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Total Dissolved Gas and Water Temperature in the Lower Columbia River, Oregon and Washington, 2003: Quality-Assurance Data and Comparison to Water-Quality Standards

Water–Resources Investigations Report 03-4306

Prepared in cooperation with the
U.S. Army Corps of Engineers

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Cover photographs:

Upper left:	Spill from Bonneville Dam on the Columbia River, from U.S. Army Corps of Engineers files.
Middle:	Map of fixed monitoring stations.
Bottom right:	Salmon in the Bonneville fish ladder, from U.S. Army Corps of Engineers files.

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By DWIGHT Q. TANNER, HEATHER M. BRAGG, and MATTHEW W. JOHNSTON

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Portland Oregon: 2003

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
cubic feet per second (ft^3/s)	0.028317	cubic meters per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

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Total Dissolved Gas and Water Temperature in the Lower Columbia River, Oregon and Washington, 2003: Quality-Assurance Data and Comparison to Water-Quality Standards

By Dwight Q. Tanner, Heather M. Bragg, *and* Matthew W. Johnston

SIGNIFICANT FINDINGS

When water is released through the spillways of dams, air is entrained in the water, increasing the concentration of total dissolved gas. Excess dissolved-gas concentrations can have adverse effects on freshwater aquatic life. The U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, collected total-dissolved-gas and water-temperature data at seven sites on the lower Columbia River in 2003. Significant findings from the data include:

- For the seven monitoring sites in water year 2003, an average of 98.9% of the total-dissolved-gas data were received in real time by the USGS satellite downlink and were within 1% saturation of the expected value, based on calibration data, replicate quality-control measurements in the river, and comparison to ambient river conditions at adjacent sites.
- Most field checks of total-dissolved-gas sensors with a secondary standard were within plus or minus 1% saturation. Field checks of barometric pressure and water temperature were usually within plus or minus 1 millimeter of mercury and plus or minus 0.1 degree Celsius, respectively.
- The variances to the States of Oregon and Washington water-quality standards for total dissolved gas were exceeded at six of the seven monitoring sites. The sites at Camas and Bonneville forebay had the most days exceeding the variance of 115% saturation. The forebay exceedances may have been the result of the cumulative effects of supersaturated water moving downstream through the lower Columbia River. Apparently, the levels of total dissolved gas did not decrease rapidly enough downstream from the dams before reaching the next site.
- From mid-July to mid-September, water temperatures were usually above 20 degrees Celsius at each of the seven lower Columbia River sites. According to the Oregon water-quality standard, when the temperature of the lower Columbia River exceeds 20 degrees Celsius, no measurable temperature increase resulting from anthropogenic activities is allowed. Transient increases of about 1 degree Celsius were noted at the John Day forebay site, due to localized solar heating.

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) operates several dams in the Columbia River Basin, which encompasses 259,000 square miles of the

Pacific Northwest. These dams are multipurpose facilities that fill regional needs for flood control, navigation, irrigation, recreation, hydropower production, fish and wildlife habitat, water-quality maintenance, and municipal and industrial water supply. When water is released through the spillways of these dams (instead of being routed through the turbines to generate electricity), ambient air is entrained in the water, increasing the concentration of total dissolved gas (TDG) downstream from the spillways. TDG conditions above 110% saturation have been shown to cause gas-bubble trauma in fish and adversely affect other aquatic organisms (U.S. Environmental Protection Agency, 1986).

The USACE regulates spill and streamflow to minimize the production of excess TDG downstream from its dams, but there is also the goal of providing for fish passage with spilled water (rather than passage through the turbines). Consequently, the States of Oregon and Washington issue variances to the TDG water-quality standards during the summer months. In order to monitor compliance with these variances, the USACE oversees the collection of near real-time TDG and water-temperature data upstream and downstream from the Columbia River Basin dams in a network of fixed-station monitors. Data from these sites are available within about 4 hours of current time.

Background

Real-time TDG and water-temperature data are vital to the USACE for dam operation and for monitoring compliance with environmental regulations. The data are used by water managers to maintain water-quality conditions that facilitate fish passage and survival in the lower Columbia River. The U.S. Geological Survey (USGS), in cooperation with the Portland District of the USACE, has collected TDG and related data in the lower Columbia River every year beginning in 1996. Current and historical TDG and water-temperature data can be found on the USGS Website at http://oregon.usgs.gov/projs_dir/pn307.tdg/. Reports that were published in 1996, 2001, and 2002 contained TDG data, quality-assurance data, and descriptions of the methods of data collection for water years 1996, 2000, 2001, and 2002 (Tanner and others, 1996; Tanner and Johnston, 2001; Tanner and Bragg, 2001; and Tanner and others, 2002, respectively).

To provide suitable data for managing and modeling TDG in the lower Columbia River, real-time hourly data for 2003 were reviewed relative to laboratory and field measurements made during instrument calibration and daily intersite comparison. Some TDG data were deleted because they were not of suitable quality. The hourly data were stored in a USGS data base (Automated Data Processing System—ADAPS); and in a USACE data base (at http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/ months). The USACE database also includes discharge and spill data.

Purpose and Scope

The purpose of TDG monitoring in the lower Columbia River is to provide the USACE with (1) real-time data for managing streamflow and spill at its project dams and (2) reviewed TDG data to evaluate conditions in relation to water-quality standards and to provide a data base for modeling the effect of various management scenarios of streamflow and spill on TDG levels.

This report describes the TDG data and related quality-assurance data from the lower Columbia River at seven sites from the forebay of the John Day Dam (river mile [RM] 215.6) to Camas, Washington (RM 121.7), (fig. 1, table 1). It is similar in format and content to the previous reports presenting TDG data for the lower Columbia River, mentioned above. Data for water year 2003 (October 1, 2002, to September 30, 2003) included hourly measurements of TDG pressure, barometric pressure, water temperature, and probe depth. Five of the sites were operated from March to September 2003, which is the usual time of spill from the dams. The sites at the forebay and tailwater of The Dalles Dam also were operated during October and part of November 2002 to evaluate the effects of spill tests during those times. Two sites (Bonneville forebay and Warrendale) were operated year-round.

Acknowledgments

The authors acknowledge the aid and funding support of the U.S. Army Corps of Engineers. Our special thanks goes to James L. Britton (USACE) for technical and logistical support of the project. The authors also acknowledge Amy Brooks (USGS) for assistance in data collection and for preparing summaries and analyses of data, and Steve Sobieszczyk for producing the map of the monitoring stations on the cover.

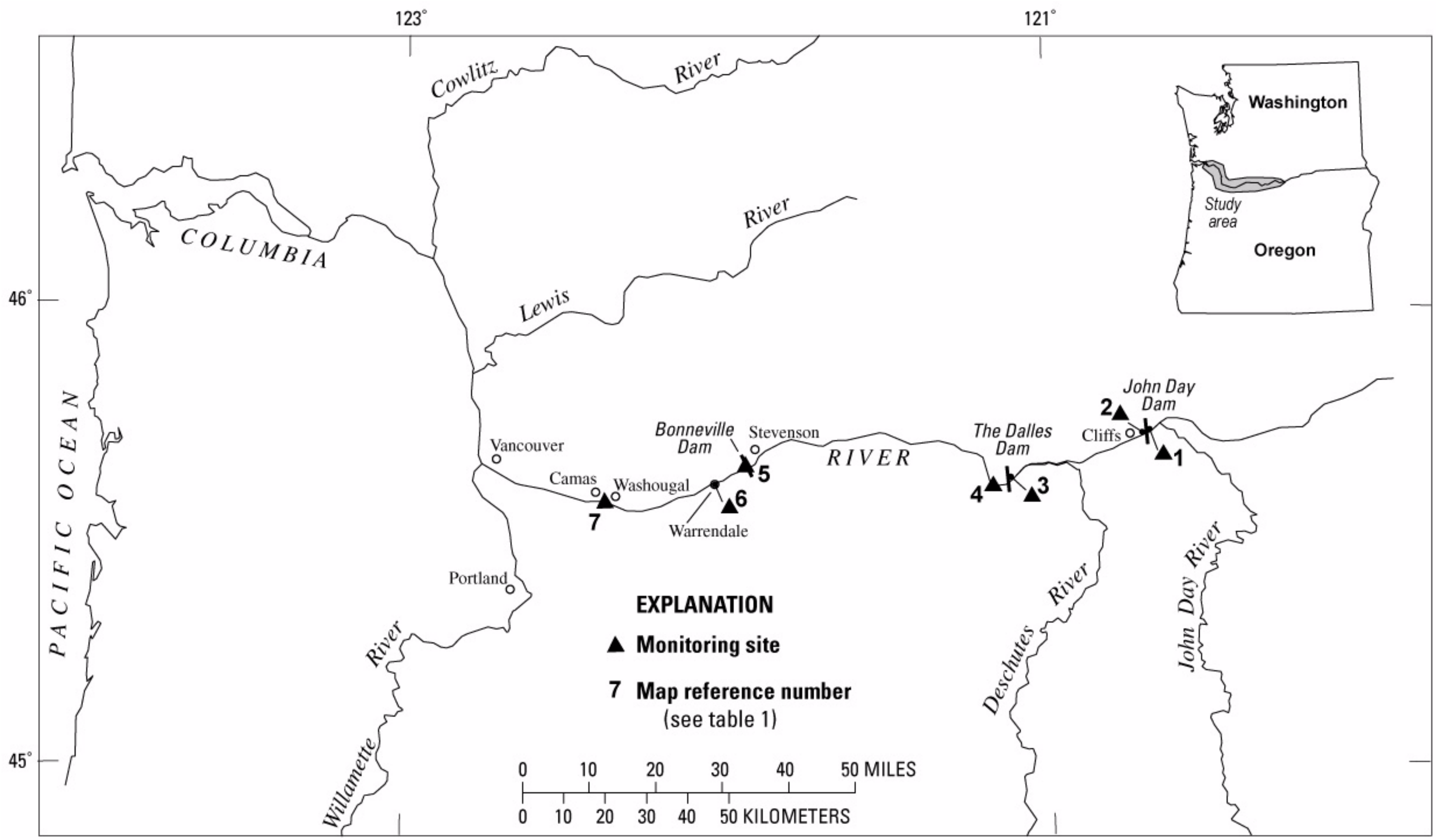

Figure 1. Location of total-dissolved-gas fixed stations, lower Columbia River, Oregon and Washington, water year 2003.

Table 1. Total-dissolved-gas fixed stations, lower Columbia River, Oregon and Washington, water year 2003

[Map reference number refers to figure 1; U.S. Army Corps of Engineers, USACE; Columbia River mile locations were determined from U.S. Geological Survey (USGS) 7.5-minute topographic maps; stations are referenced by their abbreviated name or USACE site identifier in this report, °, degree, ’, minute, ”, second]

Map reference number	USACE site identifier	Columbia River mile	USGS station number	USGS station name (abbreviated station name)	Latitude	Longitude	Period of record
1	JDA	215.6	454257120413000	Columbia River at John Day Dam forebay, Washington (John Day forebay)	45°42’57”	120°41’30”	03/20/03-09/16/03
2	JHAW	214.7	454249120423500	Columbia River, right bank, near Cliffs, Washington (John Day tailwater)	45°42’49”	120°42’35”	03/20/03-09/16/03
3	TDA	192.6	453712121071200	Columbia River at The Dalles Dam fore-bay, Washington (The Dalles forebay)	45°37’12”	121°07’12”	10/01/02-11/06/02 and 03/20/03-09/17/03
4	TDDO	188.9	14105700	Columbia River at The Dalles, Oregon (The Dalles tailwater)	45°36’27”	121°10’20”	10/01/02-11/06/02 and 03/21/03-09/17/03
5	BON	146.1	453845121562000	Columbia River at Bonneville Dam fore-bay, Washington (Bonneville forebay)	45°38’45”	121°56’20”	Year-round
6	WRNO	140.4	453630122021400	Columbia River, left bank, near Dodson, Oregon (Warrendale)	45°36’30”	122°02’14”	Year-round
7	CWMW	121.7	453439122223900	Columbia River, right bank, at Washougal, Washington (Camas)	45°34’39”	122°22’39”	03/10/03-09/18/03

METHODS OF DATA COLLECTION

Methods of data collection for TDG, barometric pressure, and water temperature are described in detail in Tanner and Johnston (2001). A summary of these methods follows: Instrumentation at each fixed station consisted of a Hydrolab water-quality probe, a Common Sensing, Inc. electronic barometer, a power supply, and a Sutron Model 8200 data-collection platform (DCP). The barometer, probe, and DCP were powered by a 12-volt battery that was charged by a solar panel and/or a 120-volt alternating-current line. Measurements were made every hour, and every 4 hours the DCP transmitted the most recent logged data to the Geostationary Operational Environmental Satellite (GOES) system (Jones and others, 1991). The data were automatically decoded and transferred to the USACE data base and to the USGS ADAPS data base. At one site, John Day tailwater, two TDG sensors were installed on the same Hydrolab to ensure that data were reliably collected at this important site.

The fixed-station monitors were calibrated every 2 weeks from March to September, 2003, and every 3 weeks for the remainder of the year, at which time Warrendale and Bonneville forebay were the only sites in operation. The field calibration procedure was as follows: A recently calibrated Hydrolab (which was used as a secondary standard) was deployed alongside of the field Hydrolab to obtain check measurements of TDG and water temperature prior to removing the field Hydrolab for calibration. Then the field Hydrolab was replaced with one that had been recently calibrated at the Oregon District Laboratory. Then the secondary standard was used to check TDG and temperature measured by the newly deployed Hydrolab in the river. The electronic barometer at the fixed-station was calibrated using a portable barometer that had been recently calibrated at the National Weather Service office located in northeast Portland.

The Hydrolab that was brought in from the field after 2 to 3 weeks of deployment was then calibrated in the Oregon District Laboratory. The integrity of the TDG membrane was checked, and the TDG sensor was calibrated at 0, 100, 200, and 300 mm Hg (millimeters of mercury) above atmospheric pressure to cover the expected range of TDG pressure in the river (approximately 100, 113, 126, and 139% saturation, respectively).

During each field calibration, the minimum compensation depth was calculated to determine whether the Hydrolab was positioned at an appropriate depth to measure TDG. This minimum compensation depth, which was calculated according to Colt (1984, p. 104) is the depth above which degassing will occur, due to decreased hydrostatic pressure. To measure TDG accurately, the Hydrolabs were positioned during each calibration visit at a depth below the calculated minimum compensation depth, wherever possible.

SUMMARY OF TOTAL-DISSOLVED-GAS DATA COMPLETENESS AND QUALITY

A summary of USGS TDG data completeness and quality for water year 2003 is shown in table 2. (The USACE satellite downlink was a parallel system, so the amount and quality of USACE data were similar). Data in table 2 were based on the total amount of hourly TDG data that could have been collected during the monitoring season. Any hour without TDG pressure data or barometric pressure data was counted as an hour of missing data for TDG in percent saturation, which is calculated as TDG pressure, in millimeters of mercury, divided by the barometric pressure, in millimeters of mercury, multiplied by 100%. The fourth column in table 2 shows the percentage of data that was received in real time and passed quality-assurance checks. TDG data were considered to meet quality-assurance standards if they were within plus or minus 1% saturation of the expected value, based on calibration data and daily checks of ambient river conditions at adjacent sites.

At each station, at least 96.6% of the data was received in real time by the USGS downlink and met quality-control checks, with an overall average of 98.9% (table 2). Most missing hourly values were due to malfunction of the data collection platform (DCP).

Table 2. Total-dissolved-gas data completeness and quality, lower Columbia River, water year 2003

[Results are based on the U.S. Geological Survey (USGS) data base; TDG, total dissolved gas]

Station name	Planned monitoring, in hours	Number of missing hourly values	Percentage of real-time TDG data passing quality-control checks
John Day forebay	4,321	146	96.6
John Day tailwater	4,321	1	100.0
The Dalles forebay	5,211	4	99.9
The Dalles tailwater	5,194	47	99.1
Bonneville forebay	8,760	94	98.9
Warrendale	8,760	93	98.9
Camas	4,630	65	98.6
Average	--	--	98.9

The lowest percentage for a station was 96.6% at John Day forebay, where data loss occurred in July and August due to a faulty DCP.

QUALITY-ASSURANCE DATA

Data collection for TDG, barometric pressure and water temperature involved several quality-control checks, including calibration of instruments in the field and in the laboratory, daily checks of the data, and data review for archiving. These methods were explained in detail in Tanner and Johnston (2001), and the results of the quality-assurance program for water year 2003 are presented in this section.

After field deployment for 2 to 3 weeks, the TDG sensors were calibrated in the laboratory. First, the unit was tested, with the membrane in place, for response to increased pressure. The membrane was then removed from the sensor and allowed to dry for at least 24 hours. Before replacing the membrane, the TDG sensor was examined independently by first comparing the TDG sensor reading to ambient barometric pressure (100% saturation). Using a certified digital pressure gage (primary standard), comparisons also were made at added pressures of 100, 200 and 300 mm Hg above barometric pressure (approximately 113%, 126%, and 139% saturation, respectively). The accuracy of the TDG sensors was calculated as the difference between the expected reading and the TDG sensor reading (expected minus actual) for each of the four test conditions, divided by the barometric pressure, and multiplied by 100%. As shown in figure 2, all of the sensor readings were within 0.5% saturation of the expected value.

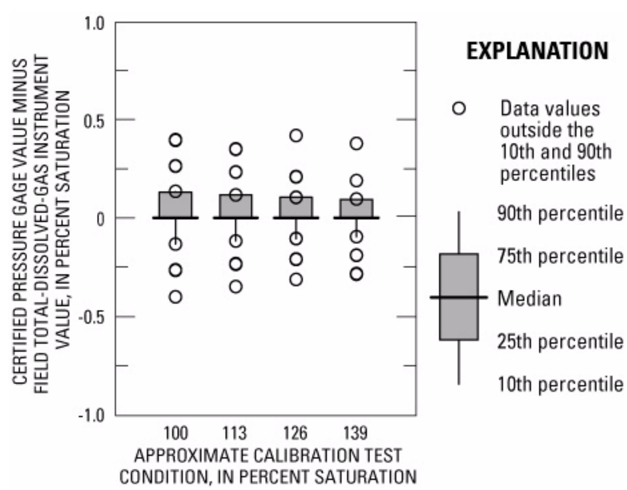

Figure 2. Accuracy of total-dissolved-gas sensors after 2 to 3 weeks of field deployment. (There were 136 tests at each pressure.)

The differences in barometric pressure, water temperature, and TDG between the secondary standard instruments and the fixed-station monitors after 2 to 3 weeks of field deployment were measured and recorded as part of the field inspection and calibration procedure. These differences, defined as the secondary standard value minus the field instrument value, were used to compare and quantify the precision between the two independent instruments. For water temperature and TDG, the measurements were made *in-situ* with the secondary standard (a recently calibrated Hydrolab) positioned alongside the field Hydrolab in the river. An aneroid barometer, calibrated every 4 to 6 weeks, served as the secondary standard for barometric pressure. Figures 3, 4, and 5 illustrate the distribution of quality-control data for each of the three parameters from all seven field sites.

The comparisons of the aneroid barometer and the electronic field barometers are shown in figure 3. Most of the field values are within plus or minus 1 mm of the standard values. The greatest difference (+4 mm Hg) was recorded at Bonneville forebay when a faulty DCP was replaced, requiring recalibration of the field barometer. The secondary standard temperature sensor and the field temperature sensor results are presented in figure 4. All of the differences are within 0.2°C (degrees Celsius), with most falling within 0.1°C.

The differences between the secondary standard TDG sensor and the field TDG sensors were calculated following equilibration of the secondary standard unit to the site conditions and before removing the field unit. The side-by-side equilibrium was considered complete after a minimum of 30 minutes when the TDG values for each sensor remained constant for 4 to 5 minutes. As shown in figure 5, most of the differences between the two TDG sensors were within plus or minus 1% saturation. The two extreme outlying data points (-19% and -24% saturation) at the Camas site were both the result of a ruptured membrane. In both cases, the Hydrolabs were removed from the site within a day of the malfunction. The other two outliers at Camas (+3.0% and +3.5% saturation) were the results of a single malfunctioning TDG sensor. Erratic TDG values were noted at Camas during one of these field inspections. The sensor and membrane, however, successfully passed the subsequent lab calibration, and the Hydrolab was redeployed. Similar erratic values were noted during the next field check and the unit was removed from service and returned to the manufacturer for repair.

During one field inspection at the John Day tailwater site, the TDG values of the two field sensors and the secondary standard were increasing during the initial part of the field calibration procedure. Due to differences in the response times of each TDG sensor, it was difficult to accurately determine the difference between the secondary standard and the two field sensors. Although both field sensors had readings of 2.0% saturation higher than the secondary standard, their accuracy in the subsequent lab calibration was within 0.3% saturation of the primary standard (certified pressure gage).

Similarly, the outlying data point at the John Day forebay site (+2.0% saturation) was the result of slow equilibration of the secondary standard during the initial field check. After 30 minutes, the difference between the field sensor and the secondary standard was 2.0% saturation. The secondary standard and the newly deployed Hydrolab equilibrated 45 minutes later with a difference of less than 0.7% saturation, confirming that the earlier problem at the site was incomplete equilibration.

EFFECTS OF SPILL ON TOTAL DISSOLVED GAS

Spill from each dam increased the level of total dissolved gas downstream from the dam. Spill data are from the USACE Website (http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/months). Spill from John Day Dam occurred on April 10 and from April 14 to August 31 (fig. 6). The spill was usually less than 170,000 ft^3/s (cubic feet per second) and usually occurred only between 7:00 p.m. and 7:00 a.m. for fish passage considerations. Figure 6 shows that TDG downstream from John Day Dam increased in response to spill from the dam, with the TDG level usually being less than 120% saturation. For several hours on late May 27 and early May 28, the TDG was larger than 120%, but the spill was not unusually large (fig. 6). There was an increase in total discharge through the dam (which includes spill) for several hours late on May 27 (fig. 7). This increase from about 300,000 ft^3/s to more than 400,000 ft^3/s occurred just before the TDG increased to above 120% saturation (fig. 7). At the John Day Dam, the spillway and the tailwater TDG monitoring station are located on the north side of the dam, and the powerhouse is located on the south side. The increased flow from the powerhouse probably constrained the spill plume towards the north (Washington State) shore of the Columbia River, resulting in a higher measured TDG at the tailwater monitoring site for a constant amount of spill.

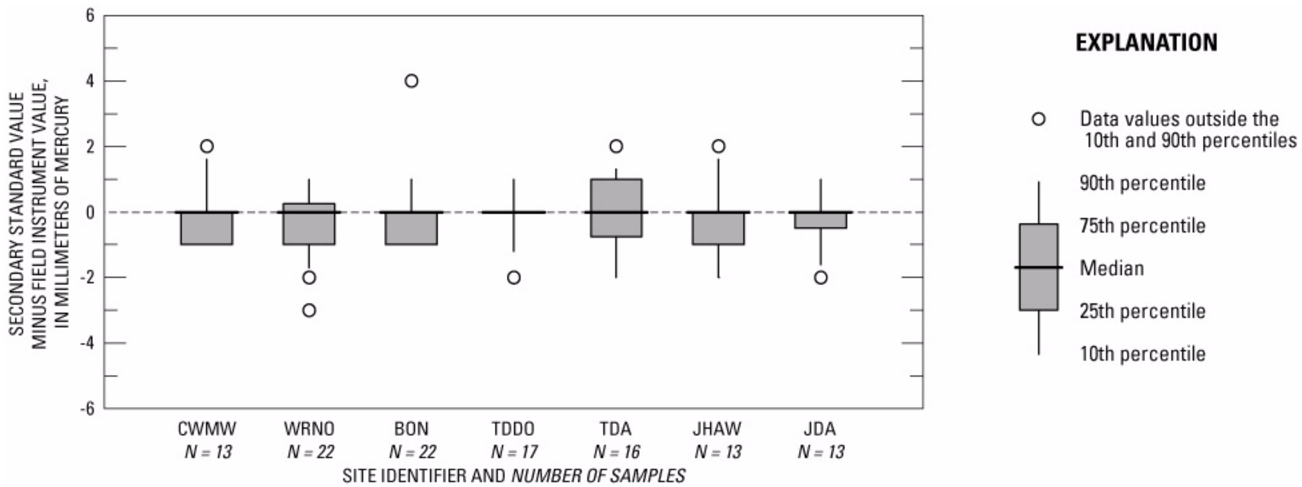

Figure 3. Difference between the secondary standard and the field barometers after 2 to 3 weeks of field deployment. (Refer to table 1 for site identifiers.)

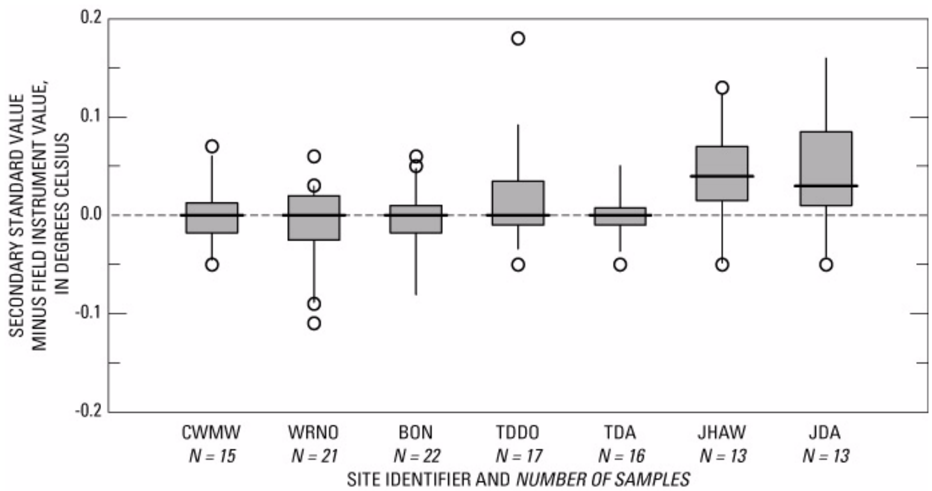

Figure 4. Difference between the secondary standard and the field temperature instruments after 2 to 3 weeks of field deployment. (Refer to table 1 for site identifiers.)

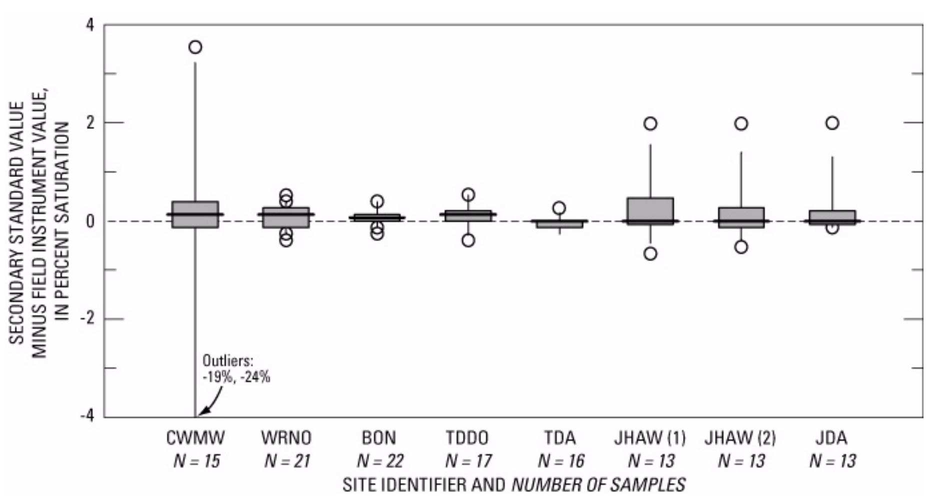

Figure 5. Difference between the secondary standard and the field total-dissolved-gas instruments after 2 to 3 weeks of field deployment. (Refer to table 1 for site identifiers.)

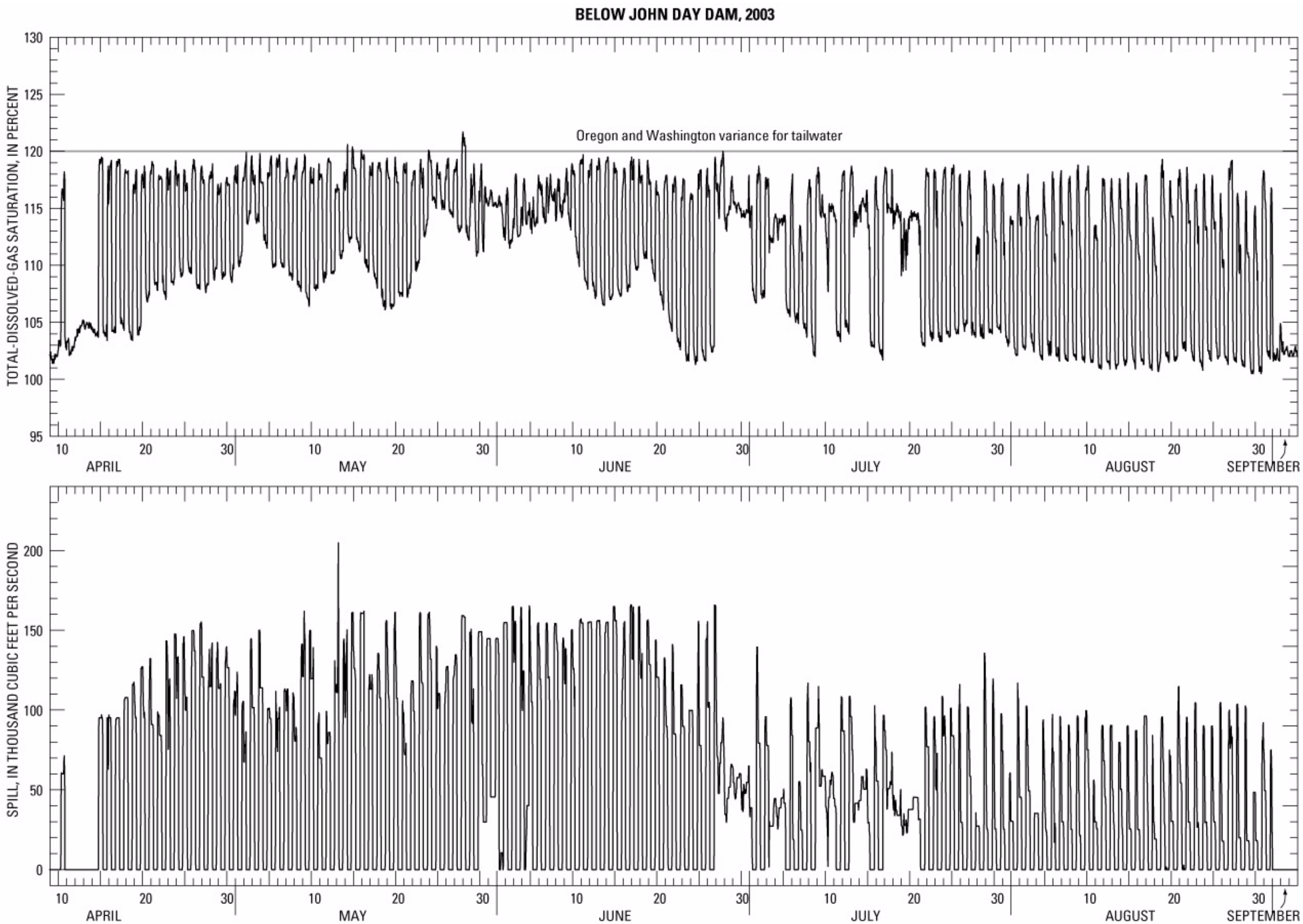

Figure 6. Total dissolved gas downstream of John Day Dam and spill from John Day Dam, April 9 to September 4, 2003.

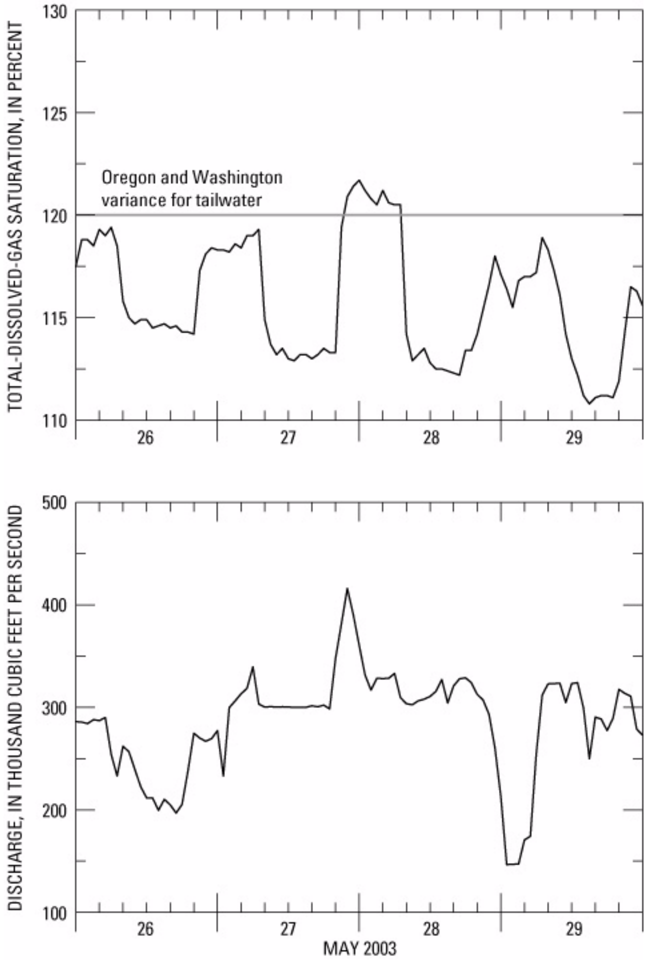

Figure 7. Total dissolved gas and discharge downstream of John Day Dam, May 26 to May 30, 2003.

Spill from The Dalles Dam (fig. 8) was almost continuous from April 14 to August 31. The spill generally was between 40,000 and 120,000 ft^3/s, resulting in a TDG level of 110 to 120% below the dam.

From April 14 to August 31, continuous spill from Bonneville Dam typically ranged from about 75,000 ft^3/s to 150,000 ft^3/s, causing TDG levels at Warrendale (which is about 6 miles downstream from Bonneville dam) to rise to about 110–120% of saturation (fig. 9). On one occasion, May 29, 2003, the TDG at the Warrendale site peaked at a value of 129% saturation and then quickly receded, even though available spill data did not show a significant increase (fig. 9). Closer examination of this event showed that there also was a peak in TDG of 126% saturation 13 hours later at the Camas site, which is about 19 miles downstream from the Warrendale site (fig. 10). The cause for these peaks was an unintentional increase in spill at Bonneville Dam, which was not documented in the spill data (Mike Schneider, USACE, written commun., 2003). From March 10 to March 12, 2003, spill from Bonneville Dam was about 50,000 ft^3/s to flush released hatchery fish to the ocean. During this spill, the TDG at the Warrendale site increased to about 105%.

COMPARISON OF TOTAL DISSOLVED GAS AND TEMPERATURE TO STANDARDS

In 2003, the States of Oregon and Washington granted the USACE variances to the water-quality standard for TDG of 110% saturation. The variance granted by the State of Oregon was a multiyear variance, covering 2003 to 2007 (Oregon Environmental Quality Commission, written commun., 2003) and the State of Washington granted a single-year variance for 2003 (Washington Department of Ecology, written commun., 2003). From April 1 to August 31, 2003, the USACE was granted variances of 115% for forebay sites (John Day forebay, The Dalles forebay, Bonneville forebay, and Camas); and 120% for tailwater sites directly downstream from dams (John Day tailwater, The Dalles tailwater, and Warrendale). The 115% and 120% variances were exceeded if the average of the highest 12 hourly values in 1 day (1:00 a.m. to midnight) was larger than the numerical standard. A separate variance of 125% was in place for all sites for the highest 2-hour average (Oregon Environmental Quality Commission, written commun., 2003), or the highest 1-hour average (Washington Department of Ecology, written commun., 2003). Although the Camas site is not located at the forebay of a dam, it is more than 24 miles downstream from Bonneville Dam, and it is regulated as a forebay site.

At six of the seven monitoring stations, the Oregon and Washington variance for TDG was exceeded at some time during water year 2003 (table 3). There were no exceedances at the John Day tailwater site. The one exceedance of the 120% variance at Warrendale occurred on May 29, 2003, and was a result of the unplanned spill mentioned above. There also was an exceedance of the 125% variance at Warrendale on this occasion.

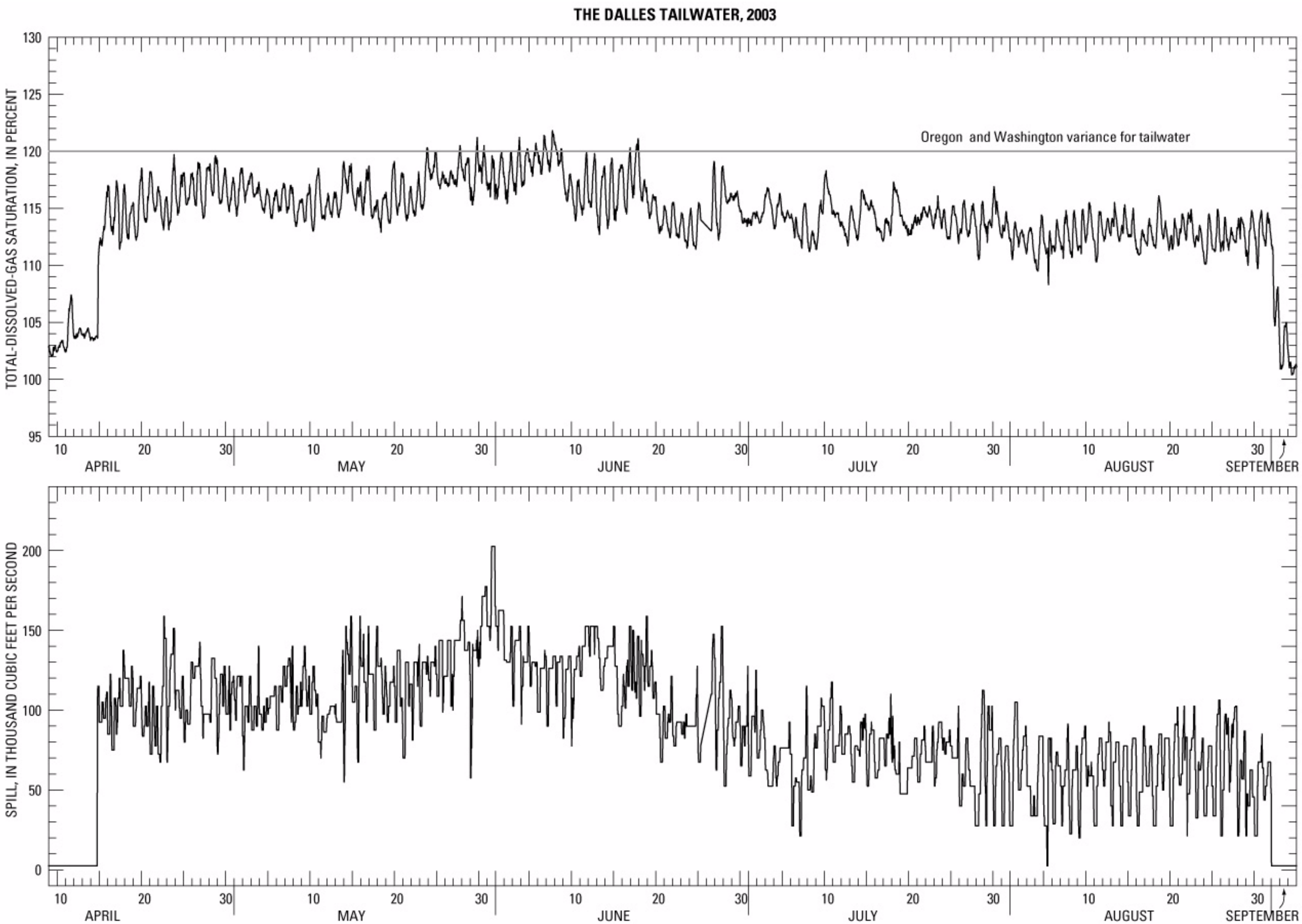

Figure 8. Total dissolved gas downstream of The Dalles Dam and spill from The Dalles Dam, April 9 to September 4, 2003.

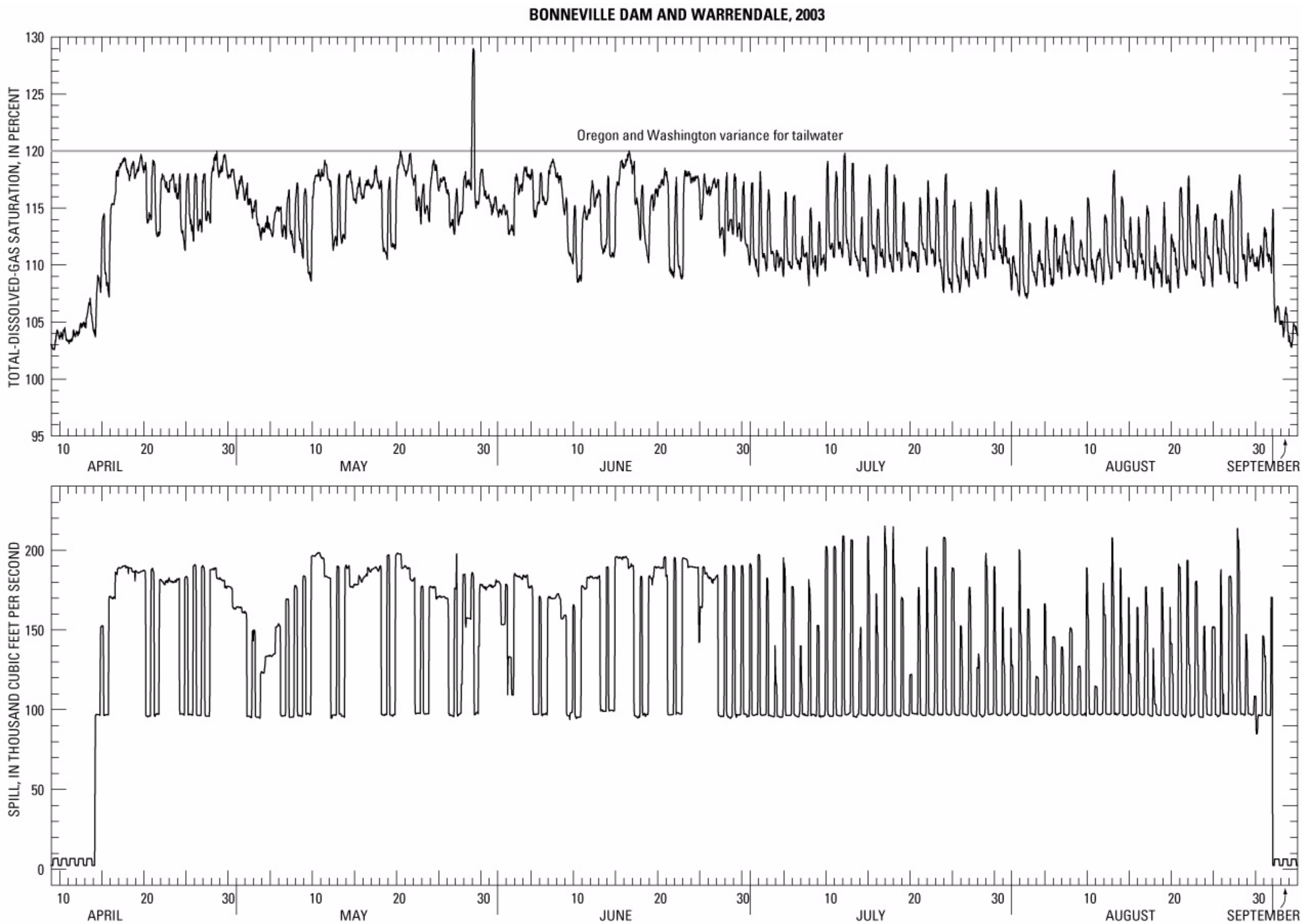

Figure 9. Total dissolved gas downstream of Bonneville Dam at Warrendale and spill from Bonneville Dam, April 9 to September 4, 2003.

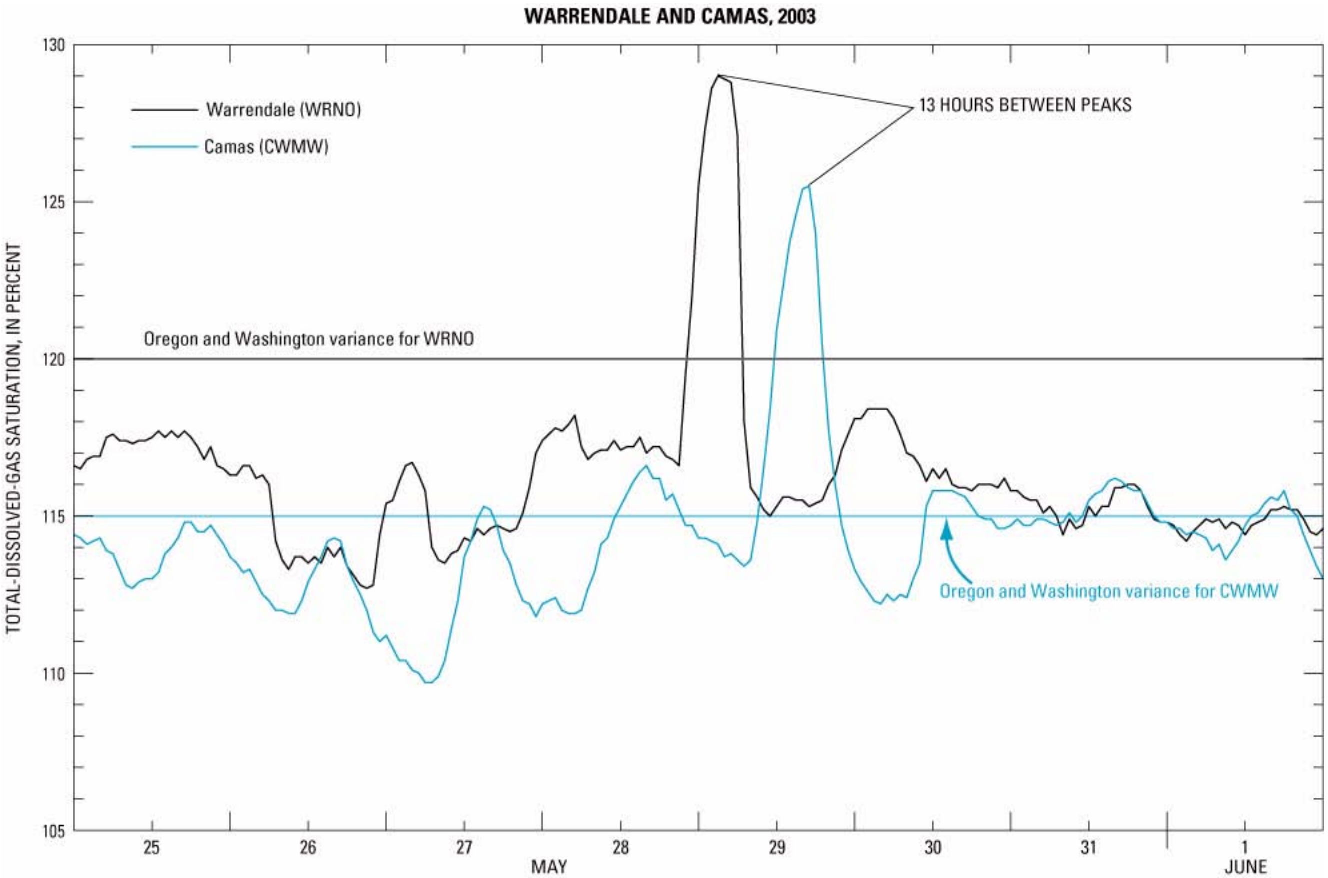

Figure 10. Total dissolved gas at Warrendale and at Camas, May 25 to June 2, 2003.

Table 3. Exceedances of States of Oregon and Washington water-quality variances for total dissolved gas, lower Columbia River, Oregon and Washington, water year 2003

[Note: At Warrendale, there was also an exceedance of the 125% variance for the highest 1- or 2-hour average. Table is based on the U.S. Geological Survey (USGS) data base.]

Station name	Numerical variance for total dissolved gas, in percent saturation	Number of days in exceedance of variance
John Day forebay	115	10
John Day tailwater	120	0
The Dalles forebay	115	9
The Dalles tailwater	120	3
Bonneville forebay	115	17
Warrendale	120	1
Camas	115	23

The site with the most exceedances was Camas, which exceeded the 115% variance 23 times, followed by Bonneville forebay, which exceeded the 115% variance 17 times. Overall, there were fewer exceedances at the tailwater sites, which had the larger variance of 120%. Available data indicate that the forebay exceedances may have been the result of the cumulative effects of significant spill throughout the lower Columbia River. The TDG levels were often near 120% at the tailwater sites (figs. 6, 8, and 9), and apparently the TDG often did not sufficiently degas to meet the 115% variance at the next downstream forebay sites. There was an increase in the median TDG concentration at the forebay sites moving downstream from John Day forebay to The Dalles forebay to Bonneville to Camas, indicating this cumulative effect (fig. 11).

Water-temperature standards that apply to the lower Columbia River are complex and depend on the effects of anthropogenic activities and the locations of salmonid rearing, spawning, and egg incubation areas. According to the State of Oregon water-quality standard, when the temperature of the Columbia River from RM 309 to the mouth exceeds 20°C, no measurable surface-water temperature increase resulting from anthropogenic activities is allowed (Oregon Department of Environmental Quality Website at http://www.deq.state.or.us/wq/wqrules/, accessed November 5, 2003).

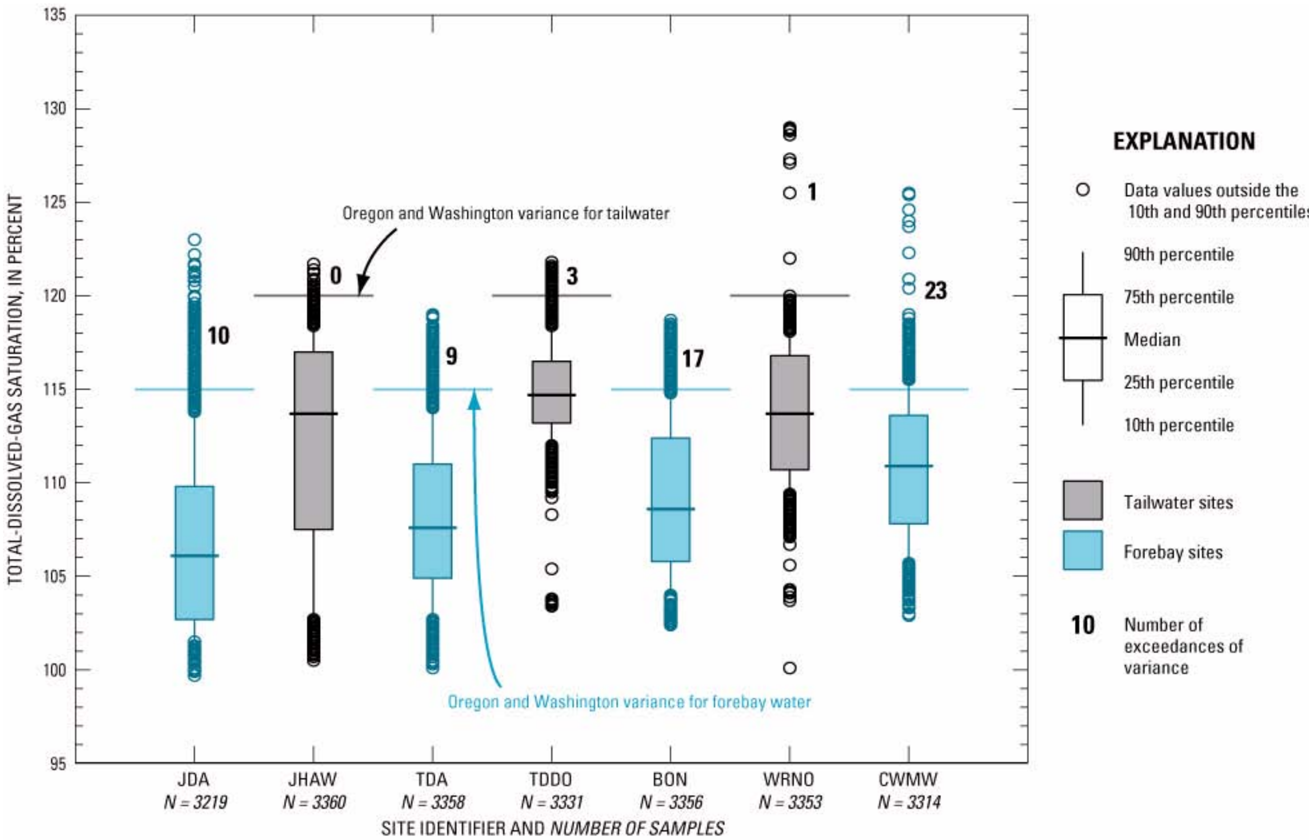

Figure 11. Distributions of hourly total-dissolved-gas data and exceedances of Oregon and Washington water-quality variances, April 14 to August 31, 2003. (Refer to table 1 for site identifiers.)

The Columbia River from RM 309 to the mouth includes all seven of the lower Columbia River TDG fixed stations that are considered in this report. Water temperatures upstream and downstream from John Day Dam were equal to or larger than 20.0°C continuously from July 13 to September 16 (fig. 12). On several afternoons during this period, the water temperature at the forebay site transiently increased to about 1°C higher than the tailwater site. This phenomenon has been described in the past (Tanner and Johnston, 2001, p. 19; and Tanner and Bragg, 2001, p. 11), and it has been attributed to localized heating of the stagnant surface layer of water near the monitoring station, which is on the upstream face of the dam. Recent data collected by the USACE show that warmer water is stratified over cooler water during warm summer days (Joe Carroll, USACE, oral commun., October 16, 2003). This stratification extends to at least 1 mile upstream from the John Day Dam.

Water temperatures upstream and downstream from The Dalles Dam were equal to or larger than 20.0°C continuously from July 14 to September 16 (fig. 13). The water temperature at The Dalles forebay was approximately equal to the temperature at The Dalles tailwater, indicating well-mixed conditions in the forebay, as contrasted to the John Day forebay.

Water temperatures upstream and downstream from Bonneville Dam are shown in figure 14. Temperatures at Bonneville forebay were equal to or larger than 20.0°C continuously from July 13 to September 13 (fig. 14). The water temperature at Warrendale (the tailwater site) was approximately equal to the temperature at Bonneville forebay, but water temperatures were more variable at Warrendale, often differing by as much as 0.2°C, and especially after spill ended on September 1 (fig. 14).

At the Camas site, the water temperature was 20.0°C or larger for most of each day from July 11 to September 13 (fig. 15). During the summer, there was a distinct diurnal or daily cycle to temperature, with an amplitude of about 1°C, a minimum at about 0900 hours, and a maximum at about 1900 hours. This is the same pattern found in the past, and perhaps indicates the characteristics of the Columbia River where it is relatively unaffected by the dams.

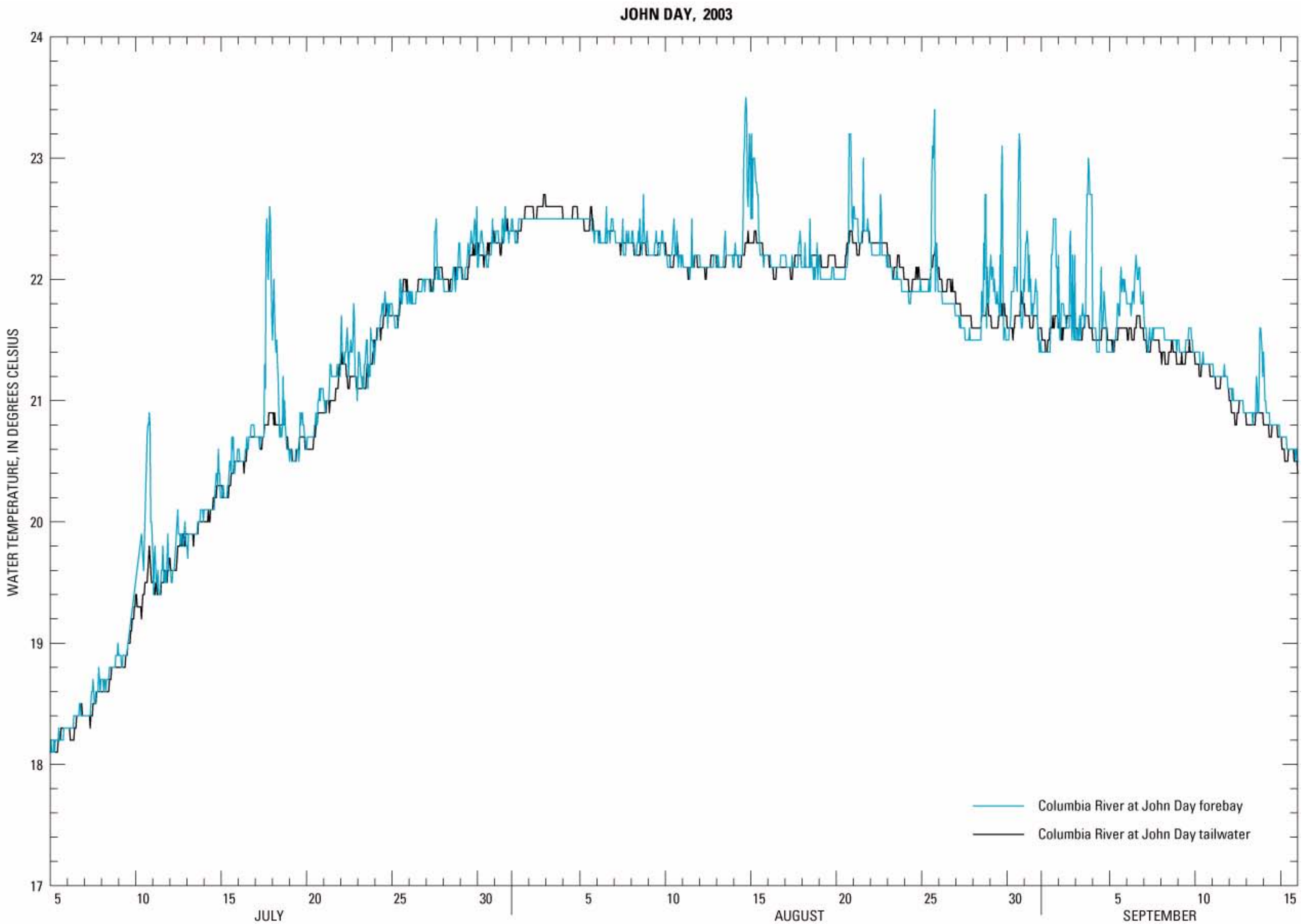

Figure 12. Water temperature upstream and downstream of John Day Dam for summer 2003.

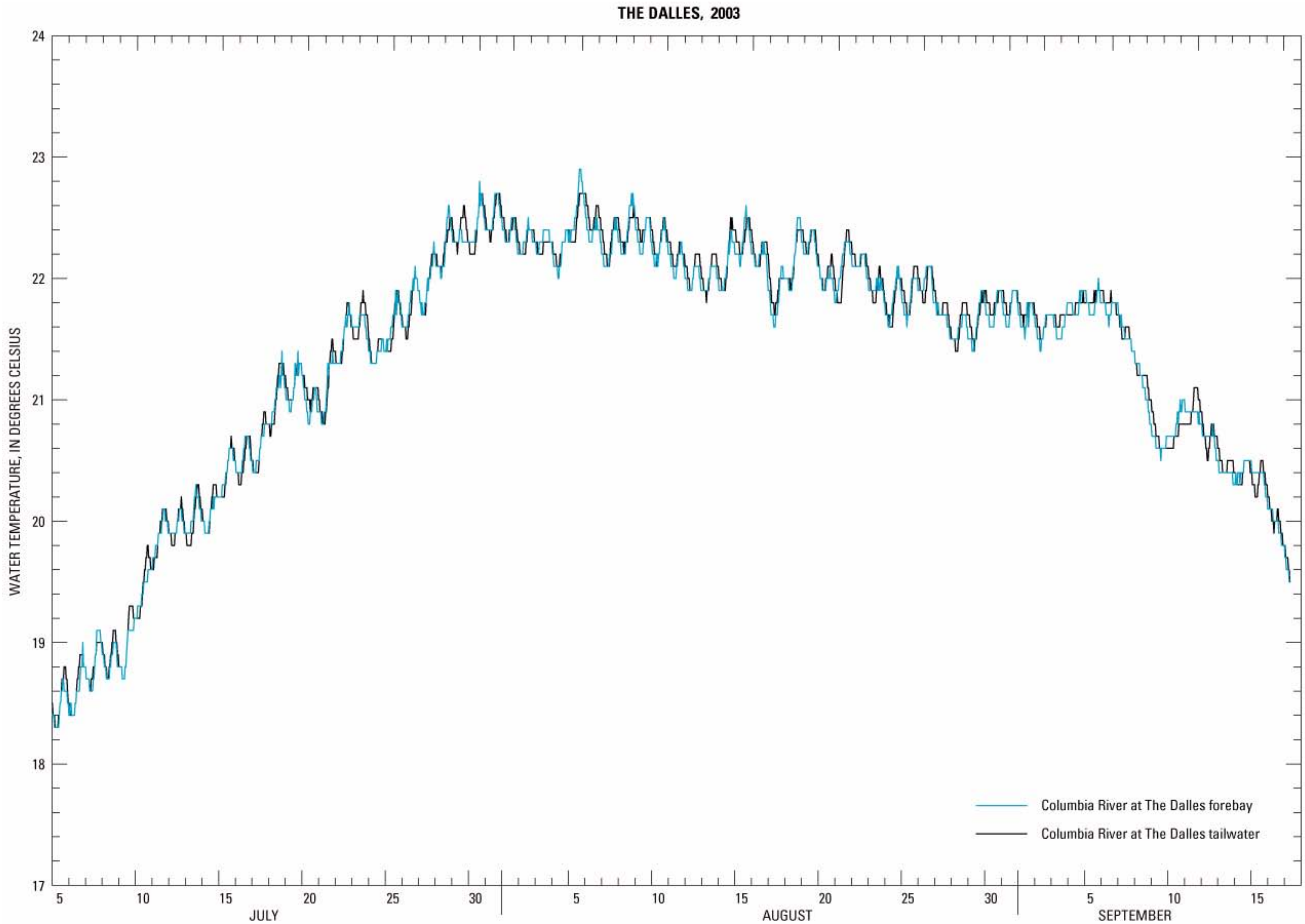

Figure 13. Water temperature upstream and downstream of The Dalles Dam for summer 2003.

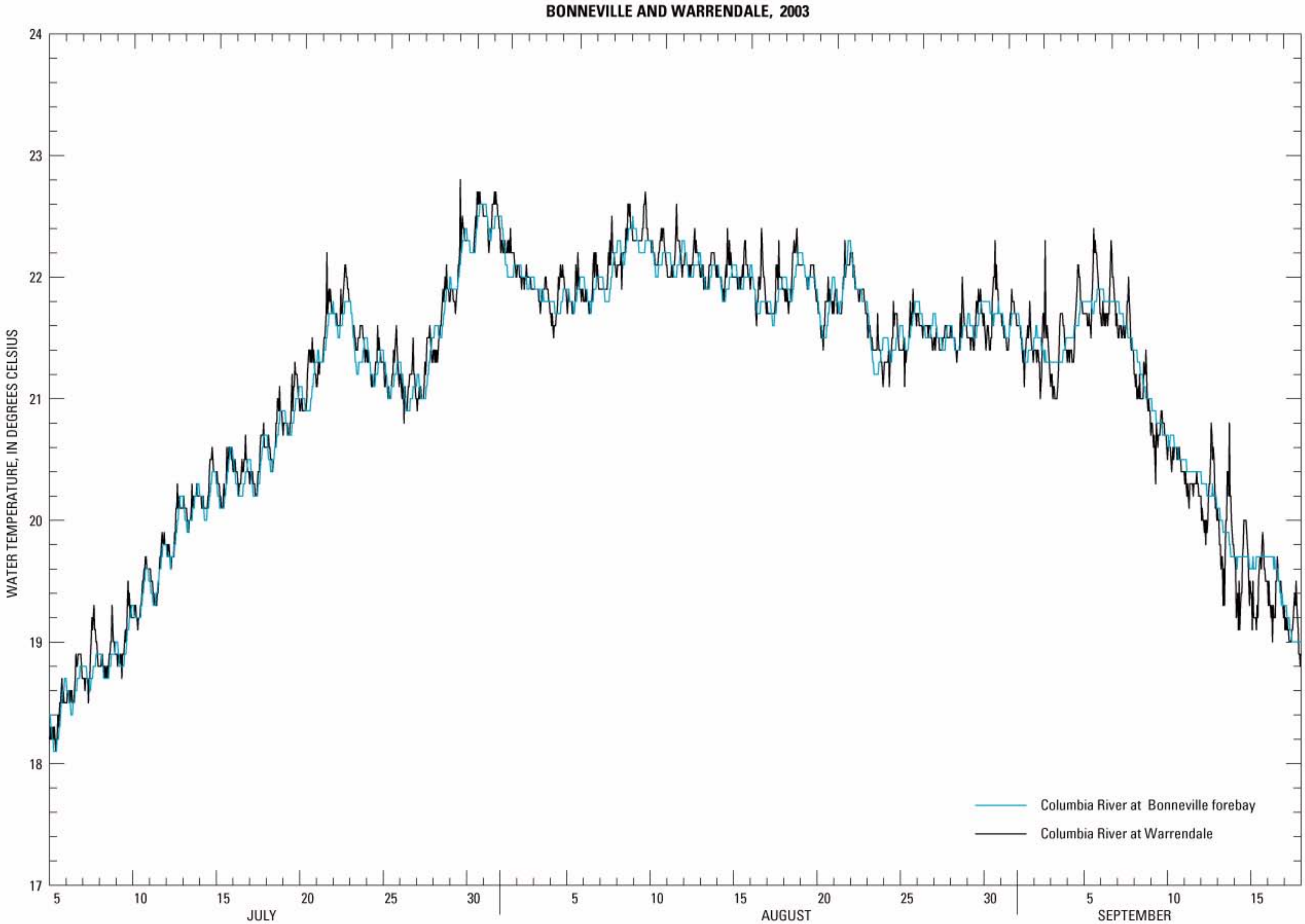

Figure 14. Water temperature upstream and downstream of Bonneville Dam for summer 2003.

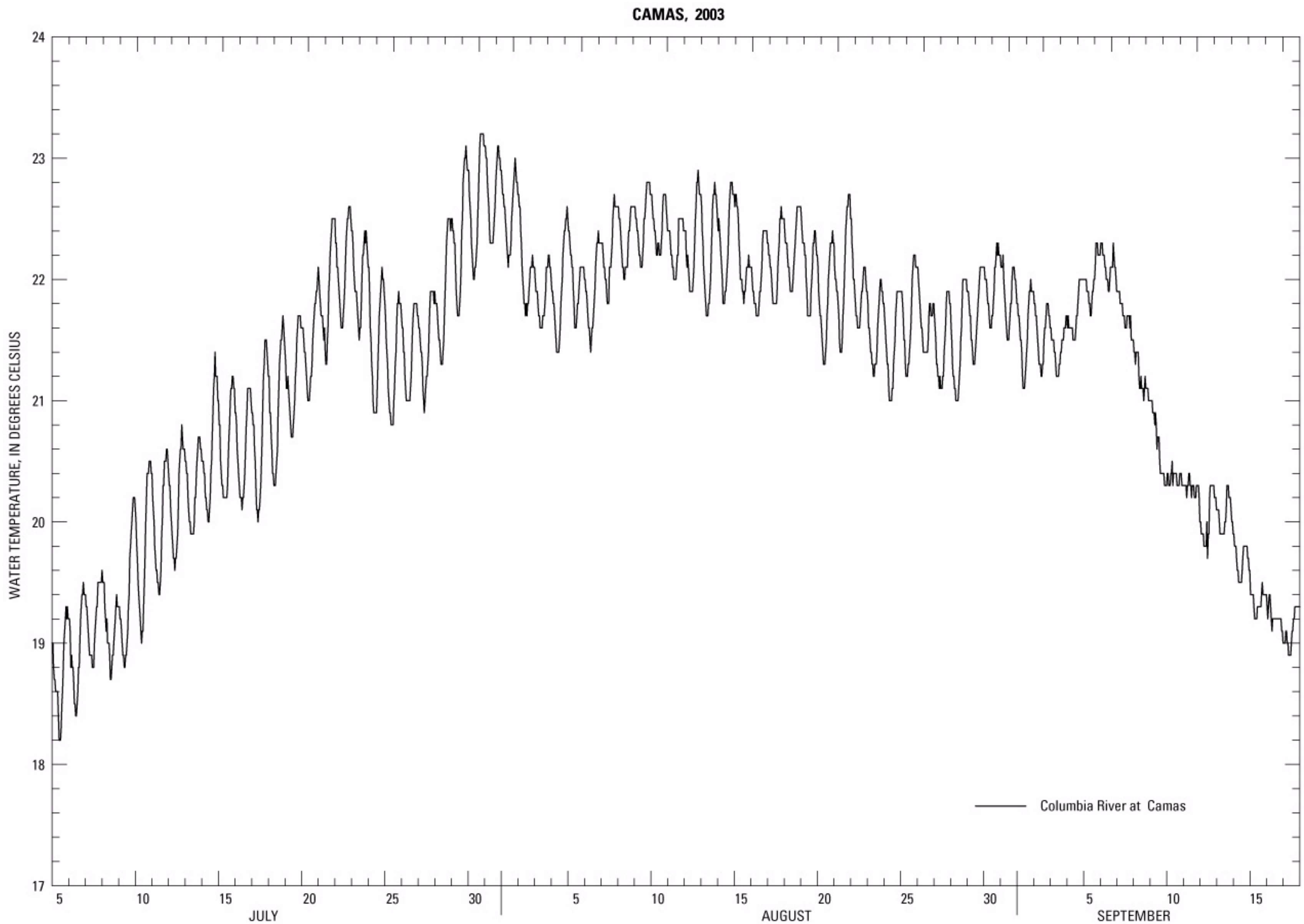

Figure 15. Water temperature at Camas for summer 2003.

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