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Water Temperature Studies at Chief Joseph Dam, Washington 2003: Data Review and Quality Assurance

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Introduction

The Columbia River drains over 670,000 square kilometers of the Pacific Northwest in the United States and Canada. The Snake, Kootenai, and Pend Oreille-Clark Fork systems are the largest tributaries of the Columbia River. The hydrology of the Columbia River system has been modified during the past 100 years due to the construction of numerous hydroelectric, irrigation, flood control, and transportation projects. The construction of these projects on the mainstem of and tributaries of the Columbia River created numerous reservoirs that have resulted in a significant alteration of the natural flow regime, river geometry, river velocity, and water residence time in the Columbia River. A consequence of the creation of reservoirs is that the thermal patterns of the Columbia River system have been altered generally resulting in increased water temperatures in the summer and fall.

Changes in the thermal regime of the Columbia River are of concern because water temperature has an impact on fish survivability, total dissolved gas saturations, the biotic community, chemical and biological reaction rates, and other aquatic processes. In addition, water temperature impacts the distribution and survival of native fish in the Columbia River system, including salmonid species listed under the Endangered Species Act (ESA). The Environmental Protection Agency (EPA), State of Washington Department of Ecology (WDOE), and State of Oregon Department of Environmental Quality (ODEQ) have listed multiple segments of the Columbia River and tributaries on the federal Clean Water Act (CWA) 303d list of impaired surface waters temperature violations of state water quality standards. Consequently, these agencies are proposing a temperature Total Maximum Daily Load (TMDL) for the Columbia River within the States of Washington and Oregon, and the Reservations of the Colville Confederated Tribes (CCT) and Spokane Tribe of Indians (STI).

The Seattle District Corps of Engineers (COE) operates one dam on the mainstem Columbia River, Chief Joseph Dam. To address the concerns over the impacts of dams and reservoirs on the thermal regime in the Columbia River and to actively participate in the proposed Columbia River temperature TMDL, the COE designed a temperature study to quantify more precisely the effect of Chief Joseph Dam on the thermal regime in the Columbia River. Baseline temperature data will allow the COE to share data and work together with other state and federal agencies to develop a more comprehensive Columbia River temperature TMDL. In addition, baseline temperature data will help the Seattle District better define the relationship between Chief Joseph Dam operations and the water temperatures in the Columbia River.

Purpose and Scope

The Seattle District Corps of Engineers conducted a surface water temperature study in the Columbia River above and below Chief Joseph Dam during 2003. The purpose of the study was to collect baseline temperature data to determine the temporal and spatial gradients in water

temperature in the Columbia River upstream and downstream of Chief Joseph Dam. The major objectives of this study were to:

- Evaluate water temperatures throughout the reservoir behind Chief Joseph Dam to determine whether significant longitudinal differences exist
- Evaluate water temperatures at different depths in the reservoir to determine vertical temperature/density gradients
- Characterize the longitudinal and lateral variability of temperature in the reservoir
- Characterize the temporal variability, both daily and seasonal, in water temperatures
- Determine representativeness of the current forebay fixed temperature monitoring station on river conditions.

These objectives were addressed using automated thermal loggers and real-time water quality probes programmed to record date, time and temperature in degrees Celsius (C) every hour. Data were collected from four (4) multiple depth automated remote water temperature logger (temperature string) stations, and two (2) single depth fixed monitoring stations. The study was conducted from June through November 2003 and focused on the Columbia River from Grand Coulee Dam downstream to Chief Joseph Dam.

Methods and Materials

Site Characterization

The Columbia River originates in the Rocky Mountains of British Columbia at an elevation exceeding 3,000 meters and flows northward for several hundred kilometers before flowing southward through a series of lakes and reservoirs toward the state of Washington (Figure 1). The Kootenai River and the Pend Oreille River enter the Columbia River north of the international border, and the Columbia River flows into Lake Roosevelt immediately south of the border. Lake Roosevelt is the 210 kilometer long reservoir formed by Grand Coulee Dam, a Bureau of Reclamation (BOR) project located at river kilometer 960. Downstream of Grand Coulee Dam the river enters Rufus Woods Lake, the 80 kilometer long reservoir formed by Chief Joseph Dam, a COE project. Chief Joseph Dam is a run-of-river dam located at river kilometer 876 on the Columbia River in Washington, about 84 kilometers downstream of Grand Coulee Dam (Figure 2). The dam is a concrete gravity dam, 72 meters high, with 19 spillway bays which abut the right bank. Rufus Woods Lake has a gross storage capacity of 728 million cubic meters, a maximum depth of about 70 meters, and a mean water residence time of about 3 days. This study was conducted in the Columbia River from Grand Coulee Dam downstream to Chief Joseph Dam (Figure 2).

The study area lies within the high-steppe, semiarid desert region of central Washington (Figure 2). The Columbia River in the study area forms the boundary between two distinct geologic provinces in the State of Washington, the Okanogan Highlands to the north and the Columbia Plateau to the south (WDNR 2004). The Okanogan Highlands are characterized by rounded mountains and narrow valleys, and are dominated by metasedimentary rocks. The Columbia Plateau is characterized by incised rivers, extensive plateaus, and anticlinal ridges. The Plateau region is dominated by basalt flows laid down by successive volcanic eruptions during the Miocene (WDNR 2004). Elevations range from about 236 meters at the Columbia River immediately downstream of Chief Joseph Dam to over 1,000 meters in the mountainous terrain that rise up from the water in the mid to upper reaches of the reservoir. Land use in the study area is dominated by rangeland, irrigated cropland, and orchards (USCOE 1985).

The climate of the study area is influenced by easterly moving weather systems from the Pacific Ocean. Winters are generally cool with November through March being the wettest months. Summers are warm and dry with little to no precipitation falling from June through September. The mean annual precipitation in the vicinity of the dam is about 25 centimeters. Total annual snowfall varies with elevation throughout the study area, with about 40 centimeters near the dam. The mean annual temperature at the dam is 10°C, with extremes recorded in the vicinity of the dam of – 30°C and 43°C (USCOE 1985).

Data Collection

Temperature data were collected using Vemco Minilog automated thermal loggers and real-time Hydrolab MiniSonde 4a water quality probes programmed to record date, time and temperature in degrees Celsius every hour. Automated thermal loggers and water quality probes were deployed at six stations in the Columbia River upstream and downstream of Chief Joseph Dam to monitor vertical, horizontal, and longitudinal temperature regimes in the Columbia River (Figure 2). Station locations and details are summarized in Table 1.

Automated thermal loggers were deployed in Lake Rufus Woods as a string attached to a buoy in a vertical profile starting at the surface (0.5 meter depth) with loggers concentrated in the region of more significant temperature gradients down to about 2 meters off of the bottom (Table 2). Data were downloaded from the loggers at the end of the deployment period and entered into a database.

Real-time water quality probes were deployed at the existing fixed monitoring stations located at the Chief Joseph Dam forebay powerhouse station (CHJ) and the Chief Joseph Dam tailwater station (CHQW) (see Table 1 and Figure 2). At station CHJ the water quality probe was located in Lake Rufus Woods near the left bank by the powerhouse. The probe was deployed directly into the water off of the boathouse's floating dock at a depth of 6 meters (see Figure 2). At station CHQW the water quality probe was deployed along the right bank of the river, 1.2 kilometers (km) downstream from the dam. The probe was placed inside an anchored perforated PVC pipe that extended into the river to a depth of at least 3 meters during low flow conditions. Instrumentation at the real-time stations consisted of a Hydrolab MiniSonde 4a water quality probe, a Common Sensing TBO-L electronic barometer, a Sutron Model 8200 data collection platform (DCP), and a power source. The barometer, probe and DCP were powered by a 12-volt battery that was charged by a 120-volt AC line. Measurements were made every hour, and every 4 hours the DCP transmitted the data via the Geostationary Operational Environmental Satellite (GOES) system to the Corps of Engineers Northwestern Division (CENWD) in Portland, Oregon. The data were then stored in the Columbia River Operational Hydromet Management System (CROHMS) database.

Quality-Assurance Procedures

Data quality control procedures for the automated thermal loggers and the water quality probes were different and are described in detail below.

Automated Thermal Loggers

Prior to field deployment, all thermal loggers were tested for accuracy in a laboratory under controlled conditions using a National Institute of Science and Technology (NIST) calibrated thermometer with an accuracy of ± 0.1°C. The data loggers used in this study have a stated

manufacturer's accuracy of ± 0.2°C. These loggers were placed in an ice water bath (about 1°C) and a room temperature water bath (about 20°C) for at least 2 hours to test logger accuracy. These water baths were stirred every 5 minutes and the temperature recorded using the NIST calibrated thermometer. The loggers were programmed to record temperature every minute while in the water bath. After retrieval, the difference between the logger's temperature and the thermometer's temperature was recorded and the data compared to the manufacturers stated logger accuracy. If a logger's accuracy was different by more than 0.3°C of the reference thermometer, the logger was not deployed in the field. A similar test for logger accuracy was completed after the loggers were retrieved from the field. The comparisons of the field temperature and the temperature standard are shown in Figures 3 and 4. In general, the field calibration results were within 0.2°C for all loggers.

Paired temperature loggers were deployed at the 6 meter depth at station CHJUPRB (see Table 2) to provide duplicate temperature records and to determine field variability for the automated thermal loggers. Data showed excellent agreement between the paired loggers with a maximum difference in temperature of 0.2°C, a mean difference of 0.0 °C and a median difference of 0.0°C.

Water Quality Probes

Water quality monitoring probes at the fixed monitoring stations were calibrated every two weeks during the 2003 monitoring season following procedures outlined in the *U.S. Corps of Engineers Plan of Action for Dissolved Gas Monitoring 2003* (USCOE 2002). Data quality assurance and calibration procedures included calibration of instruments in the laboratory and in the field. Two water quality probes were assigned to each station to allow laboratory calibrations between deployments and to provide back-up sensors in the event of equipment failure.

Prior to field service visits, water quality probes were laboratory calibrated using a NIST traceable thermometer with an accuracy of ± 0.1°C. The Hydrolab Minisonde 4a water quality probes have a stated manufacturer accuracy of ± 0.1°C. If the measurements differed by more than ± 0.2°C the probe was returned to the manufacturer for maintenance. As seen in Figure 5 most laboratory calibrations were within ± 0.1°C for temperature. Every two weeks a currently operating field probe was replaced with a laboratory-calibrated probe, which also operated as the secondary standard for the field probe. Prior to replacement every probe was field calibrated using the following method. The difference in temperature between the field probe and the laboratory calibrated probe (secondary standard) were measured *in-situ* and recorded. If the field probe disagreed with the secondary standard probe by more than ± 0.2°C for water temperature, the probe was removed and rechecked to field standards. The comparisons of the field temperature and the temperature standard are shown in Figure 5. In general, the field calibration results were within ± 0.1°C at all locations.

Data Completeness

Data completeness and quality for data collected in 2003 are summarized in Table 2. The percentage of temperature monitoring data received was calculated from the number of missing hourly values versus the number of planned hourly values. The percent of real-time temperature data passing quality assurance represents the percent of data that was received and passed the quality assurance review of data described below. As seen in Table 2, a total of five automated thermal loggers deployed in the field during the 2003 monitoring season failed to collect any data.

Once the data were received and missing data were flagged, the following quality assurance review procedures occurred. First, tables of raw data were visually inspected for erroneous data resulting from logger and probe malfunctions or improper transmission of data value codes. Second, data tables were reviewed for sudden increases in temperature that could not be correlated to any hydrologic event and may be a result of mechanical problems. Third, graphs of the data were created and analyzed in order to identify unusual spikes in the data. These spikes were then further investigated in order to identify the causes of error. Suspect data were corrected if possible. For instance, data where drift occurred can be easily adjusted through software programs. Data that could not be corrected were flagged as rejected and deleted from the database.

As shown in Table 2, problems with receiving real-time hourly temperature data were encountered during the 2003 monitoring season. Missing data for the real-time water quality probe stations CHJ and CHQW were largely due to DCP malfunctions and programming problems. Missing data for the automated thermal loggers were due to logger malfunctions resulting in no data being collected. No data were rejected for the water quality probes and automated thermal loggers.

Water Quality Criteria

The Colville Confederated Tribe (CCT) and the Washington Department of Ecology (WDOE) determine water quality criteria for the Columbia River at Chief Joseph Dam in Washington. The CCT has classified the Columbia River as a Class I water body above Chief Joseph Dam and a Class II water body below the dam. In 2003 the WDOE proposed updating their 1997 water quality standards for temperature. However, the Environmental Protection Agency (EPA) has not approved of these revised standards and therefore WDOE continues to use the 1997 temperature standards until EPA approval is received. For comparative purposes, both standards are described below. The 1997 WDOE standards classified the Columbia River above and below Chief Joseph Dam as a Class A water body, while the proposed updated 2003 standards classified the Columbia River above and below Chief Joseph Dam as a Salmon and Trout spawning non-core rearing and migration aquatic life use water body. Water quality standards for temperature at Chief Joseph Dam are presented in Table 3.

Results and Discussion

Hydrological and Meteorological Characterization

Hydrographs of average daily discharge for the Columbia River at Chief Joseph Dam for the study period of June through November 2003 and for the post-impoundment period from 1975-2003 are presented in Figure 6. Compared to the median post-impoundment river flow conditions, the Columbia River in 2003 experienced near average flows from June through November, resulting in average retention times in Lake Rufus Woods (Figure 6). The retention time in the reservoir during the study ranged from a low of 2 days during the June high flow period to a high of 9 days during the fall low flow period.

The weather station chosen to represent conditions in the study area was a Bureau of Reclamation AgriMet station located at Chief Joseph Dam. Average daily maximum and minimum air temperatures and historical data from 1971-2000 are presented in Figure 7. Maximum and minimum air temperatures were higher than historical averages during the majority of the 2003 monitoring season. The highest temperatures recorded at Chief Joseph Dam occurred during the latter part of July, with air temperatures exceeding 40°C. The lowest temperatures were recorded at the beginning of November with air temperatures below – 10°C.

Temporal and Spatial Patterns

General Overview

Temporal patterns for water temperature collected at the upstream (CHJUPRB and CHJUPLB), middle (CHJMID), forebay (CHJFB), and tailwater (CHQW) stations are presented in Figures 8, 9, and 10. Temperatures at all sites followed a similar pattern of warming from June through September and cooling in the fall, with the warmest temperatures experienced during August and September. Temperatures at the upstream and middle stations peaked at about 20°C, while temperatures at the forebay station peaked at about 21°C. Daily fluctuations in surface water temperatures were seen at all stations, with fluctuations as great as 3°C noted from June through August (Figures 8 and 9). These daily fluctuations extended down to the deepest probes at the upstream (12 meter depth) and middle (12 meter depth) stations, and down to about the 6 meter depth at the forebay station (Figures 8 and 9). Temperatures deeper than 12 meters at the forebay station showed little daily temperature fluctuations. Similarly, temperatures recorded at the tailwater station showed little daily fluctuations (Figure 10) and likely represented a mixture of the forebay water column.

Surface water temperatures at the upstream and middle stations were greater than the CCT Class I standard of 16°C from about the beginning of July through the end of October, while temperatures at the forebay station were greater than 16°C from about the middle of June

through the end of October. Surface water temperatures at the upstream and middle stations were greater than the WDOE 1997 standard of 18.0°C from about the end of July through the middle of October, while temperatures at the forebay station were greater than 18.0°C from about the middle of July through the middle of October. Temperatures at the tailwater station were greater than 18°C from about the beginning of August through the middle of October.

Vertical thermal gradients were apparent only at forebay station CHJFB as indicated by the temperature profile time histories presented in Figures 8 and 9. Maximum surface temperatures of 20 to 21°C were observed in August and September, while temperatures at depth ranged from 18.5 to 19.5 °C during this period. Vertical temperature profiles at the upstream and middle stations show that the river is completely mixed at these locations.

Plots of the seven day average of daily maximum temperatures at all stations and depths are presented in Figures 11 and 12. These data clearly show the lack of any vertical thermal gradients forming in Lake Rufus Woods except at the CHJFB station. These seven day average daily maximum temperatures were greater than the proposed WDOE 2003 standard of 17.5°C from about the end of July through the middle of October at all stations and depths.

One-Week Time Scale Focus

Expanding the time scale of Figures 8, 9 and 10 to a one-week period in August shows the difference in diurnal temperature fluctuations recorded at the upstream, middle, forebay, and tailwater stations (Figures 13 and 14). During the August 4 through August 11 time period shown, daily water temperatures fluctuated about 3°C at both upstream stations (CHJUPLB and CHJUPRB). However, each day there was a rapid 2°C decrease in temperatures between about 0400 hours and 0600 hours followed by about a 3°C temperature increase between about 0800 hours and 1100 hours. Temperatures remained stable from about 1200 hours to 2000 hours, after which they gradually decreased until the rapid drop seen each morning between 0400 hours and 0600 hours. The temperature pattern recorded at the middle station (CHJMID) was different, with the highest water temperatures recorded in the night and early morning between about 2000 hours and 0800 hours and the lowest water temperatures recorded in the afternoon between about 1600 hours and 2000 hours. At the forebay station (CHJFB) daily surface water temperatures were lowest during the early morning and gradually increased during the day to a peak in the late afternoon, while little to no temperature variations were seen at depth. Similarly, at the tailwater station (CHQW) little to no fluctuation in daily water temperatures was noted.

The temperature patterns noted at the upstream and middle stations during the August 4 to August 11 time period did not correspond to daily air temperature patterns, suggesting that water temperatures cycles were being largely controlled by Grand Coulee Dam powerhouse operations. Operations at Grand Coulee Dam for the August 4 to August 11 time period are shown together with temperatures recorded at upstream station CHJUPRB (Station CHJUPLB is not shown because of fewer sampling depths) in Figure 16. Flow rates through Grand Coulee varied during each 24-hour period based on peak power demands. In general, Grand Coulee greatly reduced flows from 0000 hours to 0500 hours, significantly increased flows starting at 0600 hours, maintained these high flows from 1200 hours to 2000 hours, and slowly decreased flows from

2000 hours to 0000 hours. Temperature data tended to mirror these flow rate changes, with rapid temperature decreases when flow rates were reduced and rapid temperature increases when flow rates were increased, resulting in a pulse of cooler water passing the upstream station (Figures 13 and 16). This pulse of cooler water was evident down reservoir at least as far as the middle station (see Figure 14) where daily temperature cycles were substantially influenced resulting in the lowest water temperatures being recorded in the afternoon. However, the pulse of cooler water was not seen at the forebay or tailwater (see Figures 14 and 15). Instead, daily temperature variations at the forebay station corresponded to daily air temperature cycles, while the lack of any daily variation at the tailwater station was likely due to the water being a mixture of the forebay water column.

Grand Coulee Dam has three powerhouses (left, right, and third) that intake water from different depths in Lake Roosevelt. The centerline elevation for the original two powerhouses (left and right) is 1040 feet (i.e. about 240 feet deep at full pool) while the centerline elevation for the newer third powerhouse is 1140 feet (i.e. about 140 feet deep at full pool). Because Lake Roosevelt thermally stratifies during the summer period (June to August) the powerhouse intake elevations influence the temperature of water released from the project with water passing through the third powerhouse being warmer than water passing through the left and right powerhouse (Bureau of Reclamation 2003). Generally, when Grand Coulee reduces flows at night the third powerhouse is taken off line and only the left or right powerhouse is operated with the third powerhouse being put back on line around 0600 hours when flows are increased. Such operational changes would result in cooler water being discharged from about 0000 hours to 0600 hours and warmer water released from about 0700 hours to 2300 hours, which may account for the changes in temperatures recorded at the Chief Joseph Dam upstream stations (CHJUPRB and CHJUPLB). In addition, when flows are reduced through the powerhouses between 0000 hours and 0600 hours, any downwelling of warmer surface waters to depth that may occur during periods of high discharge would be reduced resulting in the powerhouse drawing deeper cooler water during this time period.

Figure 17 shows temperatures at the upstream (CHJUPRB) station and Grand Coulee flows for the one week periods of June 12-17, August 4-11, and September 25 to October 2. Grand Coulee operations are similar between these dates (although flow volumes are greatest in June) however the temperature pattern is very different. For June and August, temperature patterns are relatively similar with a temperature decrease from 0000 hours to 0600 hours followed by an increase around 0700 hours and stable temperatures from about 1200 hours to 2000 hours. However, the September/October data shows little to no variation in temperature. Vertical profile thermal data collected by the Bureau of Reclamation at the Grand Coulee Dam forebay in 2003 showed that the forebay was thermally stratified in June and August, but was isothermal in late September with little to no difference in temperature between the surface and bottom (Bureau of Reclamation 2005). These data suggest that the formation of the thermocline in the forebay of Grand Coulee Dam is an important factor in determining downstream temperatures in Lake Rufus Woods.

Lateral Bias Evaluation

Upstream

Comparisons were made between the upstream stations water temperatures recorded on the left bank (CHJUPLB) and right bank (CHJUPRB) of the Columbia River to determine if any lateral bias existed (see Figure 2). The potential for temperature differences exists at these stations because Grand Coulee Dam has three powerhouses that draw water from different depths in Lake Roosevelt as described in the previous section. Thus, it is possible that different temperature waters may be released along the right bank or left bank below Grand Coulee based on which powerhouse is operating, resulting in lateral temperature differences downstream.

Paired sample t-tests were conducted by pairing depth and time between the two upstream stations and calculating the temperature difference. Table 4 shows the results of these tests during the 2003 monitoring period. The paired t-test calculates the mean difference for each pair and determines if this difference is statistically significant from zero. These data show that for the upstream stations, all station pairs were significantly different. However, the maximum mean difference for each pair was 0.16°C for the CHJUPLB-12 and CHJUPRB-12 pair, which is less than the manufacture's stated accuracy for the automated thermal loggers. Therefore, the data indicate that only minor bias (± 0.2°C) occurred between the left bank and right bank at the upstream stations that could be accounted for by instrument accuracy or slight differences in instrument depths.

Comparisons of temperature differences at similar depths between CHJUPRB and CHJUPLB were also determined graphically using box and whisker plots (Figure 18). Box and whisker plots present nonparametric statistical results including the median value, 25th and 75th percentile interquartile range, 5th and 95th percentile non-outlier range, outlier values and extreme outlier values. Although outlier temperature differences up to 1.4 °C were recorded at the 0.5-meter depth, the median difference between CHJUPRB and CHJUPLB ranged from 0.0°C at 0.5-meters to 0.2°C at 12-meters (Table 5). The interquartile spread of the data ranged from 0.0°C to 0.1°C at 0.5-meters to 0.0°C to 0.2°C at 6-meters, while the 95th percentile spread of the data ranged from –0.1°C to 0.2°C at 0.5-meters to 0.0°C to 0.4°C at 6-meters. These data suggest that the vast majority of temperature differences between CHJUPRB and CHJUPLB could be accounted for by the instrument accuracy (± 0.2 °C) as well as slight differences in instrument depths.

Forebay

Comparisons were made between water temperatures recorded at the thermal profile station located near the spillway (CHJFB) and the forebay fixed monitoring station located near the powerhouse (CHJ) to determine if any lateral bias existed in the forebay (see Figure 2). The potential for lateral temperature differences exists at these stations because station CHJ is located near the powerhouse in a shallow part of the Columbia River out of the main flow of water passing through the powerhouse. Conversely, station CHJFB is located in the thalweg of the

Columbia River immediately upstream of the dam and represents conditions in the main flow of water.

Paired sample t-tests were conducted by pairing temperatures recorded at the 6 meter depth from station CHJFB to temperatures recorded at the 6 meter depth at station CHJ and calculating the temperature difference. Table 4 shows that during the 2003 monitoring period temperatures recorded at these two stations were significantly different. However, the maximum mean difference for this pair was -0.147°C, which is less than the manufactures stated accuracy for the automated thermal loggers. Therefore, the data indicate that only minor bias (± 0.2°C) was associated with the positioning of the forebay temperature station, which could be accounted for by instrument accuracy or slight differences in instrument depths.

Comparisons of temperature differences at similar depths between CHJFB and CHJ were also determined graphically using box and whisker plots (Figure 18). Although outlier temperature differences up to -1.2 °C were recorded, the median difference between the CHJFB and CHJ was -0.1°C (Table 5). The interquartile spread of the data ranged from -0.2°C to 0.0°C, while the 95th percentile spread of the data ranged from –0.4°C to 0.1°C. These data suggest that the vast majority of temperature differences between CHJFB and CHJ could be accounted for by the instrument accuracy (± 0.2 °C) as well as slight differences in instrument depths.

Longitudinal Evaluation

Longitudinal trends in temperatures were analyzed by plotting the one-day (i.e. 24-hour) moving mean at selected depths for the upstream, middle, forebay, and tailwater stations (Figures 19 and 20). The general pattern seen during the 2003 monitoring season was for surface waters (0.5 to 1.5 meters) to be warmed slightly between the upstream and middle stations, and for substantial surface warming to occur between the middle station and the forebay station. Tailwater temperatures were similar to the upstream and middle stations, and consistently less than the forebay surface waters. In general, an average surface warming of about 1°C was recorded between the upstream stations and the forebay. Less pronounced longitudinal warming was seen for deeper waters (3 to 12 meters) with an increase of only about 0.5°C between the upstream and forebay stations. Tailwater temperatures recorded at station CHQW were consistently lower than surface forebay temperatures suggesting that the warmer forebay surface waters are mixed together with the cooler waters at depth resulting in cooler waters passing through the powerhouse.

Statistical comparisons were made between water temperatures measured at the upstream (CHJUPRB), middle (CHJMID), forebay (CHJFB), and tailwater (CHQW) stations to determine longitudinal variations in temperatures at Chief Joseph Dam. Station CHJUPLB was not included in the analysis due to the failure of the temperature logger at 3-meters to collect any data. An analysis of variance (ANOVA) was used at a significance level of $\alpha = 0.05$ to evaluate whether there were significant differences in temperatures between sampling locations. Where significant differences in temperature were detected using the ANOVA, a Tukey Honestly Significant Difference (HSD) multiple comparison test was conducted to determine which

locations and depths were significantly different from others (Zar 1984). An analysis for temperature differences between sampling locations showed that stations CHJUPRB and CHJMID were similar to station CHJQW but different from each other, while station CHJFB had significantly warmer temperatures (Table 6). A multiple comparison test between sampling locations and depths determined eight distinct homogeneous groupings (Table 6). In general, stations CHJUPRB and CHJMID at all depths had similar temperatures to the deeper forebay waters at CHJFB and to the tailwater station at CHQW. The shallower forebay waters at CHJFB were significantly warmer than all other stations and were grouped separately. These data suggest that minor surface water warming occurs at the forebay of Chief Joseph Dam but these warmer surface layers are mixed together with cooler waters at depth which results in tailwater temperatures at CHQW statistically similar to upstream temperatures at CHJUPRB.

Conclusions

Evaluation of the temperature monitoring results yielded the following conclusions:

- Temperatures at all sites followed a similar pattern of warming from June through September and cooling in the fall, with the warmest temperatures experienced during August and September. Temperatures at the upstream and middle stations peaked at about 20°C, while temperatures at the forebay station peaked at about 21°C. Daily fluctuations in surface water temperatures were seen at all stations, with fluctuations as great as 3°C noted at the upstream and forebay stations from June through August.

- Vertical thermal gradients were apparent only at the forebay. The forebay thermal gradient was weak and largely dominated by daily warming of waters resulting in a 2 to 3°C difference in temperatures between the surface and bottom.

- Water temperatures upstream of Chief Joseph Dam exceeded 16°C from about the beginning of July through the middle of October and 18°C from about the end of July through the middle of October. Temperatures recorded at the tailwater station downstream of the dam exceeded 18°C from about the beginning of August through the middle of October.

- Temperature patterns measured at the upstream and middle stations during the June through August time period suggest that daily water temperatures cycles were being largely controlled by Grand Coulee Dam powerhouse operations. At the upstream station, temperature data tended to mirror flow rate changes, with rapid temperature decreases when flow rates were reduced and rapid temperature increases when flow rates were increased, resulting in a pulse of cooler water passing the upstream and stations.

- In general, an average surface warming of about 1°C was recorded between the upstream stations and the forebay. Less pronounced longitudinal warming was seen for deeper waters (3 to 12 meters) with an increase of only about 0.5°C between the upstream and forebay stations. However, the warmer surface layers at the forebay are mixed together with cooler waters at depth (18 to 60 meters) which results in tailwater temperatures at CHQW statistically similar to upstream temperatures at CHJUPRB.

- Only minor bias (± 0.2°C) was associated with the positioning of the upstream and forebay temperature stations, which could be accounted for by instrument accuracy or slight differences in instrument depths.

- The existing fixed monitoring stations at the forebay (CHJ) and tailwater (CHQW) are representative of in-river temperature conditions upstream and downstream of Chief Joseph Dam.

References

Bureau of Reclamation 2003. Grand Coulee Dam-Lake Roosevelt initial review of three strategies to manage water temperature at Grand Coulee Dam, Draft Discussion Paper. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center. June 12, 2003.

Bureau of Reclamation 2005. Grand Coulee Dam-Lake Roosevelt forebay temperature data for 2003. Data e-mailed to Kent Easthouse (USCOE) by Norbert Cannon (BOR) on July 27, 2005.

USCOE 1985. Chief Joseph Dam, Columbia River, Washington Water Control Manual. U.S. Army Corps of Engineers, Seattle District.

USCOE 2002. Corps of Engineers plan of action for dissolved gas monitoring for 2003. In 2002 dissolved gas and water temperature monitoring report Columbia River Basin. North Pacific Division, Water Management Division, Reservoir Control Center, Water Quality Unit.

WDNR 2004. The Geology of Washington. Washington Department of Natural Resources, Web address: http://www.dnr.wa.gov/geology/geolofwa.htm, Olympia, WA.

Zar 1984. Biostatistical Analysis, Second Edition. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Tables

Table 1. Temperature station locations and sampling period, water year 2003.

Site Identifier	Station Name	Latitude	Longitude	Total Depth at Station (meters)	Temperature Monitoring Method	2003 Sampling Period
CHJUPLB	Chief Joseph Upstream Left Bank	48.04948	119.00774	18	Automated Thermal Loggers	06/11/03 - 11/19/03
CHJUPRB	Chief Joseph Upstream Right Bank	48.04259	118.9984	15	Automated Thermal Loggers	06/11/03 - 11/19/03
CHJMID	Chief Joseph Middle	48.11971	119.20541	28	Automated Thermal Loggers	06/11/03 - 11/19/03
CHJFB	Chief Joseph Forebay Spillway Side	47.99756	119.62052	68	Automated Thermal Loggers	06/11/03 - 11/19/03
CHJ	Chief Joseph Forebay Powerhouse Side	47.99389	119.64527	24	Water Quality Probe	06/11/03 - 09/15/03
CHQW	Chief Joseph Tailwater	48.00472	119.65833	7	Water Quality Probe	06/11/03 - 11/19/03

Table 2. Temperature data completeness for water year 2003.

Station Name and Abbreviation	Field Probe Number	Station Depth (meters)	Planned monitoring in hours	Number of missing hourly values	Percentage of temperature monitoring data received	Percentage of temperature data passing quality assurance
Chief Joseph Upstream Left Bank						
CHJUPLB-.5	7535	0.5	3881	0	100.0	100.0
CHJUPLB-3	7742	3	3881	3881	0.0	0.0
CHJUPLB-6	7744	6	3881	0	100.0	100.0
CHJUPLB-12	9307	12	3881	0	100.0	100.0
Chief Joseph Upstream Right Bank						
CHJUPRB-.5	7534	0.5	3881	0	100.0	100.0
CHJUPRB-3	7743	3	3881	0	100.0	100.0
CHJUPRB-6	7746	6	3881	0	100.0	100.0
CHJUPRB-6DUP	7740	6	3881	0	100.0	100.0
CHJUPRB-12	9308	12	3881	0	100.0	100.0
Chief Joseph Middle						
CHJMID-0.5	7747	0.5	3881	0	100.0	100.0
CHJMID-1.5	7748	1.5	3881	0	100.0	100.0
CHJMID-3	7745	3	3881	0	100.0	100.0
CHJMID-6	7749	6	3881	3881	0.0	0.0
CHJMID-12	7751	12	3881	0	100.0	100.0
CHJMID-24	9309	24	3881	3881	0.0	0.0
Chief Joseph Forebay Spillway						
CHJFB-0.5	7752	0.5	3881	3881	0.0	0.0
CHJFB-1.5	7753	1.5	3881	0	100.0	100.0
CHJFB-3	7754	3	3881	0	100.0	100.0
CHJFB-6	7757	6	3881	0	100.0	100.0
CHJFB-12	7755	12	3881	0	100.0	100.0
CHJFB-18	7741	18	3881	0	100.0	100.0
CHJFB-30	7756	30	3881	0	100.0	100.0
CHJFB-40	7750	40	3881	3881	0.0	0.0
CHJFB-60	9310	60	3881	0	100.0	100.0
Chief Joseph Forebay Powerhouse						
CHJ		6	2318	20	99.1	99.1
Chief Joseph Tailwater						
CHQW		4	3881	205	94.7	94.7

Table 3. Washington Department of Ecology (WDOE) and Colville Confederated Tribe (CCT) temperature standards.

Agency/Rule	Classification	Standard
Washington Department of Ecology		
WDOE 1997 Rule	Class A	Shall not exceed 18.0°C due to human activities. When natural conditions exceed 18.0°C, no temperature increase will be allowed which will raise the receiving water temperature by greater than 0.3°C.
WDOE 2003 Rule	Non-core salmon/trout	Measured by the 7-day average of the daily maximum temperatures. Shall not exceed 17.5°C. When temperature exceeds the criteria or is within 0.3°C of the criteria, and the condition is due to natural conditions, then human actions may not cause an increase of more than 0.3°C.
Colville Confederated Tribe (CCT)		
	Class I	Shall not exceed 16.0°C due to human activities. When natural conditions exceed 16.0°C, no temperature increase will be allowed which will raise the receiving water by greater than 0.3°C.
	Class II	Shall not exceed 18.0°C due to human activities. When natural conditions exceed 18.0°C, no temperature increase will be allowed which will raise the receiving water by greater than 0.3°C.

Table 4. Lateral bias paired t-test evaluation at selected upstream and forebay stations during 2003.

Paired t-test Sample Locations	Mean Difference	Standard Deviation	Number	t-test (t)	Degrees of Freedom (df)	Significance (ρ)
CHJUPLB-0.5 vs.CHJUPRB-0.5	0.04	0.132	7763	26.729	7762	**0.000**
CHJUPLB-6 vs. CHJUPRB-6	0.006	0.123	7763	4.34	7762	**0.00014**
CHJUPLB-12 vs. CHJUPRB-12	0.160	0.130	7763	108.374	7762	**0.000**
CHJFB-6 vs. CHJ	-0.147	0.177	2295	-39.58	2294	**0.000**

Table 5. Lateral bias box-plot evaluation at selected upstream and forebay stations during 2003.

Paired Sample Location	N	Median	25th percentile	75th percentile	5th percentile	95th percentile	Number of outlier data points	Number of extreme data points
CHJUPLB-0.5 vs. CHJUPRB-0.5	7763	0	0	0.1	-0.1	0.2	584	126
CHJUPLB-6 vs. CHJUPRB-6	7763	0	0	0.2	0	0.3	52	5
CHJUPLB-12 vs. CHJUPRB-12	7763	0.2	0.1	0.2	0	0.4	275	97
CHJFB-6 vs. CHJ	2295	-0.1	-0.2	0	-0.4	0.1	55	6

Table 6. ANOVA results and Tukey HSD test for homogeneous groupings.

		ANOVA ρ Values				Homogeneous Groupings							
Station Location	Mean Temperature	CHJUPRB	CHJMID	CHJFB	CHQW	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
ANOVA Test													
CHJUPRB	16.78		**0.000**	**0.000**	0.867								
CHJMID	16.87	**0.000**		**0.000**	0.410								
CHJFB	17.03	**0.000**	**0.000**		**0.000**								
CHQW	16.81	0.867	0.410	**0.000**									
Homogeneous Groupings Test													
CHJUPRB-12	16.68					****							
CHJUPRB-0.5	16.75					****	****						
CHQW	16.81					****	****	****	****				
CHJMID-3	16.82						****	****					
CHJFB-60	16.83						****	****					
CHJUPRB-6	16.84						****	****	****				
CHJUPRB-3	16.85						****	****	****				
CHJMID-0.5	16.86						****	****	****				
CHJMID-12	16.89							****	****				
CHJFB-30	16.95								****	****			
CHJFB-18	16.97								****	****	****		
CHJFB-12	17.03									****	****	****	
CHJFB-3	17.08										****	****	
CHJFB-6	17.09											****	
CHJFB-1.5	17.28												****

Figures

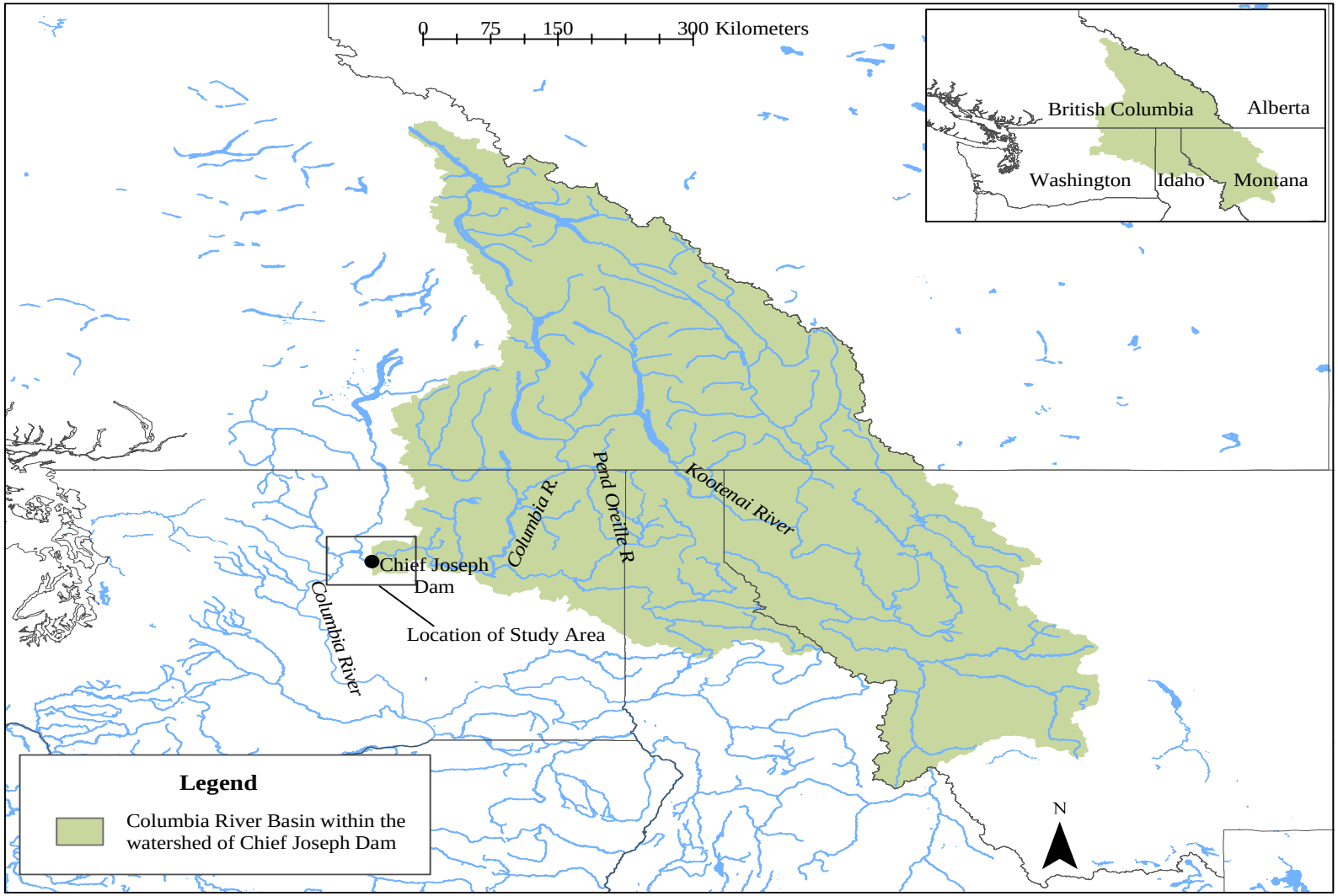
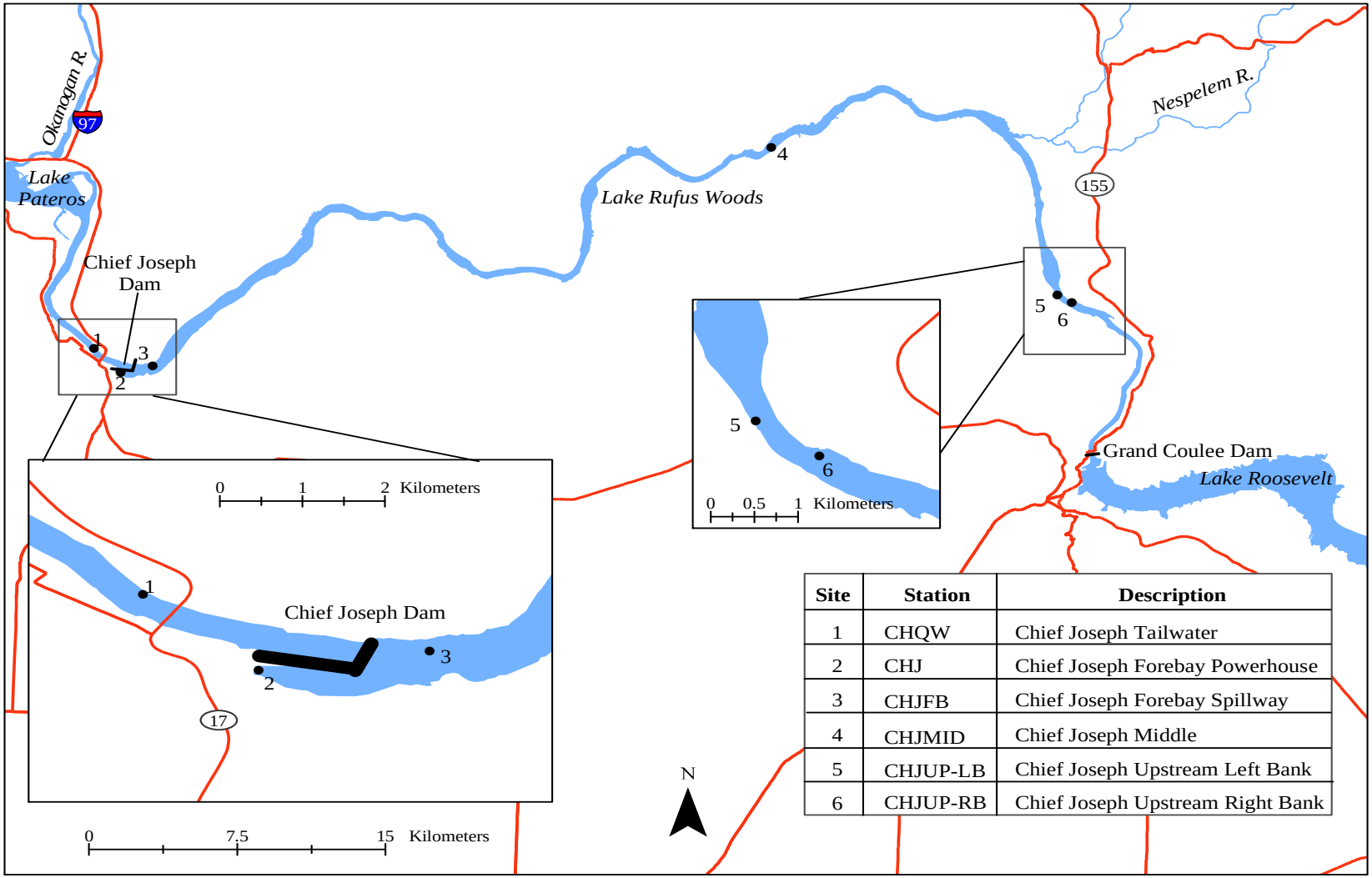


Figure 1. Location of Chief Joseph Dam and watershed.



Site	Station	Description
1	CHQW	Chief Joseph Tailwater
2	CHJ	Chief Joseph Forebay Powerhouse
3	CHJFB	Chief Joseph Forebay Spillway
4	CHJMID	Chief Joseph Middle
5	CHJUP-LB	Chief Joseph Upstream Left Bank
6	CHJUP-RB	Chief Joseph Upstream Right Bank

Figure 2. Locations of temperature monitoring stations in 2003 above and below Chief Joseph Dam, Washington.

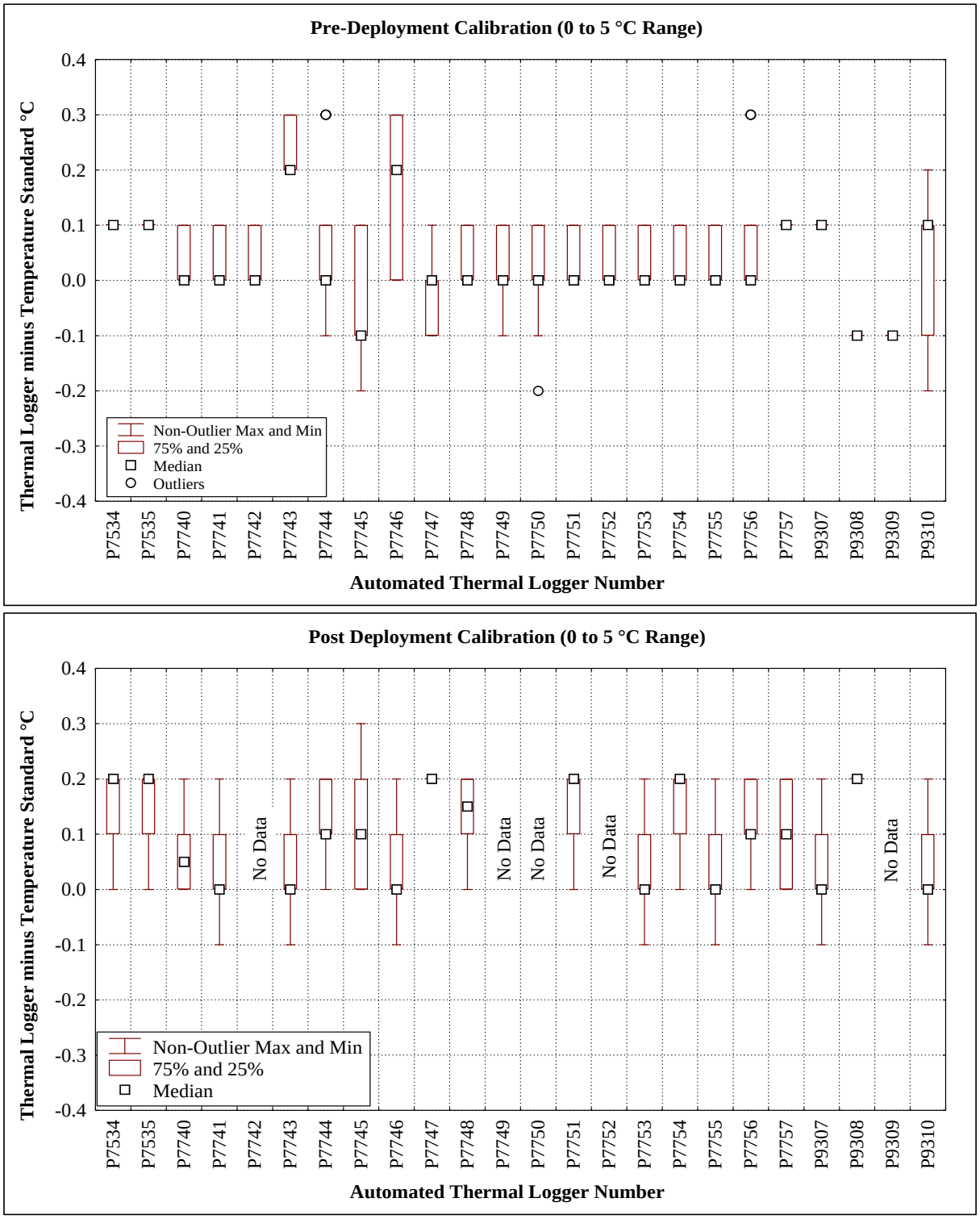


Figure 3. Difference between the automated thermal logger temperature and the NIST temperature standard for the 0 to 5°C range.

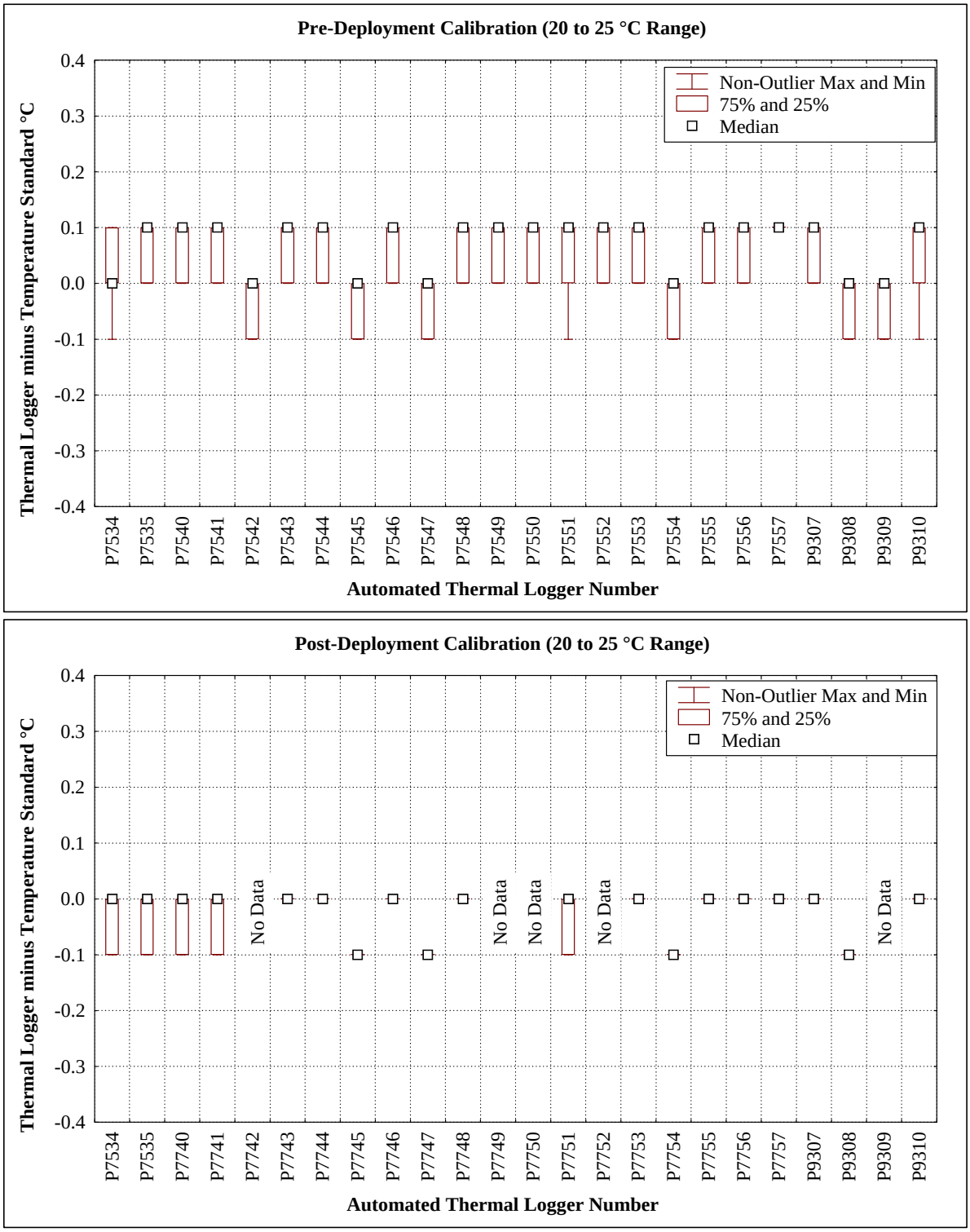


Figure 4. Difference between the automated thermal logger temperature and the NIST temperature standard for the 20 to 25°C range.

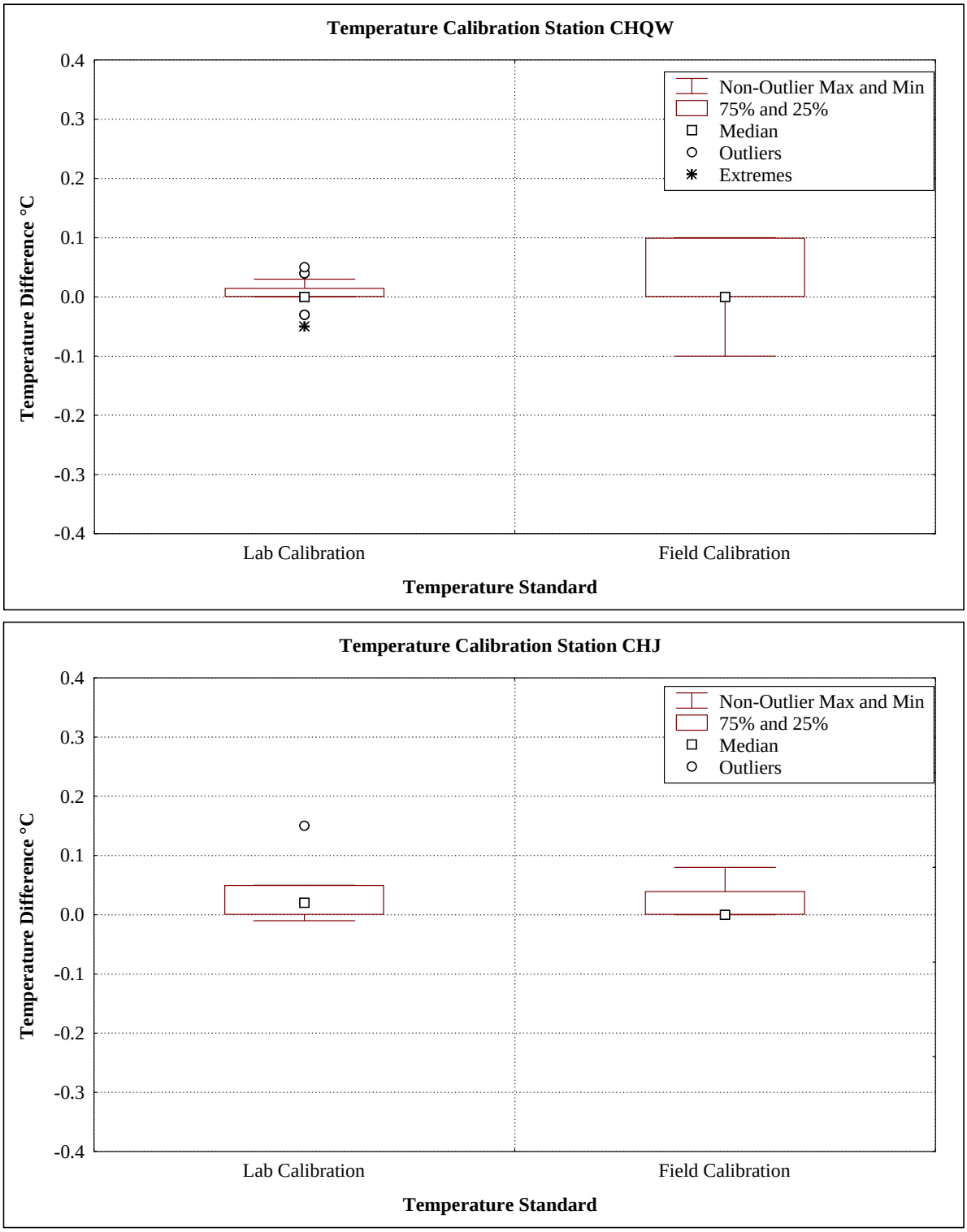
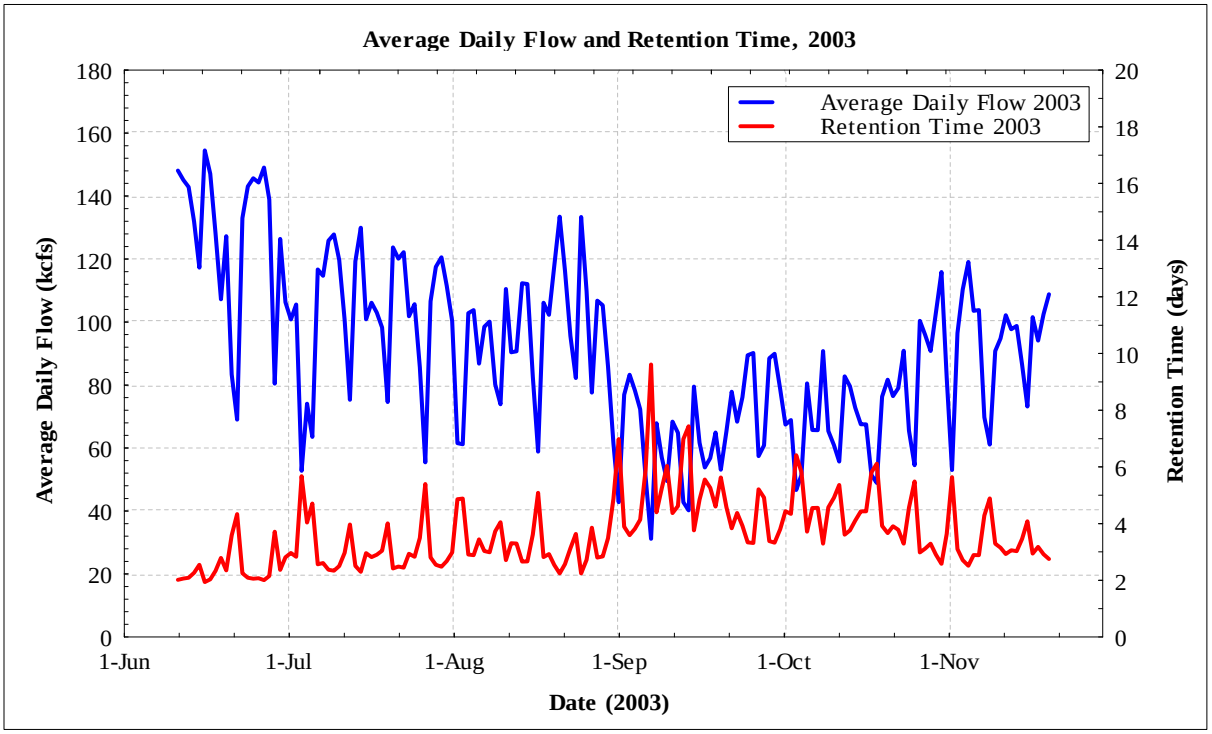


Figure 5. Laboratory and field temperature calibration data for the real-time water quality probes.



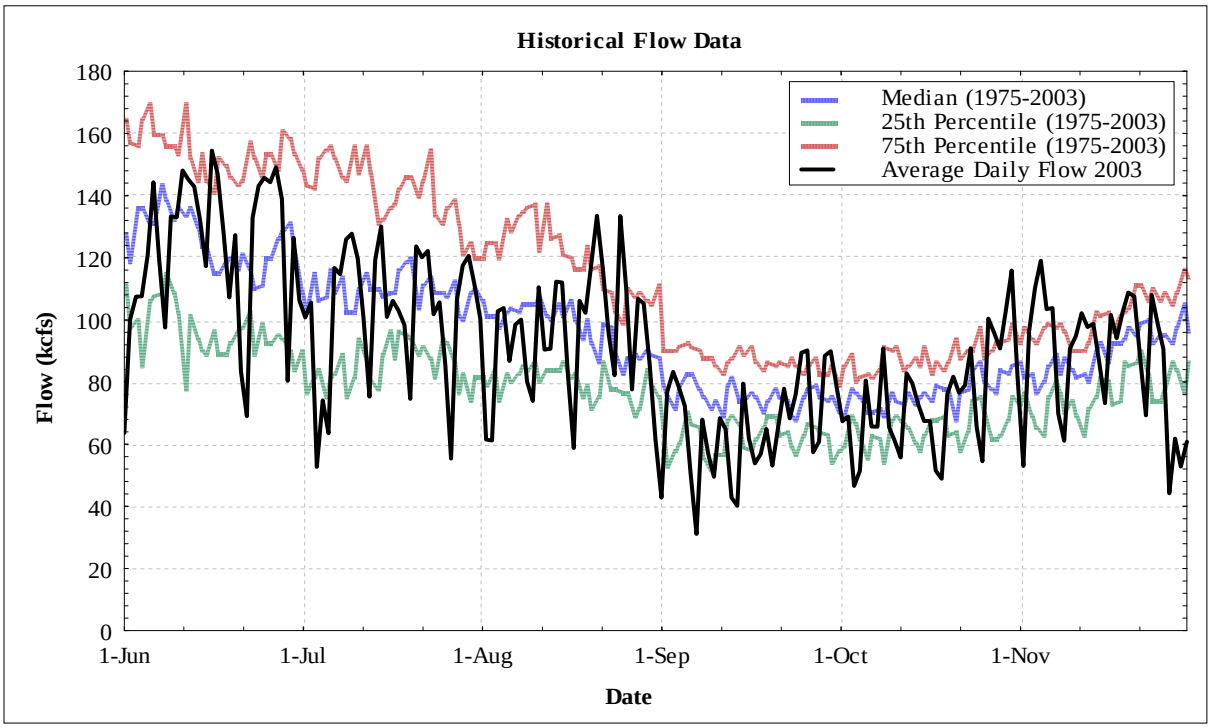


Figure 6. Historical flow data and 2003 average daily flow and retention time for the Columbia River at Chief Joseph Dam.

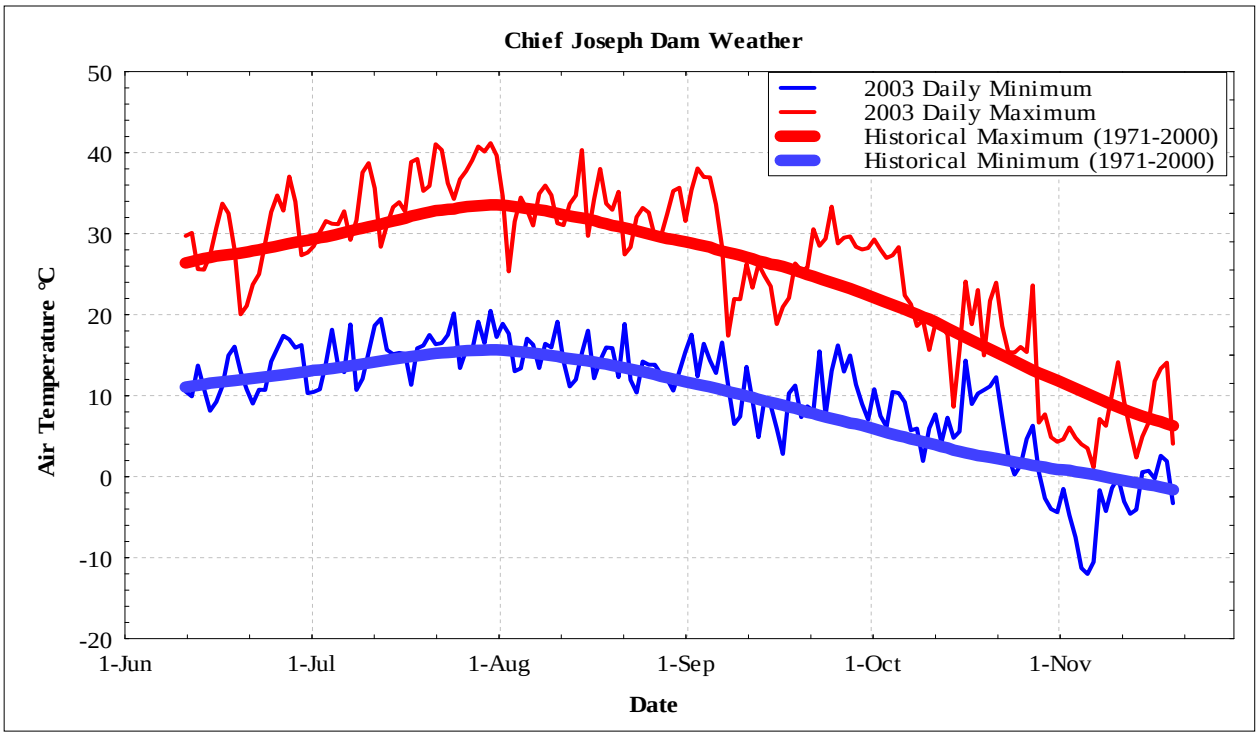


Figure 7. Historical and current meteorological data for Chief Joseph Dam.

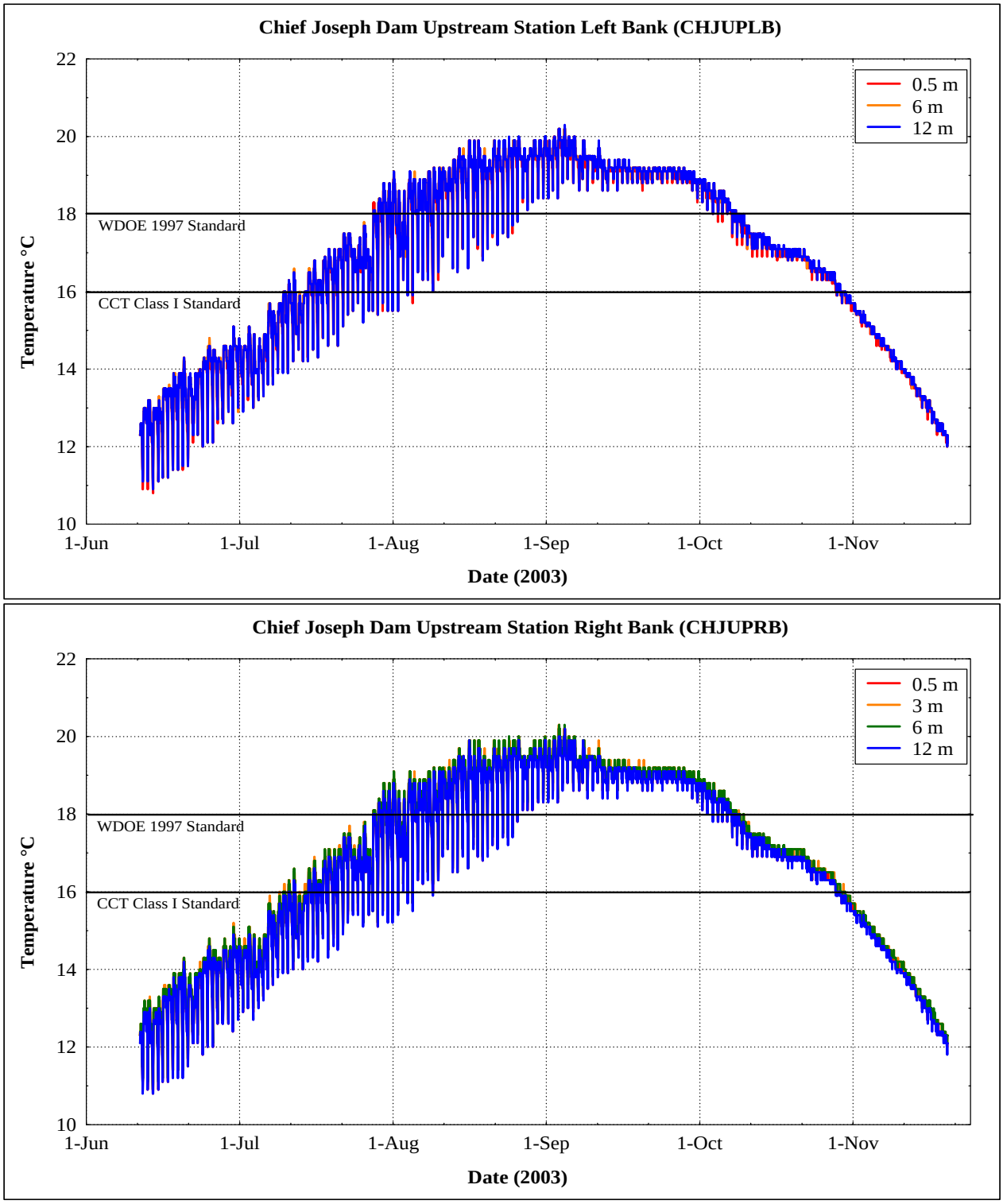


Figure 8. Temporal variation of temperature at the upstream stations.

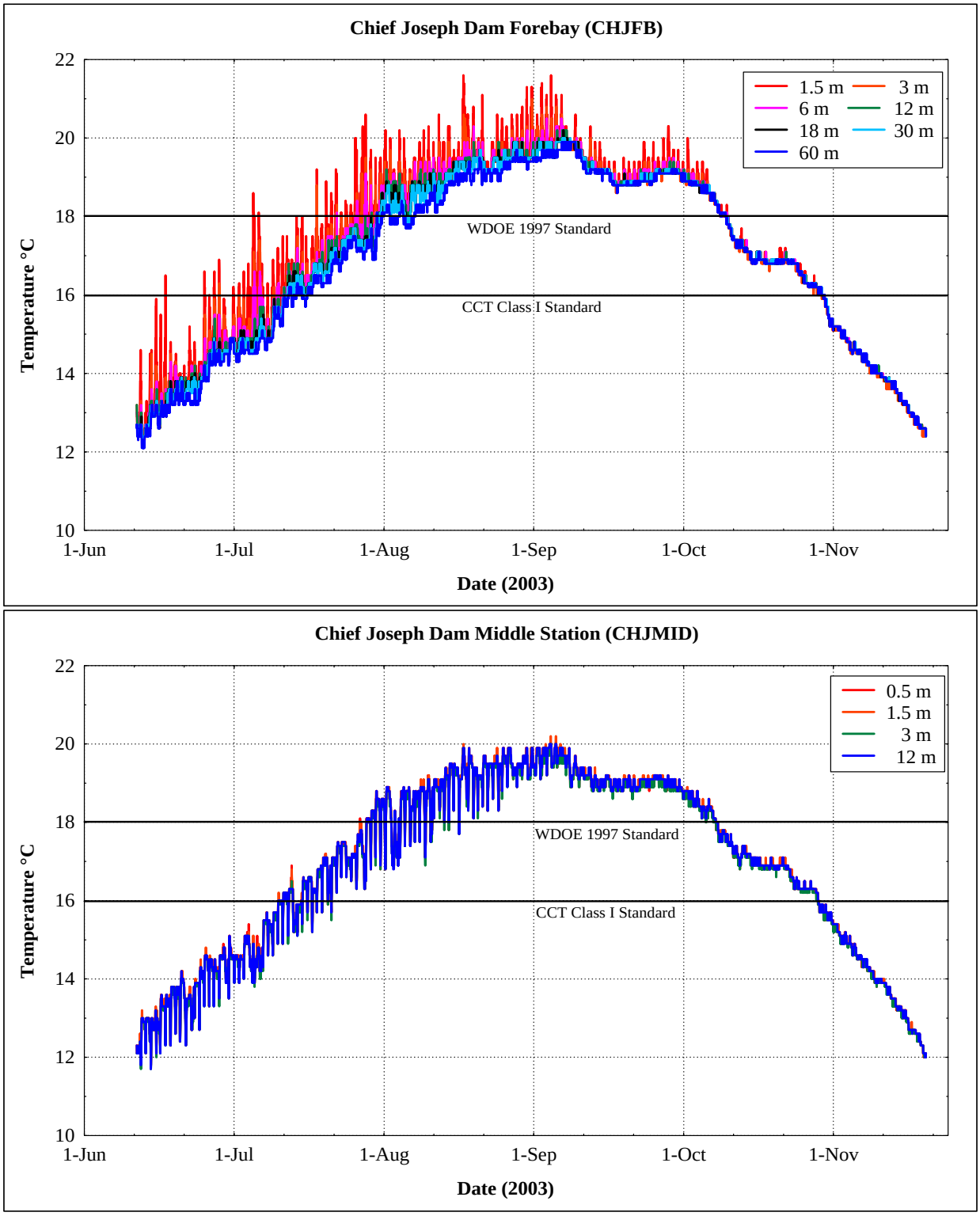


Figure 9. Temporal variation of temperature at the middle and forebay stations.

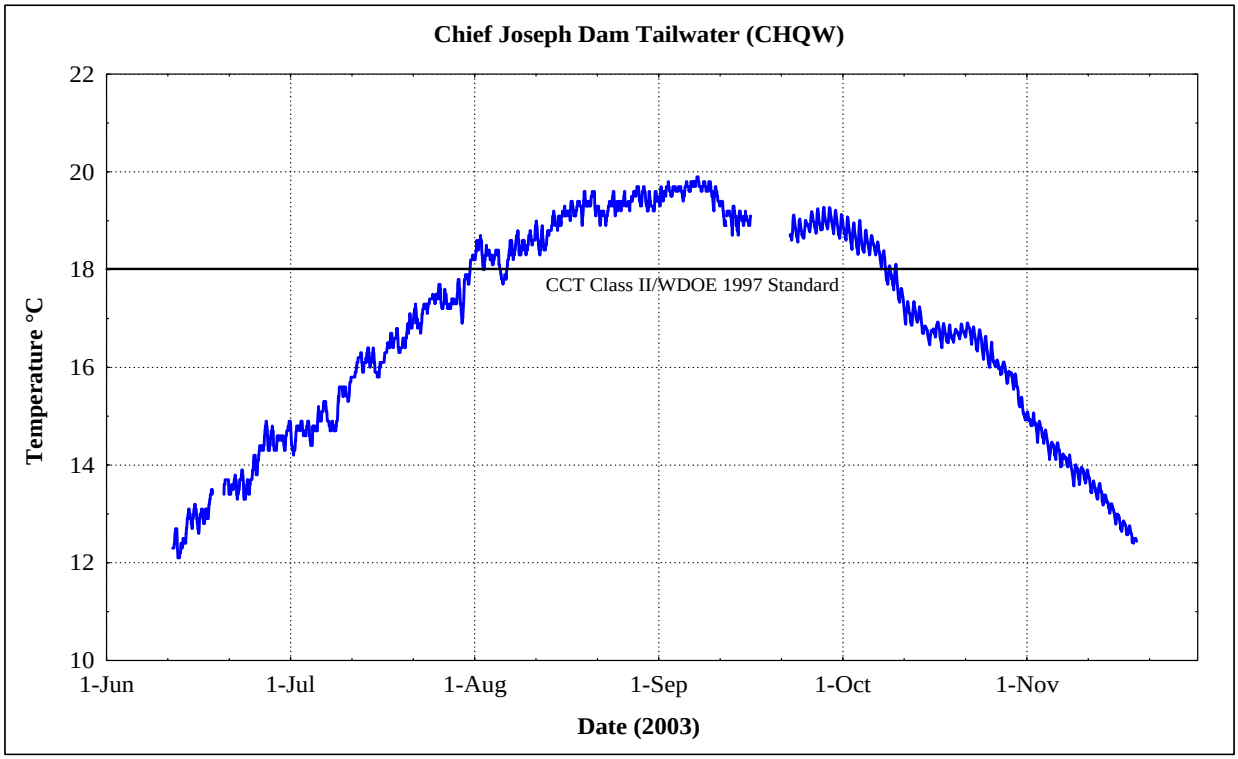
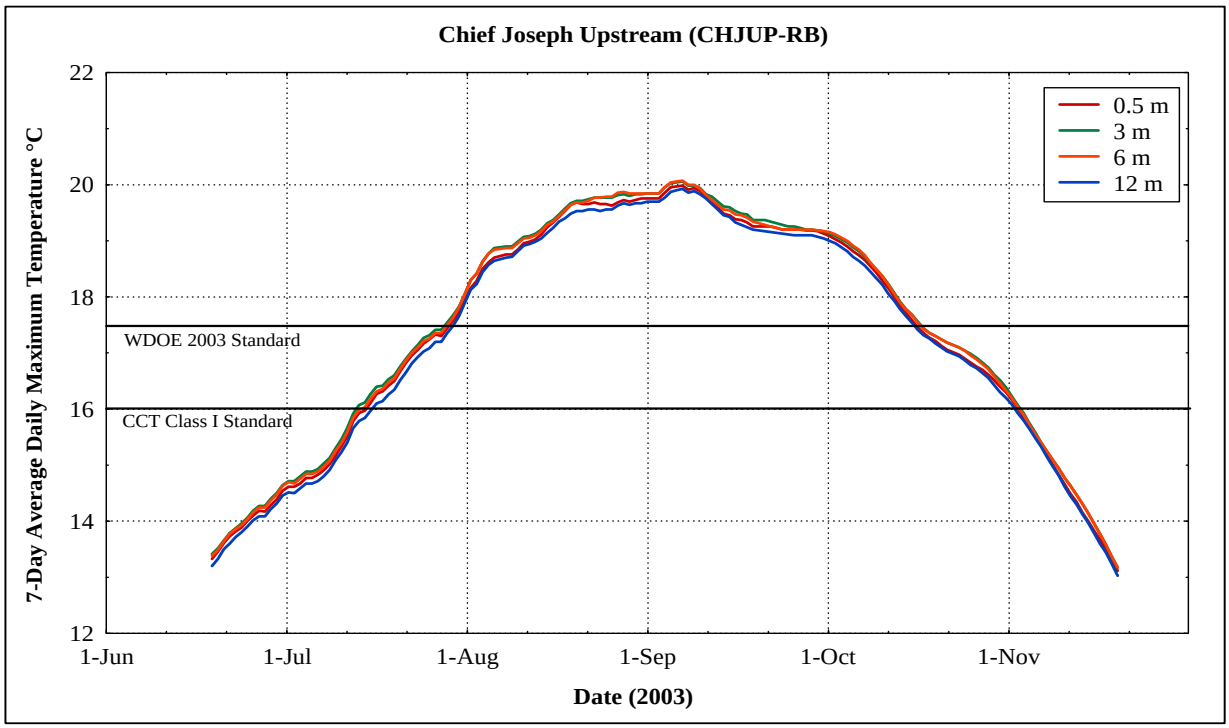


Figure 10. Temporal variation of temperature at the tailwater station.



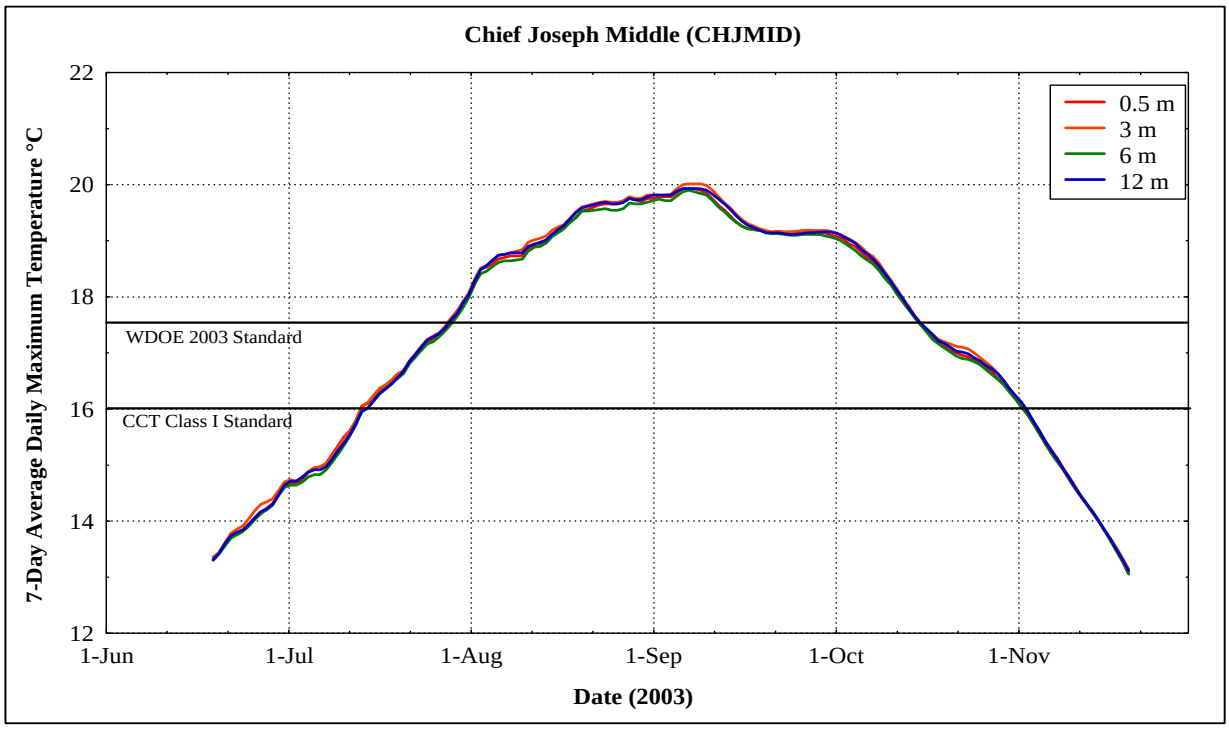


Figure 11. The 7-day average of daily maximum temperatures at the upstream (CHJUPRB) and middle (CHJMID) stations at Chief Joseph Dam.

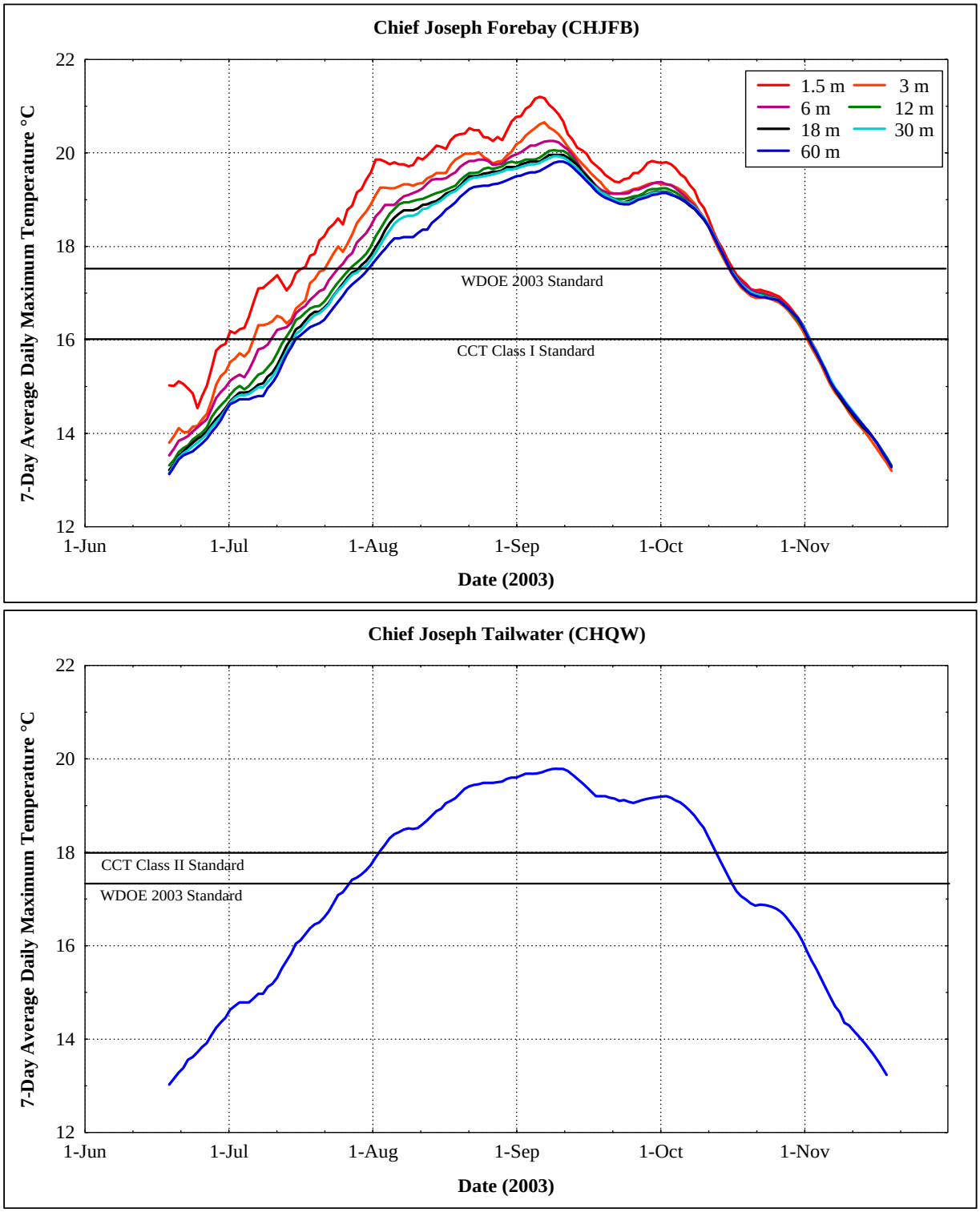
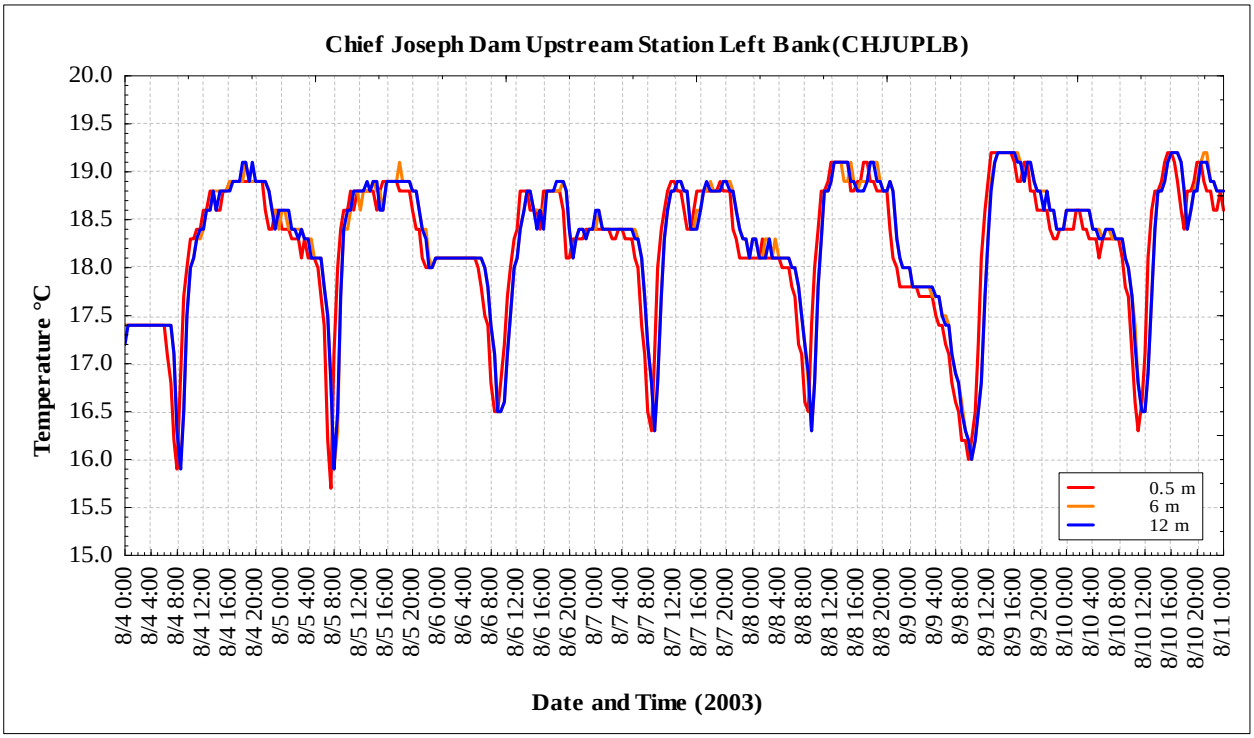


Figure 12. The 7-day average of daily maximum temperatures at the forebay (CHJFB) and tailwater (CHQW) stations at Chief Joseph Dam.



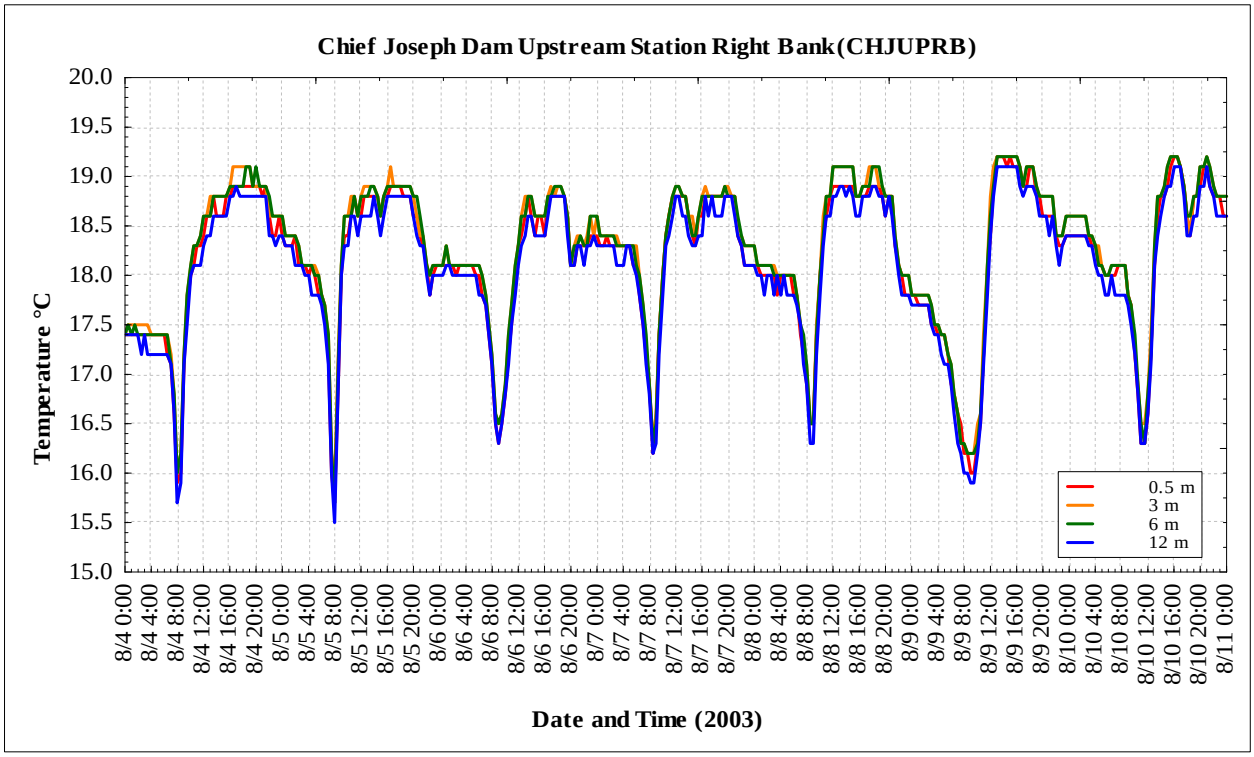
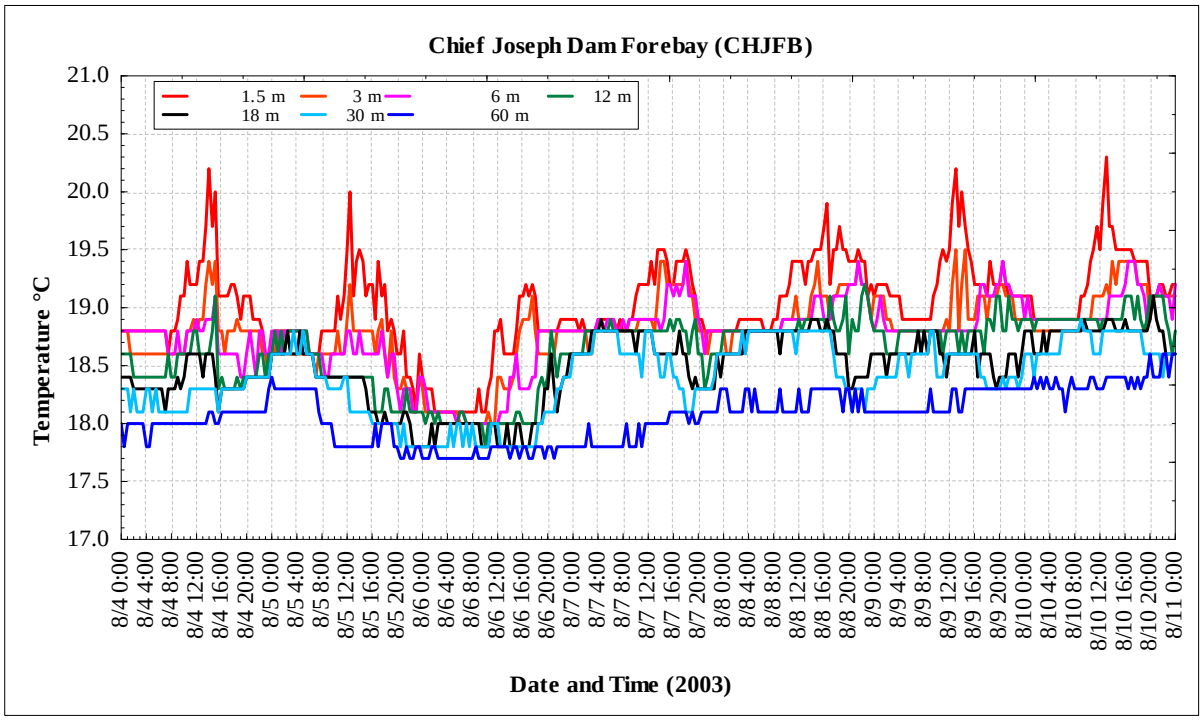


Figure 13. Temporal variation during one-week (Aug 4-11) at the upstream stations.



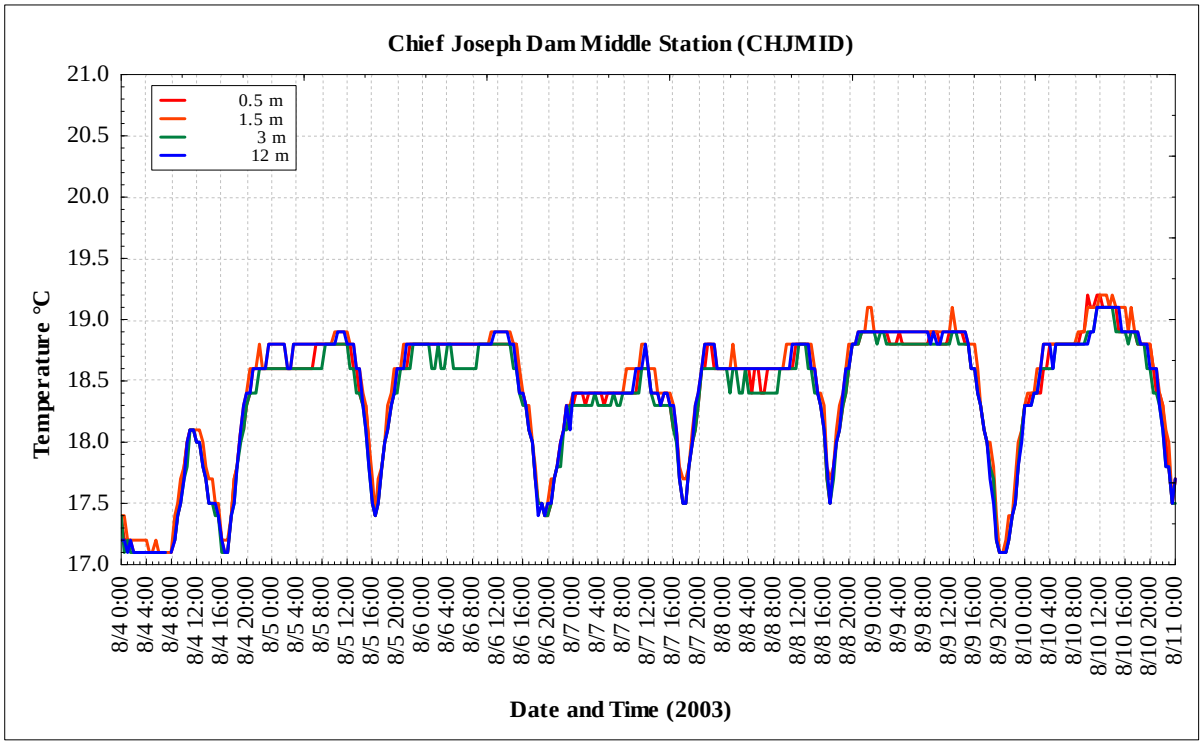


Figure 14. Temporal variation during one-week (Aug 4-11) at the middle and forebay stations.

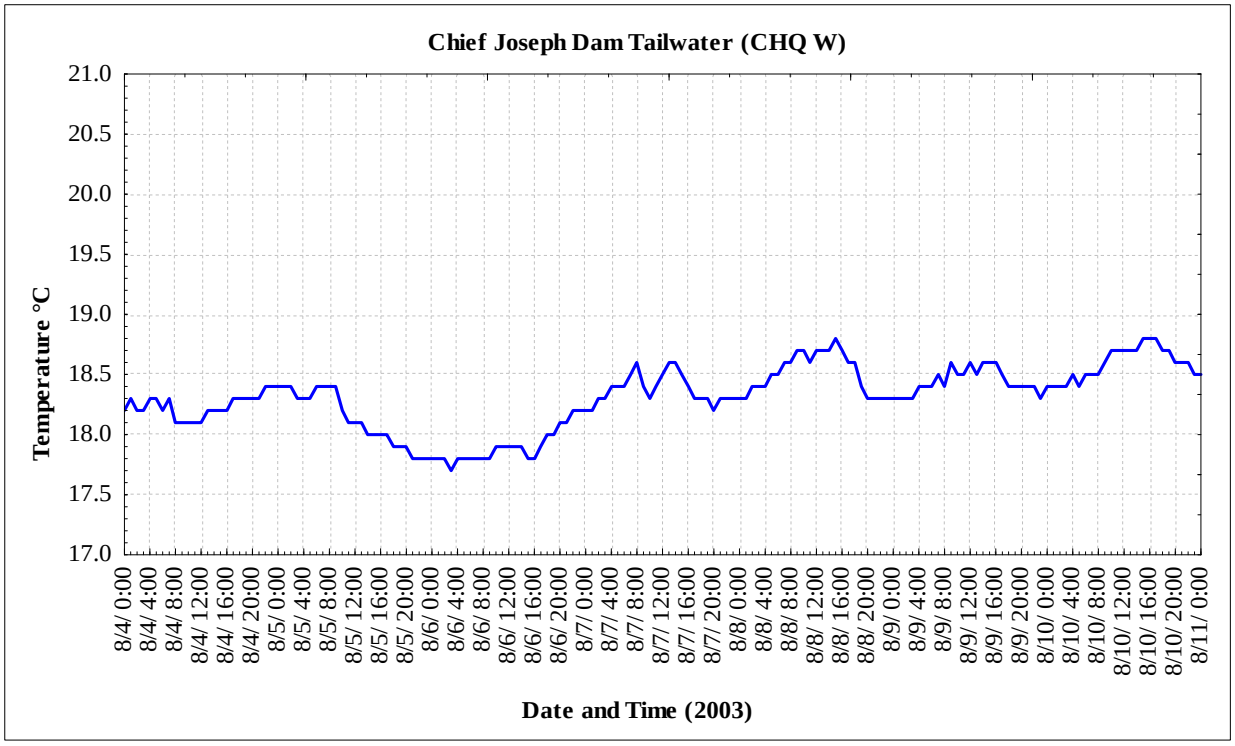


Figure 15. Temporal variation during one-week (Aug 4-11) at the tailwater station.

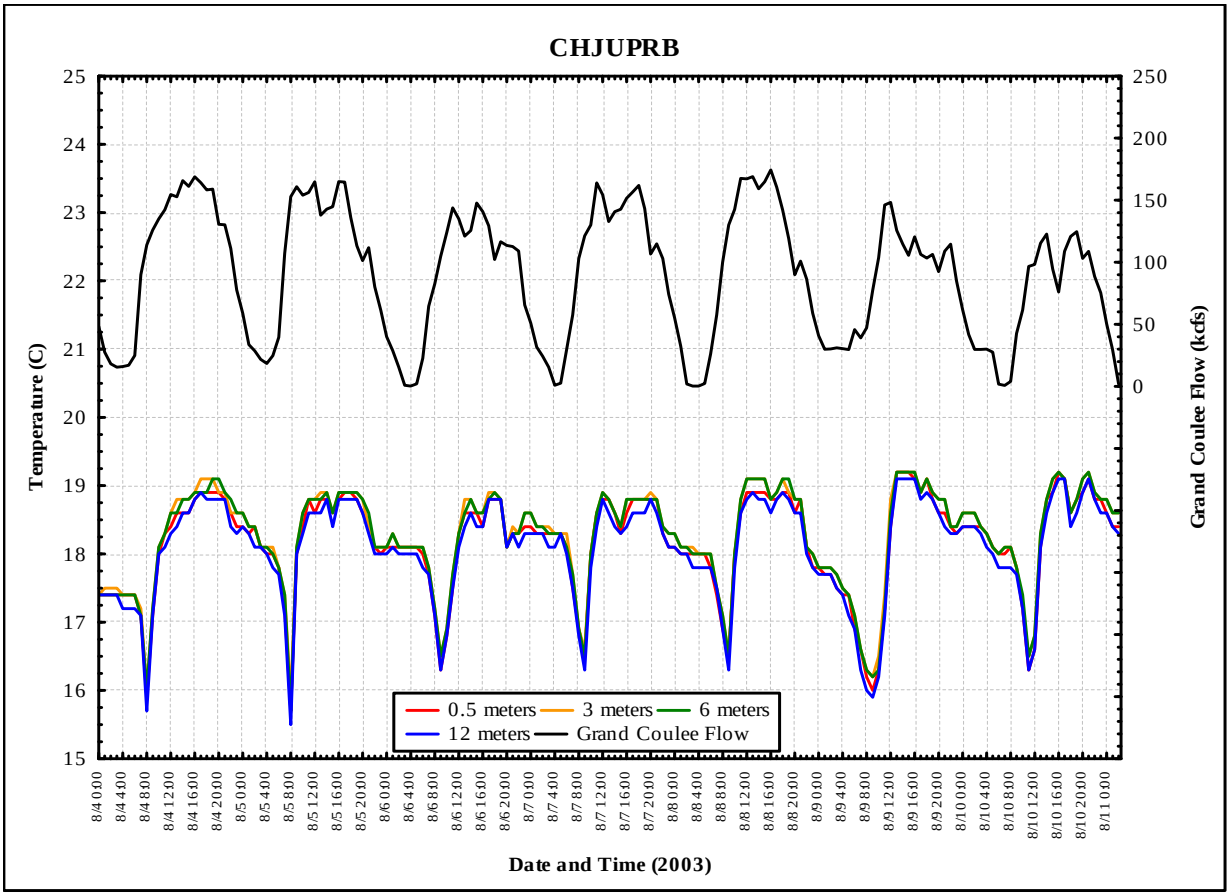


Figure 16. Temporal variation of temperature versus Grand Coulee Flows at the upstream station during one-week (Aug 4 - 11).

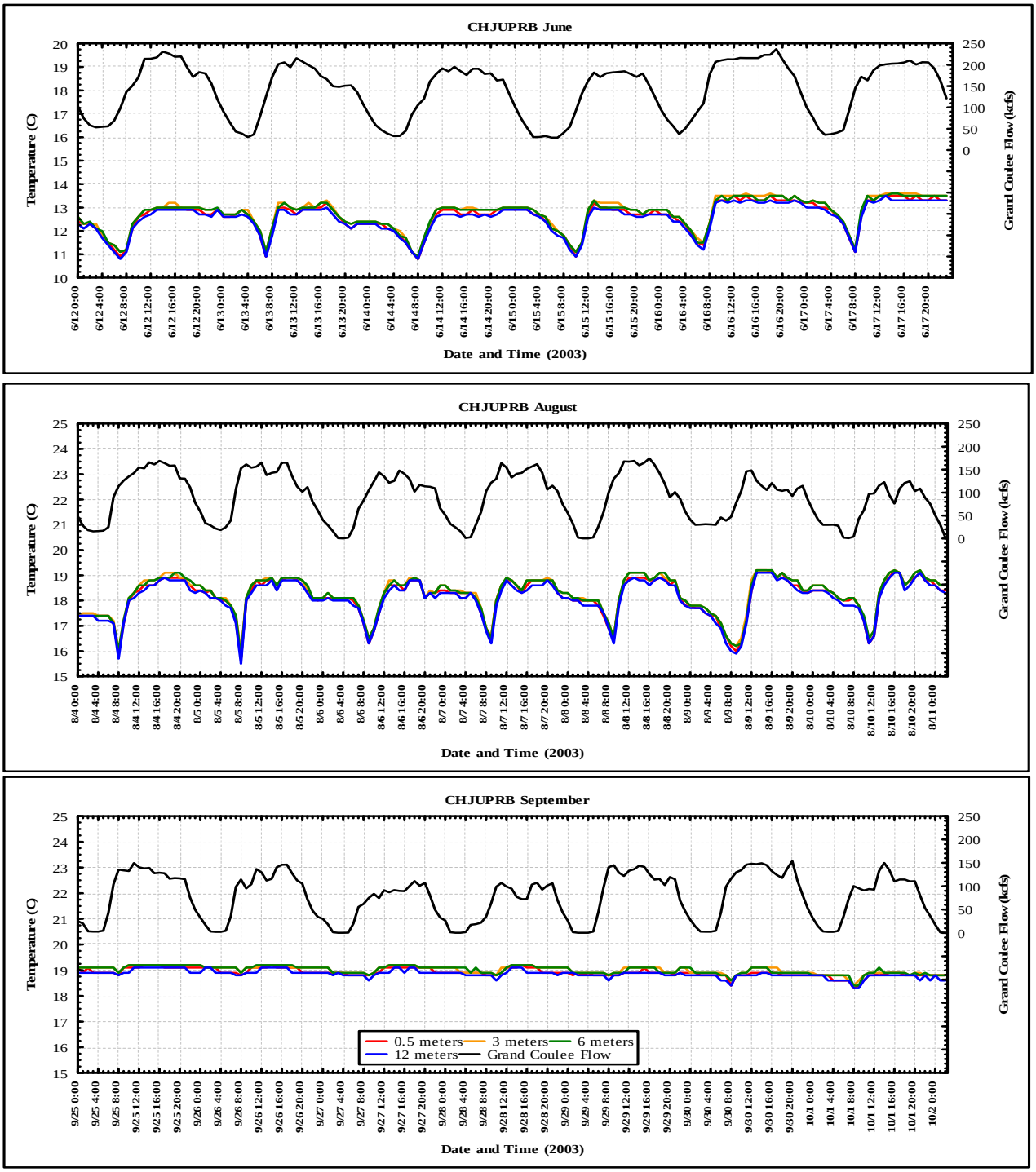


Figure 17. Temporal variation of temperature versus Grand Coulee Flows at the upstream station for one-week periods in June, August, and September/October 2003.

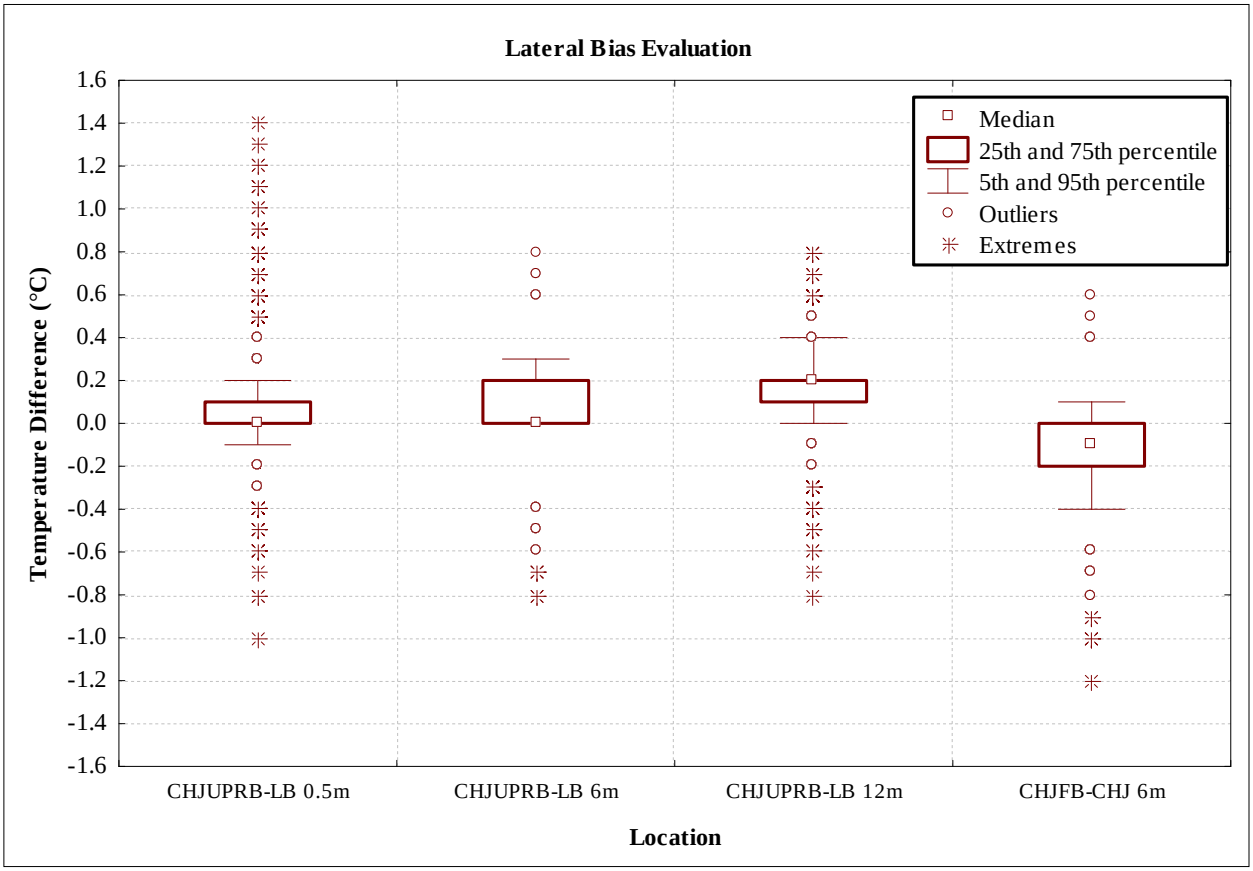
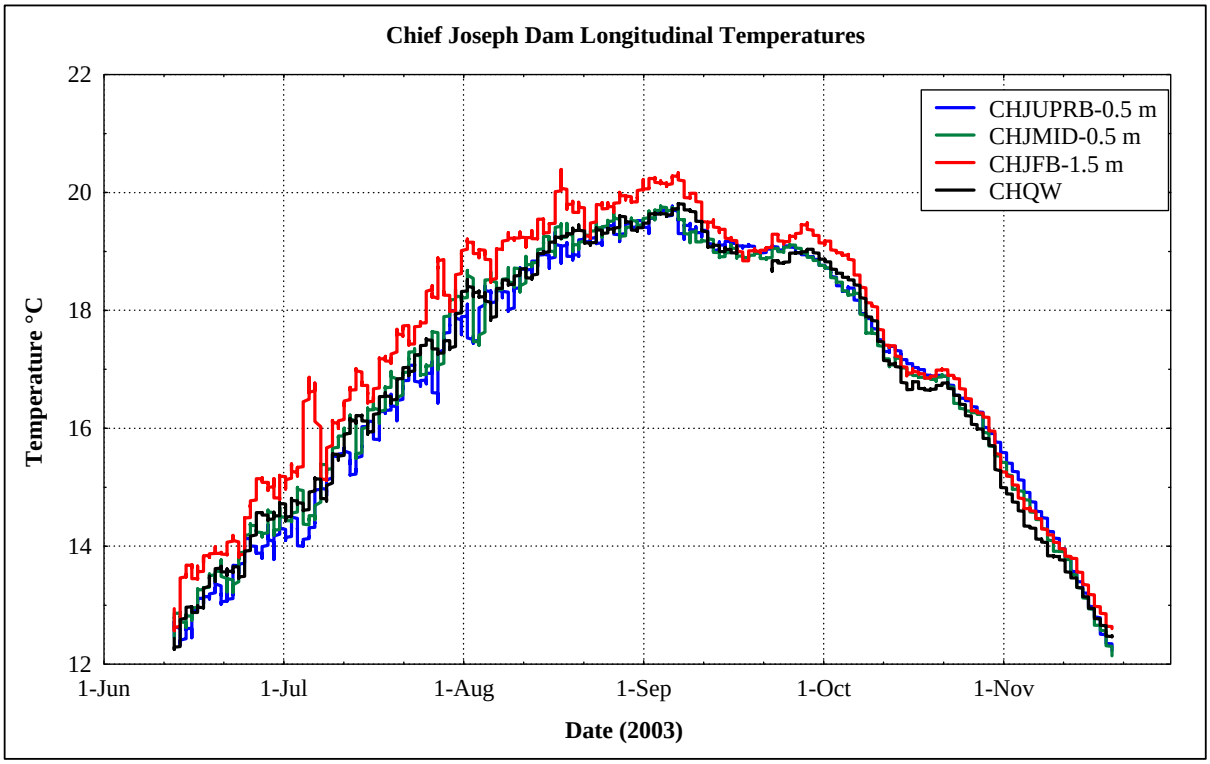


Figure 18. Lateral bias evaluation of temperature differences at the upstream stations (CHJUPRB vs. CHJUPLB) and the forebay stations (CHJFB vs. CHJ).



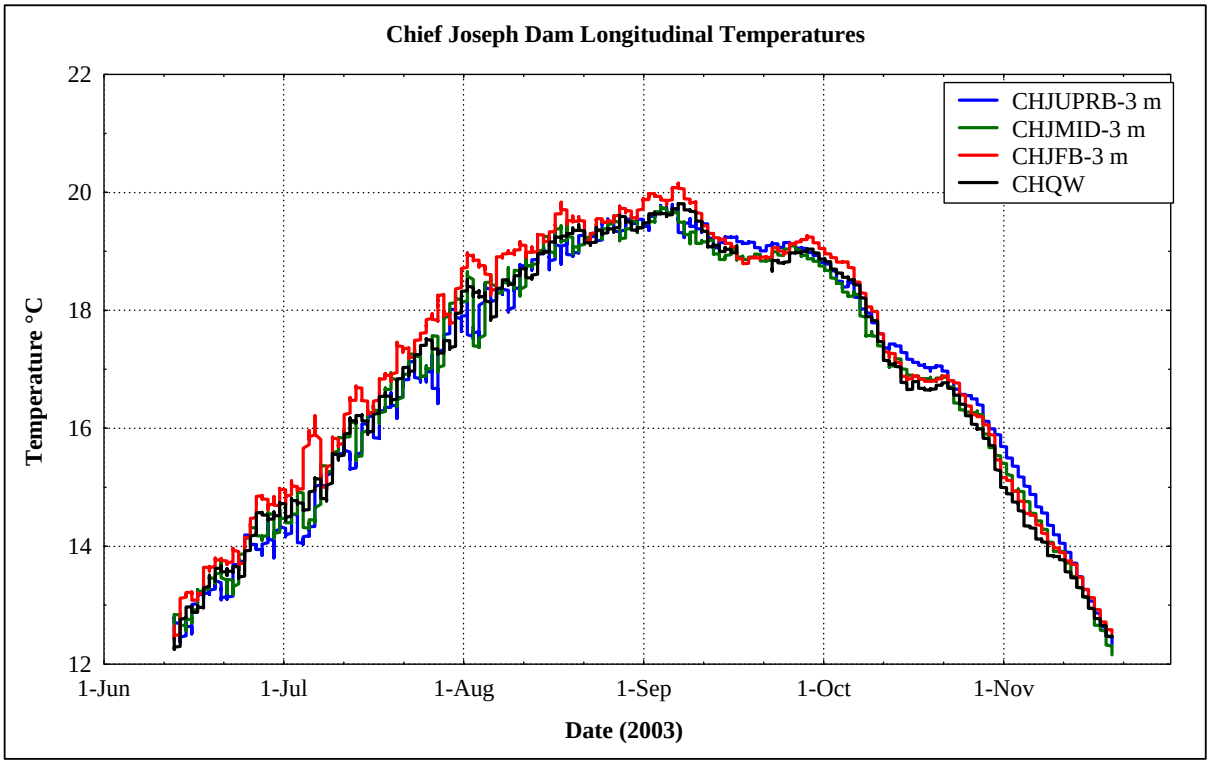


Figure 19. One-day moving mean water temperatures showing longitudinal trends at the surface and 3-meter depth.

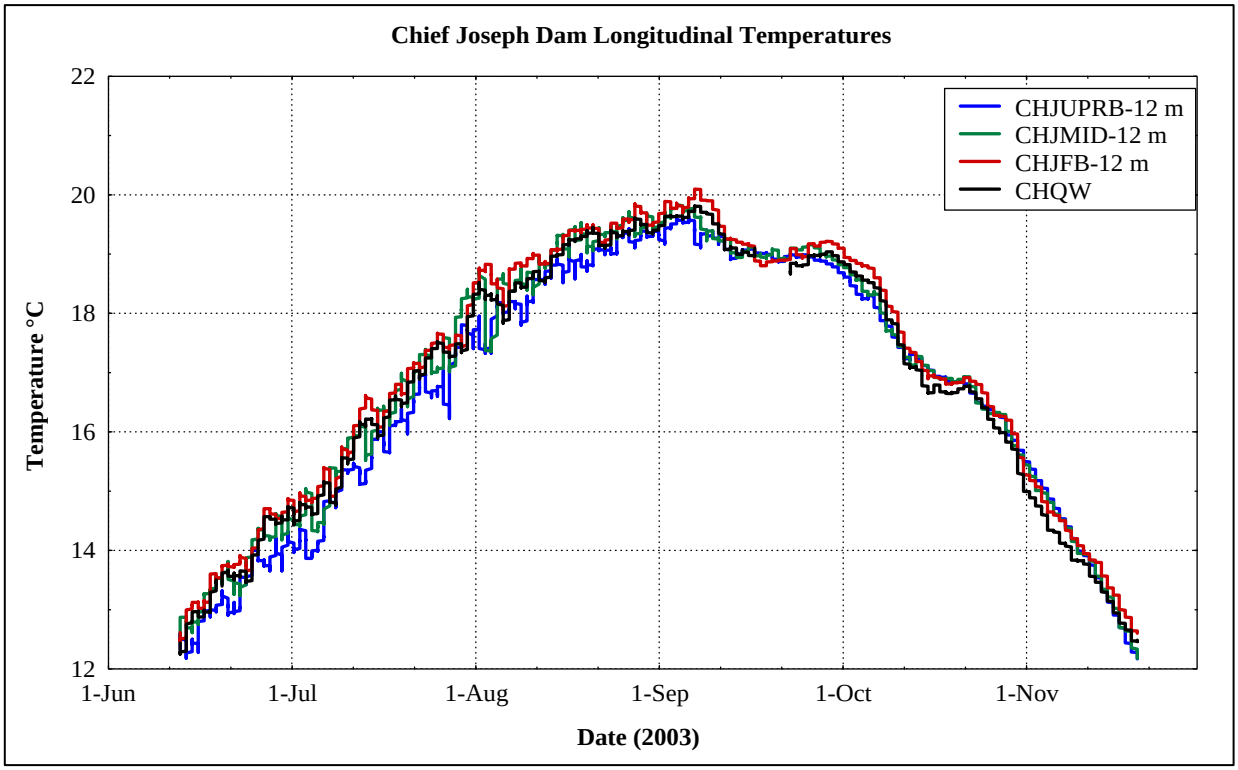


Figure 20. One-day moving mean water temperatures showing longitudinal trends at the 12-meter depth.