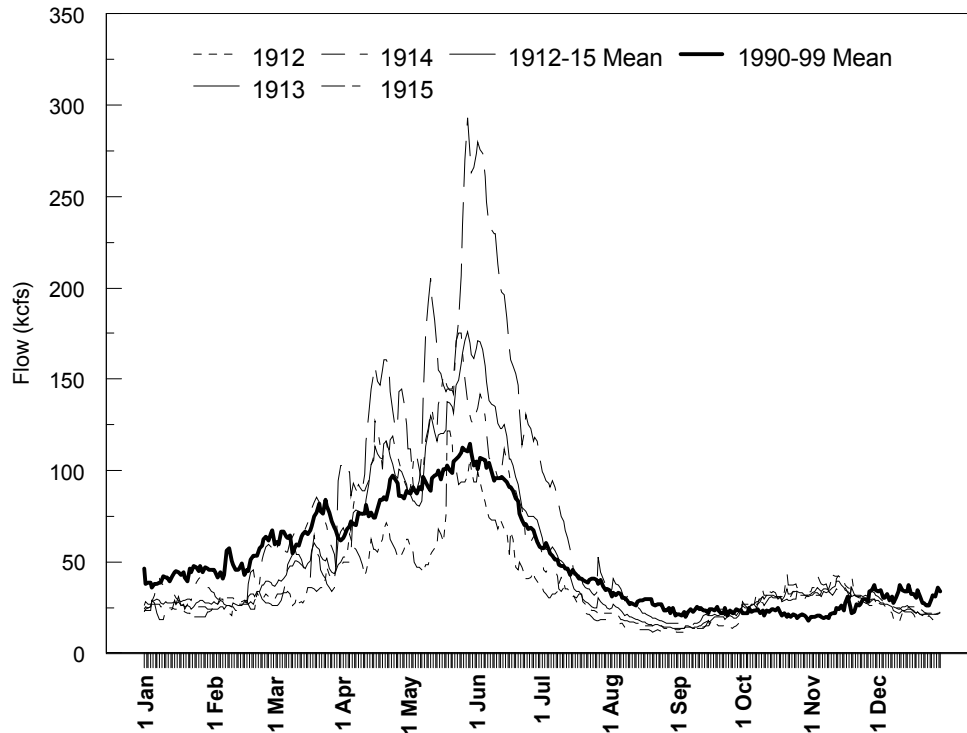


Figure 9. Snake River flows near mouth during 1912-15 and mean flows during 1990-99 period.

0.1) during the period from 1948 to 1999.

Fishway Water Temperatures.

Following is a description of water temperature conditions in and near the fishways at Ice Harbor and Lower Granite dams for the four years 1995-98. Water temperatures in the fishways typically varied 0.5°C or less during the day. For example, at Ice Harbor Dam in 1995, for all monitoring locations, daily temperature variations were 0.5°C or less 63% of the time, and 1°C or less 85% of the time. The difference between the hourly maximum temperature we recorded and daily mean was 0.5°C or less 78% of the time, and 1.0°C or less 93% of the time. Thus, the daily mean water temperature was a good approximation of temperatures experienced by fish passing the dam during daylight hours. When maximum temperatures are reported, this refers to the highest mean recorded at any location during a given day. Maximum difference in water temperatures was the difference between the coolest and warmest mean water temperatures measured at the dam each day.

Ice Harbor Dam.

Temperatures recorded in and around the south shore at Ice Harbor Dam tended to be slightly warmer than those from the north shore, mainly during July and August, but

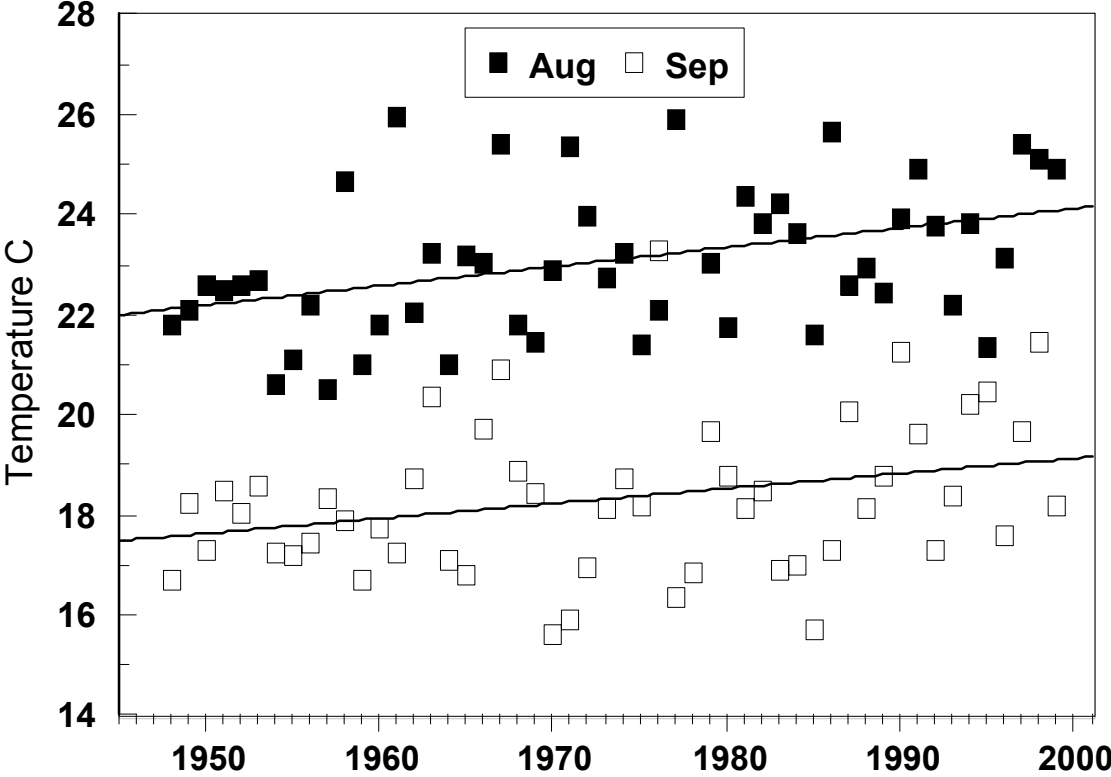
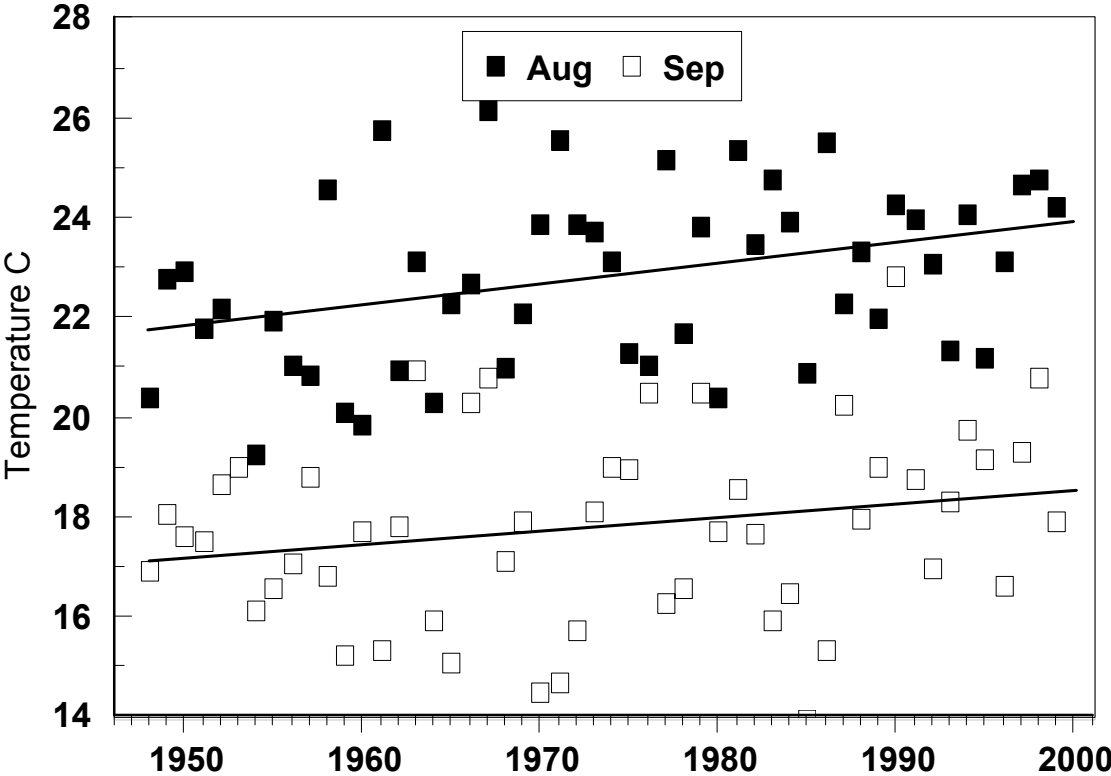


Figure 10. Mean monthly air temperatures during August and September at Lewiston, ID. (top) and Kennewick, WA, from 1948 until 1999.

differences were generally less than 0.5°C between comparable locations in the two ladders and within the accuracy range of the temperature probes.

In 1995, water temperatures were collected hourly at Ice Harbor Dam from 5 July until 19 October (Figure 11, Appendix A). In early July, water temperatures at Ice Harbor Dam were 18.0 to 18.5°C. Temperatures first reached 20°C on 17 July, peaked near at 23°C on 4 August, then returned to around 20°C again mid-August, where temperatures remained until 21 September when they dropped below 20°C for the last time. By 19 October, water temperatures in the fishway were between 15 and 16°C and declining. Daily maximum water temperatures at the dam averaged 20.1°C (95% CI = $\pm 0.5^\circ\text{C}$) in July, 20.6°C ($\pm 0.3^\circ\text{C}$) during August, 19.6°C ($\pm 0.2^\circ\text{C}$) during September, and 17.3°C ($\pm 0.4^\circ\text{C}$) through 19 October. There were 56 d when the daily mean temperature somewhere in fishway system was 20°C or higher.

Highest water temperatures at the dam were recorded in the forebay, near the water intakes and outside ladder exits. In the fishway, highest water temperatures were consistently recorded at the top of the ladder inside fishway exits and were generally lowest inside the fishway entrances. Water temperatures increased an average of 0.1°C as it passed down the main body of the fish ladder, in the weired section between top and bottom set of diffuser grates, but this temperature rise was negated by water pumped into the ladder at diffusers, especially at the bottom of the fishway (Figure 12).

The maximum difference in water temperatures recorded within the fishway at any one time (i.e. difference between warmest water in the forebay and coolest water in the tailrace) ranged from 0 to 1°C, averaging 0.3 to 0.4°C during July, August, September, and October. Temperatures were slightly warmer in the north ladder during June and September and warmer in the south ladder during July and August, but differences were usually less than 0.5°C between comparable locations in the two ladders.

In 1996, water temperatures were collected hourly at Ice Harbor Dam from 25 June until 2 November (Figure 13). At the start of July, water temperatures at Ice Harbor Dam were 15.4 to 16.1°C. Temperatures first reached 20°C on 11 July, peaked at 23°C on 26 July and then again on 10 August, and dropped below 20°C for the last time on 10 September. Daily maximum water temperatures at the dam averaged 19.7°C ($\pm 0.7^\circ\text{C}$) in July, 21.5°C ($\pm 0.1^\circ\text{C}$) during August, 18.4°C ($\pm 0.4^\circ\text{C}$) during September, and 15.7°C ($\pm 0.5^\circ\text{C}$) during October. By the end of October, water temperatures were around 13°C. There were 57 d when the mean temperature somewhere at the dam was 20°C or higher.

During the warmest time of year (10 July to 11 September), highest water temperatures were recorded at the forebay surface outside fishway exits, averaging 20.9°C ($\pm 0.2^\circ\text{C}$) for the two month period. In the fishway, highest water temperatures were recorded at the base of the ladder, averaging 20.8°C ($\pm 0.3^\circ\text{C}$) during that same period. On average, water temperatures increased about 0.4°C as it passed down the main portion of fish ladder, but temperatures were moderated by water pumped into the base of the ladder at diffusers (Figure 14). The difference between the warmest and coolest water temperatures at the dam at any one time ranged from 0 to 1.6°C, averaging 0.2, 0.8, 0.5, and 0.4°C during June, July, August, and September, respectively. Temperatures were generally warmer in the north ladder than in the south ladder, by up to 1.2°C difference in October, although during the warmest period of the

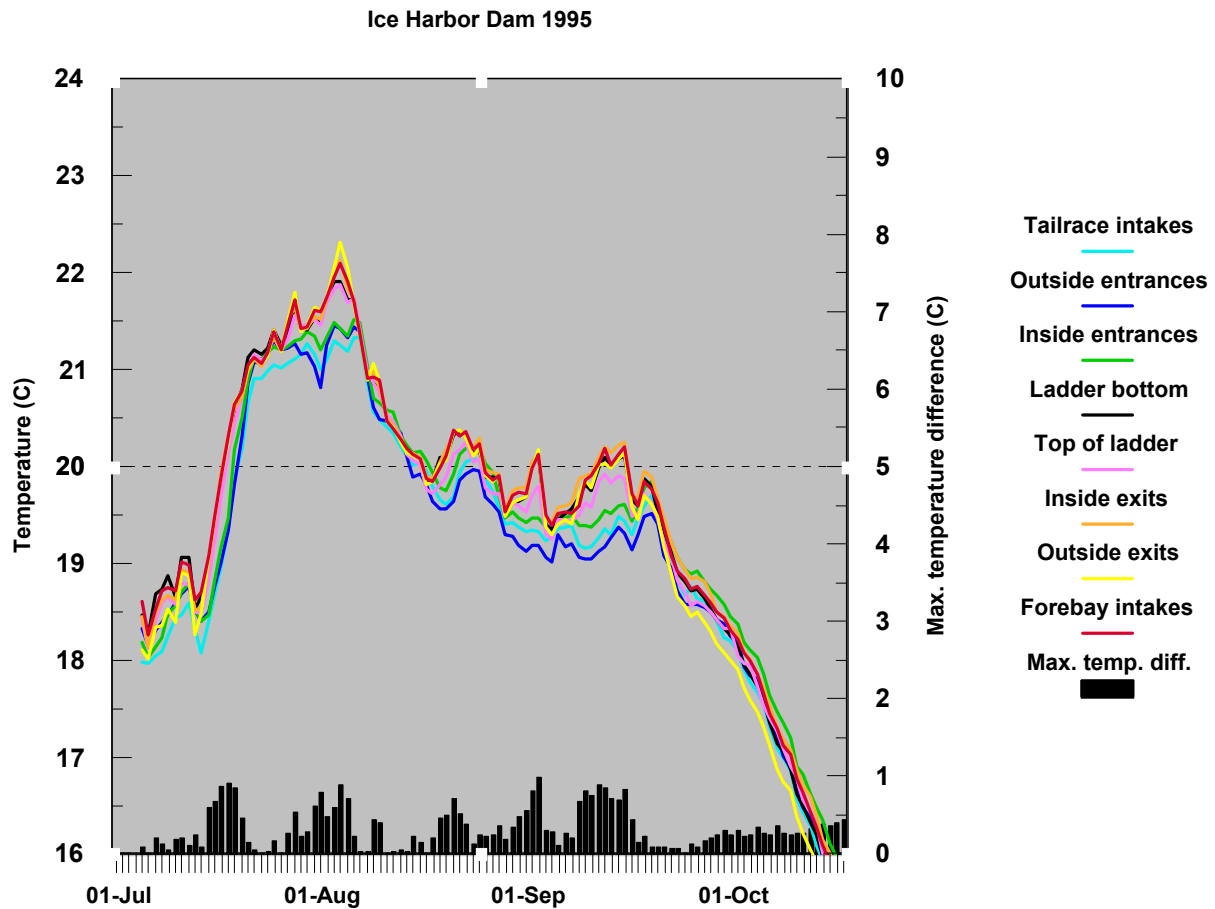


Figure 11. Water temperatures measured in and around fishways at Ice Harbor Dam in 1995.

year (10 July-11 September) differences in water temperatures were negligible between the two ladders.

In 1997, water temperatures were collected hourly at Ice Harbor Dam from 3 July until 5 November (Figure 15). In early July, water temperatures at Ice Harbor Dam were between 17.5 and 18.0°C. Temperatures first reached 20°C on 19 July, peaked at 22°C on 6 August, and dropped below 20°C for the last time on 26 September. Daily maximum water temperatures at the dam averaged 19.5°C ($\pm 0.4^\circ\text{C}$) in July, 21.2°C ($\pm 0.1^\circ\text{C}$) during August, 20.4°C ($\pm 0.2^\circ\text{C}$) during September, and 16.3°C ($\pm 0.6^\circ\text{C}$) during October. By the end of October, water temperatures were around 13.5°C. There were 67 d when the mean temperature somewhere at the dam was 20°C or higher. During the warmest time of year (19 July to 19 September), highest water temperatures were recorded at the base of the ladders (mean = 20.9°C $\pm 0.1^\circ\text{C}$) and at the forebay surface outside fishway exits (20.8°C $\pm 0.1^\circ\text{C}$) for the two month period. On average, water temperatures increased about 0.2°C as it passed down the main portion of fish ladder, but then decreased by about the same amount from water pumped into the base of the ladder at diffusers (Figure 16). The difference between warmest and coolest water

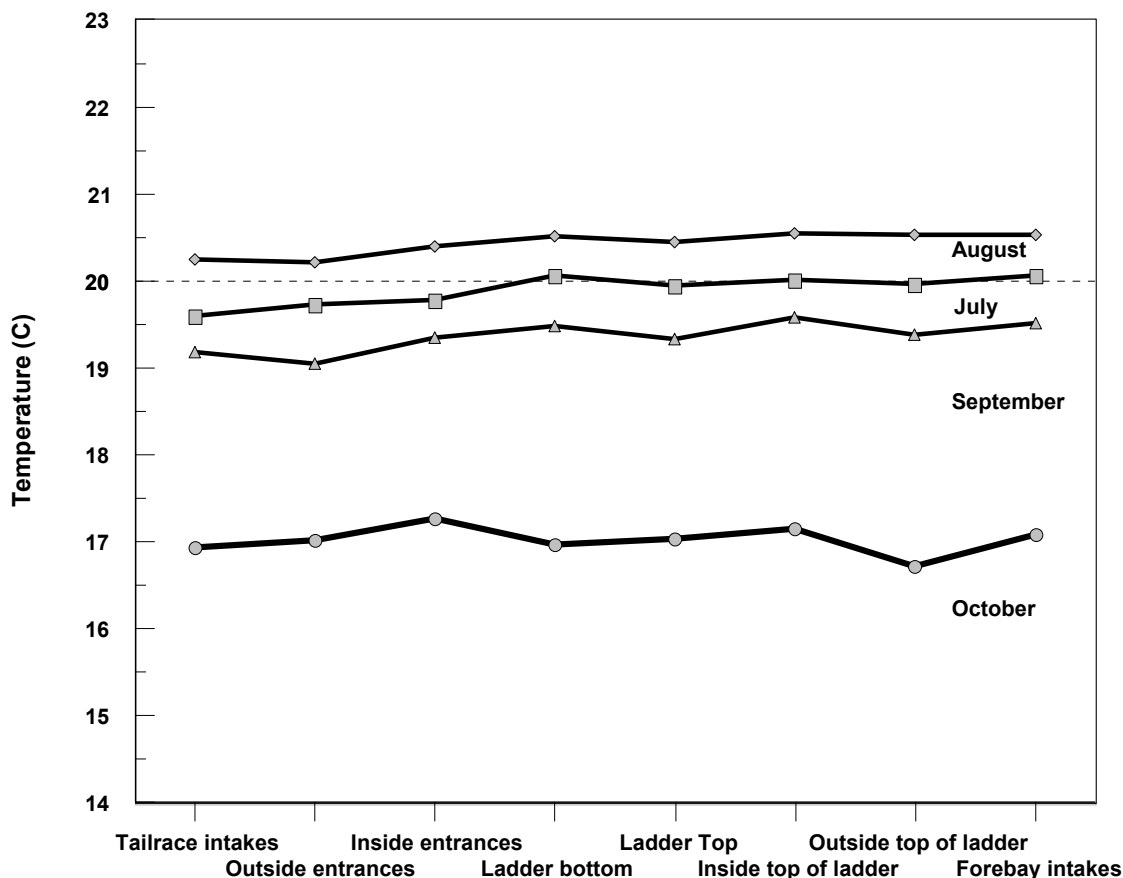


Figure 12. Monthly mean water temperatures measured in and near fishways at Ice Harbor Dam in 1995.

temperatures at the dam at any one time ranged from 0.2 to 1.1°C, averaging 0.6, 0.5, and 0.4°C during July, August, and September. Temperatures were slightly warmer in the north ladder than in the south ladder, although the differences were generally less than 0.5°C between comparable locations.

In 1998, water temperatures were collected hourly at Ice Harbor Dam from 17 June until 30 October (Figure 17). On 1 July, water temperatures at Ice Harbor Dam were between 17.5 and 17.7°C. Temperatures first reached 20°C on 10 July, peaked above 23°C on three occasions; 27 July, 4 August, and 13 August, and dropped below 20°C for the last time on 3 October. Daily maximum water temperatures at the dam averaged 20.8°C ($\pm 0.7^\circ\text{C}$) in July, 22.4°C ($\pm 0.1^\circ\text{C}$) during August, 21.4°C ($\pm 0.3^\circ\text{C}$) during September, and 17.8°C ($\pm 0.6^\circ\text{C}$) during October. By the end of October, water temperatures were around 15°C. There were 86 d when mean temperature somewhere at the dam was 20°C or higher.

During the warmest time of year (9 July to 5 October), water temperatures were fairly uniform at the dam, ranging from 21.3°C in the tailrace, to 21.7°C in the forebay. As opposed to the three previous years, there was not a noticeable increase in

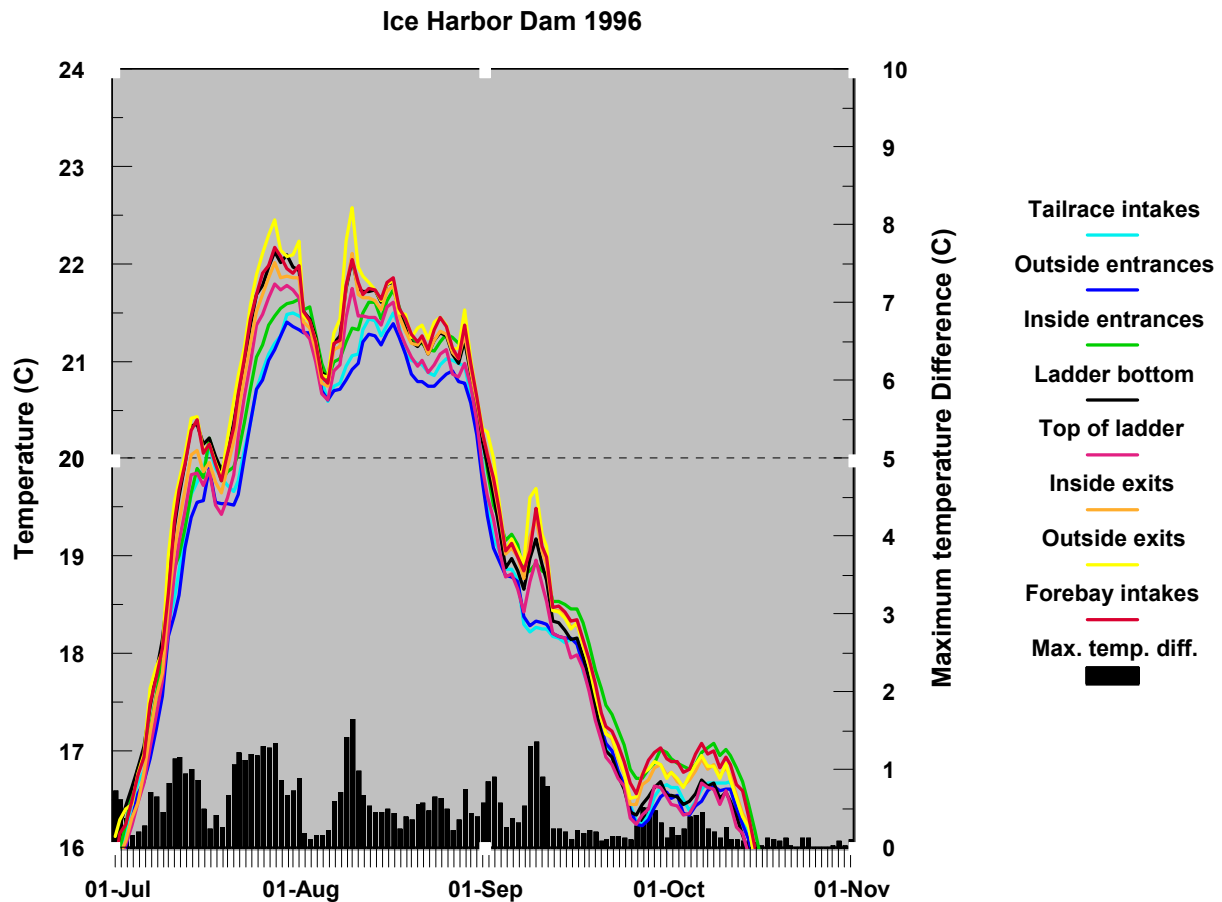


Figure 13. Water temperatures measured in and around fishways at Ice Harbor Dam in 1996.

temperatures as water passed down the main portion of fish ladder (Figure 18). The difference between warmest and coolest water temperatures at the dam at any one time ranged from 0.2 to 1.4°C, averaging 0.4, 0.5, 0.5, and 0.3°C during July, August, September, and October. Temperatures were slightly warmer in the south ladder than in the north ladder, although the differences were generally less than 0.5°C between comparable locations.

Lower Granite Dam.

In 1995, water temperatures were collected hourly at Lower Granite Dam from 4 July until 9 November (Figure 19). In early July, water temperatures at Lower Granite Dam were 17.1 to 17.5°C. Temperatures first reached 20°C on 16 July, peaked above 21°C 18 July and again 25 July, dropped to 17-18°C on 23 August before reaching a

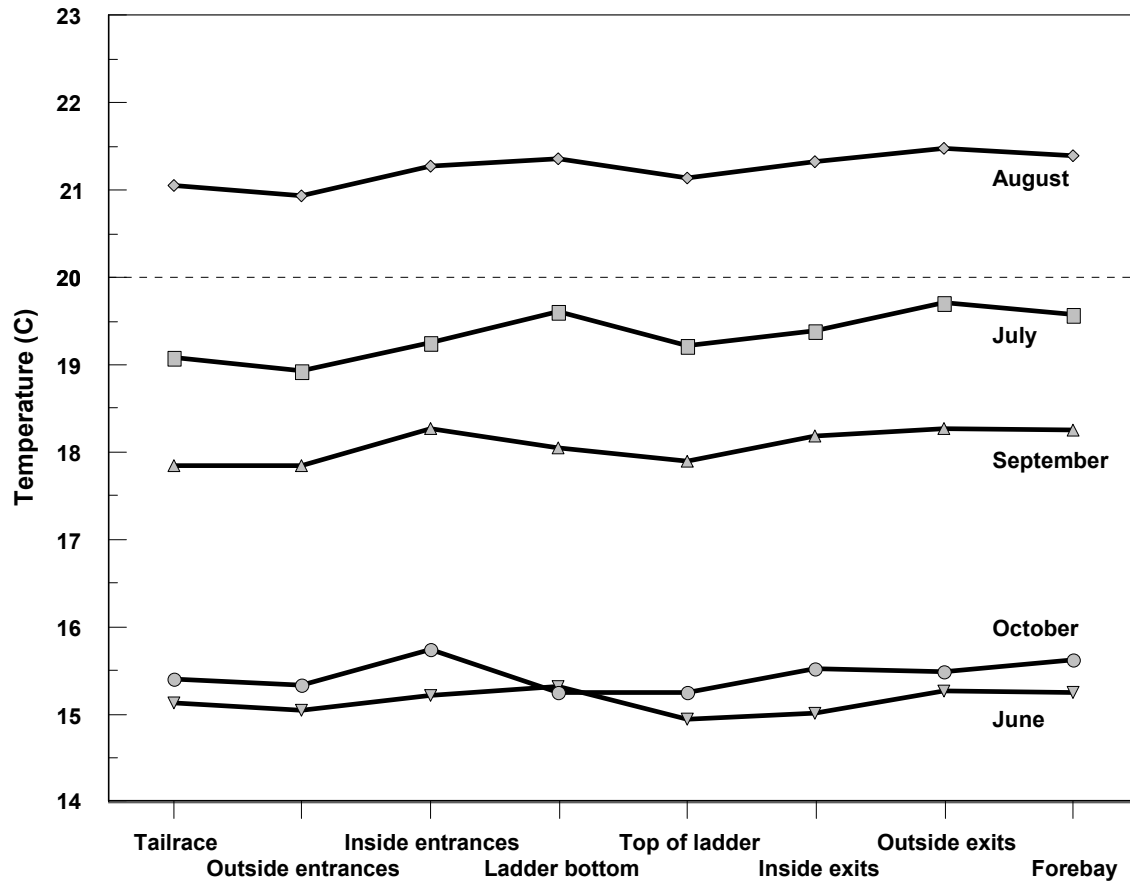


Figure 14. Monthly mean water temperatures measured in and near fishways at Ice Harbor Dam in 1996.

secondary peak at 20.5°C on 12 September. Temperatures dropped below 20°C for the last time 16 September. By the end of October water temperatures at the dam were between 10.0 and 11.0°C and dropping. Daily maximum water temperatures at the dam averaged 19.7 ($\pm 0.5^\circ\text{C}$) in July, 19.3 ($\pm 0.3^\circ\text{C}$) during August, 19.4 ($\pm 0.3^\circ\text{C}$) during September, and 14.6°C ($\pm 0.7^\circ\text{C}$) during October. There were 30 d when the daily mean temperature somewhere in system was 20°C or higher.

Highest water temperatures at the dam were recorded in the forebay, near the water intakes. In the fishway, highest water temperatures were consistently recorded at the base of the ladder and at the transition pool site. The greatest discontinuity in water temperatures occurred between fishway entrances and the transition pool recorder, averaging 0.5 to 0.7°C during July, August and September (Figure 20). The maximum difference in water temperatures recorded within the fishway at any one time (i.e. difference between warmest water in the forebay and coolest water in the tailrace) ranged from 0.3 to 2.1°C, averaging 0.9, 1.0, 0.7, and 0.5°C during July, August, September, and October.

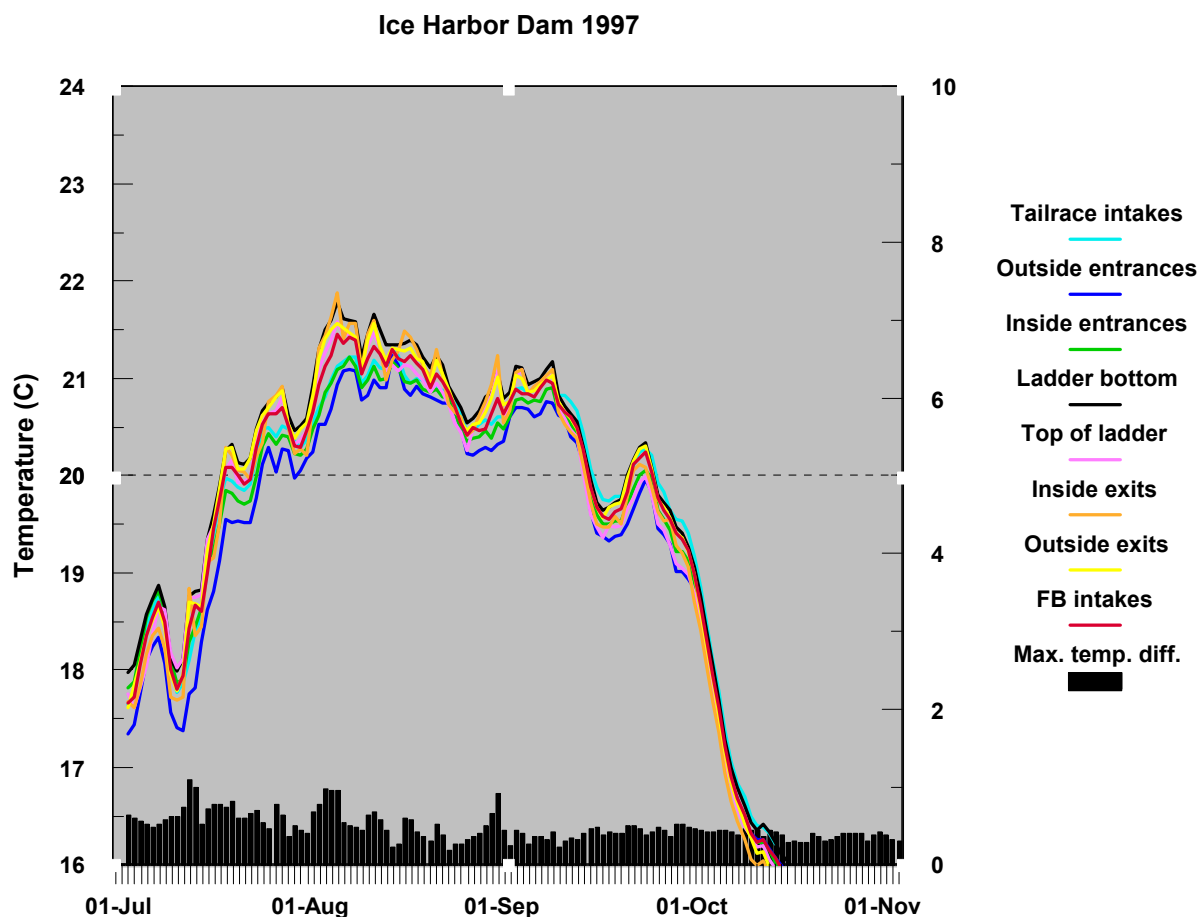


Figure 15. Water temperatures measured in and around fishways at Ice Harbor Dam in 1997.

In 1996, water temperatures were collected hourly at Lower Granite Dam from 2 July until 8 November (Figure 21). At the start of July, water temperatures at Ice Harbor Dam were 16 to 17°C. Temperatures first reached 20°C on 13 July, peaked at 22°C on 28 July, and dropped below 20°C for the last time on 25 August. Daily maximum water temperatures at the dam averaged 20.0 ($\pm 0.5^\circ\text{C}$) in July, 20.2 ($\pm 0.4^\circ\text{C}$) during August, 17.9 ($\pm 0.3^\circ\text{C}$) during September, and 15.4°C ($\pm 0.6^\circ\text{C}$) during October. By the end of October, water temperatures were around 10°C. There were 41 d when mean temperatures somewhere at the dam were 20°C or higher.

Warmest water temperatures were recorded in the forebay of the dam, near the water intake. Water temperatures were similar in the fishway from the transition pool up through the ladder exit. The greatest discontinuity in water temperatures within the fishway occurred between the entrances and the transition pool recorders, averaging 0.7, 1.7, and 0.5°C during July, August and September (Figure 22). The maximum

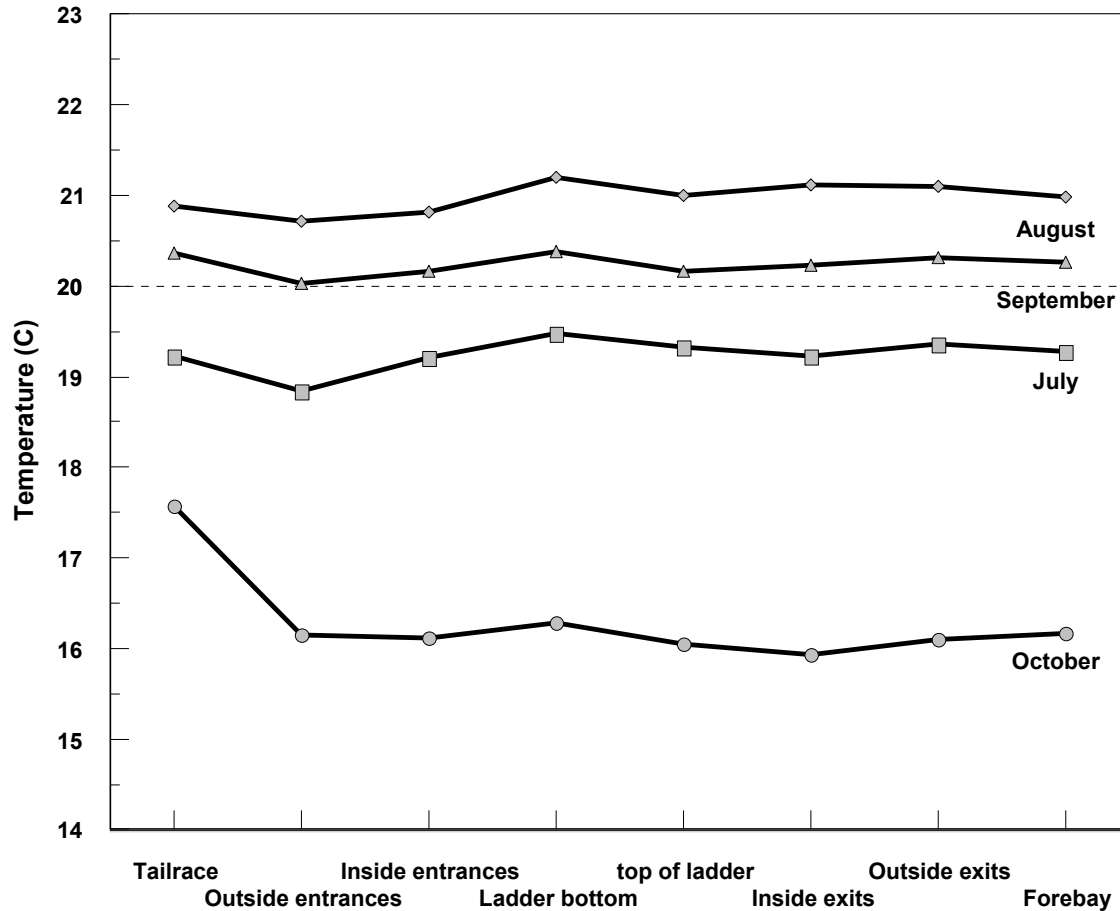


Figure 16. Monthly mean water temperatures measured in and near fishways at Ice Harbor Dam in 1997.

difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 4.4°C, averaging 1.4, 2.0, 0.9, and 0.5°C during July, August, September, and October.

In 1997, water temperatures were collected hourly at Lower Granite Dam from 1 July until 4 November (Figure 23). At the start of July, water temperatures at Lower Granite Dam were 17.0 to 17.5°C. Temperatures first reached 20°C on 3 August, peaked at 22.6°C on 9 September, and dropped below 20°C for the last time on 19 September. Daily maximum water temperatures at the dam averaged 18.8°C ($\pm 0.3^\circ\text{C}$) in July, 20.2°C ($\pm 0.2^\circ\text{C}$) during August, 20.9°C ($\pm 0.5^\circ\text{C}$) during September, and 15.4°C ($\pm 0.7^\circ\text{C}$) during October. By the end of October, water temperatures were around 11.5 to 12.0°C. There were 39 d when mean temperature somewhere at the dam was 20°C or higher.

During the warmest time of year (August and September) water temperatures were uniform though the ladder with no consistent trend for warming or cooling of water in the

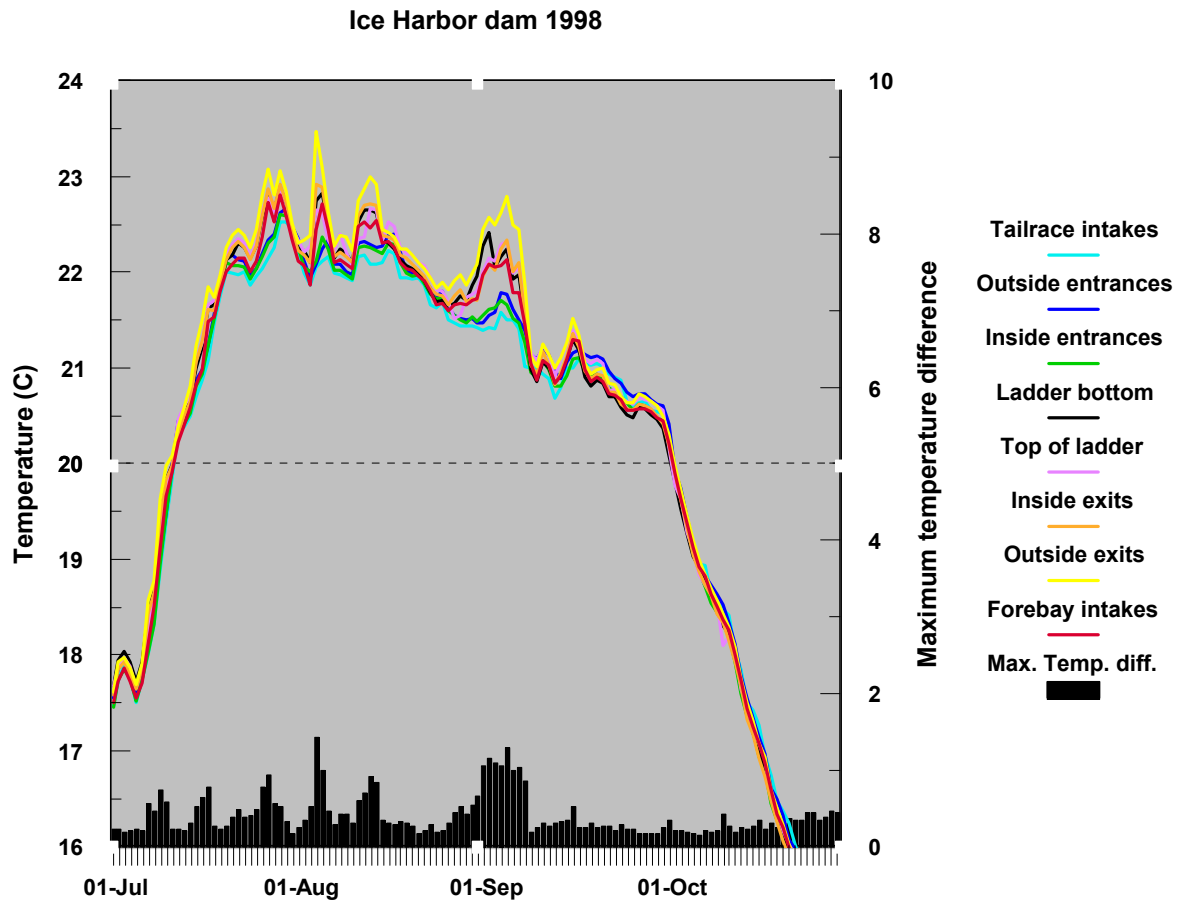


Figure 17. Water temperatures measured in and around fishways at Ice Harbor Dam in 1998.

fishway (Figure 24). The maximum difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 2.0°C, averaging 0.9, 1.0, 0.6, and 0.6°C during July, August, September, and October.

In 1998, water temperatures were collected hourly at Lower Granite Dam from 19 June until 29 October (Figure 25). At the start of July, water temperatures at Lower Granite Dam were 14.5 to 15.0°C. Temperatures first reached 20°C on 9 July, peaked at 24°C on 26 July, and dropped below 20°C for the last time on 1 October. Daily maximum water temperatures at the dam averaged 21.0°C ($\pm 0.6^\circ\text{C}$) in July, 21.8°C ($\pm 0.3^\circ\text{C}$) during August, 22.1°C ($\pm 0.3^\circ\text{C}$) during September, and 16.2°C ($\pm 0.8^\circ\text{C}$) during October. By the end of October, water temperatures were in the range of 12.0 to 12.6°C. There were 86 d when the daily mean temperature somewhere at the dam was 20°C or higher.

During the warmest time of year (6 July until 2 October) water temperatures were warmest at the forebay intakes and in the ladder down to the transition pool (Figure 26).

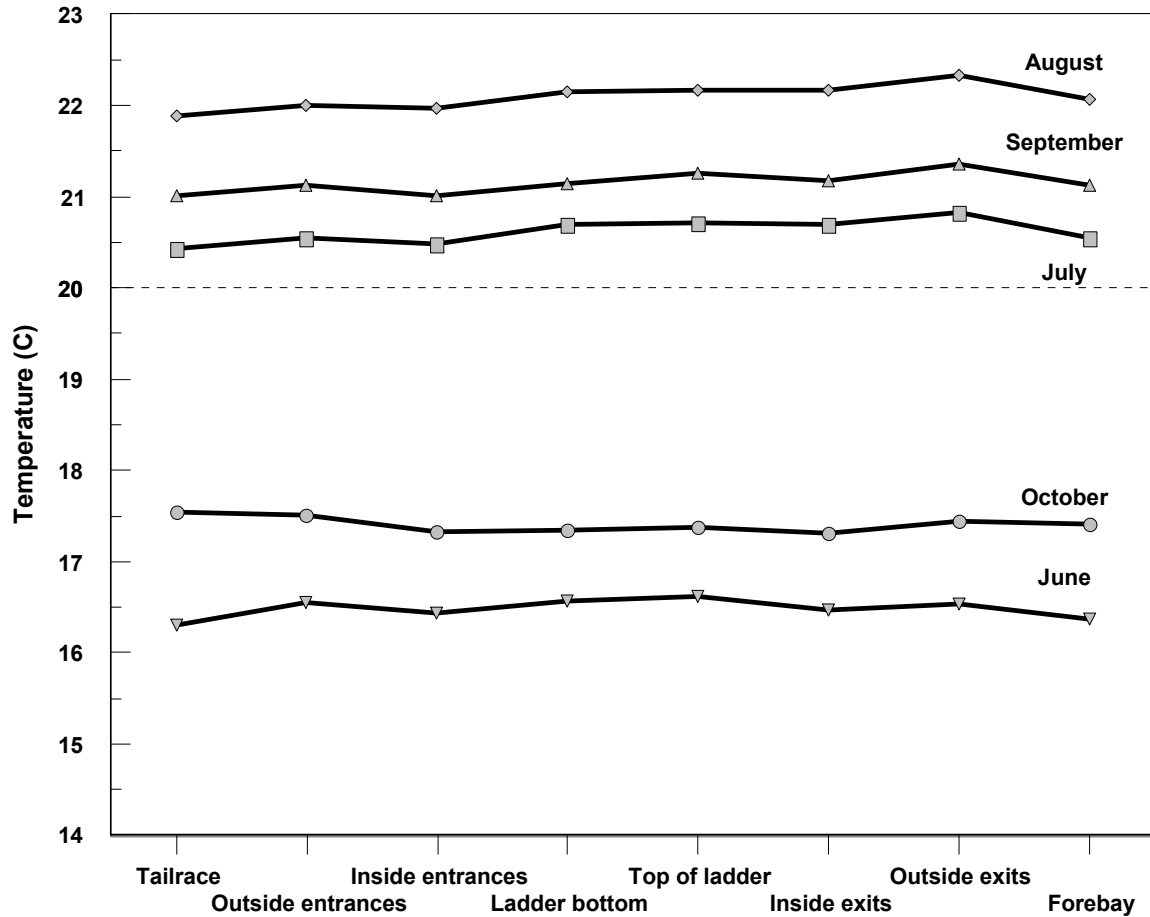


Figure 18. Monthly mean water temperatures measured in and near fishways at Ice Harbor Dam in 1998.

The maximum difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 4.5°C, averaging 1.6, 2.0, 1.1, and 1.1°C during July, August, September, and October.

Forebay Temperature Profiles

Ice Harbor Dam.

In 1995, 12 temperature surveys were completed between 12 July and 28 September. On 12 July, water temperatures were generally 19.0°C in the forebay, reaching 19.7°C near the water surface (Figure 27). By 20 July, temperatures throughout the water column were 20°C or warmer, ranging from 21.4°C near the surface to 20.1°C at 30 m depth. Peak water temperatures were recorded during the 28 July and 2 August surveys, ranging from about 21°C at 30 m depth up to 23°C at the surface. Near the water surface, temperatures remained at or above 20°C until the last survey on 28 September when temperatures were homothermic through the water

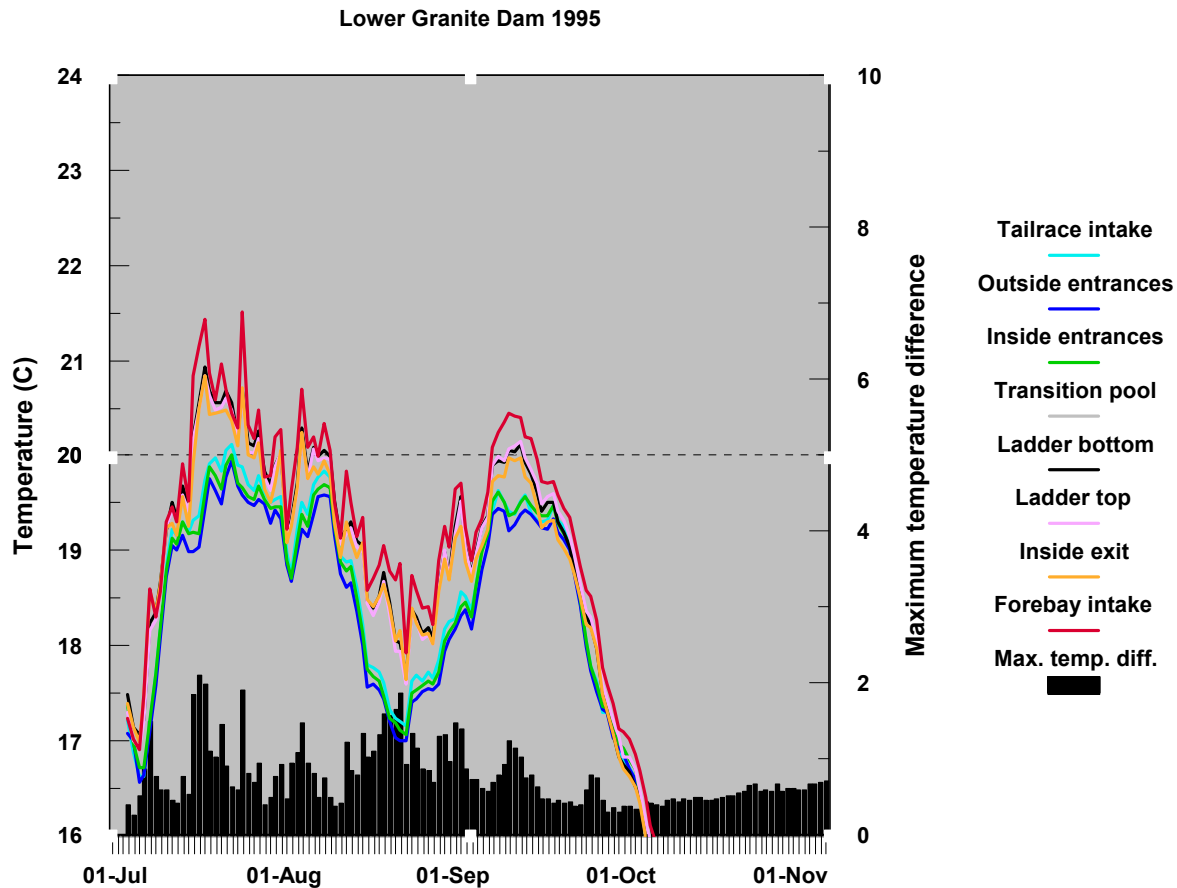


Figure 19. Water temperatures measured at in and around fishways at Lower Granite Dam in 1995.

column near 18.5°C. Temperatures at depths greater than 6 m remained near 20°C through the 25 August survey, after which temperatures were around 19°C until the last survey. The largest difference in temperatures between surface and deep water ranged from 0.1 to 3.0°C. In general the greatest variation in water temperatures occurred in the top 6 m of water.

In 1996, seven temperature surveys were completed between 5 July and 27 September. On 5 July, water temperatures were 16.5 to 17.0°C below 6 m depth, and near 18°C near the surface (Figure 28). By 20 July, temperatures throughout the water column were at or above 20°C, ranging around 20°C below 6 m depth and up to 21.4°C at the surface. Peak water temperatures were recorded during the 31 July survey, ranging from 21.5°C at 30 m depth up to 24.5°C at the surface. Water temperatures remained above 20°C until the 13 September survey, at which time water temperatures throughout the water column were 18 to 19°C. Differences in temperature between surface and water deep in the reservoir ranged from 0.7 up to 3.0°C.

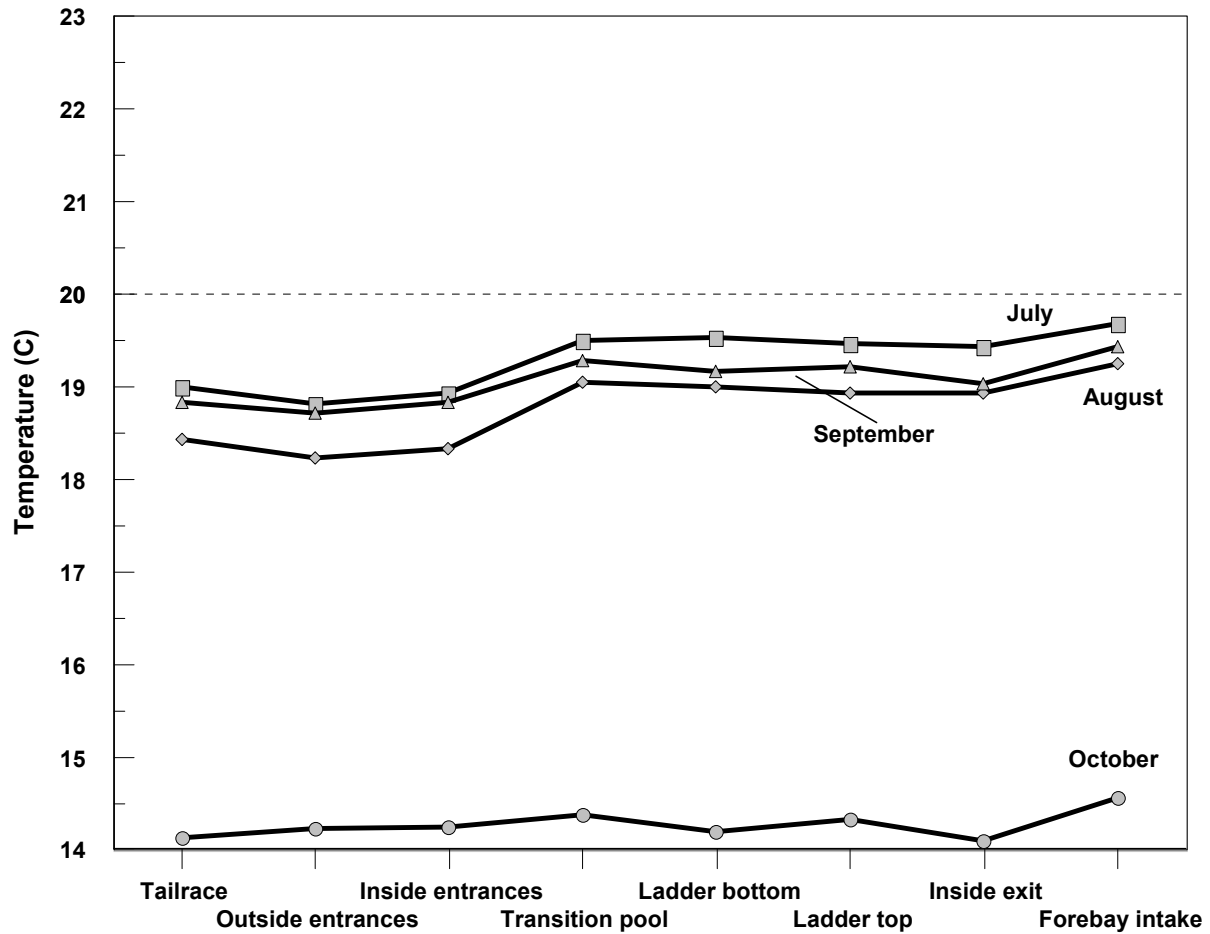


Figure 20. Monthly mean water temperatures measured in and near fishways at Lower Granite Dam in 1995.

In 1997, seven temperature surveys were completed in the forebay of Ice Harbor Dam between 3 July and 30 September. On 3 July, water temperatures were between 17.5 and 18.0°C below 6 m depth, and up to 19.2°C near the surface (Figure 29). By 17 July, temperatures near the surface had exceeded 20°C, and remained so until the last survey on 30 September. Water temperatures at depth exceeded 20°C from 1 August through the 12 September survey. Peak water temperatures were recorded during the 14 August survey, ranging from a low of 20.8°C at 30 m depth up to 21.5°C near the surface. Changes in temperature with depth ranged from 0.0 to 1.7°C through the summer. By 30 September, water temperatures were 19.2 to 19.4°C in the forebay.

In 1998, seven temperature surveys were completed in the forebay of Ice Harbor Dam between 9 July and 8 October. Temperatures near the water surface exceeded 20°C for all but the last survey, reaching 21.8 to 24.4°C (Figure 30). Temperatures at depths deeper than 6 m were around 19°C on 9 July, and then exceeded 20°C on all

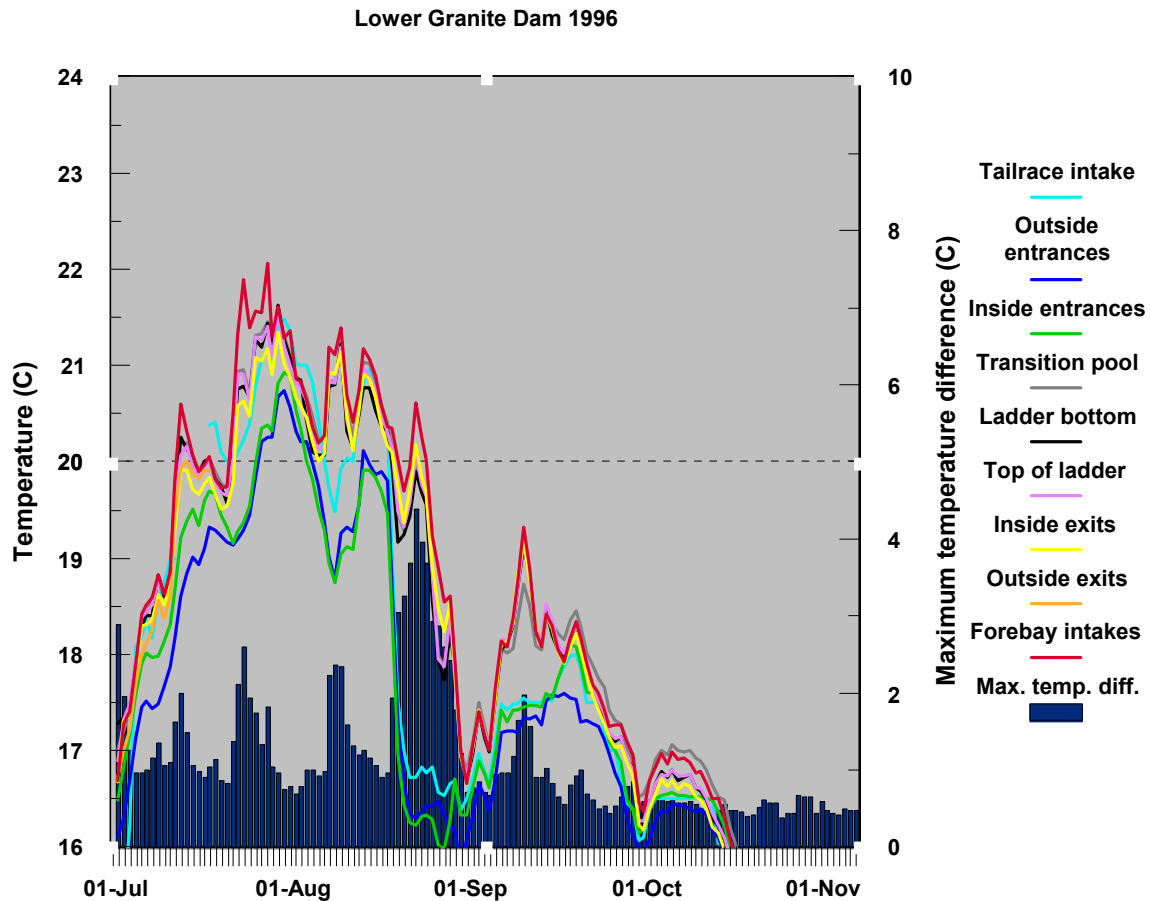


Figure 21. Water temperatures measured at in and around fishways at Lower Granite Dam in 1996.

but the last survey. During the last survey on 8 October, water temperatures through the water column were 18.6 to 18.7°C. Differences in temperature through the water column ranged from 1.5 to 3.2°C through September.

Lower Granite Dam.

In 1995, 10 temperature surveys were completed between 11 July and 15 September. Water temperatures near the surface in the forebay were near or exceeding 20°C through the summer, except during the 24 August survey when temperatures were to 19.1°C (Figure 31). Below 6 m depth, water temperatures were in the range of 19.5 to 20°C during the 26 July and 10 August surveys, otherwise temperatures at depth were below 20°C. Differences in temperature at the water surface and at 30 m depth ranged from 1 to 4°C during the year. There appeared to be little effect on temperatures in the forebay of Lower Granite Dam from water released

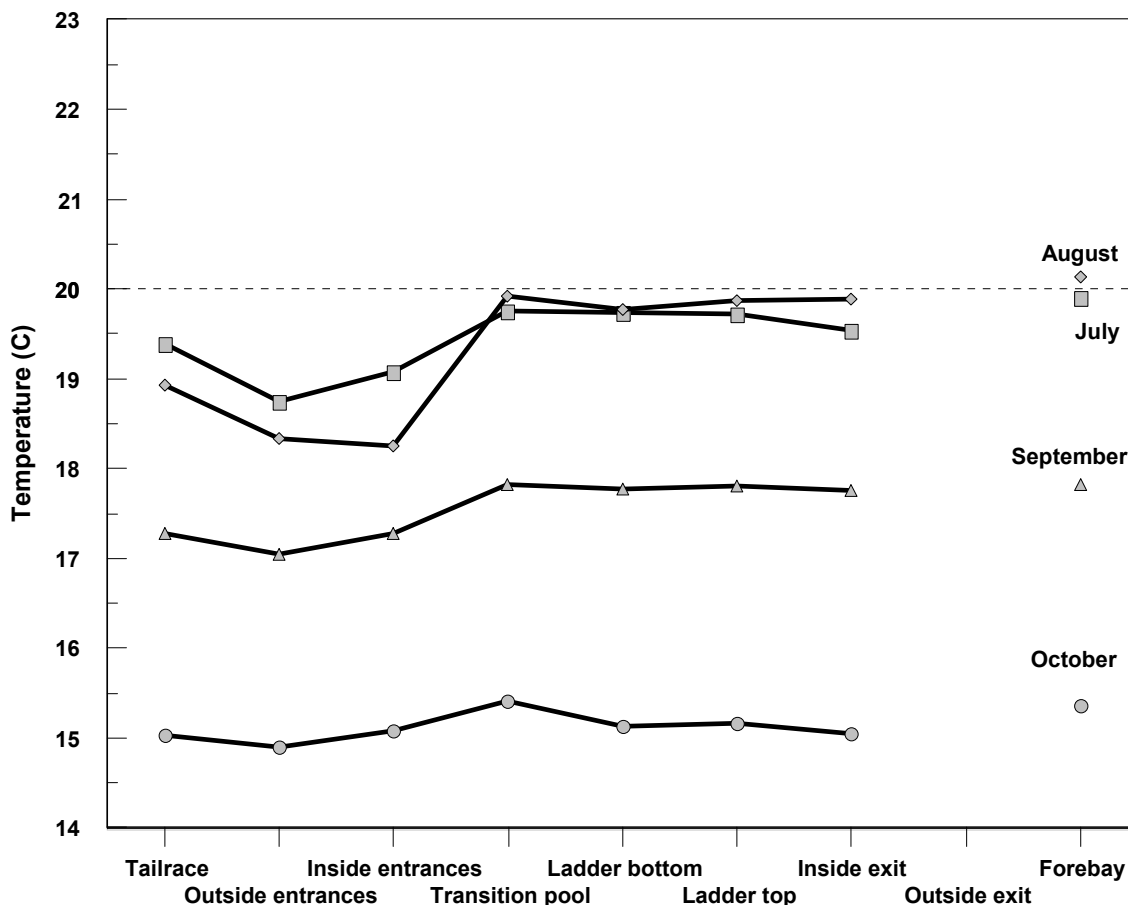


Figure 22. Monthly mean water temperatures measured in and near fishways at Lower Granite Dam in 1996.

from Dworshak Dam, which were set at about 13 to 14 kcfs from mid July through August, although water deep in the reservoir did not exceed 20°C during the summer.

In 1996, seven temperature surveys were completed between 4 July and 25 September. On 4 July, water temperatures through the water column ranged 16.6 to 17.8°C (Figure 32). Temperatures near the surface were near or exceeded 20°C for the next four surveys, from 18 July through 29 August, after which temperatures were cooler. At depths deeper than 6 m, temperatures were near 20°C on 18 July, 3 August, and 14 August, otherwise water temperatures below 20 m were 18.5°C or cooler. Differences in temperatures of surface and deep water were greatest on 14 August (2.4°C) and 29 August (3.7°C). The drop in forebay water temperatures at the end of August coincided with period of peak flows (20-22 kcfs) from Dworshak reservoir.

In 1997, seven temperature surveys were completed in the forebay of Lower Granite Dam between 7 July and 6 October. On 7 July, water temperatures through the water column were between 17.1 and 18.3°C (Figure 33). By 25 July, temperatures near the surface had reached 19.6°C, and temperatures near the surface exceeded 20°C

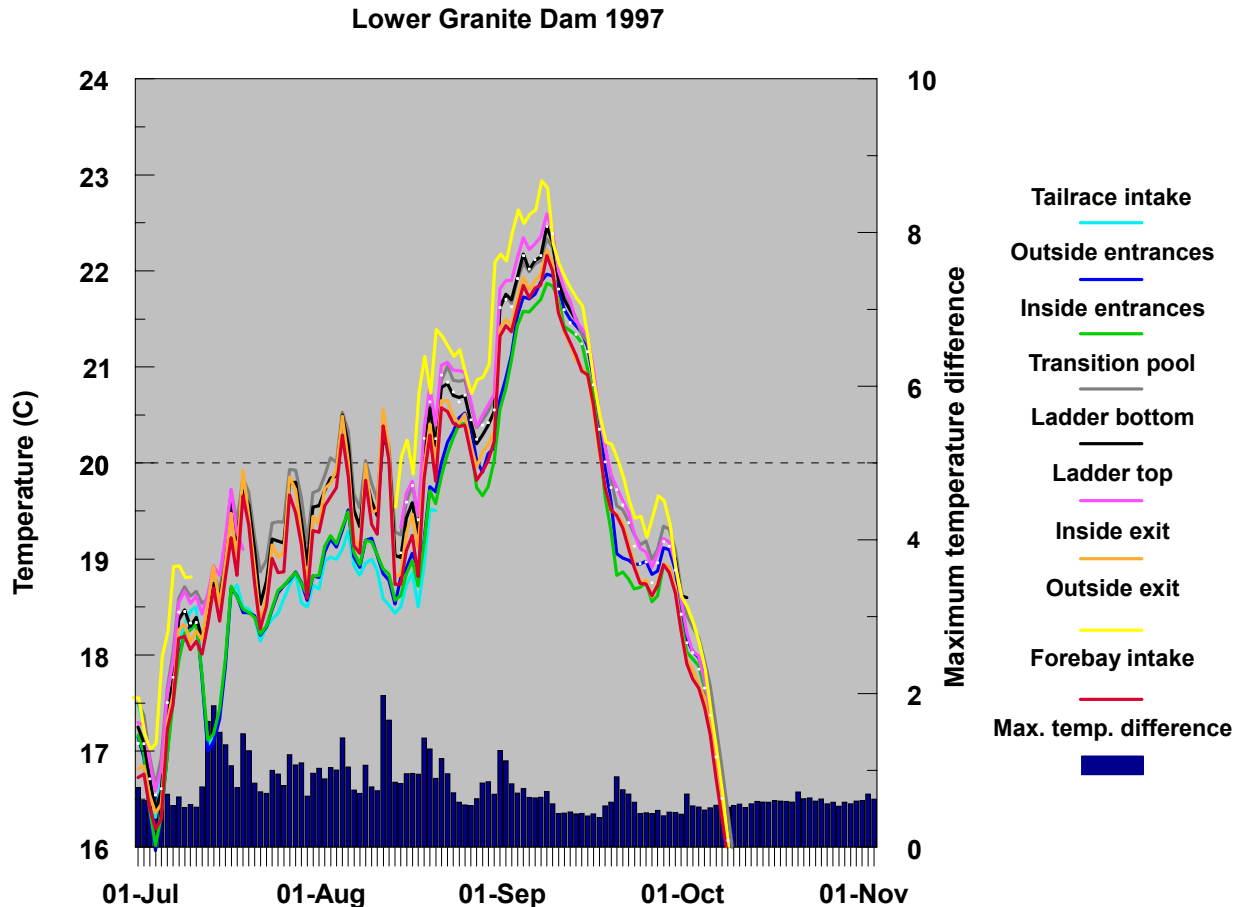


Figure 23. Water temperatures measured in and around fishways at Lower Granite Dam in 1997.

through the 16 September survey. Below 6 m, water temperatures exceeded 20°C during the 25 August and 16 September surveys, otherwise temperatures at depth were less than 20°C in the forebay. The rise in deep water temperatures to nearly 20°C coincided with a drop in flows from Dworshak reservoir below the 20 kcfs level.

In 1998, eight temperature surveys were completed in the forebay of Lower Granite Dam between 7 July and 7 October. Surface water temperatures exceeded 20°C during all but the last survey in October, peaking at nearly 25°C 14 July (Figure 34). Temperatures at depths greater than 6 m were 19.5°C or warmer for all except the first (7 July) and last (7 October) surveys. The difference between the warmest temperatures near the surface and coolest water temperatures at a depth of 30 m ranged from 2.1 to 5.3°C through the 1 September survey, after which temperatures were relatively homothermic. Significant flow releases from Dworshak reservoir were halted in late August.

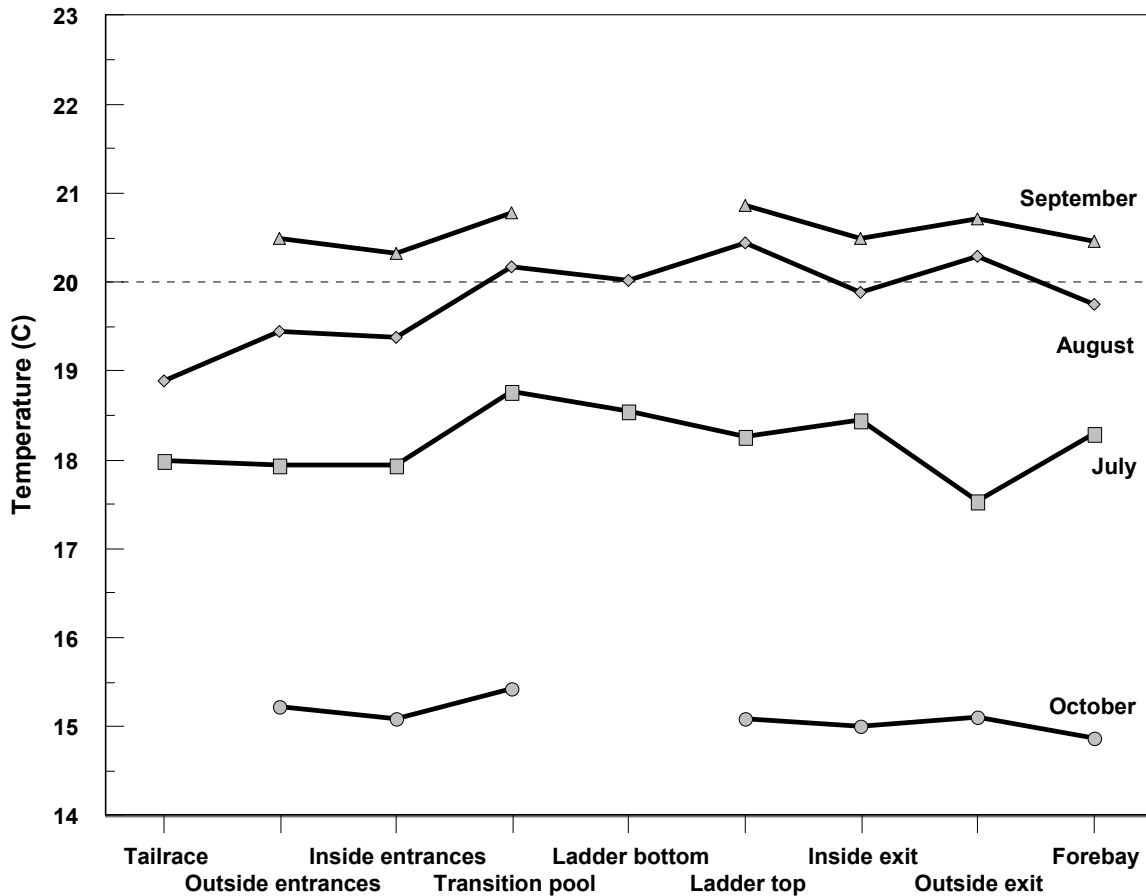


Figure 24. Monthly mean water temperatures measured in and near fishways at Lower Granite Dam in 1997.

Factors Affecting Fishway Temperatures.

Air temperatures (mean from 6-8 d prior), Snake River flow, and amount of flow released from Dworshak reservoir (6 d prior) were all significantly related to water temperatures recorded in the forebay of Lower Granite Dam (Figure 35). When each of the eight years of data were tested separately, the combination of variables that produced the best fitting model varied slightly (r^2 values all > 0.9). Overall, air temperature was the most prominent variable included in the models (8 of 8 years) followed by Snake River flow at Lower Granite Dam (7 years), flow from Dworshak Dam (6 years), and month (5 years). We next analyzed the data for each month separately across the eight years. For June, the best model included only Snake River flow at Lower Granite Dam ($r^2 = 0.4528$, $P = 0.04$). For the remaining four months, July-October, regression models included air temperature, Dworshak flow, and Snake River flow (all but August) and in many cases the squares of these variables. With all months combined, the best fitting model included month, air temperature, Snake River flow, Dworshak flow, and the squared values of air temperature and Snake River flow. When

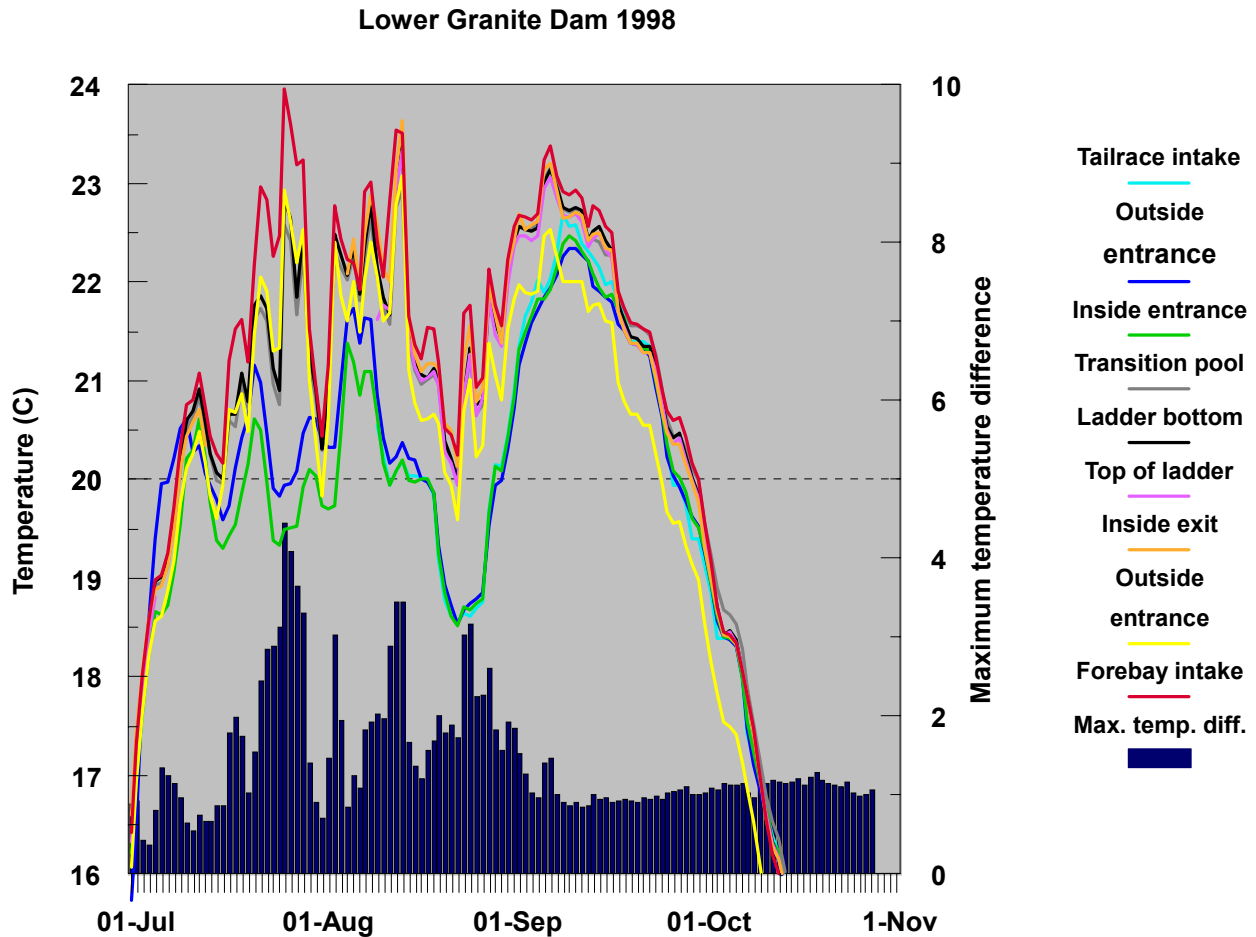


Figure 25. Water temperatures measured in and around fishways at Lower Granite Dam in 1998.

June was excluded from analysis, the best fitting model included air temperature, the square of air temperature, Snake River flow, and Dworshak flow ($r^2 = 0.9389$, $P < 0.0001$), month was no longer significant. We feel this last model;

$$GR_{temp} = AIR_{temp}(1.341) + AIR_{temp}^2(-0.0196) + SNR_{flow}(-0.0436) + DW_{flow}(-0.0871) + 2.58$$

best characterized factors influencing water temperatures at Lower Granite Dam during warm water conditions (see Appendix B for residual plots). From this model we estimate that water temperatures in the forebay at Lower Granite Dam during summer can be decreased by 1 to 3°C, when releases from Dworshak reservoir reach 50% to 60% of Snake River flows at the dam, depending on river flow and air temperature levels (Figure 36).

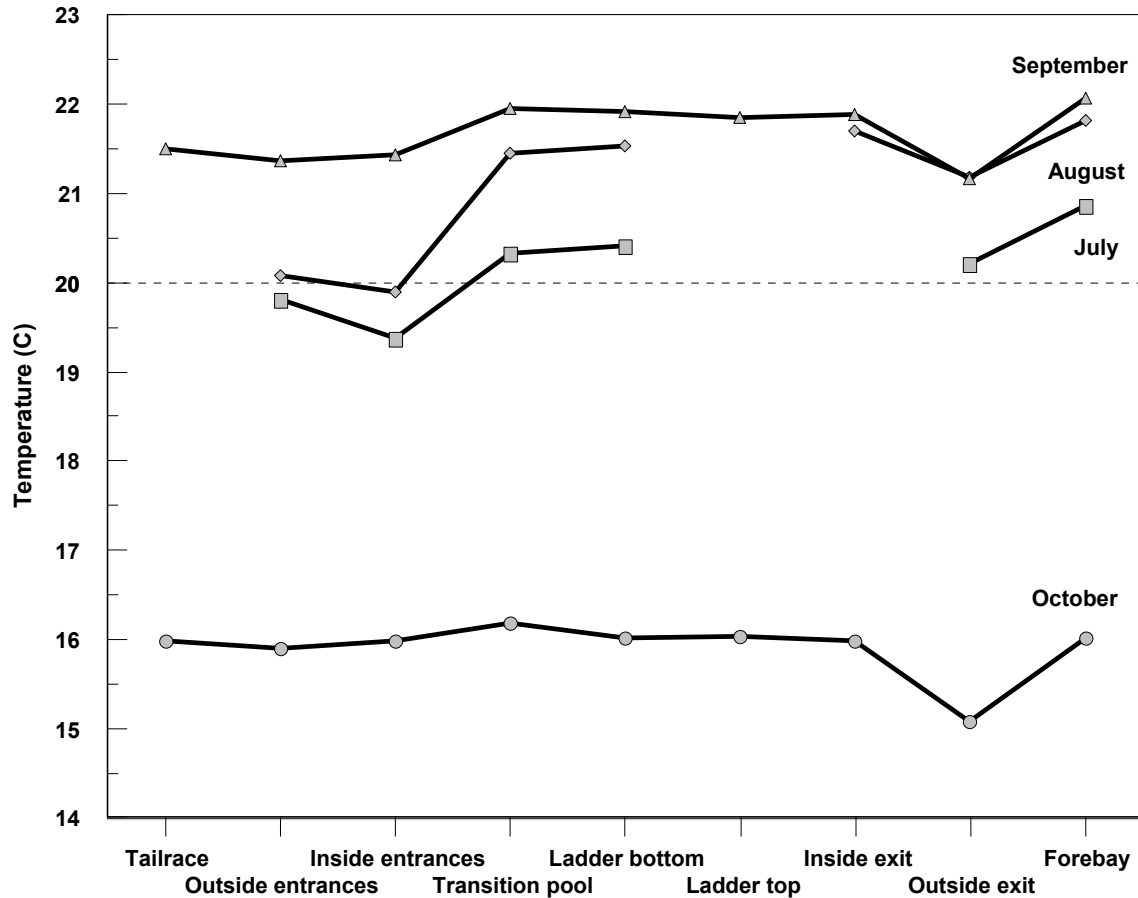


Figure 26. Monthly mean water temperatures measured in and near fishways at Lower Granite Dam in 1998.

Affects of Water Temperature on Fish Passage

Telemetry data

In 1997 and 1998, there were 71 and 91 summer and fall chinook salmon with complete travel times between McNary and Ice Harbor dams (2 were fall chinook salmon in 1997, 25 in 1998). During the period these fish traveled between the two dams, water temperatures went from 13°C to 21°C in 1997 and from 15 to 23°C in 1998 (Figure 37). Median time from when the salmon left McNary Dam until they arrived in the tailrace at Ice Harbor Dam was 1.1 d in 1997 (ranged 0.8 to 8.0 d) and 1.0 d (0.7 to 3.9 d) in 1998. Travel times in 1997 were not related to water temperatures at McNary (regression $P = 0.445$) or Ice Harbor ($P = 0.493$) dams at the time fish left McNary Dam, nor were they related to the difference in temperatures at the two dams ($P = 0.853$). Most of these fish had migrated through the area by the middle of July, prior to the onset of warm water conditions. In 1998, travel times were again not related to water

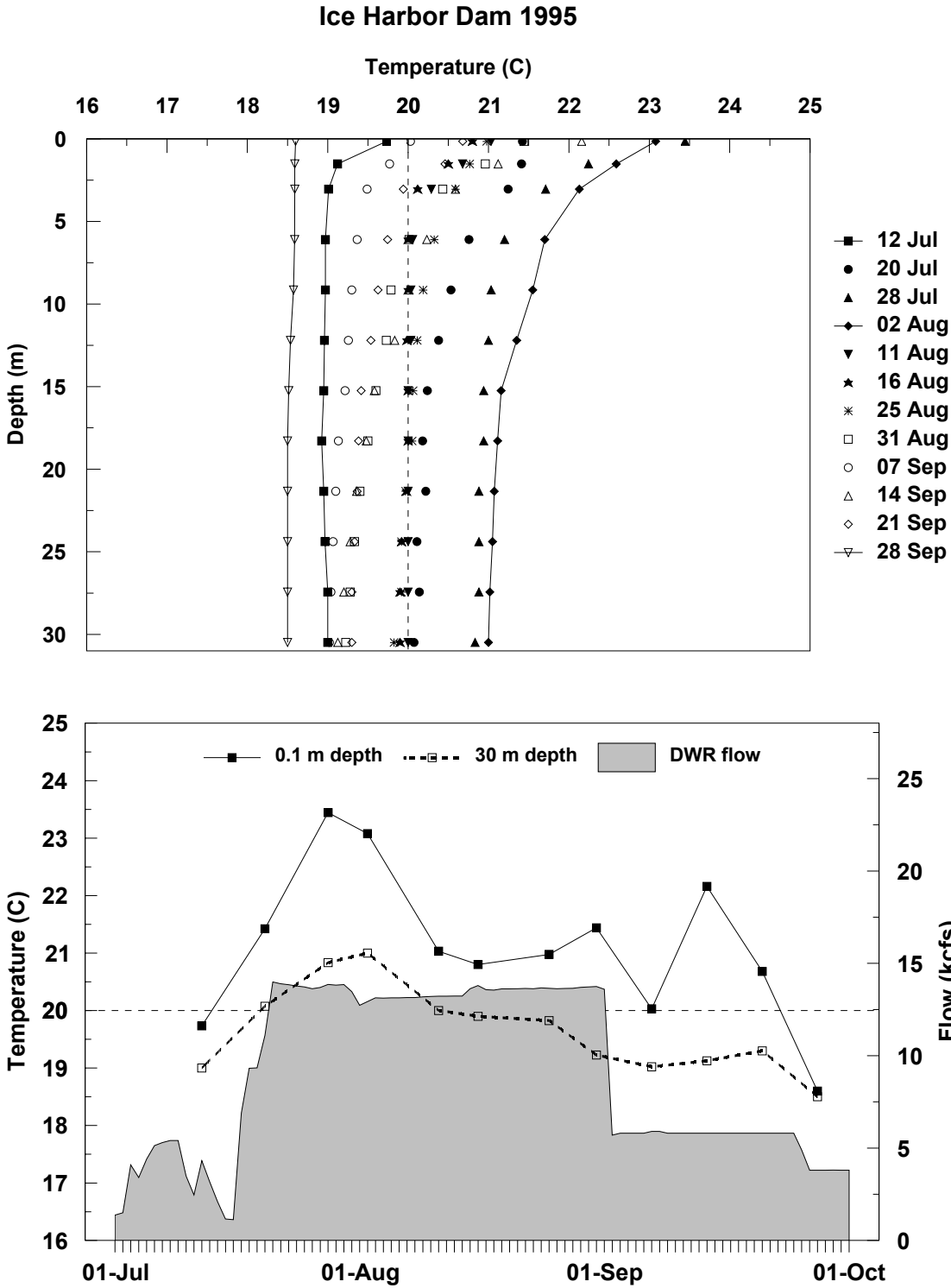


Figure 27. Temperature-depth profiles in forebay of Ice Harbor Dam in 1995 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1995 (bottom).

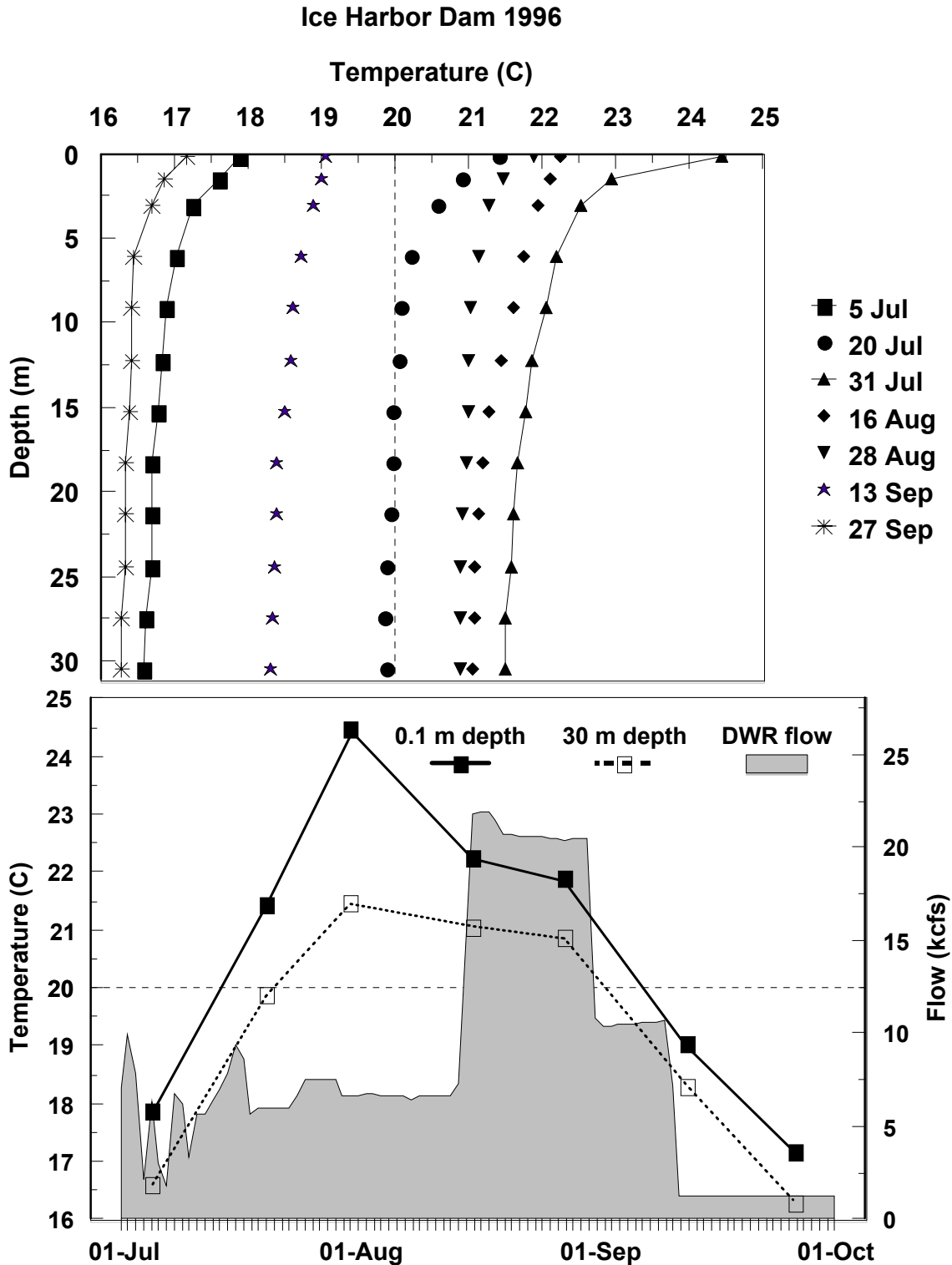


Figure 28. Temperature-depth profiles in forebay of Ice Harbor Dam in 1996 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1996 (bottom).

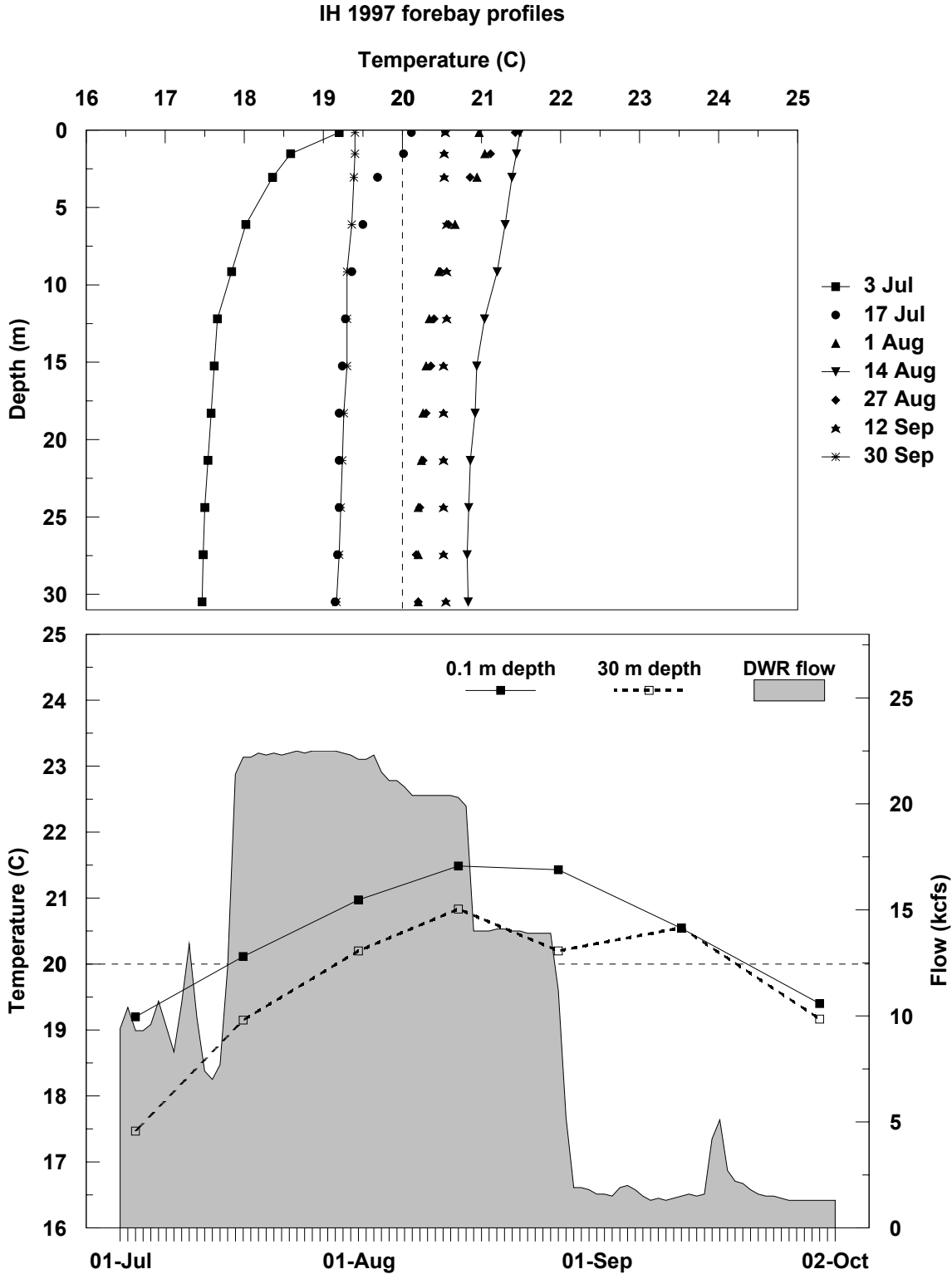


Figure 29. Temperature-depth profiles in forebay of Ice Harbor Dam in 1997 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1997 (bottom).

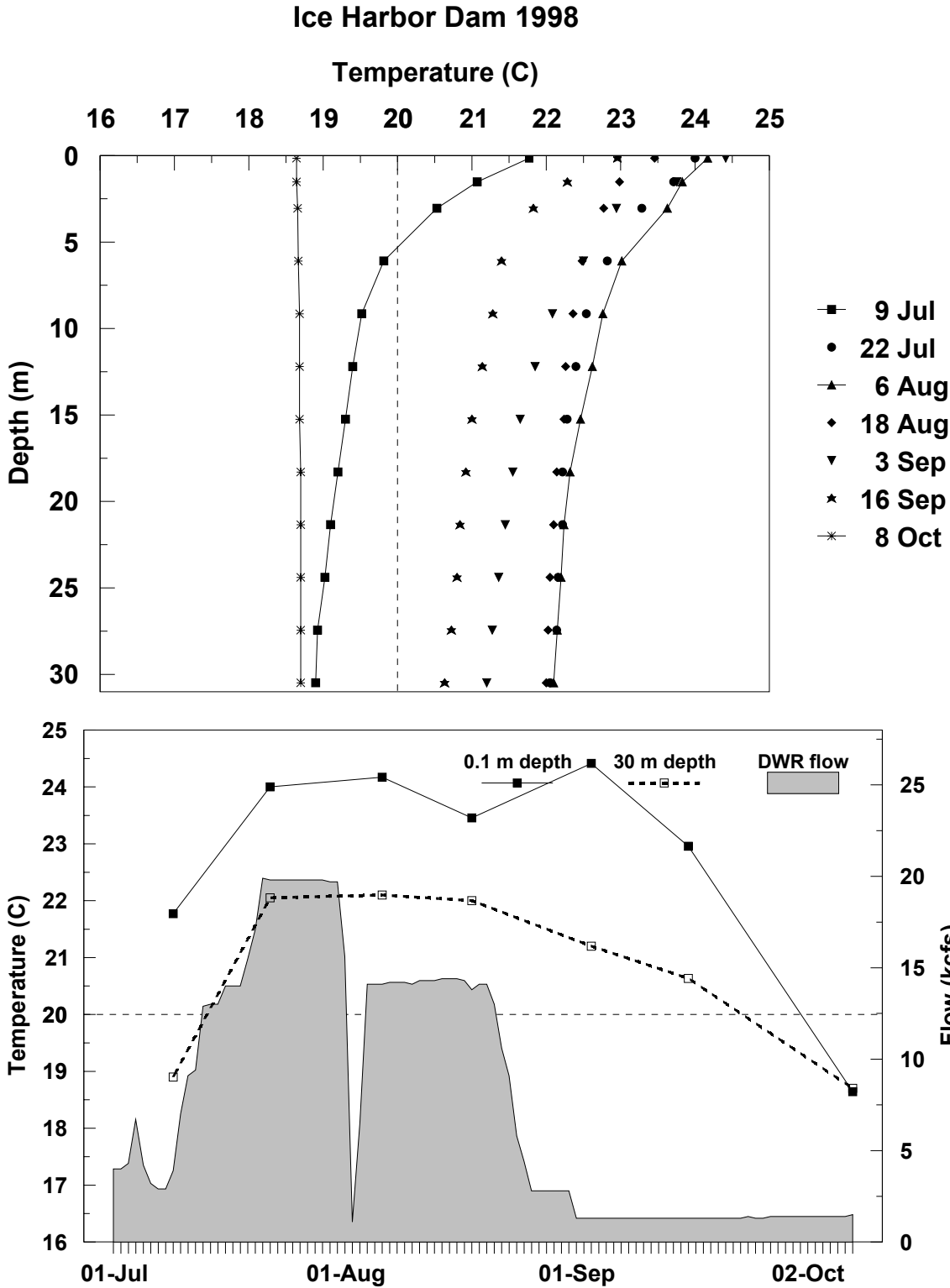


Figure 30. Temperature-depth profiles in forebay of Ice Harbor Dam in 1998 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1998 (bottom).

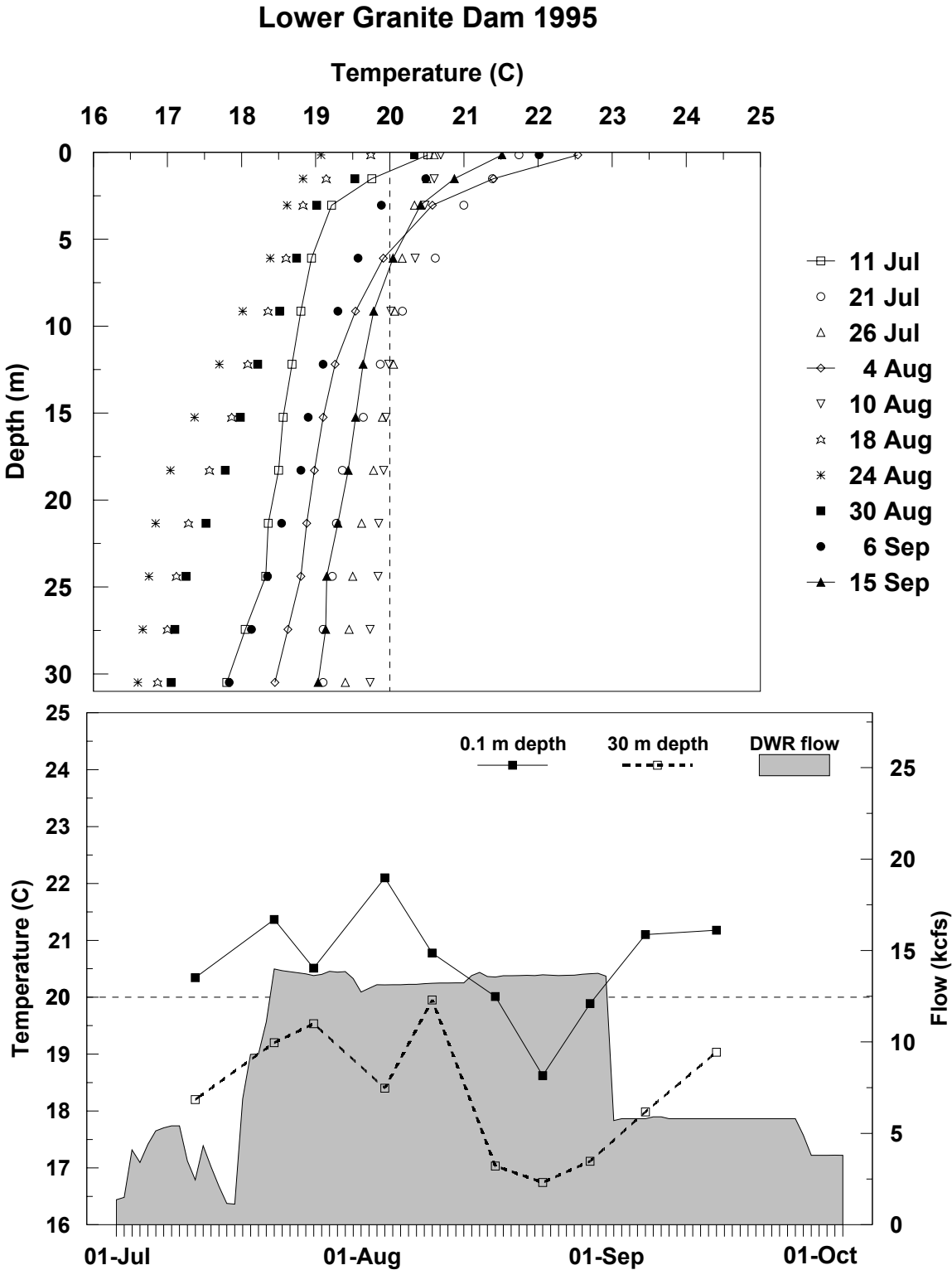


Figure 31. Temperature-depth profiles in forebay of Lower Granite Dam in 1995 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam Reservoir in 1995 (bottom).

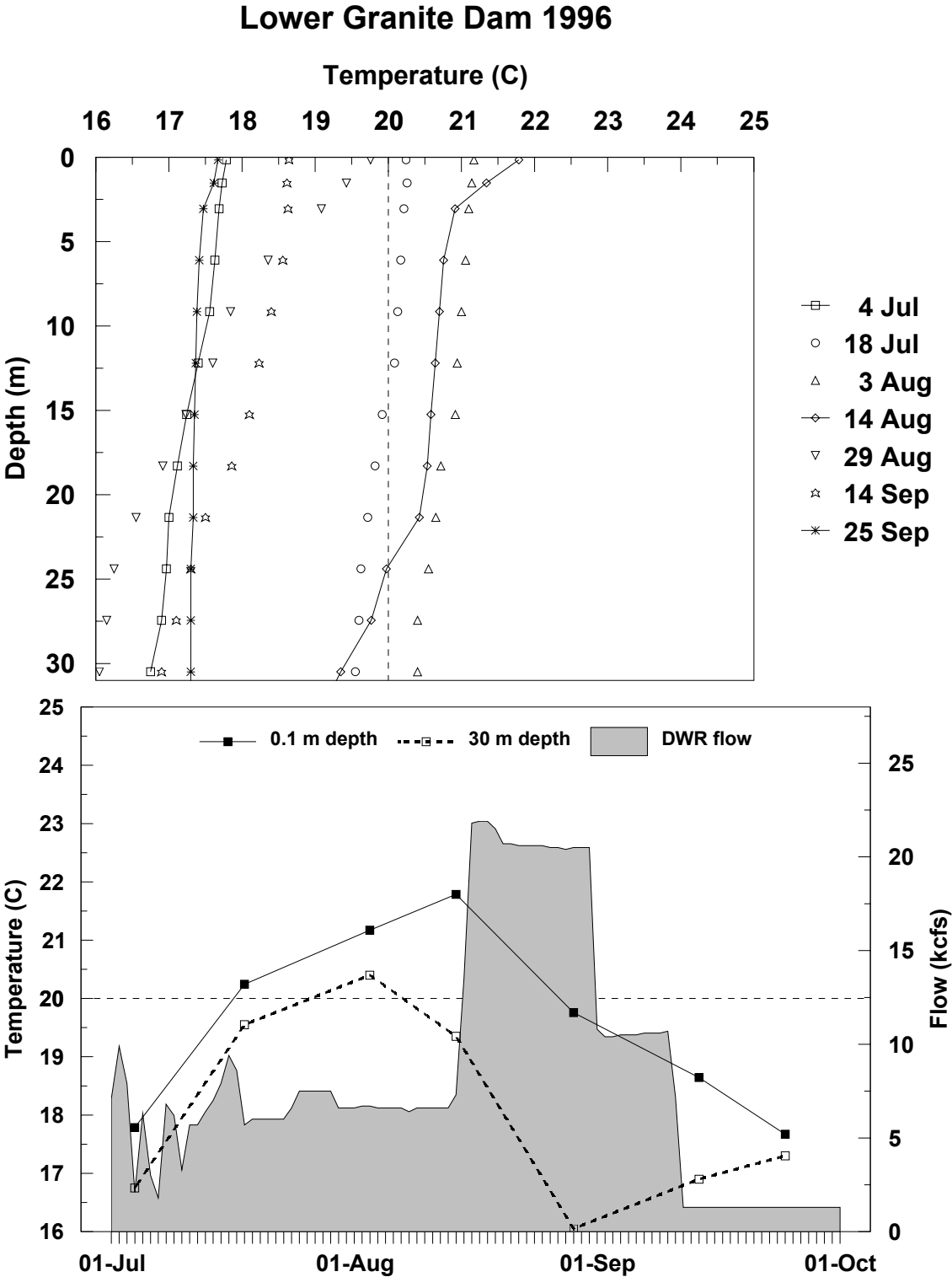


Figure 32. Temperature-depth profiles in forebay of Lower Granite Dam in 1996 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1996 (bottom).

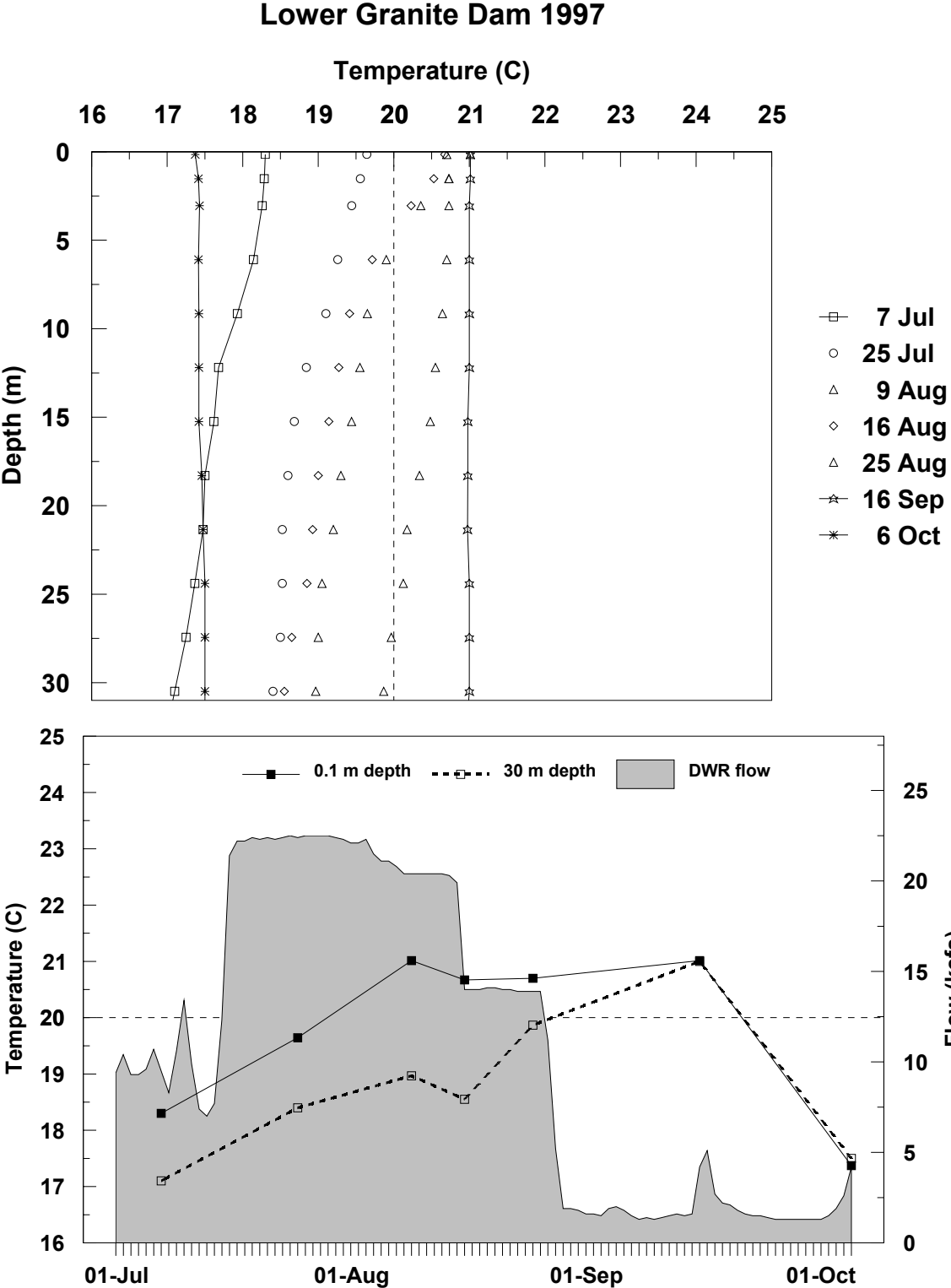


Figure 33. Temperature-depth profiles in forebay of Lower Granite Dam in 1997 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir (DWR) in 1997 (bottom).

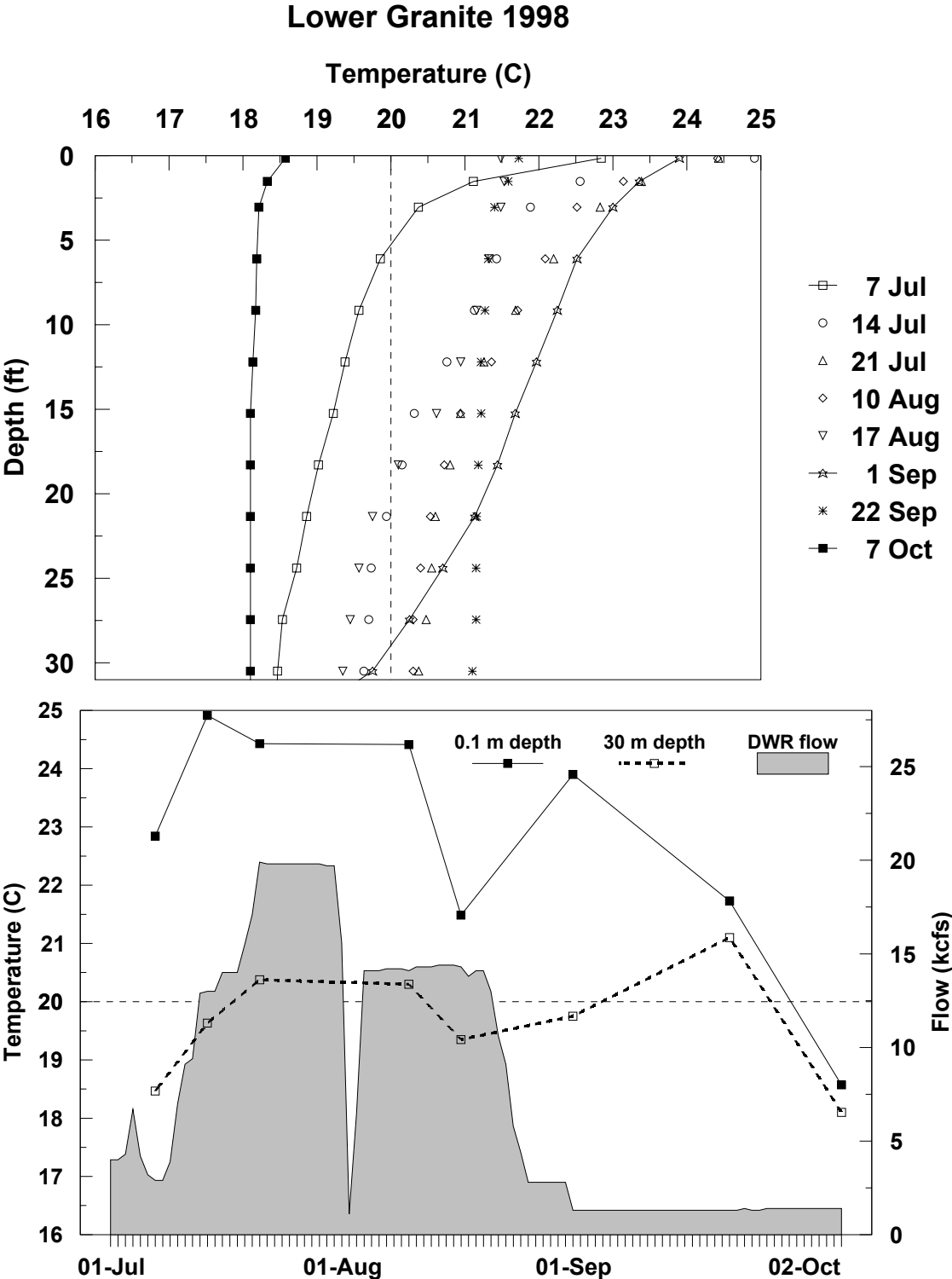


Figure 34. Temperature-depth profiles in forebay of Lower Granite Dam in 1998 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir (DWR) in 1998 (bottom).

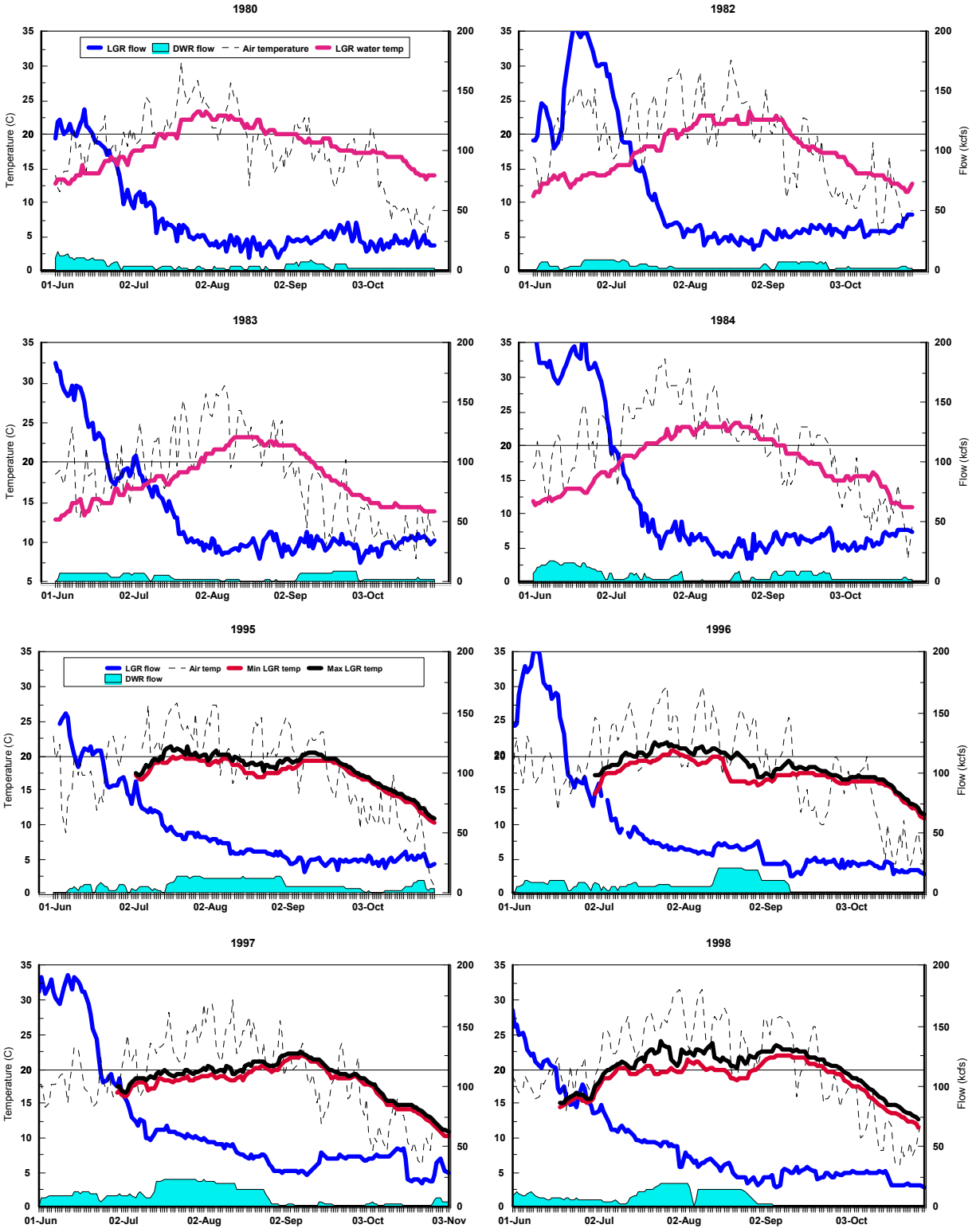


Figure 35. Water temperatures and flow at Lower Granite Dam, flow from Dworshak reservoir, and air temperature at Lewiston, Idaho during four years in the 1980's and four years in 1990's.

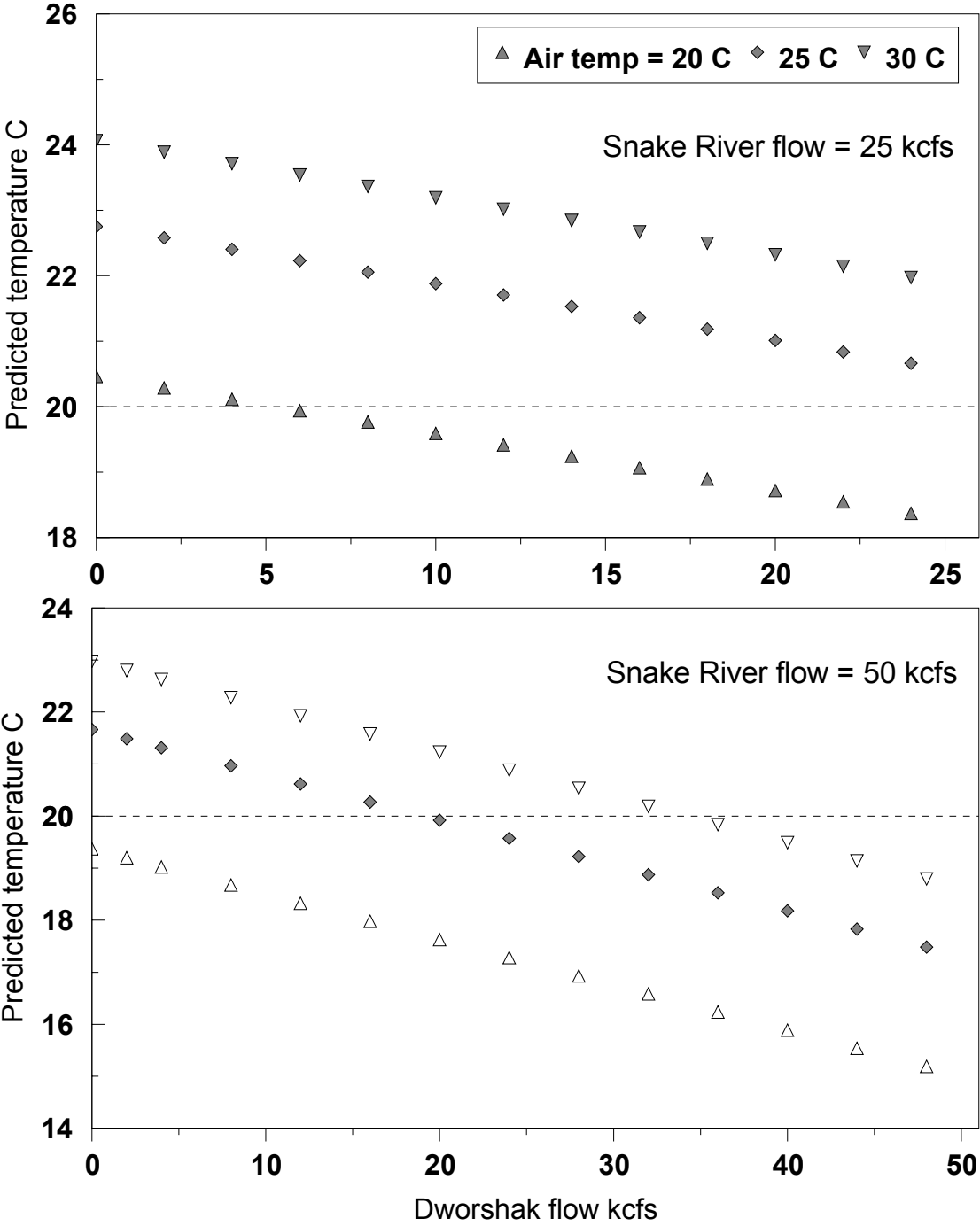


Figure 36. Predicted Snake River water temperatures in the forebay at Lower Granite Dam versus proportion of Snake River flow from Dworshak reservoir. Values calculated using polynomial regression model using proportion of river flow from Dworshak reservoir, air temperature at Lewiston, ID, and Snake River flow at Lower Granite Dam. Estimates based on low (top) and moderate (bottom) Snake River summer flow levels, and at three air temperatures.

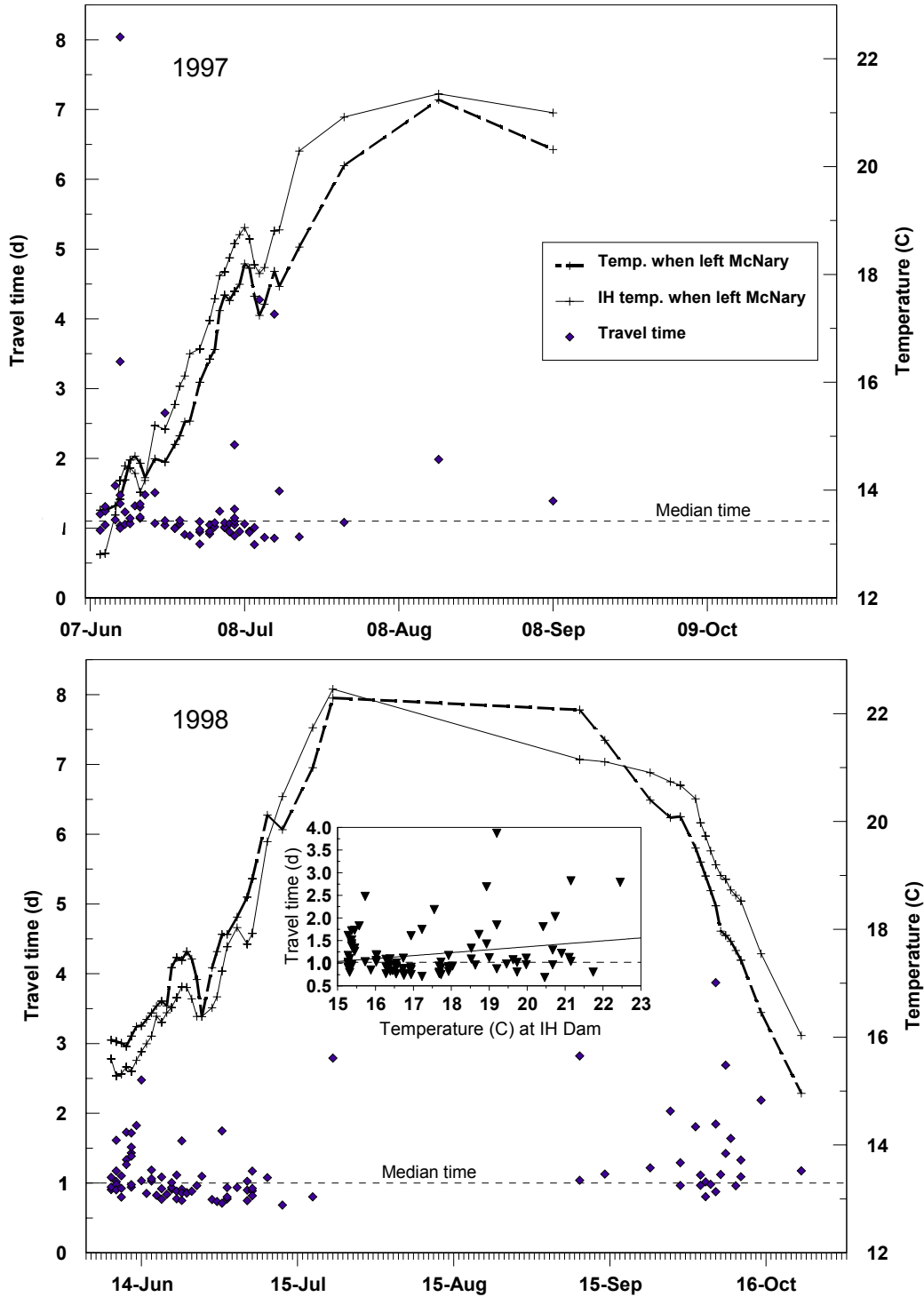


Figure 37. Travel times for summer and fall chinook salmon between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1997 and 1998, and showing significant regression between travel times and temperature at Ice Harbor Dam at time fish left McNary Dam for 1998 (inset). Dashed lines represents median travel times.

temperatures at McNary Dam at the time fish left McNary Dam (regression $P = 0.124$), but were significantly related to maximum water temperatures we measured at Ice Harbor Dam on the day they left McNary Dam ($P = 0.025$, $r^2 = 0.055$), and for the difference between the two temperatures ($P = 0.009$, $r^2 = 0.075$). Although the latter regression analyses were significant, the travel times were highly variable and the relationships were relatively weak (see Figure 37 inset). During both years salmon stopped moving between the two dams mid-July when water temperatures were approaching 20°C. During 1998, fall chinook salmon resumed passage during the second half of September when water temperature had declined to near 20°C again. No salmon with transmitters migrated between the two dams during the warmest water temperatures.

Seventy-four chinook salmon with transmitters reached Ice Harbor Dam during the summer and fall of 1997, two of which had passed McNary Dam on 5 June and so were counted as spring chinook salmon. Of the remaining 72 salmon, we had times to pass the dam for 68 fish, only 2 of which were fall-run fish. In 1998, 96 summer and fall chinook salmon reached Ice Harbor Dam and 94 salmon passed the dam. We had passage times for 90 of the 94 fish, 26 of which were fall chinook salmon. Water temperatures at the dam ranged from around 13 to over 21°C in 1997 and from 15 to over 22°C in 1998 (Figure 38). Median times to pass the dam were 16.9 h (4.6 h to 22.8 d) in 1997, and 14.4 h (3.1 h to 17 d) in 1998. In 1997, there was no correlation between passage times at Ice Harbor Dam and maximum daily water temperatures on the day fish arrived in the tailrace (regression $P = 0.109$) or at the time they exited from the top of the ladder ($P = 0.561$), nor were they related to the maximum difference in water temperatures we measured at the dam each day ($P = 0.393$). In 1998, passage times were negatively correlated with maximum water temperatures measured on the day salmon reached the tailrace of Ice Harbor Dam ($P = 0.01$, $r^2 = 0.073$), and on the day they left the dam moving upstream ($P = 0.038$, $r^2 = 0.048$), but not with the maximum difference in temperatures at the dam on the day fish reached the tailrace ($P = 0.258$). Again, passage at the dams was minimal for the two month period from mid-July until mid-September.

Median travel times between Ice Harbor and Lower Granite dams were 3.9 d (2.6 to 28.8 d) in 1997 for 65 chinook salmon (included 1 fall-run fish), and 3.6 d (2.4 to 69 d) in 1998 for 73 salmon (included 11 fall chinook salmon). Water temperatures at Lower Granite Dam ranged from 13 to almost 21°C during the time fish were passing in 1997 (Figure 39). In 1998, Snake River water temperatures ranged from 14 to near 24°C with warm water conditions almost continuous through July, August, and September. For both years, travel times were correlated to water temperatures at time fish entered the tailrace at Lower Granite Dam (regression $P = 0.004$, $r^2 = 0.122$ for 1997, $P < 0.001$, $r^2 = 0.165$ for 1998), but not to water temperatures at Ice Harbor Dam on the day they left the dam ($P = 0.704$ for 1997, $P = 0.208$ for 1998). As with other segments of their migration, few fish moved between Ice Harbor and Lower Granite dams from late July until mid-September.

We have times to pass Lower Granite Dam for 55 summer and fall chinook salmon in 1997 and 70 salmon in 1998. Median passage times were 25.3 h (5.2 h to 9.4 d) in 1997 and 26.9 h (3.8 h to 11.8 d) in 1998 (Figure 40). Passage times in 1997 were

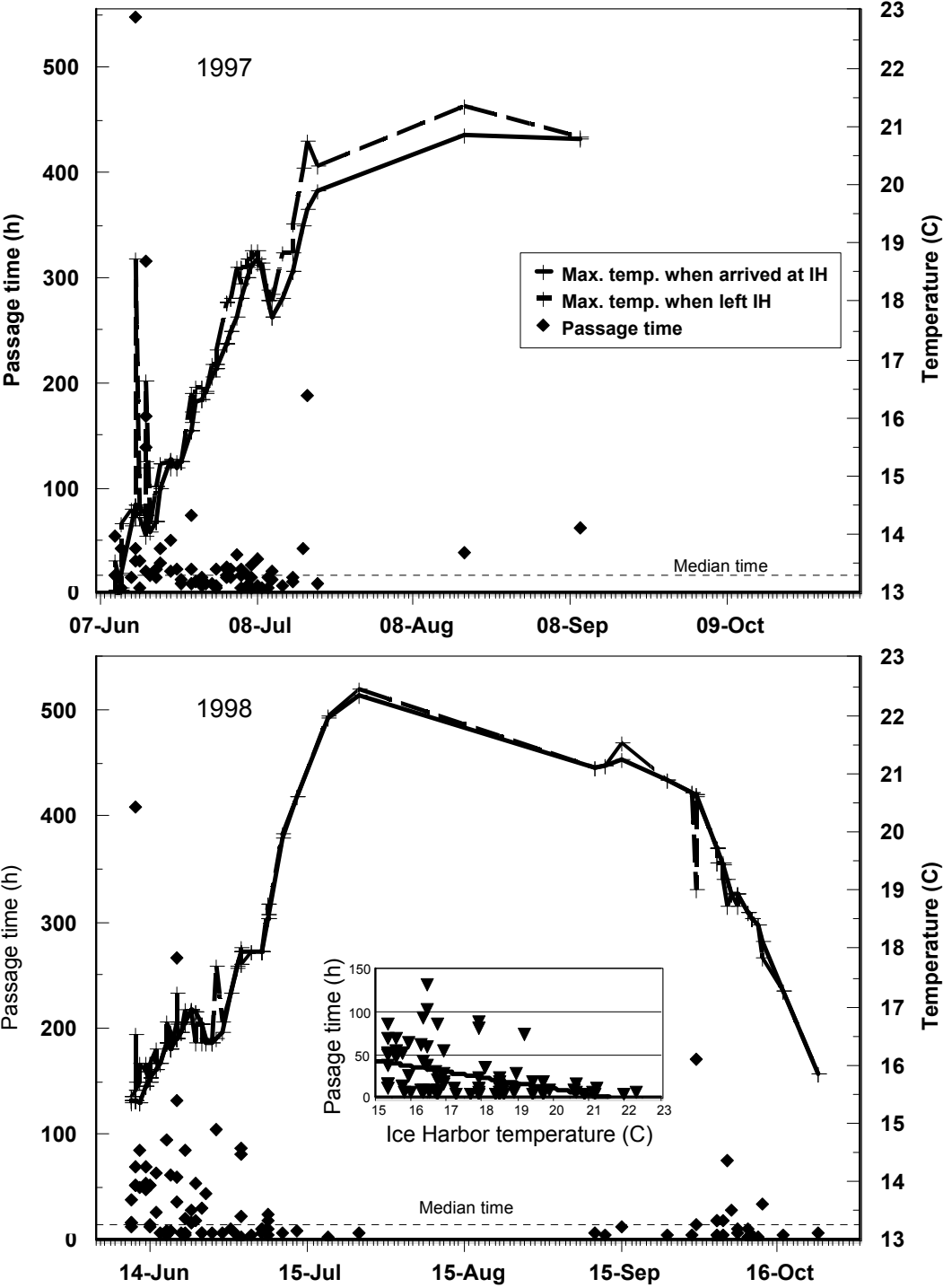


Figure 38. Times for summer and fall chinook salmon to pass Ice Harbor Dam and mean water temperatures on day fish arrived at and left the dam in 1997 and 1998, and relationship between passage times and maximum temperature on day fish arrived at Ice Harbor Dam in 1998 (inset). Horizontal dashed line represents median passage times.

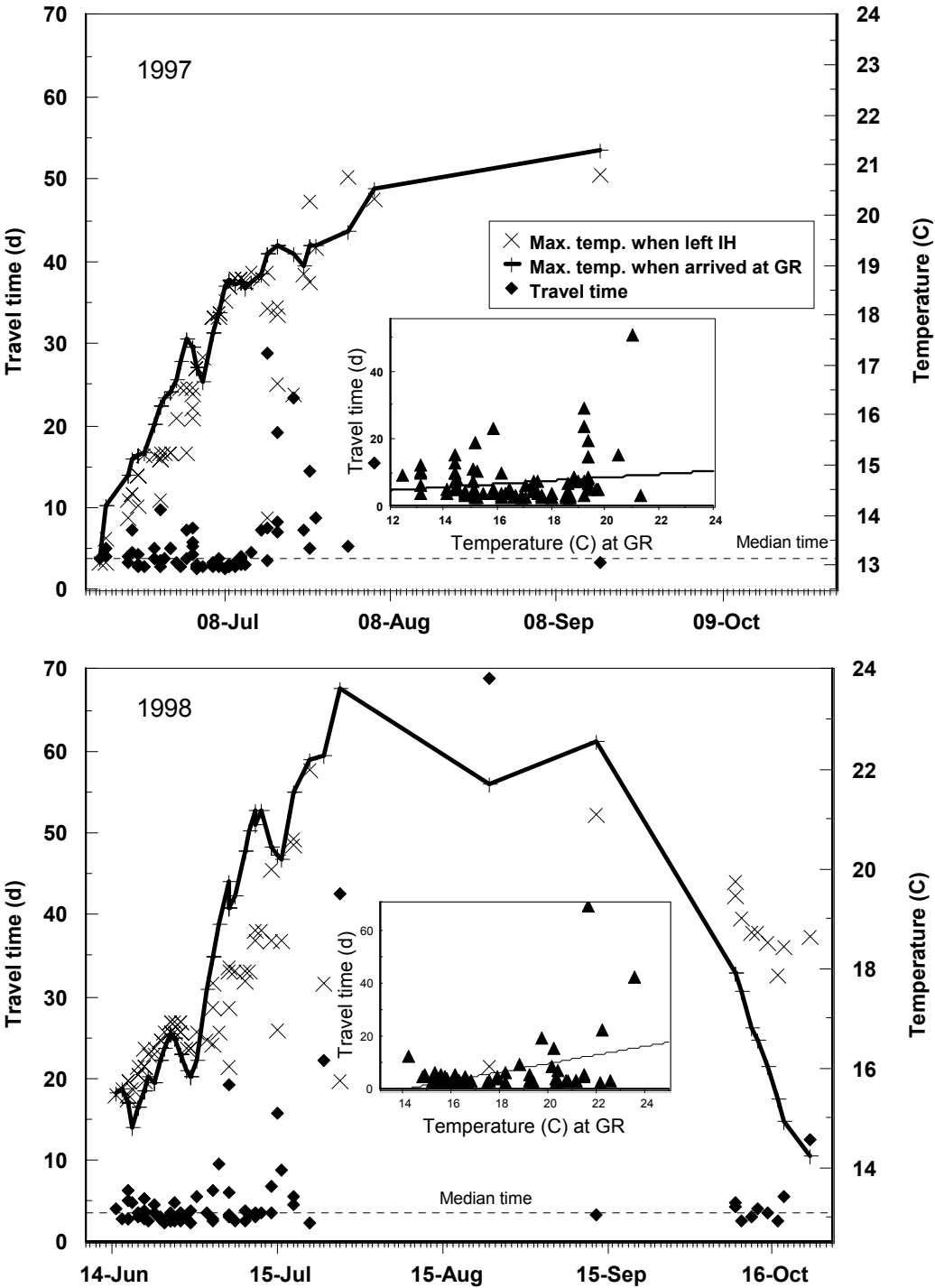


Figure 39. Travel times for summer and fall chinook salmon between Ice Harbor (IH) and Lower Granite (GR) dams and mean water temperatures on day fish left Ice Harbor Dam and arrived at Lower Granite Dam in 1997 and 1998, and significant regressions between travel times and temperature on day fish arrived at Lower Granite Dam (insets). Horizontal dashed lines represent median passage times.

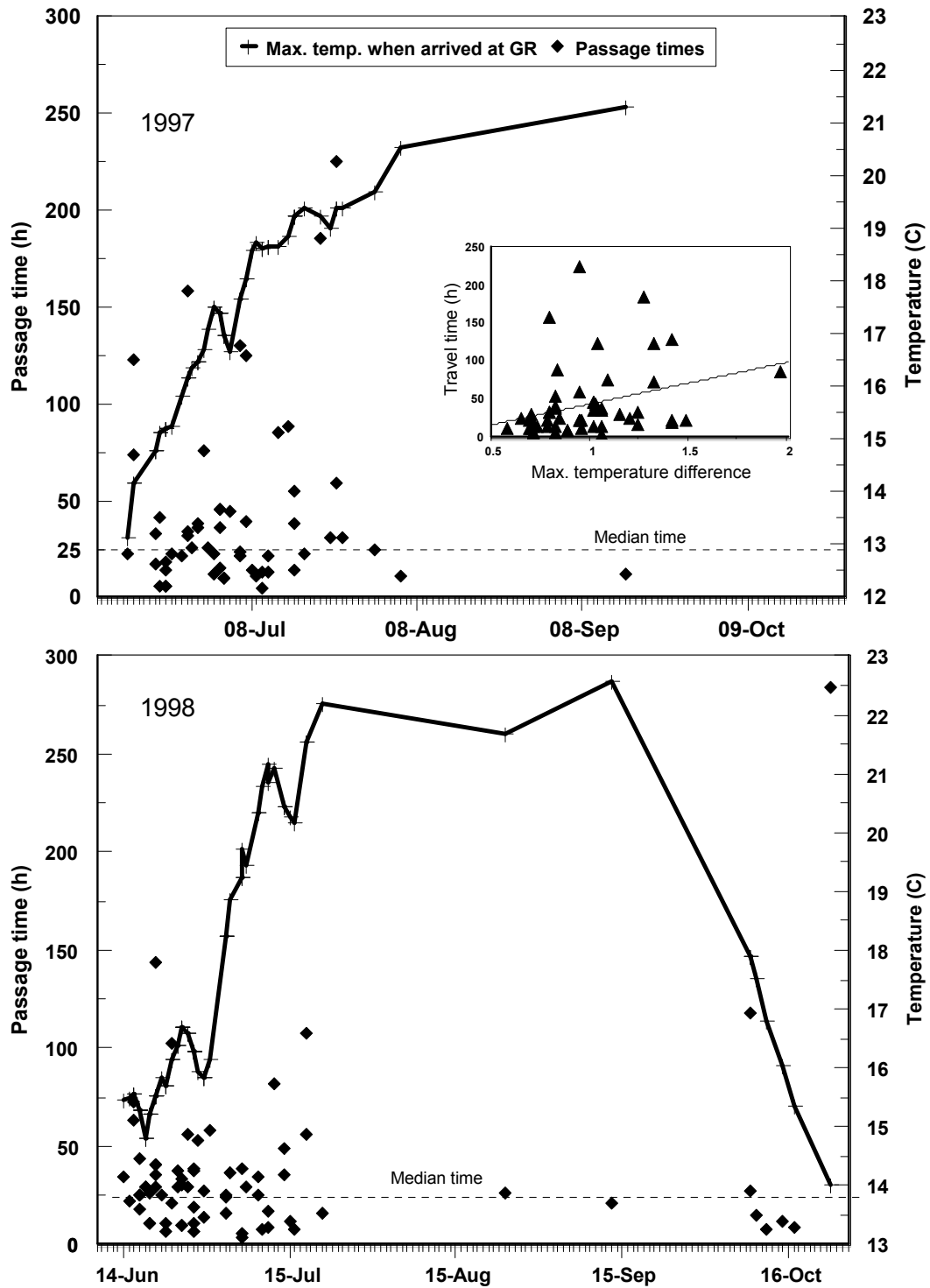


Figure 40. Times for summer and fall chinook salmon to pass Lower Granite Dam (GR) and mean water temperature on day fish arrived at the dam in 1997 and 1998, and relationship between passage times and maximum difference in water temperatures on day fish arrived at Lower Granite Dam in 1997 (inset). Horizontal dashed lines represent median passage times.

significantly related to the greatest difference between the warmest and coolest water temperatures we measured on the day fish arrived at Lower Granite Dam ($P = 0.021$, $r^2 = 0.097$), but not to maximum temperatures on the day they arrived ($P = 0.507$) or left ($P = 0.141$) the dam. In 1998, passage times were not significantly related to any of the three temperature measures at Lower Granite Dam.

Two years of telemetry data, 1996 and 1997, were available for analysis of steelhead passage through the lower Snake River. In 1996, 287 steelhead with transmitters were recorded at Ice Harbor Dam before 1 November. Of those, we recorded travel times between McNary and Ice Harbor dams for 178 steelhead. In 1997, we had travel times for 345 of 388 steelhead recorded at Ice Harbor Dam. Snake River water temperatures during the time the steelhead migrated between the two dams ranged from 13.8 to 22.1°C in 1996 and from 13.5 to 21.9°C in 1997. Median times to travel between the two dams were 2.0 d (ranged 1.0 to 73.9 d) in 1996 and 2.2 d (0.4 to 79.8 d) in 1997 (Figure 41). For both years, travel times were significantly related to Columbia River water temperatures at McNary Dam ($P < 0.001$ for 1996 and 1997) and to Snake River temperature at Ice Harbor Dam on the day fish left McNary Dam ($P < 0.001$ for 1996 and 1997). Travel times in 1996 were not related to the difference in temperatures between McNary and Ice Harbor dams on the day fish left McNary dam ($P = 0.778$), but in 1997 there was a negative correlation between travel times and difference in water temperatures at the two dams ($P = 0.009$). The r^2 values for these regressions were all less than 0.1. Three steelhead in 1996 and 12 steelhead in 1997 took longer than one month to travel between the two dams, but excluding them did not change the outcome of the analyses. Steelhead moved between the two dams through the summer, but the greatest number reached Ice Harbor Dam after mid-September when water temperatures were 20°C or lower.

There were passage times at Ice Harbor Dam for 217 steelhead in 1996 and 325 steelhead in 1997. Water temperatures at the dam during the time steelhead were passing ranged 13 to 22°C in 1996 and 12 to 22°C in 1997. Median passage times were 14.3 h (2.3 h to 54.9 d) in 1996 and 12.7 h (2.7 h to 46.1 d) in 1997 (Figure 42). Passage times in 1996 were significantly related to maximum water temperatures we measured at the dam on the day fish arrived at the dam ($P = 0.023$, $r^2 = 0.024$), but not with temperatures when fish left the dam ($P = 0.085$) or to the maximum difference in water temperatures at the dam on the day of arrival ($P = 0.098$). Passage times in 1997 were only significantly correlated with maximum temperature difference measured on the day steelhead arrived at the dam ($P < 0.001$, $r^2 = 0.08$). Two steelhead in 1996 and three steelhead in 1997 took longer than one month to pass the dam, and when removed from analysis, only water temperature at the time fish arrived at the dam was significant for passage times ($P = 0.023$, $r^2 = 0.024$) in 1996 and no variables were significant in 1997. Eight-four percent (182 fish) of the steelhead in 1996 and nearly 90% (291 fish) of the steelhead in 1997 reached the dam on or after 1 September.

Travel times between Ice Harbor and Lower Granite dams had a median of 6.1 d, (3.0 to 70.1 d) for 211 steelhead in 1996, and 5.9 d (3.0 to 93.7 d) for 271 steelhead in 1997 (Figure 43). Temperatures in the Snake River at the time the steelhead were traveling ranged from 13 to 22°C in 1996, and from 12 to near 22°C in 1997. For both years, travel times were not significantly related to water temperatures measured on the

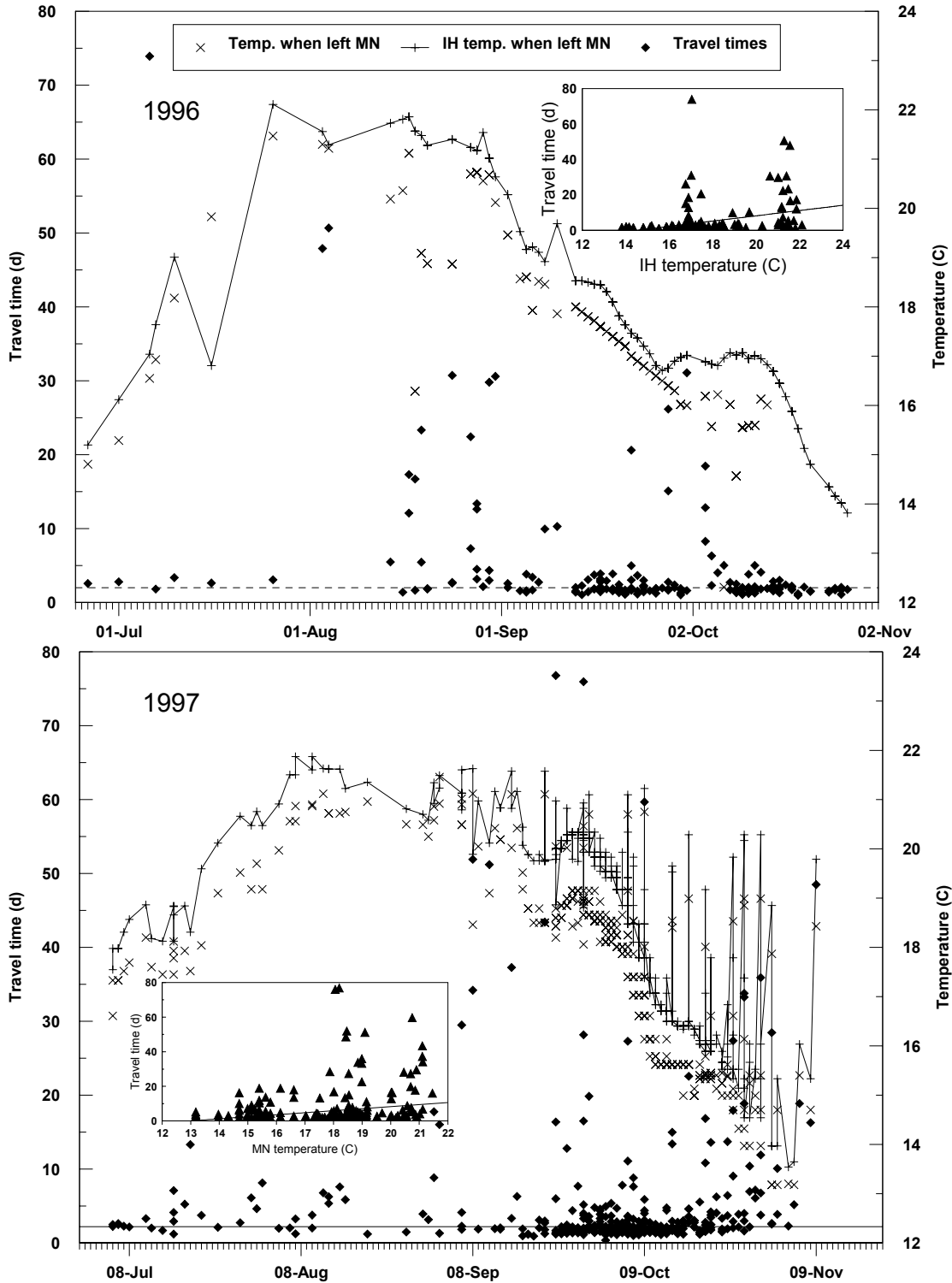


Figure 41. Travel times for steelhead between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1996 and 1997. Shown are relationships between travel times and temperature at Ice Harbor Dam in 1996, and between travel times and temperature at McNary Dam in 1997 (insets). Dashed lines represent median travel times.

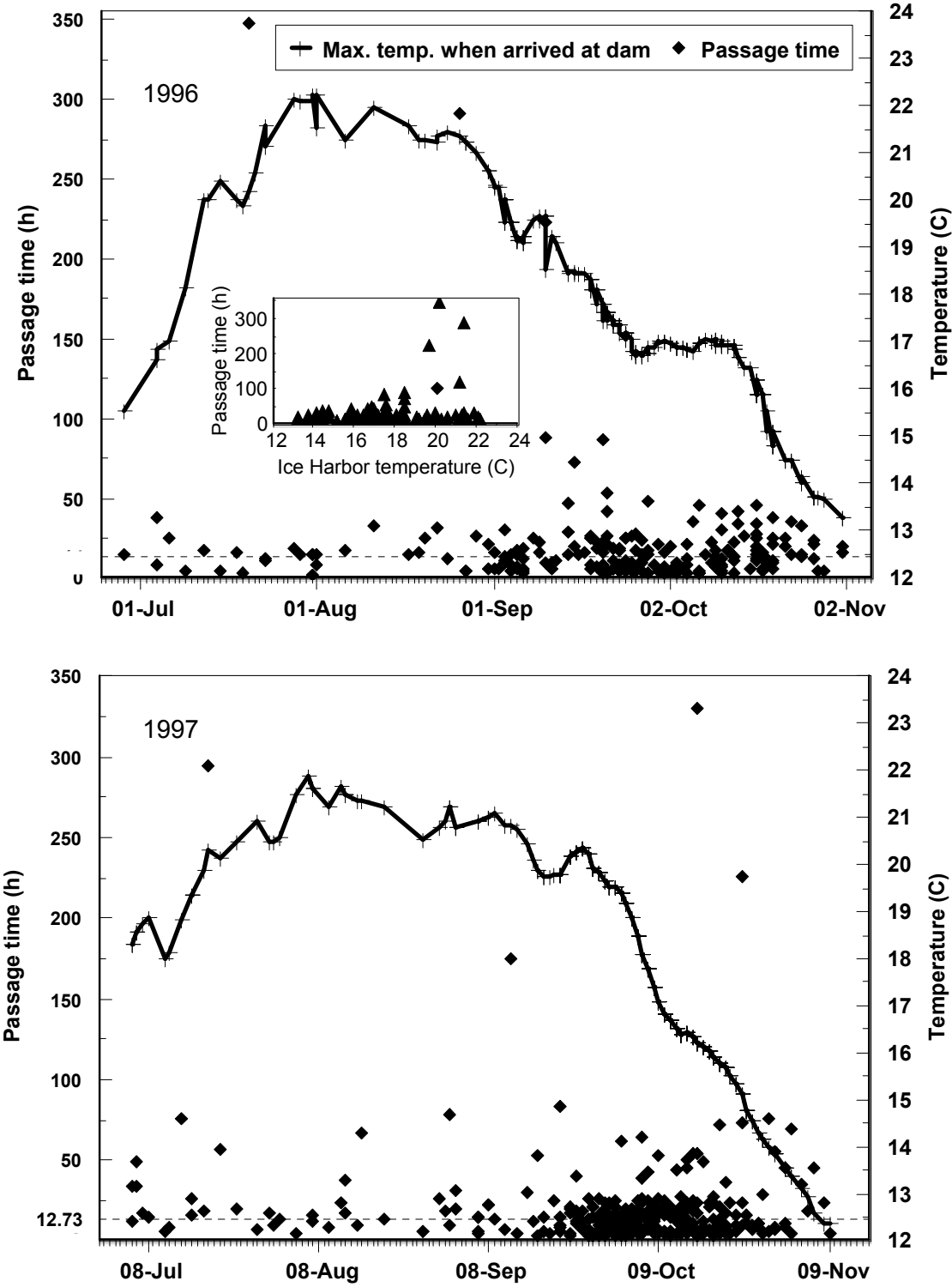


Figure 42. Times for adult steelhead pass Ice Harbor Dam and mean water temperatures on day fish arrived at the dam in 1996 and 1997, and relationship between passage times and maximum temperature on day fish arrived at Ice Harbor Dam in 1996 (inset). Horizontal dashed line represents median passage times.

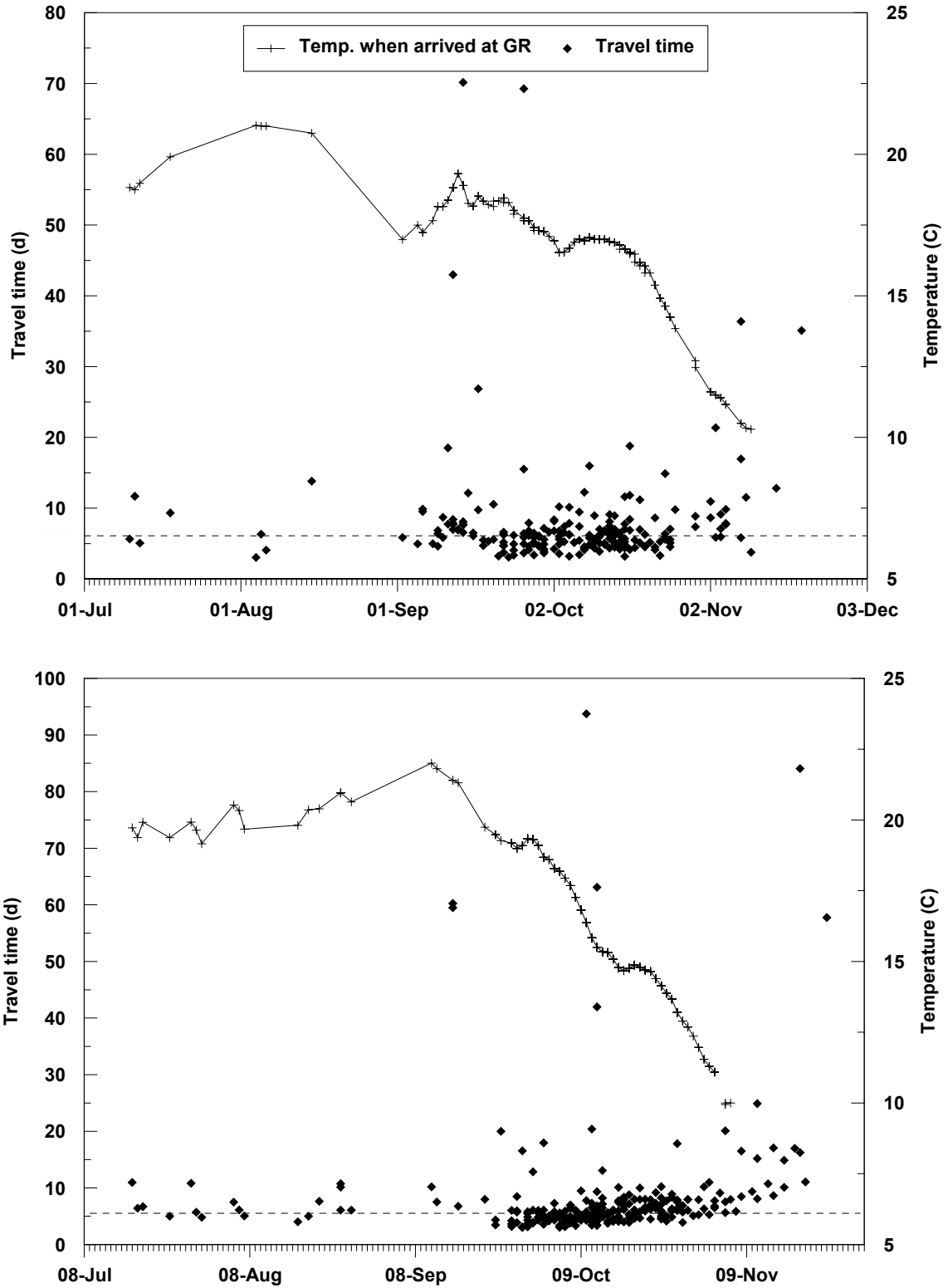


Figure 43. Travel times for steelhead between Ice Harbor and Lower Granite dams and mean water temperatures at Lower Granite Dam on the day fish arrived at the dam, in 1996 (top) and 1997 (bottom). Dashed line represents median travel times.

day fish left Ice Harbor Dam or arrived at Lower Granite Dam. Median time to pass Lower Granite Dam was 25.0 h (3.7 h to 8.4 d) for 130 steelhead in 1996, and 21.2 h (4.3 h to 20.6 d) for 168 steelhead in 1997 (Figure 44). Maximum water temperatures experienced by steelhead at time of passage ranged from 10.3 to 22.1°C in 1996 and from 11.3 to 22.1°C in 1997. Passage times were not related to water temperatures we measured at Lower Granite Dam in 1996. In 1997, passage times were significantly correlated to the maximum difference in water temperatures on the day fish arrived at the dam ($P = 0.002$, $r^2 = 0.055$), but the data was variable and the significant outcome was driven by a few outlier points at the data extremes (Figure 44).

Fish Counts Versus Water Temperatures.

The first quartile of fall chinook salmon and steelhead runs migrated past Ice Harbor and Lower Granite dams later in years when water temperatures during 1 August to 15 September were warmer (Figures 45 and 46). The relationships between passage and water temperatures were stronger at Lower Granite Dam ($P = 0.004$, $r^2 = 0.299$ for chinook salmon and $P = 0.002$, $r^2 = 0.3258$ for steelhead) than at Ice Harbor Dam ($P = 0.013$, $r^2 = 0.156$ and $P = 0.016$, $r^2 = 0.147$). Based on the calculated regression lines, a rise in water temperature of one degree correlated with an increased delay in passage of from 1.4 to 2 d for fall chinook salmon and from 4 to near 7 d for steelhead at Ice Harbor and Lower Granite dams. Year was significant in the regression analysis for steelhead at Lower Granite ($P < 0.001$, $r^2 = 0.375$), where the date that 25% of the run was counted has trended to come later since 1975.

Discussion

Based on the limited amount of data available, we saw no evidence that water temperatures at the mouth of the Snake River are warmer now than prior to impoundment. Summer water temperatures at the mouth of the Snake River are influenced by Ice Harbor Dam. When spill is terminated in the summer (i.e. mid-1980's spill ended during June or July) most of the flow in the Snake River was from turbine outflow, the deeper and potentially cooler water available in the Ice Harbor forebay. In recent years spill has been continued through August at Ice Harbor Dam, but by September most or all of the flow is from turbine outflow. In data collected at Ice Harbor Dam by Bennett et al. (1997b) one can readily see that when spill is not occurring, water temperatures in the tailrace of Ice Harbor Dam are more similar to those found near the bottom of the reservoir in the forebay of Ice Harbor Dam than to the potentially warmer water at the surface. This effect, caused from predominantly turbine flow, combined with the effect from releasing Dworshak water in recent years appears to account for the lack of significant warming of water temperatures at the mouth of the Snake River over time. Although the data record is not complete, it appears that adult salmon and steelhead do not experience warmer water conditions at the mouth of the Snake River now than existed prior to impoundment.

Since construction of Ice Harbor Dam (1962-2001), mean water temperatures in the forebay of the dam have gradually increased during October but were unchanged for June, July, August and September. We also determined that the maximum temperature

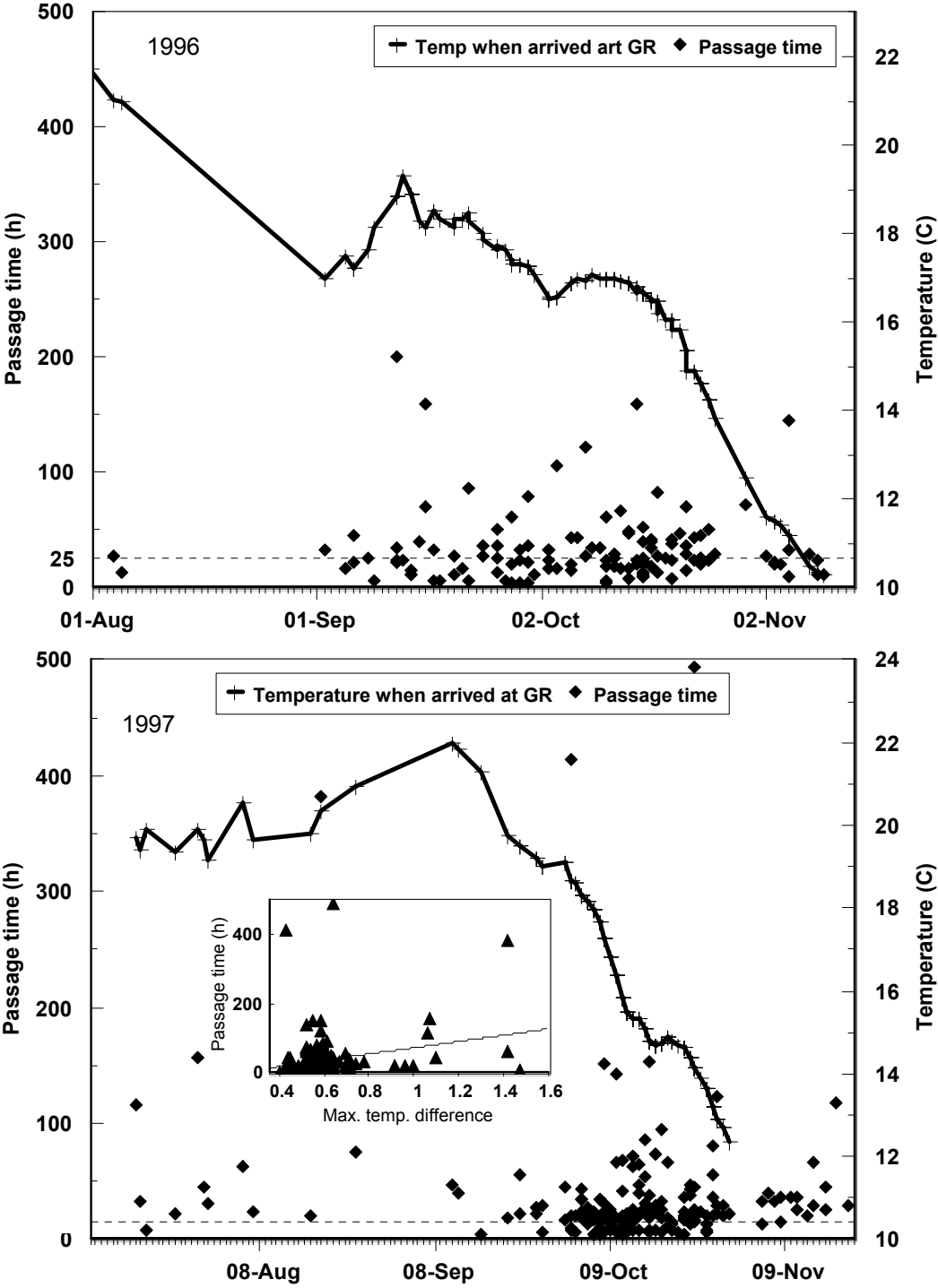


Figure 44. Times for adult steelhead pass Lower Granite Dam and mean water temperatures on day fish arrived at the dam in 1996 and 1997, and relationship between passage times and maximum temperature on day fish arrived at Lower Granite Dam in 1997 (inset). Horizontal dashed line represents median passage times.

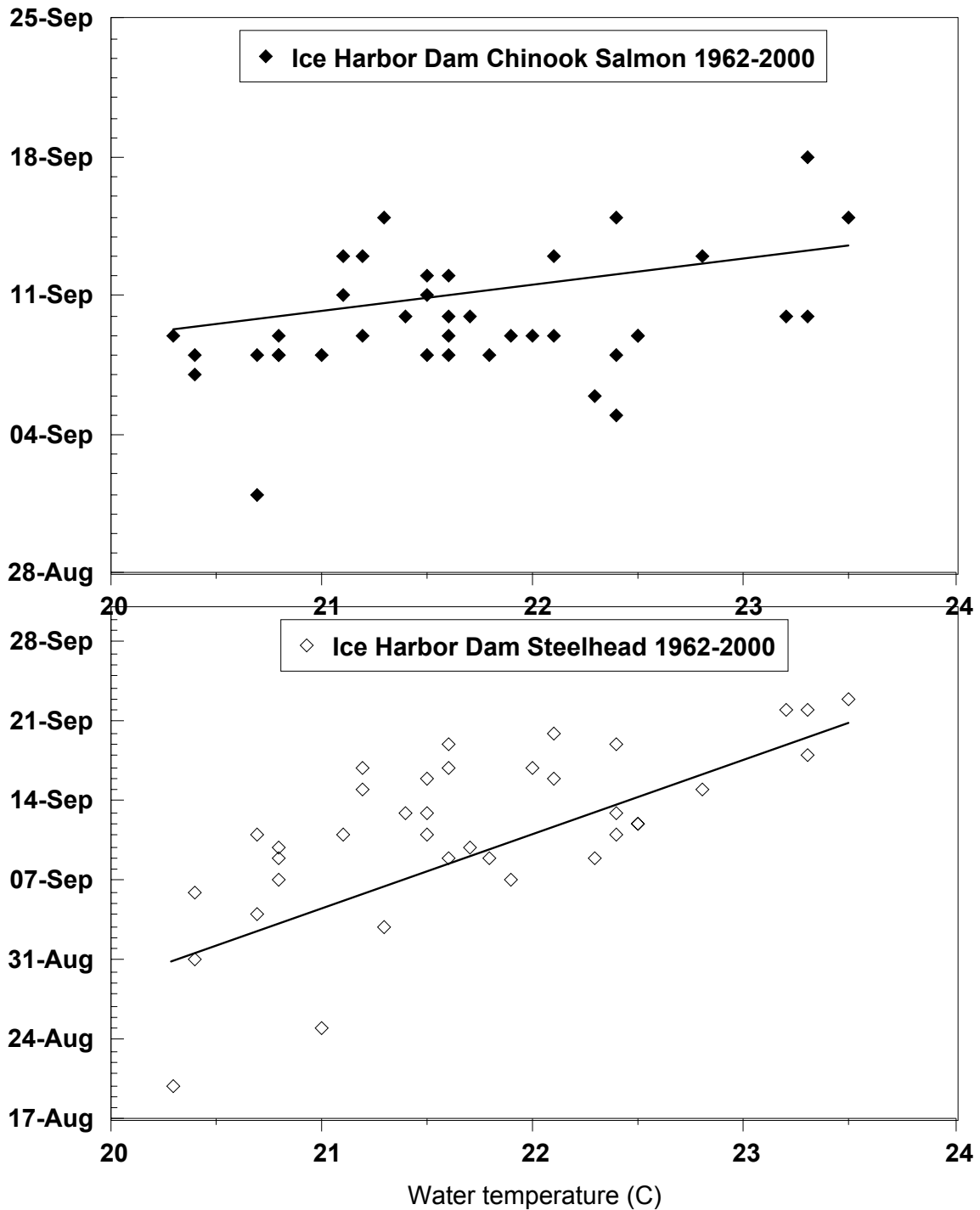


Figure 45. Date that 25% of the fall chinook salmon and steelhead runs were counted at Ice Harbor Dam versus mean water temperature measured in the forebay of the dam during the period from 1 August through 15 September for each year 1962-2000. Fall chinook salmon counts from 12 August until 31 October. Steelhead counts were from 1 June until 31 October.

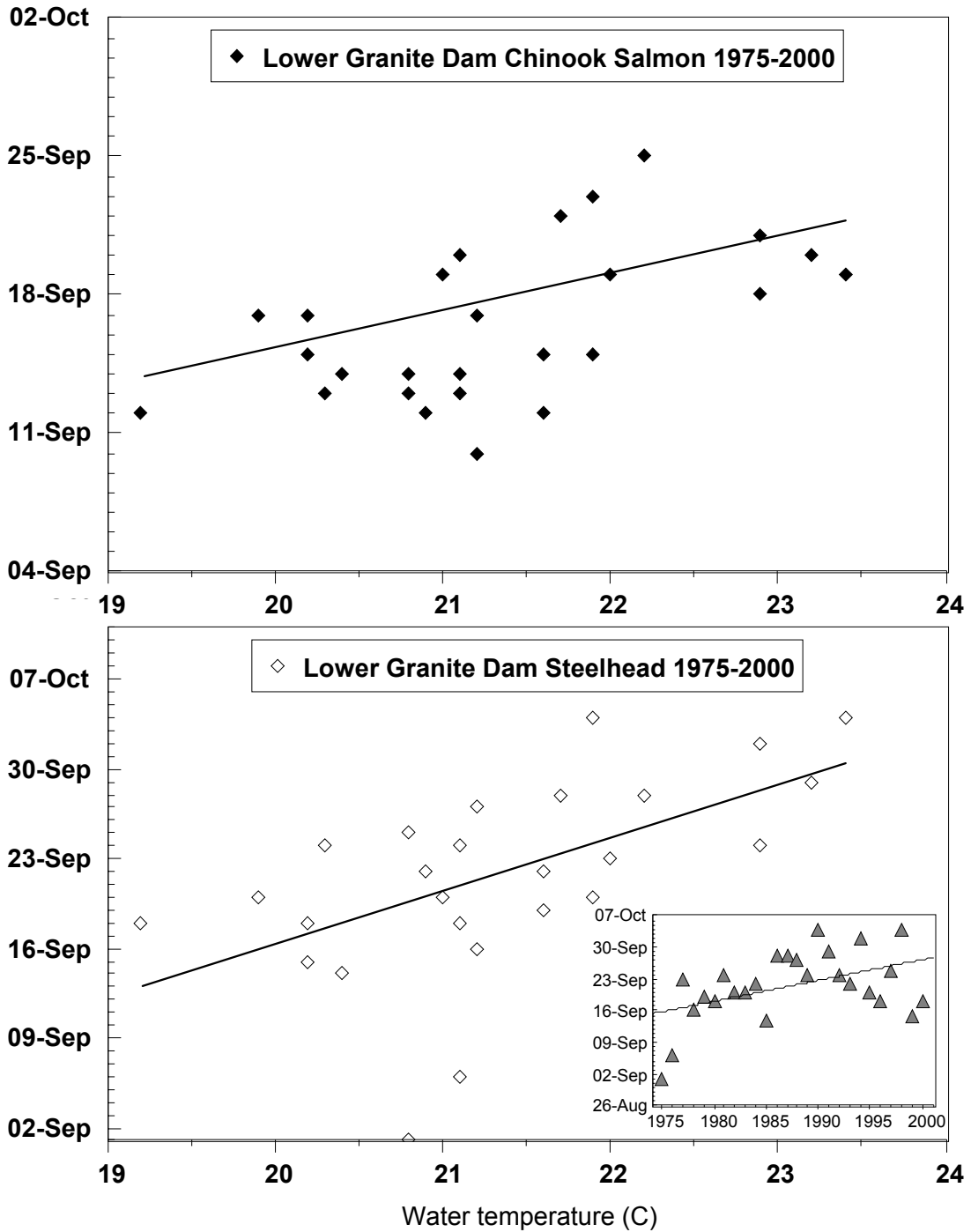


Figure 46. Date that 25% of the fall chinook salmon and steelhead runs were counted at Lower Granite Dam versus mean water temperature measured in forebay of the dam during the period from 1 August through 15 September for each year, 1975-2000. Trend for date 25% of steelhead have passed Lower Granite Dam over time shown in inset. Fall chinook salmon counts were from 18 August until 31 October. Steelhead counts were from 1 June until 15 December.

measured each year and date of maximum temperature for each year have not changed in the forebay of Ice Harbor Dam since 1962, which agrees with findings of Quinn et al. (1997). Flow levels and air temperatures were the two environmental factors we identified with the greatest influence on forebay water temperatures in the lower Snake River. Mean air temperatures in the vicinity of the lower Snake River have gradually increased over time during August and September which may partially explain warmer water temperatures in October over time in the forebay of Ice Harbor Dam. Snake River flows have large year-to-year variation, but we found no consistent pattern of change over time, which agrees with the conclusions of the National Research Council (1996) that there has not been a major shift in Snake River hydrograph over time. However, Quinn et al. (1997) concluded that summertime flows have declined significantly since 1964. The difference in the two results is probably because the previous analysis only included data up to 1994 while our analysis was based on data through 2001. The relatively good flow years that occurred in the late 1990's had a positive influence on temperatures in the lower Snake River. Water released from Dworshak Reservoir for flow augmentation and summer cooling in recent years would also have helped flatten the flow regression lines since 1994.

Warming of the surface waters in the lower Snake River reservoirs has a direct effect on temperatures in fishways. Warm water conditions ($\geq 20^{\circ}\text{C}$) occurred in the fishways at Ice Harbor and Lower Granite dams from about mid-July until mid- to late-September. Warmest water was found near the surface of the forebays where it flowed and was pumped into the tops of the fishways (see Appendix C). Cooler water, found in the tailrace from turbine outflow, was pumped into lower segments of the fishways. The greatest discontinuity in water temperatures occurred where these two sources of water mixed, near the base of the fishways. This was most evident at Lower Granite Dam where temperatures in the transition pool could be more than 4°C warmer than those from just inside the fishway entrances. This temperature discontinuity may contribute to passage delays at the dams (see below). There was little evidence that water warmed appreciably as it passed down the fishway ladders at either dam.

In the forebay of Ice Harbor Dam, water temperatures varied $1\text{-}3^{\circ}\text{C}$ between the water surface and 30 m depth, but temperatures deep in the reservoir consistently exceeded 20°C during the summer. This reduces the usefulness of using water pumped from deep in the forebay to cool fishway temperatures, although the potential for some benefit exists. For example in 1998, during the warmest summer we sampled, pumping water from 30 m depth into the fishways would have reduced water temperatures from 24 to 22°C (75 to 72°F) during summer. At Lower Granite Dam, water temperatures in the forebay were generally cooler than those measured at Ice Harbor Dam, with the exception of the warm year in 1998 when surface water temperatures were comparable between the two projects. The greatest temperature stratification occurred in the forebay of Lower Granite Dam when water was released from Dworshak Reservoir. There was less of a temperature stratification effect that could be attributed to Dworshak flows at Ice Harbor Dam because of mixing that occurred as flows passed the three upstream dams.

Cool water released from Dworshak reservoir measurably affected water temperatures in the Lower Granite Dam fishway, but cooling effects at Ice Harbor Dam

were less distinct and difficult to quantify. Specifically, when flows from Dworshak reservoir were 50 to 60% of Snake River flows at Lower Granite Dam, or in the range of about 10 to 20 kcfs, water temperatures were measurably lower at the forebay surface and in the fishway at Lower Granite Dam. This was most pronounced in 1996, when deep water temperatures declined following increase of flow from Dworshak reservoir, and in 1997 when temperatures increased following cessation of spill at Dworshak. In 1998, temperatures changed from having a 2-4°C gradient between surface and deep water when about 13 kcfs was being released from Dworshak reservoir, to being largely homothermic with depth after Dworshak flows ceased. Using regression analysis we estimated that water temperatures near the surface in the forebay and in the fishway of Lower Granite Dam were reduced by 1 to 3°C, depending on air temperatures, when flow from Dworshak reservoir were 50 to 60% of the flow at Lower Granite Dam.

Temperatures of water deeper in the reservoir were even more affected by releases from Dworshak. Bennett et al. (1997b) used a modified hydraulics model (COLTEMP) developed by the USACE to predict that temperature reductions of <0.6 to 2.2°C (<1 to 4°F) occurred at mid-depth in the Lower Granite Dam reservoir during 1991 and 1992 when 10-11 kcfs was released from Dworshak reservoir, while negligible cooling occurred at Ice Harbor Dam. Karr et al. (1997) attributed cooling effects of 4 to 5°C at mid-depth in the Lower Granite Dam forebay and 2 to 3°C at Ice Harbor Dam when flows from Dworshak reservoir were at least 20 kcfs in 1994 and 1996. The latter estimates seem overly optimistic considering no attempt was made to account for coinciding changes in air temperatures at the time.

How fish reacted to temperature conditions in the lower Snake River varied. Travel times between McNary and Ice Harbor dams for radio-tagged steelhead in 1996 and 1997, and for summer and fall chinook salmon in 1998 were significantly correlated to water temperatures; longer travel times between the two dams occurred, on average, when temperatures in the Snake River were higher. Travel times by steelhead between the two dams were also related to the difference in water temperatures at the two dams during 1997. But the relationships between travel times and temperatures were not strong or noticeably linear. This is because, although some fish took longer to travel between projects during warm water conditions, most fish migrated at rates close to the median regardless of temperature up to the point when water temperatures in the Snake River exceeded 20°C. Regression analysis as presented here are prone to overdispersion, resulting in conservative test results. However, there was a consistent pattern that movement into the Snake River stopped for the most part during the warmest water temperatures from mid-July until mid-September. Travel times between Ice Harbor and Lower Granite dams for chinook salmon trended upward when temperatures at Lower Granite Dam were higher, but travel times between the two projects for steelhead were not significantly related to prevailing water temperatures. This may have been because the steelhead had already delayed their migration outside the mouth of the Snake River and conditions were more favorable to migration by the time they had passed Ice Harbor Dam. In short, we saw evidence that some chinook salmon and steelhead would delay entry into the Snake River during warm water conditions and some chinook salmon traveled slower through the lower Snake River when water temperatures were high. There was a good correlation between when the first quartile of salmon and steelhead were counted at Ice Harbor and Lower Granite

dams and water temperatures. Fish passed the dams later, on average, in years when mean summer-time water temperatures were high, additional evidence that some salmon and steelhead will delay their upstream migration to avoid warm water conditions in the lower Snake River.

For the most part, times for radio-tagged chinook salmon to pass Ice Harbor and Lower Granite dams were not related to water temperatures except in 1997 when passage was related to maximum temperature differences at the Lower Granite Dam. Times for steelhead to pass Ice Harbor Dam were related to water temperatures in 1996 and 1997, but not so in 1997 after a few outlier fish were excluded, and passage by steelhead at Lower Granite Dam was significant for maximum temperature difference at the dam during 1997. So, we saw evidence that time to pass the dams was affected by water temperature conditions in about half the comparisons made. The lack of conclusive results in this last point was partially due to small sample sizes, especially for chinook salmon, but was also related to the fact that few of the radio-tagged fish moved in the lower Snake River during periods of the warmest water temperatures. The ebb in numbers of fish passing through the system during summer is likely an evolutionary adaptation to avoid unfavorable temperature conditions and probably occurred historically before dams were present.

In summery, there appear to be two separate reactions by adult salmon and steelhead to temperature conditions in the lower Snake River. First, fish runs may delay their upstream movement en masse when water temperatures are warm. This type of behavior allows timing adjustments in response to prevailing river conditions and probably occurred historically prior to modification of the river system by construction of dams. However, because the trend has been for later cooling of water temperatures in the Snake River, adult migrants may be spending longer periods in the estuary and lower river system waiting for temperatures to decline, or are temporarily straying into cooler lower-river tributaries. Longer residence times in the lower Columbia River could increase exposure of upriver populations to harvest in downstream fisheries, especially if fish are seeking cool water refuge in tributaries containing terminal fisheries. Additionally, because peak water temperatures are higher and occurring later in the lower Columbia River (National Resource Council 1996; Quinn and Adams 1996; Quinn et al. 1997), total temperature exposures may be higher, or residence in cooler tributaries could be longer, for fish delayed entering and passing through the lower Snake River. The ability of salmon to alter their migration timing is finite, eventually the fish must move upstream in order to reach spawning areas in time. This was most evident during the warm summer of 1998 when the fall chinook salmon run proceeded upstream through September, peaking on 1 October, even though water temperatures did not drop below 20°C until 9 October that year. Releasing water from Dworshak reservoir can be used to moderate forebay and fishway water temperatures in the late fall to more closely mimic the historic temperature-cooling profile. However, if this approach is to be used it appears that flows of at least 10 to 20 kcfs are needed from Dworshak to produce a noticeable effect and must occur about two weeks in advance of when cooling is desired at Ice Harbor Dam.

The second behavioral response to water temperatures by salmon and steelhead we saw was a delay by some fish in passing dams when temperatures were unfavorable,

when temperatures exceeded 20°C and when there was a noticeable difference in temperatures between the tailrace and forebay surface, creating a sharp delineation where these two sources of water met in the fishways. Ironically, this condition was exacerbated when water was being released from Dworshak, creating a greater discrepancy between cool water temperatures deep in the reservoirs, that were subsequently passed by turbines and picked up in the tailrace, and those warmed at the forebay surface that flowed down the fishways. One possible solution to this problem would be to use mixers, bubblers, or some other mechanism in the forebay to upwell cooler water to the surface near the fishway exits and forebay auxiliary water supply intakes. This cooler water could then flow down fishways to moderate fishway temperatures. With this option fish would not need to enter the warm surface water immediately upon exiting fishways. If water from deep in the reservoir or from the tailrace was pumped directly into fishways at existing diffusers, fish will have to transition from the tailrace to the forebay temperatures near the top of the ladder. This would move the temperature gradient from where it currently exists in the transition pool into the weired section of the fishway ladders where we have found that radio-tagged salmon and steelhead advance with less hesitation. This would also have the effect of shortening the time fish are exposed to the warmest water temperatures in the fishways.

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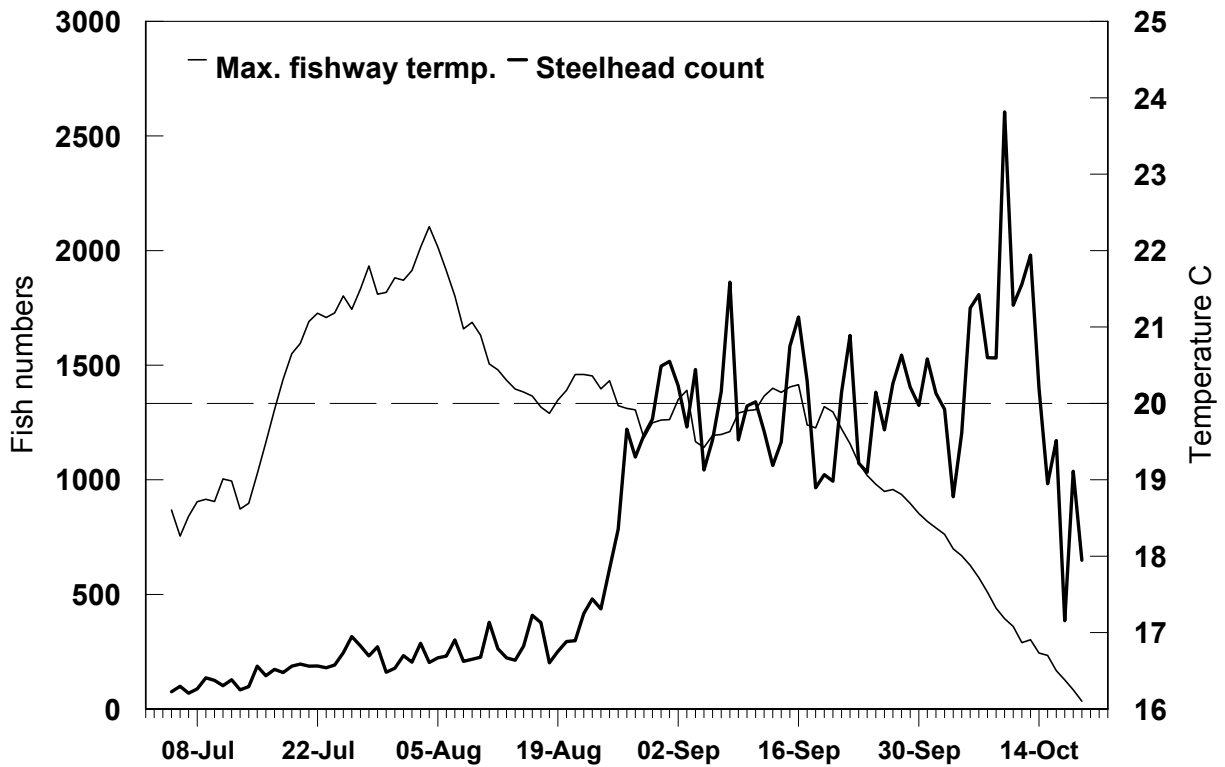
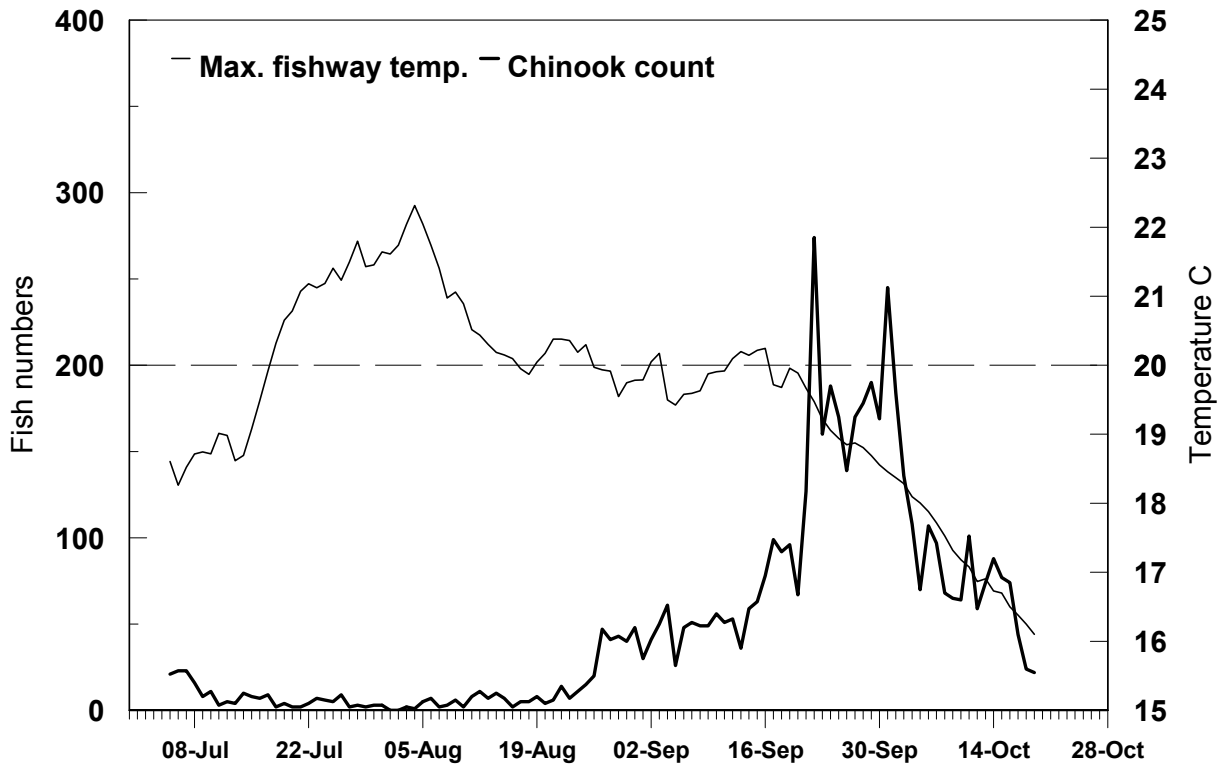
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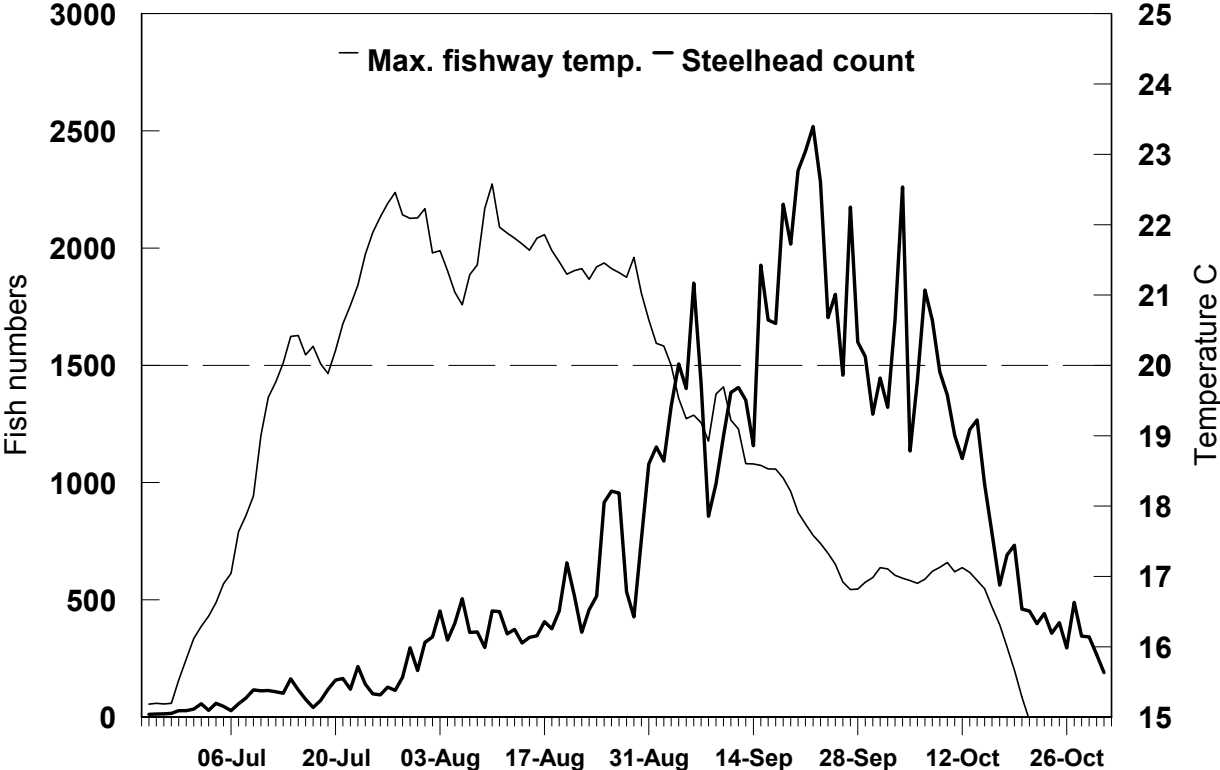
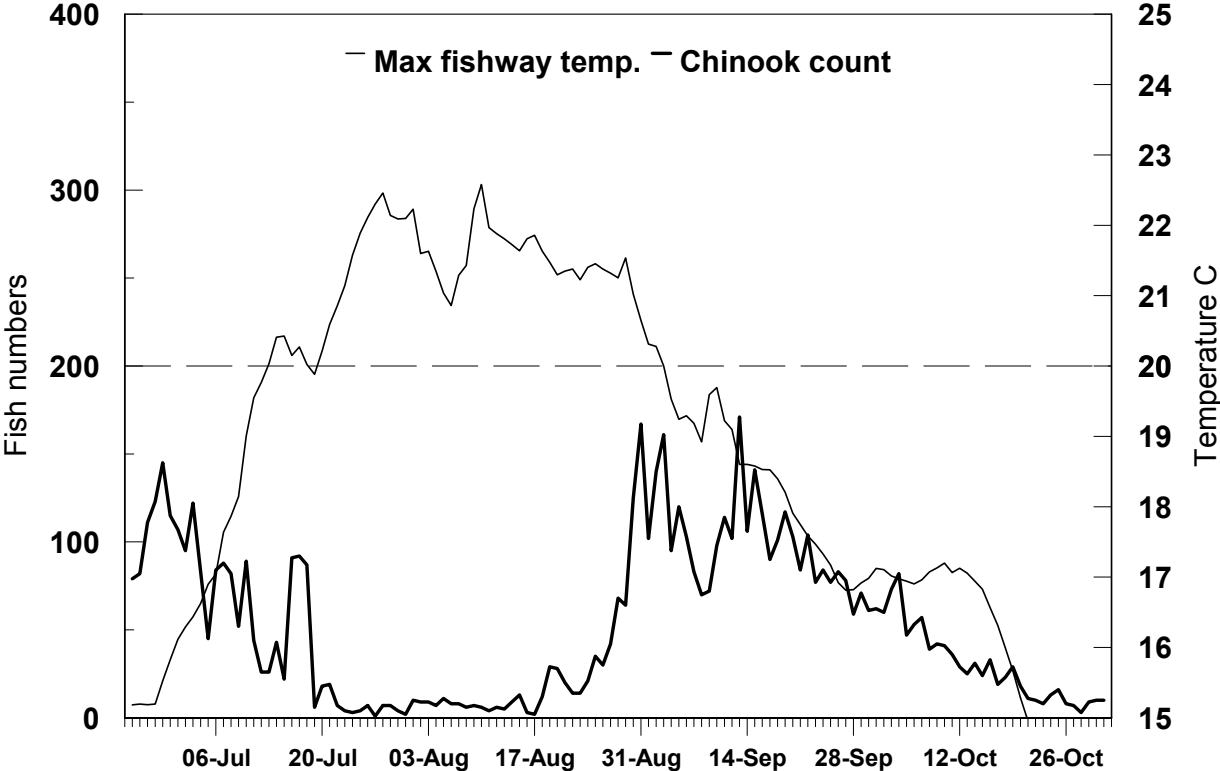
Appendix A

Adult chinook salmon and steelhead counts and maximum daily water temperatures measured in fishways at Ice Harbor and Lower Granite dams during 1995 to 1998.

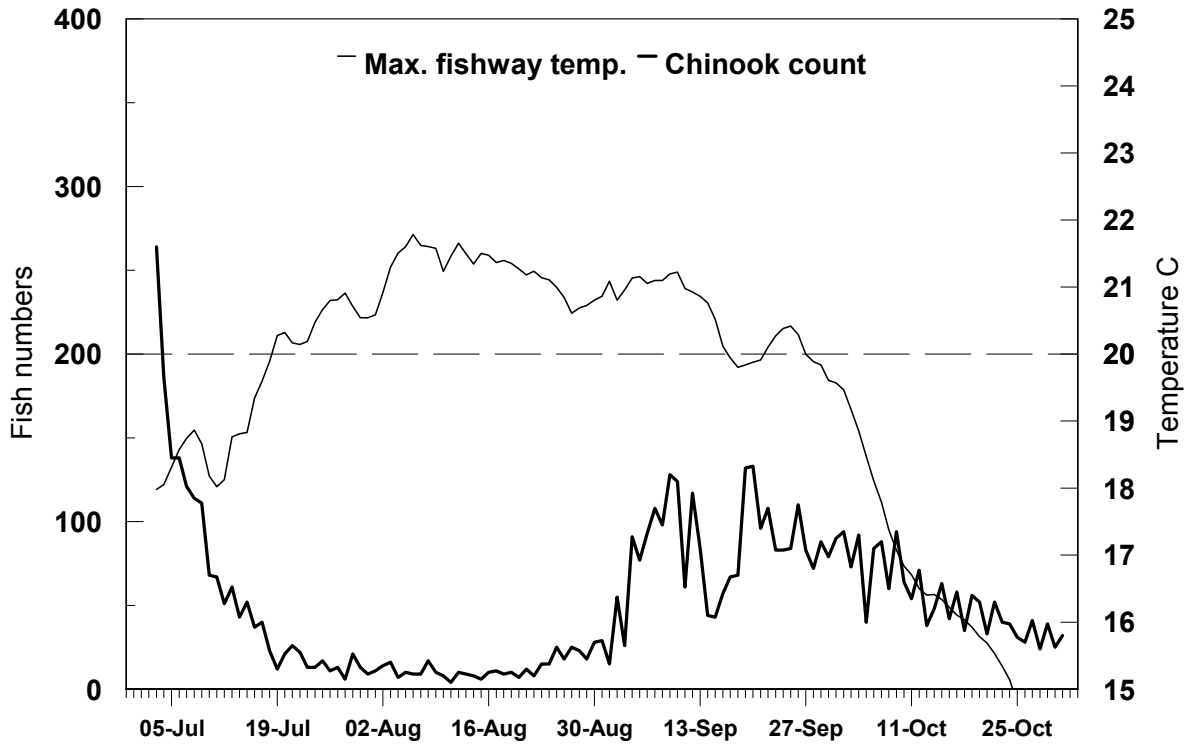
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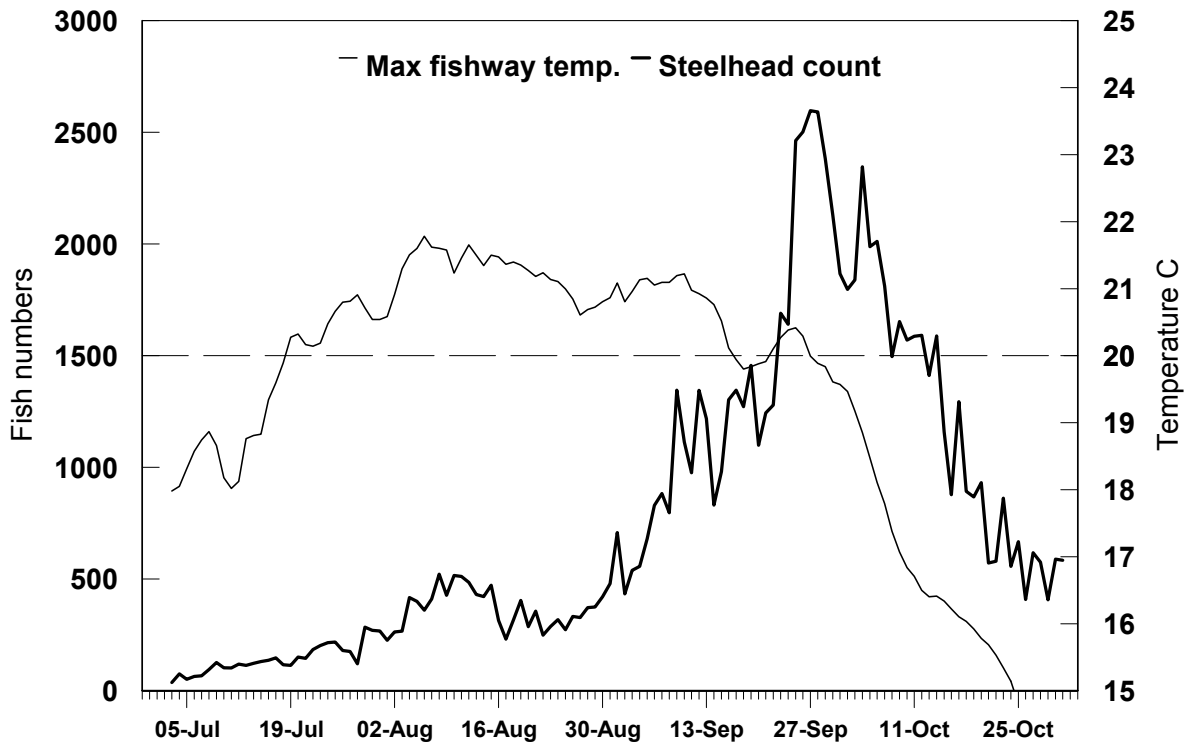
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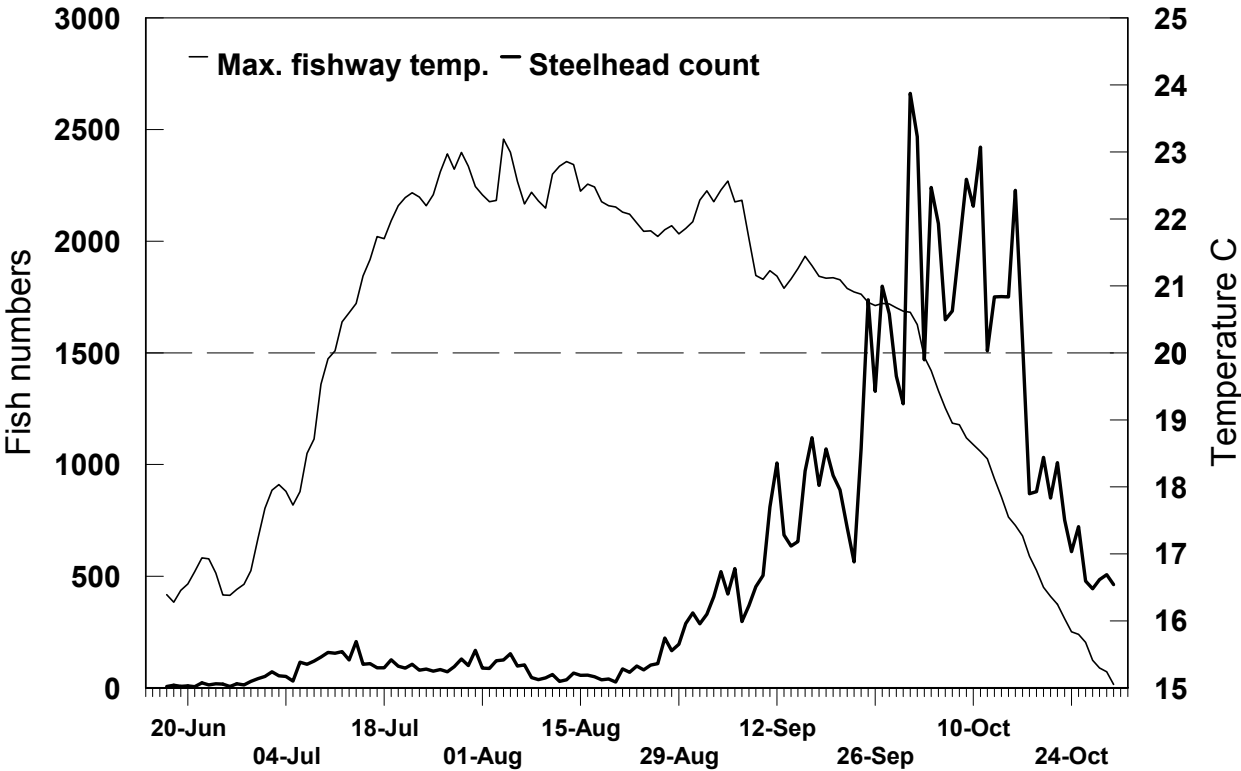
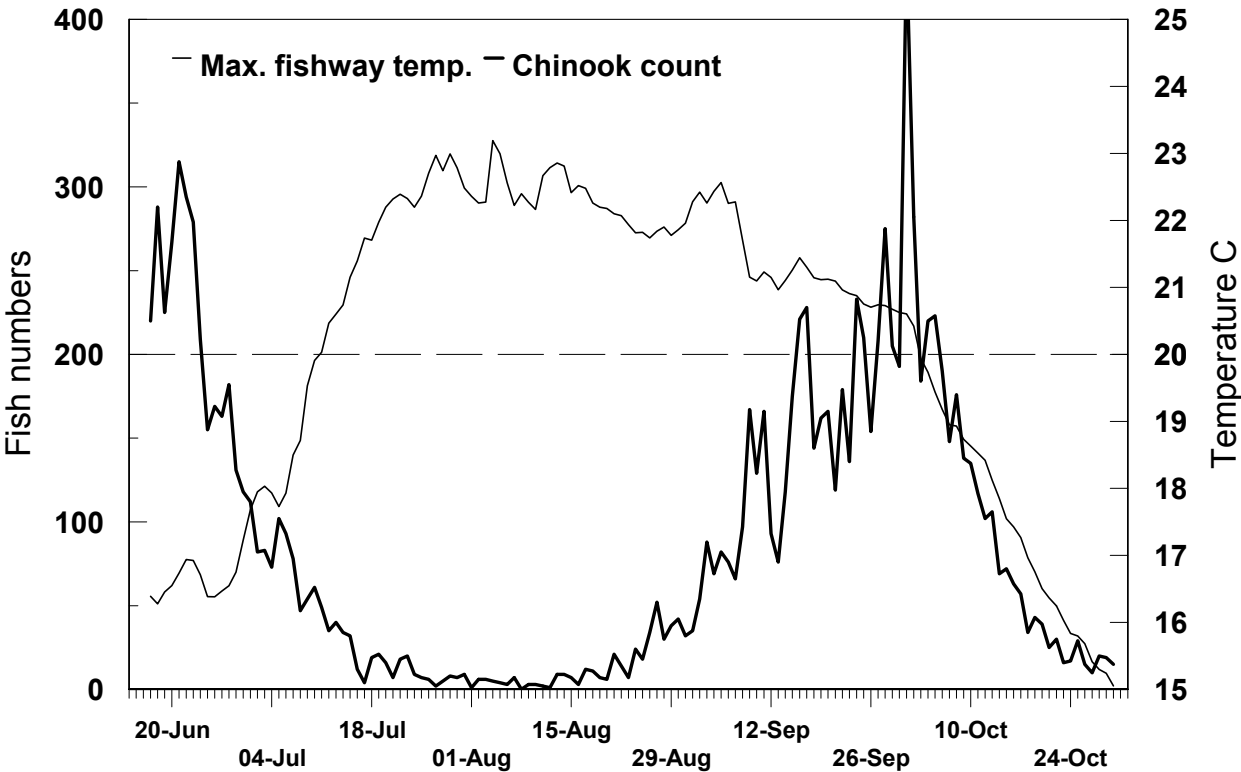
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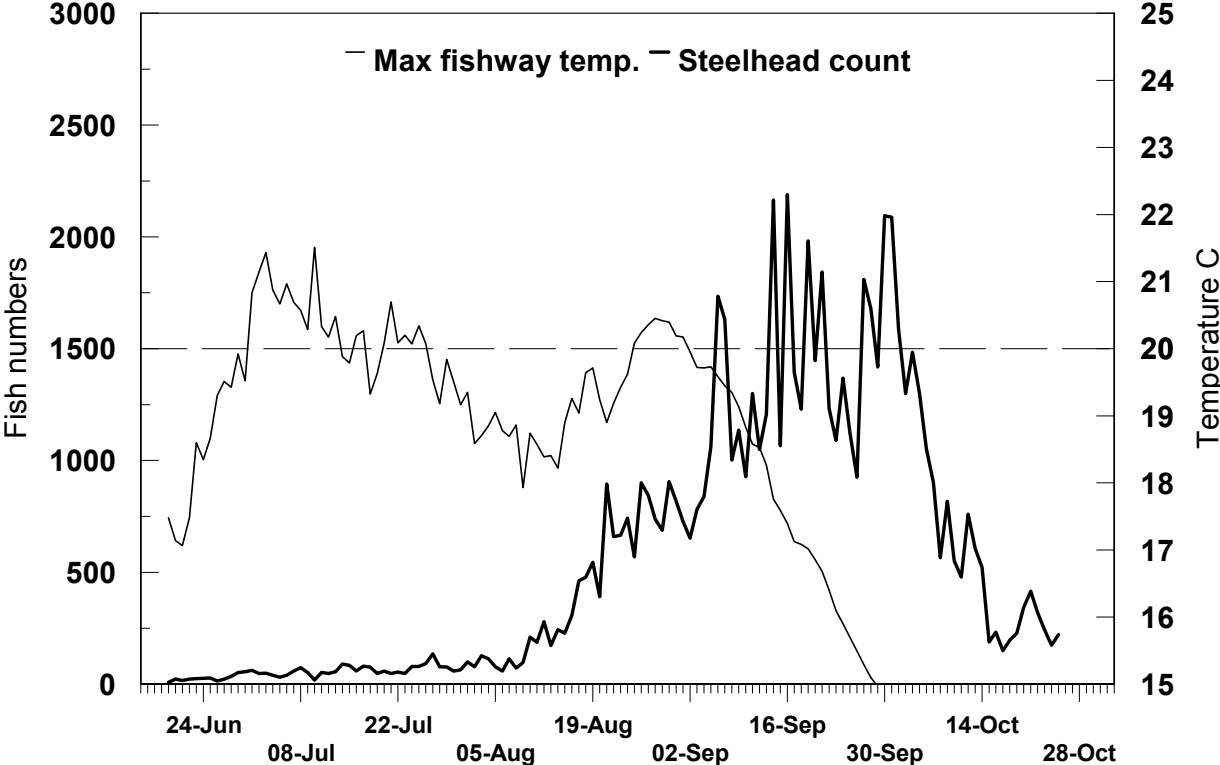
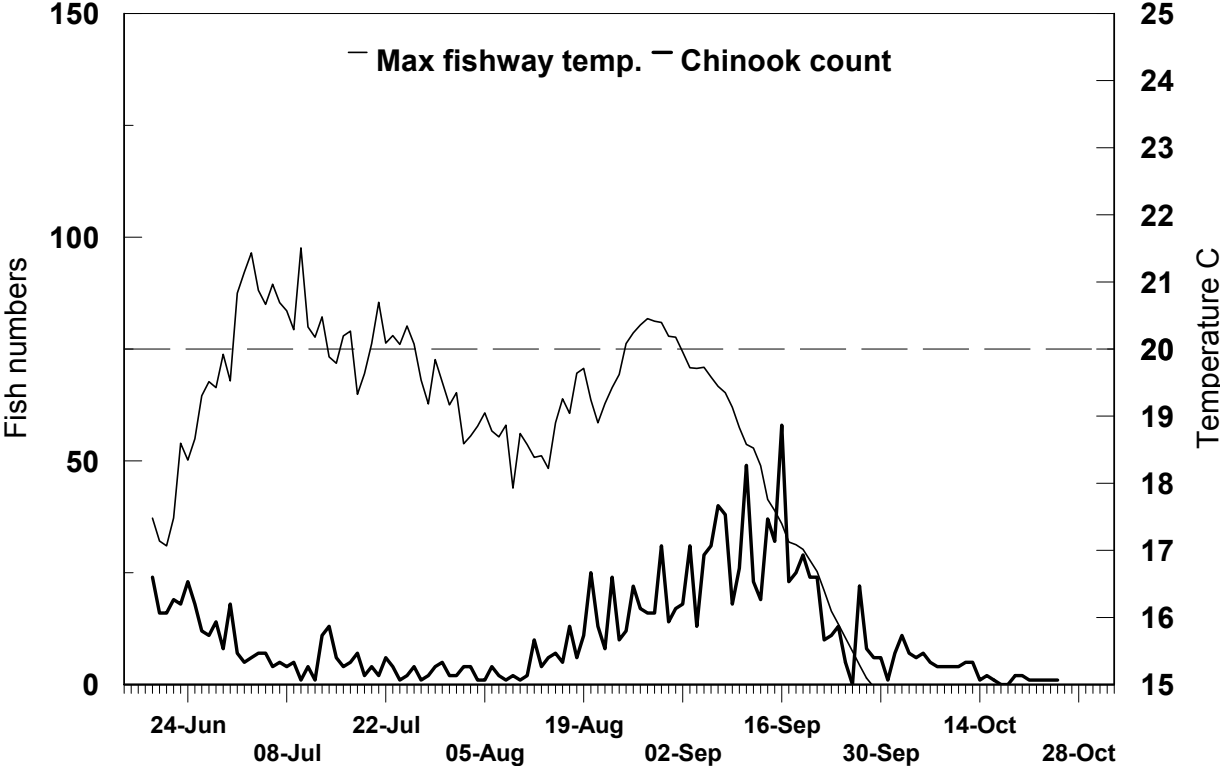
Ice Harbor 1997 steelhead



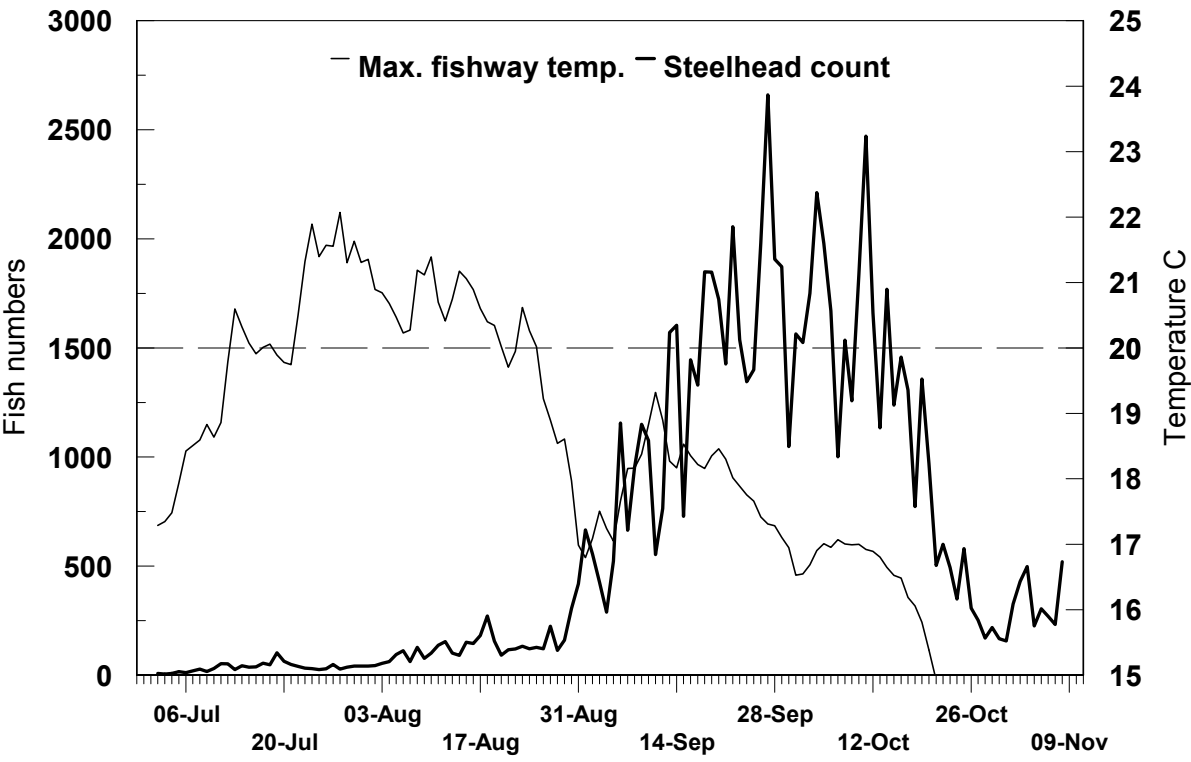
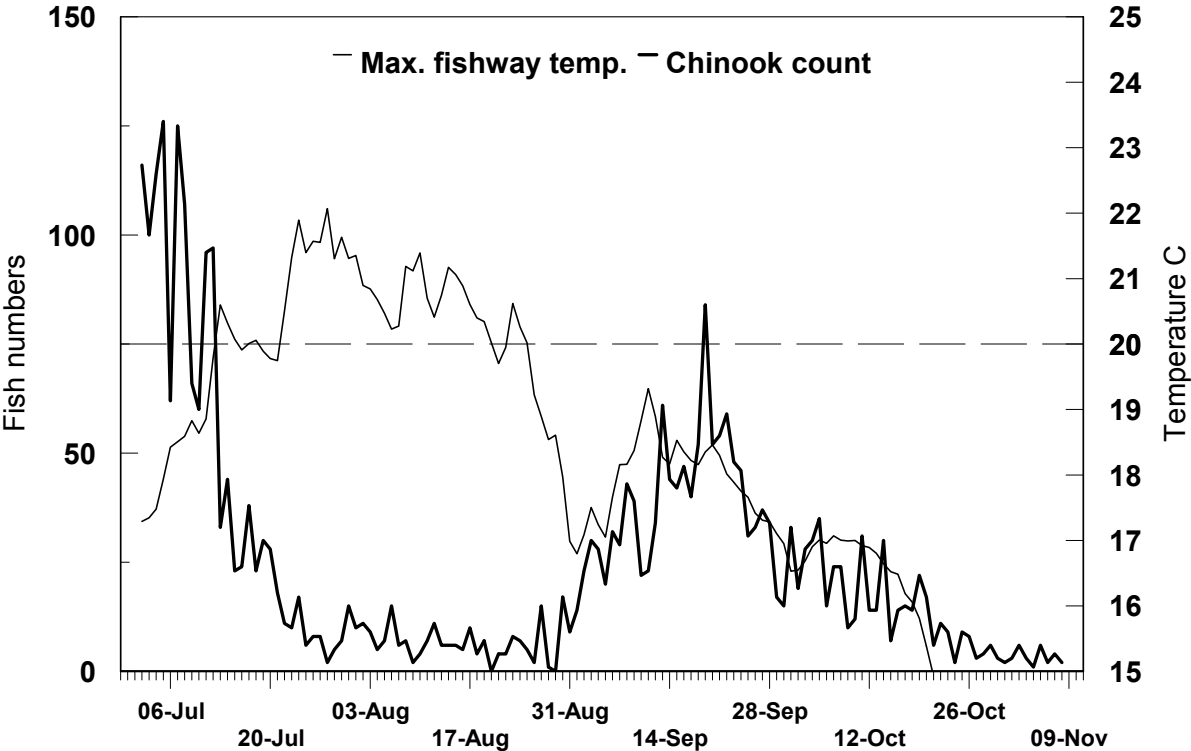
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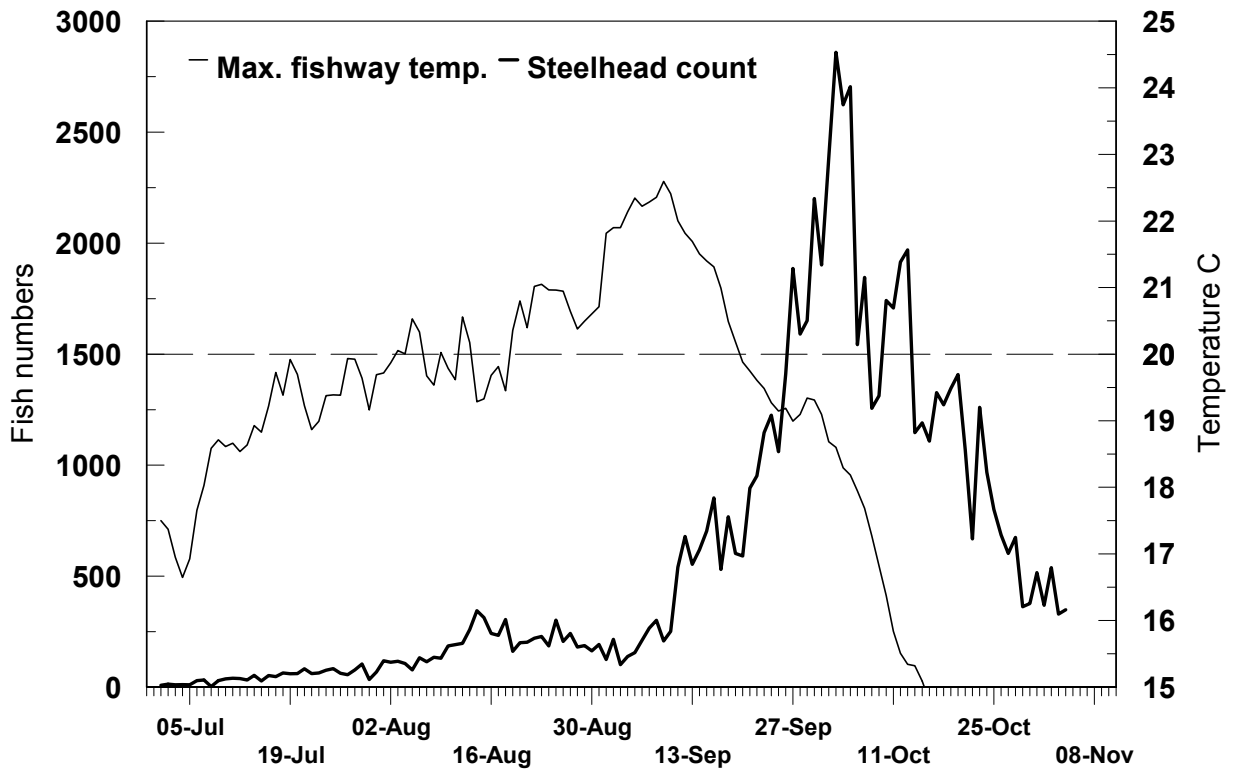
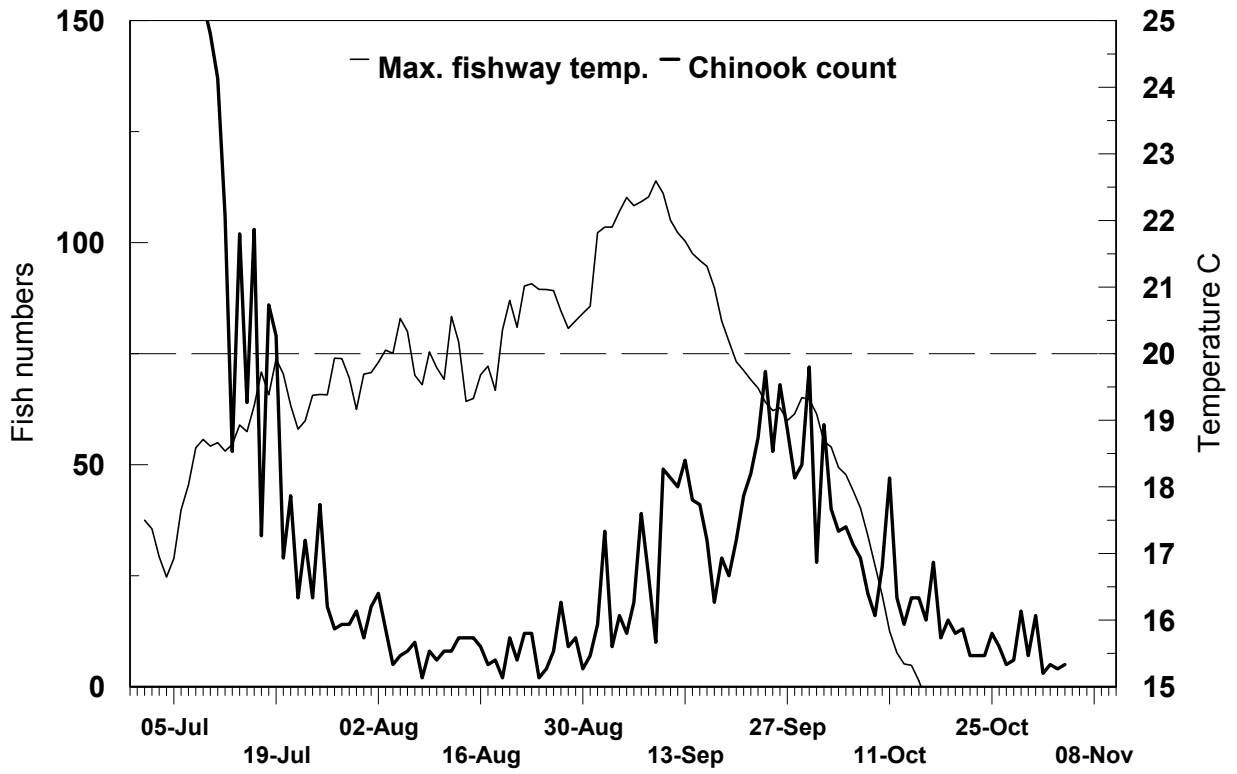
Lower Granite Dam 1995



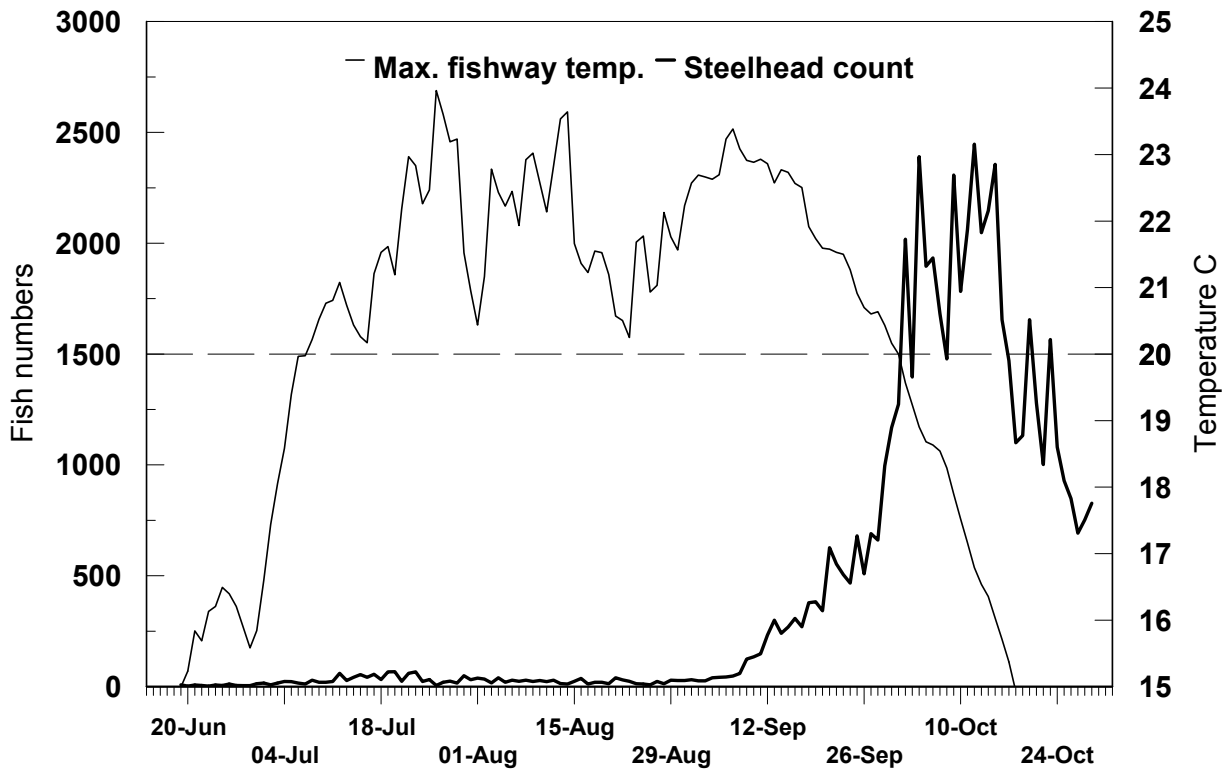
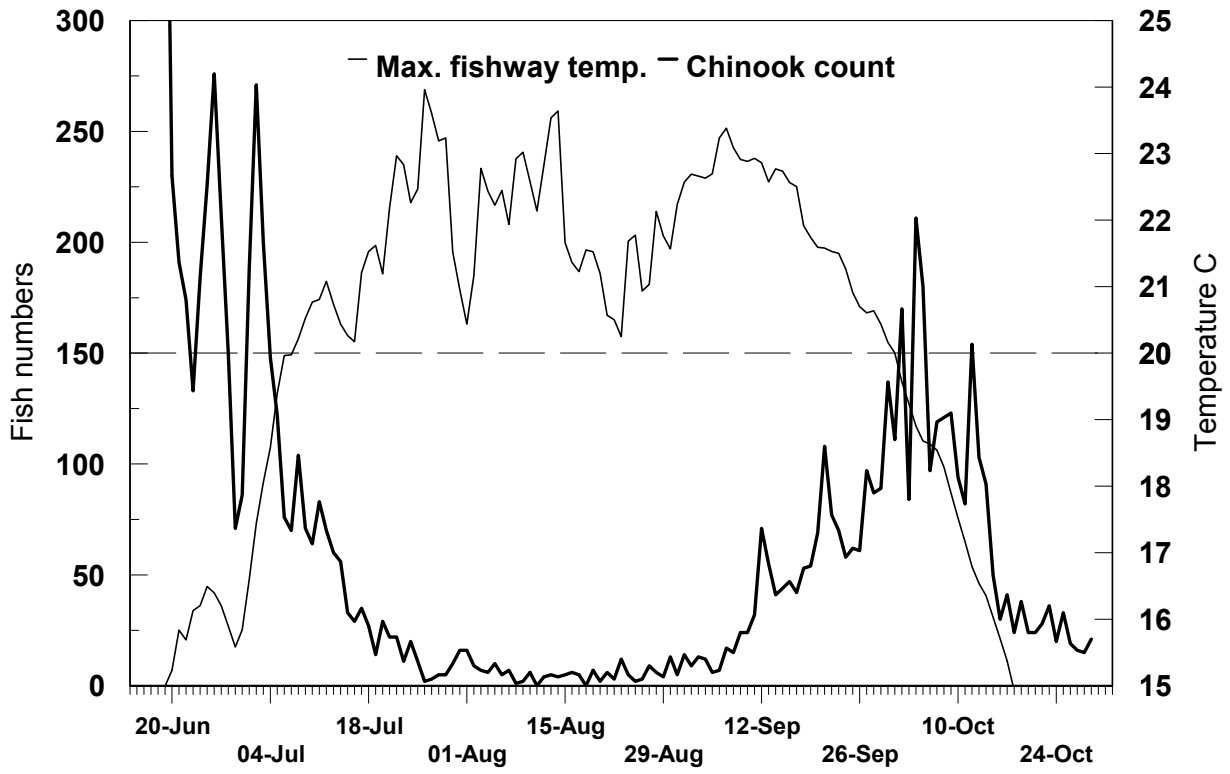
Lower Granite Dam 1996



Lower Granite Dam 1997

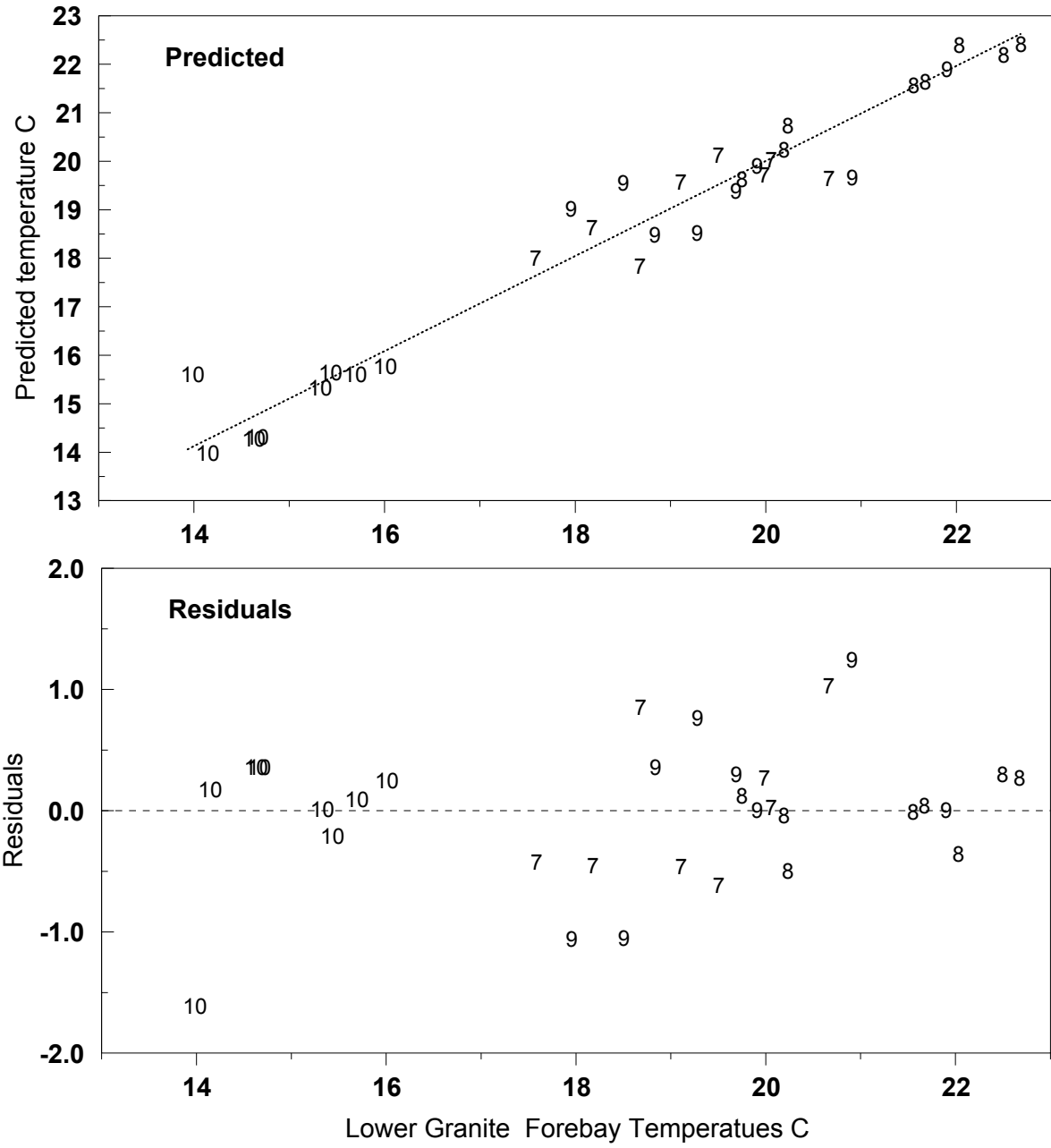


Lower Granite Dam 1998



Appendix B.

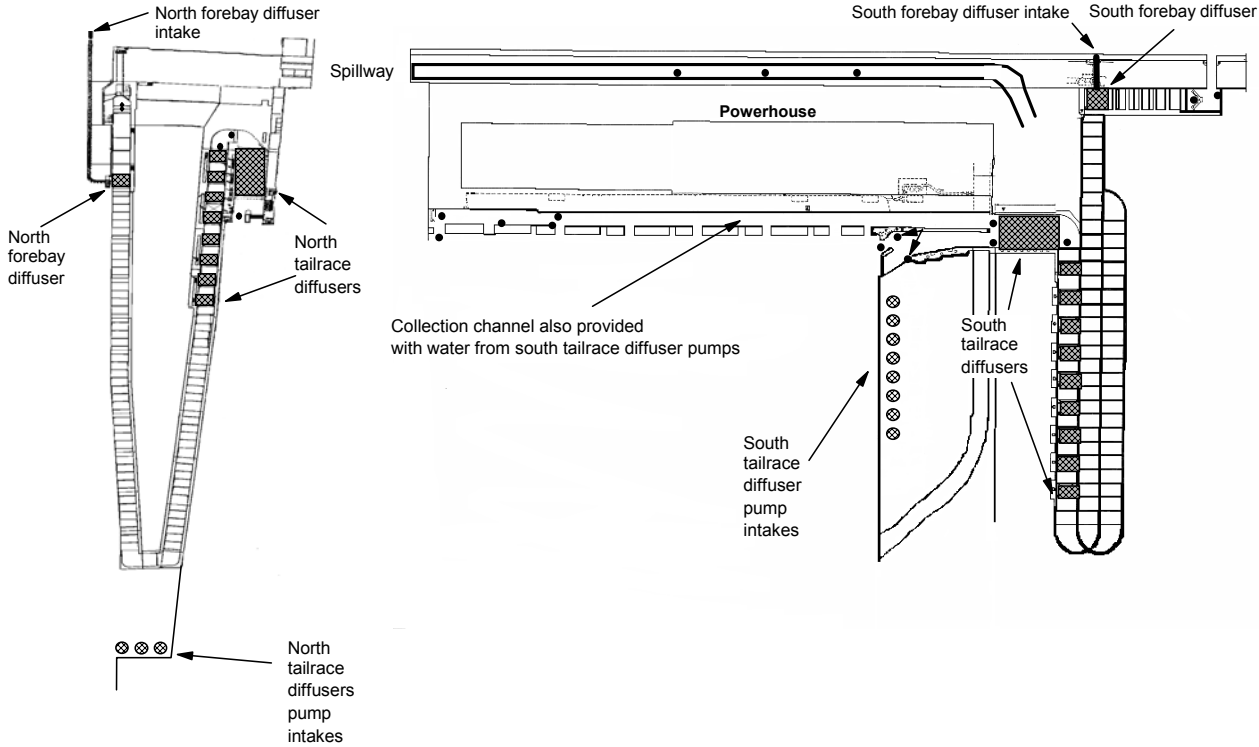
Plots of predicted values and residual errors versus observed Lower Granite Dam forebay temperatures. Labels in plots represent mean monthly temperatures for eight years of data, 1980, 1982, 1983, 1984, 1995, 1996, 1997, and 1998.



Appendix C.

Schematic of fishways and make-up water supply routes for fishways at Ice Harbor and Lower Granite dams.

Ice Harbor Dam Fishway Auxillary Water System



Lower Granite Dam Fishway Makeup Water System

