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

by

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Table of Contents

Abstract

We used recently collected and historic data to evaluate effects of warm water conditions 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 partially 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 what we considered optimal temperatures for migrating adult salmonids. 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 and through the lower Snake River, and some fish took longer to pass 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.

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 avoided the warmest surface waters in reservoirs by moving deeper in the water column. But to pass dams, adult migrants must swim near the surface to find and move through the relatively shallow (6-8 ft depth) fishways.

Water in fishways initially flow in from the surface of the forebay and is augmented by water 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 determine 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 exists 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 under development 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 (Groot et al. 1995). Oregon has adopted the water quality guideline that a 7-d moving average of maximum daily water temperatures should not exceed 17.8˚C (64˚F) in streams were 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 average 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 average temperatures were ≥ 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 combined surface area of about 13,556 ha (33,890 acres) at maximum pool levels (U. S. Army Corps of Engineers website: 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 an average flow of 1,132 m^3/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 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 determine how those temperatures affect passage of adult salmon and steelhead at the two dams.

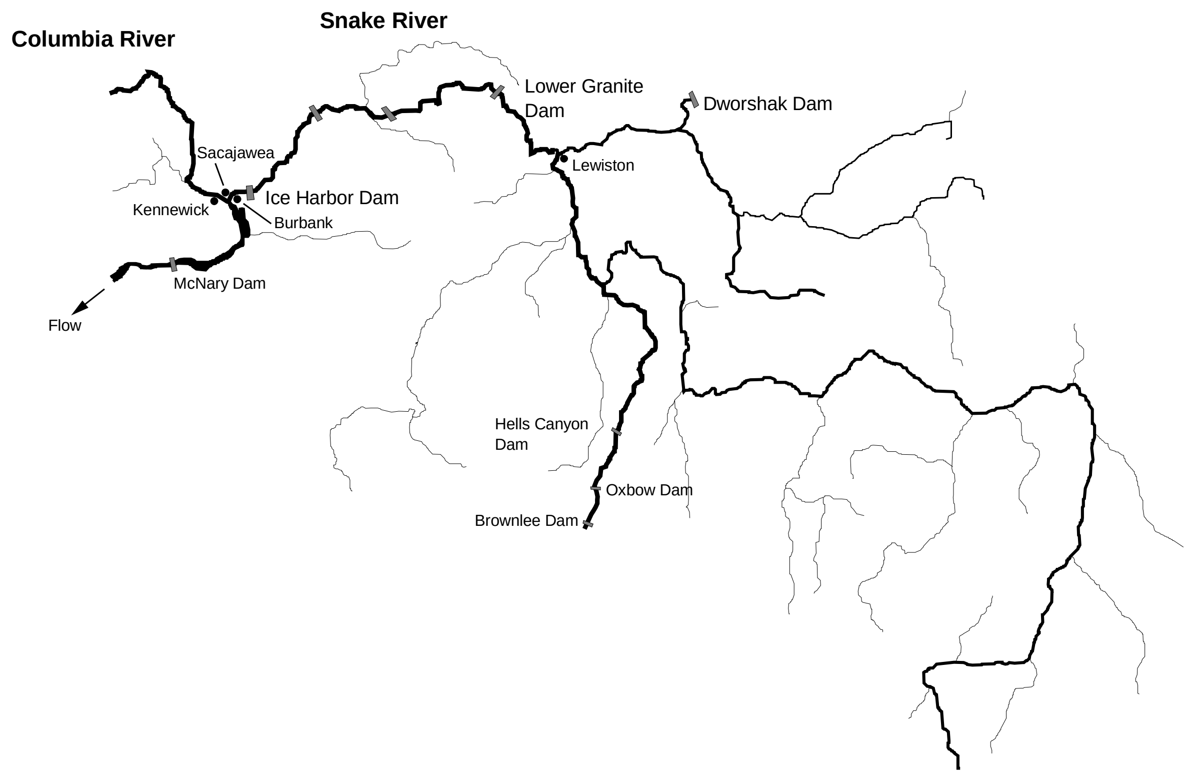


Figure 1. Map of Lower Snake River study area.

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 visually 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 in conjunction with the collection of samples for water-quality analysis, 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 averaged 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. 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. Turbine scrollcase temperatures are of water pulled from depths from 14 to 36 m below the surface. The National Oceanic and Atmospheric Administration (NOAA) has collected daily average 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 simple 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. 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

Thermal recording 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. Hourly temperatures at any one location were found to vary about 0.5ºC diurnally, and were averaged to produce one temperature per day at each recording site. Additionally, daily average 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).

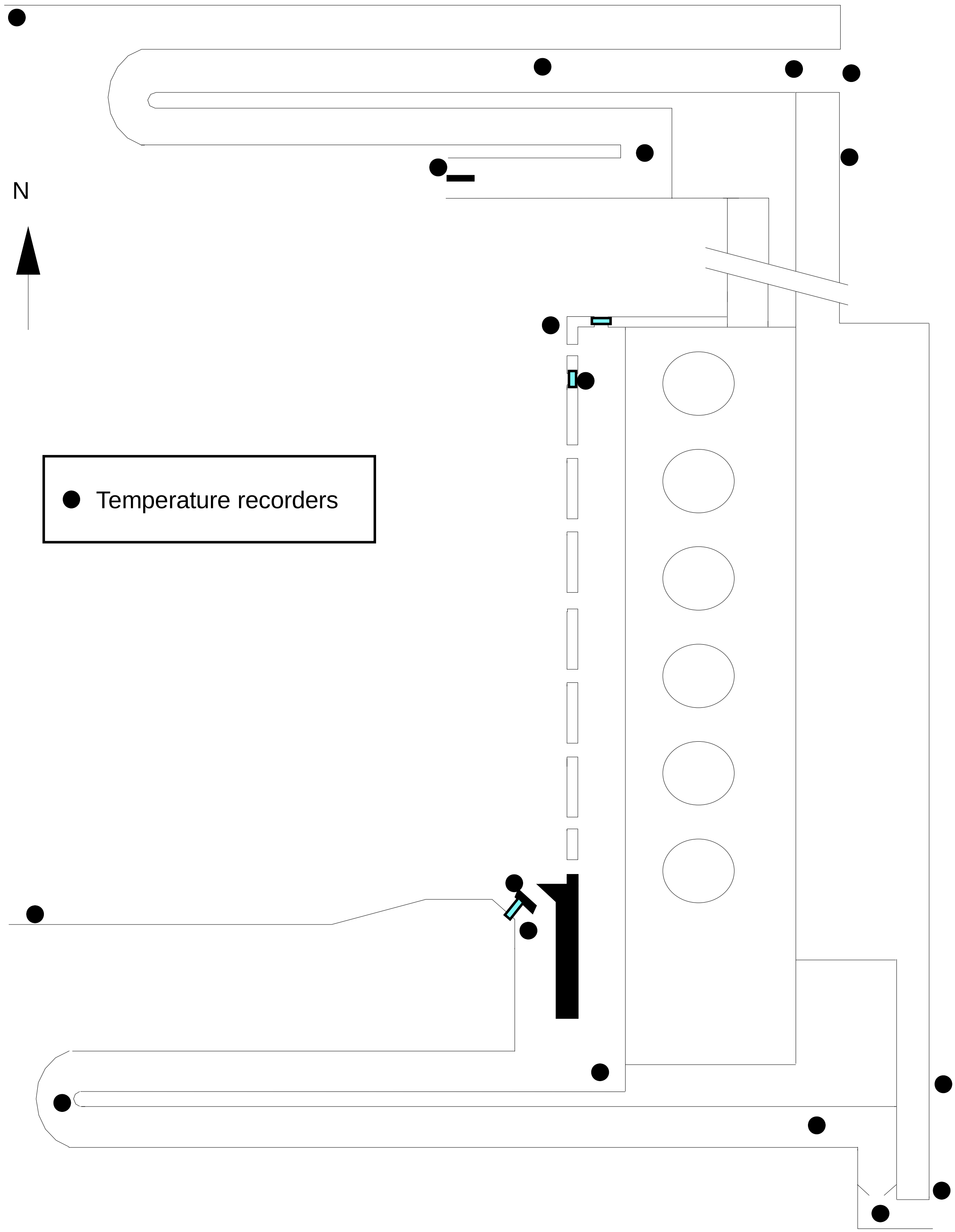


Figure 2. Location of temperature recorders used during 1995-98 at Ice Harbor Dam.

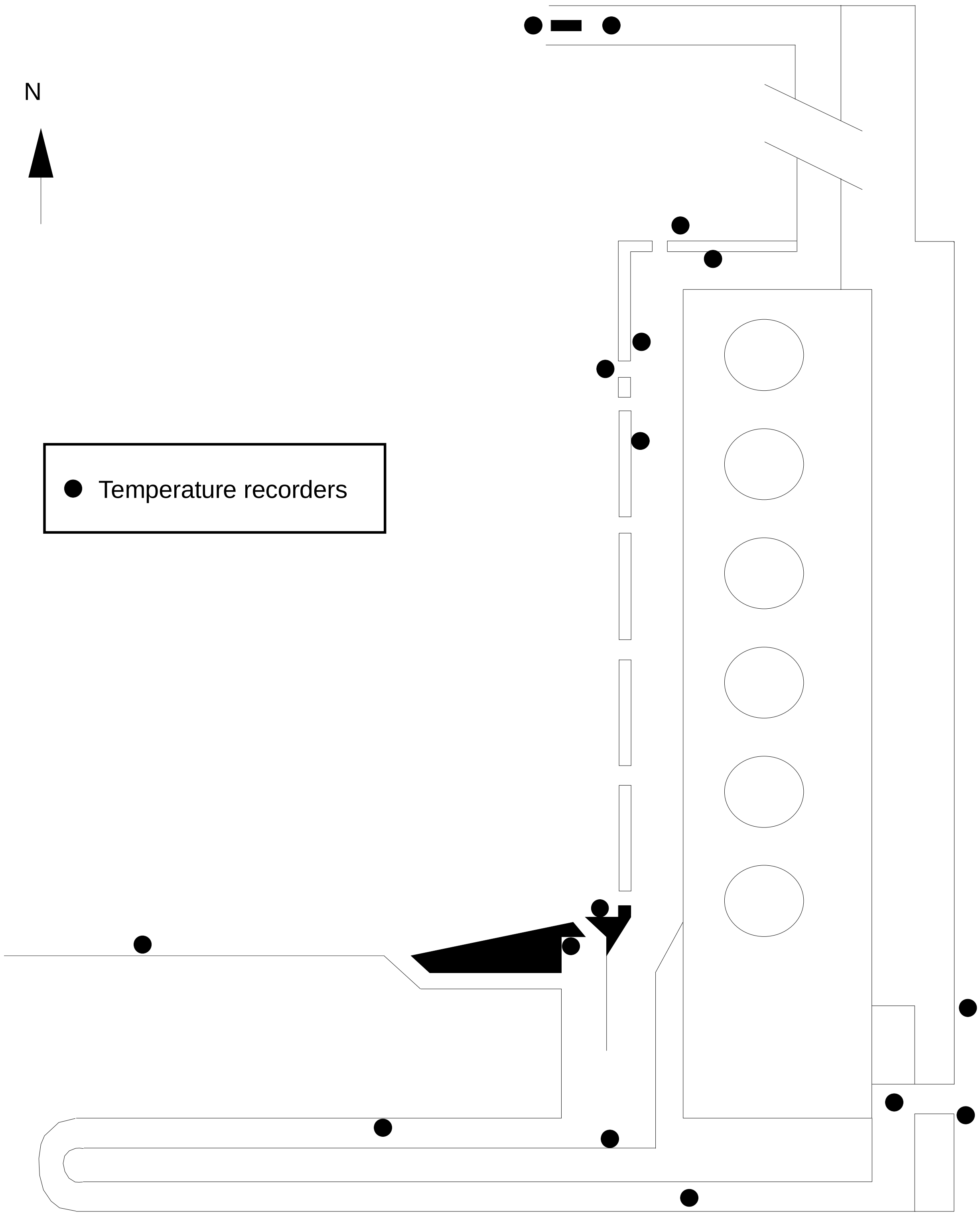


Figure 3. Location of temperature recorders used during 1995-98 at Lower Granite Dam.

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 average temperature measured at any of the eight locations on any given day (maximum daily temperature), usually near fishway exits, was used to characterize water conditions in fishways since it represented the most extreme conditions an adult migrant would experience while crossing the two dams. Warm water conditions were considered to exist if the maximum daily temperature exceeded 20ºC 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 the two dams on any given day.

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 yrs of data for this analysis, the 4 yrs during this study in the 1990’s (1995-98) with higher levels of summer flow from Dworshak, and 4 yrs 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 average daily forebay temperatures recorded by USACE at Lower Granite Dam from June through October during the 8 yrs, which was similar to the maximum daily fishway temperatures we measured during the 1995-98 period. Three 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. Snake River flow was the average flow (USACE readings) at Lower Granite Dam on the day water temperatures were recorded. Air temperatures were a three-day average 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 average 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 average for the dataset as a whole, although it may not be the best fit for any individual year. A polynomial regression equation was developed for the data using SAS statistical software (PROC RSREG, SAS Institute Inc. 1990) and used in simulations to determine relative affect of releasing water from Dworshak reservoir on 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 and 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 compared to various measures of water temperatures using simple linear regression. 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 outlyers would bias results of regression analysis, so at times analyses was performed with outlyers (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 would pass 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 at Ice Harbor Dam; 1975 to 2000 at 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). Average 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 average 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; in 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 average 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,

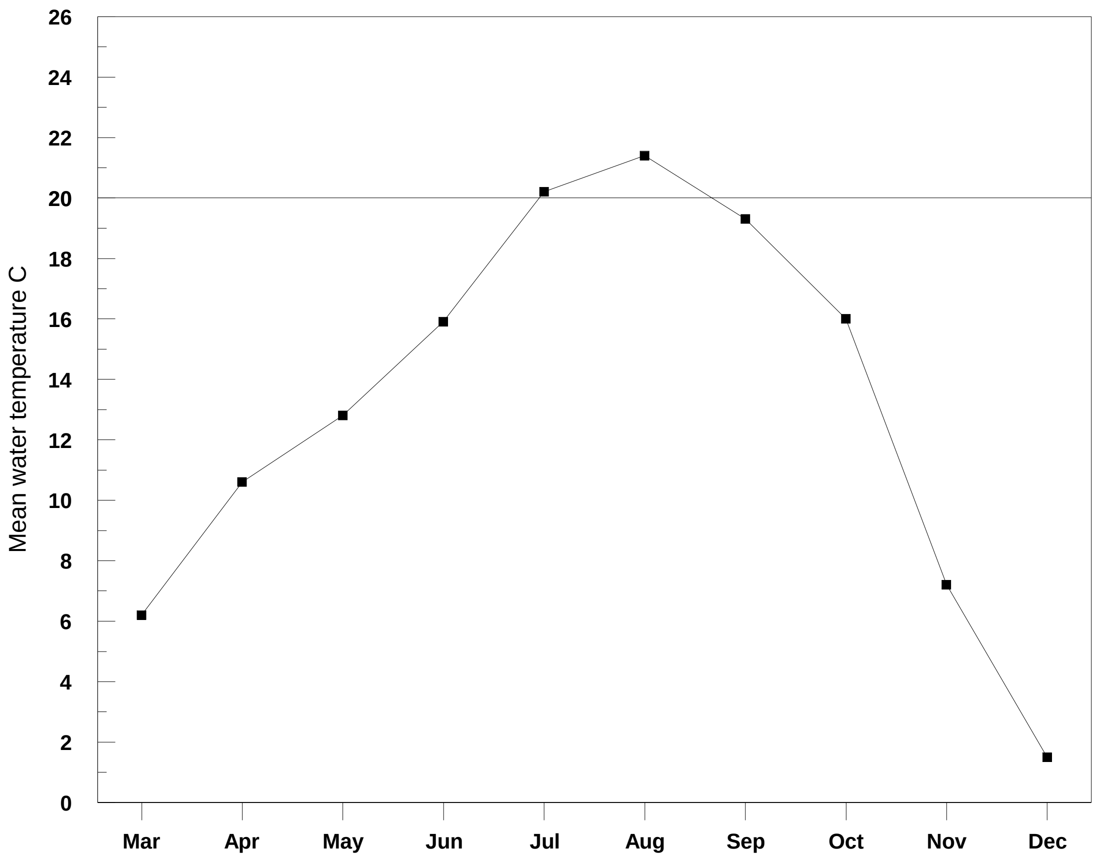


Figure 4. Mean monthly water temperatures near mouth of the Snake River during 1954-56 (Sacajawea, WA). Taken from Sylvester (1958).

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 20ºC or higher an average 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 average monthly temperatures in June (Regression P = 0.031, R^2 = 0.212), July (P = 0.019, R^2 = 0.245), 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. In 1962 Brownlee and Oxbow dams were in place. Between 1962 and 1973, five mainstem dams were constructed on the Snake River (Hells Canyon, Lower

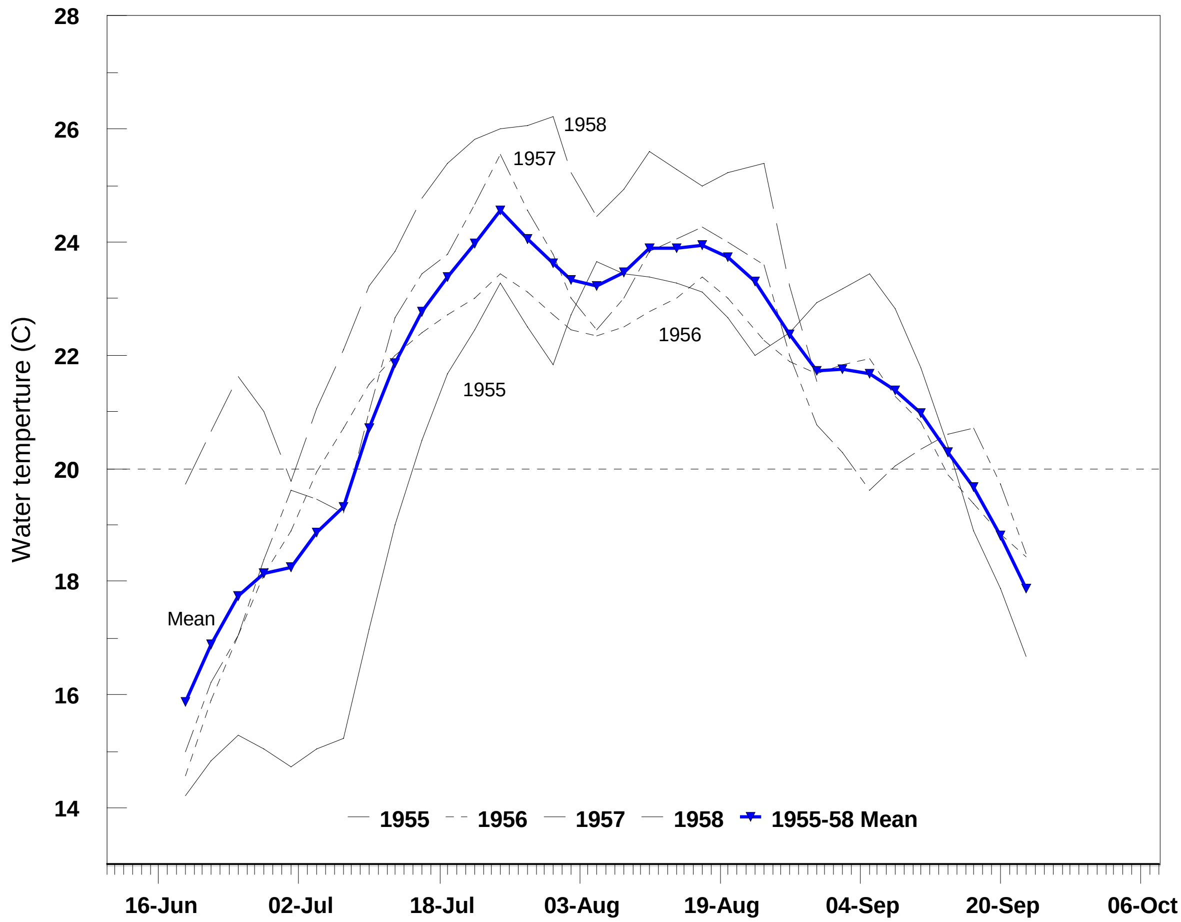


Figure 5. Water temperatures recorded at mouth of the Snake River (Sacajawea, WA) during 1955-58, and mean water temperatures for the four years. Taken from Eldridge (1963) and Bennett et al. (1997).

Monumental, Little Goose, Dworshak, and Lower Granite). Following impoundment of the lower Snake River by Ice Harbor Dam, average monthly water temperatures in the forebay generally increased during October ($P = 0.011$, $R^2 = 0.171$) and were unchanged during June ($P = 0.131$), July ($P = 0.536$), August ($P = 0.055$), and September ($P = 0.373$) during the period 1962-99 (Figure 7). The monthly maximum temperature (highest daily average for each month) was unchanged for June ($P > 0.4$), July ($P > 0.7$), August ($P = 0.109$), September ($P > 0.9$), and October ($P > 0.3$) since 1962. Likewise, variability in temperature data for each month (standard deviation of daily average temperatures) was unchanged during June, July, August, September and October since 1962. The date of maximum daily average temperature in the forebay of

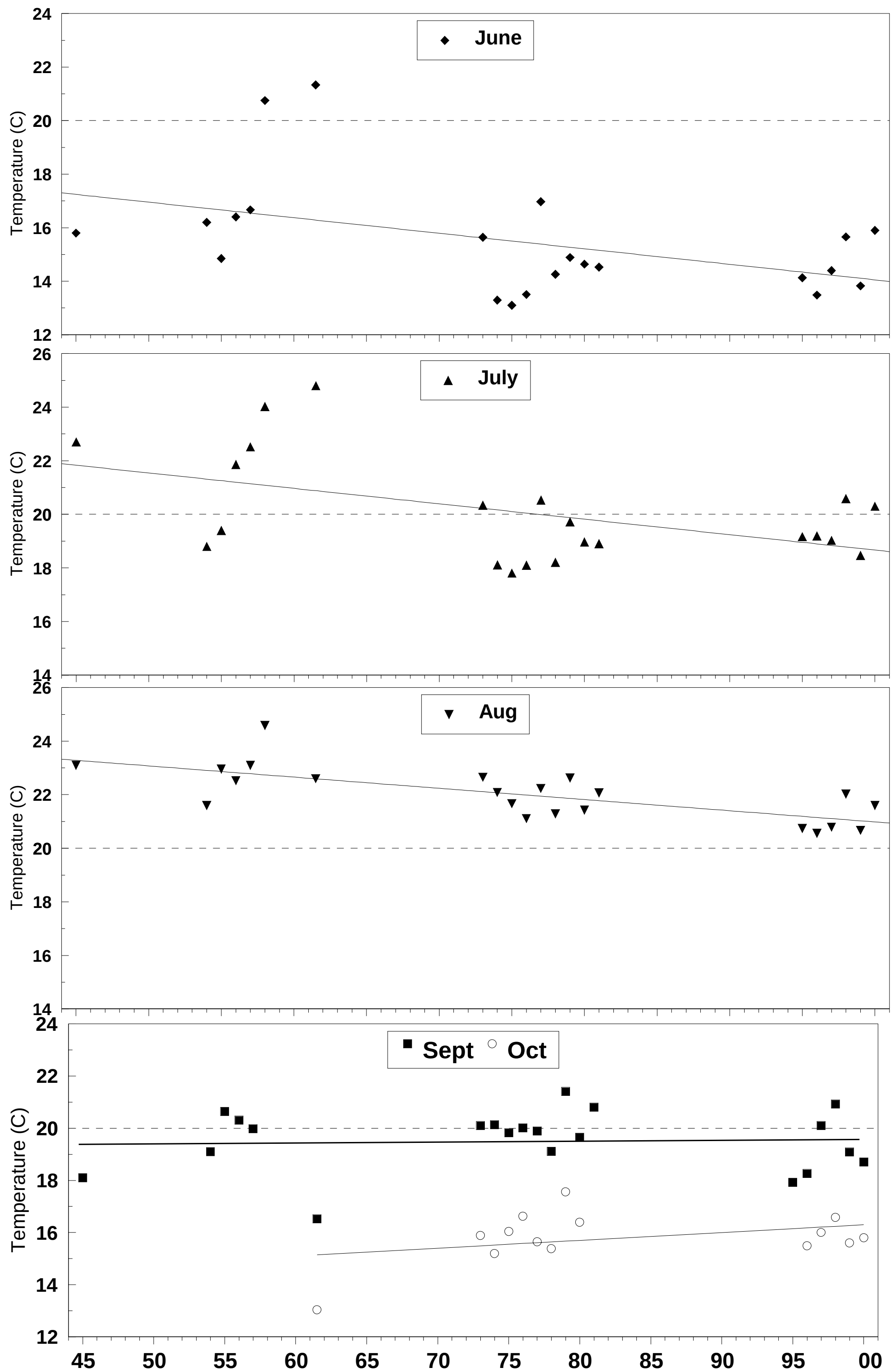


Figure 6. Average monthly temperatures near mouth of Snake River. Temperatures from 1990's collected at USACE site 5.8 km downstream from Ice Harbor Dam. Earlier data were from USGS sites at the mouth of the Snake River, 16 km downstream from the dam.

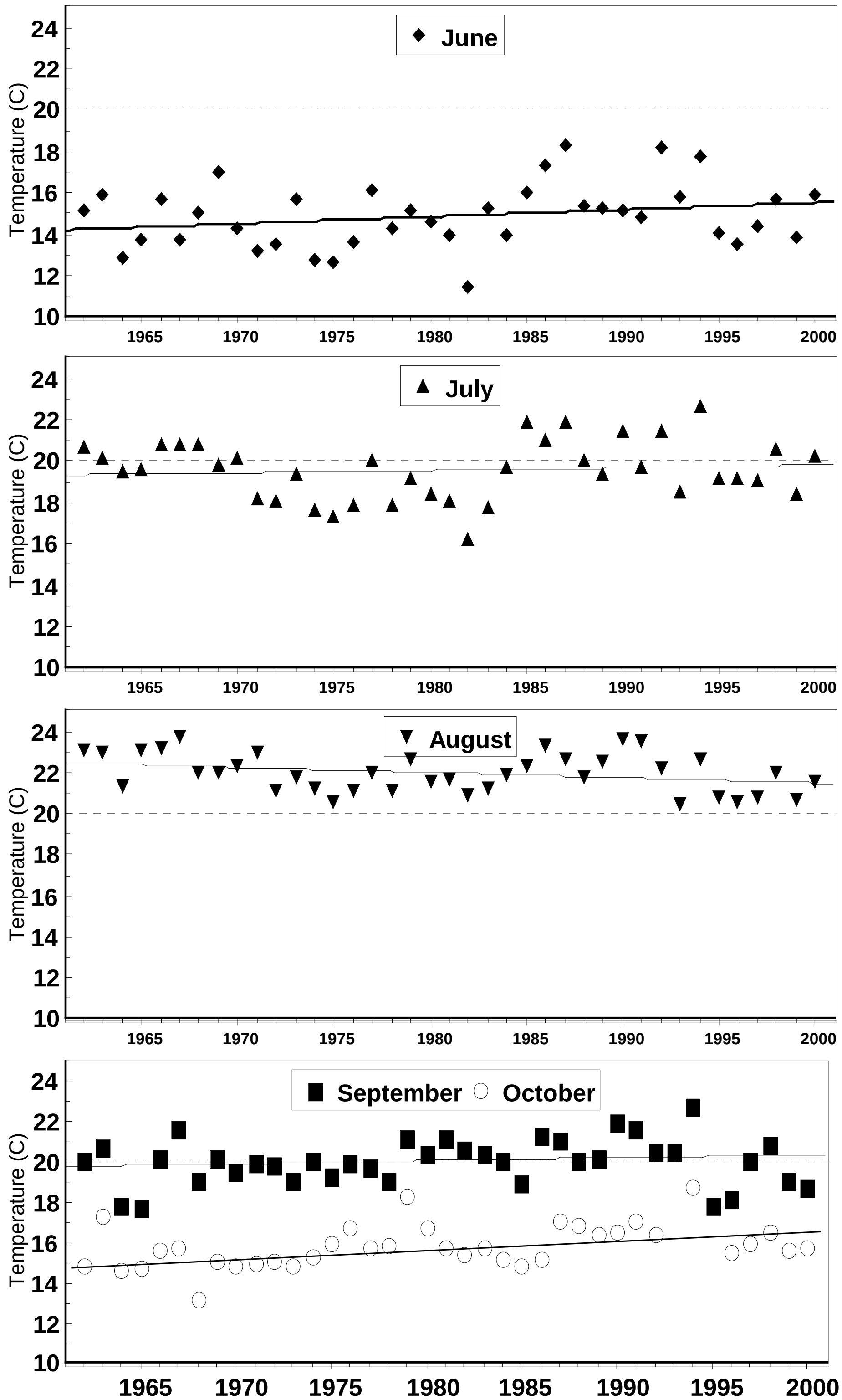


Figure 7. Mean monthly temperatures in forebay of Ice Harbor Dam. Forebay temperatures collected hourly at depth of 5 m since May 1983. Daily scrollcase temperatures used prior to 1983.

Ice Harbor Dam for each year has not changed ($P > 0.7$), being about 23ºC 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 ($P > 0.228$), July ($P > 0.378$) and October ($P < 0.272$) and have increased during August ($P < 0.001$, $R^2 = 0.2203$) and September ($P < 0.001$, $R^2 = 0.361$) (Figure 8). Since 1962, when Ice Harbor Dam came into operation, the trend has been for increased flows during August over time ($P < 0.042$, $R^2 = 0.108$) 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 ($P < 0.01$, $R^2 = 0.161$), and during September at Kennewick ($P < 0.04$, $R^2 = 0.0863$) (Figure 10). Air temperatures during the remaining months at the two locations have not changed significantly ($P > 0.1$) 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 0.5ºC or less during the day, thus, the daily average 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 average recorded at any location during a given day. Maximum difference in water temperatures was the difference between the coolest and warmest average water

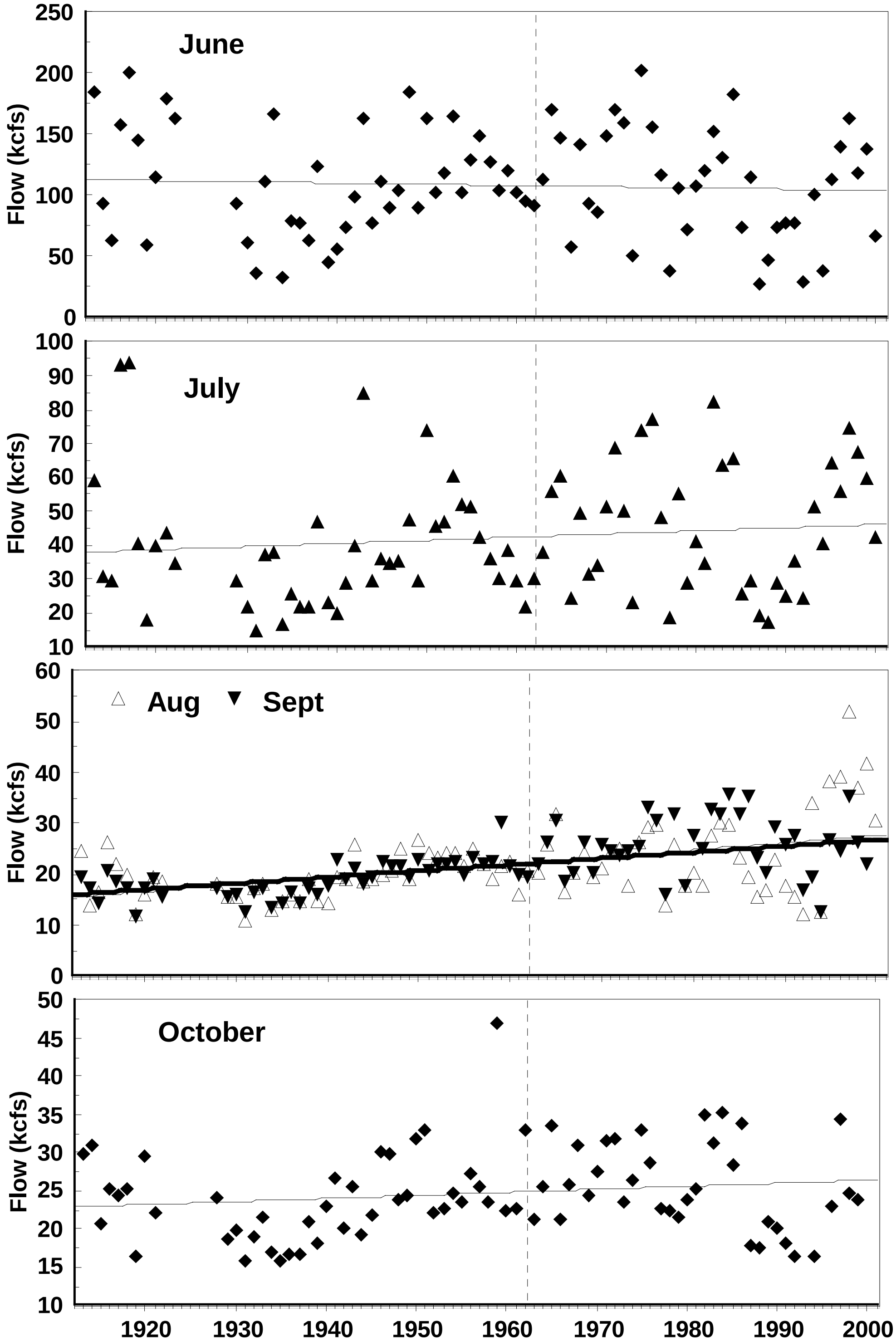


Figure 8. Mean monthly flows near mouth of the Snake River. Flows from 1913-15 are from USGS gauging station at Snake River mouth. Flows from 1916 to 1961 from USGS gauging station at Clarkston, WA, and would not account for inputs from Palouse and Tucannon rivers. Flows during 1962-99 were colleted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

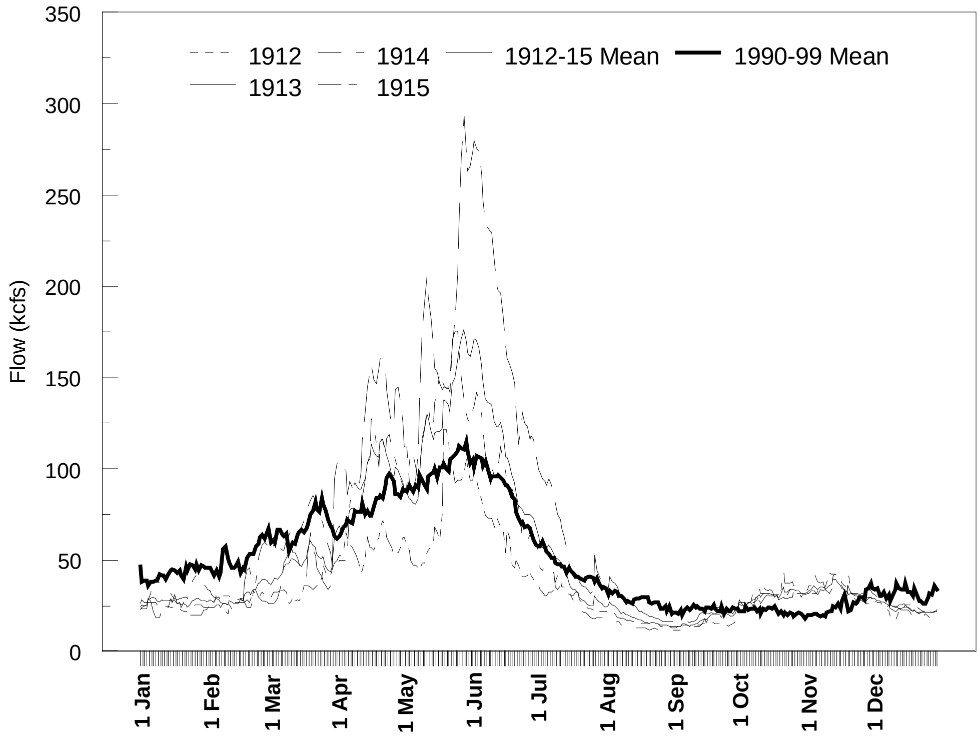


Figure 9. Snake River flows near mouth during 1912-15 and mean flows during 1990-99 period.

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 differences were generally less than 0.5ºC 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). In early July, water temperatures at Ice Harbor Dam were 18.0 to 18.5ºC. Temperatures first reached 20ºC on 17 July, peaked near at 23ºC on 4 August, then returned to around 20ºC again mid-August, where temperatures remained until 21 September when they dropped below 20ºC for the last time. By 19 October, water temperatures in the fishway were between 15 and 16ºC and declining. Daily maximum water temperatures at the dam averaged 20.1ºC (95% CI = $\pm$ 0.5ºC) in July,

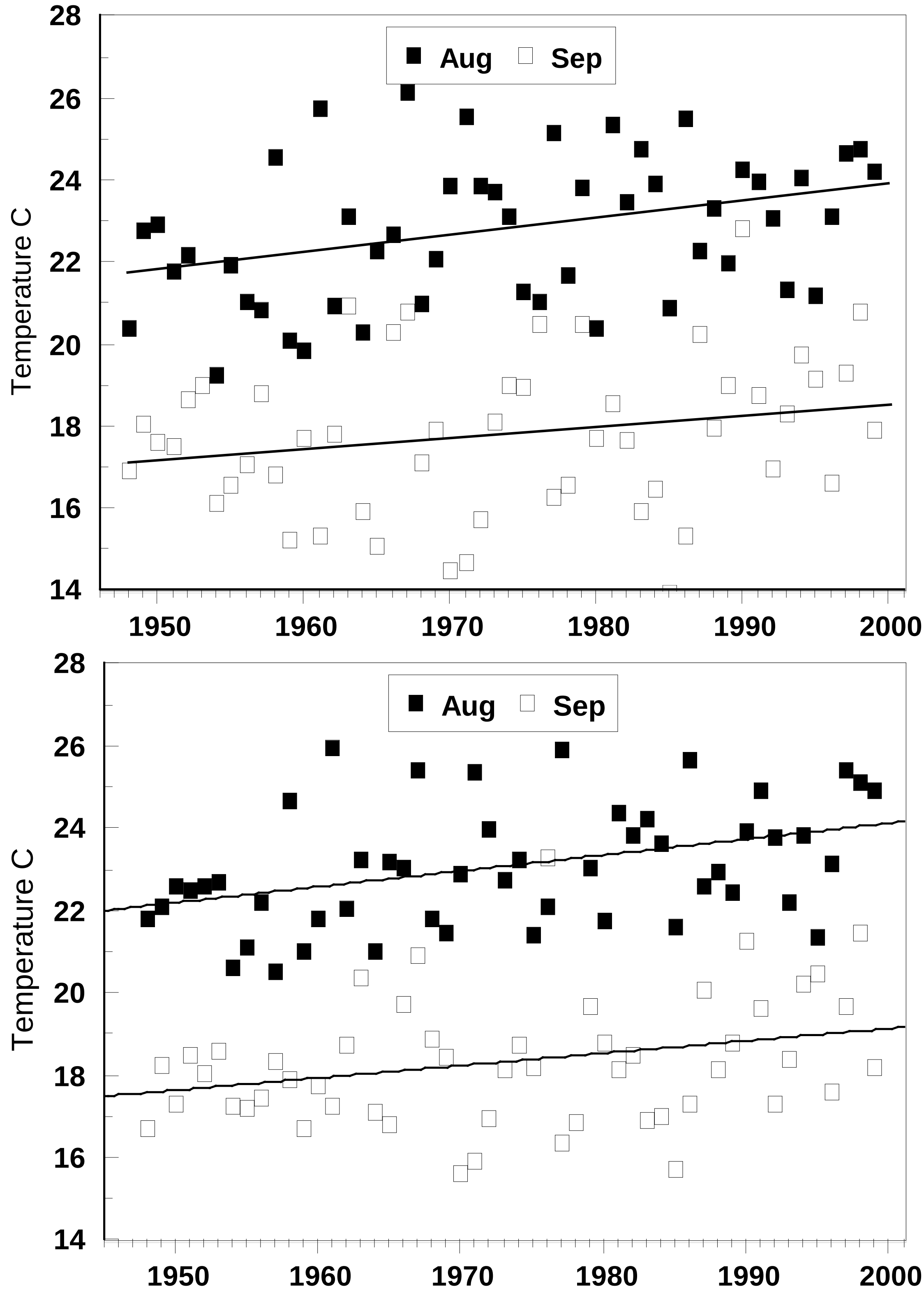


Figure 10. Mean monthly air temperatures during August and September at Lewiston, ID. (top) and Kennewick, WA from 1948 until 1999.

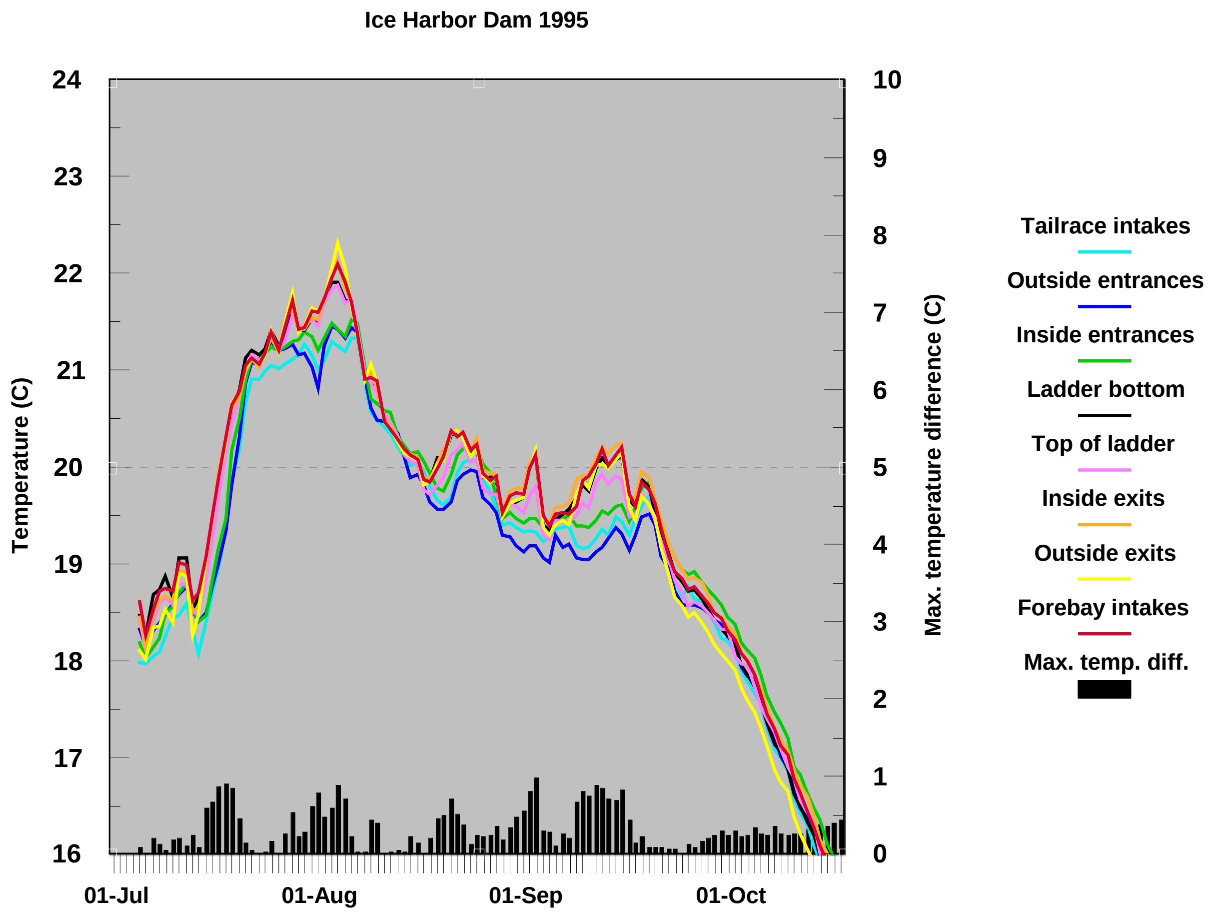


Figure 11. Water temperatures measured in and around fishways at Ice Harbor Dam in 1995.

20.6ºC (± 0.3ºC) during August, 19.6ºC (± 0.2ºC) during September, and 17.3ºC (± 0.4ºC) through 19 October. There were 56 d when the daily average temperature somewhere in system was 20ºC 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 0.1ºC 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).

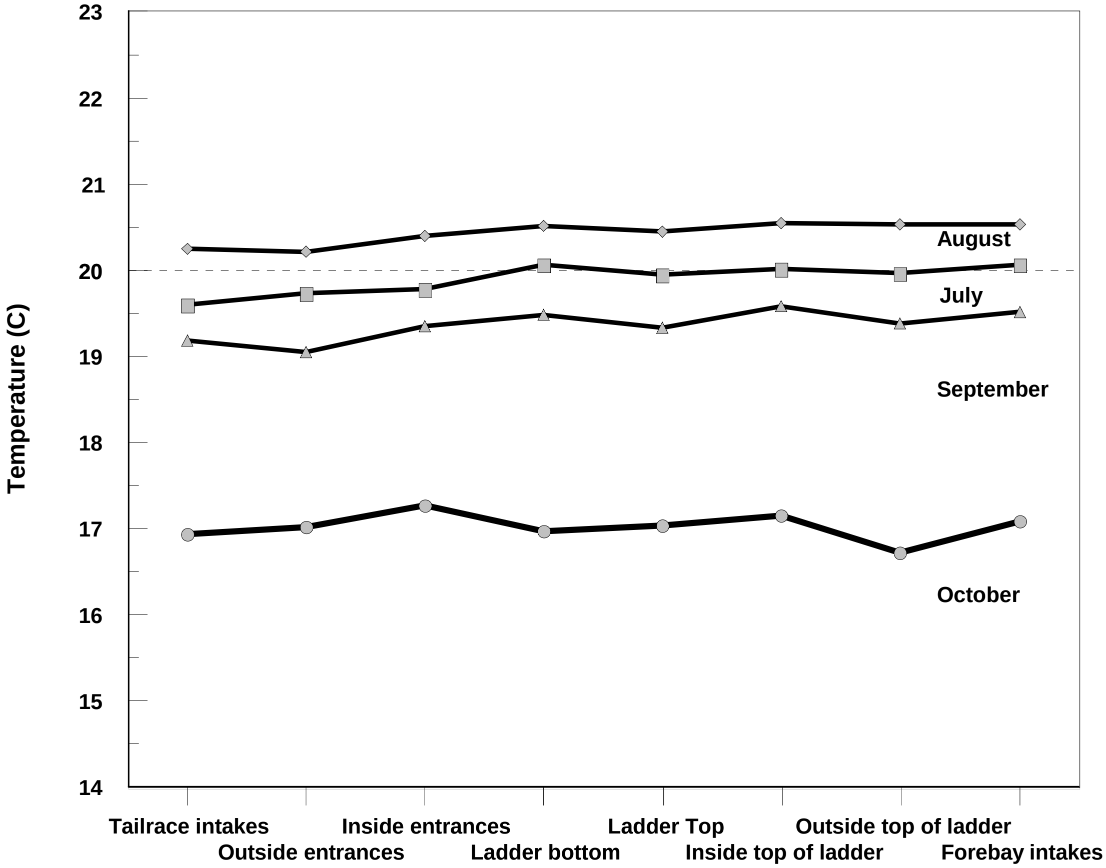


Figure 12. Monthly average water temperatures measured in and near fishways at Ice Harbor Dam in 1995.

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 1ºC , averaging 0.3 to 0.4ºC 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 0.5ºC 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 16.1ºC. Temperatures first reached 20ºC on 11 July, peaked at 23ºC on 26 July and then again on 10 August, and dropped below 20ºC for the last time on 10 September. Daily maximum water temperatures at the dam averaged 19.7ºC (±

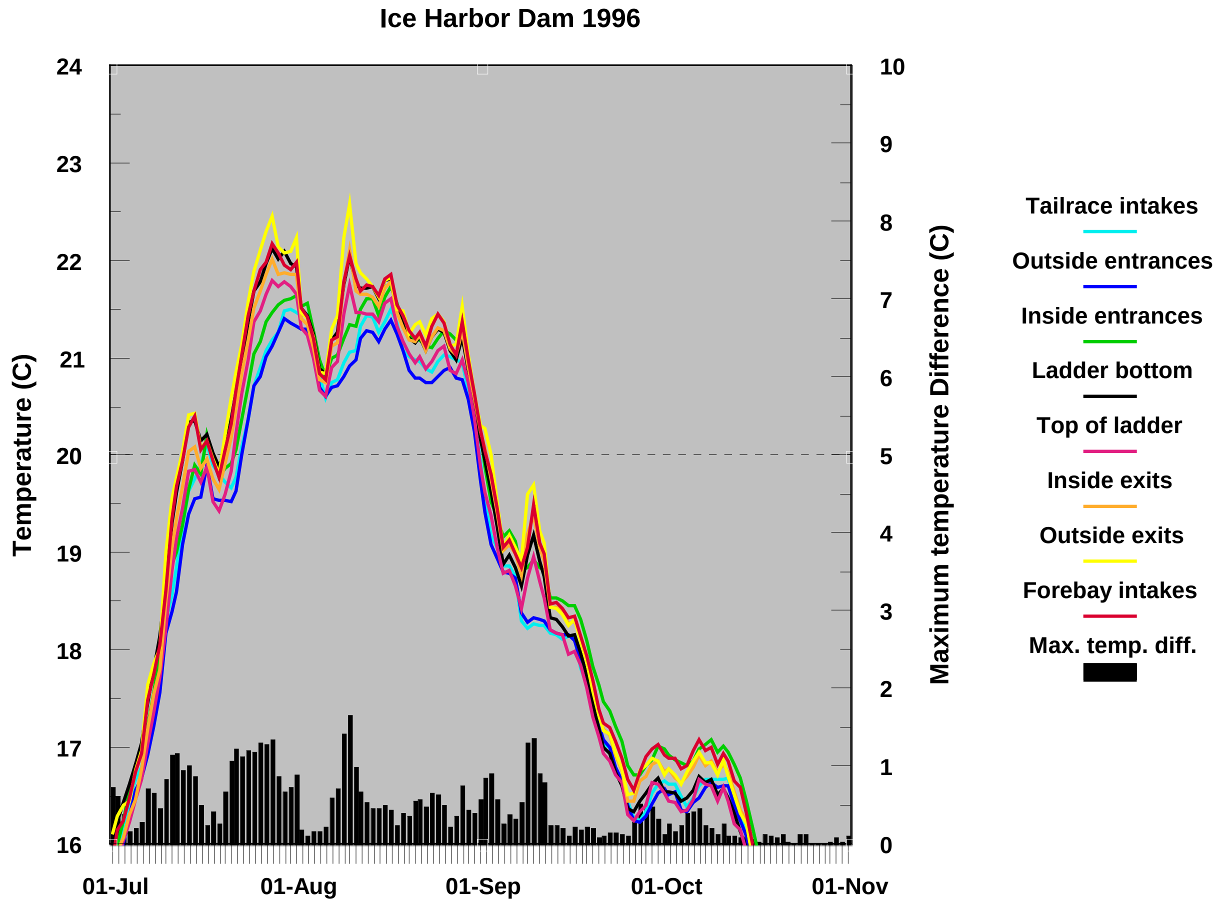


Figure 13. Water temperatures measured in and around fishways at Ice Harbor Dam in 1996.

0.7ºC) in July, 21.5ºC (+ 0.1ºC) during August, 18.4ºC (+ 0.4ºC) during September, and 15.7ºC (+ 0.5ºC) during October. By the end of October, water temperatures were around 13ºC. There were 57 d when the average temperature somewhere at the dam was 20ºC 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 20.9ºC (+ 0.2ºC) for the two month period. In the fishway, highest water temperatures were recorded at the base of the ladder, averaging 20.8ºC (+ 0.3ºC) during that same period. On average, water temperatures increased about 0.4ºC 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 1.6ºC, averaging 0.2, 0.8, 0.5, and 0.4ºC during June, July, August, and September, respectively. Temperatures were generally warmer in the north ladder than in the south ladder, by up to 1.2ºC difference in October, although during the warmest period of the 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 18.0ºC. Temperatures first reached 20ºC on 19 July, peaked at 22ºC on 6 August, and dropped below 20ºC for the last time on 26 September. Daily maximum water temperatures at the dam averaged 19.5ºC ($\pm$ 0.4ºC) in July, 21.2ºC ($\pm$ 0.1ºC) during August, 20.4ºC ($\pm$ 0.2ºC) during September, and 16.3ºC ($\pm$ 0.6ºC) during October. By the end of October, water temperatures were around 13.5ºC. There were 67 d when average temperature somewhere at the dam was 20ºC 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 = 20.9ºC $\pm$ 0.1ºC) and at the forebay surface outside fishway exits (20.8ºC $\pm$ 0.1ºC) for the two month period. On average, water temperatures increased about 0.2ºC 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 temperatures at the dam at any one time ranged from 0.2 to 1.1ºC, averaging 0.6, 0.5, and 0.4ºC 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 0.5ºC 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 17.7ºC. Temperatures first reached 20ºC on 10 July, peaked above 23ºC on three occasions; 27 July, 4 August, and 13 August, and dropped below 20ºC for the last time on 3 October. Daily maximum water temperatures at the dam averaged 20.8ºC ($\pm$ 0.7ºC) in July, 22.4ºC ($\pm$ 0.1ºC) during August, 21.4ºC ($\pm$ 0.3ºC) during

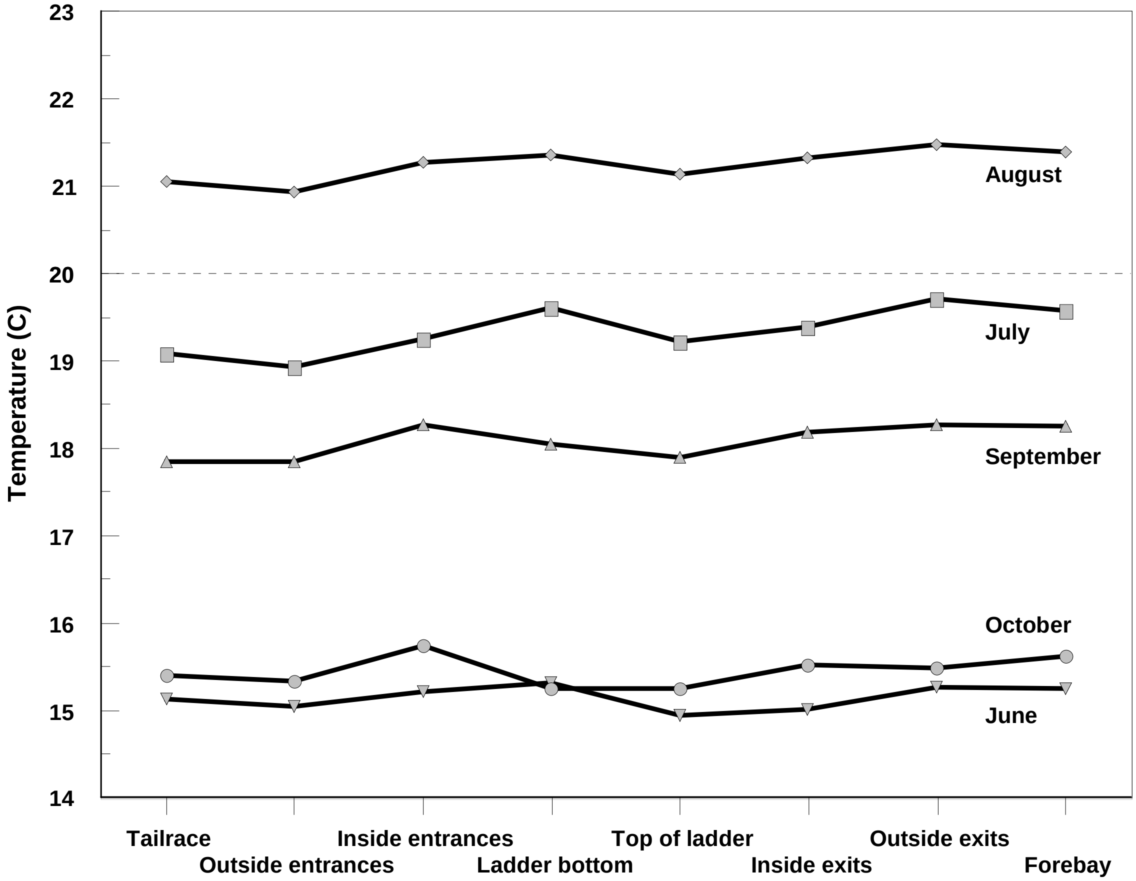


Figure 14. Monthly average water temperatures measured in and near fishways at Ice Harbor Dam in 1996.

September, and 17.8ºC (+ 0.6ºC) during October. By the end of October, water temperatures were around 15ºC. There were 86 d when average temperature somewhere at the dam was 20ºC or higher.

During the warmest time of year (9 July to 5 October), water temperatures were fairly uniform at the dam, ranging from 21.3ºC in the tailrace, to 21.7ºC in the forebay. As opposed to the three previous years, there was not a noticeable increase in 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 1.4ºC, averaging 0.4, 0.5, 0.5, and 0.3ºC 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 0.5ºC between comparable locations.

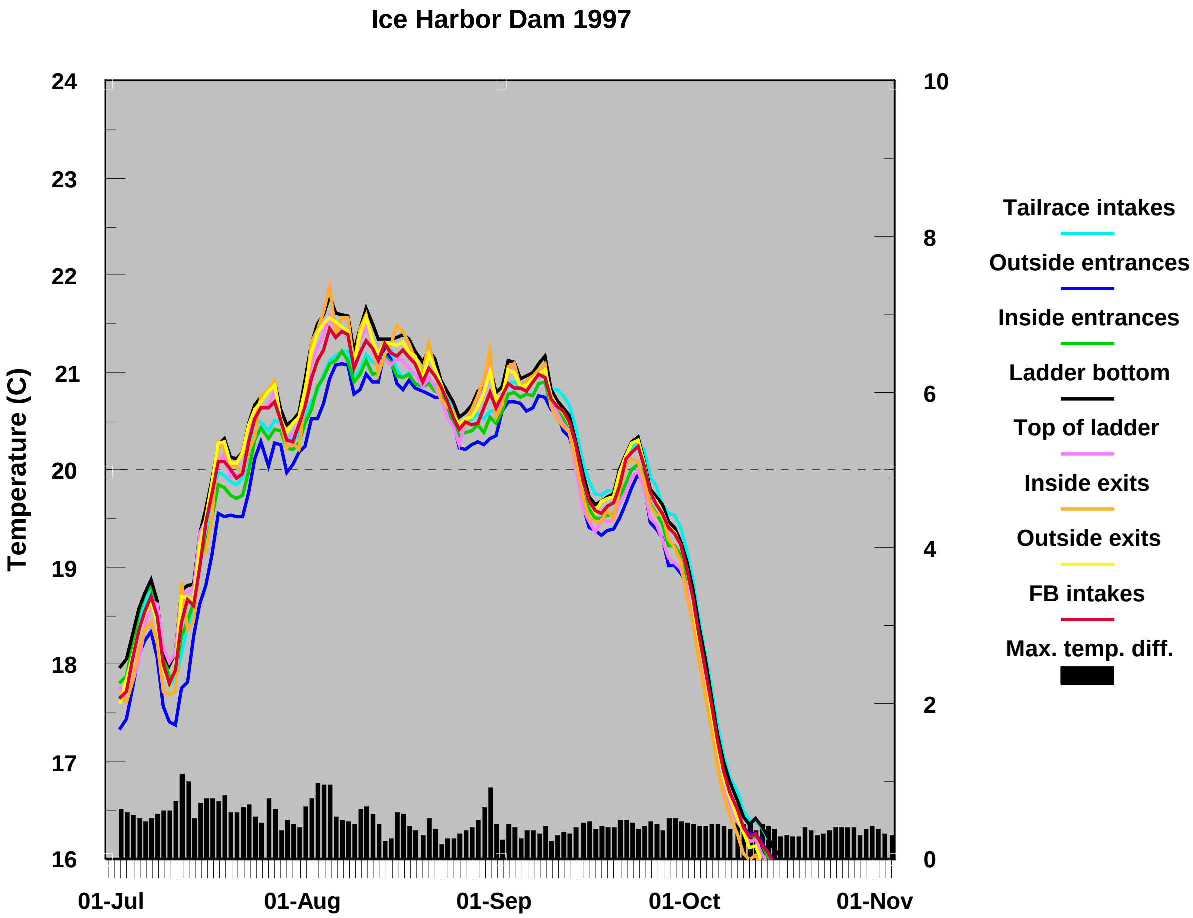


Figure 15. Water temperatures measured in and around fishways at Ice Harbor Dam in 1997.

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 17.5ºC. Temperatures first reached 20ºC on 16 July, peaked above 21ºC 18 July and again 25 July, dropped to 17-18ºC on 23 August before reaching a secondary peak at 20.5ºC on 12 September. Temperatures dropped below 20ºC for the last time 16 September. By the end of October water temperatures at the dam were between 10.0 and 11.0ºC and dropping. Daily maximum water temperatures at the dam averaged 19.7 (± 0.5ºC) in July, 19.3 (± 0.3ºC) during August, 19.4 (± 0.3ºC) during

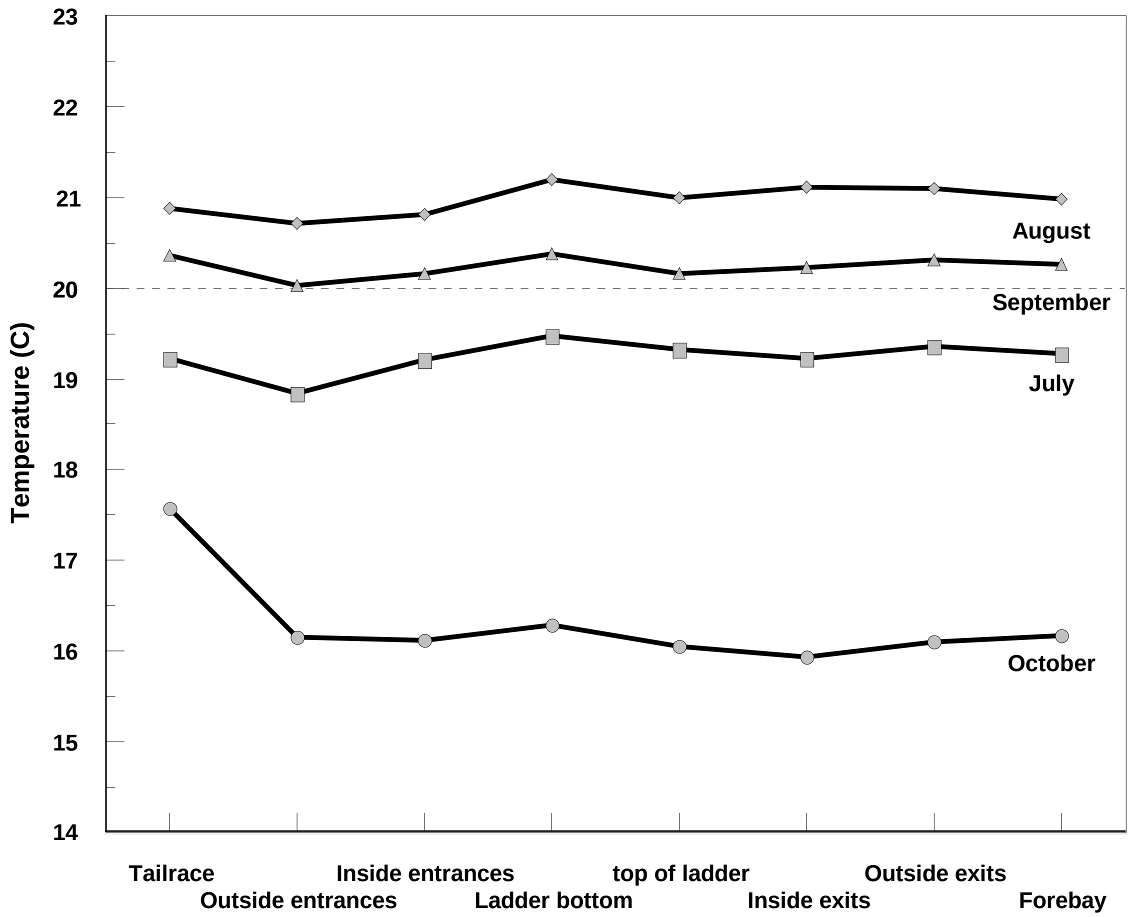


Figure 16. Monthly average water temperatures measured in and near fishways at Ice Harbor Dam in 1997.

September, and 14.6ºC (± 0.7ºC) during October. There were 30 d when the daily average temperature somewhere in system was 20ºC 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 0.7ºC 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)

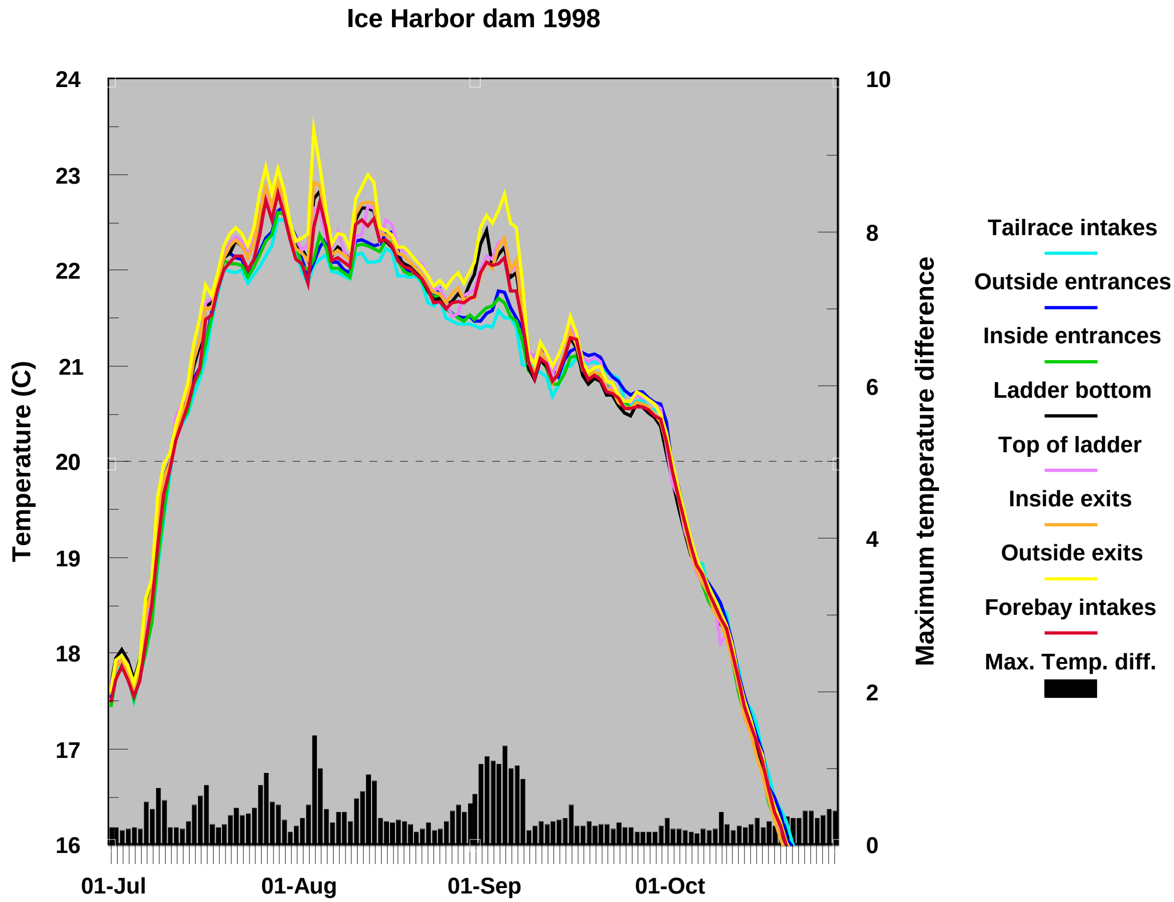


Figure 17. Water temperatures measured in and around fishways at Ice Harbor Dam in 1998.

ranged from 0.3 to 2.1ºC, averaging 0.9, 1.0, 0.7, and 0.5ºC during July, August, September, and October.

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 17ºC. Temperatures first reached 20ºC on 13 July, peaked at 22ºC on 28 July, and dropped below 20ºC for the last time on 25 August. Daily maximum water temperatures at the dam averaged 20.0 (± 0.5ºC) in July, 20.2 (± 0.4ºC) during August, 17.9 (± 0.3ºC) during September, and 15.4ºC (± 0.6ºC) during October. By the end of October, water temperatures were around 10ºC. There were 41 d when average temperatures somewhere at the dam were 20ºC or higher.

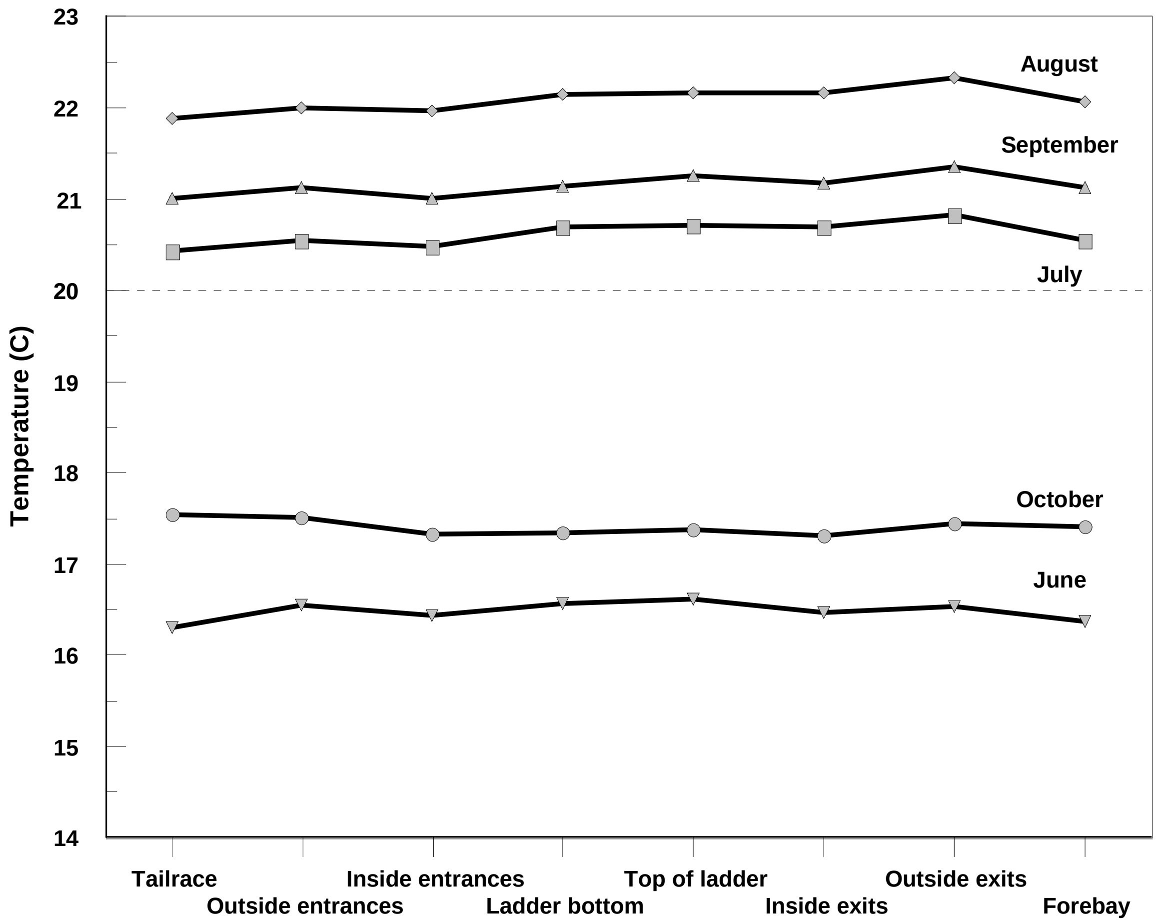


Figure 18. Monthly average water temperatures measured in and near fishways at Ice Harbor Dam in 1998.

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 0.5ºC during July, August and September (Figure 22). The maximum difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 4.4ºC, averaging 1.4, 2.0, 0.9, and 0.5ºC during July, August, September, and October.

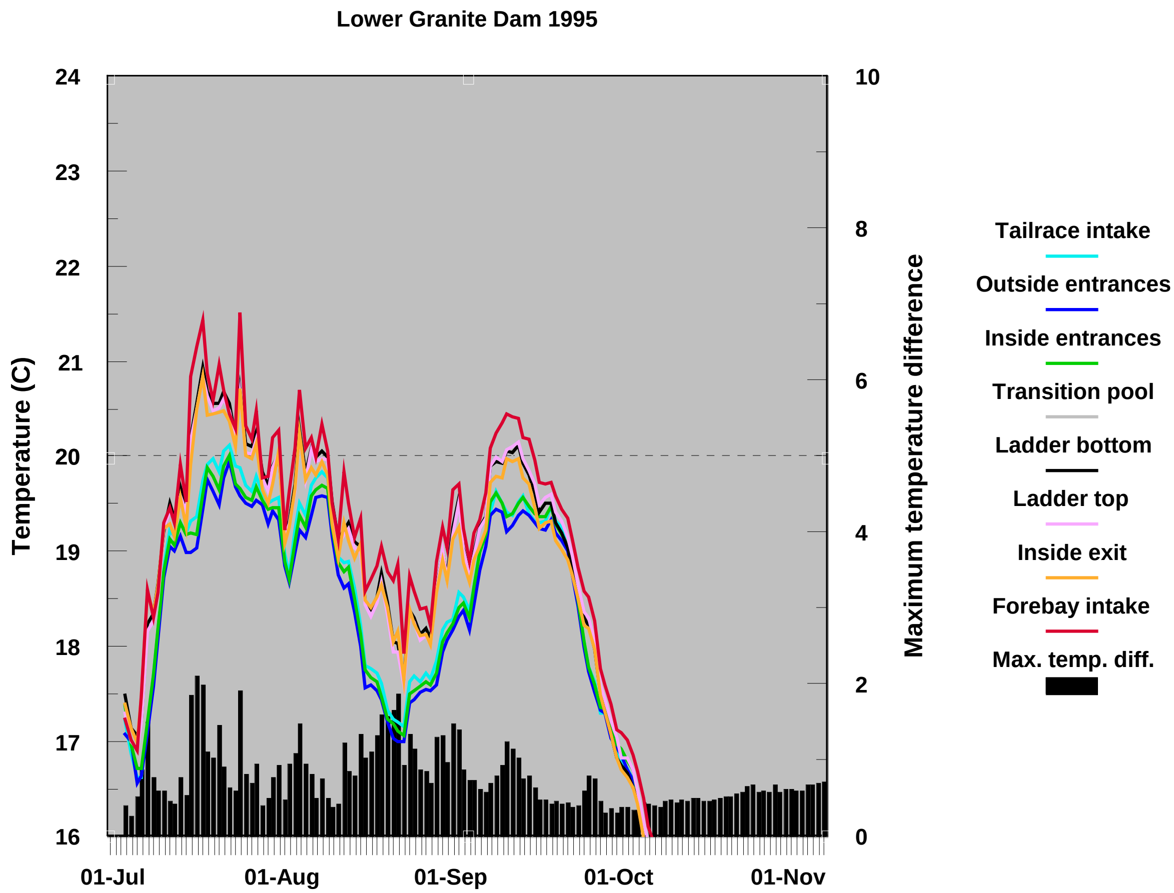


Figure 19. Water temperatures measured at in and around fishways at Lower Granite Dam in 1995.

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 17.5ºC. Temperatures first reached 20ºC on 3 August, peaked at 22.6ºC on 9 September, and dropped below 20ºC for the last time on 19 September. Daily maximum water temperatures at the dam averaged 18.8ºC (± 0.3ºC) in July, 20.2ºC (± 0.2ºC) during August, 20.9ºC (± 0.5ºC) during September, and 15.4ºC (± 0.7ºC) during October. By the end of October, water temperatures were around 11.5 to12.0ºC. There were 39 d when average temperature somewhere at the dam was 20ºC or higher.

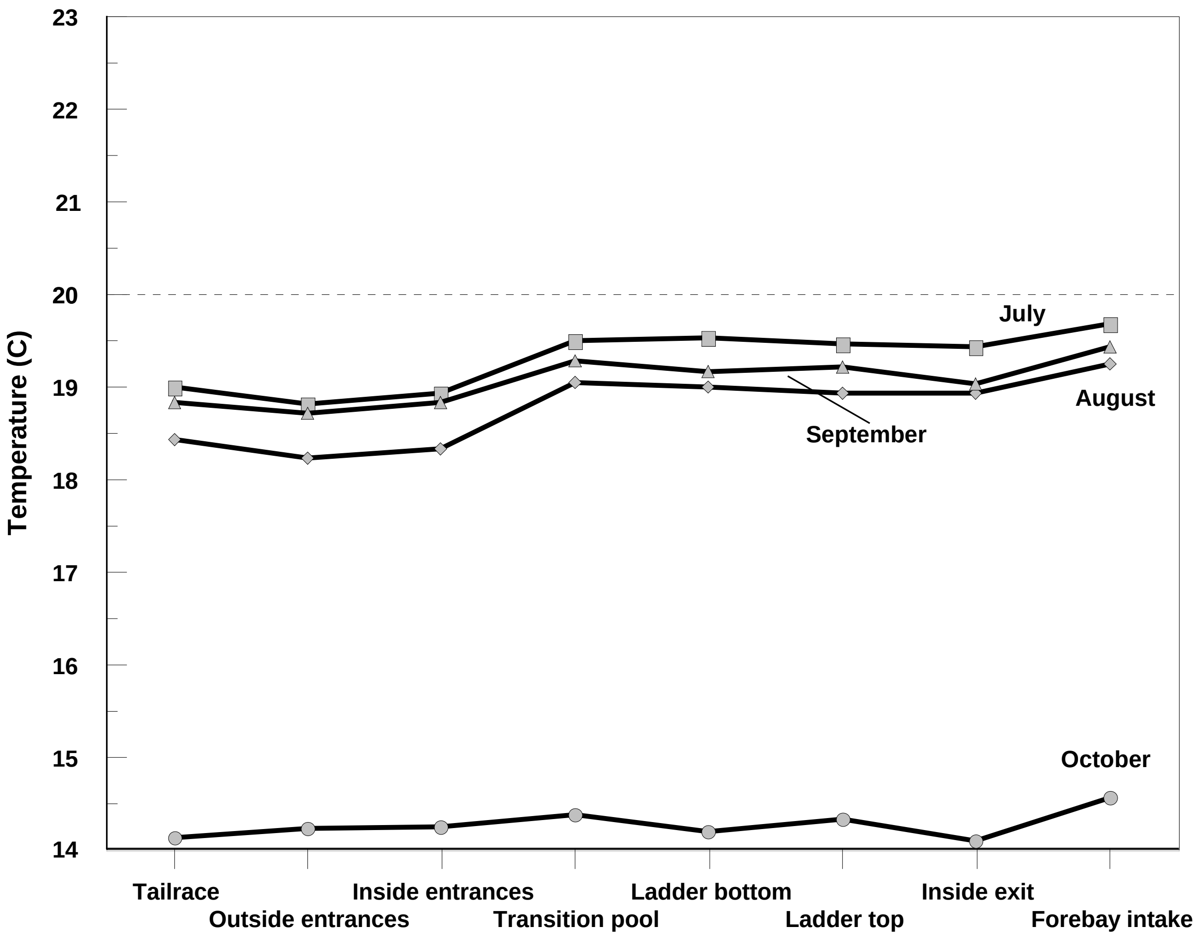


Figure 20. Monthly average water temperatures measured in and near fishways at Lower Granite Dam in 1995.

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 fishway (Figure 24). The maximum difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 2.0ºC, averaging 0.9, 1.0, 0.6, and 0.6ºC 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 15.0ºC. Temperatures first reached 20ºC on 9 July, peaked at 24ºC on 26 July, and dropped below 20ºC for the last time on 1 October. Daily

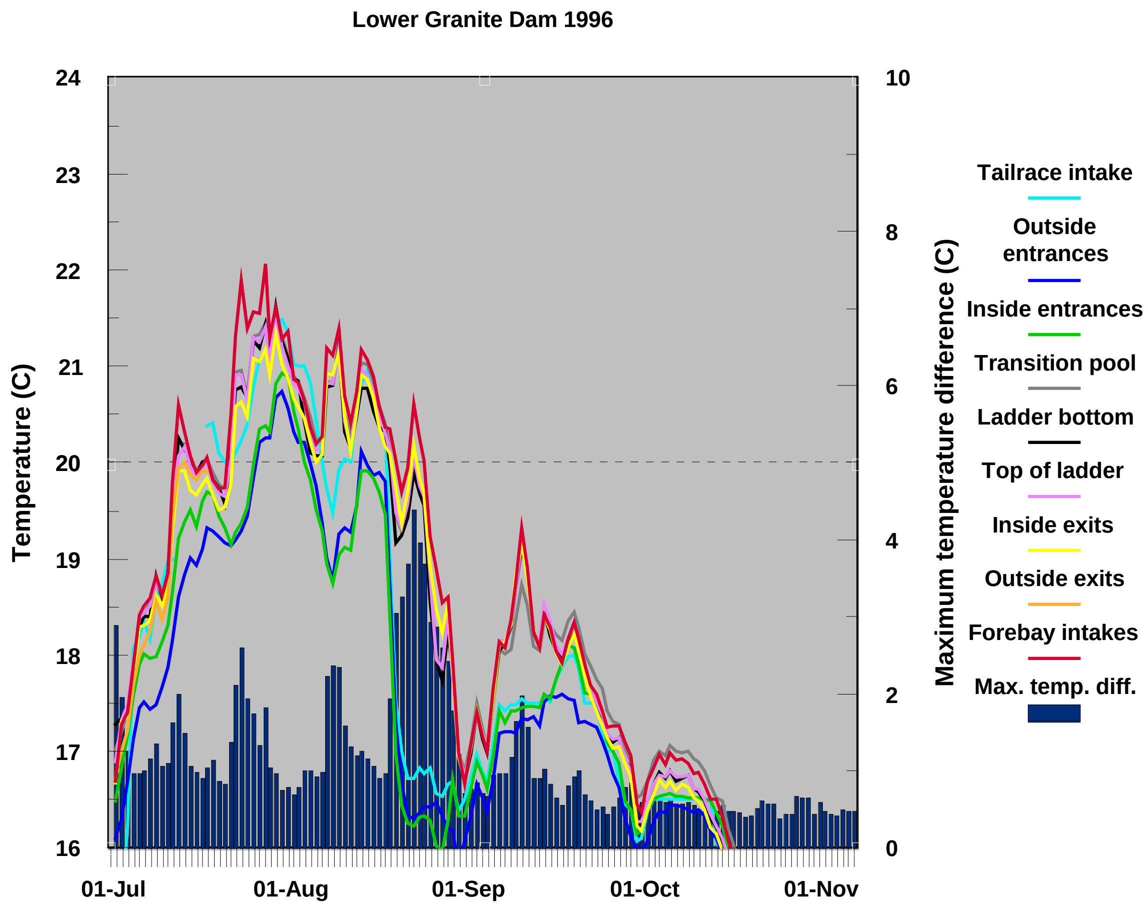


Figure 21. Water temperatures measured at in and around fishways at Lower Granite Dam in 1996.

maximum water temperatures at the dam averaged 21.0ºC (± 0.6ºC) in July, 21.8ºC (± 0.3ºC) during August, 22.1ºC (± 0.3ºC) during September, and 16.2ºC (± 0.8ºC) during October. By the end of October, water temperatures were in the range of 12.0 to 12.6ºC. There were 86 d when the daily average temperature somewhere at the dam was 20ºC 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). The maximum difference in water temperatures recorded at the dam at any one time ranged from 0.4 to 4.5ºC, averaging 1.6, 2.0, 1.1, and 1.1ºC during July, August, September, and October.

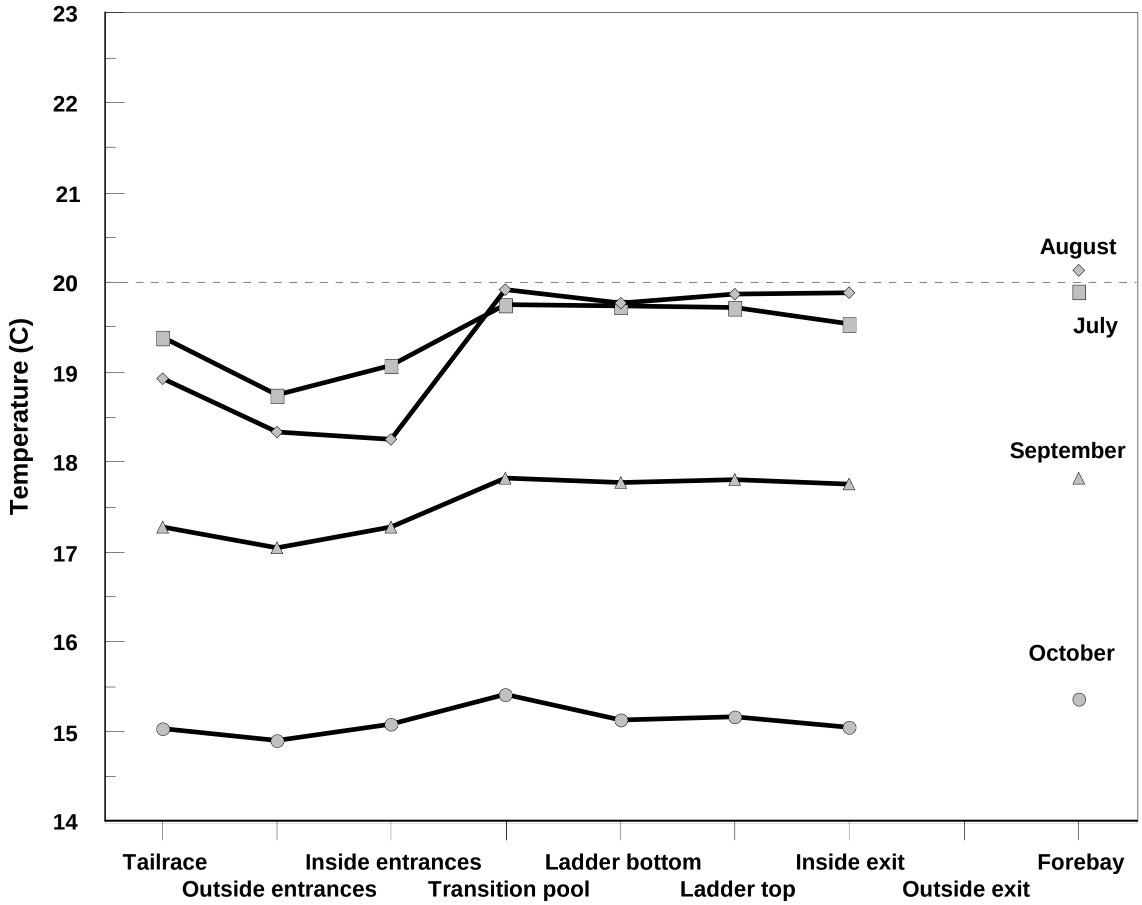


Figure 22. Monthly average water temperatures measured in and near fishways at Lower Granite Dam in 1996.

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

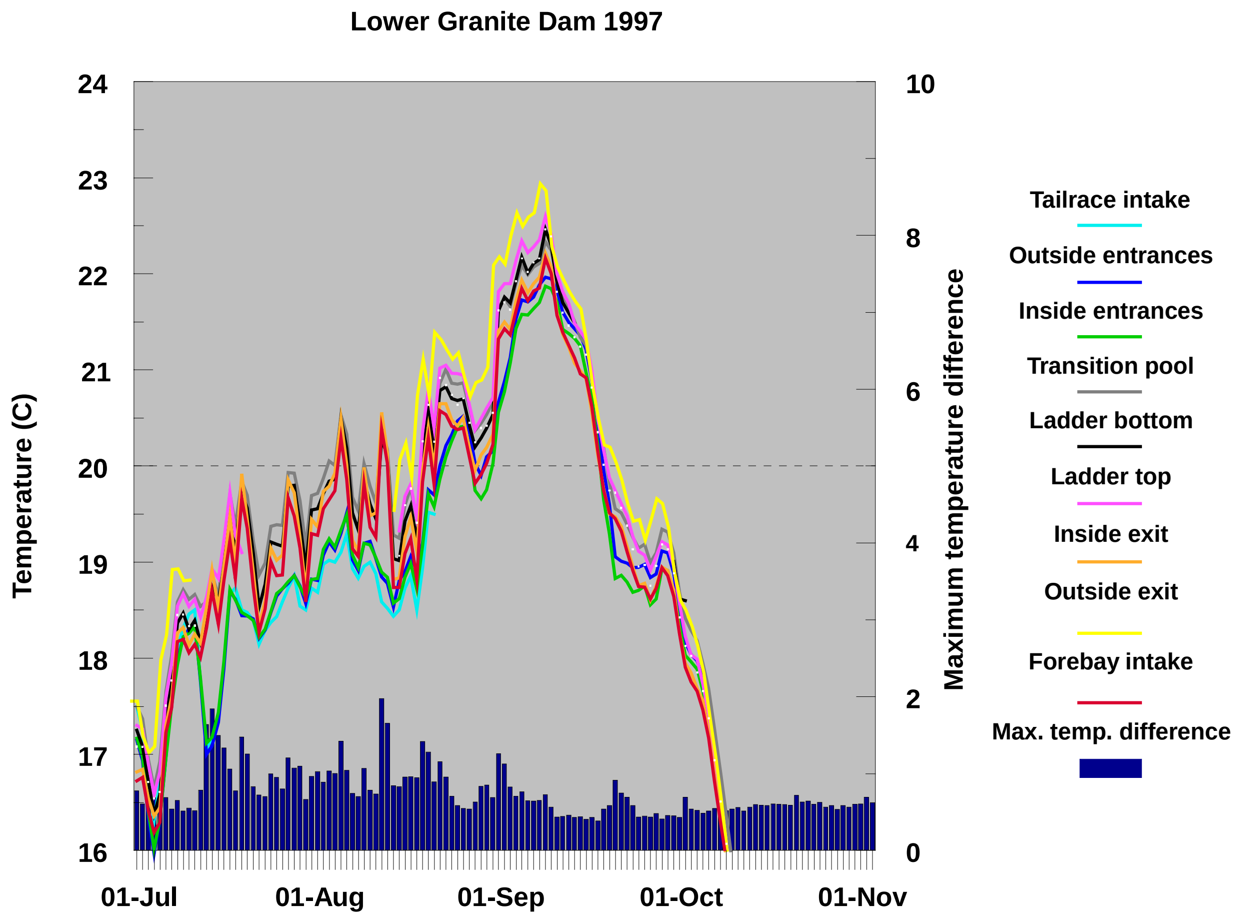


Figure 23. Water temperatures measured in and around fishways at Lower Granite Dam in 1997.

column near 18.5ºC. Temperatures at depths greater than 6 m remained near 20ºC through the 25 August survey, after which temperatures were around 19ºC until the last survey. The largest difference in temperatures between surface and deep water ranged from 0.1 to 3.0ºC. 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 17.0ºC below 6 m depth, and near 18ºC near the surface (Figure 28). By 20 July, temperatures throughout the water column were at or above 20ºC, ranging around 20ºC below 6 m depth and up to 21.4ºC at the surface. Peak water temperatures were recorded during the 31 July survey, ranging from 21.5ºC at 30 m depth up to 24.5ºC at the surface. Water temperatures

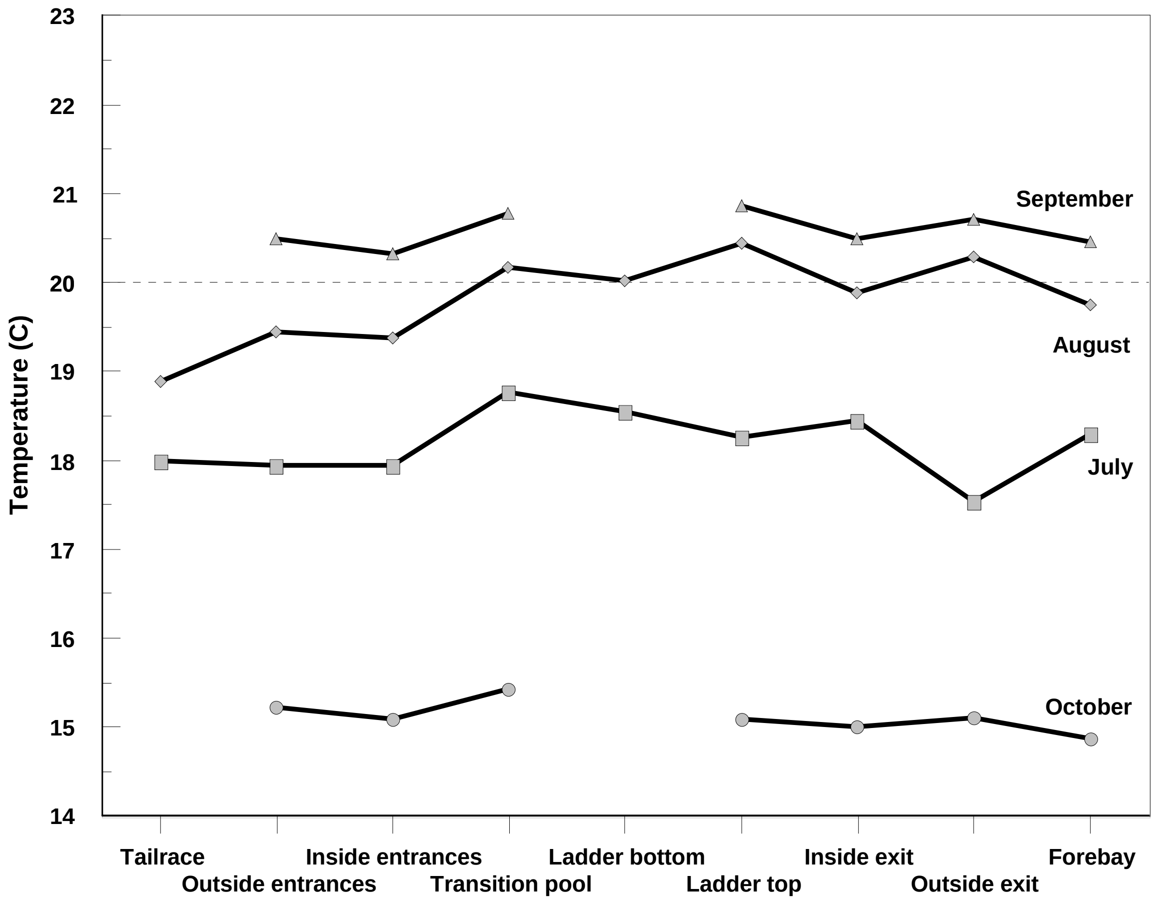


Figure 24. Monthly average water temperatures measured in and near fishways at Lower Granite Dam in 1997.

remained above 20ºC until the 13 September survey, at which time water temperatures throughout the water column were 18 to 19ºC. Differences in temperature between surface and water deep in the reservoir ranged from 0.7 up to 3.0ºC.

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 18.0ºC below 6 m depth, and up to 19.2ºC near the surface (Figure 29). By 17 July, temperatures near the surface had exceeded 20ºC, and remained so until the last survey on 30 September. Water temperatures at depth exceeded 20ºC from 1 August through the 12 September survey. Peak water temperatures were recorded during the 14 August survey, ranging from a low of 20.8ºC at 30 m depth up to 21.5ºC near the

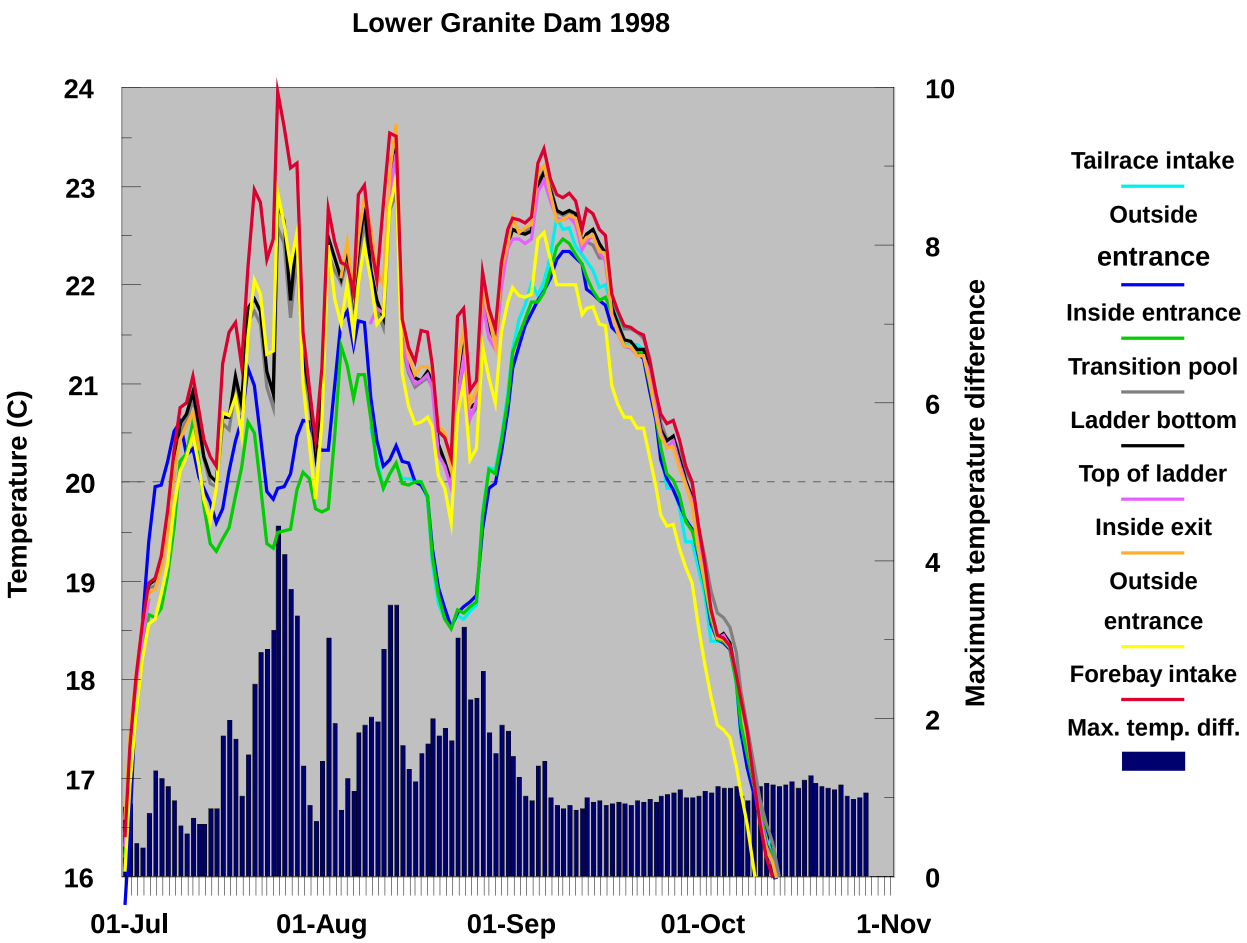


Figure 25. Water temperatures measured in and around fishways at Lower Granite Dam in 1998.

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 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.

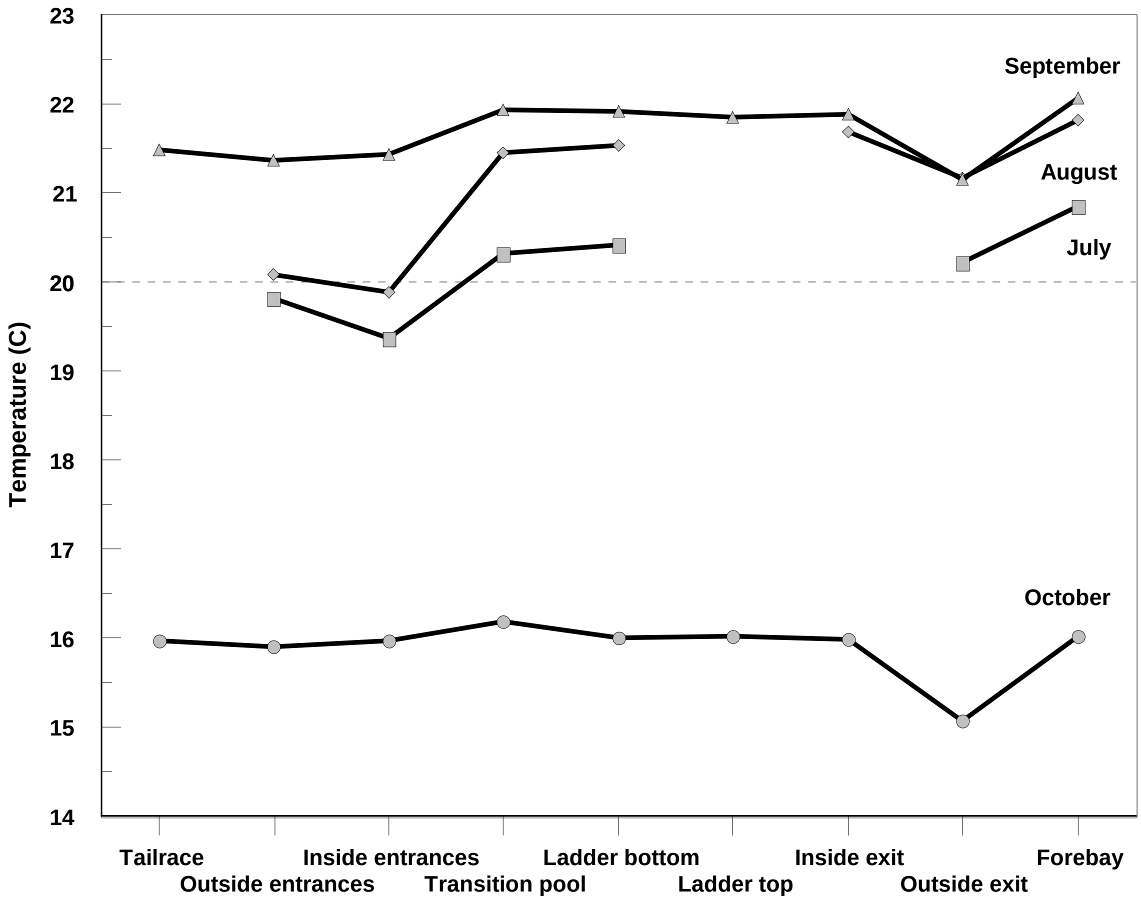
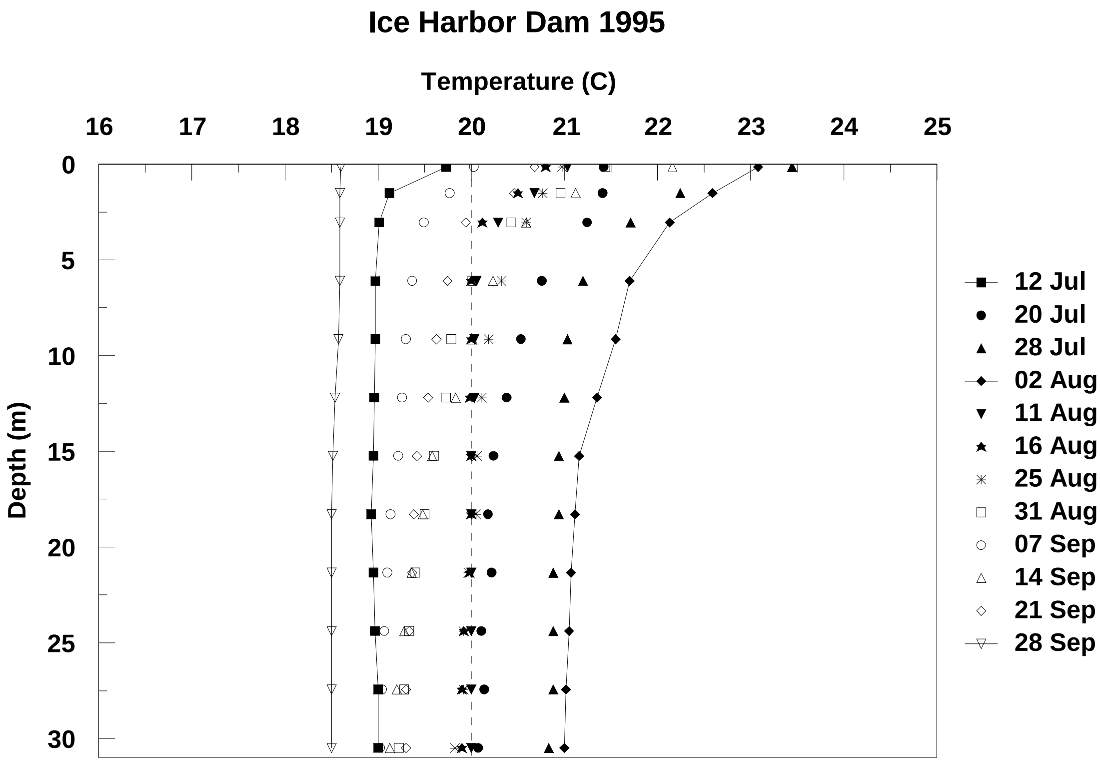


Figure 26. Monthly average water temperatures measured in and near fishways at Lower Granite Dam in 1998.

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 20ºC through the summer, except during the 24 August survey when temperatures were to 19.1ºC (Figure 31). Below 6 m depth, water temperatures were in the range of 19.5 to 20ºC during the 26 July and 10 August surveys, otherwise temperatures at depth were below 20ºC. Differences in temperature at the water surface and at 30 m depth ranged from 1 to 4ºC during the year. There appeared to be little effect on temperatures in the forebay of Lower Granite Dam from water released 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 exceeded 20ºC during the summer.



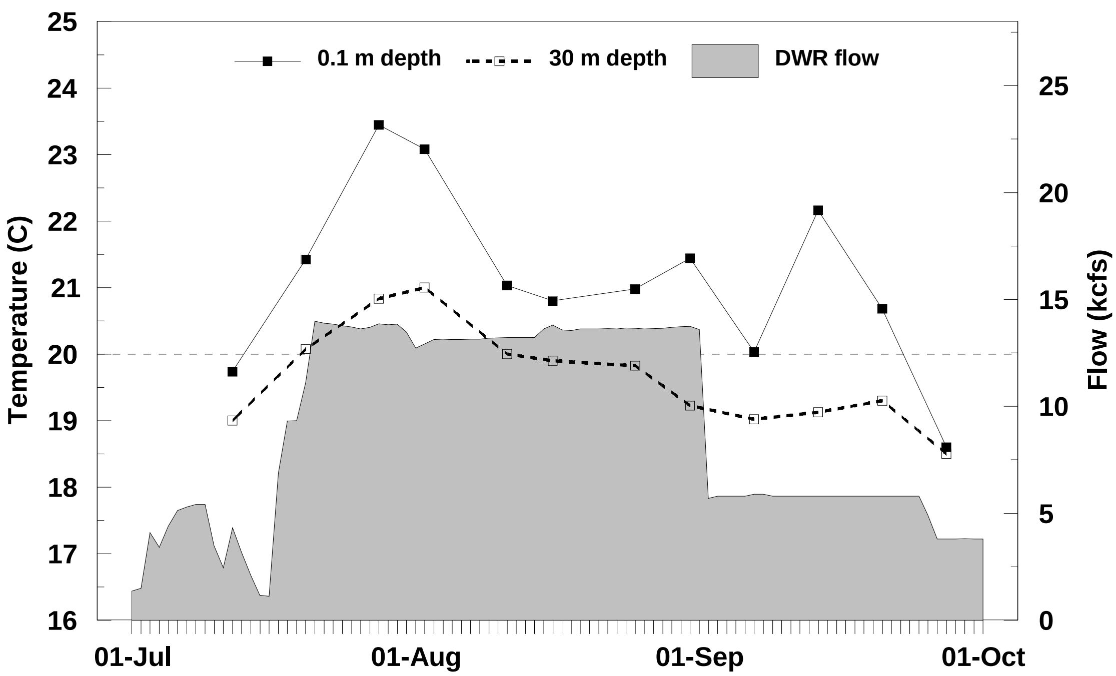


Figure 27. Temperature-depth profiles in forebay of Ice Harbor Dam in 1995 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1995 (bottom).

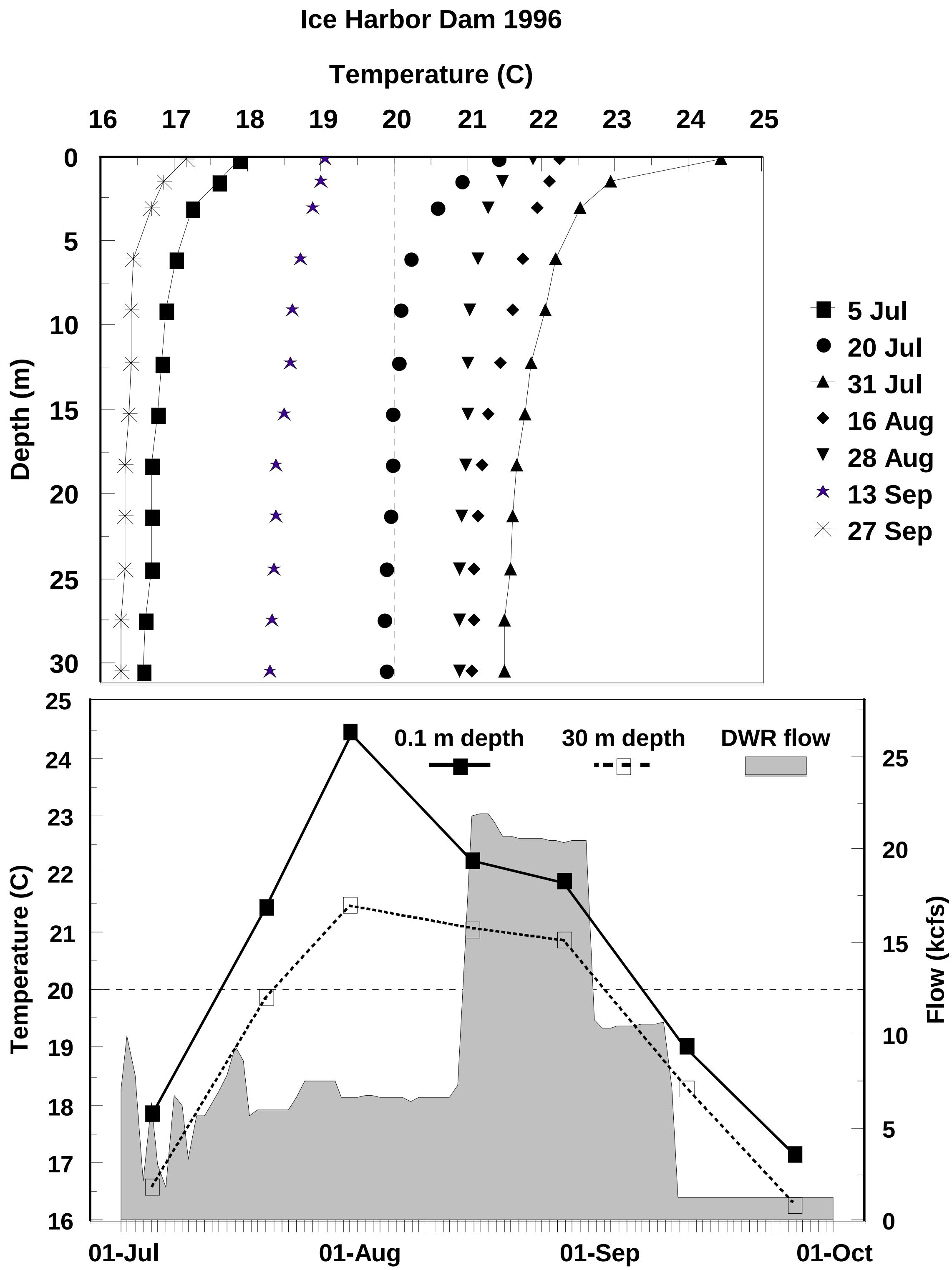


Figure 28. Temperature-depth profiles in forebay of Ice Harbor Dam in 1996 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1996 (bottom).

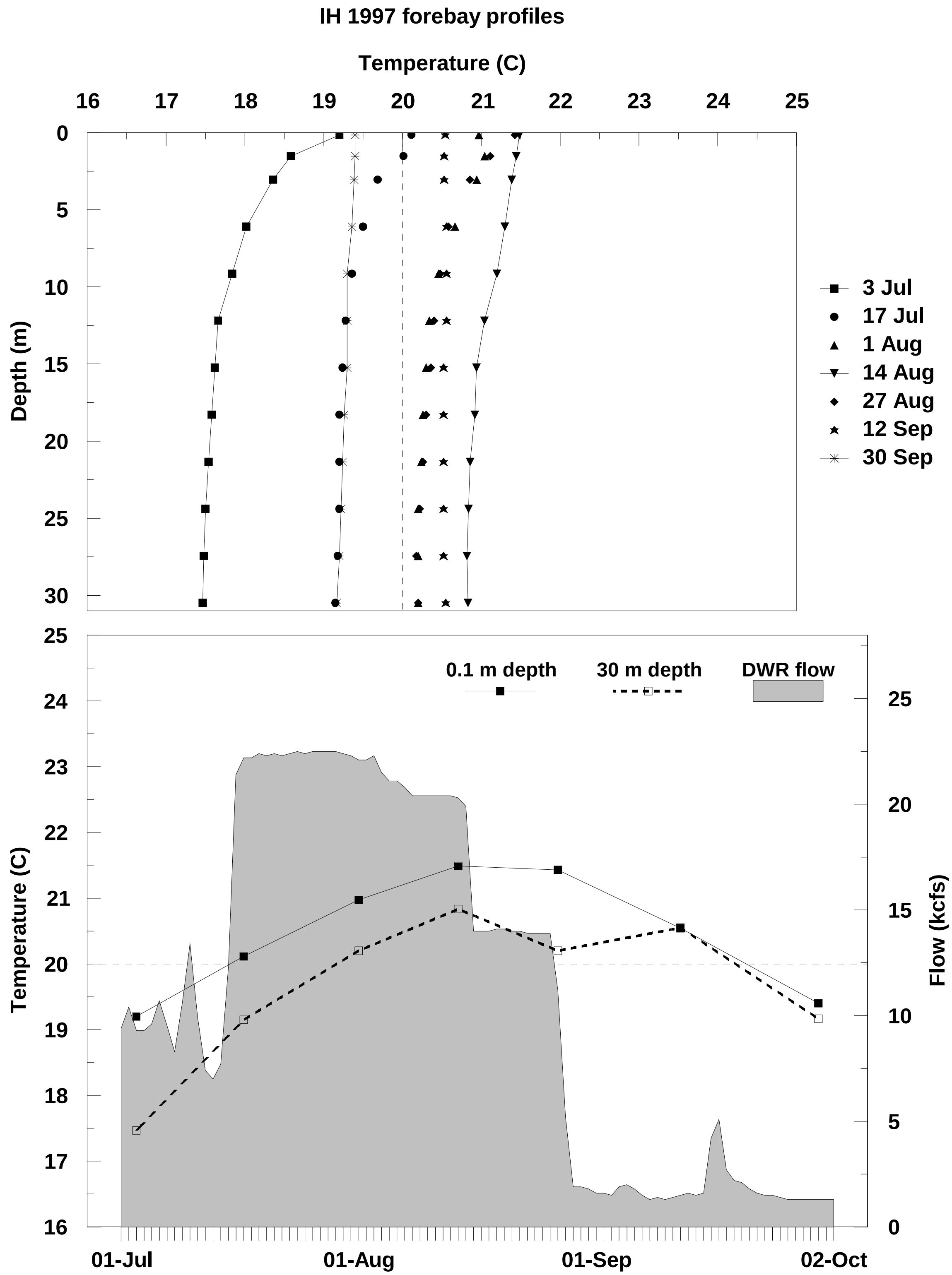


Figure 29. Temperature-depth profiles in forebay of Ice Harbor Dam in 1997 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1997 (bottom).

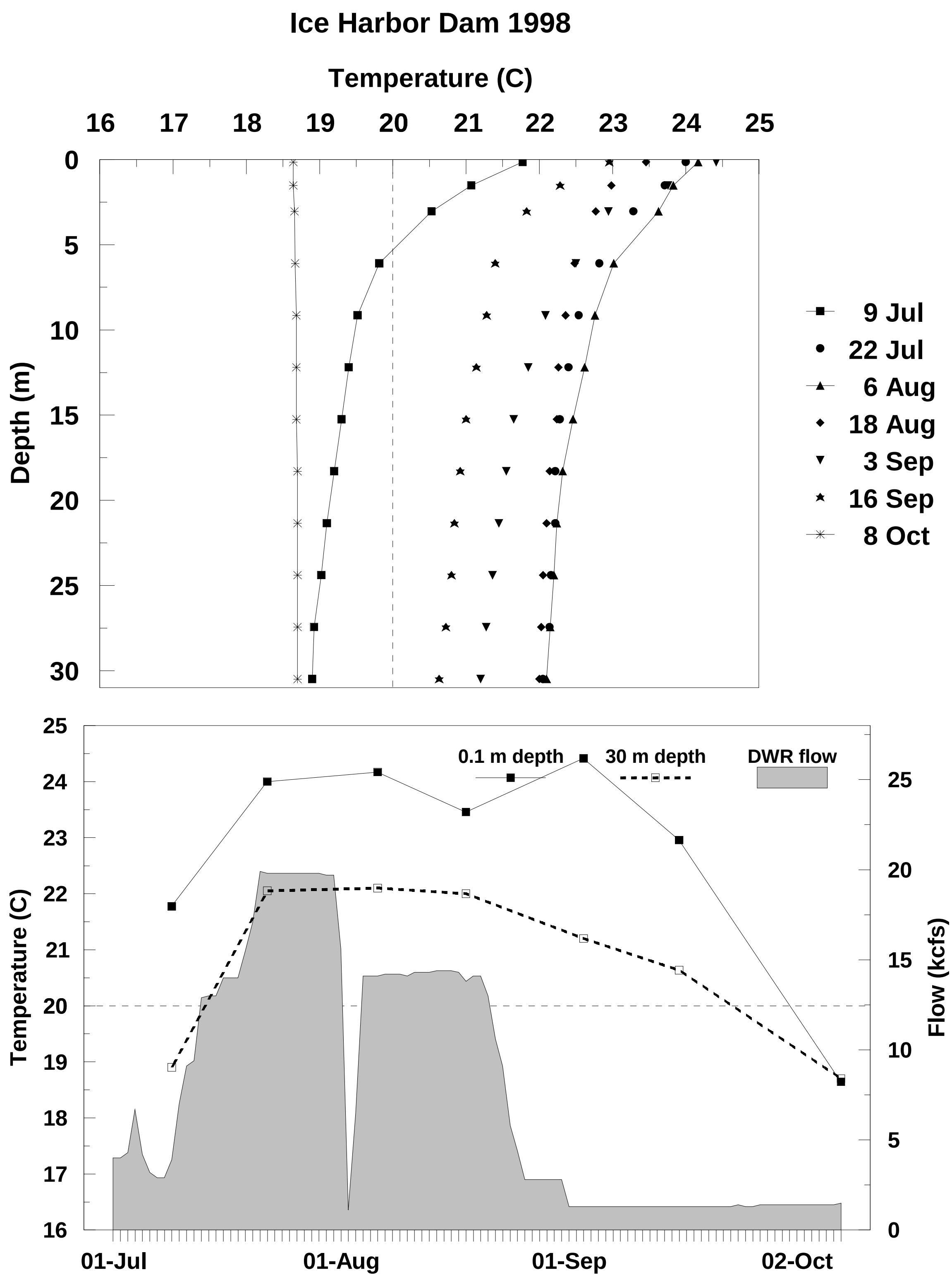


Figure 30. Temperature-depth profiles in forebay of Ice Harbor Dam in 1998 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1998 (bottom).

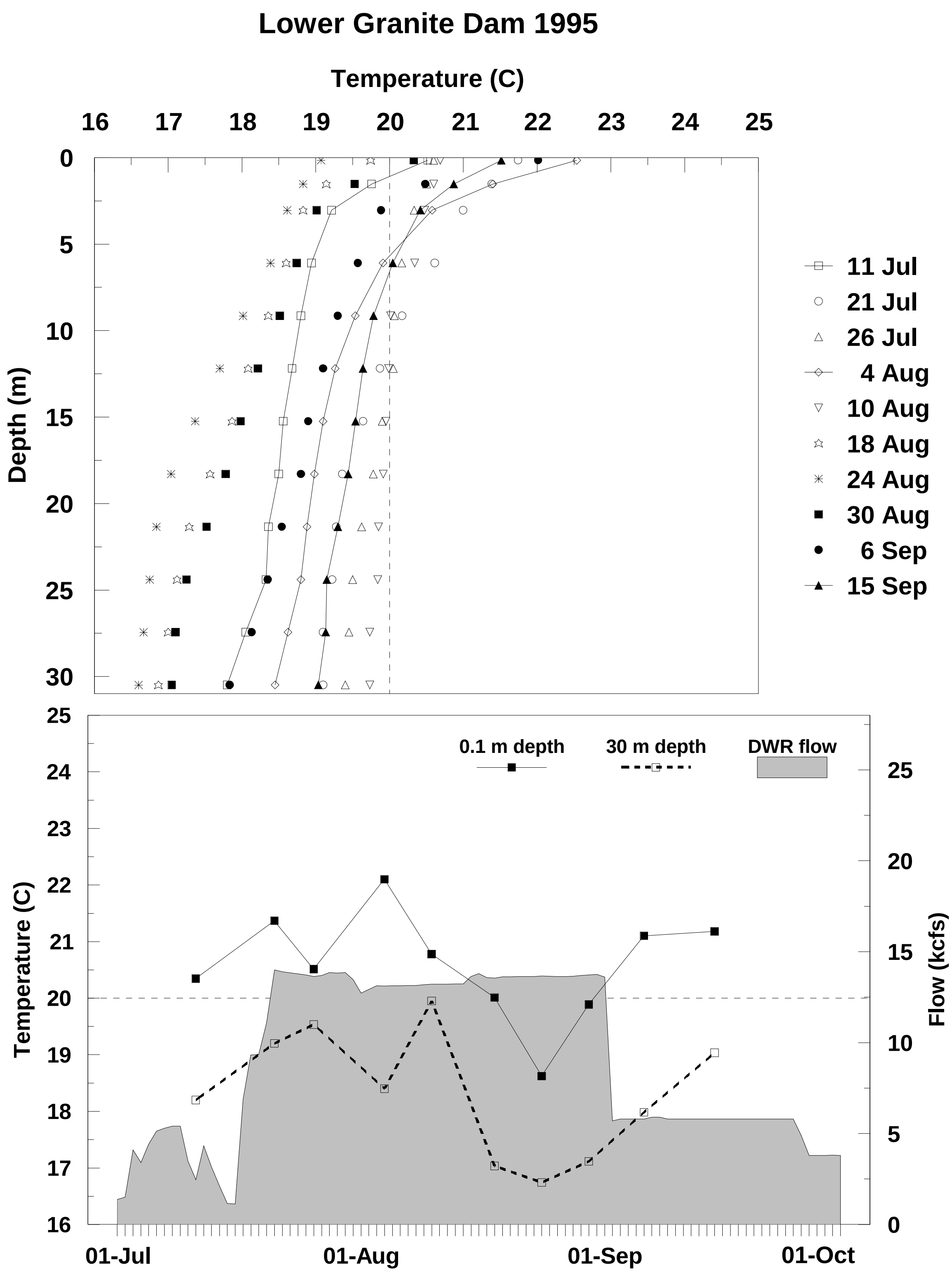


Figure 31. Temperature-depth profiles in forebay of Lower Granite Dam in 1995 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam Reservoir in 1995 (bottom).

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 17.8ºC (Figure 32). Temperatures near the surface were near or exceeded 20ºC 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 20ºC on 18 July, 3 August, and 14 August, otherwise water temperatures below 20 m were 18.5ºC or cooler. Differences in temperatures of surface and deep water were greatest on 14 August (2.4ºC) and 29 August (3.7ºC). 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 to 18.3ºC (Figure 33). By 25 July, temperatures near the surface had reached 19.6ºC, and temperatures near the surface exceeded 20ºC through the 16 September survey. Below 6 m, water temperatures exceeded 20ºC during the 25 August and 16 September surveys, otherwise temperatures at depth were less than 20ºC in the forebay. The rise in deep water temperatures to nearly 20ºC 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 20ºC during all but the last survey in October, peaking at nearly 25ºC 14 July (Figure 34). Temperatures at depths greater than 6 m were 19.5ºC 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 5.3ºC through the 1 September survey, after which temperatures were relatively homothermic. Significant flow releases from Dworshak reservoir were halted in late August.

Factors Affecting Fishway Temperatures.

Air temperatures (average 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). The three

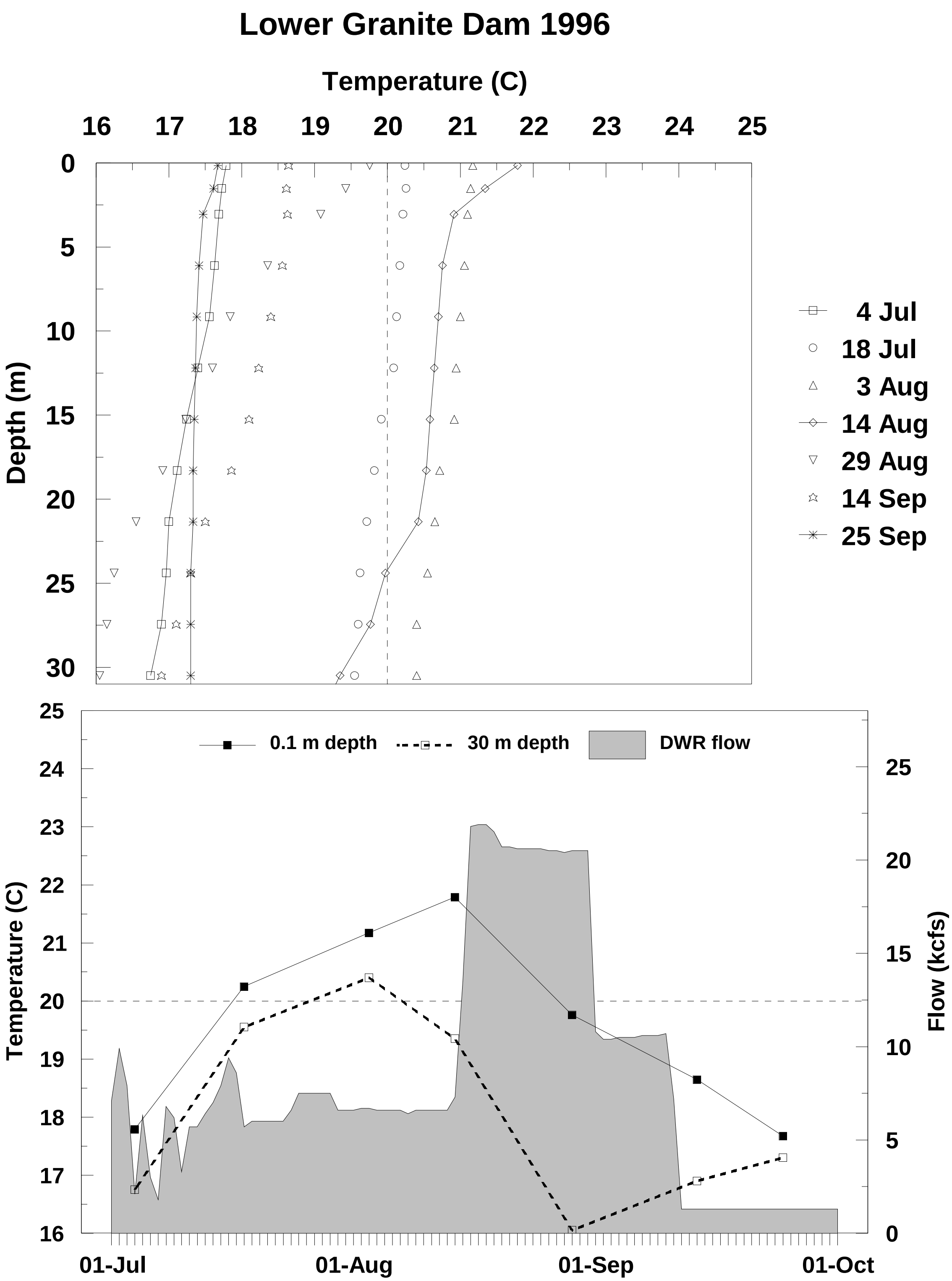


Figure 32. Temperature-depth profiles in forebay of Lower Granite Dam in 1996 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir in 1996 (bottom).

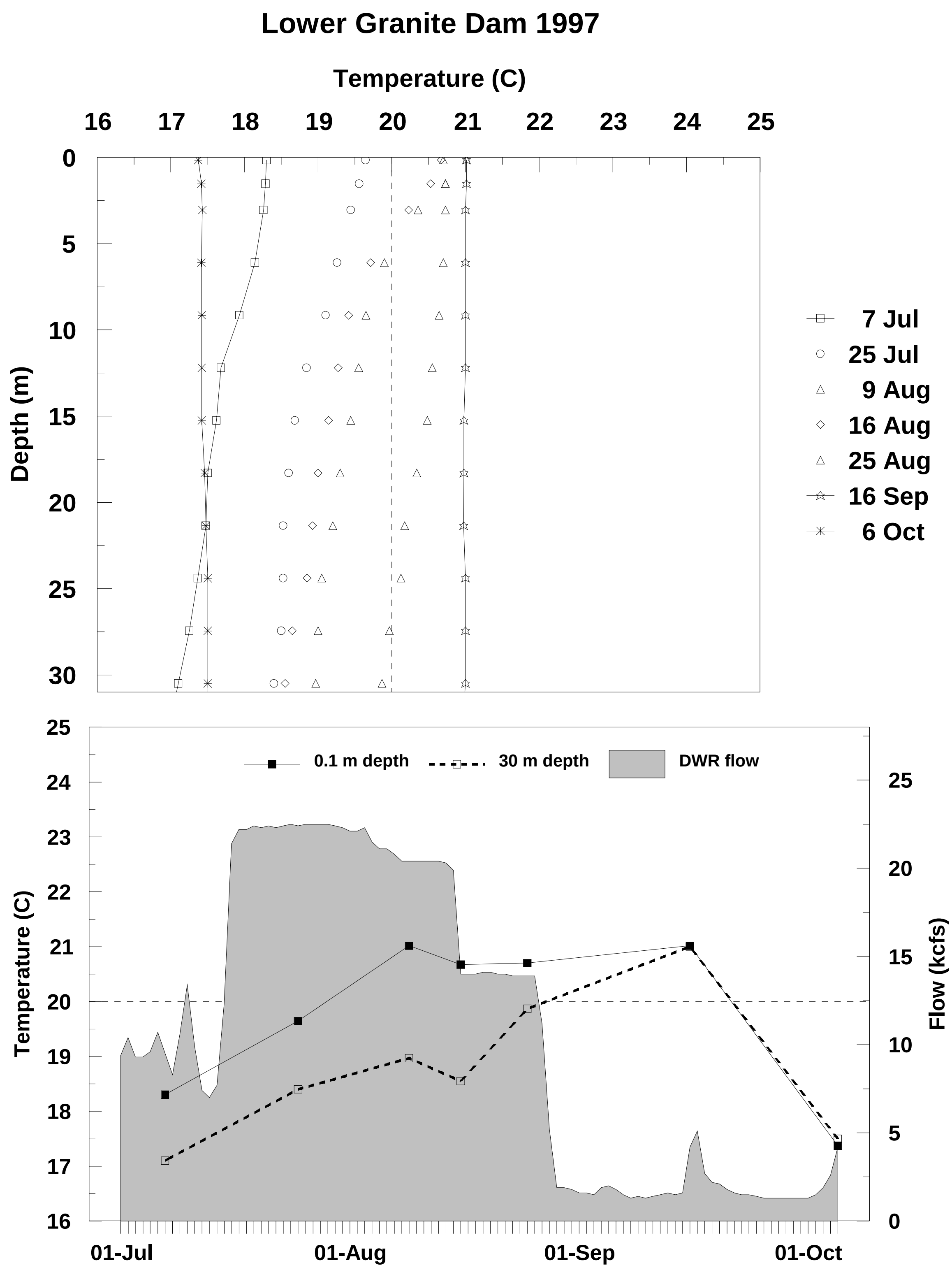


Figure 33. Temperature-depth profiles in forebay of Lower Granite Dam in 1997 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir (DWR) in 1997 (bottom).

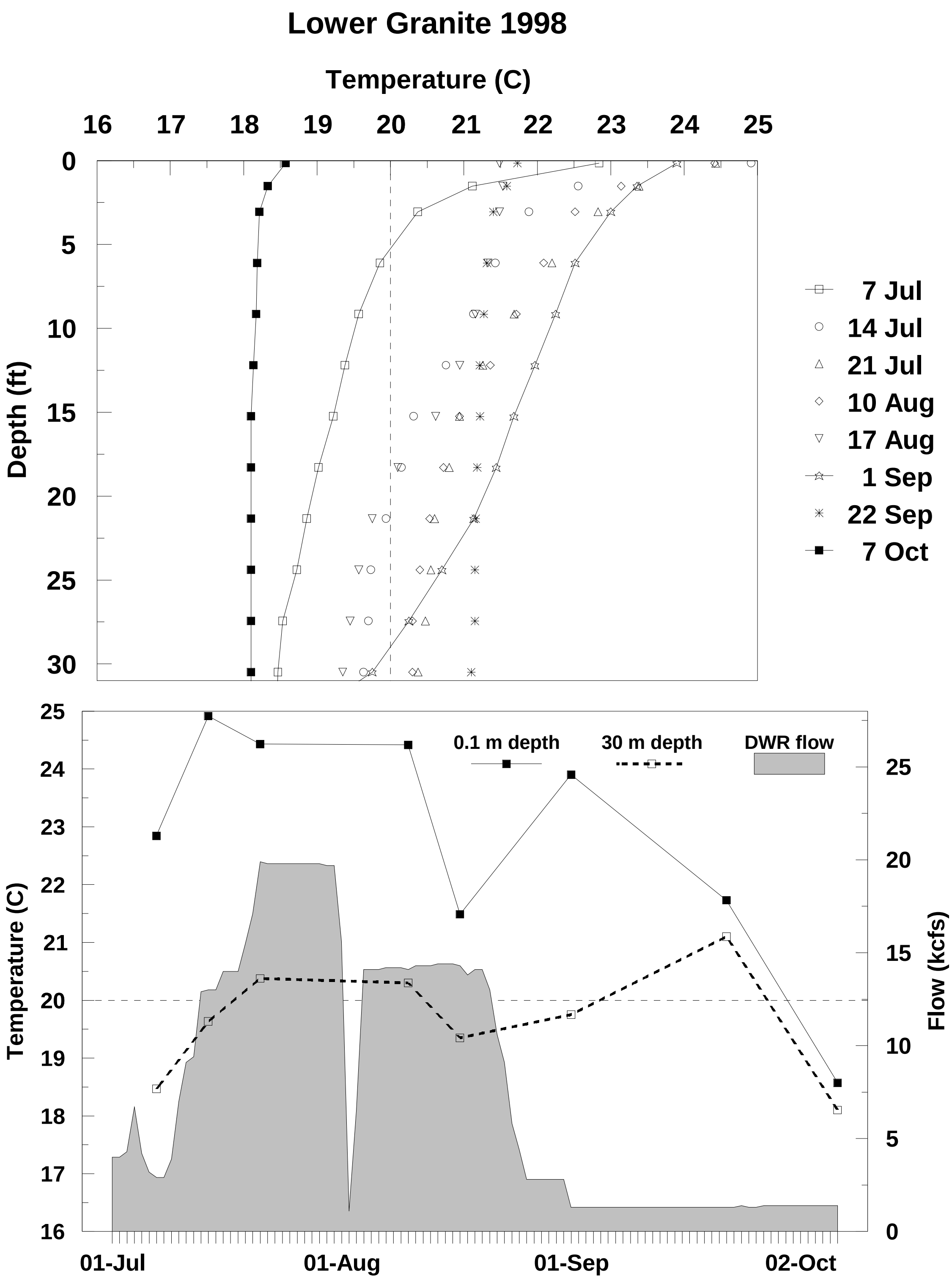


Figure 34. Temperature-depth profiles in forebay of Lower Granite Dam in 1998 (top) and water temperatures near surface and at 30 m depth in Ice Harbor Dam forebay and flow from Dworshak Dam reservoir (DWR) in 1998 (bottom).

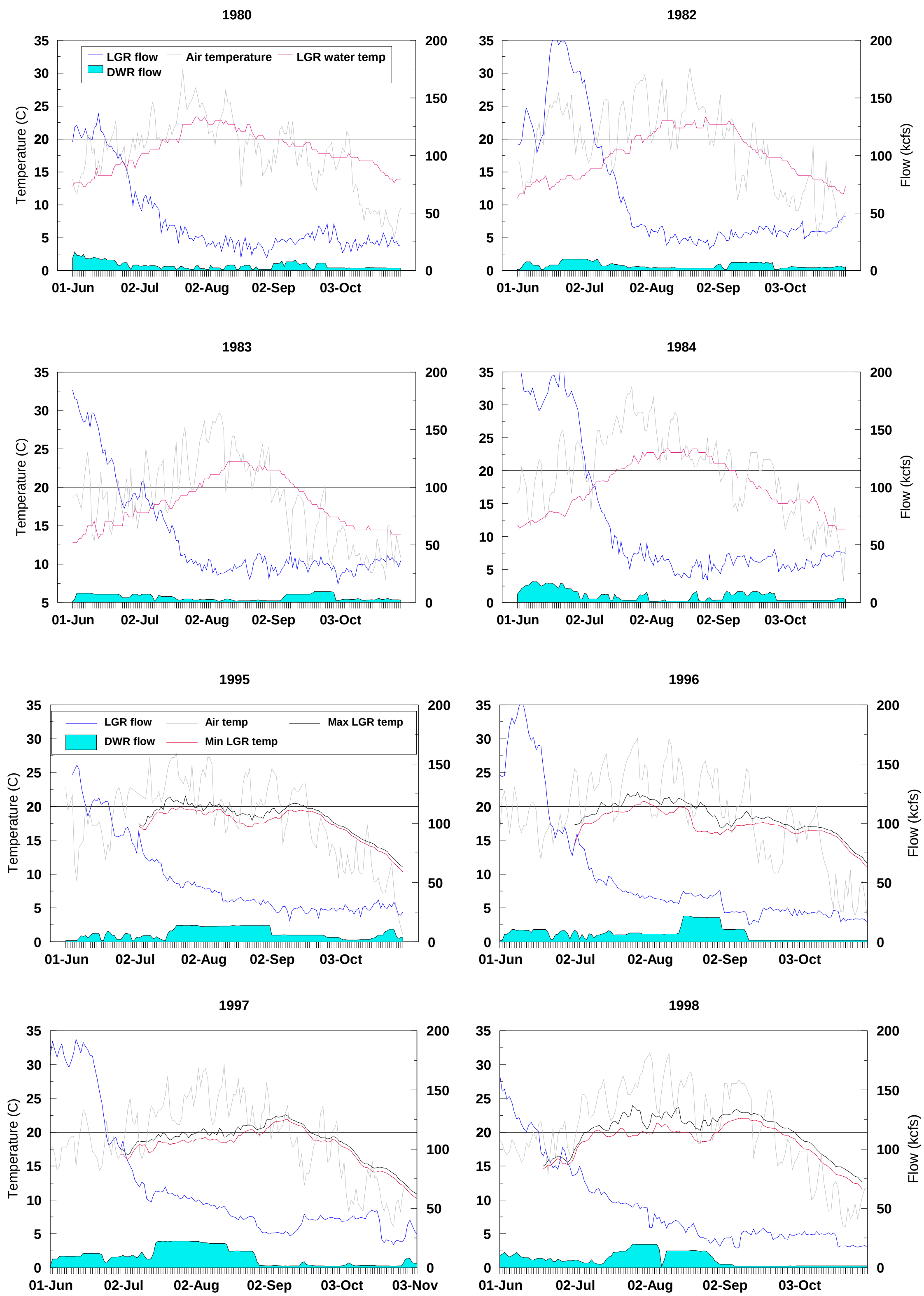


Figure 35. Water temperatures and flow at Lower Granite Dam, flow from Dworshak reservoir, and air temperature at Lewiston, Idaho during four years in the 1980's and four years in 1990's.

variables combined accounted for 72% of the variation in water temperatures using multiple linear regression analysis ($P < 0.0001$). Air temperature was the most important variable related to water temperatures (partial $R^2 = 0.667$), followed by flow ($R^2 = 0.045$) and proportion of flow from Dworshak reservoir ($R^2 = 0.012$). A polynomial model for water temperature and the three river condition variables (forebay/fishway temperature = G*(0.01823) + D*(3.69393) + T*(1.018279) + G*D*(0.063775) + G*T*(-0.00267) + D*T*(-0.386761) + G^2*(-0.00007) + D^2*(1.0136817) + T^2*(-0.011237) + 5.217166, where G = flow at Lower Granite Dam, D = flow from Dworshak reservoir 6 d prior, and T = 3 d mean air temperature at Lewiston, ID; $P < 0.0001$, $R^2 = 0.763$) was used to estimate effect of water released from Dworshak reservoir on water temperatures at Lower Granite Dam during summer. Using the polynomial relationship, we estimated that water temperatures in the forebay at Lower Granite Dam during summer can be decreased by 1 to 3ºC, depending on river flow and air temperature conditions, when releases from Dworshak reservoir reach 50% to 60% of Snake River flows at the dam (Figure 36).

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 13ºC to 21ºC in 1997 and from 15 to 23ºC 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 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

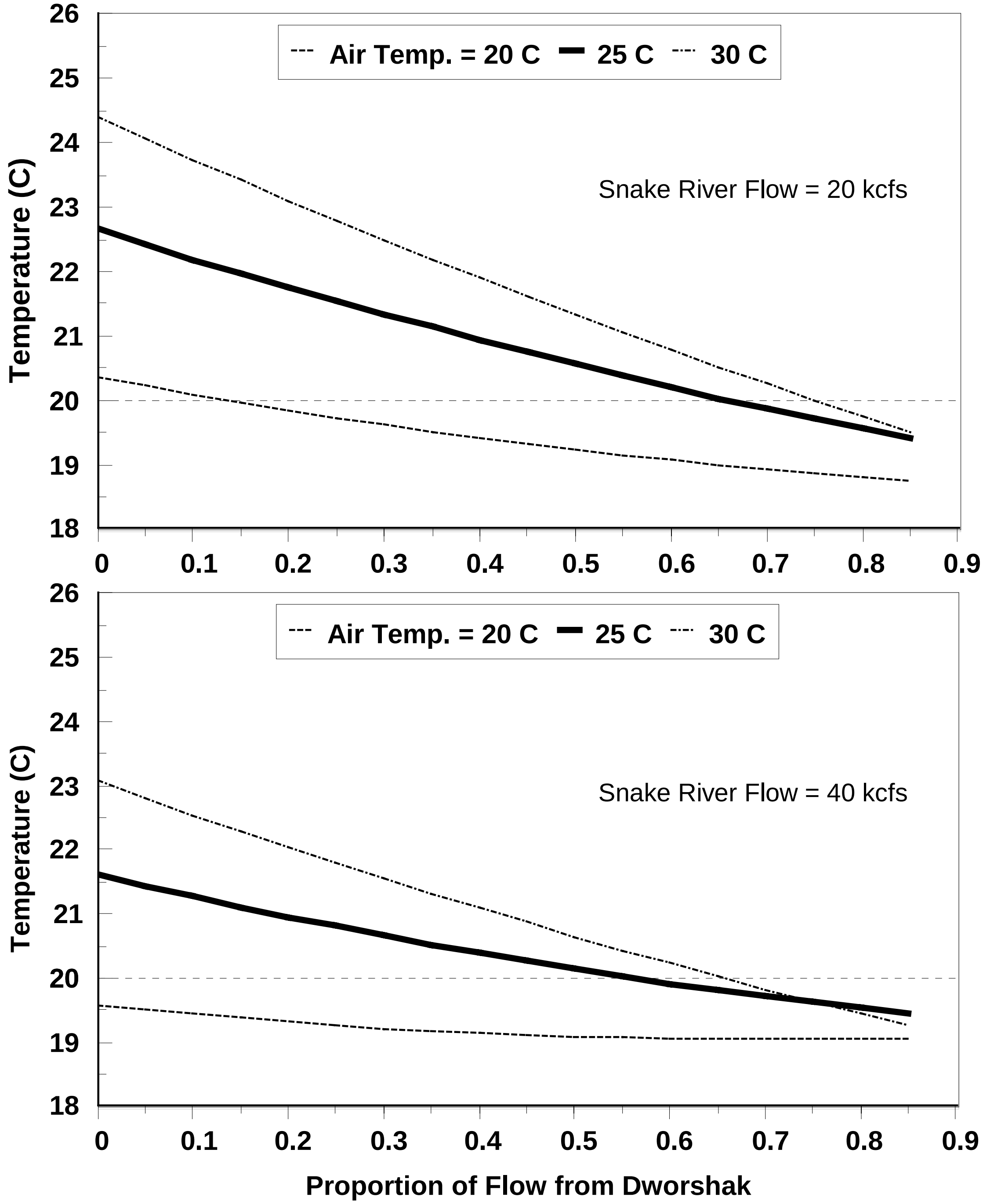


Figure 36. Predicted Snake River water temperatures in the forebay at Lower Granite Dam versus proportion of Snake River flow from Dworshak reservoir. Values calculated using polynomial regression model using proportion of river flow from Dworshak reservoir, air temperature at Lewiston, ID, and Snake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

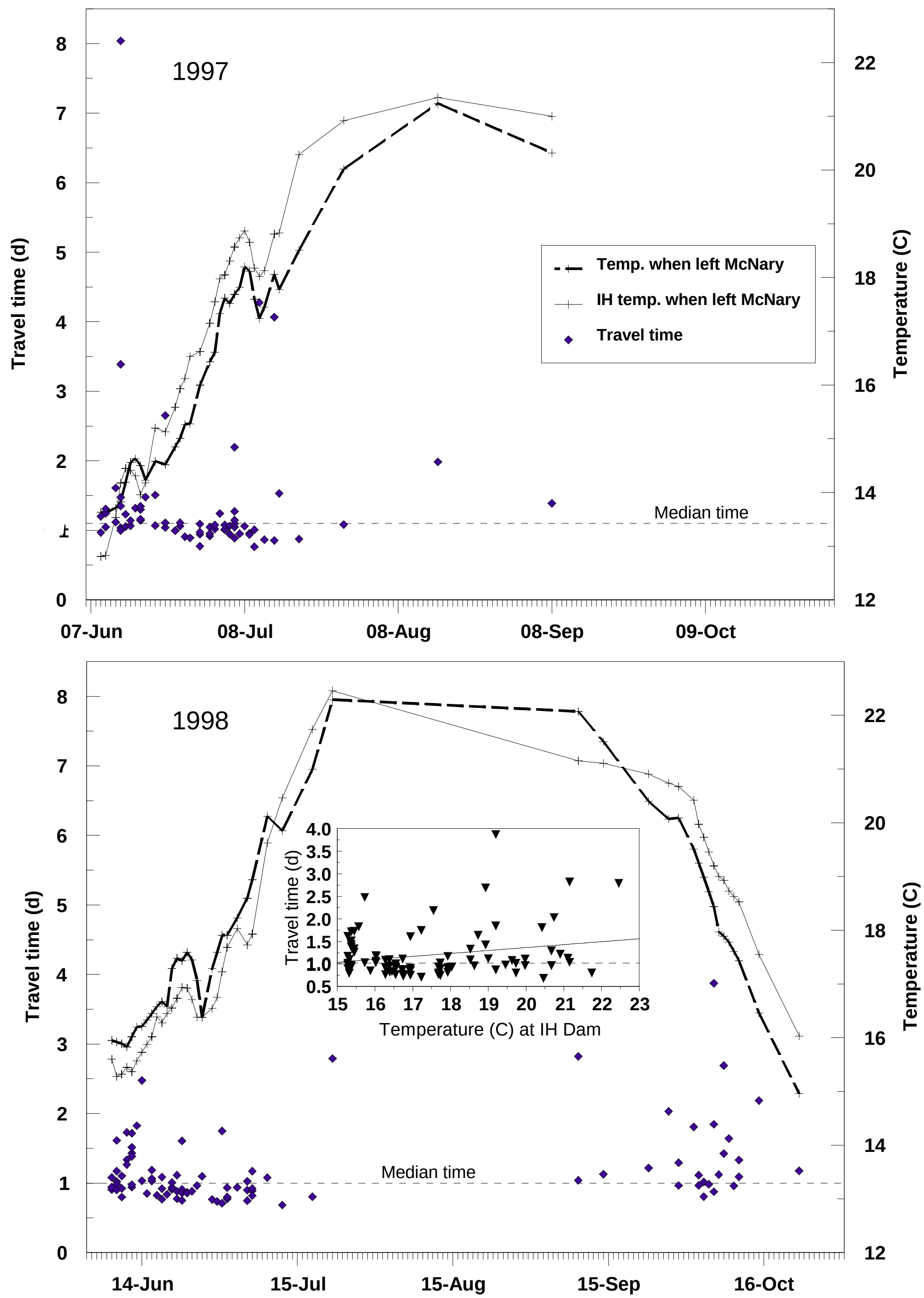


Figure 37. Travel times for summer and chinook salmon between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1997 and 1998, and showing significant regression between travel times and temperature at Ice Harbor Dam at time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

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). The salmon were divided into distinct summer and fall groups based on the time they reached Ice Harbor Dam, so no salmon with transmitters migrated between the two dams during the warmest water temperatures.

Seventy-four chinook salmon with transmitter 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 21ºC in 1997 and from 15 to over 22ºC 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).

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 21ºC during the time fish were passing in 1997 (Figure 39). In 1998, Snake River water temperatures ranged from 14 to near 24ºC 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

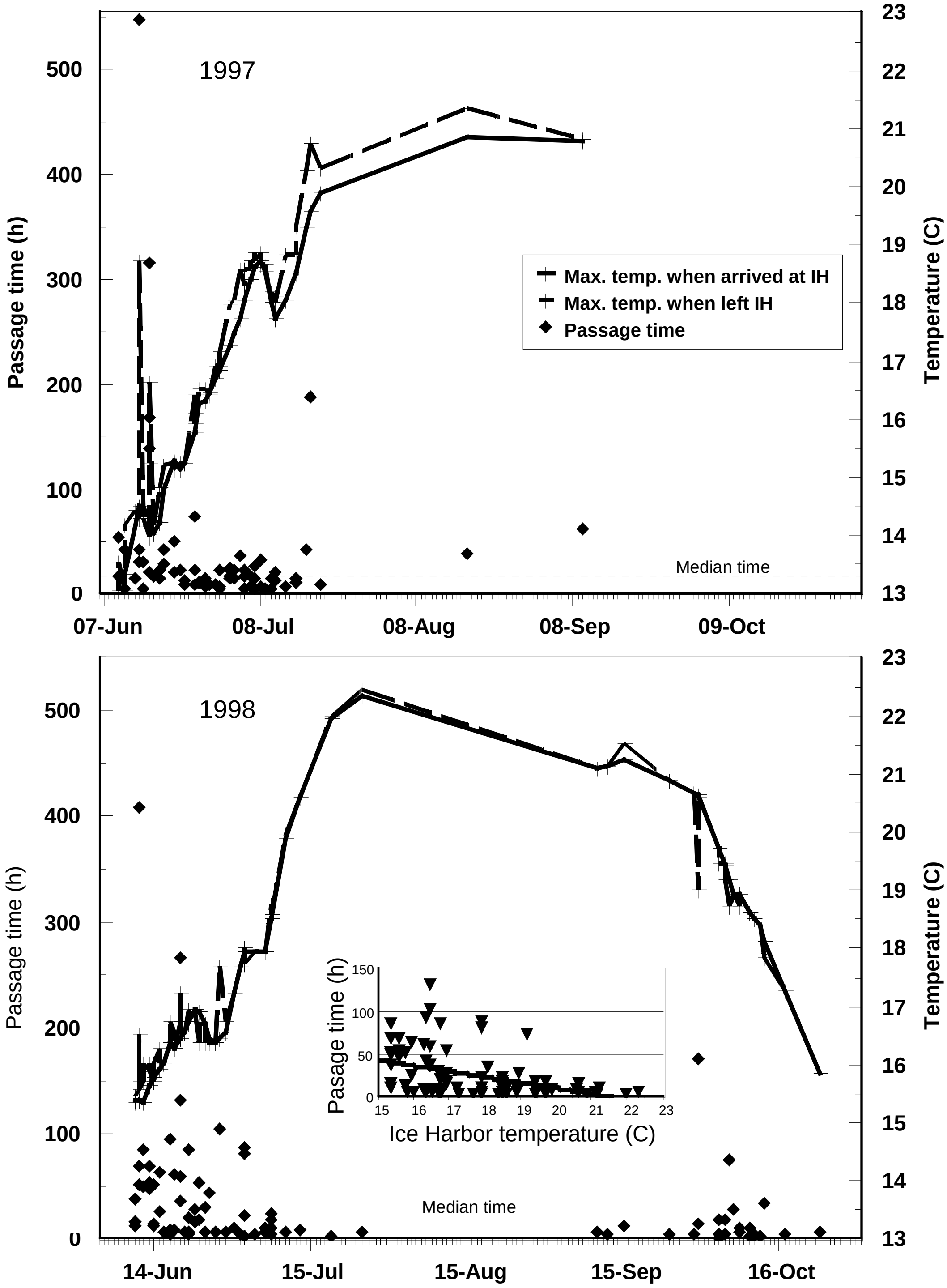


Figure 38. Times for summer and fall chinook salmon to pass Ice Harbor Dam and mean water temperatures on day fish arrived at and left the dam in 1997 and 1998, and relationship between passage times and maximum temperature on day fish arrived at Ice Harbor Dam in 1998 (inset). Horizontal dashed line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

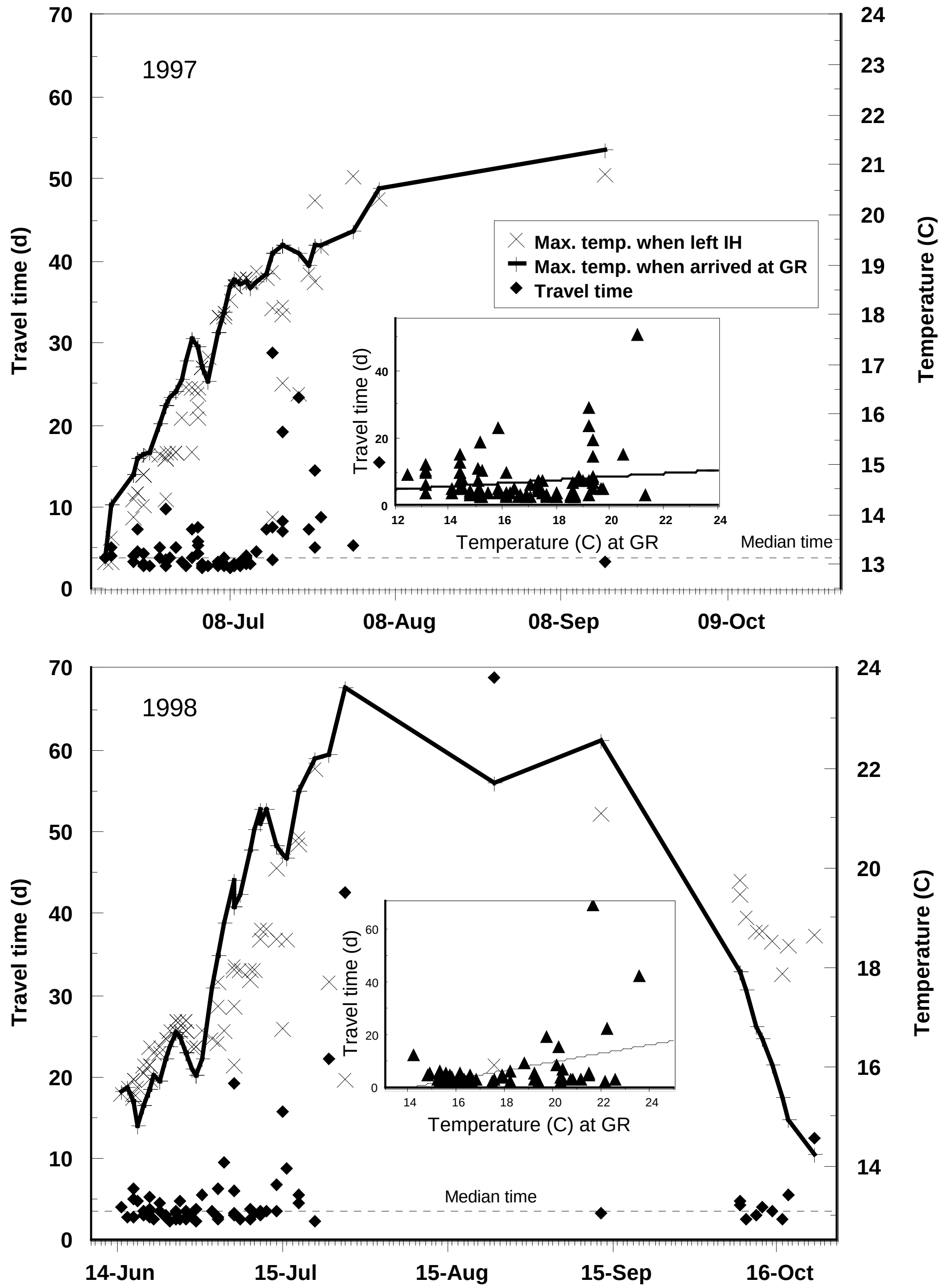


Figure 39. Travel times for summer and fall chinook salmon between Ice Harbor (IH) and Lower Granite (GR) dams and mean water temperatures on day fish left Ice Harbor Dam and arrived at Lower Granite Dam in 1997 and 1998, and significant regressions between travel times and temperature on day fish arrived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

= 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).

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 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 22.1ºC in 1996 and from 13.5 to 21.9ºC 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.

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

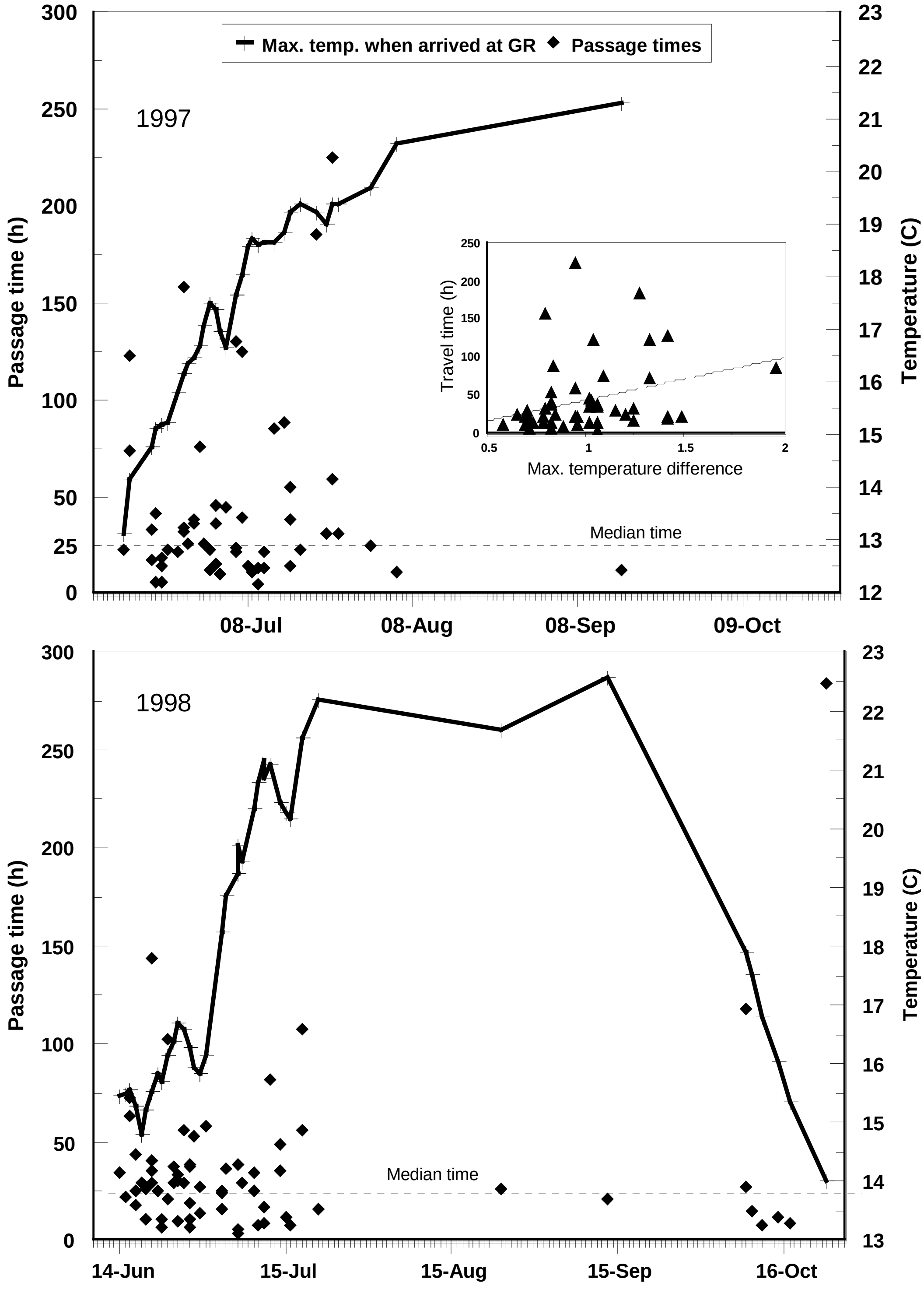


Figure 40. Times for summer and fall chinook salmon to pass Lower Granite Dam (GR) and mean water temperature on day fish arrived at the dam in 1997 and 1998, and relationship between passage times and maximum difference in water temperatures on day fish arrived at Lower Granite Dam in 1997 (inset).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

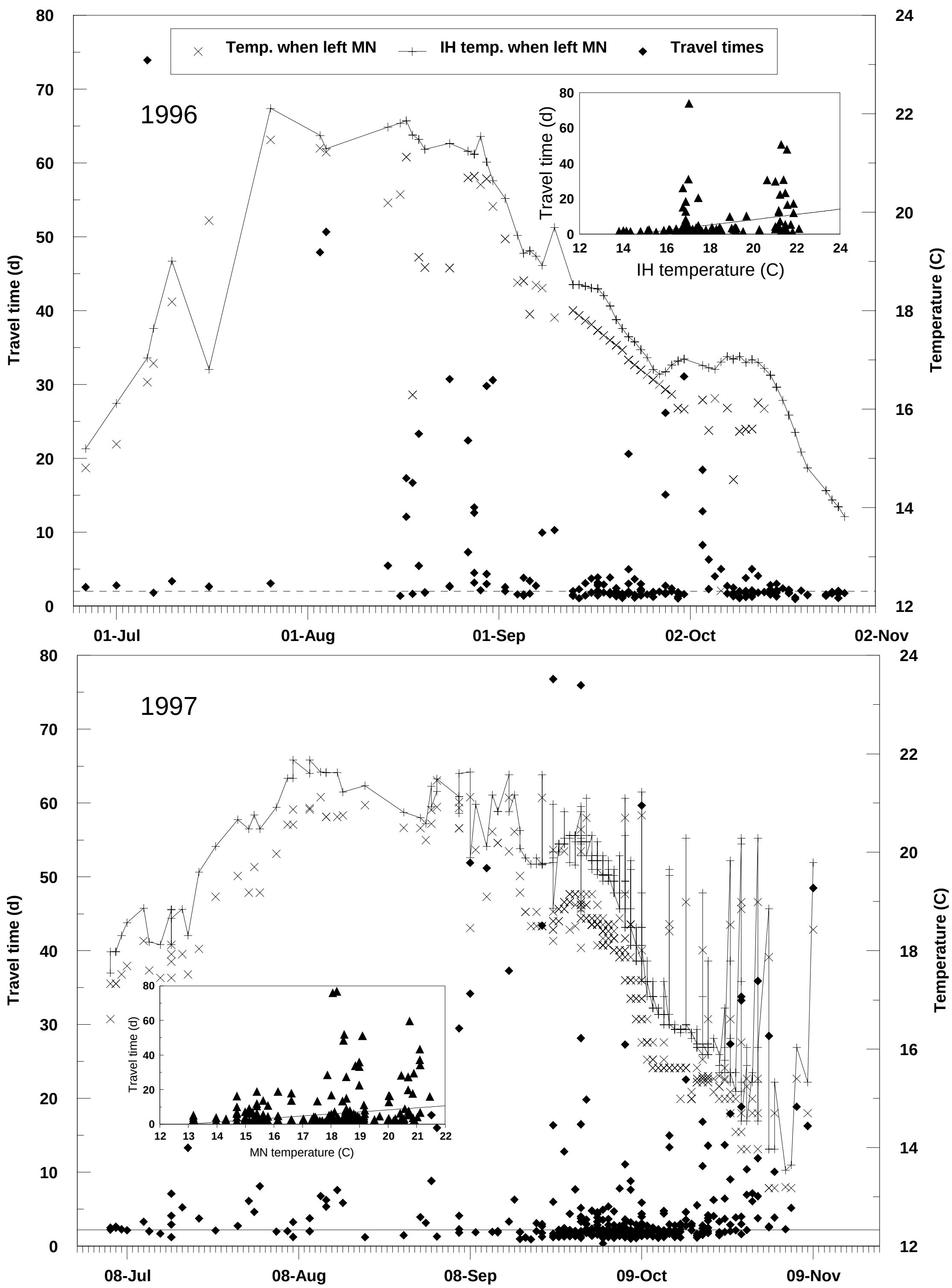


Figure 41. Travel times for steelhead between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1996 and 1997. Shown are relationships between travel times and temperature at Ice Harbor Dam in 1996, and between travel times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

passing ranged 13 to 22ºC in 1996 and12 to 22ºC 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 were in 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 22ºC in 1996, and from 12 to near 22ºC in 1997. For both years, travel times were not significantly related to water temperatures measured on the 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 22.1ºC in 1996 and from 11.3 to 22.1ºC 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 ($P = 0.002$, $R^2 = 0.055$), partially due at least to a few outlyer points at the data extremes (Figure 44).

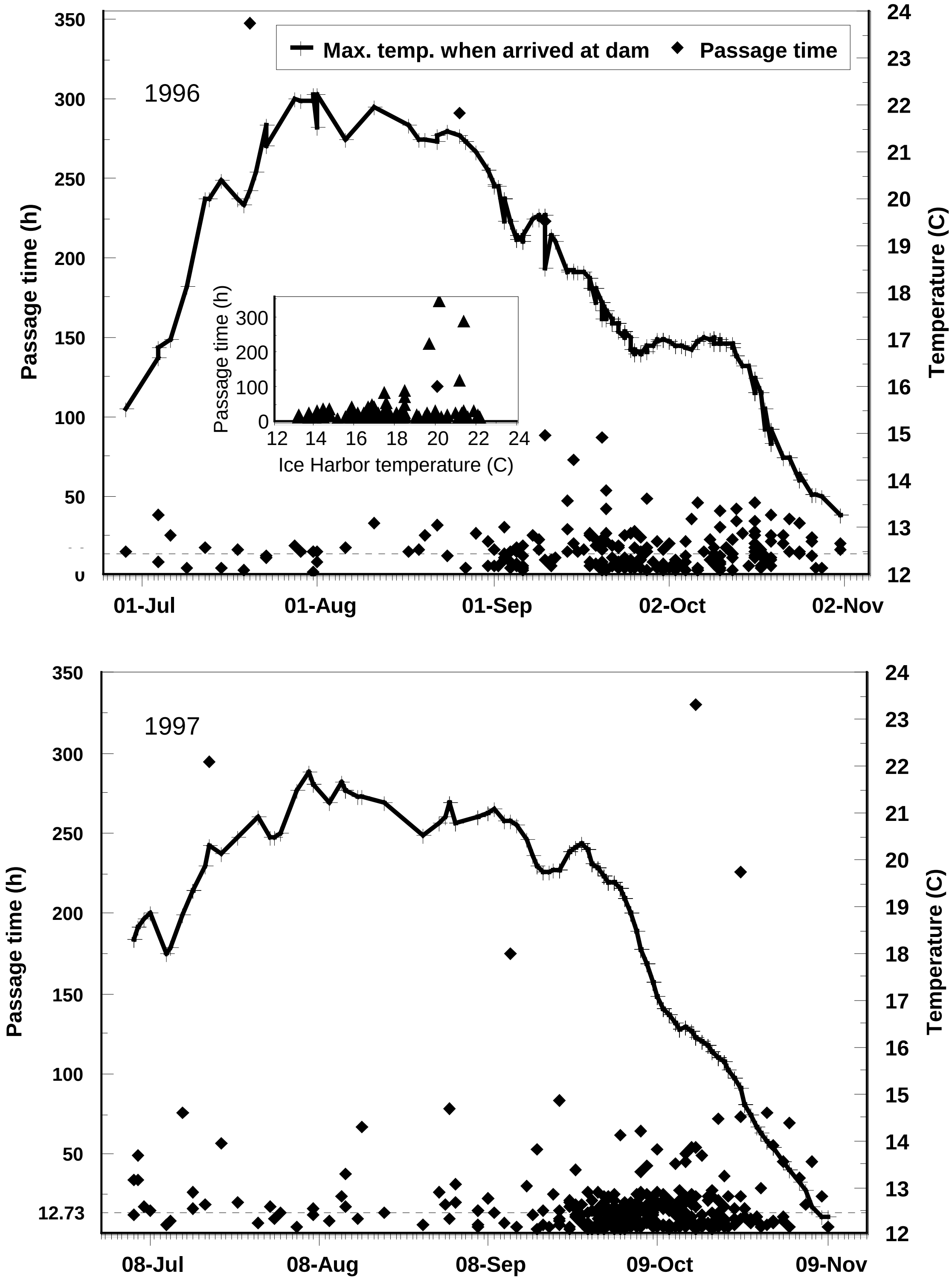
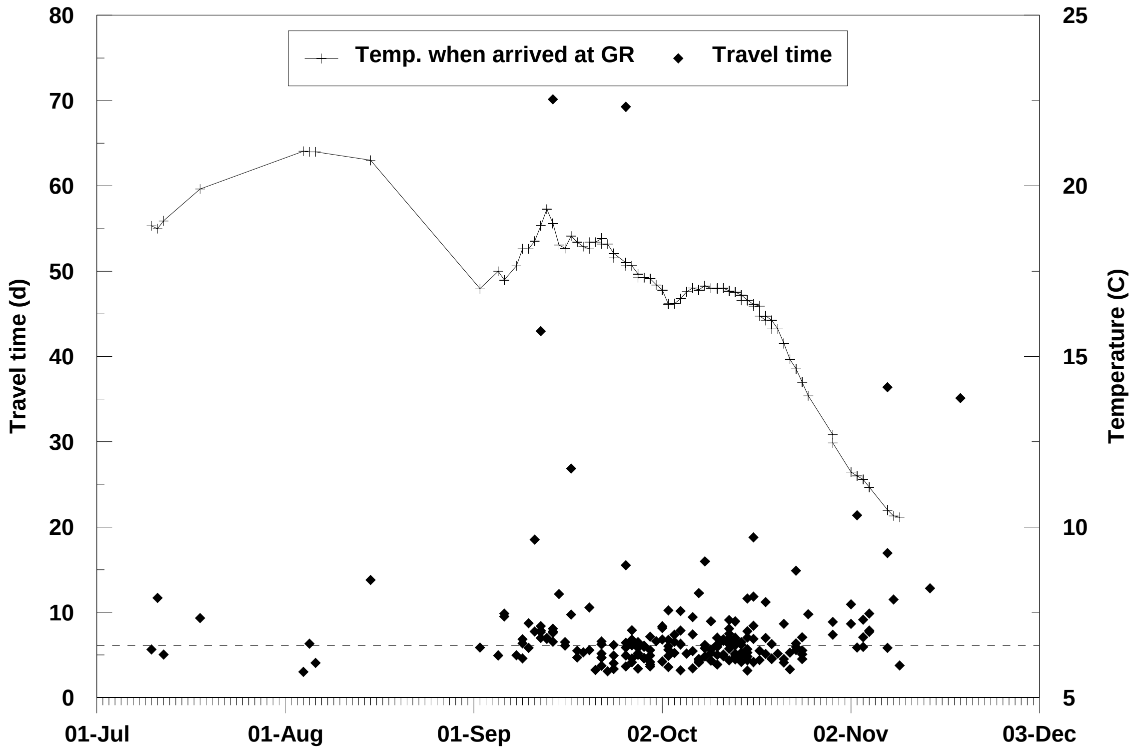


Figure 42. Times for adult steelhead pass Ice Harbor Dam and mean water temperatures on day fish arrived at the dam in 1996 and 1997, and relationship between passage times and maximum temperature on day fish arrived at Ice Harbor Dam in 1996 (inset). Horizontal dashed line represents median passage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



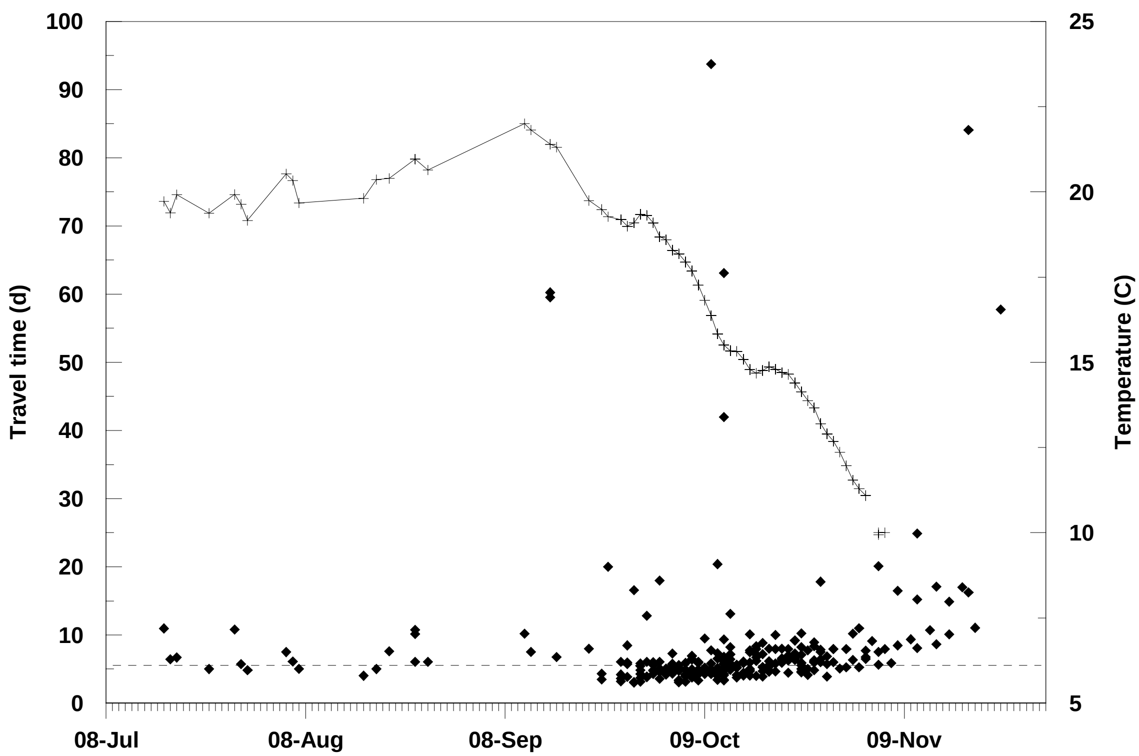


Figure 43. Travel times for steelhead between Ice Harbor and Lower Granite dams and mean water temperatures at Lower Granite Dam on the day fish arrived at the dam, in 1996 and 1997. Dashed line represents median travel times.

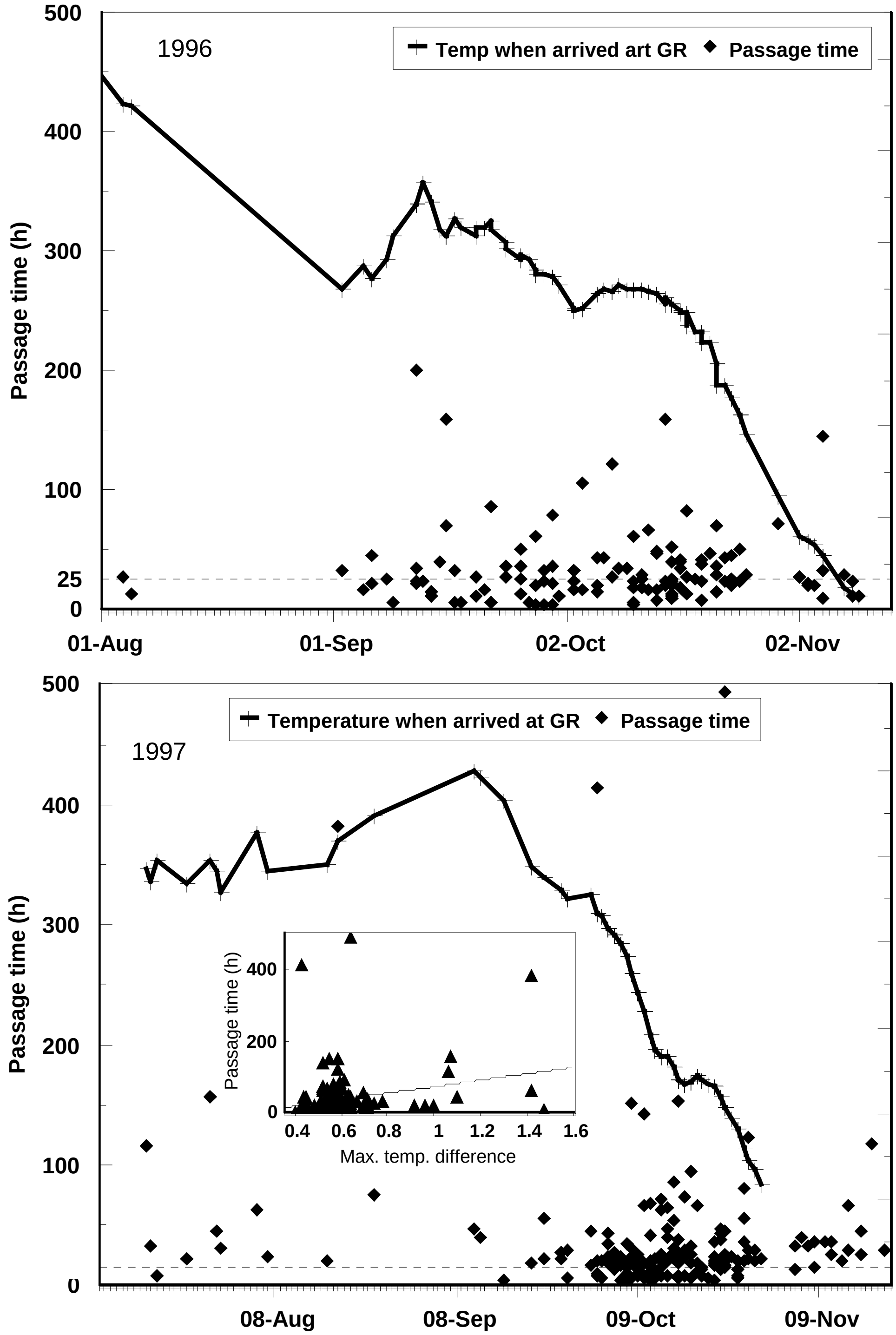


Figure 44. Times for adult steelhead pass Lower Granite Dam and mean water temperatures on day fish arrived at the dam in 1996 and 1997, and relationship between passage times and maximum temperature on day fish arrived at Lower Granite Dam in 1997 (inset). Horizontal dashed line represents median passage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

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 have warmed over time, generally they appear to have remained unchanged or to have declined during some months since prior to impoundment by the four lower Snake River dams. Summer water temperatures at the mouth of the Snake River are influenced by operations at Ice Harbor Dam because most of the water at that time of year is from turbine outflow. In data collected by Bennett et al. (1997b) one can readily see that 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. Adult salmon and steelhead do not experience warmer water conditions at the mouth of the Snake River now than existed prior to impoundment.

Since Ice Harbor Dam was completed water temperatures in the forebay have gradually increased during October and were unchanged for June, July, August and September. The maximum temperature measured each month and date of maximum temperature for each year have not changed since 1962, which agrees with findings of Quinn et al. (1997). Flow levels and air temperatures were the two environmental

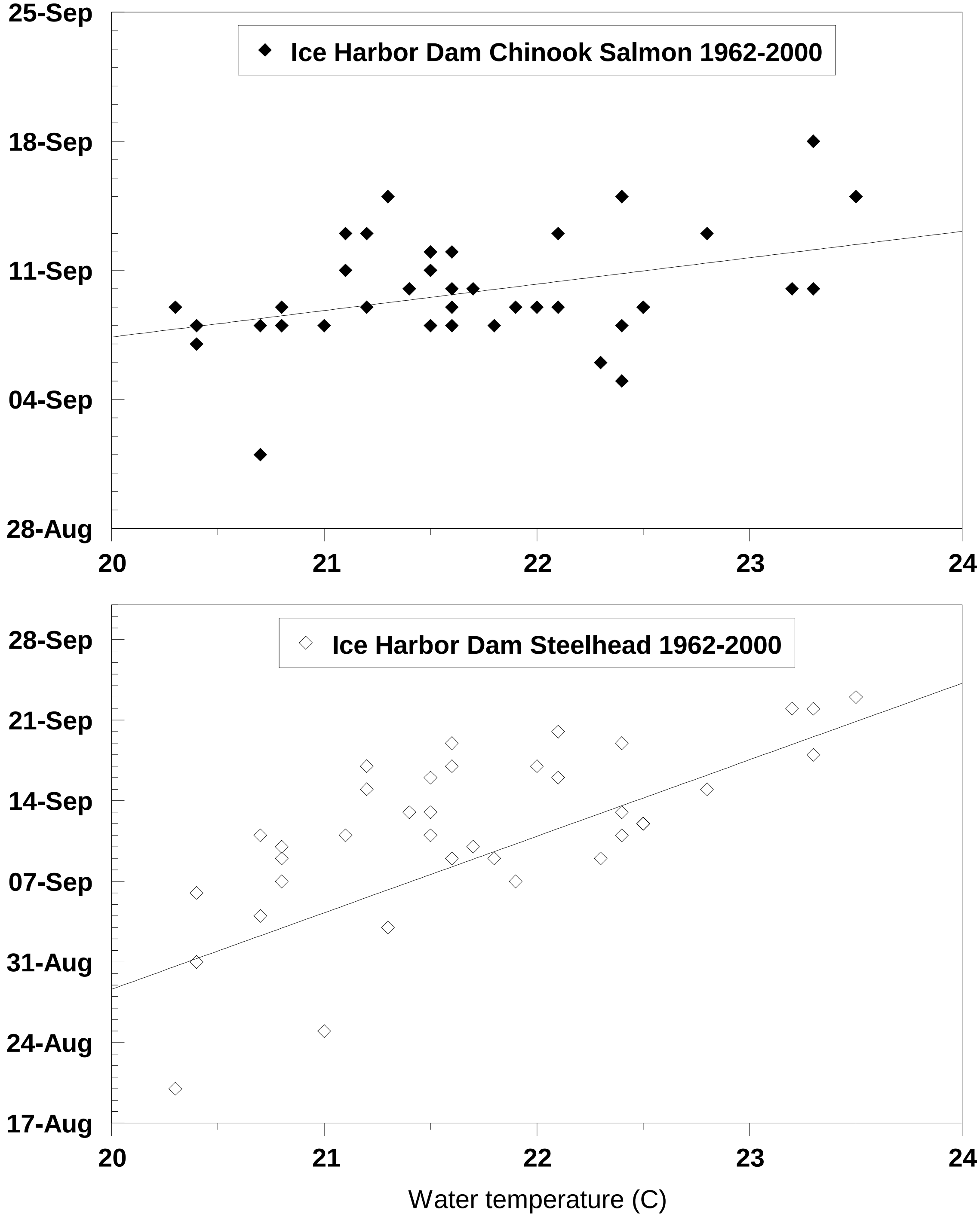


Figure 45. Date that 25% of the fall chinook salmon and steelhead runs were counted at Ice Harbor Dam versus mean water temperature measured in the forebay of the dam during the period from 1 August through 15 September for each year 1962-2000. Fall chinook salmon counts from 12 August until 31 October.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

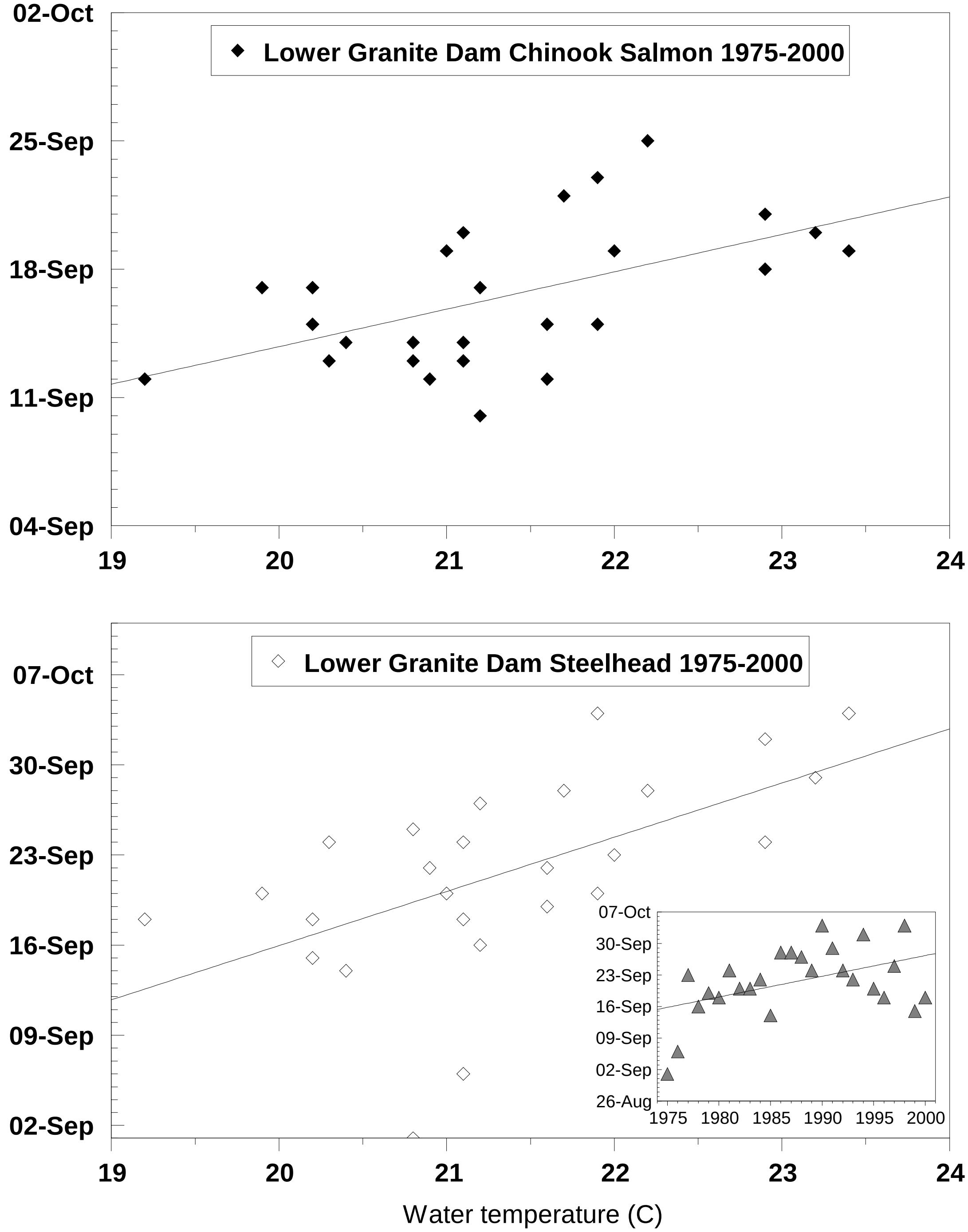


Figure 46. Date that 25% of the fall chinook salmon and steelhead runs were counted at Lower Granite Dam versus mean water temperature measured in forebay of the dam during the period from 1 August through 15 September for each year, 1975-2000. Trend for date 25% of steelhead have passed Lower Granite 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.

factors we identified with the greatest influence on forebay water temperatures in the lower Snake River. Average 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 2000. 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 (≥ 20ºC) 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. 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 4ºC 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 1-3ºC between the water surface and 30 m depth, but temperatures deep in the reservoir consistently exceeded 20ºC 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 22ºC (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 20 kcfs or higher, 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 2-4ºC 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 1-3ºC, depending on air temperatures, when flow from Dworshak reservoir were 40-60% 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 Corps to predict that temperature reductions of <0.6 to 2.2ºC (<1 to 4ºF) 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 5ºC at mid-depth in the Lower Granite Dam forebay and 2 to 3ºC 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 occurred, on average, with higher water temperatures. 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. Regression analysis as presented here are prone to overdispersion, resulting in conservative test results. 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. 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, but not steelhead, traveled slower through the lower Snake River when water temperatures were high. In contrast to radio-telemetry data, there was a relatively 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 years when average summer-time water temperatures were high, additional evidence that some salmon and steelhead will delay their upstream migration to avoid warm water conditions.

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 outlyer 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 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.

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 too 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 drop. 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 on 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 20ºC until 9 October that year. Releasing water from Dworshak reservoir can be used to moderate 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 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. This cooler water could then flow down fishways and be picked up at diffuser pump intakes to moderate fishway temperatures. With this option fish would also not have to enter the warm surface water immediately upon exiting fishways. If water from deep in the reservoir is 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 to the weired section of the fishway ladders where we have found that radio-tagged salmon and steelhead advance with little 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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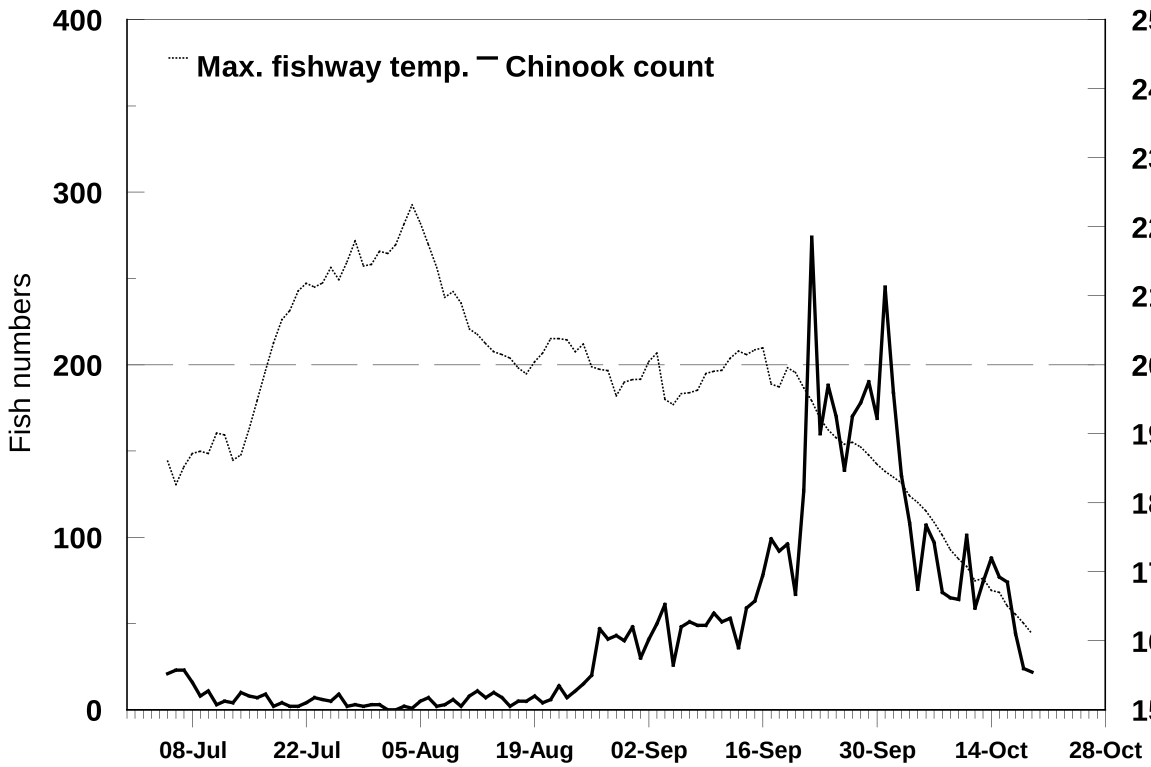
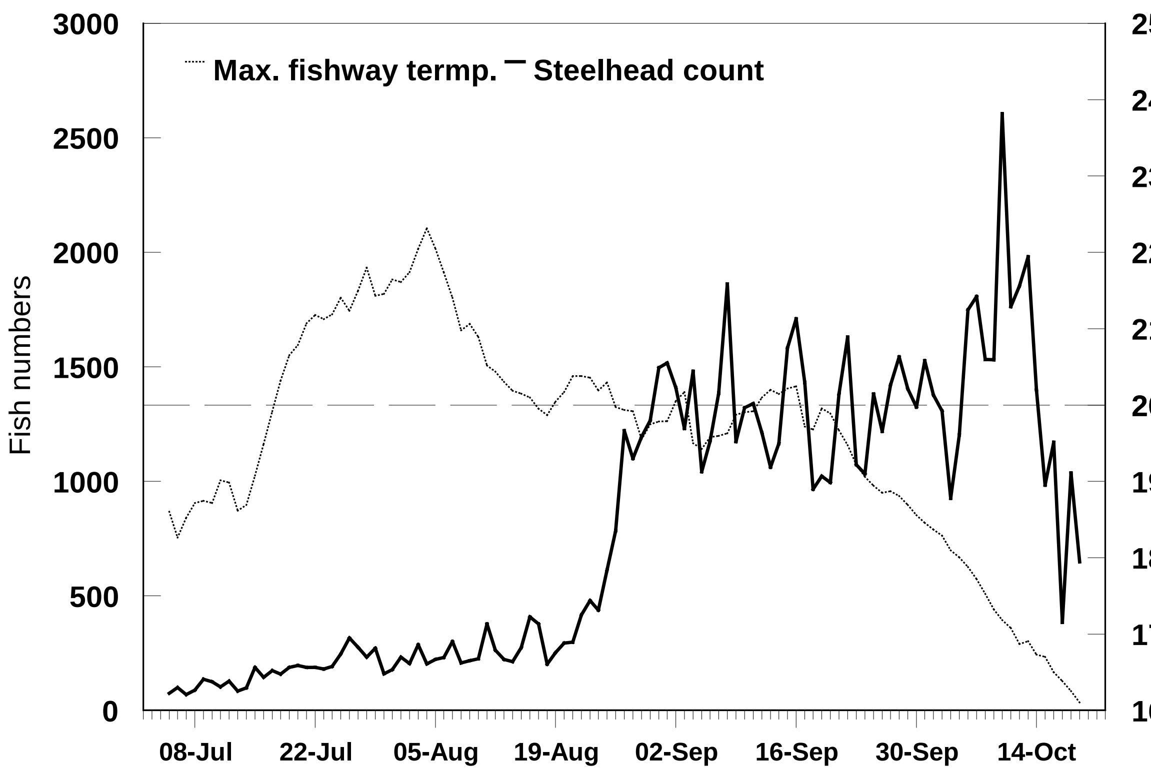
Appendix A

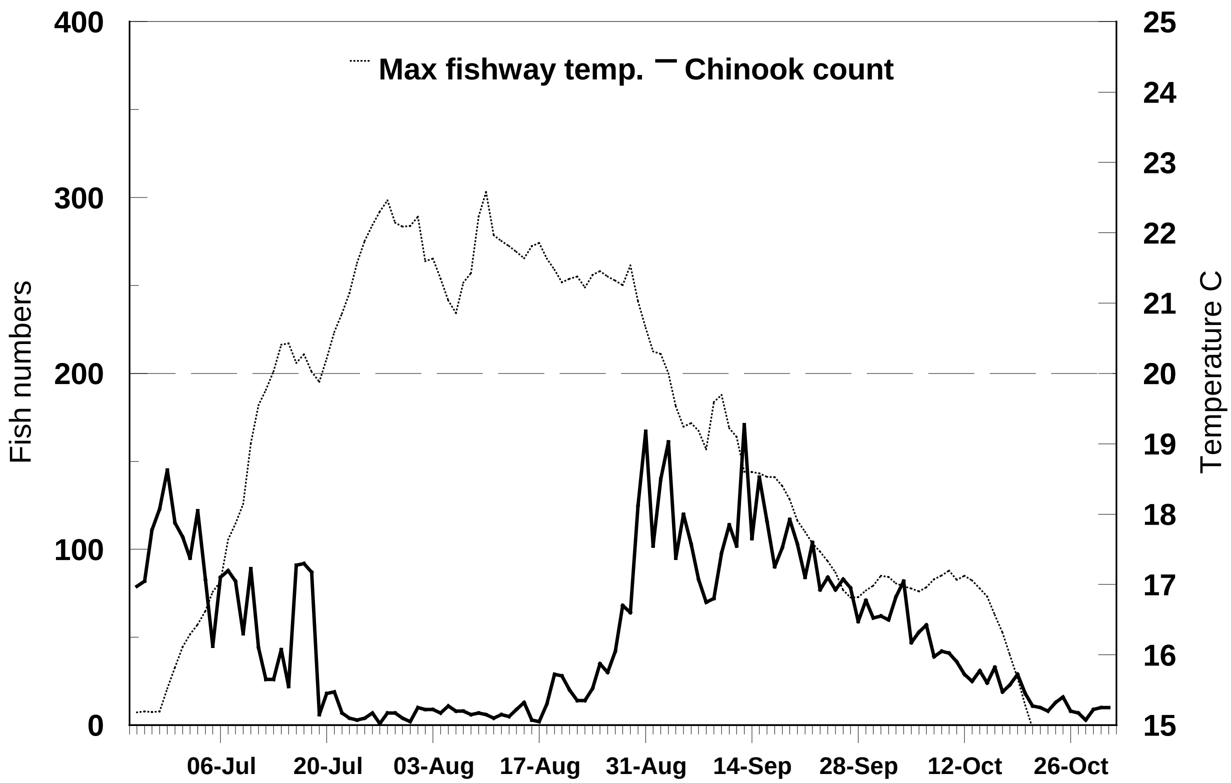
Adult chinook salmon and steelhead counts and maximum daily water temperatures measured in fishways at Ice Harbor and Lower Granite dams during 1995 to 1998.

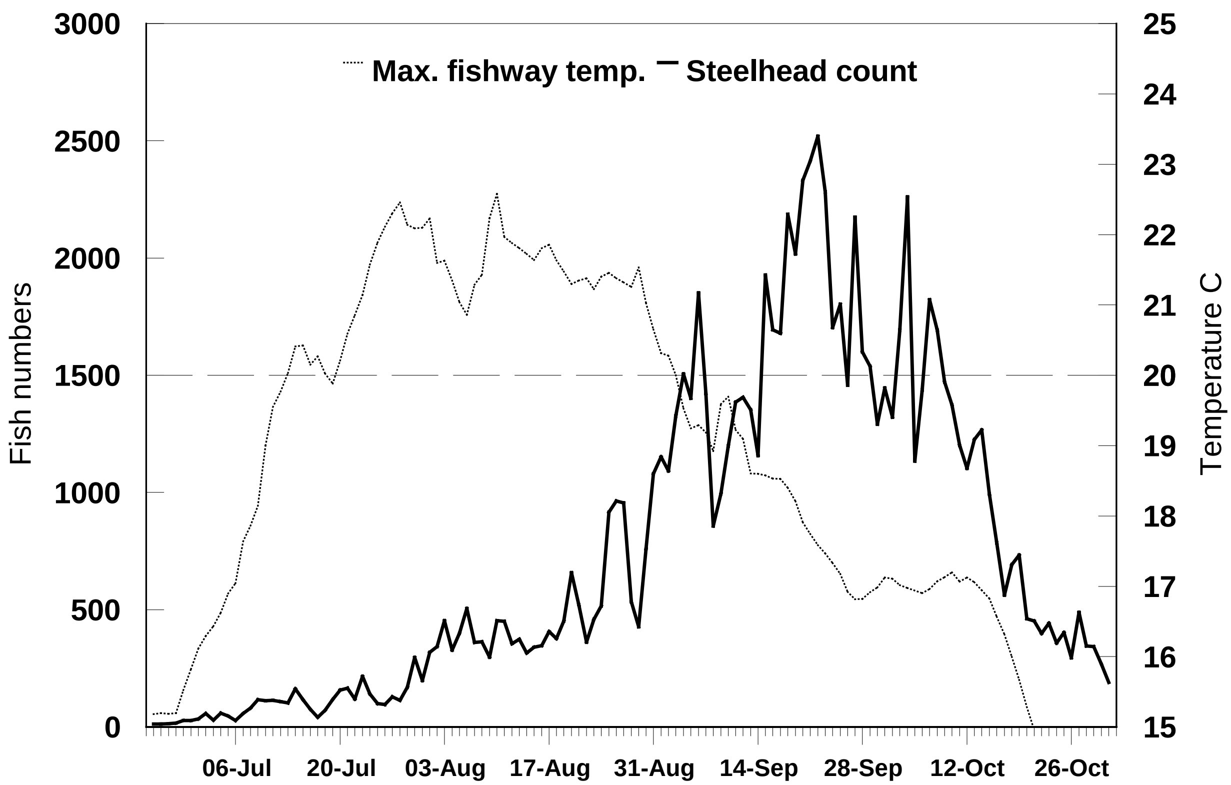
Ice Harbor Dam 1995





Ice Harbor Dam 1996





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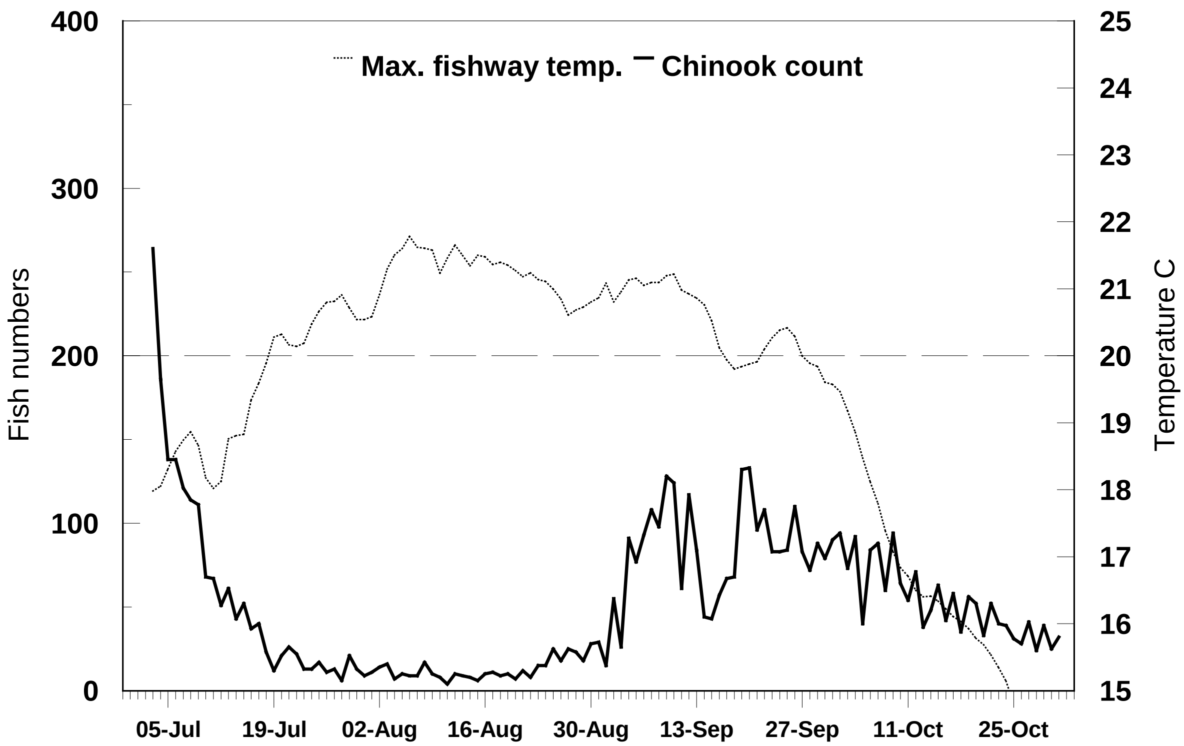
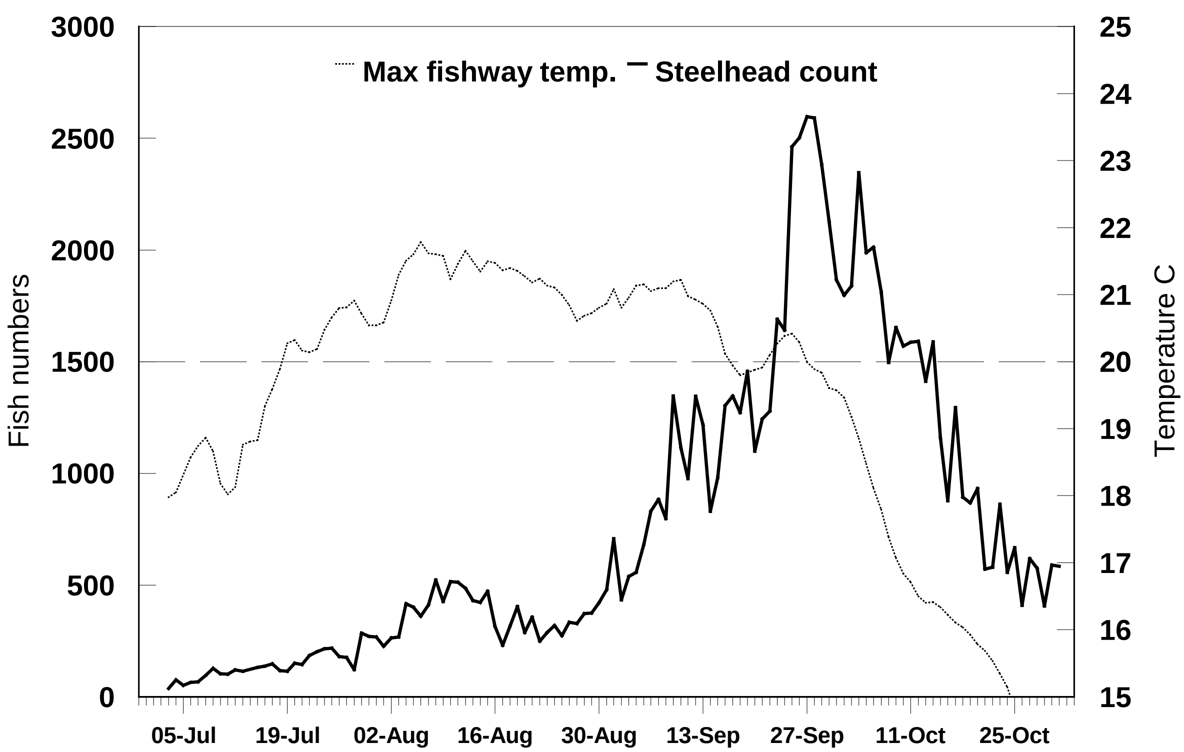
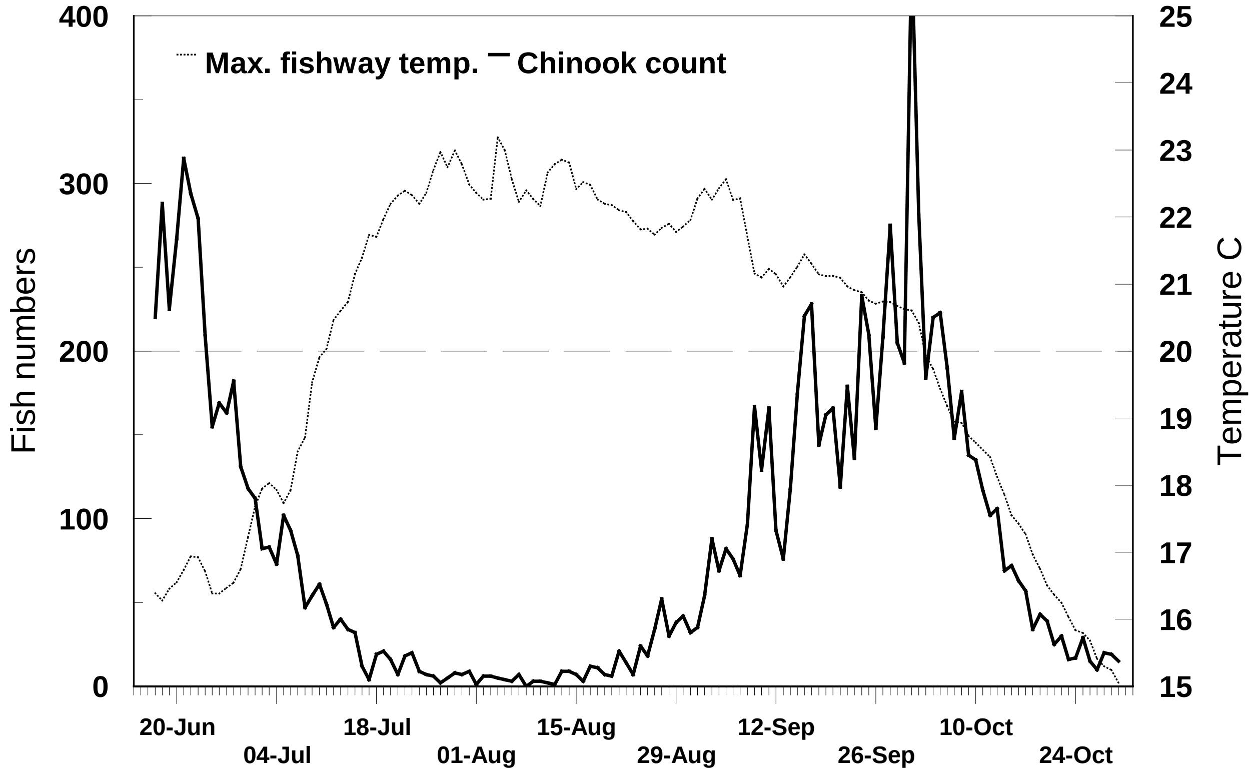
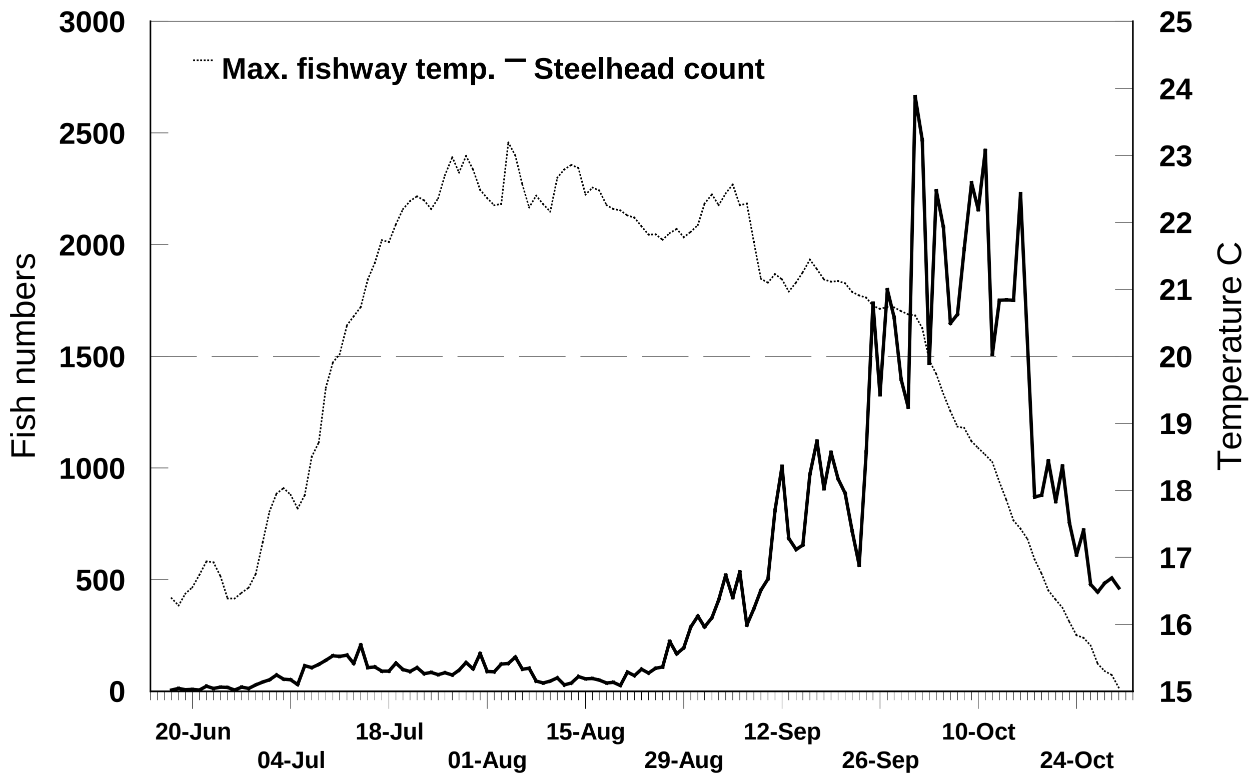


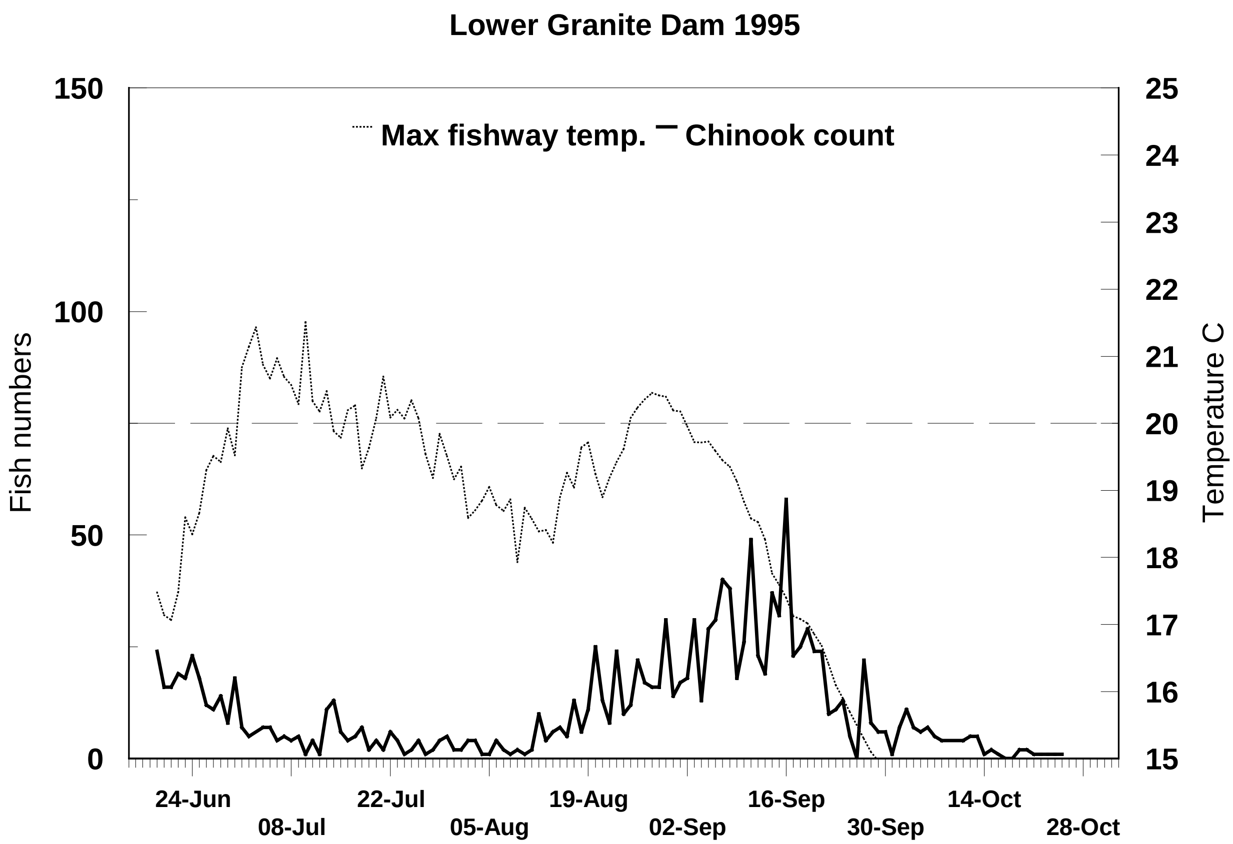
Ice Harbor 1997 steelhead

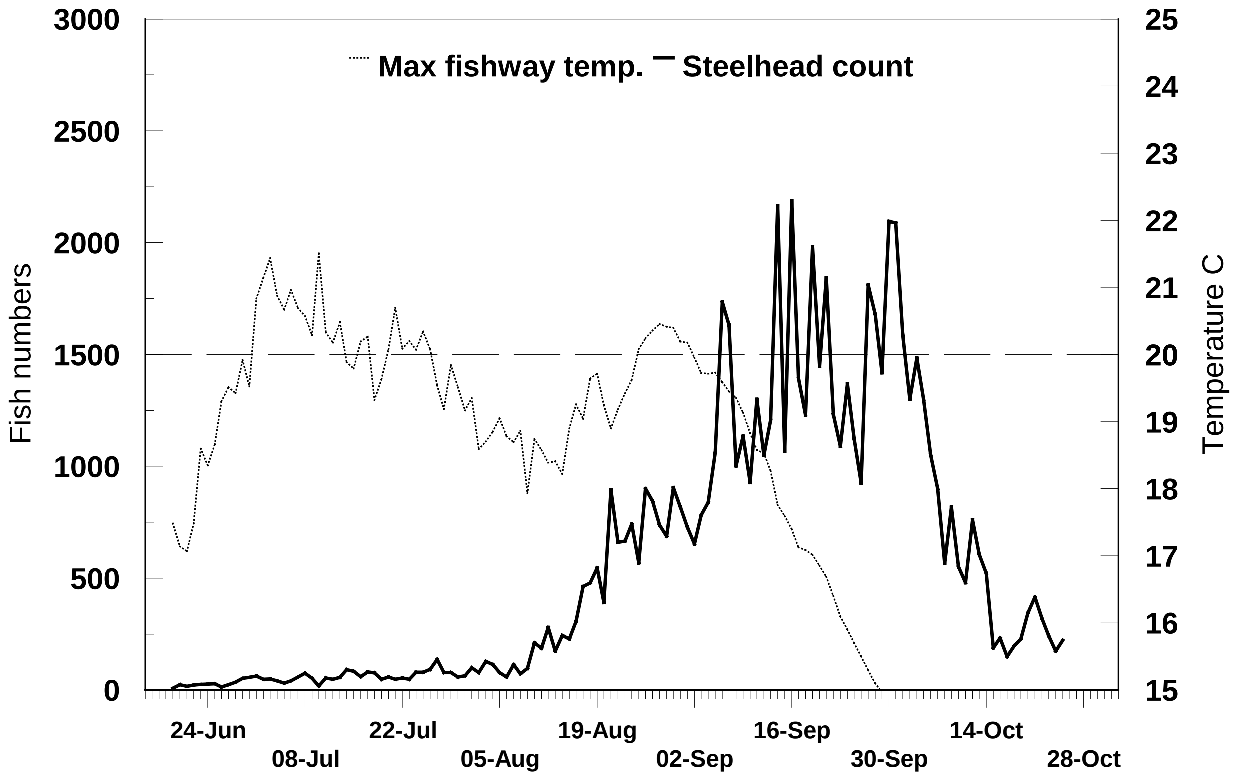


Ice Harbor Dam 1998

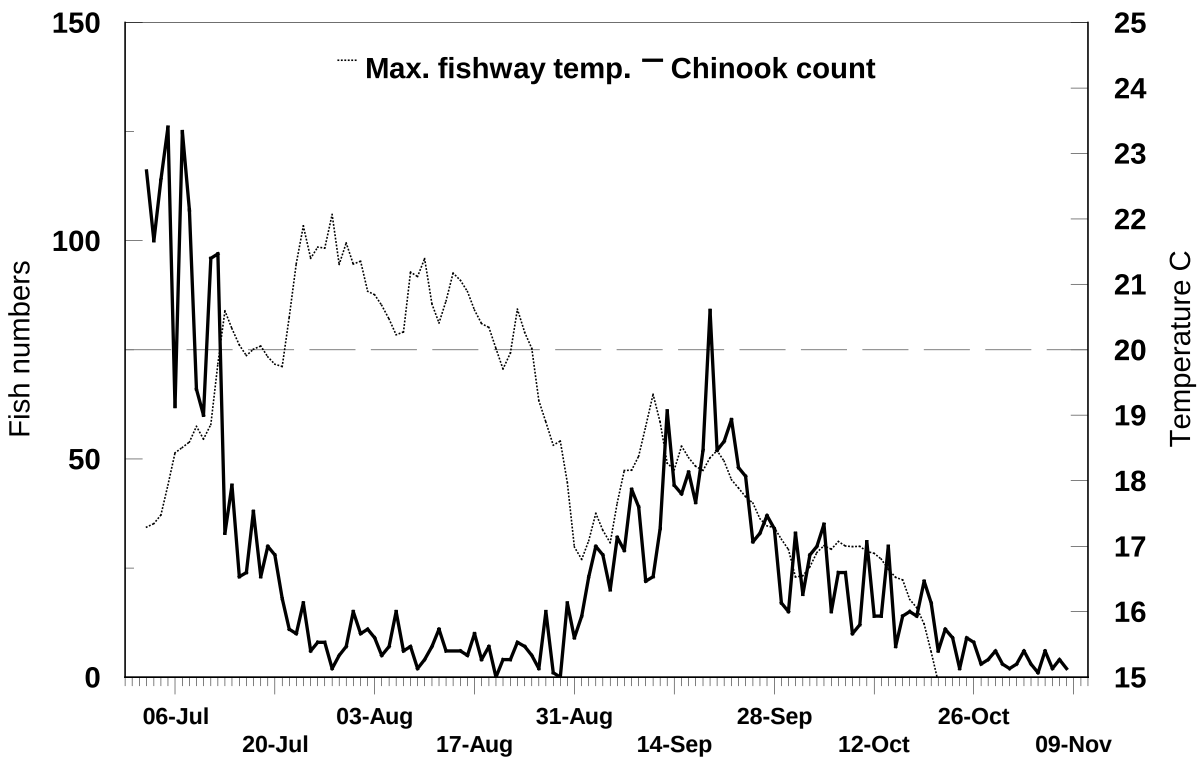


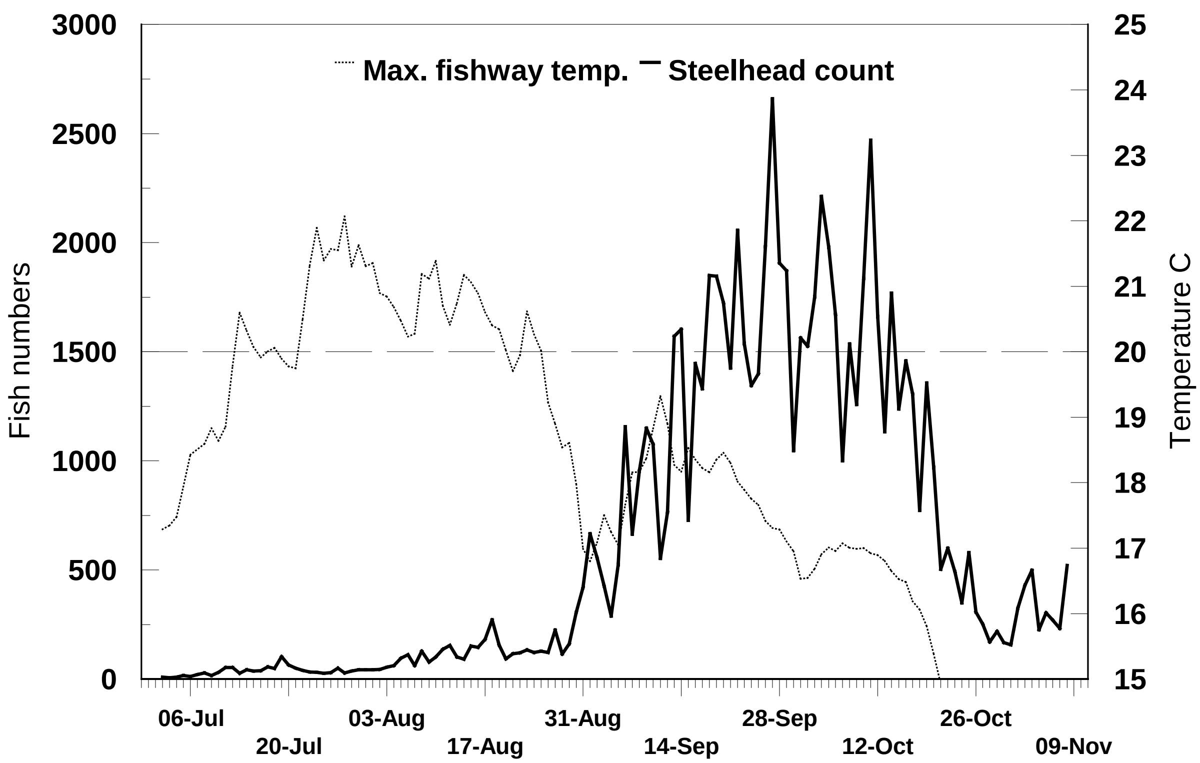



Lower Granite Dam 1995
Max fishway temp.
Chinook count
Fish numbers
Temperature C
150
100
50
0
25
24
23
22
21
20
19
18
17
16
15
24-Jun
08-Jul
22-Jul
05-Aug
19-Aug
02-Sep
16-Sep
30-Sep
14-Oct
28-Oct

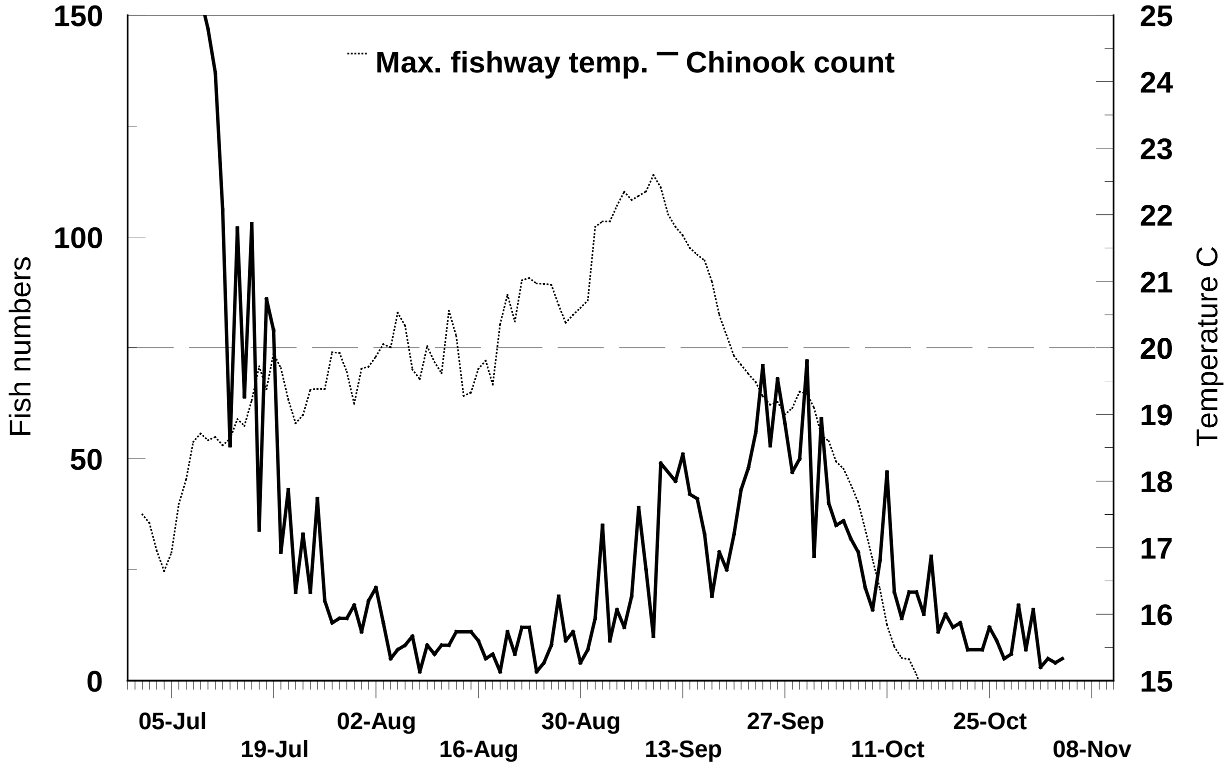

Max fishway temp.
Steelhead count
Fish numbers
Temperature C
3000
2500
2000
1500
1000
500
0
25
24
23
22
21
20
19
18
17
16
15
24-Jun
08-Jul
22-Jul
05-Aug
19-Aug
02-Sep
16-Sep
30-Sep
14-Oct
28-Oct

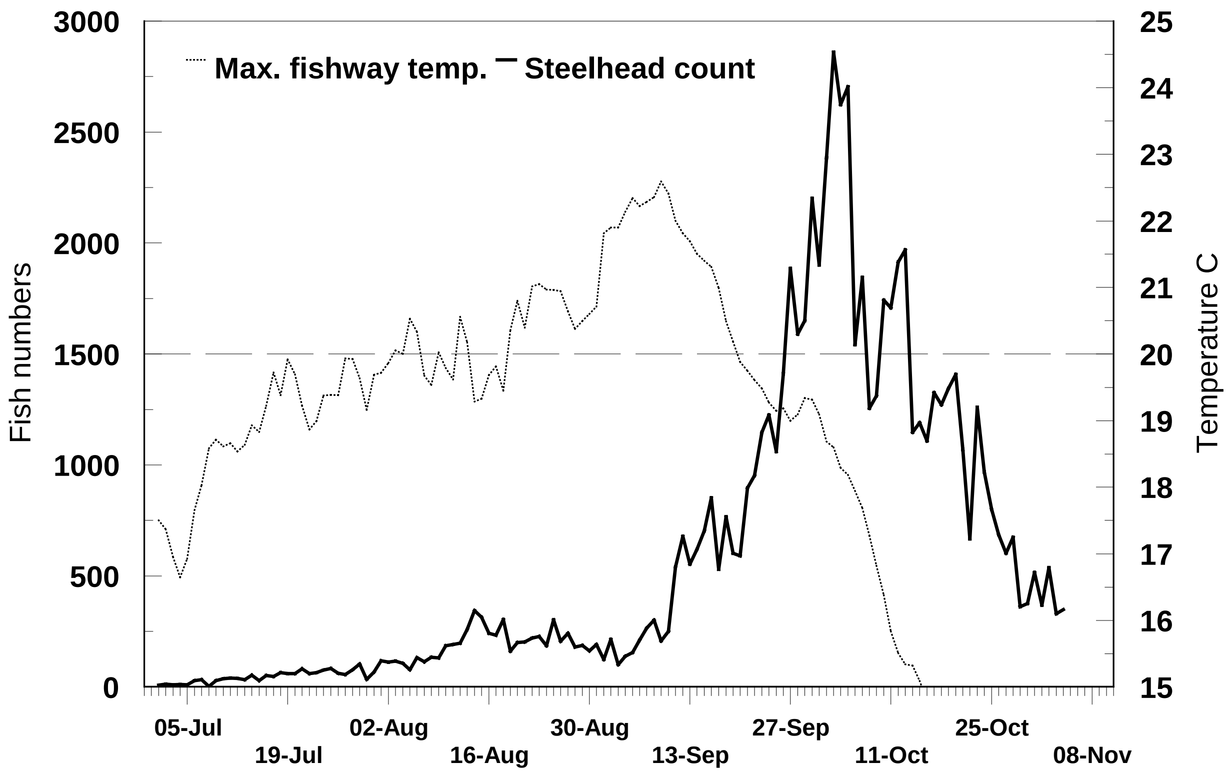
Lower Granite Dam 1996





Lower Granite Dam 1997





Lower Granite Dam 1998