CEERDC-EP-P May 26, 2003

MEMORANDUM FOR RECORD

SUBJECT: Water Quality Study of TDG, Temperature, and Dissolved Oxygen Spatial and Temporal Variations Downstream of Bonneville Dam, June 8-22, 2001.

1. Introduction. The voluntary spill operations at Bonneville Dam (Figure 1) have been part of the effort to improve anadromous fish survival in the Columbia River Basin since 1985 (USACE, 2002). Spill operations at Bonneville generate total dissolved gas (TDG) pressures that often exceed the state water quality standards and waivers at established downstream fixed monitoring stations. More recently, emphasis on TDG pressure compliance has been the subject of concern for salmon redds located near Ives Island, below Bonneville Dam. The TDG pressures exceeding water quality standards limit the amount of voluntary spill that can be scheduled.

2. The influence of spillway operations at Bonneville Dam coupled with the open river conditions of the receiving water results in complex spatial and temporal distribution of TDG pressures in the Columbia River. Understanding the genesis of these TDG patterns is critical for responsibly managing voluntary spill operations at Bonneville Dam. The TDG pressures below Bonneville Dam are influenced by the timing and magnitude of spillway flows, background TDG pressures, the magnitude and distribution of powerhouse flows, meteorologic conditions, biological productivity, heat exchange, and wind generated degassing. The following investigation concentrates on characterizing the spatial and temporal variations in TDG pressure above and below Bonneville Dam. The primary focus of this investigation involved characterizing the TDG pressures near the Camas/Washougal fixed monitoring station and the representativeness of the shore based sampling station.

3. Background. A series of near-field investigations have been conducted at Bonneville Dam to determine the TDG exchange associated with spillway releases. A study of TDG production below Bonneville Dam conducted in July 1997 (Wilhelms and Schneider, 1997) found that TDG saturation associated with spillway releases ranged from 123 to 137 percent during standard spills of 40 to 250 kcfs. A second study was conducted during February 1999 (Schneider, 1999) to determine the TDG exchange associated with spillbays with and without flow deflects. This study found the TDG exchange was highly correlated with unit spillway discharge with the standard spillway bay producing higher TDG pressures than spill bays with flow deflectors for discharges up to 10 kcfs. Both of these studies concluded that the TDG levels observed at the tailrace fixed monitoring stations (Warrendale, Skamania) were not representative of TDG produced by spillway releases. These studies focused on the TDG pressures generated in the spillway exit channel and did not investigate the transport and mixing of project flows downstream to the Camas/Washougal fixed monitoring station (CWMW FMS).

4. The following investigation concentrates on the spatial and temporal variations in TDG and associated aquatic processes in relation to project operation at Bonneville Dam in an effort to describe the representativeness of the CWMW FMS data. The study area includes Bonneville Dam to just downstream of the CWMW FMS located 24 miles downstream of the dam. The effects of water temperature, dissolved oxygen, and wind on TDG pressures were included in this investigation.

5. Temperature affects on TDG pressure (Charles Ideal Gas Law) have been documented in many of the DGAS studies (USACE, 2002) and in routine water quality monitoring conducted by the Corps of Engineers. Typical daily cycles during the warm, sunny periods of the year for water downstream of Bonneville Dam range from 1-2 degrees C for much of the river. This variation in temperature can introduce as much as 30 mm Hg of change in TDG pressures (or about 4% TDG saturation) on a daily basis.

6. Other aquatic sources and sinks that may greatly impact TDG pressures in highly productive systems such as the Lower Columbia River below Bonneville Dam include aquatic community metabolism. This biological phenomenon affecting dissolved oxygen (DO) and carbon dioxide concentrations are well documented in the scientific literature. Recent monitoring (May 25, 2001, USGS personal communication) at the CWMW FMS documented daily cycles in DO as great as 1.0 mg/l. At 16 degrees C, this would account for about 16 mm Hg in TDG pressure change or 2% TDG saturation.

7. Wind has a variable effect on TDG pressures downstream of Bonneville Dam. High winds, which produce breaking waves, may reduce TDG pressures by 30-70 mm Hg or 4-10 % TDG saturation. Windy days are frequent in the Lower Columbia River.

8. Objective. The purpose of this field investigation is two-fold. The Engineering Research Development Center (ERDC) was to review historical data related to the riverine processes affecting TDG pressure variation below Bonneville Dam. Secondly, the ERDC was to conduct field studies designed to describe the spatial and temporal variations in TDG and associated aquatic processes in relation to project operation at Bonneville Dam. Specific objectives follow:

- Determine the representativeness of the CWMW FMS location in relation to TDG pressures and concentration, water temperature, and dissolved oxygen concentration
- Relate daily TDG cycles to daily water temperature cycles
- Relate daily TDG cycles to daily DO cycles
- Relate TDG variation to wind and wave conditions in the Lower Columbia River
- Relate TDG variation to spill and resulting TDG production at Bonneville Dam

9. Approach. The investigation focused on the downstream riverine reach below Bonneville Dam and describes the changes in TDG properties in this reach resulting from routine project operations, upstream TDG pressures, meteorological conditions, and natural riverine processes. Data collected during the investigation include water quality, geographic locations of instruments, plant operations, water elevation, water velocity,

water discharge, and meteorological conditions. An array of automated remote instruments were deployed for logging time histories of the required water quality parameters at numerous locations from Bonneville Dam downstream to one half mile below the CWMW FMS.

10. Study Design. An array of automated remote instruments were deployed for logging time histories of the required water quality parameters at numerous locations from Bonneville Dam, river mile 145.7, downstream to just below the CWMW FMS at river mile 121.6. Twenty automatic wireless logging water quality instruments were deployed in the complete TDG sampling array. The instrument array was established to determine the TDG pressure upstream and downstream the dam, near the tailwater fixed monitoring station, and near the CWMW FMS. An overview of the study area and water quality sampling array is shown in Figure 2. The contents of Table 1 summarize the instrument station position, river mile, water column depth, and flow information.

11. Instrumentation included the DS4 and MiniSonde water quality sensors constructed by the HydroLab Corporation. Parameters recorded included date, time, instrument depth, water temperature, total dissolved gas (TDG) pressure, dissolved oxygen (DO) concentration, and internal battery voltage. These data were collected at fifteen-minute intervals during the deployment period, June 8 – 22, 2001.

12. In addition to data from the 20 temporary monitoring stations deployed during this field study, data from four total dissolved gas fixed monitoring system (TDGFMS) stations staffed by the Corps of Engineers Portland District were also incorporated into the analysis. The four stations are located (1) in the forebay of Bonneville Dam (BON) river mile 146.5, (2) Skamania (SKAW) on the Washington side of the Columbia River, (3) Warrendale (WRNO) on the Oregon side of the river 6 miles downstream of Bonneville Dam at river mile 140.2, and (4) CWMW 26 miles downstream of the dam at river mile 121.6 (Figure 2). These additional monitors recorded local barometric pressure but not DO concentration. The recording interval for the TDGFMS stations is one hour. See Appendix A for detailed calibration and quality assurance/and quality control procedures.

13. The water quality instruments were deployed in a spatial pattern adequate to quantify the water quality and transport processes characteristic of the river/reservoir system during the testing. One instrument was placed on the downstream side of each Powerhouse, at mid-Powerhouse No.1 (PH1) and at the south end of Powerhouse No. 2 (PH2) at the end of the south fishway entrance as shown in Figure 3. A transect of three instruments (SWP1, SWP2, SWP3) were positioned in the Bonneville spillway channel at 1500-1800 ft downstream of the structure. The positioning of this transect provided direct assessment of the lateral gradients and dynamics in TDG pressures associated with the spillway operation during the testing. A description of station locations can be found in Table 1.

14. A transect of three TDG sensors (TWP1, TWP2, TWP3) were located at river mile 140.7, approximately 0.5 miles upstream of the Warrendale (WRNO) and Skamania

(SKAW) fixed monitoring station. The Skamania gage is located at the end of a dock in an embayment along the Washington shore as shown in Figure 4. This transect was located upstream of the fixed monitoring stations to be positioned in direct downstream flow in the river. The TDG sensors were positioned in the south, central, and north sections of the river as shown in Figure 5.

15. Eight instruments were deployed laterally from the CWMW FMS at river mile 121.6, positioned approximately 100 m apart as shown in Figure 6 (CWP1, CWP2, CWP3, CWP4, CWP5, CWP6). This transect of stations captures the temporal and spatial variability in total dissolved gas pressure, temperature and dissolved oxygen. One vertical profile of three instruments, referenced as CWP6B (bottom), CWP6M (mid-depth), and CWP6S (surface), were located adjacent to the CWMW FMS at the Camas marina shown in Figure 7. The depths for the vertical profile were near surface at one meter, mid-depth at 3.5 m, and bottom at 8 m. An auxiliary instrument was positioned 0.4 miles downstream of the CWMW transect in deep water at station R46 (Figure 6).

16. Three auxiliary instruments were located upstream of the CWMW FMS to describe the water quality characteristics of the water approaching the CWMW transect. One instrument (G49) was positioned 0.9 miles upstream of the CWMW transect in 8 m of water at river mile 122.5 as shown in Figure 6. The second upstream auxiliary station (NM), was positioned at river mile 123.5, about 1.9 miles upstream from the CWMW FMS in shallow water near the north shore (Figure 2). A third instrument was placed 5.4 miles upstream of the CWMW FMS at Corbett Landing (Corbett), near the south shore at river mile 127. This instrument was positioned near the primary Columbia River channel.

17. Instrument deployment methods varied depending on location and water conditions. In general, instruments out of the immediate area of docks, bridges, navigation structures etc. were set using normal anchor, buoy, and/or shore based cabling for deployment. Instruments deployed nearer the project were cabled from the structure itself and set using steel housings and anchors.

18. A portable weather station was deployed below Powerhouse No. 1 as shown in Figure 3. This station logged air temperature, wind speed and direction, barometric pressure, relative humidity, and solar radiation data at five-minute intervals. Additional meteorological data was available from a National Weather Service network weather station located at the Portland Troutdale Airport, latitude 45.55111 degrees north/longitude 122.40889 degrees west as shown in Figure 8.

19. Project Description. Bonneville Dam is about 6400 feet long and includes two powerhouses, a spillway, two navigation locks, multiple fish ladders, and four islands as shown in Figure 1. A total of six 59-megawatt units and eight 77-megawatt turbines reside in Powerhouse No. 1 and No. 2 respectively. The effective hydraulic capacity during the fish passage season, assuming a fully functional 1st and 2nd powerhouse, is 120 and 144 kcfs, respectively. The 18-bay spillway is approximately 1100 feet long, and has twelve 50.75 ft-high vertical lift gates and six 60-ft high wheel gates. The spillway crest

is located at elevation 24 with a normal pool elevation ranging from 71.5 to 76.5 feet mean sea level (msl). Spillway bays 4-15 and 18 have deflectors that are 12 feet long and are located at 14 feet msl. The stilling basin is a horizontal apron-type with a double row of sloping baffle blocks as illustrated in Figure 9. The stilling basin is 147 feet long with an invert elevation of –16 feet msl for the first 71 feet msl and drops to –24 feet msl for the remaining length. An irregular concrete apron is at the end of the stilling basin and usually slopes downward to the tailrace topography. The old lock is 76 feet wide by 500 feet long. It discharges into a navigation lock channel that joins the releases from Powerhouse No. 1 approximately 1200 feet downstream of the lock. The new lock is 86 feet by 675 feet and discharges into a channel that joins the discharge from the remainder of the project about 2600 feet downstream of the lock. Powerhouse discharges and lock operation only indirectly influence the spillway flow conditions by changing the local tailwater elevation.

20. The bathymetry of the channel downstream of the spillway (Figure 10) is highly irregular ranging in elevation from near zero to –60 feet msl. The tailwater pool elevation ranged widely during the testing period, from 8 – 15 feet msl. The largest expanse of deep water is directly downstream of bay 5. The channel bottom then slopes upward to an elevation of approximately –10 feet msl near the mouth of the spillway exit channel with a corresponding channel width of 850 feet. The spillway exit channel then slopes downward to meet the tailrace channel of Powerhouse No. 2. The general topography in the Columbia River channel below the dam (Figure 2) is wide and shallow. The thalwag, or deepest section of the river, meanders from bank to bank and is located near the Washington shore near the Camas/Washougal fixed monitoring station.

21. Project Operating Conditions and Hydrodynamics. The 2001 Columbia River water year has been reported as one of the lowest flow years on record. Project operations and river stage information recorded during the test period are depicted in Figure 11. The ratio of spill discharge to total project flow was highly variable for the test period. Total river flow during the test ranged from 87 – 184 kcfs with an average discharge of 137 kcfs. Powerhouse discharges were highly variable and were primarily from Bonneville Powerhouse 2. Powerhouse 1 was used intermittently but mostly during the last portion of the study and peaking at 50 kcfs flow. Tailwater varied from 8-15 feet msl and averaged 12.3 feet msl during the test period. Spill discharge was held constant at 50 kcfs from June 8-15, and then reduced to 0 kcfs from June 16-22. A summary of daily average operations is listed in Table 2.

22. The spill pattern during the study period was non-uniform using only 10 of the 18 spill bays featuring outside bays without flow deflectors. The spill pattern (kcfs/bay) during the study is depicted in the Figure 12. Fifty-six percent of the flow was released through bays without flow deflectors. A photograph of the aerated flow conditions in the spillway channel is shown in Figure 13. The entrained air extends into the spillway channel downstream of the active bays with eddies set up between these release points.

23. The bulk travel time of releases from the Bonneville spillway to the Camas/Washougal fixed monitoring station can be estimated by observing the transport

of total dissolved gas plumes. The average travel time of releases was on the order of 14-18 hours during the study period. The spatial variability in the flow field throughout the Columbia River below Bonneville dam results in the dispersion of project spill. The flow field near the tailwater fixed monitoring station is shown in Figure 14. These data were collected using an Acoustic Doppler Current Profiler and reflect conditions during June 1996 (USACE, 2002). The abrupt expansion in the flow field along with a channel deepening results in large regions of flow recirculation in the region bounding the tailwater fixed monitoring stations. These flow patterns will moderate the magnitude and delay the arrival of TDG pressures observed at the monitoring stations.

24. The Columbia River thalweg falls on the northern side of the channel by the fixed monitoring station at Camas/Washougal. The majority of the channel flow and highest velocities also can be found in the northern half of the channel. The depth averaged flow field collected during June 1996 is shown in Figure 15 near the Camas/Washougal FMS. The shallow point bar located on the southern side of the channel restricts the amount of flow along the southern shore.

Results: Meteorology

25. Air temperature. Air temperatures cycled diurnally throughout most of the testing period, as shown in Figure 16 with hourly water temperature ranging as much as 23 C in a single day. The daily maximum air temperatures were similar at the Troutdale and Bonneville weather station with peak temperatures reaching about 31 C on June 19. A cold front moved through the region on June 10 and 11, lowering air temperatures and departing from the typical diurnal heating and cooling patterns. Temperatures ranged between 5 – 17 degrees Celsius through June 11-12. By 13 June, daily thermal patterns returned but showed no net temperature rise. A warming weather pattern was felt throughout the region from June 18 to the end of the study period. The water temperatures were observed to be highly correlated to the air temperatures demonstrating a cooling trend during June 11-12 and a warming pattern during the last five days of the study period. The water temperatures upstream of Bonneville Dam were observed to be cooler than at the Camas/Washougal location during much of the study period.

26. Barometric pressure. The average Barometric pressure during the study period was 765 mm Hg with 90 percent of the occurrences ranging from 761.5 to 768.5 mm Hg. Barometric pressure rose steadily at both the Bonneville and Troutdale stations through June 18, with a significant depression during the cold front June 11-12 of about 759 mm Hg. Pressures peaked on June 18 at 771 mm Hg, then trended downward after June 18. Pressures appeared to cycle diurnally throughout most of the testing period as shown in Figure 17. The daily change was on the order of 4-8 mm Hg.

27. Solar radiation. The variation in solar radiation was closely related to the responding air and water temperatures observed through the study period. Figure 18 displays low solar radiation levels on June 11-13 indicating cloudy days that resulted in cooling conditions for system temperatures. There were some partly cloudy days on either side of these days, which attenuated the maximum peaks in solar radiation. The daily solar

radiation peaks were consistent in magnitude following June 13 through the end of the field study.

28. Wind. The average hourly wind speeds were highly variable from day to day and between weather station locations during the study period. The average hourly wind speed as shown in Figure 19 at the Bonneville and Troutdale weather stations. At Troutdale, wind tended to drop off in the evening and build up during the daytime. The daytime increase in wind speed was likely due to winds generated from convective heating. Peak wind speeds occurred at Troutdale as the cool front moved in around June 11. However, high wind speeds were also measured at the Bonneville weather station at different points in time. Low speeds were measured at both stations on June 19 and 20. The wind speed characteristics were generally different between the two stations located only 25 miles apart. This likely is related to the variable topography and the resulting microclimates that characterize the Columbia River Gorge weather.

Results: Water Quality

29. Bonneville Forebay. TDG levels in the forebay of Bonneville Dam (BON) during the test ranged from 770 – 840 mm Hg, or 101.4- 110.7% TDG as shown in Figure 20. TDG pressures declined gradually over the course of the testing period with the maximum of 840 mm Hg recorded on June 8. Low amplitude diurnal cycles were evident on the order of 10 mm Hg.

30. Water temperatures measured at the BON FMS tracked closely those temperatures measured in the spillway channel. Temperatures ranged between 15.6 – 17.8 degrees Celsius, with coolest temperatures measured on June 13. Daily temperature fluctuations of approximately 0.5 degrees Celsius were common, as shown in Figure 21. The maximum water temperatures occurred near midnight with the minimum temperatures following the peak temperature by about 8-10 hours.

31. There was no dissolved oxygen data collected from the Bonneville forebay or immediate tailwater channel.

32. Spillway Channel. TDG levels in the spillway below Bonneville ranged from 910 – 960 mm Hg, or 120 – 126% TDG, as shown in Figure 20 and averaged about 121.5%. The standard deviation of the TDG saturation was small for all three stations ranging from 4.5 to 5.5 mm Hg (0.6-0.7 %). The small variance in TDG saturation over tailwater elevations ranging from 9.5 to 15.5 ft suggests a consistent plunging flow for these flow conditions. During 50 kcfs spill, June 7 – June 16, the TDG saturation on station SWP3 (north spillway) were about 3-4% saturation (22-30 mm Hg) higher than SWP2 (mid-channel), indicating higher TDG production in the northern section of the spillway channel. The historic average TDG saturation at the exit of the spillway channel for a slightly different spill pattern, tailwater elevation, and spill discharge were observed in February of 1997 to be 123% for a 44 kcfs spill and during February of 1999 to be 125.4% during a spill of 52.6 kcfs. The instrument at station SWP1 data (south spillway) malfunctioned on June 12 and tracked more closely with station SWP2 than SWP3 when

functioning. When spill ended, stations SWP2 and SWP3 tracked more closely, and appeared to cycle diurnally, possibly in response to daily changes in water temperature. The TDG saturation after June 16 did not return to forebay TDG levels because of the TDG exchange associated with fish ladder releases and constant end bay spills of 1000 cfs.

33. The water temperatures in the spillway channel were similar to water temperatures measured in the forebay as shown in Figure 21. Temperatures ranged between 15.4 - 17.6 degrees Celsius for stations SWP2 and SWP3 generally trending upwards through June 11, downward through June 13 during a cold front and upward again thereafter. Daily temperature cycles on the order of 0.5 degrees Celsius were common.

34. Dissolved oxygen data was available from station SWP2 throughout the study period. The dissolved oxygen ranged from 10–11 mg/l during spill and 8 – 9.5 mg/l after June 16 as shown in Figure 22. The dissolved oxygen was supersaturated during spill at about 107% compared to 119.7 % for total dissolved gas. The difference in levels of saturation between oxygen and total dissolved gas suggests that oxygen was under-represented in the exchange of atmospheric gases in aerated flow whereas Nitrogen was likely over-represented. After spill-ceased the oxygen concentration declined to a saturation of only 90%. Clear diurnal cycles in oxygen were not evident in this dataset.

35. Tailwater Reach. The mixing zone between the spillway and powerhouse flows extended beyond the instruments deployed in the tailwater reach. The highest TDG pressures for all stations were measured during spill through June 16, as shown in Figure 23. Station TWP1, which was located closest to the south shore, experienced the highest pressures ranging from about 111% to 116% saturation (850 – 890 mm Hg) during spill. These peak TDG saturations near the south bank reflect spillway water diluted primarily by the second powerhouse flows. The TDG saturation at station TWP1 was consistently higher (greater by 2 percent saturation) than conditions observed about ½ mile downstream at the Warrendale (WRNO) FMS. The two stations located on the north side of the channel, TWP2 and TWP3, experienced lower TDG pressures than the south shore based stations but higher levels than observed in the forebay of Bonneville Dam. Station TWP3 often tracked about 5-9 % lower than TWP1 and 2 % lower than the Skamania FMS. All five of the tailwater reach stations TDG observations converged after spill was stopped on June 16. The north and south bank eddies influence both the magnitude and timing of TDG pressures recorded at the fixed monitoring station at Warrendale and Skamania.

36. The temperature data collected near the tailwater fixed monitoring stations were similar to the temperature data observed at the Dam. The temperature response at the Warrendale did indicate some perturbation during the afternoon hours as shown in Figure 24.

37. Oxygen data was collected on two stations, TWP1 and TWP2 near the tailwater fixed monitoring stations as shown in Figure 25. The dissolved oxygen data at TWP1 was similar to the data in the spillway channel with concentrations ranging from 10.3 to

almost 10.8 mg/l during the spill period and abruptly falling after June 16. DO levels continued to drop off for the rest of the testing period to a minimum of about 9.0 mg/l. The oxygen measurements on the north side of the channel were heavily biased by powerhouse flows and changed little when spill was terminated on June 16. The source of the difference between dissolved oxygen at the TWP1 and TWP2 stations after June 16 is unknown.

38. <u>CWMW Transect</u>. A series of water quality stations were located laterally across the Columbia River at river mile 121.6 near the Camas/Washougal fixed monitor station. A north shore station was established adjacent to the CWMW station consisting of three vertically positioned instruments. The TDG saturation observed at the surface (CWP6S), mid-depth (CWP6M), and bottom (CWP6B) instruments were nearly identical to the observation at the CWMW station as shown in Figure 26. Instruments at two of the remaining stations malfunctioned during the study period. The TDG response from CWP2 monotonically decreased during the study period, which is characteristic of being slowly covered by sediment. The instrument on CWP5 malfunctioned with no data recovered from this station.

39. The TDG saturation across stations CWP1, CWP3, CWP4, and CWP6 were similar throughout the study period with hourly characteristics shaped by the ambient conditions above Bonneville Dam, the added TDG pressure generated in spillway releases, and in-river influences caused by heat exchange and DO cycling. The first day of the study, June 8 experienced TDG saturation exceeding 115% across all of the stations near the Camas/Washougal FMS as shown in Figure 27. The forebay TDG saturation was also at the highest level during the testing period at 111%. The daily variation in TDG saturation often experienced late afternoon/early evening maxima that corresponded closely with the thermal maximum in the river. The daily TDG maximum was absent during June 11 and greatly attenuated during June 12, which corresponded with cool and cloudy conditions. The TDG saturation closer to the thalweg at stations CWP3 and CWP4 were often slightly higher than conditions observed near the north shore at CWMW during Bonneville spill operations. Average TDG levels dropped by 5% saturation (30-40 mm Hg) once spill ended on June 16. In general, the declining TDG pressures originating from Bonneville forebay corresponded to a decline in the pressures measured at the Camas instruments. During no spill, the lowest TDG saturation observed at the Camas instruments generally corresponded to the Bonneville forebay pressure levels. However, the daily maximum TDG pressures after June 16 were often 3-5% higher near the CWMW FMS compared to conditions in the forebay of Bonneville Dam. This net gain in TDG saturation of after June 16 was attributed to the in-river processes influencing TDG pressure. The TDG saturation at station CWP1 was observed to deviate from the pattern observed across the other instruments in the river. This departure from typical TDG saturation could have been caused by inadequate circulation around the pressure membrane or elevated rates of off gassing localized in the shallow channel near the south shore.

40. Strong diurnal temperature cycling dominated the thermal conditions across the sampling stations at Columbia River mile 121.6. The daily variation in water

temperature was prominent at all of the stations near the Camas/Washougal FMS. The range in water temperature was often as high as 1.5 C at stations on this transect as shown in Figure 28. Average daily water temperatures followed a cooling trend until June 13 at which point warming began. Temperatures ranged from a low of about 15.3 degrees Celsius on June 13 to about 18.5 degrees Celsius on June 22. Temperatures followed a diurnal cycle, with dampened cycles from June 11 – 13 that corresponded to a cold weather system. CWP1 had the greatest diurnal range.

41. The variation in dissolved oxygen concentration also demonstrated a strong daily cycle with peak concentrations in phase with the thermal patterns. The variation in daily DO concentration typically ranged from 0.3 to 0.6 mg/l as shown in Figure 29. Stations CWP3 (mid-channel) and stations CWP6 (bottom and middle) experienced the most reliable DO observations. The dissolved oxygen patterns followed the TDG pressure trends, with higher levels during spill and slightly lower concentration during the no-spill period. Diurnal cycles of as great as 1 mg/l were measured. Note that this reflects an actual change in mass that is distinguishable from the higher TDG pressures resulting from temperature fluctuations. Dissolved oxygen levels were consistently highest at the bottom and middle instruments of CWP6, located adjacent to the CWMW TDGFMS. Alternately, the lowest DO levels were recorded at CWP3, measuring an average of 0.5 mg/l lower than the average DO level at CWP6.

42. Auxiliary Stations. Three auxiliary stations (R46, G49, and Corbett) were located close to the Columbia River thalweg between river miles 121 and 127. All three of the auxiliary stations located in deep water responded similarly to stations CWP3 and CWP4. TDG saturation dropped from an average of about 110% to an average of about 104% (6% lower) at the auxiliary stations when spill ended at Bonneville Dam, as shown in Figure 30. TDG pressures fluctuated diurnally for all periods except the June 11-13 time frame. TDG pressures at the three stations were very similar, differing by a maximum of about 0.5%.

43. A fourth station NM was located in the shallows near the north shore upstream of the CWMW FMS. The TDG saturation at station NM was similar to conditions at CWMW except during the final three days of the study as shown in Figure 30. The low TDG saturation recorded during this period was likely the result of poor flow circulation past the TDG membrane.

44. Water temperatures followed a cooling trend until June 13 at which point warming began, as shown in Figure 31. Temperatures ranged from a low of about 15 degrees Celsius on June 13 to about 18 degrees Celsius on June 21 and followed diurnal cycles, with dampened cycles from June 11 – 13 that corresponded to the arrival of a cold weather system. The daily temperatures at the three stations were very similar, varying by about 0.25 degrees Celsius.

45. The three stations follow similar dissolved oxygen patterns with diurnal peaks and a lack of peaking during the cold weather system June 11-13, as shown in Figure 32. Dissolved oxygen levels were higher during the spill at Bonneville and dropped by

approximately an average of 0.75 mg/l during the no-spill period. DO levels at the three auxiliary stations were similar throughout the testing period, differing on the order of 0.5 mg/l maximum.

Analysis and Discussion

46. Water Quality Criteria Evaluation. A useful analysis of TDG monitor data has been to calculate the parameter corresponding to the variance compliance criteria for the state of Oregon during fish spill. This number is calculated as the average of the 12 highest hourly reading collected on each calendar day. Figures 33, 34, and 35 depict this calculated value for the downstream, tailwater, and spillway stations sampled during the testing. The Bonneville forebay monitor data is shown in each of the figures for comparison to upstream background levels.

47. There were 10 downstream stations, defined as those stations located from river mile 121.2 to 127, and stations adjacent to the Camas Washougal fixed water quality monitor. The mean value of these stations for the spill portion of the test was 110.4 +/- 2.7% TDG saturation (95% confidence interval). This decreased to 104.6 +/-0.6 following cessation of spill from Bonneville Dam on June 16. The individual station values for this six-mile reach of the river were never more than 2% different from the daily reach average and generally within 1% saturation (Figure 33). Station CWP1, not located in the main river flows, showed the most deviation from the average and then only on a couple of dates. The waivered criterion for the downstream stations is 115 %. None of the 10 downstream stations exceeded this value during the study when the percent river spilled ranged from 31-43 percent and ambient TDG saturation ranged from 104-108%. A summary of the daily average TDG variance across the 10 downstream stations can be found in Table 3.

48. There were five stations located in the tailwater reach from river mile 140.2 to 140.7. Figure 34 indicates a high degree of variability associated with these stations during the spill period of testing. The calculated reach TDG saturation averaged 110.3 +/- 6.4 % during spillway operation from June 9 until June 15. Even though the average over stations was similar to that for the downstream stations, individual station values may demonstrate large apparent differences in the calculated criteria. During the no spill period, the tailwater station daily average dropped off significantly to 103.2 +/- 1.3 % TDG saturation. These results indicate little difference during the no spill period between the tailwater stations and the downstream stations. The waivered criterion of 120 % for the tailwater reach was not exceeded during the test period. The 50 kcfs Bonneville project spill coupled with background concentration of TDG accounted for 6-7 % TDG during the test period at both the downstream and tailwater stations. A summary of the daily average TDG variance across the 5 tailwater stations can be found in Table 4.

49. The spillway data depicted in Figure 35 is limited to only 2 stations but both stations represent the water passing through the spillway and indicate high TDG saturation averaging 121.7 +/- 4.1 for the days of spill. This differs significantly from the stations located further downstream due to the lack of mixing with powerhouse flows. These

stations were in exceedance of the waiver criterion of 120 % TDG saturation during the entire period of 50 kcfs spill. During the non-spill period, these observations reflect waters discharged through the end spill bays and fish ladders and do not reflect conditions of the bulk river flow.

50. Natural Processes Contributing to the TDG Levels. One of the more remarkable trends apparent in the TDG data during the testing was the daily or diel cycling in water temperature, DO concentration, and TDG saturation. This is most apparent in the downstream stations as depicted in Figures 27 and 30. The TDG saturation fluctuated daily by as much as 5 % at many of these stations with no apparent relationship to operations at Bonneville Dam. Figure 36 depicts TDG pressure plots for stations CWP6B and CORBETT on just June 13 and 14th. The two stations cycle by 25-40 mm Hg TDG each day peaking at 2000 hours with minimum pressures occurring at about 0800 hours each day. Figure 37 shows the minimum and maximum values for both the concentration of DO and water temperature for the two stations to coincide with the pressure minimums and maximums on June 13-14. The DO change represents a change in mass of dissolve gas that will result in a direct change in TDG pressure. For a known or standard temperature, this pressure change attributable to a change in DO concentration can be calculated. For the water temperatures (~16°C) occurring during testing, a change of 1.0 mg/l DO would account for a 16 mm Hg change in TDG pressure. If we hold TDG mass constant then a change in water temperature of 1°C would account for a 22 mm Hg TDG pressure change. The daily cycles TDG pressure occurring throughout the testing can then be attributed to diel cycles in water temperature and community metabolism resulting in DO concentration change.

51. Since barometric pressure is applied in the calculation of TDG percent saturation, then independent of changes in TDG pressures, the saturation values will vary by 1 % for each shift of 7.6 mm Hg atmospheric pressure. The study documented daily changes for individual stations to be in the order of 3 to 8 mm Hg. This could result in a variation in TDG saturation for a station over a day or could account for differences between stations using different barometers.

52. Wind effects were not discernable during the field study of June 8-22 however earlier data for the month of May (Figure 38) indicate significant degassing to occur on both May 22 and again on May 28 in conjunction with increased wind events. TDG pressures at the Camas Washougal fixed water quality monitor decreased by 20-40 mm Hg TDG for these two events.

53. The gas laws can be used to estimate the influence of a change in an environmental factor on the measure of TDG saturation. Table 5 depicts typical changes in TDG that may occur coincidental with changes in background water conditions, solar input, wind, and barometric pressures all for constant project spill and generation. For instance with initial TDG saturation of 110 % and if the barometric pressure increases by 8 mm Hg, water temperature warms 1 degree from 16 to 17 C, and DO concentration increases by 0.8 mg/l from photosynthesis the resultant TDG saturation would be equal to 115.8 percent or a 5.8 % increase in TDG saturation would result. In addition, following winds

of 18 mph for a day, the TDG saturation would be reduced to 108-110 %. Considering the dynamics of these naturally occurring processes then we would expect frequent and sometimes significant variation in the TDG pressures and or saturation of the Columbia River waters below Bonneville Dam.

CONCLUSIONS AND RECOMMENDATIONS

54. Camas Washougal Downstream Water Quality Station The wide temporal viability in TDG saturation at the Camas Washougal FMS can be attributed to a wide variety of sources. The spilling operation can generate high TDG pressures in the water passing through the spillway. The sequencing of both spill and generations flows can result in a range of percent spill conditions that can generate wide variations in the average TDG saturation in the Columbia River. In addition, upstream TDG conditions determine what load will be released from powerhouse operations at Bonneville. The natural barometric pressure and thermal and biological cycles in the river also contribute to the daily variability in the river TDG pressures. The daily water temperature and dissolved oxygen concentration cycles in the Columbia River experienced at the downstream sampling locations were as significant in producing daily variations in TDG saturation as were the changes in spill and powerhouse operations. The uncertainty of these natural processes coupled with the potential of wind degassing, will result in considerable challenges to meeting the variance criteria through managing spillway operations at Bonneville Dam. In light of the uncontrolled or natural sources of variability in TDG in the river reach below Bonneville it is unlikely that management of Bonneville spill operation based on the Camas Washougal water quality station can result in better than a +/- 2 % TDG saturation control at the station. This means if we are managing for 115% at CWMW river mile 121.6 then we could expect a range of approximately 113-117 % TDG. However in light of TDG sampling uncertainty over time and space measurements within this range are likely not significantly different.

55. Subtle spatial variations in TDG saturations were observed in the Columbia River near the Camas Washougal fixed monitoring station. During spillway releases, the highest TDG pressures were generally located in the middle of the channel. Without spillway releases the highest TDG pressures were generally observed in the littoral region near the channel banks. The range in spatial TDG saturation for ten stations located between river miles 121.1 and 127 as defined by the daily average of the 12 highest hourly observations was less than 1-2 percent saturation. Since a high degree of temporal variability in TDG occurs in both the shallow water or littoral zones and the deeper mid river zones with only minimal spatial differences, then only limited benefits (in meeting the objectives of a TDG FMS) could be expected from relocating the Camas/Washougal Fixed Monitoring Station.

Tailwater Water Quality Monitoring Stations

56. The tailwater fixed monitoring stations sample TDG conditions in a developing mixing zone. TDG levels can be muted by station location in the re-circulation zones prominent along side the Columbia River at river mile 140-142. Due the lack of mixing,

the TDG saturation is often ambiguous being highly dependent on project operations. For instance which powerhouse is operating at the time of TDG sample can affect the readings. The shore based location of WRNO and SKAW stations nearly always result in measures not representative of spillway flows. For the reasons mentioned above the tailwater FMS locations are inconsistent with most other tailwater FMS stations in Columbia River Basin. Since neither SKAW nor WRNO meet the requirements for a tailwater or a downstream mixed river TDG FMS station location, alternative sampling locations such as at the exit of the spillway channel would provide for a more consistent and meaningful measure of TDG pressures generated by Bonneville Dam operations.

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Schneider, M. L. 1999b. “Total Dissolved Gas Exchange at Bonneville Dam,” CEWES-HS-L Memorandum for Record dated 25 July 1999. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

Wilhelms, S. and M. L Schneider. 1997b. “Near-Field Study of TDG in the Bonneville Spillway Tailwater,” CEWES-HS-L Memorandum for Record dated 10 July 1997. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

USACE. 2002. Dissolved Gas Abatement Phase II, Technical Report, April 1996, U.S. Army Corps of Engineers, Portland District, Walla Walla District.

Table 1. Station Descriptions

Station	Deployment Date	Retrieval Date	Time Retrieval	Site Name	Location Comment	Latitude Degree	Latitude Minute	Longitude Degree	Longitude Minute	River Mile	Station Reach
R46	6/8	6/22	1300	0.4 mi downstream of Camas/ Washougal Fixed Monitoring Station	R46, 18-40', Flow	45	34.43890	122	23.37057	121.2	DS
CWP6B	6/8	6/22	1415	Camas/Washougal Fixed Monitoring Station	Bottom, 25’, Flow P6, CWMW	45	34.61680	122	22.84175	121.6	DS
CWP6M	6/8	6/22	1415	Camas/Washougal Fixed Monitoring Station	Middle, 12’, Flow, P6, CWMW	45	34.61680	122	22.84175	121.6	DS
CWP6S	6/8	6/22	1415	Camas/Washougal Fixed Monitoring Station	Surface, 3', Flow, P6, CWMW	45	34.61680	122	22.84175	121.6	DS
CWP3	6/8	6/22	1410	Camas/Washougal Fixed Monitoring Station	CWMW, P3, 39', Flow	45	34.49133	122	22.85689	121.6	DS
CWP2	6/8	6/22	1350	Camas/Washougal Fixed Monitoring Station	CWMW, P2, 29', Flow	45	34.44065	122	22.88875	121.6	DS
CWP1	6/8	6/22	1330	Camas/Washougal Fixed Monitoring Station	CWMW, P1, 10', No Flow	45	34.38157	122	22.88983	121.6	DS
CWP4	6/8	6/22	1440	Camas/Washougal Fixed Monitoring Station	CWMW, P4, 40', Flow	45	34.53446	122	22.81976	121.6	DS
CWP5	6/8	6/22	1430	Camas/Washougal Fixed Monitoring Station	CWMW, P5, 35', Flow	45	34.57592	122	22.83677	121.6	DS
G49	6/8	6/22	1250	0.9 mi upstream of Camas/ Washougal Fixed Monitoring Station	G49, 22', Flow	45	34.31093	122	21.63795	122.5	DS
NM	6/8	6/22	1240	1.9 mi upstream of Camas/ Washougal Fixed Monitoring Station	Nav. Marker, 18', Low Flow	45	34.03718	122	20.59439	123.5	DS
Corbett	6/8	6/22	1225	Corbett Landing	R62, 28', Flow, Corbett Station Ramp	45	32.53840	121	17.44152	127.0	DS
TWP1	6/11	6/22	1120	RM 140.7, south shore, .5 mi upstream of Warrendale	R88, P1, 42, .5 mi upstream WRNO	45	36.76853	122	1.65448	140.7	TWE

Table 1. Station Descriptions (continued)											
Station	**Deployment Date**	**Retrieval Date**	**Time Retrieval**	**Site Name**	**Location Comment**	**Latitude Degree**	**Latitude Minute**	**Longitude Degree**	**Longitude Minute**	**River Mile**	**Station Reach**
TWP2	6/11	6/22	1150	RM 140.7, north shore, .5 mi upstream of Skamania	R88, P2, 62', .5 mi upstream of SKAW	45	36.85921	122	1.63333	140.7	TWE
TWP1	6/11	6/22	1135	RM 140.7, north shore, .5 mi upstream of Skamania	R88, P1, 49', .5 mi upstream SKAW	45	36.86161	122	1.68060	140.7	TWE
Fishout	6/9	6/22		Downstream of Bonneville Dam	Fish Outfall, 50'	45	38.03269	122	57.82435	144.5	SPW
Fishout	6/9	6/22	1030	Downstream of Bonneville Dam	Fish Outfall, 50'	45	38.09767	121	57.77600	144.5	SPW
SWP1	6/9	6/22	1005	1500-1800 ft downstream of Bonneville Dam	Spillway Channel, P1	45	38.64456	121	56.74950	145.5	SPW
SWP2	6/9	6/22	1005	1500-1800 ft downstream of Bonneville Dam	Spillway Channel, P2	45	38.67977	121	56.73167	145.5	SPW
SWP3	6/9	6/22	1005	1500-1800 ft downstream of Bonneville Dam	Spillway Channel, P3	45	38.71616	121	56.74064	145.5	SPW
PH2	6/9	6/22		South end of Powerhouse No. 2	PH2, end of S. fish entrance	45				145.7	SPW
PH1	6/9	6/22		Mid-Powerhouse No. 1	PH1, middle of draft tube deck	45				145.7	SPW

Table 2. Summary of Daily Average Bonneville Dam Operations, June 8-22, 2001							
Date	**Avg of Qtotal**	**Max of Qtotal**	**Min of Qtotal**	**Avg of Qspill**	**Max of Qspill**	**Min of Qspill**	**% Spill**
6/8	154.5	179.5	130.8	48.9	48.9	48.9	31.7
6/9	159.5	178.3	132.5	48.9	48.9	48.9	30.7
6/10	114.4	127.8	102.2	49.6	49.6	49.6	43.4
6/11	142.6	159.8	109.4	49.6	49.6	49.6	34.8
6/12	164.1	185.5	120.6	49.6	49.6	49.6	30.2
6/13	155.1	170.8	143.8	49.6	49.6	49.6	32.0
6/14	131.8	149.0	109.2	49.6	49.6	49.6	37.6
6/15	124.8	161.0	92.3	49.6	49.6	49.6	39.7
6/16	124.3	143.4	91.1	2.4	2.4	2.4	1.9
6/17	100.9	109.4	89.3	2.4	2.4	2.4	2.4
6/18	121.1	141.8	83.2	2.4	2.4	2.4	2.0
6/19	149.5	178.2	127.0	2.4	2.4	2.4	1.6
6/20	141.9	158.2	109.1	2.4	2.4	2.4	1.7
6/21	132.9	153.0	95.1	2.3	2.4	1.2	1.7

Table 3. Downstream Reach Stations Daily Average Total Dissolved Gas Saturation based on the Average of the 12 Highest Hourly Observation in a Calendar Day, June 2001												
DATE	**BON**	**CORBETT**	**CWMW**	**CWP1**	**CWP3**	**CWP4**	**CWP6B**	**CWP6M**	**CWP6S**	**G49**	**NM**	**R46**
6/9	108.0	112.1	111.4	112.0	111.9	111.6	111.2	111.1	111.0	112.2	111.1	112.0
6/10	107.2	112.5	111.7	110.6	112.2	111.9	111.7	111.6	111.3	112.3	111.8	112.2
6/11	106.7	112.5	111.4	109.6	112.8	112.4	111.3	111.1	110.7	112.9	111.3	112.8
6/12	104.3	108.8	107.5	107.9	108.8	108.5	107.4	107.4	107.5	109.0	107.8	108.8
6/13	104.7	110.4	110.0	110.1	110.0	109.7	109.9	109.9	110.0	110.3	109.8	110.0
6/14	104.4	110.6	109.8	109.8	110.2	109.9	109.8	109.6	109.8	110.7	109.6	110.2
6/15	104.0	111.0	109.9	108.5	110.9	110.6	110.1	109.8	110.1	111.3	109.7	110.8
6/16	103.6	108.8	109.4	109.0	109.5	109.3	109.5	109.3	109.3	109.7	108.9	109.8
6/17	103.1	104.4	105.0	104.8	104.3	104.3	104.9	105.0	105.2	104.5	104.5	104.3
6/18	102.8	104.6	105.4	105.3	104.6	104.6	105.5	105.5	105.7	104.9		104.5
6/19	102.4	104.9	106.4	106.2	104.7	104.8	106.3	106.4	106.6	105.0	104.7	104.8
6/20	102.7	104.4	105.5	104.9	104.1	104.1	105.5	105.6	105.8	104.3		104.1
6/21	102.7	104.2	105.8	105.0	104.0	104.0	105.3	105.5	105.6	104.3		104.0
6/22	102.3	102.1	104.6	102.1	102.4	102.3	102.5	102.6	102.3	102.6		102.4

Table 4. Near Dam Reach Stations Daily Average Total Dissolved Gas Saturation based on the Average of the 12 Highest Hourly Observation in a Calendar Day, June 2001									
DATE	**BON**	**SKAW**	**SWP1**	**SWP2**	**SWP3**	**TWP1**	**TWP2**	**TWP3**	**WRNO**
6/9	108.0	110.2	119.8	118.6	122.8				113.8
6/10	107.2	111.7	121.9	120.1	124.5				115.4
6/11	106.7	110.6		120.2	124.1	113.5	108.4	105.7	113.9
6/12	104.3	107.4		120.0	123.8	113.6	108.1	105.4	111.8
6/13	104.7	108.0		119.8	123.6	113.4	107.6	106.3	112.4
6/14	104.4	108.7		120.1	124.1	115.1	107.3	106.6	113.1
6/15	104.0	109.2		119.8	123.6	115.3	107.6	106.8	113.3
6/16	103.6	105.4		119.7	119.7	106.7	104.6	104.5	107.9
6/17	103.1	103.6		115.4	113.1	104.3	103.7	103.5	104.3
6/18	102.8	103.5		107.5	106.1	103.8	103.3	103.7	104.0
6/19	102.4	103.0		106.8	106.2	103.1		103.2	103.3
6/20	102.7	103.0		107.4	106.2	103.2		103.4	103.4
6/21	102.7	103.0		108.9	107.8	103.0		103.1	103.1
6/22	102.3	102.4		107.8	106.3	101.8		101.4	102.4

Table 5. Changes in TDG (resulting from naturally occurring processes downstream of Bonneville Dam)					
Variable	**Bonneville Conditions**	**ΔBP (8 mm Hg)**	**Δtemp (0.5-1.0 °C)**	**ΔDO (0.4-0.8 mg/l)**	**Δwind (18mph)**
TDG % Sat	110	111.2	113-114.1	113.8-115.8	108.5-110.5
BP (mmHg)	760	752	752	752	752
Temp (C°)	16.0	16.0	16.5-17.0	16.5-17.0	16.5-17.0
O_2 (mg/l)	10.9	10.9	10.9	11.3-11.7	10.4-10.6
Wind (mph)	0	0	0	0	18
TDG (mm Hg)	836	836	850-858	856-871	816-831
0_2 (mm Hg)	172	172	175-177	181-190	168-171
N_2 (mm Hg)	642	672	653-660	653-660	626-638
N_2 (mm Hg)	17.8	17.8	17.8	17.8	16.9-17.2
Comp Z (m)	3.4	3.8	4.4-4.7	4.7-5.3	2.9-3.5

Figure 1. Location of Key Features at Bonneville Dam

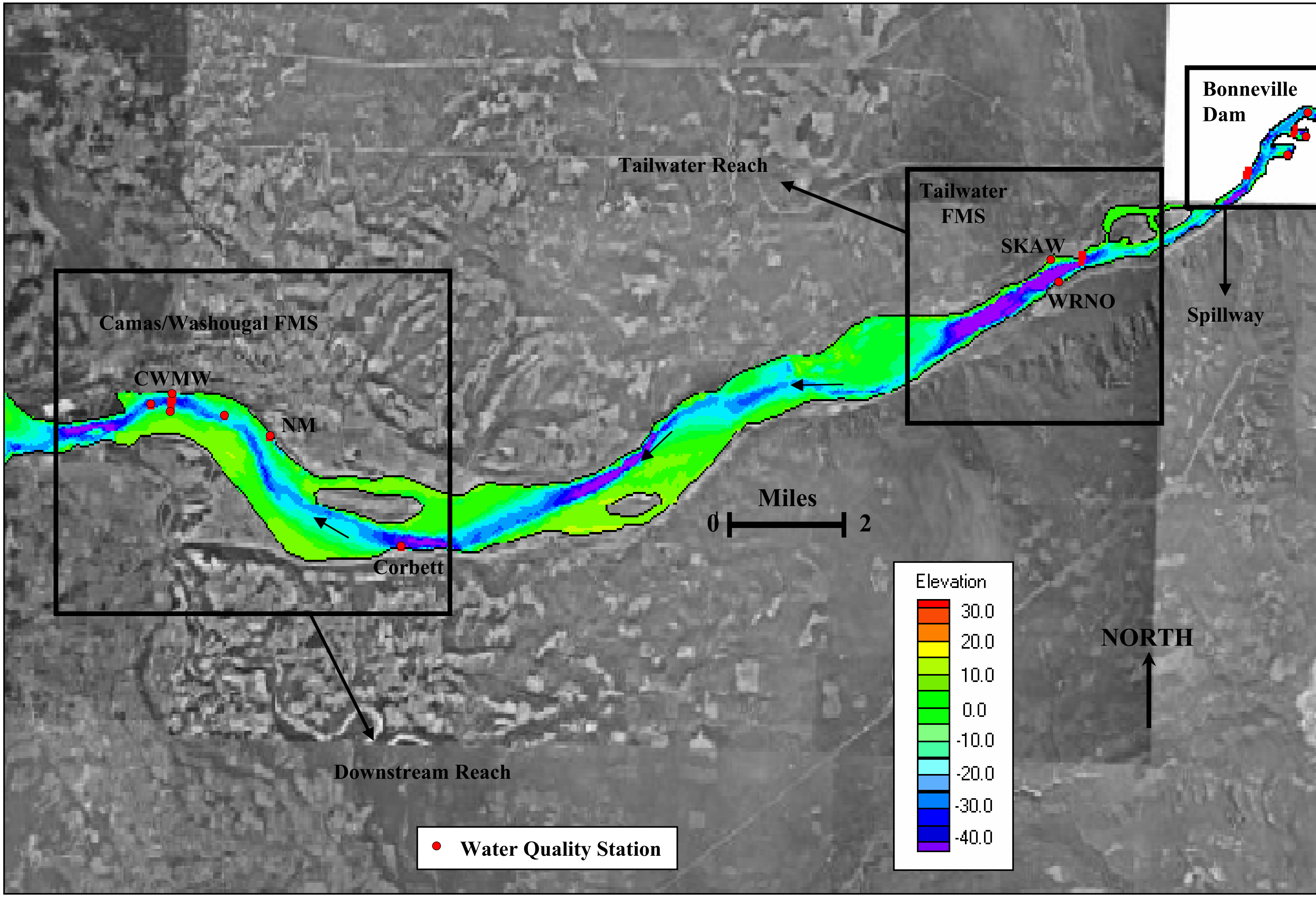

Figure 2. Study Area of Water Quality Study of TDG, Temperature, and Dissolved Oxygen Spatial and Temporal Variations Downstream of Bonneville Dam, June 8-22, 2001.

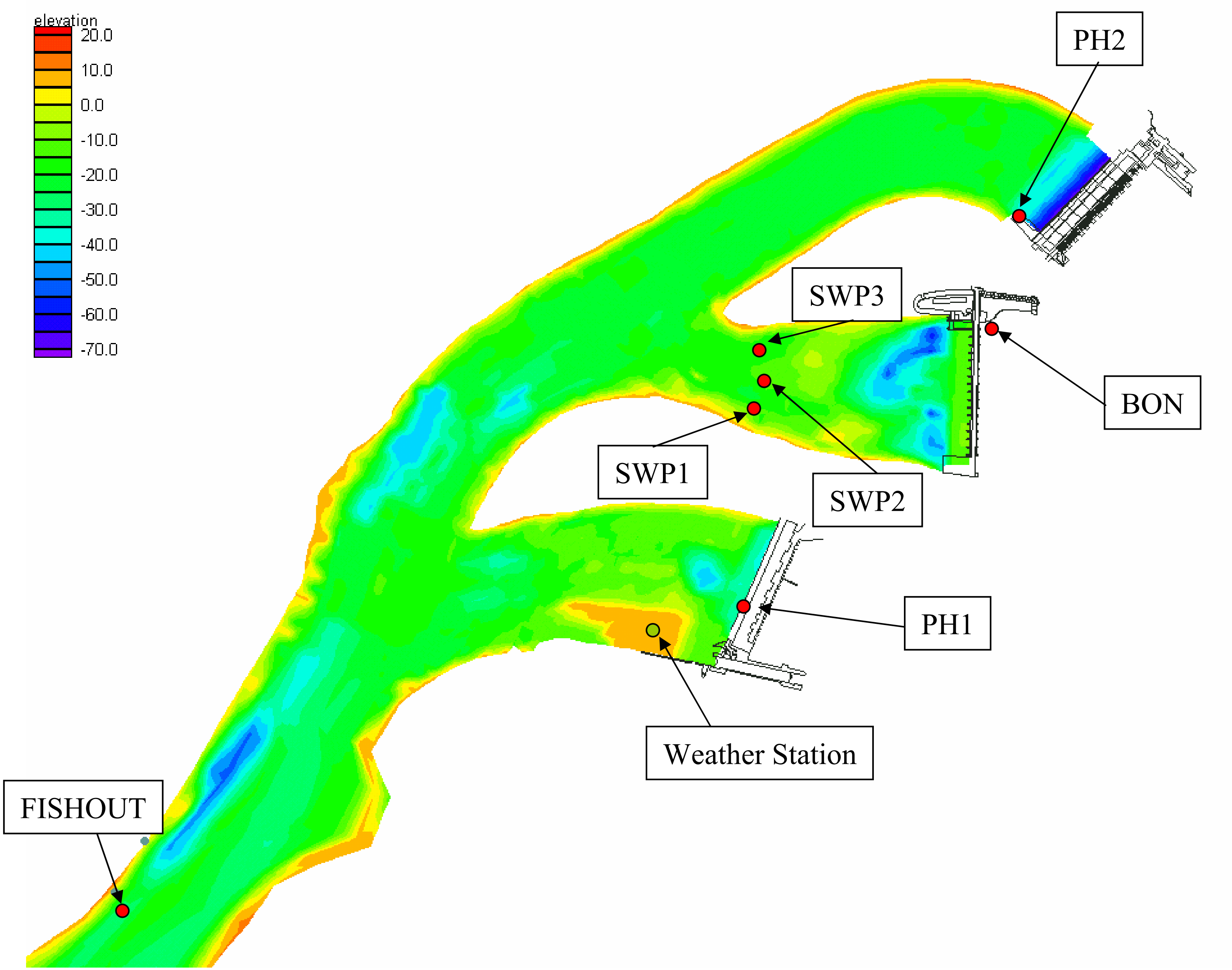

Figure 3. Instrument locations 1500-1800 ft. below Bonneville Dam.

Figure 4. Skamania fixed monitoring station, looking south, located at river mile 140.5.

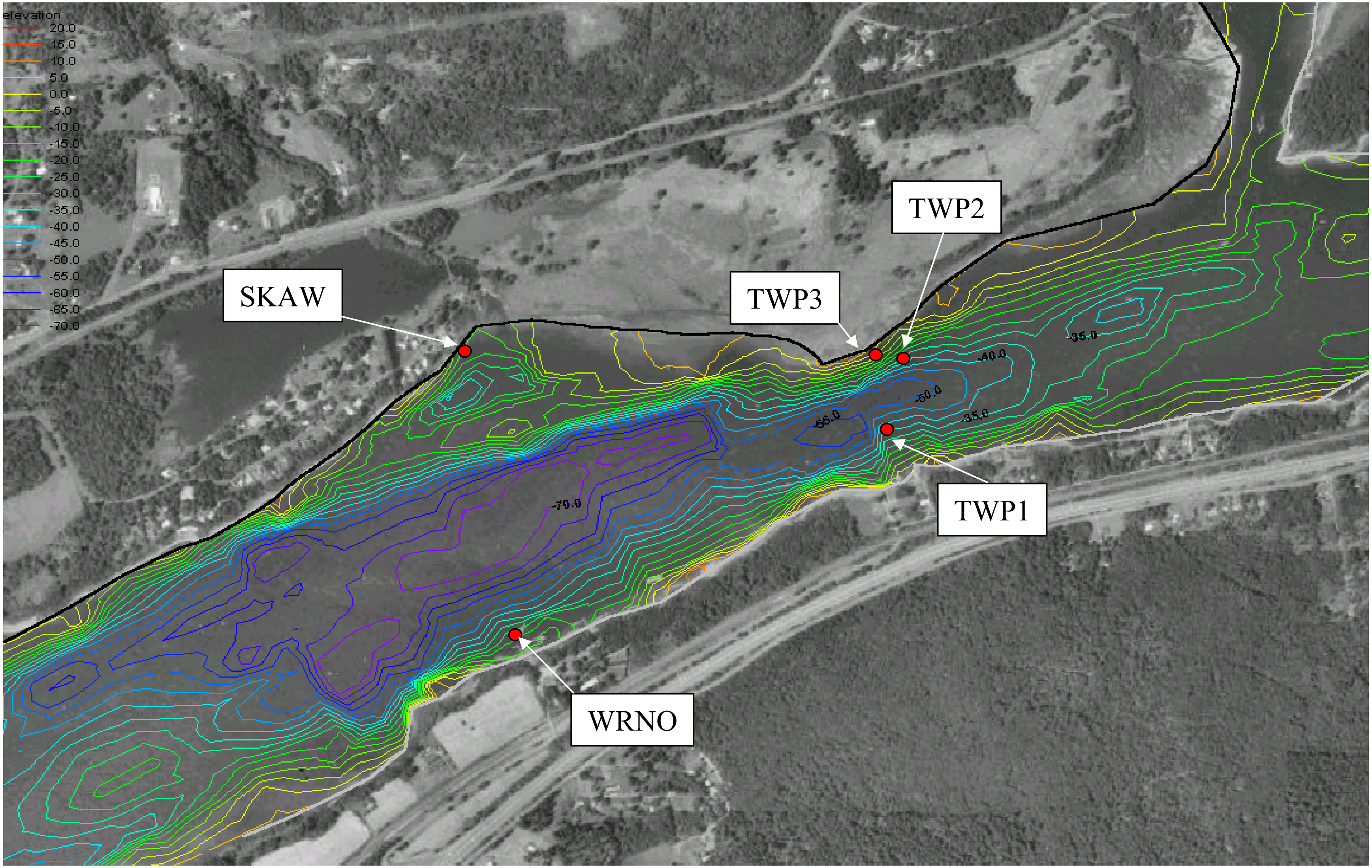

Figure 5. Instrument locations adjacent to Bonneville tailwater stations.

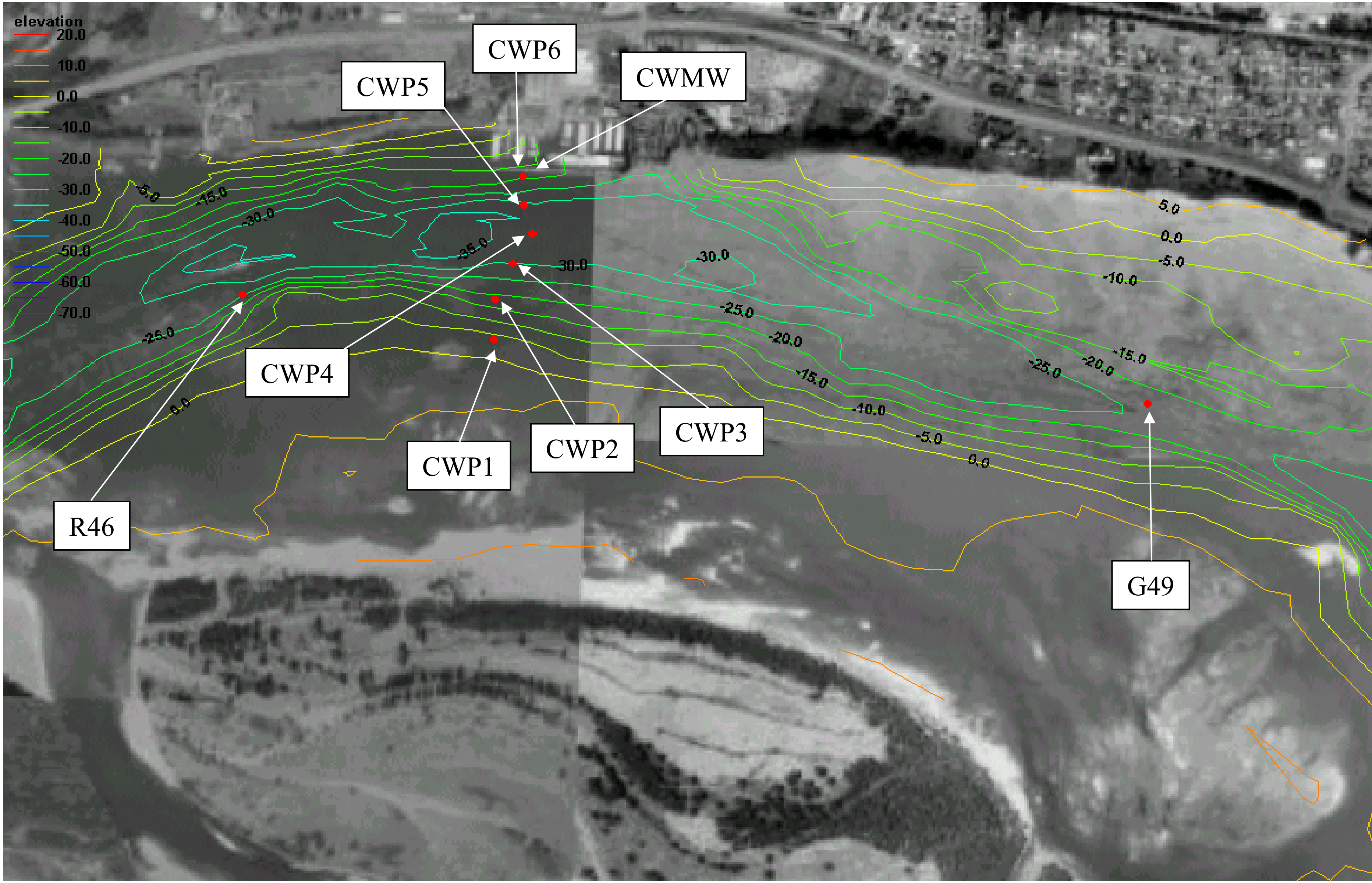

Figure 6. Instrument locations near CWMW FMS and Channel Bathymetry.

Figure 7. Camas/Washougal fixed monitoring station, looking east, (CWMW FMS) located at river mile 122.

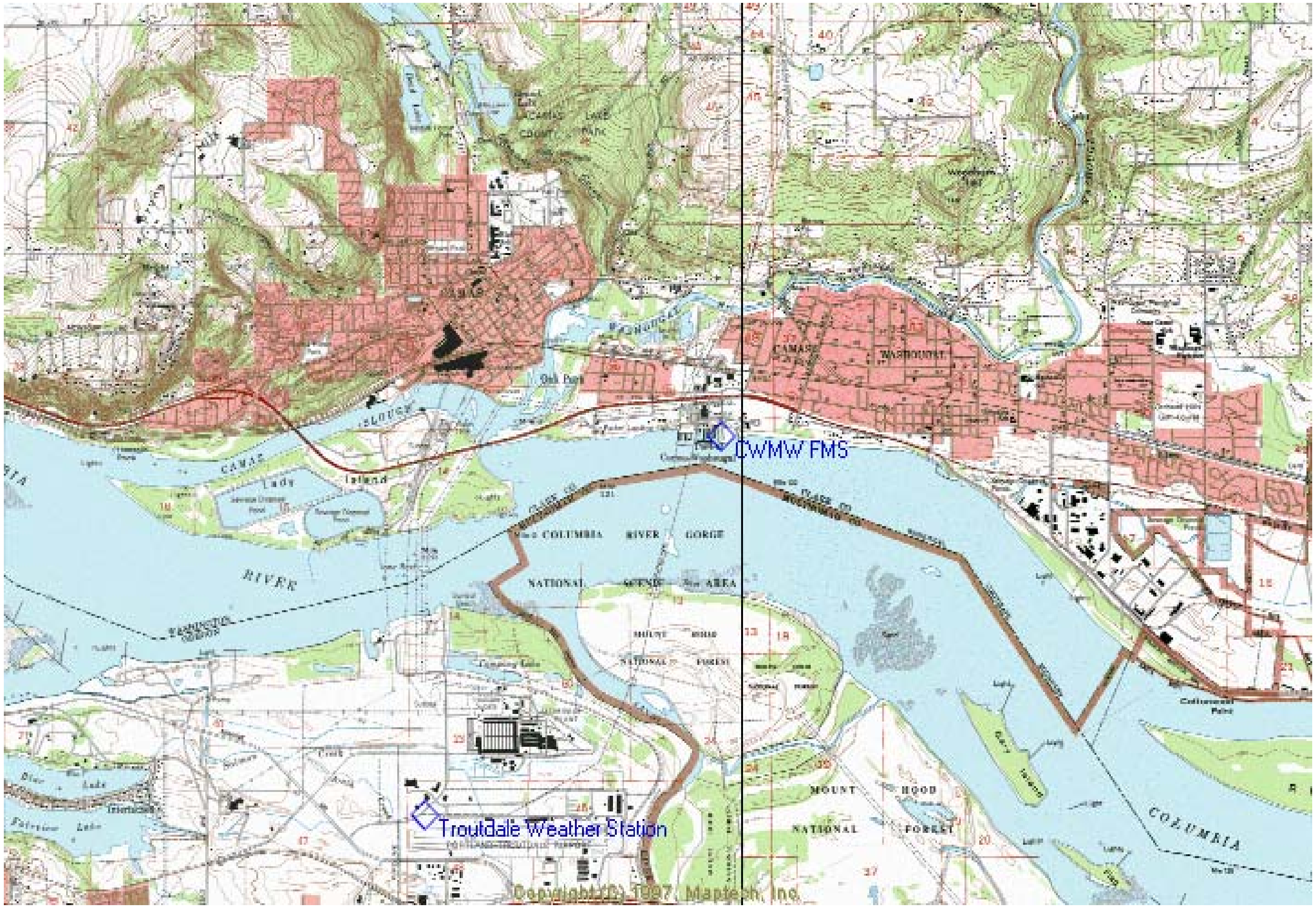

Figure 8. Troutdale Weather Station at River Mile 120, Latitude 45.55 degrees north, 122.41 degrees west relative to CWMW FMS.

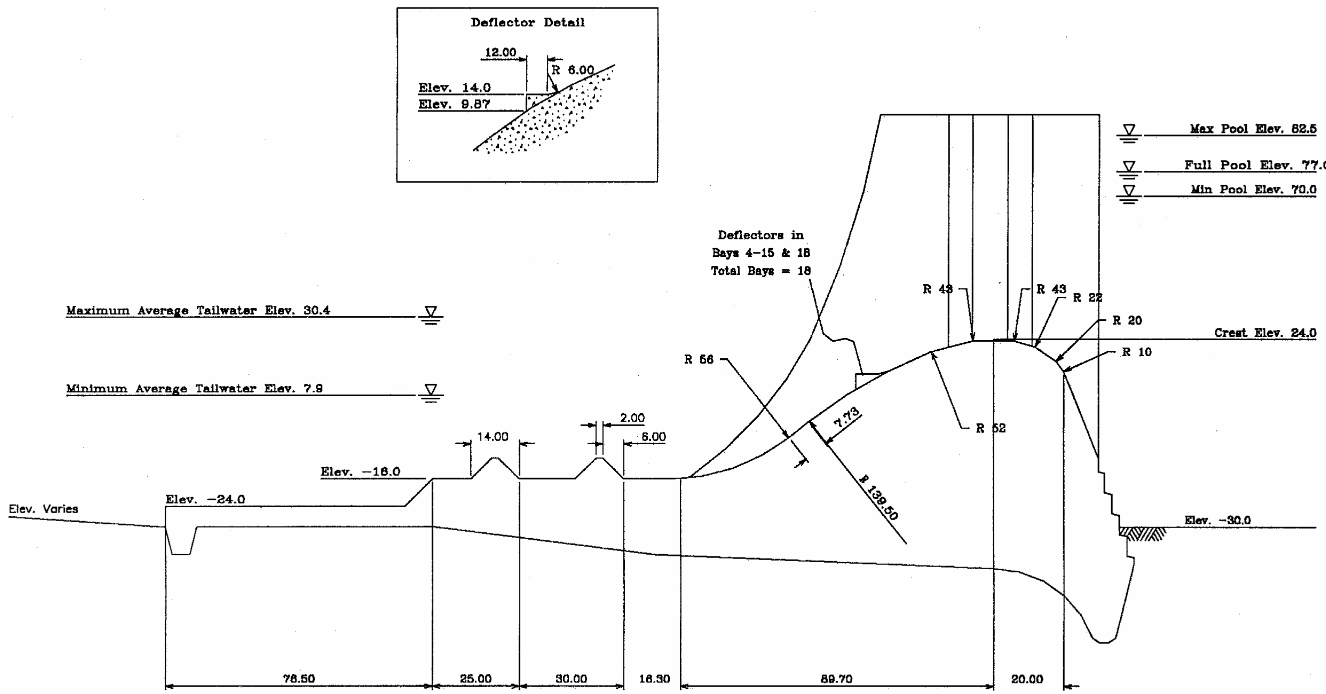

Figure 9. Configuration of spillway deflectors.

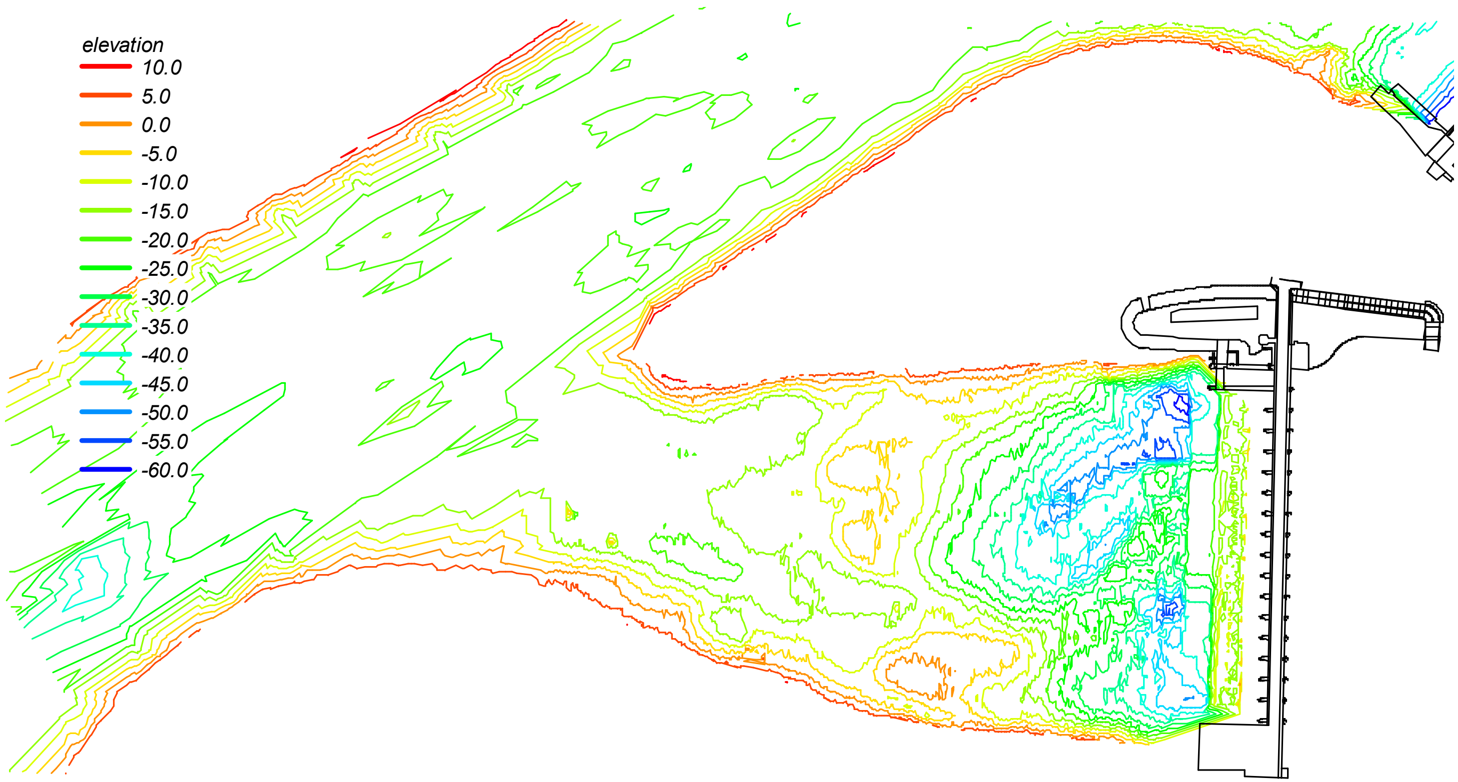

Figure 10. Bathymetry downstream of Bonneville spillway.

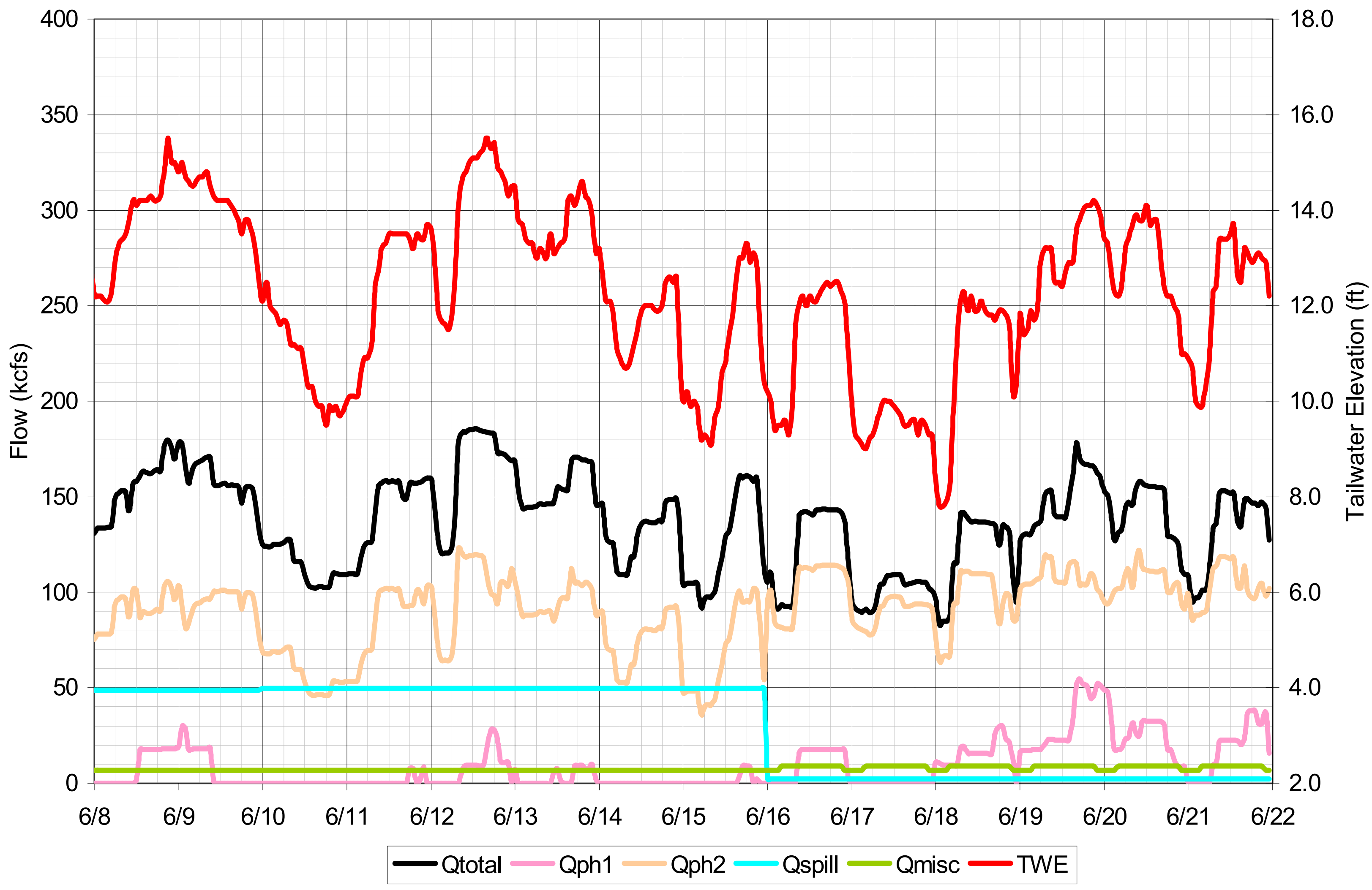

Figure 11. Bonneville Dam Operations from June 8 – June 21, 2001

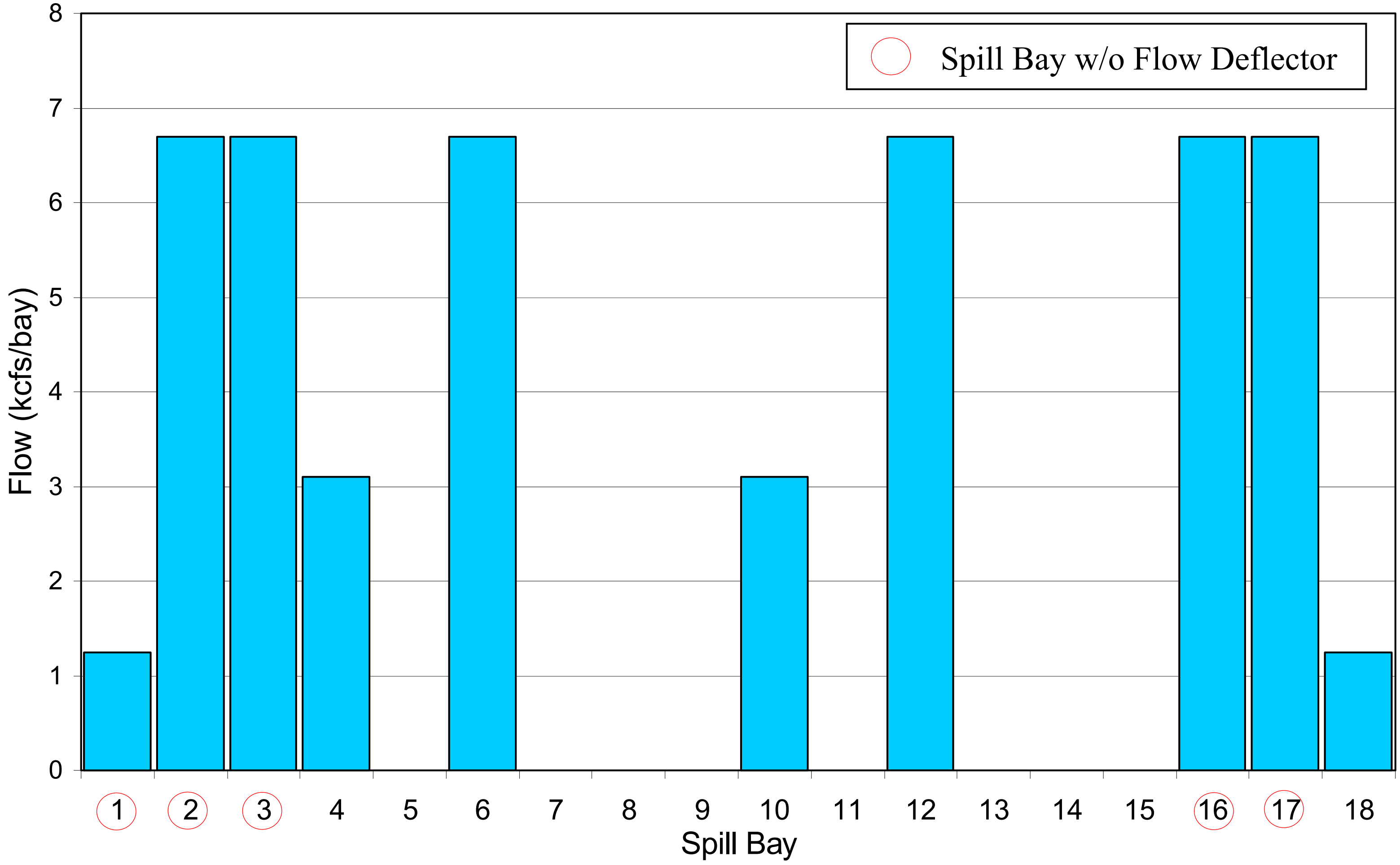

Figure 12. Spill rates from 18 bays collected June 9, 2001

Figure 13. Standard spill pattern of 50 kcfs at Bonneville Dam.

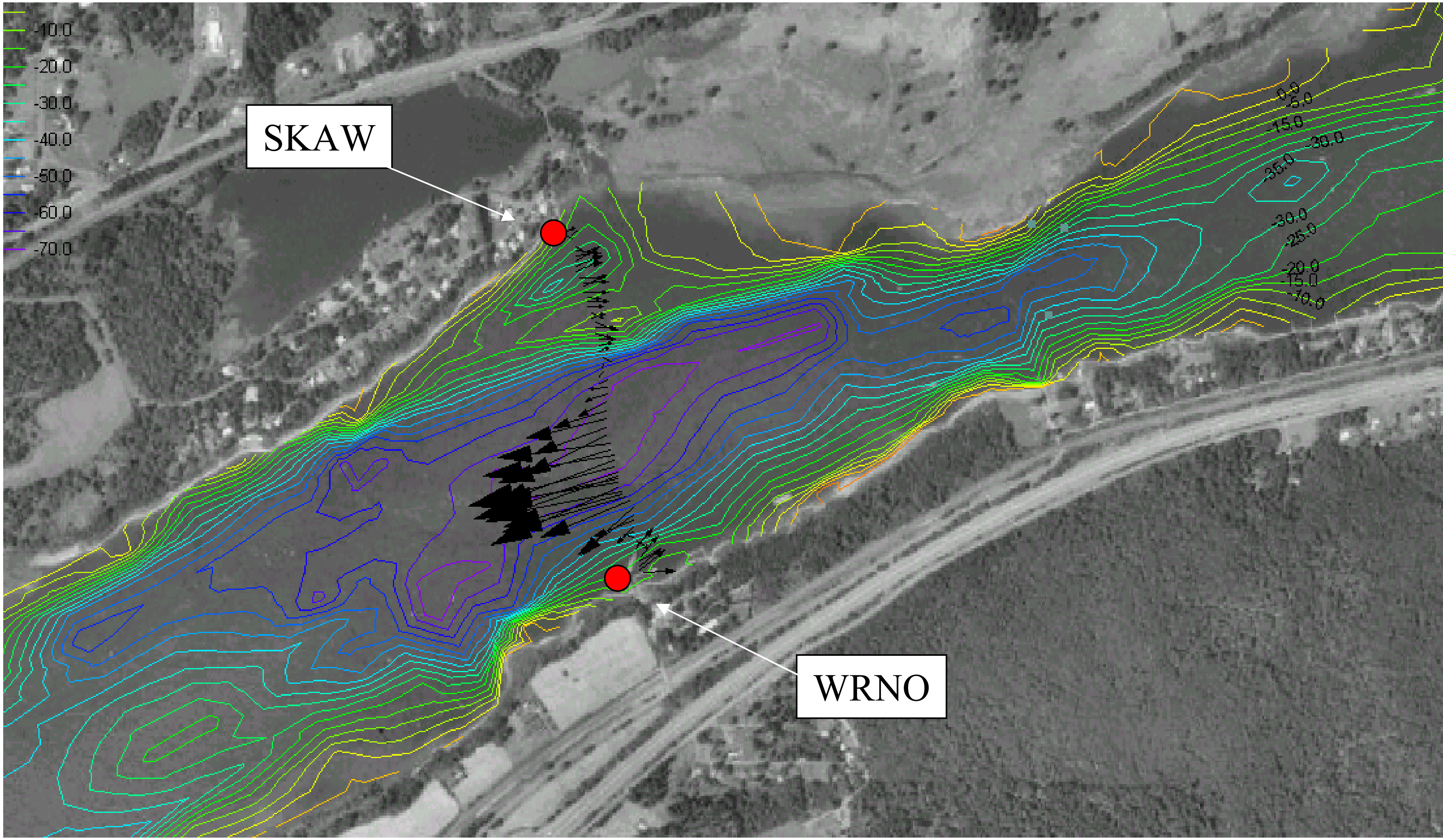

Figure 14. Columbia River Flow Distribution at the SKAW/WRNO Tailwater Monitors.

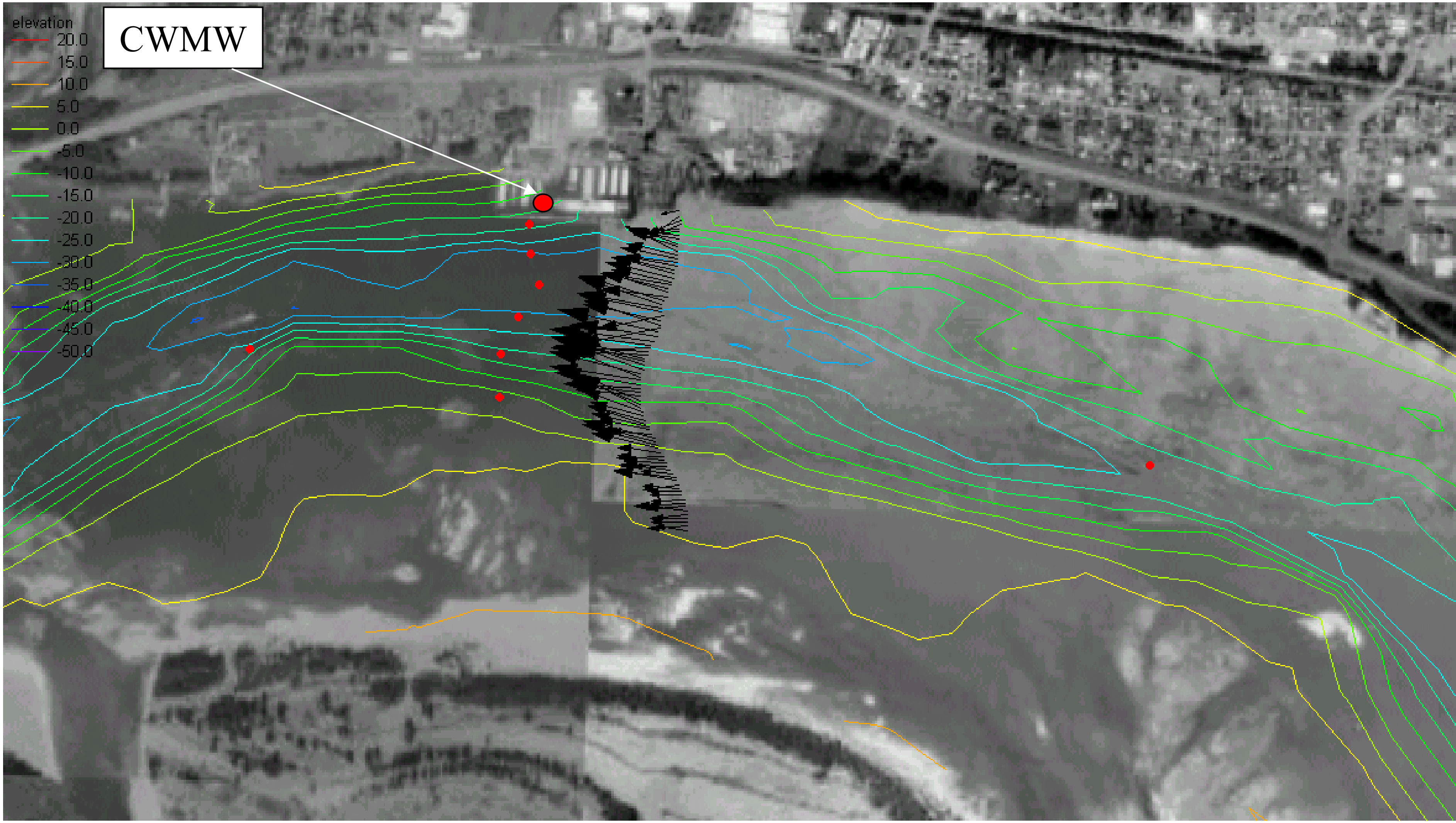

Figure 15. Columbia River Flow Distribution at Camas/Washougal FMS

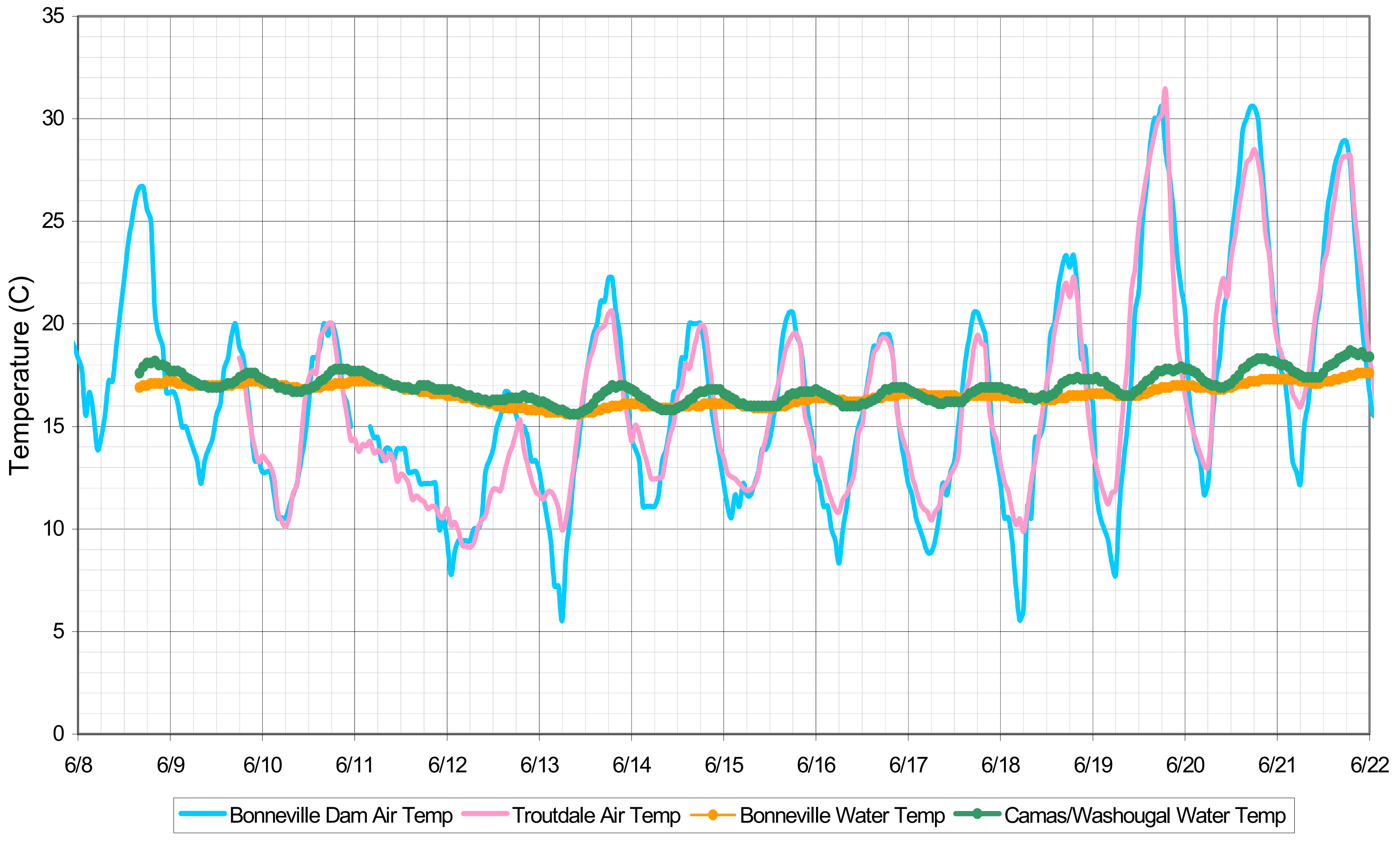

Figure 16. Hourly Air Temperatures As Measured at Troutdale and Bonneville Weather Stations and Hourly Water Temperatures above Bonneville Dam and at the Camas/Washougal Fixed Monitoring Station.

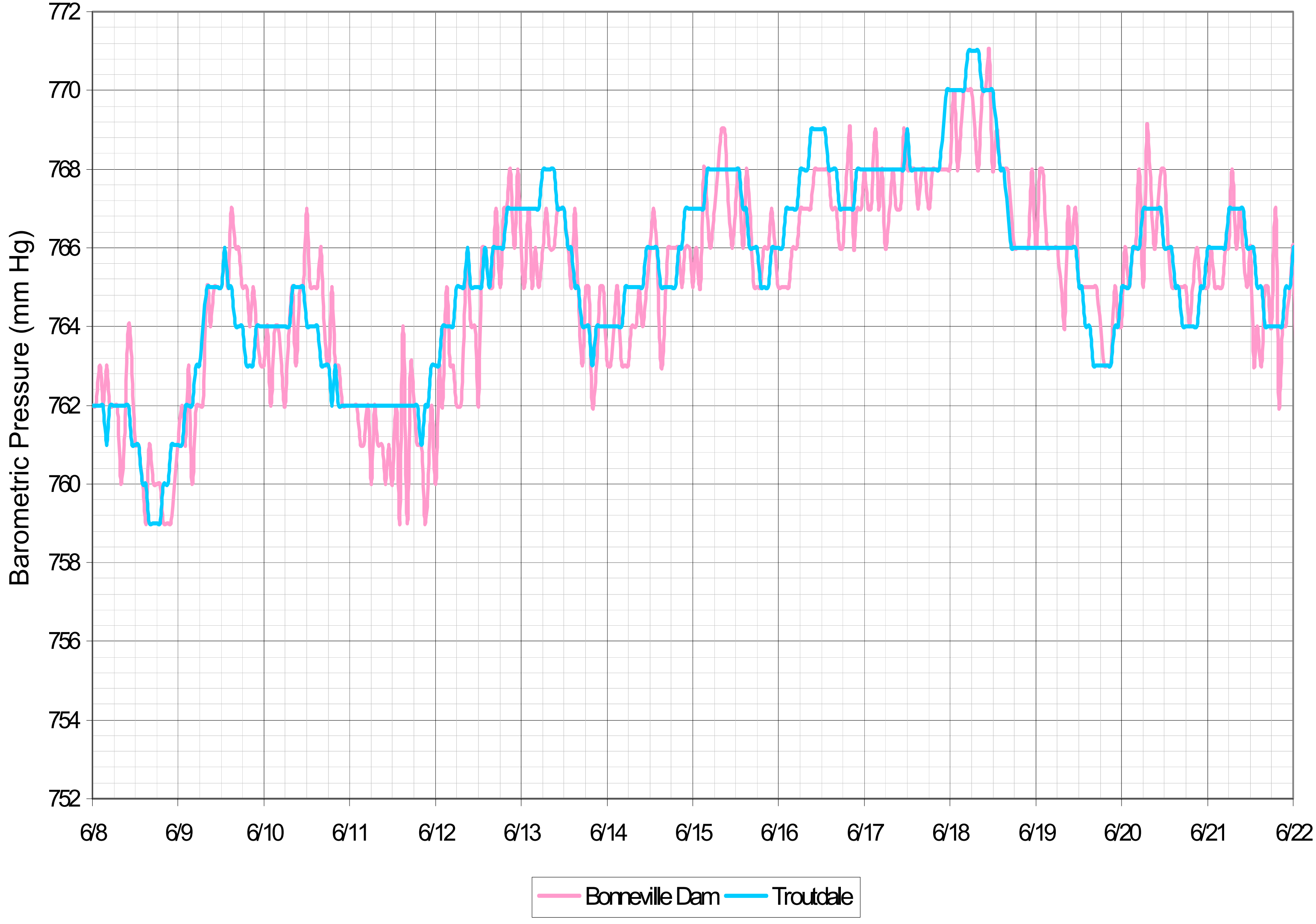

Figure 17. Barometric Pressure as measured at Troutdale and Bonneville Dam.

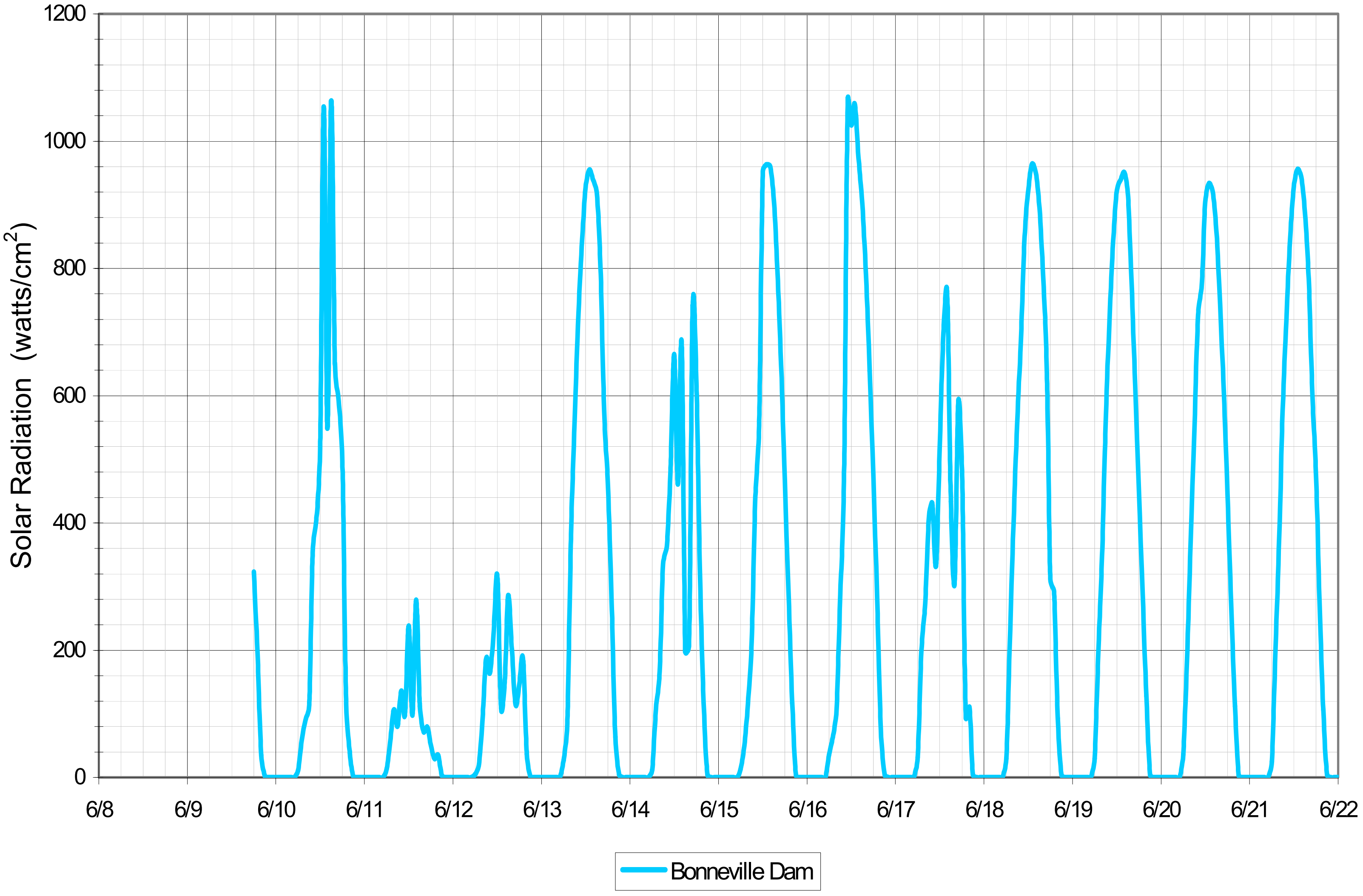

Figure 18. Solar Radiation as measured at Bonneville Dam.

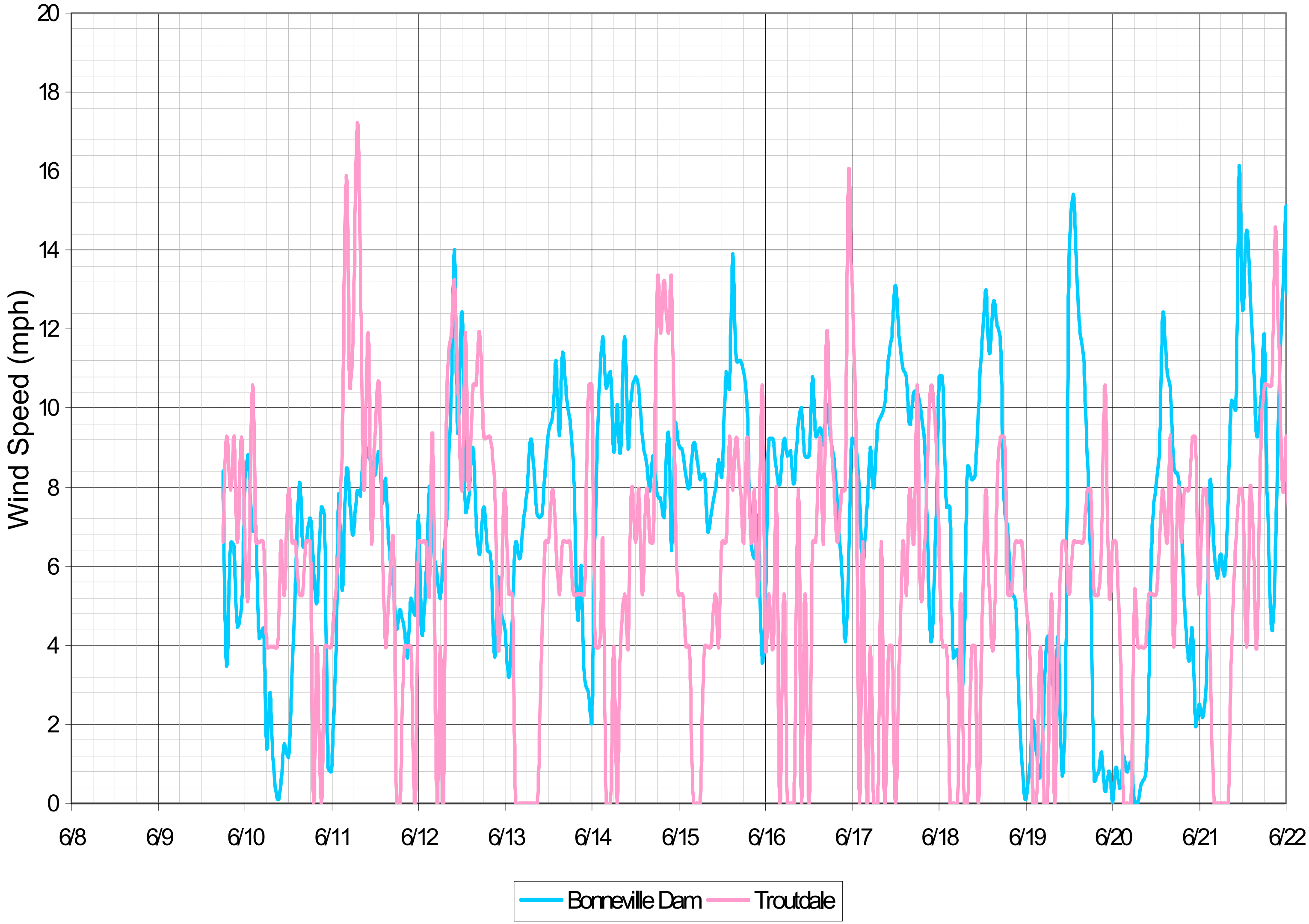

Figure 19. Wind Speed as measured at Troutdale and Bonneville Dam Weather Stations, June 8-22, 2001.

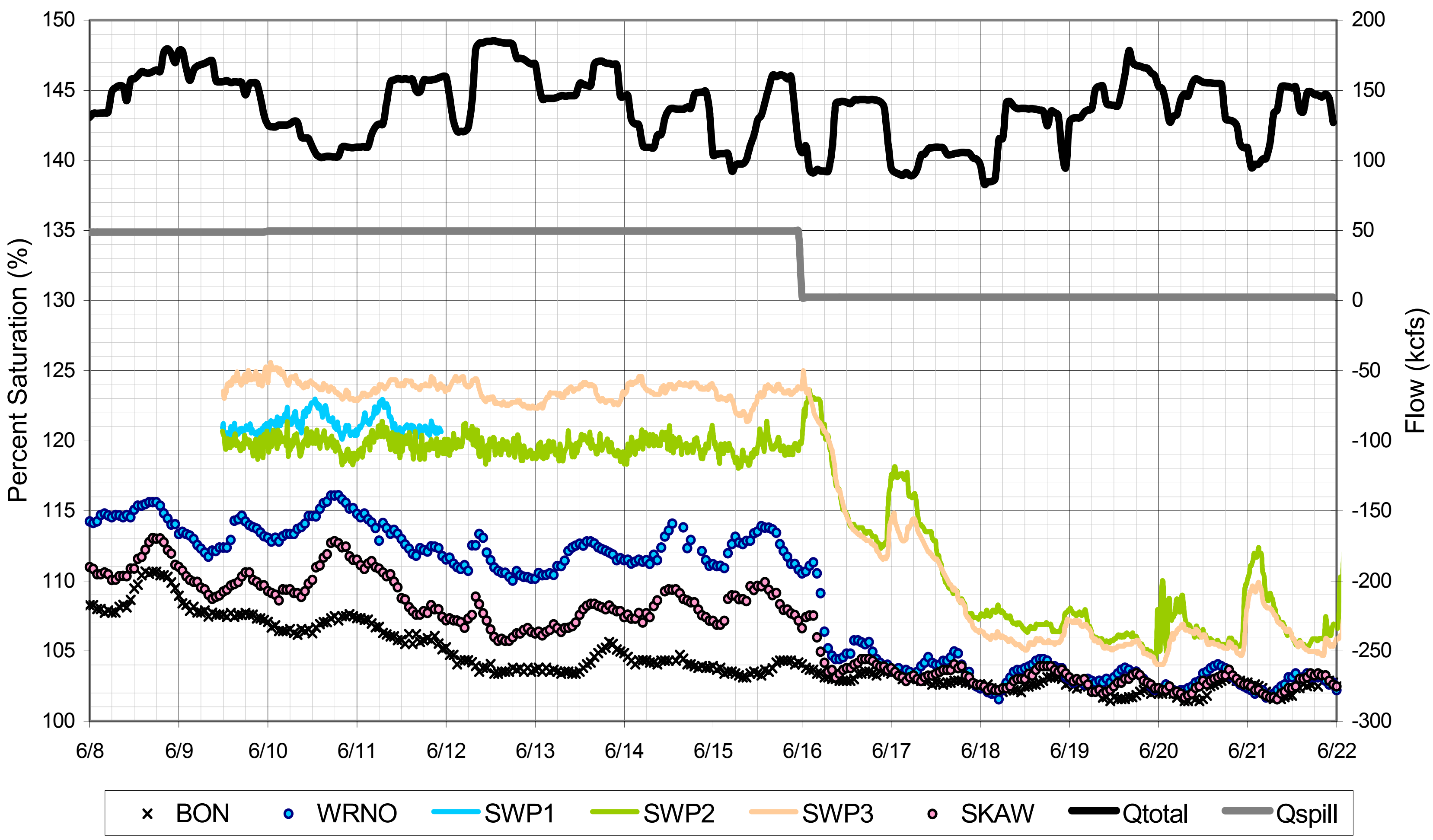

Figure 20. TDG Saturation in the Spillway Channel June 8-21, 2001

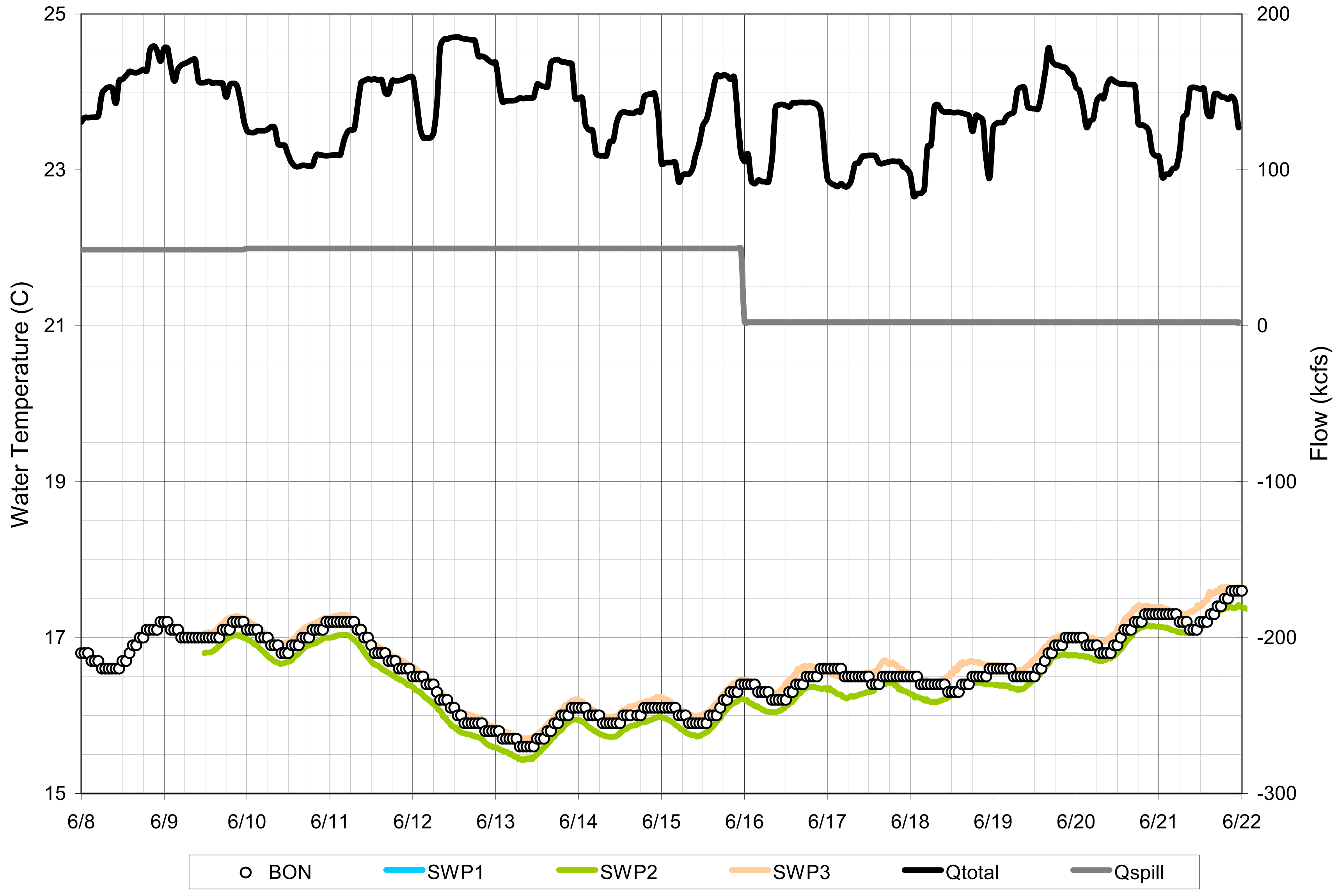

Figure 21. Water Temperatures at Bonneville Dam June 8-21, 2001

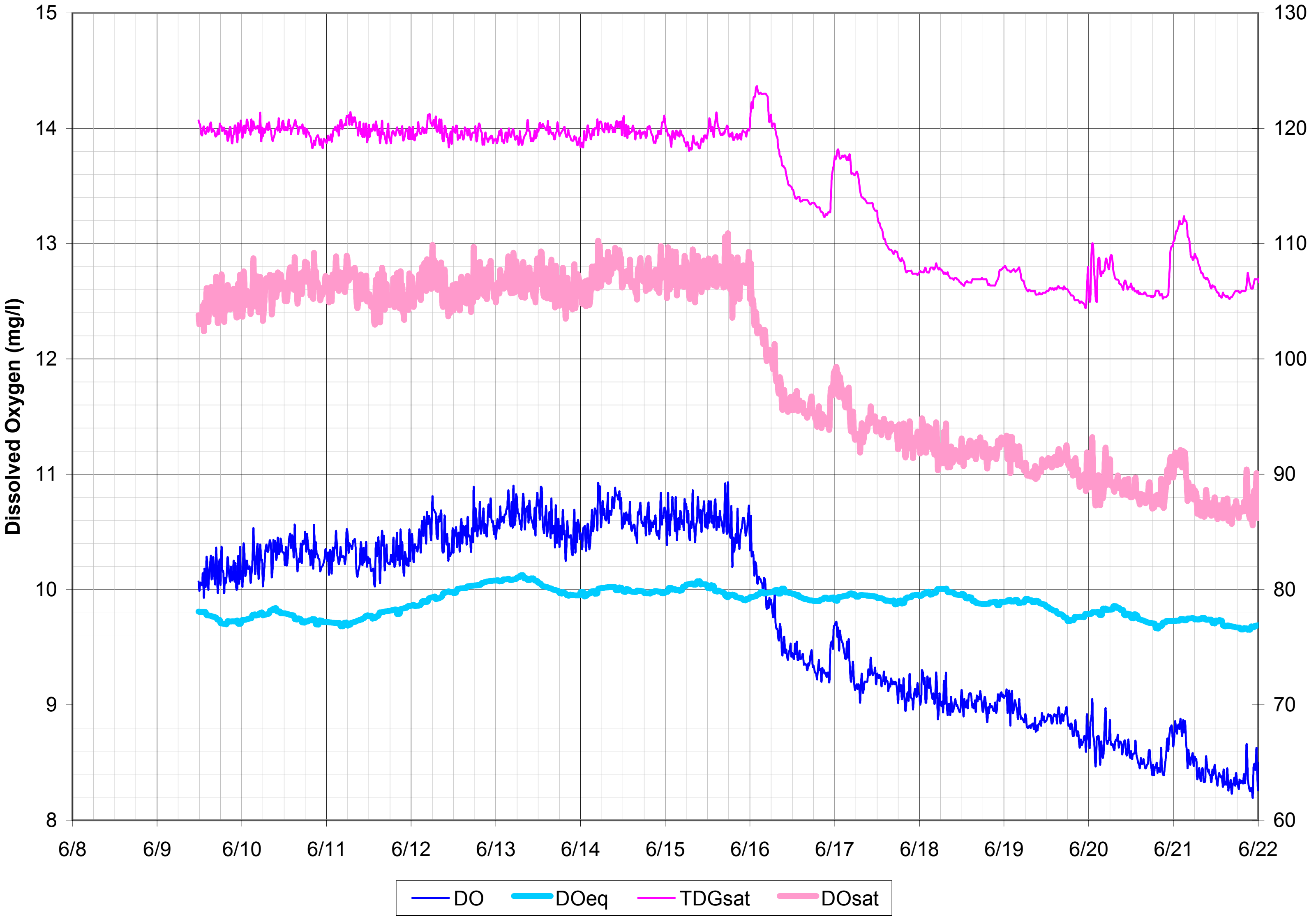

Figure 22. Observed Dissolved Oxygen Concentrations and Percent Saturation of Oxygen and Total Dissolved Gas in the Spillway Channel at Bonneville Dam, June 18-22, 2001. (Station SWP2)

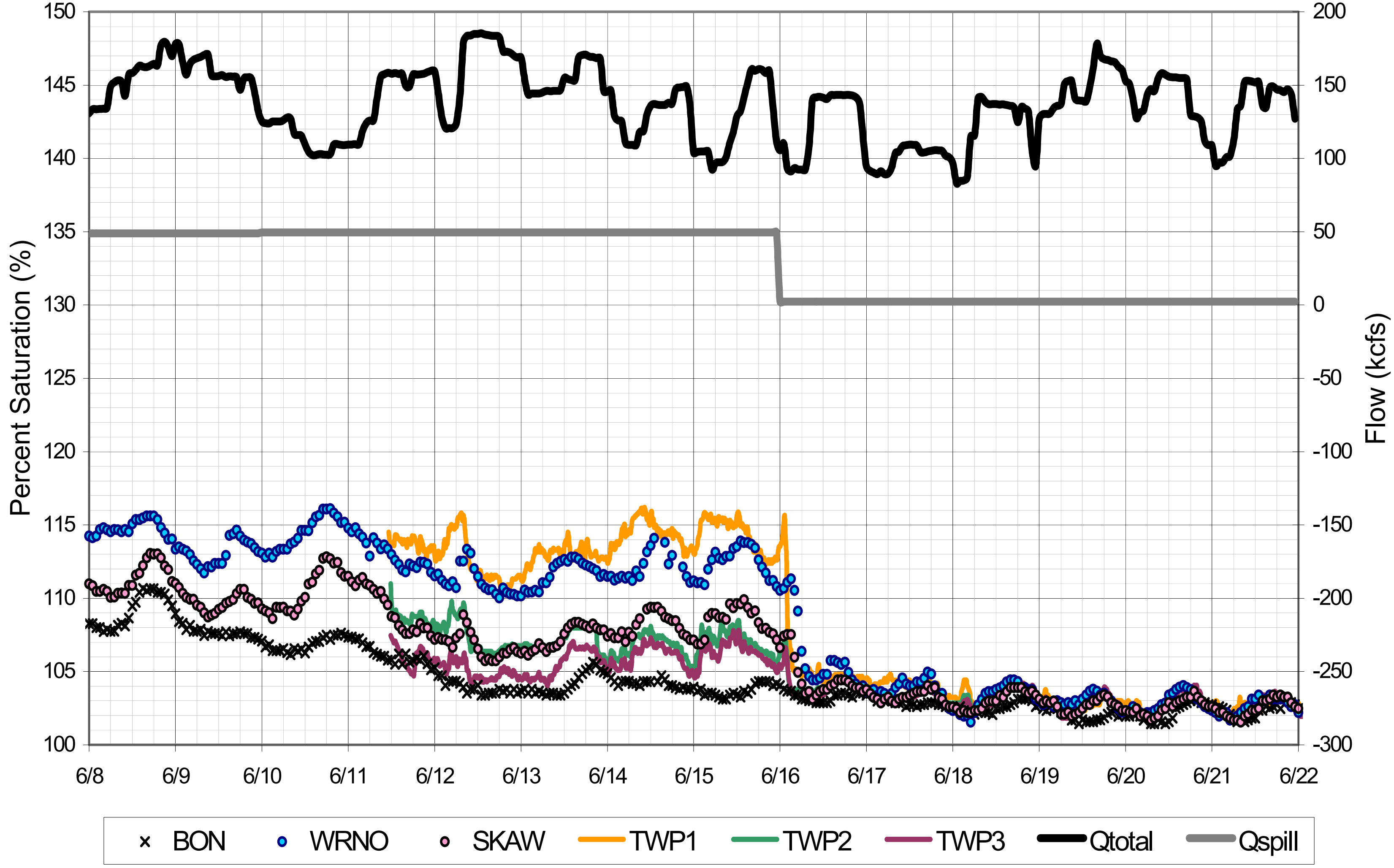

Figure 23. TDG Saturation in the Tailwater Reach below Bonneville Dam, June 8-21, 2001

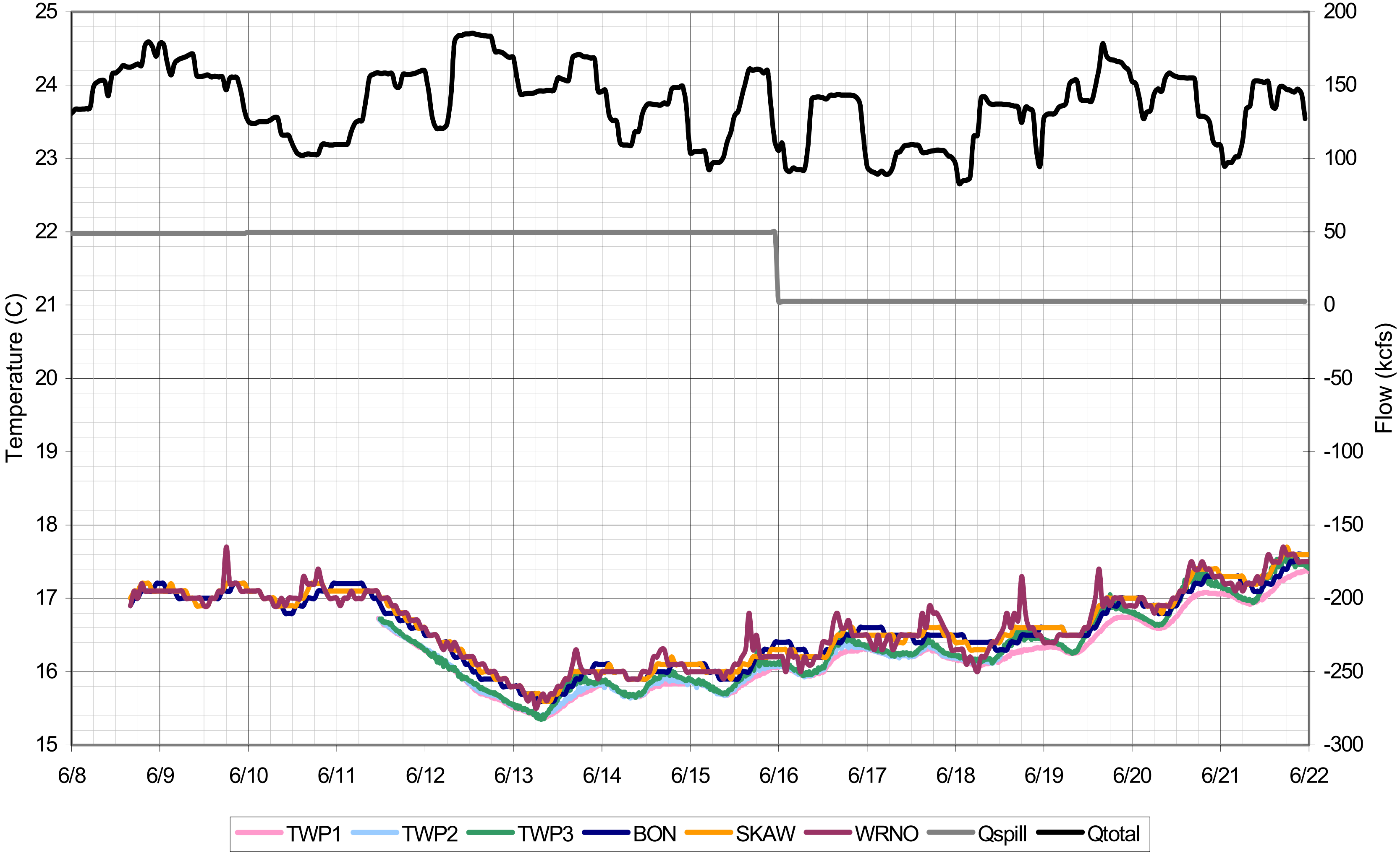

Figure 24. Water Temperature at Tailwater stations June 8-21, 2001

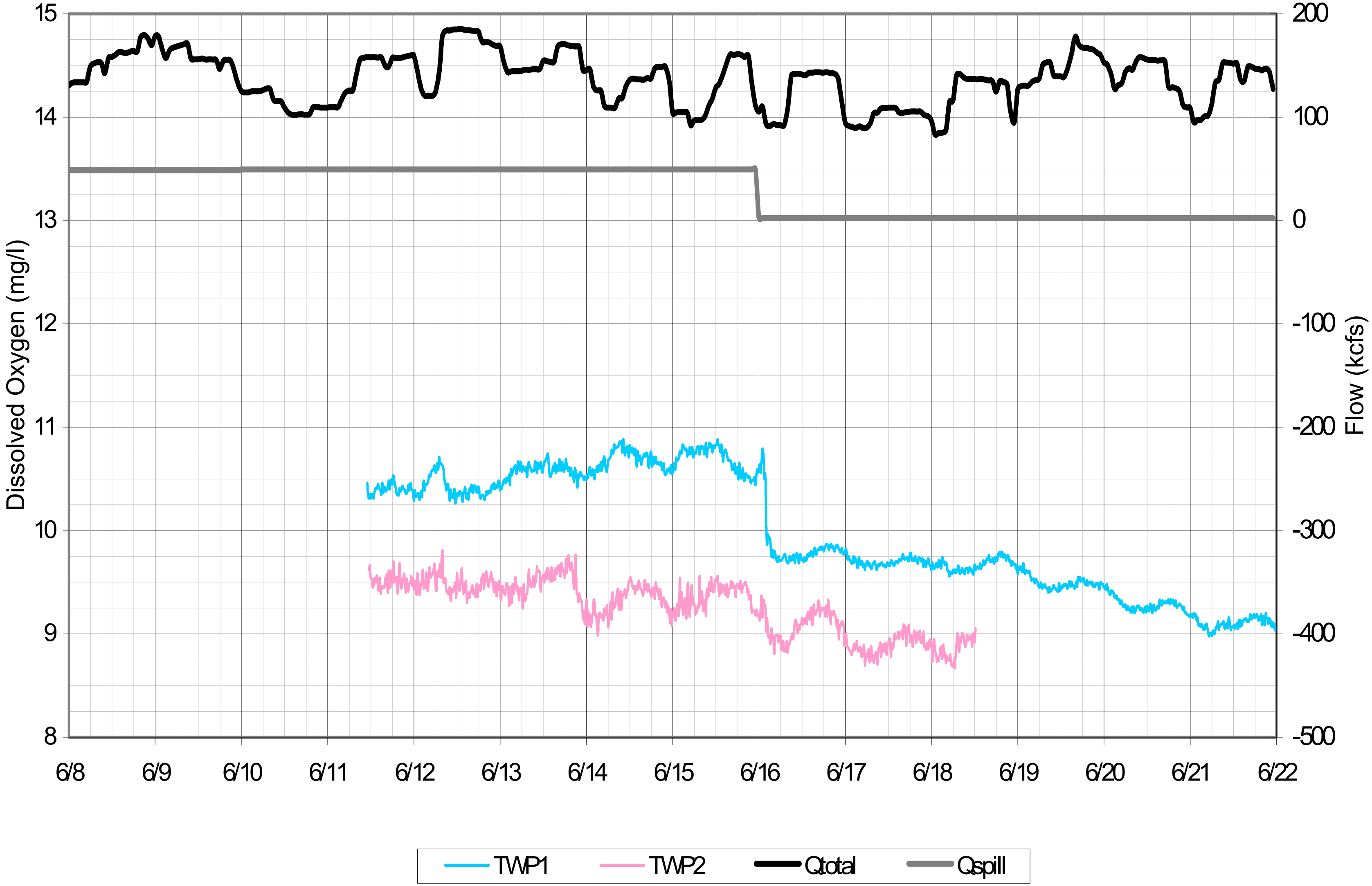

Figure 25. Dissolved oxygen and Bonneville Dam Operations at Tailwater stations June 8-21, 2001

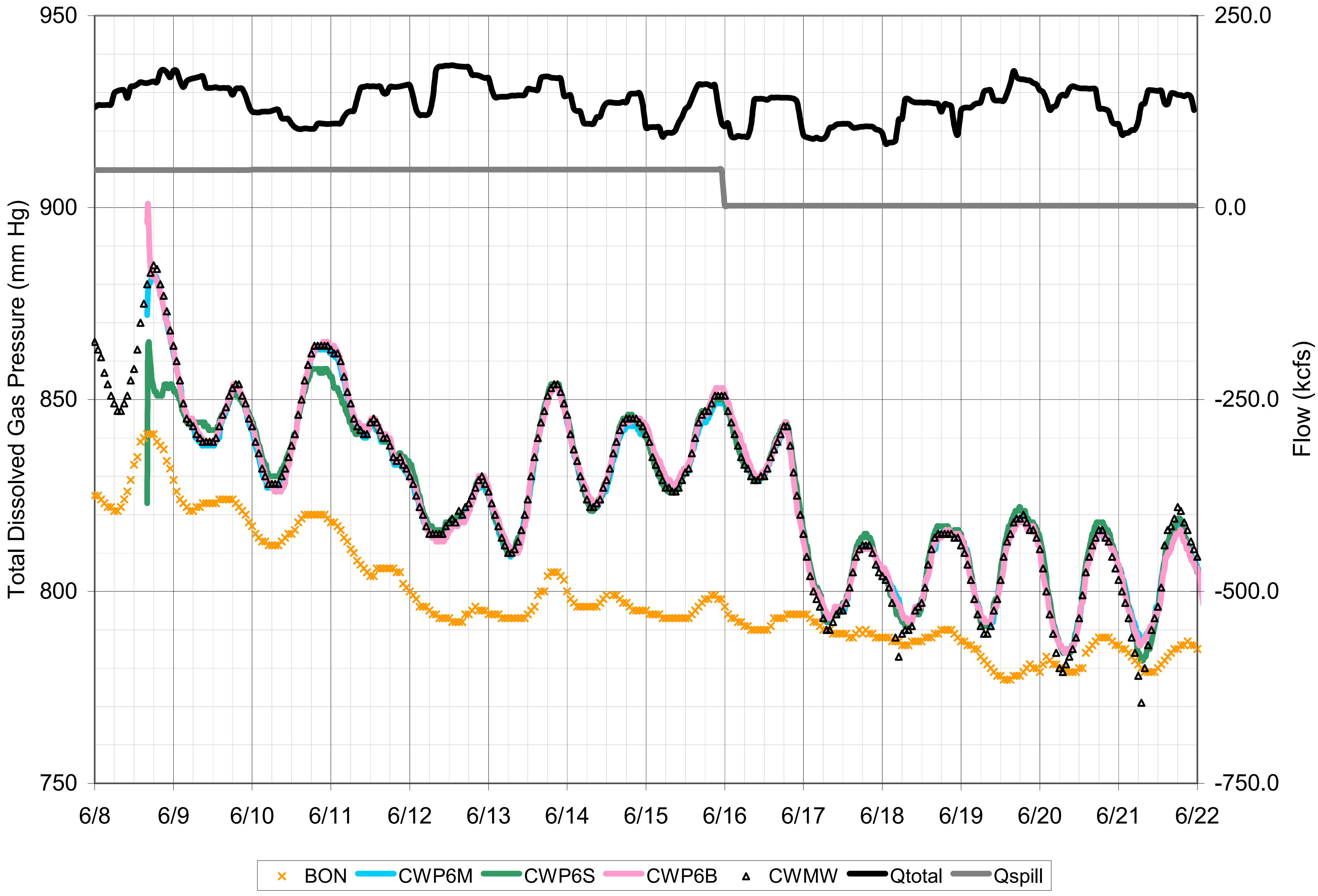

Figure 26. TDG Pressures at the Camas/Washougal station and Bonneville forebay for June 8-21, 2001

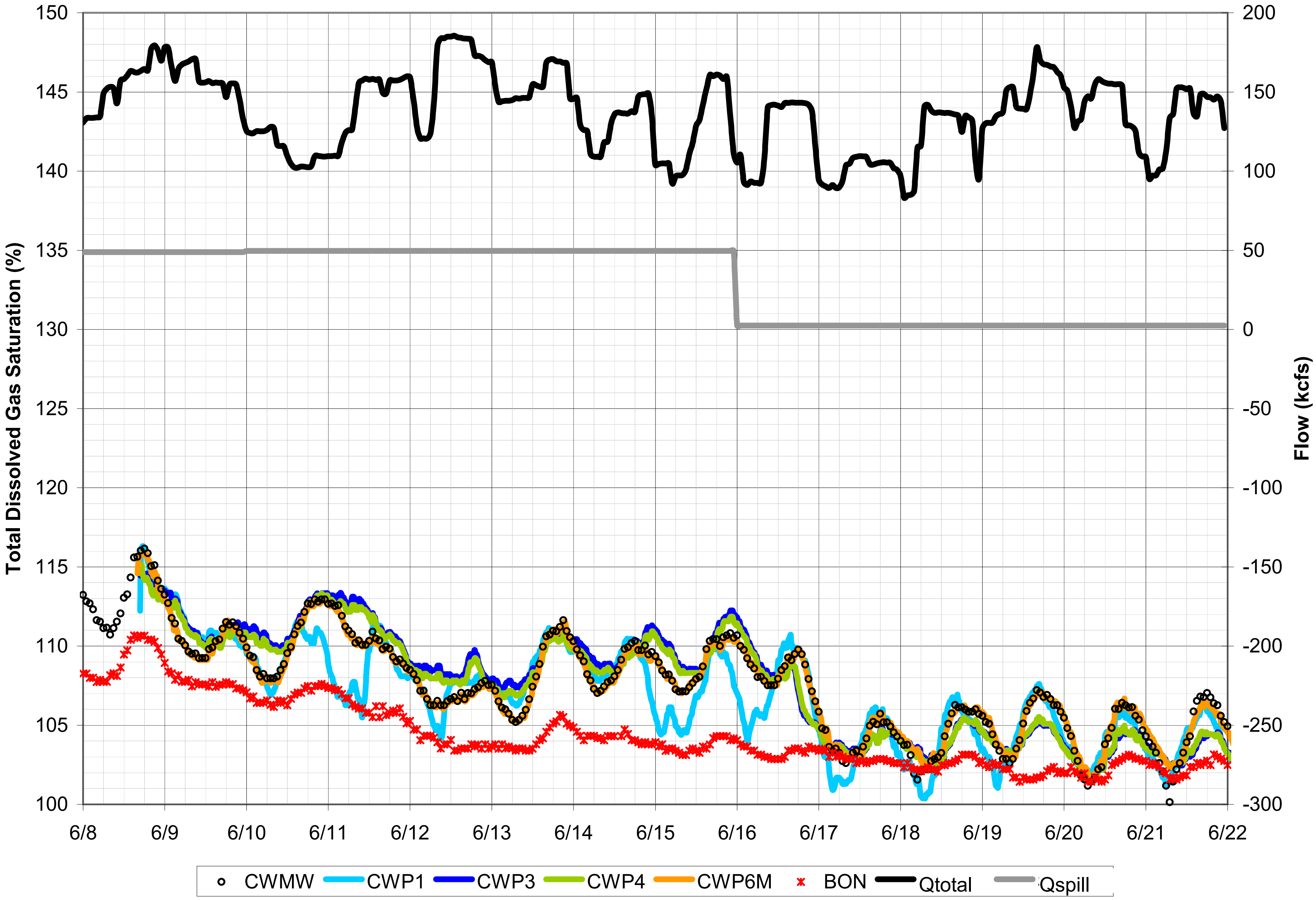

Figure 27. TDG Saturations near the Camas/Washougal Fixed Monitoring Station and in the Bonneville forebay during June 8-21, 2001

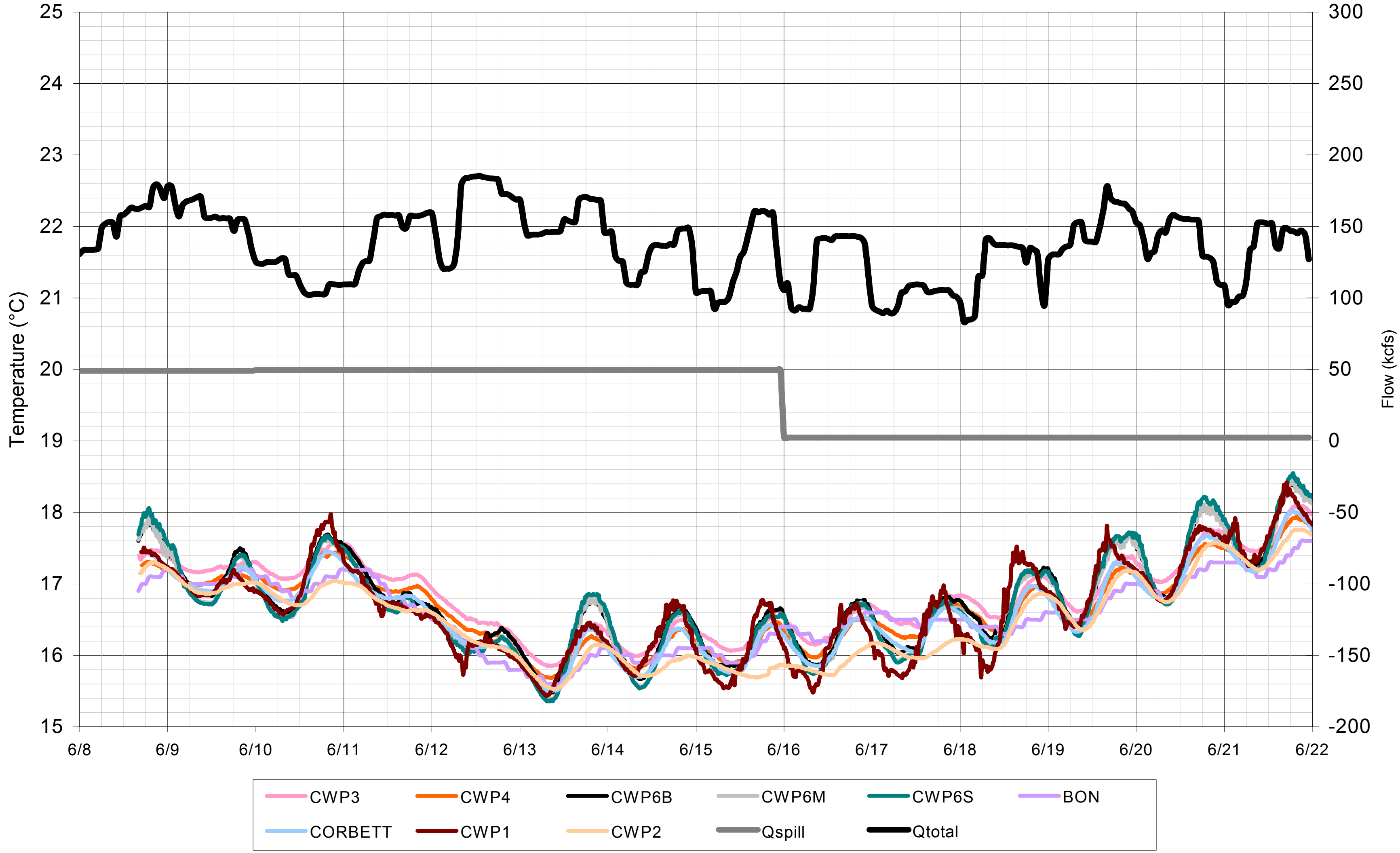

Figure 28. Water temperatures near Camas/Washougal fixed monitoring station and in the Bonneville forebay for June 8 – 21, 2001.

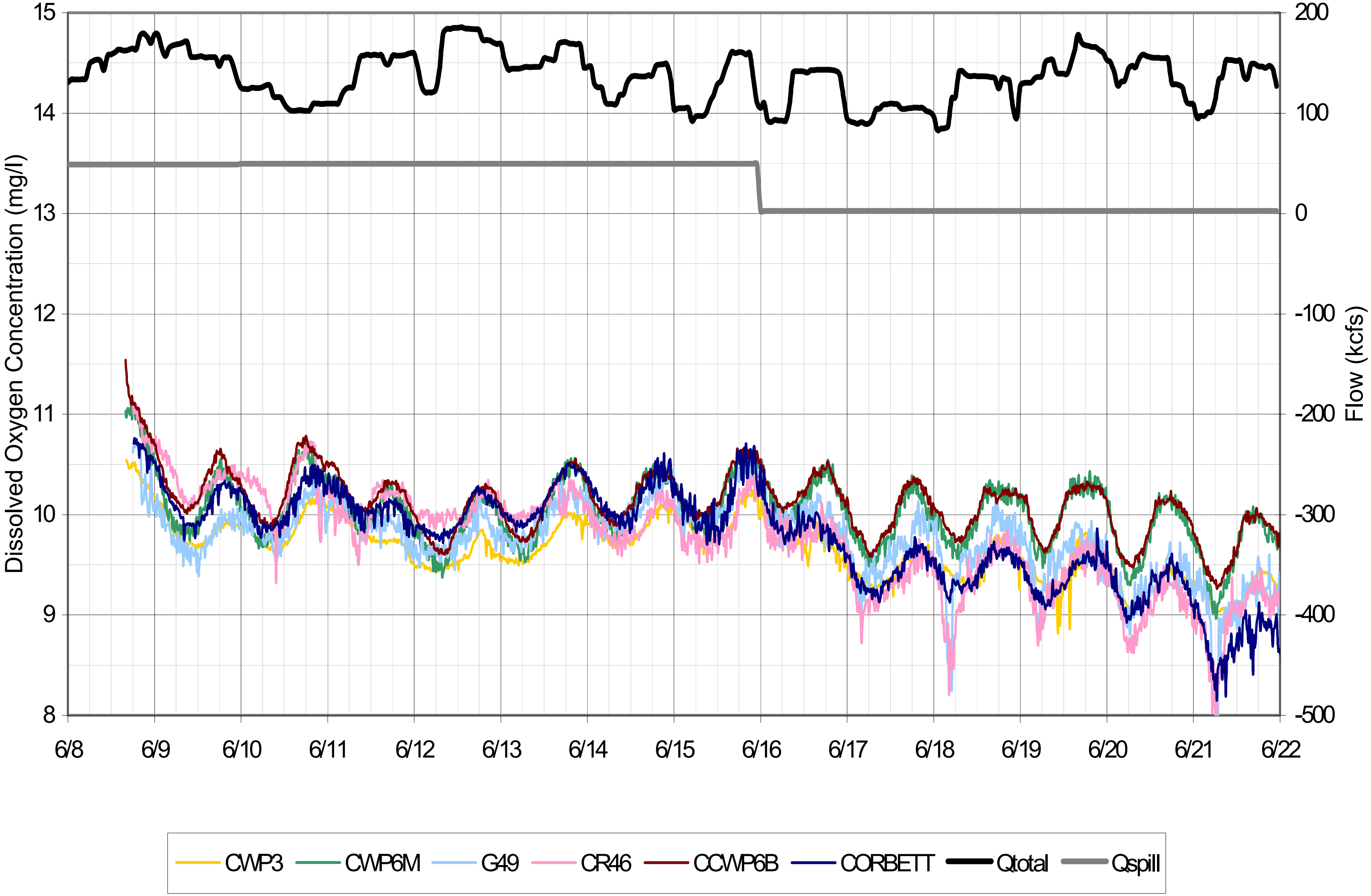

Figure 29. Dissolved oxygen concentrations in the Columbia River near the Camas/Washougal fixed monitoring station, June 8 – 21, 2001.

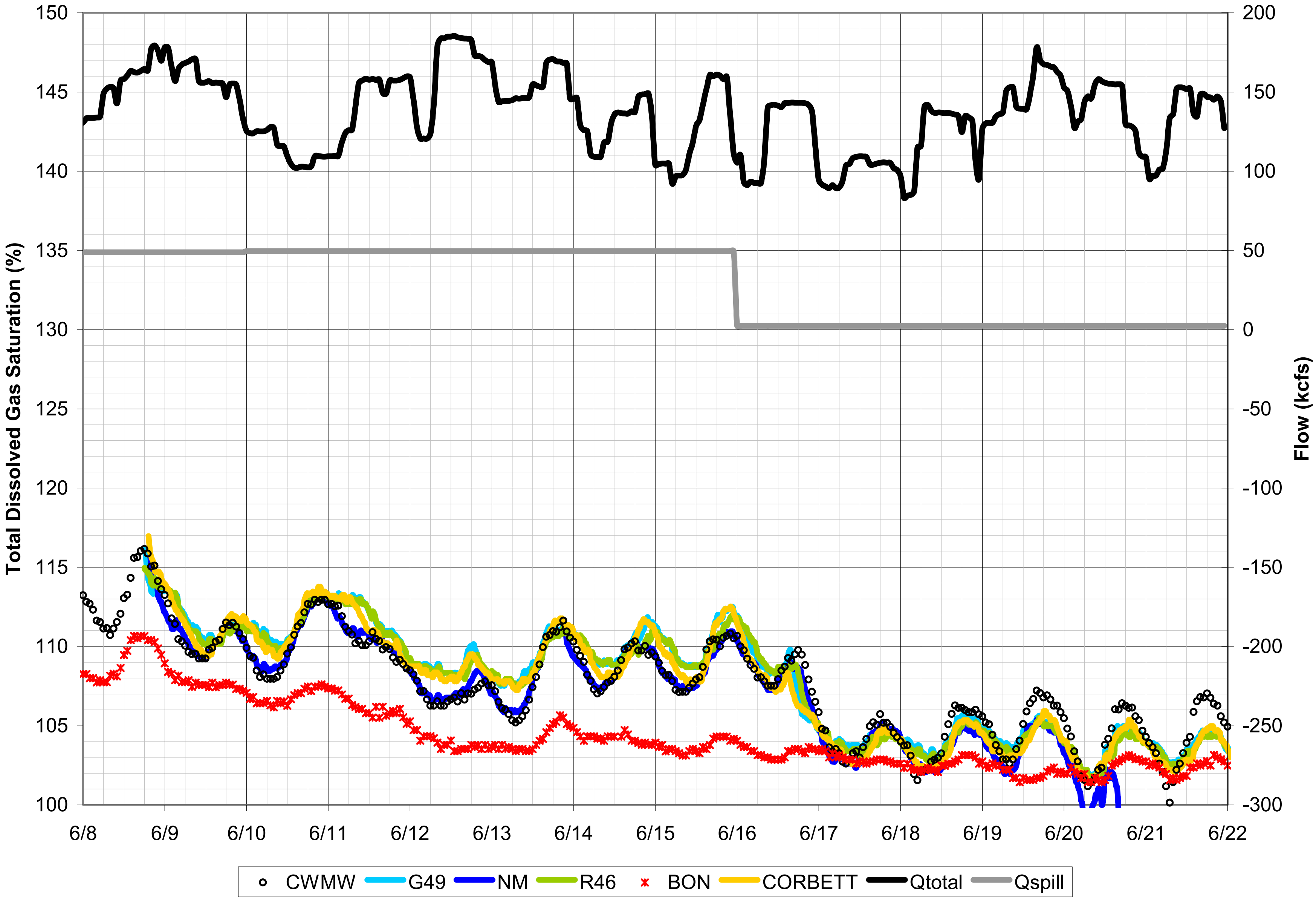

Figure 30. TDG Saturation at Auxillary Statations near Camas/Washougal Fixed Monitoring Station, Columbia River.

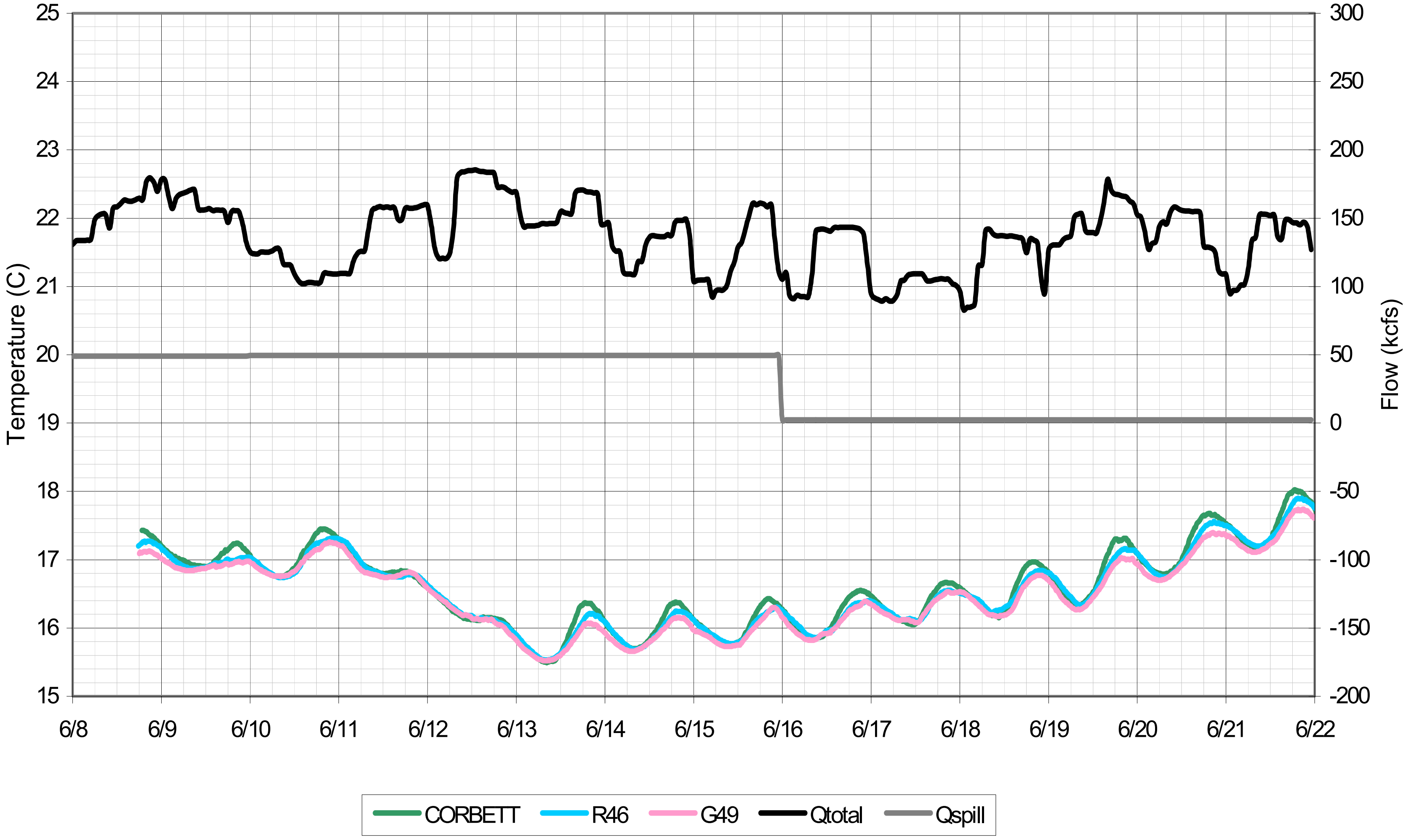

Figure 31. Water temperatures at auxiliary stations, June 8 – 21, 2001.

Figure 32. Dissolved oxygen at auxiliary stations, June 8 – 21, 2001.

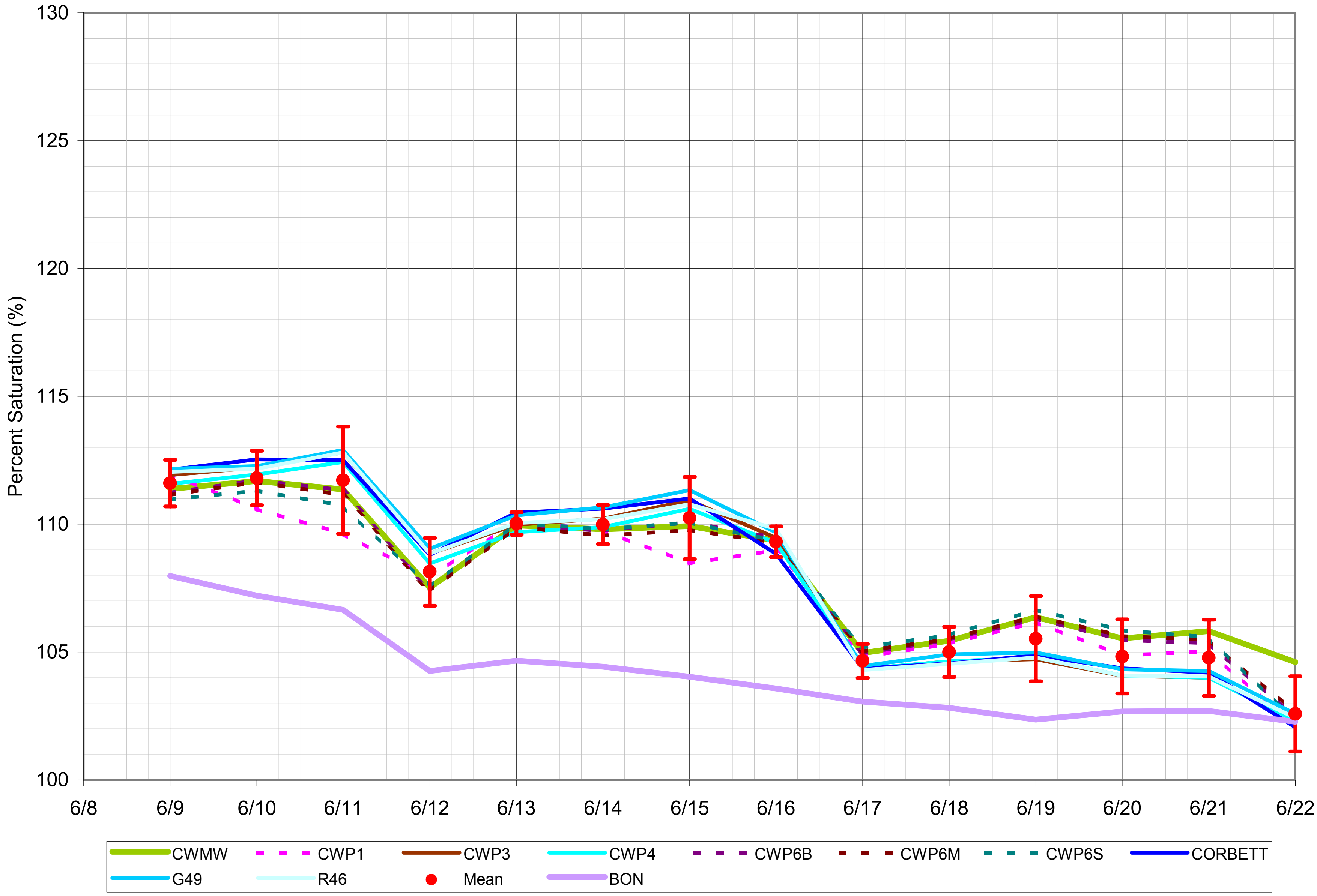

Figure 33. Daily Average of the 12 Highest Hourly Observations of Total Dissolved Gas Saturation for Stations Near the Camas/Washougal Fixed Monitoring Station.

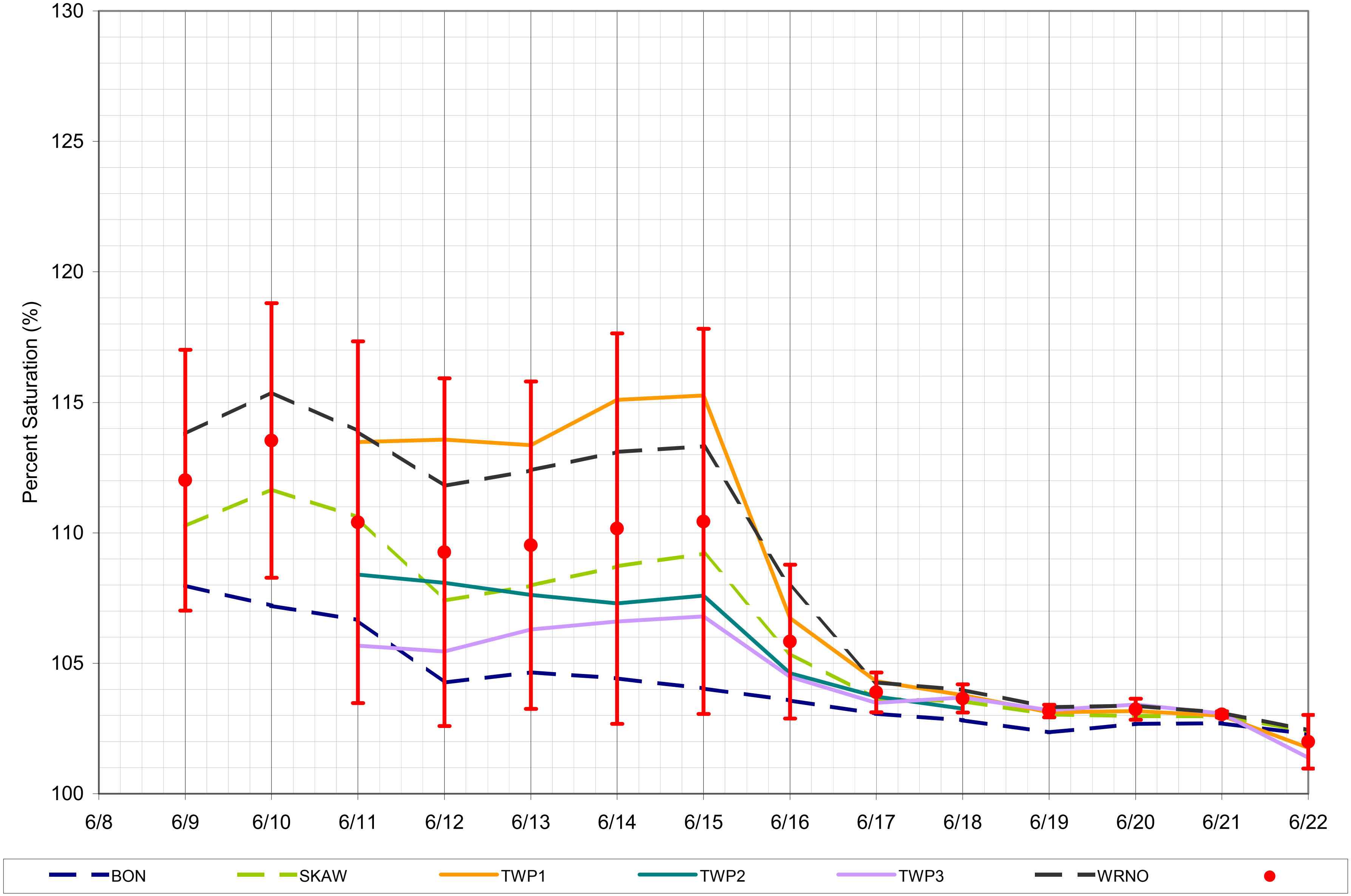

Figure 34. Daily Average of the 12 Highest Hourly Observations of Total Dissolved Gas Saturation for Stations Near the Bonneville Tailwater Fixed Monitoring Station.

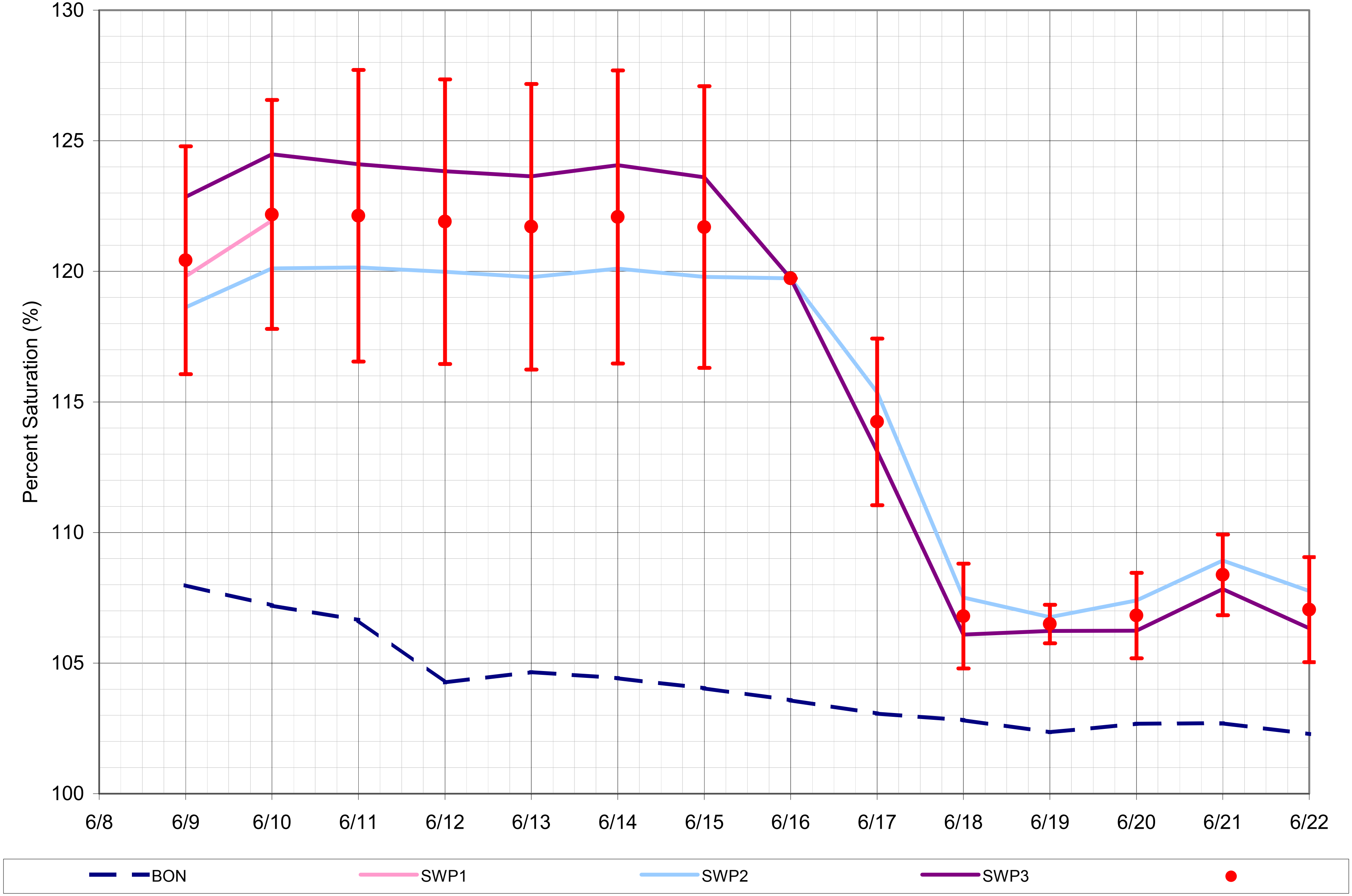

Figure 35. Daily Average of the 12 Highest Hourly Observations of Total Dissolved Gas Saturation for Stations in the Bonneville Spillway Channel.

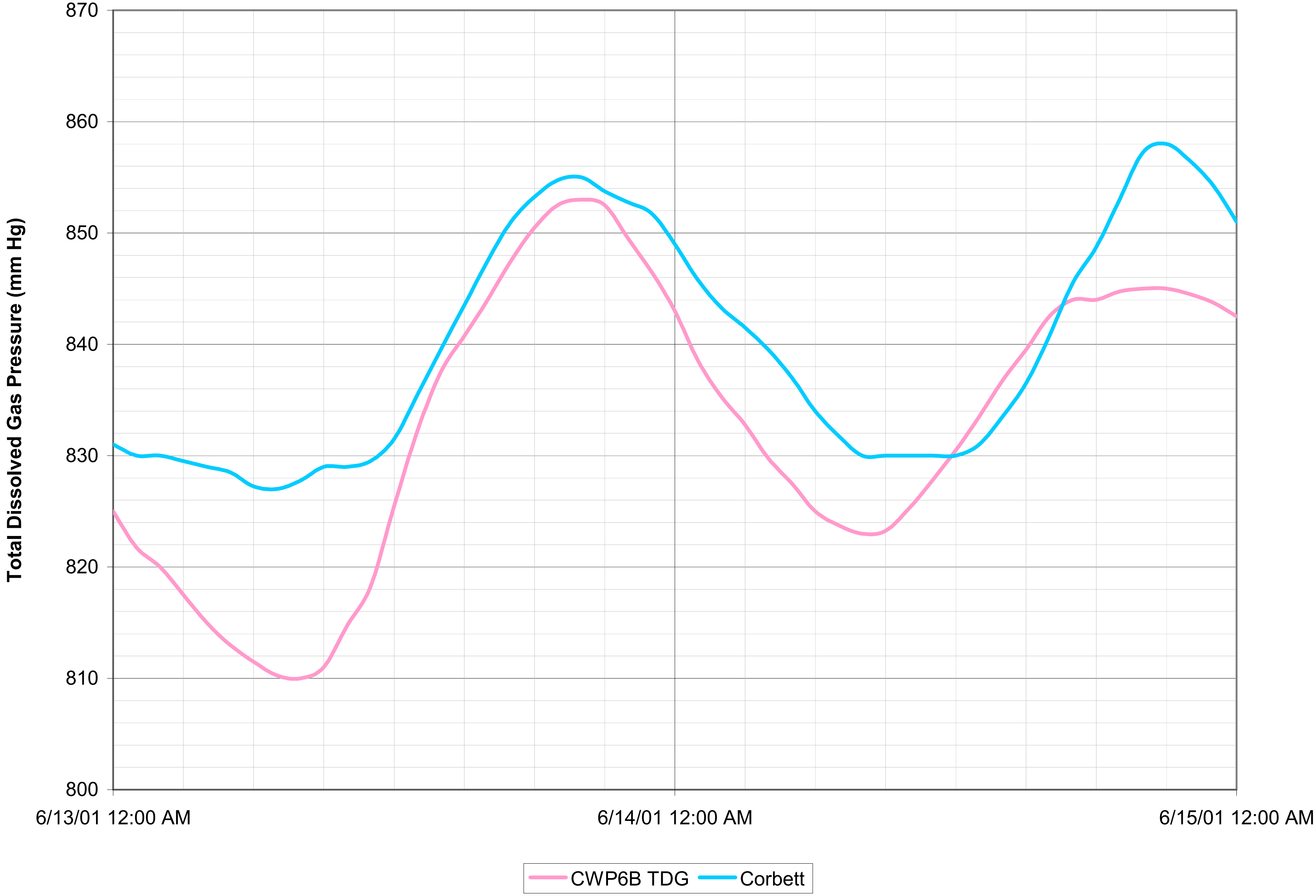

Figure 36. Daily Variation in Total Dissolved Gas Pressure for Stations Below Bonneville Dam .

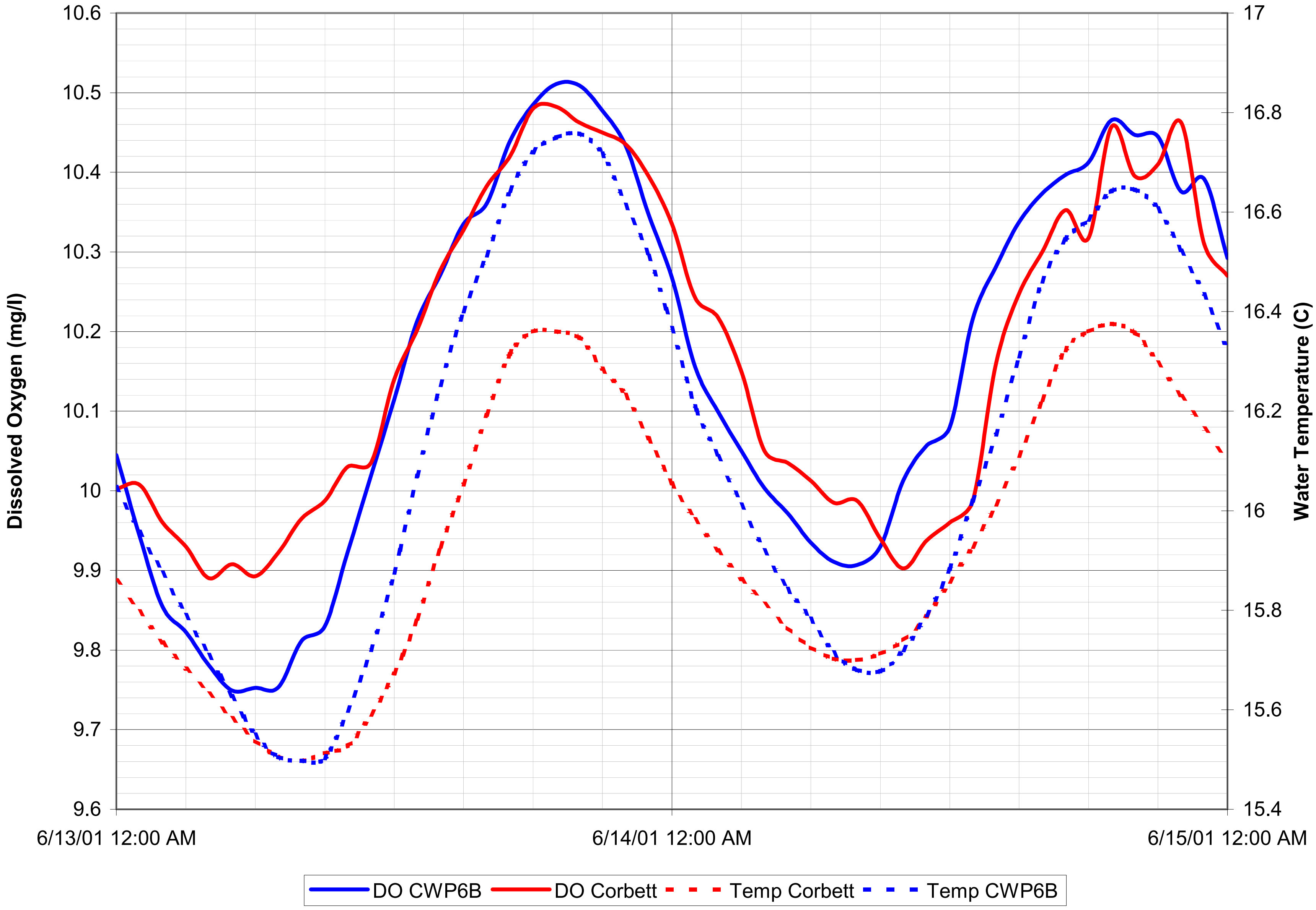

Figure 37. Daily Variation in Water Temperature and Dissolved Oxygen Concentration for Stations Below Bonneville Dam.

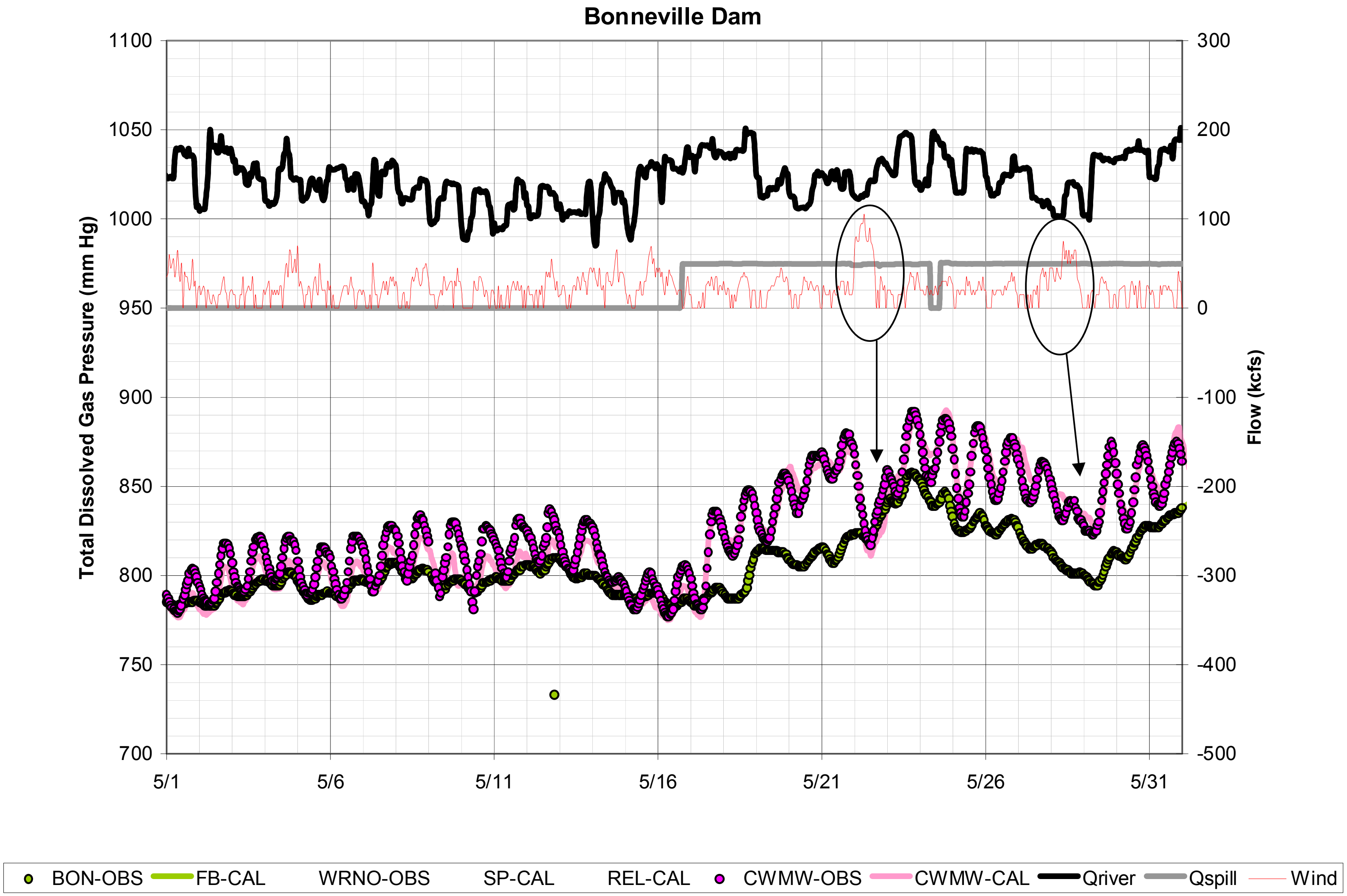

Figure 38. Wind Related TDG Response at the Camas/Washougal FMS, May 2001 (Wind Speed in mps x 10).

Appendix A: Total Dissolved Gas Field Studies: Methodology Water Quality Instrument Calibration, Maintenance, and Precision

The Hydrolab Corp. model DS4A® and minisonde 4A® were used exclusively for water quality monitoring in the Lower Columbia River TDG Field Studies of 2001. These instruments are wireless and capable of remotely logging temperature, depth, specific conductance, dissolved oxygen (DO), and TDG for a one to two-week deployment period depending on logging interval and water temperature. Colder waters have a major impact on battery life and can cut the periods to four day or less on a 15-minute sampling interval. Programming, calibration, and maintenance procedures of the instruments followed manufacturers' recommendations per instrument manuals. Any changes or modifications in instrument handling were implemented only after consulting with factory technicians. Calibration checks and adjustments were performed on all instruments within two days prior to each deployment. Post deployment checks on calibration were completed as soon after retrieval as possible for evaluation of instrument drift and accuracy. An evaluation of instrument performance based on calibration drift was conducted to verify proper equipment operation and define the confidence limits for collected data.

Calibration of Total Dissolved Gas Sensor

The Hydrolab tensionometers used for measuring TDG pressures employ semi-permeable membranes connected to pressure transducers with associated electronics to directly measure in situ total dissolved gas pressure. Air calibrations for TDG were performed using either a certified mercury column barometer or portable field barometers that have been calibrated to a certified mercury column barometer. TDG was calibrated by comparing the instrument readings (in mm Hg) to those of the standard barometer at atmospheric conditions. TDG response slope checks were performed by adding known amounts of pressure, usually 100 and 300 mm Hg, directly to the transducer, and then adjusting the instrument reading accordingly to properly span the range of interest. The membrane is bypassed during these calibrations so that the probe itself is calibrated, rather than the probe/membrane combination. Direct comparisons of membrane off vs. membrane on vs. membrane on and wet have been made in past DGAS work and resulted in no appreciable difference in the calibrated measures. The condition of the membrane and any condensation trapped inside it can influence readings and result in erroneous data or instrument calibration.

An inspection for leaks is performed on the membrane itself before completing the calibration routine. One of the checks employed involves immersing the membrane in seltzer water (super saturated with carbon dioxide). The expected result of a properly functioning membrane is an immediate jump in the TDG reading of at least 300mm Hg. Membranes are also visually inspected for leaks and condensation moisture trapped inside the membrane. The leaks will usually appear as large darker spots in the membrane and indicate that water has entered the silastic tubing. This can occur from either leaks through a tear in the membrane or water vapor diffusion and then condensation inside the membrane. Defective membranes are replaced before use.

Calibration of Dissolved Oxygen Sensor

DO calibration followed procedures developed in the COE DGAS field sampling program. A water bath was employed to rapidly calibrate more than one instrument at a time. The water bath serves as a calibration chamber. After equilibration in this water bath, multiple instruments can then be calibrated to a standardized instrument. By adding a motor-driven propeller sleeved in a ported cylinder to the 50-gallon batch tank, it is possible to achieve a steady state, homogeneous mixture of water approximately 97% saturated with air at a constant temperature. One instrument is designated as the standard for comparison and calibrated for specific conductance, depth, and DO (in air). Once the standard instrument and tank are prepared, several Winkler titration analyses are run to further verify the dissolved oxygen concentration in mg/l of the calibration tank. Adjustments are made to agree with the Winkler titration of DO at this point. The remaining instruments are then adjusted to read the same as the standard instrument for DO, specific conductance, and depth. Additional Winkler DO titrations are performed throughout the calibration procedure to ensure consistency for the rest of the instruments.

Water Quality Calibration Data from COE Total Dissolved Gas Field Studies

Calibration checks and necessary adjustments performed on the Hydrolab instruments have been documented during the 1996, 1997, 1998, 1999, 2000, 2001, and 2002 field sampling for the COE DGAS program on the Columbia and Lower Snake Rivers. The status of each of the parameters before and after each calibration check and adjustment is kept in a calibration log. Data gathered from logs kept on calibration activities were examined as a group, reflecting a pooled data set of all instruments for all deployments. The data assessed in this evaluation reflect only the calibrations performed on instruments before and after deployments that resulted in readings that are included in the study database. Logs for instruments requiring large-scale adjustments exceeding factory recommendations are not included in the data set. In addition, data logs resulting from instruments determined to be malfunctioning based on quality assurance criteria established by the manufacturer are not incorporated into the study database.

An analysis was completed to provide summary statistics defining the variability about the mean of the instrument drift and calibration error (Table 1). The individual data points comprising the population analyzed were the difference between the post-deployment reading of the parameter and a standard calibration value. DO and TDG were the only parameters evaluated in this assessment because they were the primary parameters in this study.

The mean ±2 standard deviations (SD) post operation calibration shifts in DO over all years and instrument types was 0.05 mg/l ± 1.08 mg/l. The mean ±2 SD post deployment calibration shift in TDG pressure over all years and instrument types was 0.44 mm Hg ± 6.5 mm Hg. The variation in DO has remained constant over all years at an approximate SD of 0.5 mg/l. Improved quality assurance and control measures for conducting the TDG calibrations and handling has apparently resulted in reduced variability in the overall accuracy of the instruments used. The TDG calibration checks have gone from an average SD of 5.8 mm Hg in the 1996 sampling year to a low of 0.71 mm Hg SD average for the TDG field studies conducted during the 2001 sampling year. The 19 instruments used in the Rocky Reach study during 2002 had a mean drift in the TDG calibration of 0.47 mm Hg ± 0.77 m Hg. This indicates individual measures of TDG pressure to be within 0.8 mm Hg of the values for 95% of the measures.

Table 1. DGAS Post Deployment Calibration Check for Drift in DO (mg/l) and TDG (mm Hg).

YEAR	Parameter	N	Min.	Max.	Mean	Std. Deviation
1996	DO	253	-2.2	2.1	0.13	0.56
	TDG	233	-21.0	19.0	0.14	5.8
1997	DO	459	-2.4	1.5	0.04	0.42
	TDG	494	-16.0	18.0	0.43	3.5
1998	DO	295	-2.3	2.0	0.04	0.68
	TDG	316	-7.0	8.0	0.67	2.1
1999	DO	183	-1.5	1.27	-0.03	0.42
	TDG	244	-8.0	13.0	0.71	1.69
2000	DO	30	-1.0	0.8	-0.1	0.47
	TDG	73	-4.0	3.0	0.29	1.21
2001	DO	28	-0.4	1.2	0.24	0.35
	TDG	44	-2.0	1.0	0.09	0.71
2002	DO	0	-	-	-	-
	TDG	93	-2.0	3.0	0.0	0.99
Combined Years	DO	1248	-2.4	2.12	0.05	0.52
	TDG	1499	-21.00	19.0	0.44	3.27

Of the approximately 1,500 TDG and DO post deployment calibrations performed over the seven TDG sampling seasons, a small percentage have resulted in “out of tolerance” readings or other errors during calibration. Though these numbers do not necessarily reflect the number of times the instruments were serviced by field personnel or by factory technicians, they do suggest that there is a very low frequency of deployments resulting in erroneous measurements. Barring any unforeseen complications or errors associated with deployment and post-calibration handling, the instruments used in TDG field sampling produced accurate data. Most calibrations revealed that the instruments’ measurement error generally fell within what could be considered an acceptable range of drift. The overall range in drift observed was a bit wider than that defined by the manufacturers (± .2 mg/l DO and ± 1 mm Hg TDG pressure). It should be noted, however, that manufacturer-defined expected error is based on optimal lab conditions, not the field conditions and time intervals in which the instruments were required to function. An additional consideration is the fact that calibration conditions and methods were modified and refined during the DGAS program so that the most accurate and efficient calibrations possible were maintained. It is likely that more experience resulted in the culmination of techniques that could afford tighter calibration data. The instruments accuracy or drift (± 0.77 mm Hg TDG) demonstrated during the Rocky Reach study was within manufacturers specifications of ± 1 mm Hg TDG pressure.

Water Quality Instrument Precision for COE Total Dissolved Gas Field Studies

In addition to the calibration accuracy data described above the precision of the water quality instruments have been evaluated using three other approaches. These include the computation of SD's for individual instruments sampling in a time series in similar waters under near steady state conditions (both laminar flow and turbulent aerated flow below spill ways). The second approach has been to collect paired data using two like instruments deployed together in the same river conditions. The third method of evaluation has been to summarize data from collections of similar instruments located in close proximity for short periods when water conditions especially TDG pressures remained constant (steady state conditions).

During the near field TDG study conducted at the John Day Dam during 2000, a representative set of instruments was evaluated for precision of TDG measures. The analysis was conducted on 30 separate instruments for up to 10 different periods of one to two hours each. Each period was selected to meet the requirement of near steady state regarding flow and expected TDG conditions. The objective was to limit the variability of TDG to just that associated with or inherit in the individual instruments and not due to changing water conditions. The measures were taken and logged on a 15-minute time interval for all instruments producing 4 to 8 reading per instrument per selected period. This design resulted in a grand total of 279 samples of 4 to 8 readings each. The analysis resulted in a mean standard deviation of 0.59 mm Hg ± 0.88 SD for the TDG pressure readings and a mean standard deviation of 0.08 % ± 0.12 SD for the associated TDG saturation readings. The TDG saturation analysis also incorporated the error associated with barometric pressure measures collected during the studies. This would allow the calculation of mean TDG pressures for different periods during the John Day testing to have 95 % CL of ± 1.18 mm Hg. If this variance were applied to all instruments then paired sample means for separate treatments using the same instrument with differences of more than 2.36 mm Hg would be significantly different

The same data set has been analyzed by grouping all water quality instruments on a sampling transect. This varied from 2 to 8 instruments on each of 6 transects. Again time series measures for TDG pressure and saturation were selected for up to 10 separate periods of testing or flow. These times cases were selected for steady state conditions in flow and TDG to represent variability within groups of gas instrument for the same waters. The outcome produced 57 different samples having a mean standard deviation of 1.89 mmHg ±1.04 SD for the pressure readings and a mean standard deviation 0.25 ±0.14 SD for the associated TDG saturation readings. This analysis of grouped instruments results in 95 % CL for sample means of ±3.8 mm Hg.

The third approach in examining variation of field gas measures incorporated a paired instrument approach where two instruments were tied together and deployed at river sampling stations. The data collection was conducted during the 2000 John Day Near Field study and past river sampling studies conducted by the DGAS field sampling team in 1998 and 1999. Reading differences in TDG pressure was calculated for entire deployment logs of 11 pairs of readings. Under the above conditions, the resulting differences are due to uncertainty or bias introduced in the calibration of the individual instruments. The pressure readings were logged on 15-minute time intervals in each case. Since the rate of gas diffusion through the membranes used by the TDG instruments is highly variable readings collected during times of rapid change were eliminated from the analysis. Table 2 depicts the results of one sample paired T test applied to the 11 paired instrument sampling logs. The analysis was conducted for both TDG pressure and saturation readings. The gross mean standard deviation for the 11 paired samples is 1.89 ±1.25 mm Hg pressure and 0.23 ±0.16 % saturation. As would be expected the overall mean of the differences for both TDG pressure, 0.18 mm Hg (95% CI = -3.86 to 4.22 mm Hg) and saturation, 0.03 %(95% CI = –0.59 to 0.65) were not significantly different from 0.

In light of the above described quality assurance methods and uncertainty evaluation of the TDG procedures it appears that with a minimal replication of measures it is possible to significantly discriminate between sample means differing by only a few mm Hg or fractions of a percent TDG saturation. This general conclusion should apply in the application of either paired or multiple instrument sampling. In addition, under the current practices for calibration, the average instrument accuracy falls into the same range of about ± ½ % TDG saturation. ±

Table 2. Paired TDG Sample Log Analysis, Calculations Made on Paired Reading Differences.

Pair		N	Mean Difference	Standard Deviation
CWFMS	mm Hg	631	1.14	2.78
	% Saturation	582	0.16	0.37
LMO6954P	mm Hg	614	-2.94	3.33
	% Saturation	581	-0.41	0.23
LW13974P	mm Hg	998	-0.57	0.53
	% Saturation	909	-0.07	0.07
MN00614P	mm Hg	929	-0.45	1.09
	% Saturation	868	-0.06	0.13
RIST3P3	mm Hg	459	1.01	1.08
	% Saturation	459	0.14	0.14
RIST3P5	mm Hg	481	0.32	0.76
	% Saturation	481	0.04	0.10
T1P3	mm Hg	835	-3.26	3.70
	% Saturation	688	-0.51	0.54
T1P5	mm Hg	857	3.71	2.82
	% Saturation	708	0.62	0.34
T5P4	mm Hg	1058	1.35	0.94
	% Saturation	788	0.24	0.07
T5P6	mm Hg	739	1.89	3.18
	% Saturation	755	0.25	0.43
T6P5	mm Hg	937	-0.27	0.63
	% Saturation	786	-0.05	0.08
Means	mm Hg		0.18 ± 2.03	1.89 ± 1.25
	% Saturation		0.03 ± 0.31	0.23 ± 0.17