CEERD-HR-F (1110-2-1403b) 3 November 1999

MEMORANDUM FOR RECORD

SUBJECT: Total Dissolved Gas Field Investigations at Chief Joseph Dam, 6-11 June 1999

1. Introduction. Total dissolved gas (TDG) generated by the dams on the Middle Columbia River contributes to system wide TDG and reduces the ability to provide fish protective spill at downstream dams. The Seattle District (NWS), Corps of Engineers (CE) has investigated both structural and operational solutions to abating TDG at Chief Joseph Dam (CJD) in "Initial Appraisal Report (IAR) of Dissolved Gas Abatement at Chief Joseph Dam" (NWS 1998). This investigation reviewed 18 alternatives or combinations of alternatives and proposed to carry forward several of these alternatives for further consideration. The alternative for spillway flow deflectors was considered one of the more likely for success in abating dissolved gases at CJD. Since this alternative has proven effective at reducing TDG at other CE dams, it was recommended for further study as a long-term measure. Operational changes or strategies were recommended as short-term priority alternatives.

2. Current Investigation. NWS gave short-term priority for conducting an intensive TDG field study at Chief Joseph Dam during 1999. The US Army Engineer Waterways Experiment Station (WES) was tasked with conducting this study directed at describing spatial and temporal dynamics in TDG both near the structure and downstream in the receiving waters. The study provides a description of current dissolved gas conditions and processes as related to CJD operation. The information gained provides a better understanding the gas exchange processes, particularly dissolved gas production from spill and gas dissipation downstream from the project. Results from this study will also enable the determination of benefits associated with gas abatement measures evaluated for CJD such as spillway deflector installation. The following paragraphs outline the objectives and approach for the field-testing conducted the week of 6 June requiring a total of 5 days of testing to complete.

3. The degree of mixing between powerhouse and spillway releases was investigated since this is important to the total flux of TDG introduced into the Columbia River. In addition, the study characterized transport, mixing, and degassing of dissolved gas that may occur in Lake Pateros, to the forebay of the next downstream dam, Wells Dam, located 25 miles below CJD. It is believed that significant degassing may occur in the area know as "Brewster Flats," about halfway between CJD and Wells Dam, where the river is shallow and wide.

4. Objectives. The purpose of the field study is to more clearly define and quantify processes that contribute to dissolved gas transfer during spillway releases at Chief Joseph Dam. In general, the transfer of dissolved gas is thought to be a function of the unit spillway discharge, spill pattern, spillway geometry, stilling basin and tailwater depth and flow conditions, forebay TDG concentration, project head differential, and water temperature. This study will focus on resolving questions regarding accurate source and sink descriptions of mass conservation of dissolved gases from below the dam to an area adjacent to the downstream water quality fixed

monitor. TDG time history information as related to specific project operation is of particular interest. The data will be analyzed to provide estimates of the gas transfer throughout the tailwater area that should provide guidance on the relative importance of gas exchange processes within the stilling basin and in the downstream tailrace. The specific objectives of the field investigations are as follows:

- Describe dissolved gas exchange processes in the tailwater for various spillway/powerhouse operational scenarios
- Describe transport, mixing, and exchange characteristics of the tailrace/tailwater/Lake Pateros area for selected spillway/powerhouse operational scenarios
- Characterize and evaluate the functional operation of the present fixed monitoring systems in both the tailwater and forebay of Chief Joseph dam
- Provide recommendations for future WQ monitoring as needed for gas abatement
- Provide recommendations for minimizing TDG resulting from Chief Joseph project operations

The conclusions drawn from this effort will aid in the identification of operational and structural measures that reduce dissolved gas supersaturation.

5. Approach. A single TDG monitoring study was conducted to address the stated objectives. The spatial and temporal patterns of TDG gas pressures were investigated in the region downstream of Chief Joseph Dam on 6-11 June 1999 using an array of automated remote logging water quality instruments. Spillway bay and discharge were systematically varied during the test with individual spillbay discharges ranging from 1 kcfs to 10 kcfs per bay. The instruments were deployed along lateral transects and in a series of longitudinal profiles and recorded time history of TDG pressures, water temperature, and dissolved oxygen as operational changes were implemented. Hence, lateral and longitudinal gradients in TDG pressures were investigated downstream of the spillway. Manual water quality and velocity data were collected to quantify the TDG exchange associate with the project operation. The work included near-field sampling (immediate tailrace/tailwaters often within aerated flow) and far-field sampling (downstream of the tailwater and out of the aerated flow).

6. Site Description. Chief Joseph Dam stretches over one mile across the rolling Columbia River at river mile 545.1. Behind the dam, lies Rufus Woods Lake, which extends 51 miles upstream to Grand Coulee Dam. Chief Joseph Dam discharges into Lake Pateros, which extends 29.5 miles to Wells Dam. Designed, constructed, and operated by the U.S. Army Corps of Engineers, Chief Joseph Dam is the Corps' largest power-producing dam. The powerhouse consists of 27 main generators with a hydraulic capacity of 219 kcfs and a nameplate capacity of 2069 MW. The Chief Joseph powerhouse is oriented in an east-west direction about 90 degrees to the spillway as shown in Figure 1. The spillway at CJD has a total length of 980 ft and consists of 19 radial gate-controlled bays. The width of each bay is 49 ft as measured from the centerline of the piers, and

the radial gates have a width of 36 ft. Piers, 13 ft in maximum width, separate the bays. The spillbays are numbered from 1 to 19 from north to south. The elevation of the spillway crest is 901.50 ft. The operating pool for Rufus Woods Lake ranges from elevation 950 to 956 ft. The tailwater elevation typically ranges between elevations of 780 to 790 ft depending upon the total river flow and Lake Pateros pool elevation. The stilling basin at Chief Joseph Dam has a length of 167 ft and a stepped end sill with a height of 11 ft. Energy dissipation is provided by a series of baffle blocks located near the end of the stilling basin with a height of 11 ft. The invert elevation of the stilling basin apron is at 743 ft resulting in a typical depth of flow about 36-42 ft as shown in Figure 2. An end wall extending the length of the stilling basin bounds the north side of the spillway adjacent to bay 1. The tailwater channel bed elevation varies in elevation downstream of the end sill ranging in elevation from 740 downstream of bays 6 and 7 to elevation of 755 ft downstream of bays 9 through 19 as shown in Figure 3. Other prominent topographic features include a depression in the channel bottom to elevation 725 ft downstream of the end sill below bay 7. The channel bed elevation gradually rises in elevation downstream of the spillway to an elevation of about 755 ft downstream of the powerhouse.

7. Study Design. The study employed an array of 25 automated remote logging instruments capable of describing the complete water quality time histories. Three of the stations corresponded with the fixed monitoring stations (FMS) upstream of CJD (CHJ), downstream of CJD (CHQW), and at the forebay of Wells Dam (WEL). The instruments were deployed in a spatial pattern adequate to quantify the water quality and hydrodynamic processes characteristic of the river/reservoir system. The general siting of water quality monitoring transects from Chief Joseph Dam to Wells Dam is shown in Figure 4. In addition, the instruments were programmed to measure and log data on a routine time interval of 15 minutes. The variables monitored include total dissolved gas (TDG), dissolved oxygen (DO), temperature (T), and depth (Z). Manual sampling for TDG and DO was conducted where and when necessary to supplement the automated approaches. The velocity field below the dam to the tailwater FMS was collected throughout the study using mobile Acoustic Doppler Current Profiling (ADCP) equipment. Auxiliary velocity transecting was conducted throughout the Brewster Flats area on 8 June as shown in Figure 4. A weather station was deployed near Brewster Flats to monitor the meterologic conditions throughout the study period.

8. The intent of the instrument array was to quantify the TDG flux at various locations in the Columbia River near and downstream of the CJD. The TDG instruments were deployed on multiple transects located above the dam, immediately below the spillway and powerhouse, at the tailwater water FMS, above Brewster Flats, just downstream of Brewster Flats, and in the forebay of Wells Dam. This deployment array provided direct assessment of the lateral and longitudinal gradients and dynamics in TDG concentrations throughout study area during the period of 6-11 June 1999. This information can be used to provide descriptions of the gas exchange characteristics of the existing CJD spillway, stilling basin, and tailrace channel.

9. Figure 5 depicts sampling stations in the near field of Chief Joseph Dam. Three stations were located in the forebay of CJD: near the north end of the spillway in spillbay 1 (CHJNSW), between the spillway and powerhouse (CHJFBMID), and at the forebay FMS (CHJFBPH). Two

sampling stations were deployed in the tailrace channel below the powerhouse between turbine units 4 and 5 (CHJDFTE) and units 23 and 24 (CHJDFTW). Five sampling station were located uniformly across the channel downstream of the spillway but upstream of the powerhouse, approximately 400 ft downstream of the stilling basin endsill. This series of stations were designated as Transect T1 (CHJT1P1-CHJT1P5). A single water quality sampling station was located 100-ft downstream of the stilling basin end sill downstream from spillbays 18 and 19 (CHJT0P1) to provide information of TDG pressures exiting the stilling basin.

10. Transect T2 was located downstream of the Highway 17 bridge at Bridgeport WA adjacent to the existing tailwater fixed water quality monitor. This transect consisted of five sampling stations (CHJT2P1-CHJT2P5) evenly distributed across the channel with Station CHJT2P5 located close to the FMS instrument (CHQW) as shown in Figure 6. The tailwater FMS instrument was deployed near the end of a perforated conduit deployed from the right channel bank about 1.25 miles below the dam.

11. The additional downstream transects in Lake Pateros allow the characterization of TDG dissipation down to the Wells Dam forebay, located 29 miles below CJD. A transect was located upstream and downstream of the Brewster Flats region as shown in Figure 7. Transect T4 was positioned at river mile 537.6 upstream of the Brewster Flats region. Instruments were deployed near the north and south banks of Lake Pateros at Stations CHJT4P1 and CHJT4P4. The downstream transect at Brewster Flats was located at the Highway 173 bridge adjacent to Brewster Flats at river mile 530.0. This transect consisted of four stations (CHJT3P1-CHJT3P4) located uniformly across the channel just below the bridge.

12. The TDG properties in the forebay of Wells Dam were recorded by three sampling stations located on the west (WELFBW), middle (WELFBMID), and east (WELFBE) sections of the dam as shown in Figure 8. The middle station was sited on the same pier as the forebay fixed monitoring station (WEL) at a depth of about 20 ft. The east and west stations were located adjacent to turbine bays 1 and 10.

13. Velocity data describing flow distributions at selected TDG transects were taken to allow the estimation of TDG flux down the river as well as hydrodynamic interactions between generation and spill water. Most of the velocity work was conducted between Chief Joseph Dam and the tailwater FMS and included bank to bank transects of the velocity field during different test conditions (Figure 4). These data will support the rating of operational scenarios with TDG production. It will also provide support in describing transport processes throughout the receiving waters. Stage and velocity information collected during this study will also be used to calibrate and verify the general physical model of Chief Joseph Dam. Auxiliary velocity transects were taken throughout the Brewster Flats area to document the distribution of flow through this wide channel reach.

14. Manual sampling of water quality conditions was conducted on one-second intervals during all the mobile velocity sampling work directly below the dam. This information provides a means of identifying dissolved oxygen gradients and aggregate TDG pressures at high spatial

resolution. Manual sampling of the Methow and Okanogan Rivers was also conducted at several intervals during the test to document the TDG, DO, and water temperature characteristics of these tributary side flows.

15. A weather station was set up near the Brewster Flats area to document the meteorologic conditions during the testing period. The wind speed and direction, air temperature, relative humidity, barometric pressure, and solar radiation were logged on five-minute intervals throughout the study period. The influence of wind events has been found to be an important determinant of degassing rates in the lower Columbia River.

16. Operating Conditions and Test Schedule. The operating conditions scheduled during the TDG exchange study at CJD encompassed a combination of spillway and powerhouse operating scenarios. Spillway and hydropower discharges were systematically varied to achieve a range of operating conditions while maintaining an average total river flow of about 180 kcfs. The test schedule considered a wide range of variables including tailwater elevation, spill pattern, unit spillway discharge, and variations in powerhouse loadings. A total of 14 spillway discharge events were scheduled during the period of 6 June through 10 June 1999. The total river flow ranged from 86 kcfs to a maximum of 198 kcfs as shown in Figure 9. The tailwater elevation was closely correlated to total river flow and ranged from 778.4 to 787.0 ft during the study period. Total river flow during Events 11 and 14 were reduced to cause low tailwater elevations allowing a comparison of TDG exchange for the same specific discharge at higher tailwater conditions observed during Events 9 and 12, respectively.

17. The project operating conditions, headwater and tailwater stage, and spill patterns sampled during the 14 spillway discharge events are summarized in Table 1. This schedule allowed project TDG rating for a wide range of spillway releases and patterns. The test unit spillway releases ranged from approximately 1 kcfs to 10 kcfs per bay (18 to 97 kcfs for the entire spillway). Partial spill patterns and intermediate periods of no spill were scheduled to reduce the magnitude and duration of elevated TDG plumes released from Chief Joseph Dam during the test period. Test conditions were not scheduled during 8 June to review TDG data downstream at Wells Dam in terms of compliance with TDG constraints. The compliance criteria involved the highest 12 hours average TDG should not exceed 120 percent saturation in the Wells forebay.

18. The standard spill pattern was scheduled for 10 of the 14 spill events as shown in Figure 10. This resulted in individual specific spillbay releases of 1, 2, 3.1, 4.2 and 5.4 kcfs/bay. Spillway discharges were then concentrated on the south side of the structure to achieve higher per spillbay discharges of 3.0, 4.0, 7.8, and 10.1 kcfs but for smaller volumes. The two lower partial spill pattern events were paired up with full pattern spill releases of the same specific discharge allowing the determination of partial patterns on TDG exchange.

19. The fate of powerhouse discharges was of interest in this study. Powerhouse releases potentially interact with spillway discharges both within and downstream of the highly aerated flow regime. Powerhouse discharges ranged from 50.1 to about 164.9 kcfs to allow a total river discharge of approximately 180 kcfs throughout most of the test. Two powerhouse-operating

scenarios based on the location of turbines were tested. During 6 June the east side of the powerhouse carried the primary load during the spill test. On the following day 7 June the hydropower load was shifted to the west end of the powerhouse away from the spillway as three spill events were repeated. These series of tests were scheduled to determine if the amount of powerhouse discharge entrained into the aerated spillway release was dependent upon the powerhouse unit in operation.

20. The duration of Spill Events 9 and 12 were extended beyond 2 hours to create a larger volume of supersaturated water to track throughout Lake Pateros. Side channel inflow, air/water interface degassing, and dispersion and mixing with the previous project releases results in the reduction in peak TDG pressures as supersaturated plumes move through the Lake Pateros.

21. The Methow and Okanogan Rivers contributed a significant portion of the total inflow into Lake Pateros during the study period. The inflow hydrograph for Lake Pateros is shown in Figure 11 for the study period. The inflows for the Methow and Okanogan Rivers were obtained from the USGS and reflect daily average flows. The flow in the Methow ranged from 14.5 kcfs to a low of 11 kcfs during the study period while the Okanagon ranged from high of 13.5 kcfs to a low of 6.1 kcfs. The contribution of side channel inflows declined from an average of 15 percent at the beginning of the study period to about 10 percent during the final days of the study.

Results

22. Hydrodynamics. A total of 79 separate velocity transects were collected during the 5-day study period. The velocity data focused on flow distributions just downstream of the Highway 17 bridge at the tailwater FMS location (Transect T2). The velocity transects were also routinely conducted near Foster Creek with the intended usage for calibration of the general model of Chief Joseph Dam. Information from the ADCP was reduced and incorporated into a relational database. The position of each sampling location was translated into Washington North state plane coordinates. Each record in this database contains the time, location, water depth, velocity vector, and estimated discharge. A total of 200,594 records are in the velocity database.

23. The depth-averaged velocities along selected transects were generated for each of the test conditions. The two-dimensional depth-averaged velocity fields were calculated to determine the flow distribution throughout the channel at Transect T2. The depth-averaged velocity field for Spillway Event 4 is shown in Figure 12. The velocity field is skewed toward the north bank near the Foster Creek transect with maximum velocities approaching 10 fps. A recirculation cell was apparent against the left bank at this location. The flow distribution near the tailwater FMS was nearly symmetric with maximum velocities of 8 fps. The velocities near the middle of the channel were larger than the near-shore velocities at this transect.

24. TDG Dynamics. The TDG pressures recorded by the instrument arrays were converted to percent saturation by dividing by the local barometric pressure as determined by a reference barometer (uncorrected for altitude) at the tailwater fixed monitoring stations in the forebay of

Wells Dam (WEL), in the forebay of Chief Joseph Dam (CHJ), and at the tailwater FMS below CJD (CHQW). The barometric pressure in the forebay of CJD was typically about 3 mmHg lower than observed at Well Dam forebay as shown in Figure 13. The barometric pressure at the tailwater station below CJD was from 2 to 6 mmHg greater than observed at Wells Dam. The magnitude and range of barometric pressures observed at the tailwater station below CJD appears to be suspect due to the close proximity with the forebay station and similarity in elevation with the Wells Dam forebay station. The barometric pressure ranged from a low of 737 mmHg at the CJD forebay station to a high of 752 mmHg at the tailwater station during the testing period as shown in Figure 13.

25. TDG pressure is a direct function of water temperature with increased pressures resulting from increasing water temperatures. The water temperatures in Lake Pateros were a function of the thermal properties of inflowing water from Lake Roosevelt, surface heat exchange during transport through Rufus Woods Lake and Lake Pateros, and the thermal properties of flow from the Methow and Okanogan Rivers. The water temperatures at the forebay FMS stations at CJD and Wells Dam and selected in-pool stations are shown in Figures 14 and 15 for the duration of the study. The water temperatures appear to be influenced by both daily cycling and rising temperatures arriving from the upper Columbia River. The water temperature increased nearly 1 ^{o}C during 8-11 June at both dams. The water temperature at the forebay FMS station at CJD ranged from 12.3 °C to 13.4 °C during the study period. The water temperatures at Wells Dam were typically from 0 to 0.4 ^{o}C colder than observed at CJD. The water temperatures in the Methow and Okanagon Rivers were observed to be colder than temperatures in the Columbia River. During the morning hours on 10 June water temperatures in the Okanagon and Methow Rivers were found to be 12.0 ^{o}C and 8.9 ^{o}C, respectively. The colder side channel flows contributed to the cooler temperatures observed at Wells Dam.

26. Dissolved gas data were retrieved from 24 of the 25 instruments deployed during the Chief Joseph TDG exchange test. In addition to the study instrument array, the fixed monitoring station data for the forebay and tailwater (CHJ and CHQW, respectively) at Chief Joseph Dam and the Wells Dam forebay station (WEL) logged barometric pressure and TDG pressure on a 60-minute interval. A total of 12699 values were recorded from fixed position instruments during the study period starting at 0100 hrs on 6 June and ending at midnight on 11 June. The fixed position instruments were retrieved on 11 June in a downstream sequence. The data were incorporated into a relational database and merged with project operation, velocity, and local barometric pressure observations. Additional water quality observations were recorded from manual sampling instruments aboard the WES research vessels.

27. The observed TDG data are presented in several time history plots and discussed in detail in the following paragraphs. Intermittent TDG data records are displayed as symbols in the forthcoming figures whereas observed TDG data on regular 15-minute intervals are represented by solid lines. The results are presented in groups of stations ordered by first along lateral transects and conclude with a discussion of longitudinal gradients in TDG pressures downstream of the project.

28. CJD Forebay and Powerhouse Stations. The TDG saturation approaching Chief Joseph Dam remained nearly constant during the study period ranging from 109 percent on 6 June to 111 percent on 10 June. All CJD forebay water quality stations registered similar TDG pressures during the study period as shown in Figure 16. The TDG saturation of hydropower releases below the west end of the powerhouse as measured at Station CHJDFTW, also closely followed the TDG saturation measured at the forebay stations. These data suggest that powerhouse discharges do not change the TDG content observed in the forebay of the dam. These observations were consistent with other studies (Schneider and Wilhelms, 1998) measuring the TDG content of powerhouse releases at main-stem projects in the lower Columbia River. The TDG saturation measured on the east side of the powerhouse (CHJDFTE) located between units 4 and 5, resulted in TDG pressures higher than ambient conditions during spillway discharges and selected hydropower operations. The aerated plume associated with spillway releases was observed to encroach upon the turbine releases from bays 1-6. The TDG saturation below the east side of the powerhouse was significantly lower during heavy loading of the east end of the powerhouse on 6 June as compared to the heavy loading over the west end of the powerhouse on the following day of 7 June. The highest TDG saturation recorded at Station CHJDFTE of 139 percent occurred during the partial Spill Event 8. The east end of the powerhouse experienced elevated TDG pressures even during the modest spillway releases involving unit spillway discharge of 2 kcfs/bay or larger. On several occasions, the TDG saturation over the east end of the powerhouse experienced was elevated above ambient conditions without the presence of spillway releases. Typically during the middle of the night, the TDG saturation at Station CHJDFTE was several percent higher than background levels. These elevated pressures could have resulted from changing circulation patterns below the dam transporting residual spill water into the eastern portion of the powerhouse. A recirculation cell downstream of the spillway could retain water with elevated TDG saturation for extended time periods. The inefficient operation of a turbine could result in the entrainment of air into flow through the turbine or tailrace boil resulting in an increase of TDG pressure.

29. Lateral TDG Patterns, Transect T1. The highest TDG saturation observed anywhere in the Columbia River basin of 175 percent was observed during a partial spill pattern on 6 June of only 48.4 kcfs just downstream of the stilling basin at Station CHJT0P1 (near the north bank). The TDG saturation exceeded 165 percent on three other occasions at this same station as shown in Figure 17. In each case, the highest TDG levels corresponded with partial spill patterns (Events 4, 8, 10, and 13), where only the south side of the spillway was in use. The strong lateral gradients in TDG saturation generated during the partial patterns reflects conditions where only 3 of the 5 stations on Transect T1 were located in the aerated flow regime below the spillway. The stations located below the north end of the spillway were located in a recirculation cell returning water back into the stilling basin and eventually into the spillway discharge. The standard spill pattern resulted in TDG saturation that increased with spillway discharge. Spill Events 1 and 5 (1 kcfs/bay) resulted in only a small increase in the TDG saturation above background levels at 112 percent. The TDG saturation of 125-127 percent resulted from the 2 kcfs/bay discharge associated with Spill Event 9. Spill Events 2 and 6 (3 kcfs/bay) yielded TDG saturation levels

ranging from 130-134 percent. The standard spill events with unit discharges of 4-5 kcfs/bay resulted in TDG levels ranging from 134 to 142 percent across Transect T2. The maximum TDG pressure during the standard spill patterns generally was located near the middle of the spillway at Station CHJT1P3. The TDG saturation generally reached constant levels within 2 hours of the initiation of a spill event. The TDG levels on Transect T2 returned to ambient conditions about 4-6 hours after the termination of spillway discharges.

30. Lateral TDG Patterns, Transect T2. The lateral TDG saturation on Transect T2 reflects releases from both the powerhouse and spillway. The instrument located at Station CHJT2P2 malfunctioned and did not record any data during the study. The highest TDG saturation on Transect T2 typically was found at Station CHJT2P5 as shown in Figure 18 with the peak TDG pressures of 134-135 percent observed during the spillway discharges associated with unit spillway discharges of 4 kcfs/bay and higher. The maximum saturation on Transect T2 was nearly 40 percent saturation less than maximum level observed at Station CHJT0P1 during partial spill pattern events. The TDG saturation on Transect T2 was a function of both upstream TDG saturation, the percent river spilled and unit discharge of the spillway release. The TDG saturation associated with standard Spill Events 1 and 5 (1 kcfs/bay or 16.9 kcfs) yielded only a marginal increase in TDG saturation on Transect T2 with levels ranging from 109-110 percent. The spillway discharge of 35.4 kcfs or 2 kcfs/bay resulted in TDG saturation reaching 123 percent at the tailwater FMS. The higher TDG pressures associated with changing operation conditions generally required from 30-45 minutes to arrive at on Transect T2. Stations CHJT2P3 and CHJT2P4 were generally located in the mixing zone where spillway releases were mixed with powerhouse flows. Higher TDG pressures were observed on these stations when the percentage of river spilled increased. The TDG saturation on the south side of the channel at Station CHJT2P1 reflected only powerhouse flows with the exception of a small increase during Spill Event 14. The slight elevation of TDG saturation observed near the dam during the hydropower operation in the early morning hours of 8 June were also observed on Transect T2. The TDG conditions as measured at the FMS (CHQW) were 1-2 percent higher than conditions observed across Transect T2 outside of the testing conditions. The responsiveness of the instrument located at the Station CHQW to changes in TDG pressure was also found to be quite different than observed at other stations on Transect T2 during spillway events. The increase in TDG pressures as measured at Station CHQW lagged conditions measured at nearby Station CHJT2P5 by as much a 1 hour as shown in Figure 19. The return to lower TDG pressures after spillway releases was also found to be much slower at the CHQW station. The two possible explanations for the different response of monitored TDG levels at CHQW is slow water exchange around the instrument or a malfunctioning instrument. It was difficult to determine if equilibrium conditions were achieved at Station CHQW due to the slow response of this instrument to the changing TDG conditions in the river.

31. Lateral TDG Patterns, Transects T3-T4. The lateral distribution of TDG saturation measured upstream and downstream of the Brewster Flats reach was monitored on Transects T4 and T3, respectively. The transect upstream of Brewster Flats was located at river mile 538.5 or about 6.6 miles downstream of the dam. The time of travel from the dam to the upstream end of Brewster Flats was estimated using the arrival of the maximum TDG saturation at Stations

CHJT4P1 and CHJT4P4. The estimated time of travel to Transect T4 ranged from 2.25 to 2.75 hours over the testing period. The mean flow velocity was 2.65 mph or 3.9 fps over the upper third of Lake Pateros. The lateral gradient in TDG saturation was only about 2 percent across Transect T4 with higher TDG levels located on the right bank which corresponded with the spillway releases as shown in Figure 20. The highest TDG levels observed on Transect T4 corresponded with spillway discharges of 90-96 kcfs with maximum levels ranging from 119 to 123 percent. The mixing of powerhouse and spillway discharges resulted in decreasing TDG extremes as a function of distance downstream from Chief Joseph Dam.

32. The irregular channel conveyance properties throughout Brewster Flats significantly changed the characteristics of the TDG plume in Lake Pateros. The channel reach through Brewster Flat is roughly 5.5 miles long and included the tributary inflows from Okanogan River. The thalweg of the Columbia River runs along the north bank of Brewster Flats, which is over 8000 ft wide with a mean depth of flow less then 15 ft. Transect T3 was located at the downstream end of Brewster Flats located just downstream of the Highway 173 bridge. The velocity profiling through this Brewster Flats indicated the majority of the flow followed the thalweg through the northern section of this channel. The inflows from the Okanogan River were highly visible through this region with the turbid side flow hugging the north bank of Brewster Flats. A satellite photo of the turbid Okanogan River side flow is shown in Figure 21. The arrival of the peak TDG pressures at Transect T3 (roughly the halfway point between Wells and Chief Joseph Dams) ranged from 7.25 to 8 hours after being released through the spillway at CJD. The mean velocity of flow through the upper half of Lake Pateros was about 1.95 mph or 2.86 fps. The travel time through Brewster Flats was 5.5 hours on average, which translates to a little over 1.5 mph. The peak TDG levels on Transect T3 ranged from 120-121 percent (Figure 20). The passage of the TDG plume at Stations CHJT3P1 and CHJT3P4 was of longer duration but with smaller peak levels in comparison to properties in the middle of the channel. The peak TDG saturation at the south and north stations on Transect T3 were 5-7 percentage points less than observed at the interior stations. The occurrence of lower peak TDG levels should not necessarily be interpreted as a loss of mass but possibly a redistribution of mass. The creation of larger lateral TDG pressures downstream of Brewster Flats as compared to the entrance, were due to the dispersion and mixing of Columbia River water within this channel area and the introduction of Okanagon River flows.

33. Lateral TDG Patterns, Wells Dam. Three water quality stations were added at Wells Dam to the west (WELFBSW), east (WELFBPH), and middle (WELFBMID) sections of the structure. The middle station was paired with the forebay FMS at Wells Dam (WEL). The maximum TDG saturation observed at Wells Dam was 116 percent for a duration of less than three hours on 11 June 1999 as shown in Figure 22. The lateral gradients in TDG saturation at Wells Dam were generally less than 2 percent saturation throughout the entire test period. The TDG data from the paired instruments located near the middle of Wells Dam were nearly identical during the study period. The peak TDG levels measured at the forebay FMS at Wells Dam were correlated with spillway events at Chief Joseph Dam. The estimated travel time of TDG plumes through Lake Pateros ranged from 20.25 to 17.5 hours. The shorter travel times were attributed to a reduction in storage in Lake Pateros during the second half of the study period as shown in Figure 23. The mean velocity of mass transport through Lake Pateros ranged from 1.45 to 1.65 mph or 2.13 to 2.42 fps.

34. Longitudinal TDG Patterns. The variation in spill volume and percent river spilled during the testing period produced a series of TDG plumes moving through Lake Pateros with a wide range of characteristics. The time series of TDG saturation on Transects T1, T2, T3, T4, and the forebay of Wells Dam are shown in Figure 24. The maximum TDG saturation associated with Chief Joseph spillway releases decreased significantly with distance from the dam. The development of a mixing zone below CJD tended to erode the maximum TDG saturation and increase the minimum TDG saturation. The peak TDG saturation associated with Spill Event 4 was found to be 168, 134, 123, 121, and 113 percent for sampling stations on Transect T1, T2, T3, T4, and the forebay FMS at Wells Dam. The mixing and dispersion of spillway releases from CJD together with the dilution from side channel flows resulted in the decreasing peak level of TDG in spillway releases.

35. TDG Production at Chief Joseph Dam. The added TDG loading at Chief Joseph Dam is primarily associated with aerated flow conditions associated with spillway releases. The powerhouse releases transmit TDG levels in the forebay to the tailwater channel. Powerhouse releases interact with spillway discharges within or downstream of the aerated flow regime below the spillway. The powerhouse releases entrained into the bubbly flow conditions below the spillway can significantly increase the effective TDG loading at Chief Joseph Dam. Powerhouse discharges mixing with spillway discharges downstream of the aerated flow regime will dilute TDG pressures but not significantly alter the net TDG loading generated at CJD.

36. The experiment design of TDG exchange study at CJD incorporated a range of operation parameters. The parameters evaluated included unit spillway discharge, spill pattern (full or partial), tailwater elevation, and powerhouse operation (East or West). The response of the TDG saturation on Transects T1 and T2 were used to quantify the TDG exchange over 14 different spillway discharge events. Transect T1 was located upstream of the direct influences from powerhouse flows but was often located within the highly aerated plume where the exchange of atmospheric gases were not yet completed. Transect T2 was located at the tailwater FMS well downstream of the aerated flow but well before spillway and powerhouse flows were well mixed. Station CHJT2P5 was used as an estimate of TDG levels generated from spillway releases. The data from Station CHJT2P5 was selected because it was well downstream of the highly aerated spillway flow conditions and located near the right bank away from potential dilution with powerhouse flows.

37. The TDG saturation was found to be an exponential function of the unit spillway discharge. The flow-weighted unit spillway discharge was calculated and regressed against the TDG saturation measured at Station CHJT2P5 for 13 of the 14 events. The observations from Event 8 were not used in this evaluation because of the encroachment of the mixing zone at Station CHJT2P5. Event 8 involved a partial pattern with a spillway discharge of 27 kcfs or less than 16 percent of the entire river flow. The TDG levels for Event 8 on Transect T1 were significantly higher than observed at Station CHJT2P5. The TDG saturation at the end of each testing period was used in this evaluation. The duration of constant spillway flow was 1.5 hours or greater for all events except Event 14 which was terminated prematurely due to system power generation

constraints. The flow weighted unit discharge was selected because of the non-uniform spill patterns used on 9 and 10 June. A total of 13 observations were pooled from 13 different spill events with total spillway flows ranging from 16.9 to 96.5 kcfs. The TDG saturation was found to be an exponential function of unit spillway discharge as shown in Figure 25 and Equation 1. The TDG saturation reached an upper limit of 134 percent for unit spillway discharges of 4.2 kcfs/bay and higher. The standard error of this regression was 0.81 percent saturation and the r^2 was 0.99.

$$TDG_{sat} = 134.3 - 55.40e^{(-.847q_s)} \qquad 1$$

Where
TDG_{sat}=Total Dissolved Gas Saturation (%)
q_s = Unit Spillway Discharge (kcfs/Bay)

38. The velocity distribution at Transect T2 was used to calculate the flow weighted average TDG saturation at this location. The channel was divided into four sectors each corresponding with an active water quality station and the discharge in each sector was determined. The weighting factor for each station was set equal to the sector discharge divided by the total river flow. The dimensionless flow distribution on Transect T2 was found to be insensitive to the specific operating conditions at the project. The weighting coefficients used for Stations CHJT2P1, CHJT2P3, CHJT2P4, and CHJt2P5 were 0.2041, 0.3362, 0.2714, and 0.1883, respectively. Conservation principles were applied to estimate the aggregate TDG saturation associated with spillway discharges as a function of spillway and powerhouse flows, TDG saturation of powerhouse discharges (CHJDFTW), and the average TDG saturation observed on Transect T2 as described by Equation 2.

$$TDG_{sp} = \frac{Q_{tot}TDG_{T2} - Q_{gen}TDG_{gen}}{Q_{spill}} \qquad 2$$

Where

Q_{tot}= Total River Flow (kcfs)
Q_{spill}= Spillway Discharge (kcfs)
Q_{gen}=Generation Discharge (kcfs)
TDG_{gen} = Total Dissolved Gas Saturation of Generation Discharges (%)
TDG_{T2} = Average TDG Saturation on Transect T2 (%)
TDG_{sp}= Total Dissolved Gas Saturation of Spillway Discharges (%)

The results of this calculation for events using the standard or full spill patterns are shown in Figure 26 along with the TDG saturations observed at the water quality stations on Transect T1. The estimated TDG saturation of spillway flows closely matched the magnitude and trend of the observations at the tailwater FMS. The largest error of estimate corresponded with the smallest spillway discharge (1 kcfs/bay) where spillway TDG saturation was similar to the background TDG levels in the river. The TDG conditions observed on Transect T1 also reflected the non-linear relationship between TDG exchange and unit spillway discharge. The observed TDG saturation on Transect T1 was generally greater than or equal to the observed TDG saturation at CHJT2P5. The slightly higher observations of TDG saturation on Transect T1 may be attributed to the further exchange of TDG downstream of the sampling station. The TDG gas exchange within the aerated flow regime downstream of the stilling basin has been found to be dominated by bubbles stripping dissolved gas from the water column as the mean depth of bubbles rises above the compensation depth (Schneider and Wilhelms, 1996). The close correspondence between independent measures of TDG exchange at Chief Joseph Dam support the conclusion that during standard spill patterns the TDG saturation measured at the tailwater FMS is representative of TDG levels in spillway releases. The agreement of the mass conservation formulation with direct observations of TDG saturation in Transects T1 and T2 was found without a powerhouse entrainment component. This observation suggests that the interaction of spillway and powerhouse discharges during standard spillway releases up to 96.5 kcfs does not substantially increase the TDG loading below CJD.

39. The production of TDG pressures during spillway releases as determined from this study compared favorably to historic conditions for unit spillway discharges up to 5 kcfs/bay. The unit spillway discharge during the 1997 spill season is shown in Figure 27 along with the results from this study. The maximum TDG pressure generated in this study was 134 percent as compared 144.5 percent in 1997. The depth of flow below the spillway during the high flow conditions in 1997 was up to 8 ft deeper than conditions observed during June of 1999. This additional 8 ft of depth represents a 20 percent increase in mean depth of flow in the tailrace channel, which could account for the higher exchange rates as a function of unit discharge.

40. The exponential relationship between TDG production and unit spillway discharge was also observed at Ice Harbor Dam prior to the installation of spillway flow deflectors (Schneider and Wilhelms, 1997). At Ice Harbor Dam, the TDG saturation approached a maximum threshold between 139 and 145 percent for unit spillway discharges of 8 kcfs/bay and higher. The TDG production for CJD during 1997 and Ice Harbor Dam during 1996 prior to the addition of flow deflectors, are shown in Figure 28 as a function of discharge per bay. The data from CJD during 1997 does not appear to have reached an upper threshold as observed at Ice Harbor Dam. The discharge per ft would be a better means of comparing the specific discharge between these two projects since spillbay widths at Chief Joseph Dam were 49 ft as compared to 62 ft at Ice Harbor Dam. This would result in a closer correspondence of TDG production as a function of spillway discharge between Ice Harbor and Chief Joseph Dams.

41. The scheduling of partial spill patterns using only 9 bays was a result of an effort to reduce the impacts of elevated TDG supersaturation in the mid-Columbia River during the testing period. Several spillway events were scheduled to compare the TDG production of a standard and partial spillway release for the same unit spillway discharge. Partial and full spillway releases were scheduled for unit spillway releases of 5 kcfs/bay (Events 3 and 4) and 3 kcfs/bay (Events 6 and 8) on 6 and 7 June 1999. The results of these paired tests are mixed with TDG levels significantly higher on Transect T1 during the partial spillway events. The TDG saturation at all five stations on Transect T1 is shown for all 14 events in Figure 29. The comparison of TDG saturation

for Events 3 and 4 indicates the partial spill resulted in increased TDG saturation ranging from 8 to 34 percent saturation. The TDG saturation increased on four of the five stations on Transect T1 for Events 6 and 8. The TDG saturation on Transect T2 is shown in Figure 30 for all 14 events. The maximum TDG saturation at Station CHJT2P5 was found to be same for Events 3 and 4 despite the significantly higher levels observed on Transect T1. The TDG saturation associated with the partial Spill Event 8 at Station CHJT2P5 was significantly less than comparable conditions observed during Event 6. The encroachment of the mixing zone to Station CHJT2P5 was partially responsible for the lower TDG levels during Event 8. The estimated spillway TDG saturation using Equation 2 resulted in higher TDG levels associated with both partial patterns as shown in Figure 31 which supports the observation made on Transect T1. These observations raise serious questions concerning the usefulness of partial spill patterns for estimating the TDG exchange associated with standard patterns with the same specific discharge.

42. The powerhouse loading was shifted from the east end on 6 June to the west end on 7 June to determine if the interaction of powerhouse and spillway discharges change. On 6 June, turbine units 1 through 14 were scheduled to generate power during the testing period. The hydropower load was shifted to the west end of the powerhouse away from the aerated spillway discharges on 7 June. The total spill discharges of 16,9, 55.4, and 96.5 kcfs were scheduled on both 6 and 7 June as Events 1, 2, 3, 5, 6 and 7, respectively. The resultant TDG saturation on Transects T1 and T2 as shown in Figures 29 and 30 indicate very little difference between these paired test conditions. The integration of transect TDG and estimation of spillway TDG as outlined in Equation 2 also supports the conclusion that the total loading associated with spillway releases from CJD was independent of the operating conditions of the powerhouse.

43. The influence of the tailwater channel depth on TDG exchange was investigated during spillway events conducted on 10 June. A spillway discharge of 35 kcfs (Event 9) was established during the early morning hours with tailwater conditions ranging from 783 to 784.5 ft as shown in Figure 9. During the afternoon of 10 June (Event 11), the powerhouse discharges were reduced by almost 90 kcfs resulting in falling tailwater elevations reaching a minimum elevation of 778.4 ft or almost 6 ft lower than conditions maintained earlier in the day. The influence of tailwater channel depth was explored through comparing TDG saturation in Transects T1 and T2 and through estimates of the average TDG of spillway flows based on Equation 2. On Transect T1 (Figure 29) the TDG saturation for Events 9 and 11 were similar. The maximum TDG saturation at Station CHJT2P5 was 125 percent for the lower tailwater conditions during Event 11 as compared to 122.5 percent for Event 9. The TDG saturation associated with spillway flows was estimated using mass conservation principle outlined in Equation 2. The estimated TDG saturation for Event 11 was slightly higher than estimated for Event 9 as shown in Figure 31. The very high percentage of the river spilled coupled with the malfunction of the instrument at Station CHJT2P2 may have resulted in slightly higher estimates for the TDG content of spillway releases for Event 11. These findings do not fully support the assumption of a positive relationship between TDG exchange and tailwater depth of flow. A second flow condition at low tailwater conditions was aborted on 10 June due to power management constraints. The single test conditions at a low tailwater elevation did not afford a rigorous determination of the role of tailwater elevation on TDG exchange at CJD. The evaluation of historic TDG data from the tailwater FMS along with project operations data may provide additional insight into the influence of tailwater depth on TDG production at CJD.

44. The transport of TDG plumes through Lake Pateros caused by spillway releases from CJD were influenced by the side channel inflows from the Methow and Okanogan Rivers, meteorologic conditions, dispersion and mixing CJD releases, and gross water movement based on operations at both Chief Joseph and Wells Dam. The amount of storage in Lake Pateros changed significantly during the testing period with pool elevations at Wells Dam ranging from 781 ft on 7 June to 775 ft on 9 June. This total volume in Lake Pateros was estimated during each hour of the testing period at a function of the forebay water surface at Wells Dam. The hourly storage volume was approximated by the following equation, which assumes a linear variation in reservoir storage between the minimum and maximum operating pool for Lake Pateros.

$$Vol = 9.7*FBE-7244.7 \qquad 3$$

Where

Vol = Lake Pateros Volume (Acre-ft)
FBE = Forebay Elevation at Wells Dam (ft)
$781 > FBE > 771$

45. The time of travel through Lake Pateros was based upon a plug flow analogy. The theoretical time of travel through Lake Pateros was estimated from the cumulative hourly discharge from Wells Dam and the corresponding volume in Lake Pateros as estimated from equation 3. The theoretical travel time was determined by the time required for the cumulative volume of Well's releases to equal the storage volume in Lake Pateros. This theoretical travel time was reduced by 10 percent to account for the non-uniform lateral distribution of flow causing a shorter travel time of the main plume located in the thalweg of the channel. The 10 percent reduction in travel time was selected to match the observed arrival of elevated TDG pressures at Wells Dam. The estimated travel time through Lake Pateros for the duration of the study period is shown in Figure 32. The travel time ranged from 16.2 hour on 10 June to 19.8 hours on 6 June.

46. The average hourly loading observed at Transect T2 was routed through Lake Pateros using the estimated travel time based on plug flow conditions, dilution from side channel inflows, and dispersion from non-uniform transport of spillway releases from CJD. The influence from temperature differences was not accounted for in this analysis. The average TDG pressure on Transect T2 was estimated from a flow weighted average of pressures observed from all four active stations. The side channel TDG pressures of 771 mmHg and 764 mmHg were assigned to the Methow and Okanogan Rivers, respectively. The average TDG pressure at Wells Dam was approximated from the flow weighted inflow from CJD, Methow River, and Okanogon River. The routing of these TDG pressures to Wells Dam without dispersion is shown in Figure 33. The timing of TDG events is closely reproduced with this approximation but the magnitudes and duration of elevated TDG pressures at Wells Dam are significantly in error. The heterogeneity in the velocity field throughout Lake Pateros will result in a differential transport of TDG plumes. The variation of channel features throughout Brewster Flats results in widely different

times of travel through this reach. This differential transport will cause the mixing of water released at different times from CJD. A normal distribution with a standard deviation of 10 hours was used to redistribute or smooth the TDG pressures in time. The routing of TDG pressures to Wells Dam based on inflows from CJD, the Methow River, and the Okanogan River subject to dispersive processes approximated by a normal distribution smoothing function (Standard Deviation=10 hrs) is shown in Figure 34. The standard deviation of the smoothing function was determined fitting the characteristics of the estimated TDG pressures at Wells Dam with observed conditions. The timing, magnitude, and duration of the estimated TDG pressures at Wells Dam were well represented by this approximation. The estimate errors of peak TDG pressures were generally well within 8 mmHg or about one percent saturation while the average estimate error was less than 4 mmHg. The routing procedure is mass conserving and does not account for any degassing through the water surface during transport through the pool. The relatively close comparison of TDG loading at Wells Dam suggests minimal degassing occurred in Lake Pateros during this study period from 6-10 June 1999.

47. An independent analysis of TDG loading throughout Lake Pateros was conducted to assess the degree of in-pool degassing. The flow-weighted averaged TDG pressure was integrated over a 24-hour period at Transects T2, T3, and Wells Dam to arrive at estimates of TDG loading by river mile. The starting and ending times for integration of observed data varied from transect to transect and day to day to cover a short period prior and after elevated TDG pressures. The TDG pressures returned to ambient levels at each transect prior to the arrival the following day's spillway discharge. The weighting coefficients outlined in paragraph 38 were applied at Transect T2. The weighting coefficients applied at Transect T3 were 0.2, 0.3, 0.3, and 0.2 for Stations CHJT3P1, CHJT3P2, CHJT3P3, and CHJT3P4, respectively. The weighting coefficients applied across the Wells Dam stations were 0.2, 0.6, and 0.2 for Stations WELFBPH, WELFBMID, and WELFBSW, respectively. The CJD project discharges were used at Transects T2 and T3 while the Wells Dam discharges were applied at the downstream transect.

48. The results from this analysis are summarized in Table 2 for conditions associated with operations at CJD on 6-10 June. The influence of the Okanogan River was added to the conditions at Transect T2 to estimate the average TDG at Transect T3. In a similar manner, the side channel flows from the Methow and Okanogan Rivers were added to the conditions at Transect T2 to estimate the TDG pressures at Wells Dam. The TDG pressures at CJD forebay were from 4.5 to 19.5 mmHg less than the corresponding TDG pressures at Wells Dam with the exception of conditions on 8 June (no spillway discharges) when the TDG pressures at CJD forebay were greater than at Wells Dam. The reduction in TDG pressures between Transect T2 and T3 ranged from 4.3 to 11.1 mmHg, much of which can be associated with side channel inflow from the Okanogan. The reduction in TDG pressures between Transect T3 and the Wells Dam forebay ranged from 2.4 to 7.9 mmHg. Again, much of the reduction in TDG pressures below Brewster Flats can be associated with the side channel inflow from the Methow River. The comparison of flow-weighted TDG pressures at Wells Dam suggests little loss of mass during transport through the pool.

49. Total dissolved gas criteria for the tailwater fixed monitoring stations as stated in the 1997 Biological Opinion (NMFS, 1997) were not violated during this test. The highest 12 hour TDG saturation measured during the testing period at Wells Dam was 113.5 percent on 11 June as listed in Table 3. The TDG conditions at the tailwater FMS were routinely in violation of the stated criteria with the maximum 12-hr average saturation ranging from 122.8 to 128.8 during days with spillway discharge and the maximum 2-hr TDG saturation ranging from 133.2 to 137.0. The spill cap associated with TDG levels of 120 percent would fall between 1 and 2 kcfs/bay or 18-36 kcfs total spill. Short duration spillway releases of 36 kcfs could be implemented without exceeding 125 percent saturation at the tailwater FMS.

Conclusions

50. The following conclusions were drawn from a preliminary review of velocity and TDG data taken in conjunction with spillway releases from Chief Joseph Dam during 6-11 June 1999. The manual water quality and velocity sampling data will be incorporated into subsequent analyses of these observations providing refined estimates of TDG mass loading and the entrainment rate powerhouse releases.

51. The average TDG production from standard spillway releases at Chief Joseph Dam was found to be an exponential function of the unit spillway discharge. The TDG saturation ranged from 111 percent for a unit spillway discharge of 1 kcfs/bay to 134 percent for spillway discharges of 5 kcfs/bay and larger.

52. The TDG saturation as measured at the tailwater FMS was representative of spillway releases. If the percentage of river spilled is less than 15 percent, observations at the tailwater FMS were biased by dilution with powerhouse releases. Strong lateral gradients in TDG pressure were apparent across the river at the tailwater FMS with conditions on the left bank reflecting powerhouse releases and TDG pressures on the right bank reflecting conditions in spillway discharges.

53. The average TDG pressure introduced into Lake Pateros can be estimated using the project operations data together with forebay and tailwater TDG observations. The flow weighted TDG pressure can be estimated by associating the tailwater TDG pressure with the spillway discharge and the forebay TDG pressure with the powerhouse discharge.

54. The water quality data recorded on the instrument at the tailwater FMS was significantly different than the data recorded at nearby stations during the testing period. The time of response of TDG pressures measured at CHQW were much longer than observed at Station CHJT2P5. The peak and background saturation as measured at CHQW was 2-3 percent higher than the paired observations from temporary stations used during the study. The water temperature at CHQW was also about 1 ^{o}C higher than water temperatures measured at Transect T2. These findings indicate a consistent difference in the calibration and/or operation of the CHQW FMS for both dissolved gas pressure and water temperature with measurements made with the field studies research instruments. The expected accuracy in TDG based on historical calibration drift data and as presented in Appendix A for the research instruments is within 7 mm hg of the true dissolved gas pressure or within approximately 1 percent TDG saturation.

55. The TDG pressures of powerhouse releases were nearly identical to TDG pressures measured in the forebay. The powerhouse releases simply pass on TDG conditions created at upstream dams. Several events during lower total river flows indicated a slight elevation (1-2 percent saturation) of TDG saturation associated with releases from the east end of the powerhouse.

56. The redistribution of powerhouse releases from the east to west ends of the powerhouse did not influence TDG loading delivered from CJD. The entrainment of powerhouse releases into the aerated plume of spillway discharges appears to be quite small and does not significantly influence the TDG produced during project operation.

57. Partial spill patterns generated significantly different TDG loading than the standard spill pattern with the same unit spillway discharge. The partial spill pattern yielded higher TDG pressures than the standard pattern for both 3 and 5 kcfs/bay spillway flows. Partial spill patterns cannot be used to reliably estimate the TDG exchange associated with standard spill patterns at Chief Joseph Dam.

58. The influence of tailwater elevation on TDG exchange was not rigorously quantified by these testing results. The duration of Event 14 was too short to determine the effects of tailwater depth on TDG exchange at CJD. The lower tailwater elevations associated with Event 11 (2 kcfs/bay) resulted in both lower and higher TDG pressures at Transect T1 when compared to conditions observed during Event 9.

59. Powerhouse and spillway releases quickly mix in the first 5 miles below CJD. The TDG pressures were nearly uniform at the upstream end of Brewster Flats during test conditions monitored on 6 and 7 June. The mixing of powerhouse and spillway releases greatly attenuated the peak TDG pressure generated during testing conditions. The degree of peak attenuation will be a function of the magnitude of spillway releases and ambient TDG pressures arriving from upstream dams.

60. The contribution of flows from the Methow and Okanogan Rivers provided a significant contribution to TDG pressures in the Columbia River and forebay at Wells Dam. The lower TDG content of these side channel flows coupled with the cooler water temperatures resulted in the moderation of TDG pressures in Lake Pateros and in the forebay of Wells Dam.

61. The variation in transport characteristics in Brewster Flats resulted in the dispersion of high TDG plumes generated during spillway releases from CJD. This dispersion leads to mixing of waters released at different time periods, the subsequent attenuation of peak TDG pressures, and longer duration of elevated pressures observed below the Brewster Flats reach.

62. The magnitude of in-pool degassing from Transect T2 down to the Wells Dam forebay was found to be an average of 12 mm Hg (Table 2) for the conditions observed during this testing period. The moderate wind conditions coupled with the low ambient TDG levels contributed to

these findings. The strong wind events on 5 June may have contributed to a decrease in TDG pressures as observed in the forebay of Wells Dam on the June 5th and 6th. The exchange of TDG at the water surface may be an import process during other lake conditions involving higher ambient TDG pressures and windy conditions.

63. The time of travel of TDG plumes through Lake Pateros ranged from 16 to 20 hours. The deeper flow conditions in the lower half of Lake Pateros contribute to lower mean velocities of flow in this region. The lowest velocity conditions were found in the Brewster Flats regions due to the wide and shallow channel cross section throughout this reach.

64. The impacts of this test on the daily average TDG pressures observed at Wells Dam were minimal. The hourly average TDG pressure at Wells Dam during the period from 6-11 June was 109.8 compared to 109.7 measured in CJD forebay. The lower TDG contribution from side channel flows cancelled out the higher TDG pressures generated during scheduled spillway discharges.

65. Total dissolved gas criteria for forebay fixed monitoring stations as stated in the 1997 supplemental biological opinion were not violated during this test. The highest 12-hour TDG saturation measured during the testing period at Wells Dam was 113.5 percent on 12 June. The TDG conditions at the tailwater FMS were routinely in violation of the 12-hr and 2-hr TDG constraints of 120 and 125 percent, respectively.

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References

Seattle District Corps of Engineers, "Chief Joseph Dam Dissolved Gas Abatement Study", Nov. 1998.

Schneider, M. L. and Wilhelms,S.C., 1998. " Total Dissolved Gas Exchange during Spillway Releases at Little Goose Dam,February 20-22, 1998," CEWES-HS-L Memorandum for Record dated December 10, 1998, US Army Waterways Experiment Station, Vicksburg MS.

Schneider, M. L. and Wilhelms,S.C., 1996. " Near Field Study of Total Dissolved Gas in The Dalles Spillway Tailwater" CEWES-HS-L Memorandum for Record dated December 16, 1996, US Army Waterways Experiment Station, Vicksburg MS.

Schneider, M. L. and Wilhelms,S.C., 1997. "Total Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater, June 27-28", 996 CEWES-CS-L Memorandum for Record dated 27 January, 1997, US Army Waterways Experiment Station, Vicksburg MS.

National Marine Fisheries Service, Supplemental Biological Opinion 1997, " Endangered Species Act Section 7 Consultation Regarding 1994-1998 Operation of the Federal Columbia River Power System and Juvenile Transportation Program in 1995 and Future Years.", Available from: NMFS, Northwest Region, 7600 Sand Point Way N.E., BIN C15700 Bldg. 1, Seattle, Washington 98115.

RD Instruments. 1995. Direct Reading and Self-contained Broadband Acoustic Doppler Current Profiler Technical Manual, San Diego, CA.

Appendix A. Water Quality Instrument Calibration and Maintenance

The Hydrolab Corp. Model DS4® was used exclusively for water quality monitoring in the Chief Joseph Dam TDG Field Studies. The model DS4® 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. 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. Adjustments and calibrations 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

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 a portable field barometer that had 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. 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. The membrane is bypassed during these calibrations so that the probe itself is calibrated, rather than the probe/membrane combination. The condition of the membrane and any condensation trapped inside it could influence readings and result in a false calibration.

An inspection for leaks was performed on the membrane itself before completing the calibration routine. One of the checks employed involves immersing the membrane in seltzer water. 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 through a tear. Defective membranes were replaced before use.

Calibration of Dissolved Oxygen

DO calibration followed procedures developed in the CE DGAS field sampling program. A water bath was employed so that more than one instrument could be rapidly calibrated 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 percent 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. Several additional Winkler titrations are performed throughout the calibration procedure for the rest of the instruments to ensure consistency.

Water Quality Calibration Data from COE DGAS Field Studies

Calibration checks and necessary adjustments performed on the Hydrolab DS4 instruments® have been documented during the 1996, 1997, 1998, and 1999 field sampling for the CE DGAS program on the Lower Columbia and Lower Snake Rivers. The status of each of the parameters before and after each calibration check and adjustment was 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 DS4s and all deployments. The data assessed in this evaluation reflect only the calibrations performed on instruments before and after deployments that resulted in readings that were included in the study database. Logs for instruments requiring large-scale adjustments exceeding factory recommendations were not included in the data set. In addition, data logs resulting from instruments determined to be malfunctioning based on normal quality assurance criteria established by the manufacturer were 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 it's expected 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) post operation calibration shift in DO over all years and instrument types was 0.07 mg/l ±1.07 mg/l. The mean (±2 standard deviations) post deployment calibration shift in TDG pressure over all years and instrument types was 0.43 mm Hg ± 3.8 mm Hg.

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

YEAR	Parameter	N	Minimum	Maximum	Mean	Std. Deviation
1996	DO	253	-2.2	2.1	0.13	0.56
	TDG	235	-21.0	19.0	0.14	5.8
	TDG	235	-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
	TDG	494	-16.0	18.0	0.43	3.5
1998	DO	296	-2.3	2.1	0.06	0.68
	TDG	316	-7.0	8.0	0.67	2.1
	TDG	316	-7.0	8.0	0.67	2.1

1999	DO	25	-0.7	0.9	0.06	0.38
	TDG	24	0.0	6.0	0.67	1.6
	TDG	24	0.0	6.0	0.67	1.6
Combined	DO	1033	-2.4	2.1	0.07	0.54
Years	TDG	1069	-21.00	19.0	0.44	3.7

Of the approximately 1,100 TDG and DO pre-deployment calibrations performed over the four DGAS sampling seasons, only 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 DGAS 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 range we 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.

Appendix B. Velocity Instrumentation and Methods

Acoustic Doppler Current Profiler (ADCP)

A vessel-mounted RD Instruments® acoustic Doppler current profiler (ADCP) was used to measure water velocity and discharge. The instrument used was a 600 kHz ADCP with 20º convex transducers. The manufacturer's specifications state the instrument's accuracy to be within ±3 cms^{-1}, as configured.

The ADCP utilizes four ceramic transducers capable of emitting and receiving sound signals to measure the change in frequency (Doppler shift) of reflected sound energy. Energy is reflected by *scatterers* (suspended particles, e.g. phytoplankton) that are assumed to be moving in the same direction and at the same velocity as the water in that layer. The ADCP measures its own movement, via boat movement, and subtracts its motion from the water velocity measurements to track the distance traveled by the ADCP for discharge calculations.

Every signal set emitted by the ADCP consists of four water and four bottom *pings* (individual sound bursts). *Water pings* are signals reflected from scatterers and *bottom pings* are signals reflected from the river bottom. The ADCP differentiates between water and bottom pings based on the relative intensity of the return signals since return signals from the bottom are of greater intensity owing to the hardness of the bottom relative to that of the scatterers. A set of four pings of each type constitutes an *ensemble*.

The ADCP is moved across the river channel from shore-to-shore as slowly as possible, thus allowing many ensembles to be averaged for flow measurements. The river cross-section is referred to as a *transect* with each movement across referred to as a *pass*. The cross-sections are subdivided into one meter by ten-meter cells called *bins*. The upper portion of the profile is unmeasured because of the submergence of the transducers and the mechanics of the sound transmission. The unmeasured upper layer is approximately 1m thick. Velocity measurements for the bottom 6 percent of the profile are excluded due to interference between the four sound cones. The ADCP estimates discharge for the upper and lower unmeasured sections by extrapolating from the nearest good measurements.

Further discussion of the technical workings of the ADCP is beyond the scope of this work. Interested readers are directed to the "Direct Reading and Self-contained Broadband Acoustic Doppler Current Profiler Technical Manual" (RD Instruments 1995).

Global Positioning System (GPS)

A Trimble Navigation global positioning system (GPS) model AGGPS was used to geo-reference the ADCP data and water quality data. The manufacturer's specifications stated the instrument's position accuracy to be within 16 m. Geo-referencing of the velocity data allowed them to be projected onto real-world maps. Although the ADCP generates detailed records of its movements over the river bottom, it had no means of referencing its starting location in earth coordinates. Position data will be collected independently of, and coincident with the velocity data. The position data will be merged with the incoming ADCP data such that the final data set contained both.

ADCP Sampling Protocol

ADCP data collection is designed to coincide with the water quality sampling. While it is desirable to have multiple passes for all transects, time limitations may preclude intensive sampling.

ADCP Data Processing

The ADCP reports the water velocity components in the north/south, east/west, and vertical directions for each bin in a pass. From these, the ADCP calculates the discharge for each bin in the measured section of the profile, and extrapolates the discharge for the unmeasured top and bottom layers. The component discharges are summed across a transect to yield the total discharge. To compute an accurate total discharge, it is necessary for the ADCP to consider the direction of the flow with respect to the ADCP's movement. This is important so that upstream flow, resulting from eddies or other phenomena are subtracted from the total discharge estimate. A more thorough discussion of discharge extrapolation and measurement may be found in the "Direct Reading and Self-contained Broadband Acoustic Doppler Current Profiler Technical Manual" (RD Instruments 1995).

ADCP Data Analysis

The ADCP data acquisition software will produce the following three files for each pass:

1. A *raw* data file consisting of every ensemble collected during a pass,
2. A *navigation* file consisting of all of the GPS data collected during a pass,
3. A *processed* data file consisting of ADCP and GPS data that had been averaged to the operator specified interval (in units of time or space).

To perform meaningful analyses, it was necessary to translate the ADCP text files into a format that was usable by data management software.

Table 1. Chief Joseph Dam and Spillway Operating Conditions, 6-10 June 1999

Spill Event	Date	Time	Forebay Elevation (ft)	Tailwater Elevation (ft)	Total River Flow (kcfs)	Power-house Flow (kcfs)	Spillway Flow (kcfs)	Spill Bay Discharge (kcfs)																		
								B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19
1	06/06/99	0800-1000	954.0	784.8	178.1	161.2	16.9	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	06/06/99	1000-1145	954.5	784.3	182.1	126.8	55.3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3	06/06/99	1400-1545	954.9	784.7	184.1	87.6	96.5	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
4	06/06/99	1600-1745	954.8	784.8	185.8	137.4	48.4	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5
5	06/07/99	0800-0930	953.1	786.8	181.8	164.9	16.9	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	06/07/99	1000-1145	953.1	784.7	177.2	122.7	54.5	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
7	06/07/99	1400-1545	953.7	786.0	180.4	84.8	95.6	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
8	06/07/99	1600-1745	953.7	785.6	183.0	155.5	27.5	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3
9	06/09/99	0500-0945	951.3	783.3	173.2	137.8	35.4	0	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2
10	06/09/99	1400-1545	951.5	783.1	184.3	93.7	90.6	0	0	0	0	0	0	0	0	0	0	10	10	10	9	9	9	9	9	9
11	06/09/99	1700-1845	954.6	778.9	86.5	50.1	36.4	0	2	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2
12	06/10/99	0500-1000	950.8	785.4	196.6	121.3	75.3	0	4	4	4	4	4	4	4	4	5	5	4	4	4	4	4	4	4	4
13	06/10/99	1400-1545	950.9	784.6	197.7	127.5	70.2	0	0	0	0	0	0	0	0	0	0	8	8	8	7	7	7	7	7	7
14	06/10/99	1600-1645	952.3	781.8	89.2	51.7	37.5	0	0	0	0	0	0	0	0	0	0	5	4	4	4	4	4	4	4	4

Event	Date	Start	End	Qriver	Qgen	Qspill	CHJT2P1	CHJT2P3	CHJT2P4	CHJT2P5
1	6/6/99	8:15 AM	10:00 AM	178.1	161.2	16.9	108.7	108.6	109.0	109.3
2	6/6/99	10:15 AM	11:45 AM	182.1	126.8	55.3	108.6	109.4	118.7	129.7
3	6/6/99	2:00 PM	3:45 PM	184.1	87.6	96.5	109.4	116.0	129.2	133.5
4	6/6/99	4:00 PM	5:45 PM	185.8	137.4	48.4	108.7	109.7	120.5	133.4
5	6/7/99	8:00 AM	9:30 AM	181.8	164.9	16.9	109.0	108.7	109.1	109.4
6	6/7/99	10:00 AM	11:45 AM	177.2	122.7	54.5	108.7	109.9	118.5	129.6
7	6/7/99	2:00 PM	3:45 PM	180.4	84.8	95.6	109.4	116.9	129.6	133.6
8	6/7/99	4:00 PM	5:45 PM	183.0	155.5	27.5	109.3	109.5	113.7	123.3
9	6/9/99	5:00 AM	9:45 AM	173.2	137.8	35.4	109.1	109.2	113.0	122.6
10	6/9/99	6:00 AM	3:45 PM	184.3	93.7	90.6	109.8	118.1	129.2	133.9
11	6/9/99	5:00 PM	6:45 PM	86.5	50.1	36.4	109.5	112.6	122.3	125.2
12	6/10/99	5:00 AM	10:00 AM	196.6	121.3	75.3	109.8	111.3	124.4	134.3
13	6/10/99	2:00 PM	3:45 PM	197.7	127.5	70.2	110.0	112.7	125.0	133.7
14	6/10/99	4:00 PM	4:45 PM	89.2	51.7	37.5	110.6	119.4	128.6	133.5

Event	Start	Start	End	Qriver	Qgen	Qspill	CHJT0P1	CHJT1P1	CHJT1P2	CHJT1P3	CHJT1P4	CHJT1P5
1	6/6/99	8:15 AM	10:00 AM	178.1	161.2	16.9	111.4	111.5	112.2	111.5	111.4	111.1
2	6/6/99	10:15 AM	11:45 AM	182.1	126.8	55.3	134.8	131.3	132.7	133.3	130.4	129.7
3	6/6/99	2:00 PM	3:45 PM	184.1	87.6	96.5	147.3	133.8	135.9	138.2	138.9	135.9
4	6/6/99	4:00 PM	5:45 PM	185.8	137.4	48.4	172.9	168.1	149.9	146.3	150.9	146.2
5	6/7/99	8:00 AM	9:30 AM	181.8	164.9	16.9	111.8	111.9	112.3	111.5	111.5	111.4
6	6/7/99	10:00 AM	11:45 AM	177.2	122.7	54.5	136.5	133.6	134.7	133.2	130.4	129.7
7	6/7/99	2:00 PM	3:45 PM	180.4	84.8	95.6	147.2	138.0	136.8	140.2	137.1	134.4
8	6/7/99	4:00 PM	5:45 PM	183.0	155.5	27.5	146.6	139.9	132.0	134.0	132.8	133.3
9	6/9/99	5:00 AM	9:45 AM	173.2	137.8	35.4	126.2	125.3	127.3	126.5	126.5	125.0
10	6/9/99	6:00 AM	3:45 PM	184.3	93.7	90.6	166.1	145.9		140.0	142.3	143.2
11	6/9/99	5:00 PM	6:45 PM	86.5	50.1	36.4	129.9	122.3		130.8	124.7	124.7
12	6/10/99	5:00 AM	10:00 AM	196.6	121.3	75.3	137.0	120.1		140.9	139.0	136.2
13	6/10/99	2:00 PM	3:45 PM	197.7	127.5	70.2	172.7	152.7		142.0	149.7	145.1
14	6/10/99	4:00 PM	4:45 PM	89.2	51.7	37.5	158.8	148.1		138.5	139.4	139.9

Event	Start	Start	End	Qriver	Qgen	Qspill	CHJFBMID	CHJFBNSW	CHJFBWPH	CHJFMS	CHJDFTE	CHJDFTW
1	6/6/99	8:15 AM	10:00 AM	178.1	161.2	16.9	108.9	108.9	108.9	109.3	108.9	108.3
2	6/6/99	10:15 AM	11:45 AM	182.1	126.8	55.3	109.2	108.9	109.2	#N/A	115.7	108.4
3	6/6/99	2:00 PM	3:45 PM	184.1	87.6	96.5	109.1	109.1	109.2	#N/A	120.9	108.8
4	6/6/99	4:00 PM	5:45 PM	185.8	137.4	48.4	109.1	108.9	109.2	#N/A	126.0	108.7
5	6/7/99	8:00 AM	9:30 AM	181.8	164.9	16.9	109.0	108.9	108.9	#N/A	110.7	109.0
6	6/7/99	10:00 AM	11:45 AM	177.2	122.7	54.5	109.3	109.2	109.3	#N/A	132.7	108.6
7	6/7/99	2:00 PM	3:45 PM	180.4	84.8	95.6	109.6	109.3	109.6	#N/A	131.0	109.3
8	6/7/99	4:00 PM	5:45 PM	183.0	155.5	27.5	109.6	109.5	109.3	#N/A	137.8	109.3
9	6/9/99	5:00 AM	9:45 AM	173.2	137.8	35.4	109.7	109.6	109.6	#N/A	112.7	109.0
10	6/9/99	6:00 AM	3:45 PM	184.3	93.7	90.6	109.9	110.4	109.7	#N/A	127.2	109.2
11	6/9/99	5:00 PM	6:45 PM	86.5	50.1	36.4	110.1	110.0	109.7	#N/A	115.1	109.5
12	6/10/99	5:00 AM	10:00 AM	196.6	121.3	75.3	110.5	110.4	110.3	110.9	112.3	109.5
13	6/10/99	2:00 PM	3:45 PM	197.7	127.5	70.2	110.7	110.5	110.8	#N/A	128.9	109.9
14	6/10/99	4:00 PM	4:45 PM	89.2	51.7	37.5	111.1	110.7	110.8	#N/A	126.0	111.3

Table 3. Daily Summary of Transect Array and Fixed Monitoring Station Total Dissolved Gas Saturation.											
Date	Total Dissolved Gas Saturation (%)										
	Chjfb[+] Array-3	CHJ-FMS	T1 Array-5	T2 Array-4	CHQW-FMS			T3 Array-4	Welfb[#] Array-3	WEL-FMS	
	24 Hr	24 Hr	24 Hr	24 Hr	24 Hr	12 Hr*	2 Hr*	24 Hr	24 Hr	24 Hr	12 Hr*
6/6/99	109.1	109.5	122.2	111.1	117.4	123.7	137.0	109.3	107.1	107.1	107.4
6/7/99	109.2	109.6	119.7	110.8	116.7	122.8	133.7	110.4	109.9	110.0	111.5
6/8/99	109.8	110.2	110.0	109.3	110.8	111.2	111.8	109.5	109.9	109.9	111.0
6/9/99	109.8	110.2	120.2	111.6	117.6	124.4	133.2	110.0	108.6	108.4	108.8
6/10/99	110.5	110.9	124.2	113.3	120.2	128.8	136.1	112.8	111.3	111.5	112.4
6/11/99	109.6	111.3	110.0	108.9	111.0	111.2	111.7	109.7	111.9	112.5	113.5

* 2 or 12 highest hourly measurements.
+ Chief Joseph Dam Forebay
# Wells Dam Forebay

Table 2. Flow Weighted Average Total Dissolved Gas Pressure at Selected Columbia River Transects (24 hour average)									
Date	Starting Time for 24 Hour Flow-Weighted Average			Total Dissolved Gas Pressure (mmHg)					
	CJD FB & Transect T2	Transect T3	Wells Forebay	CJD Forebay	Transect T2	Transect T2 + Okanogan	Transect T2 + Methow and Okanogan	Transect T3	Wells Forebay
6/6	9:00 AM	15:00 PM	24:00 PM	809.6	831.8	826.8	822.5	824.8	817.5
6/7	9:00 AM	15:00 PM	24:00 PM	812.6	832.9	827.3	821.3	822.8	817.1
6/8	9:00 AM	15:00 PM	24:00 PM	816.0	817.7	814.3	811.5	813.4	807.8
6/9	4:00 AM	10:00 AM	22:00 AM	816.5	836.1	831.5	828.5	831.1	824.9
6/10	4:00 AM	10:00 AM	22:00 AM	822.3	848.2	840.5	835.9	843.2	840.8

Okanogan Inflows added to Transect T2 Pressures
& Okanogan and Methow Inflows added to Transect T2 Pressures

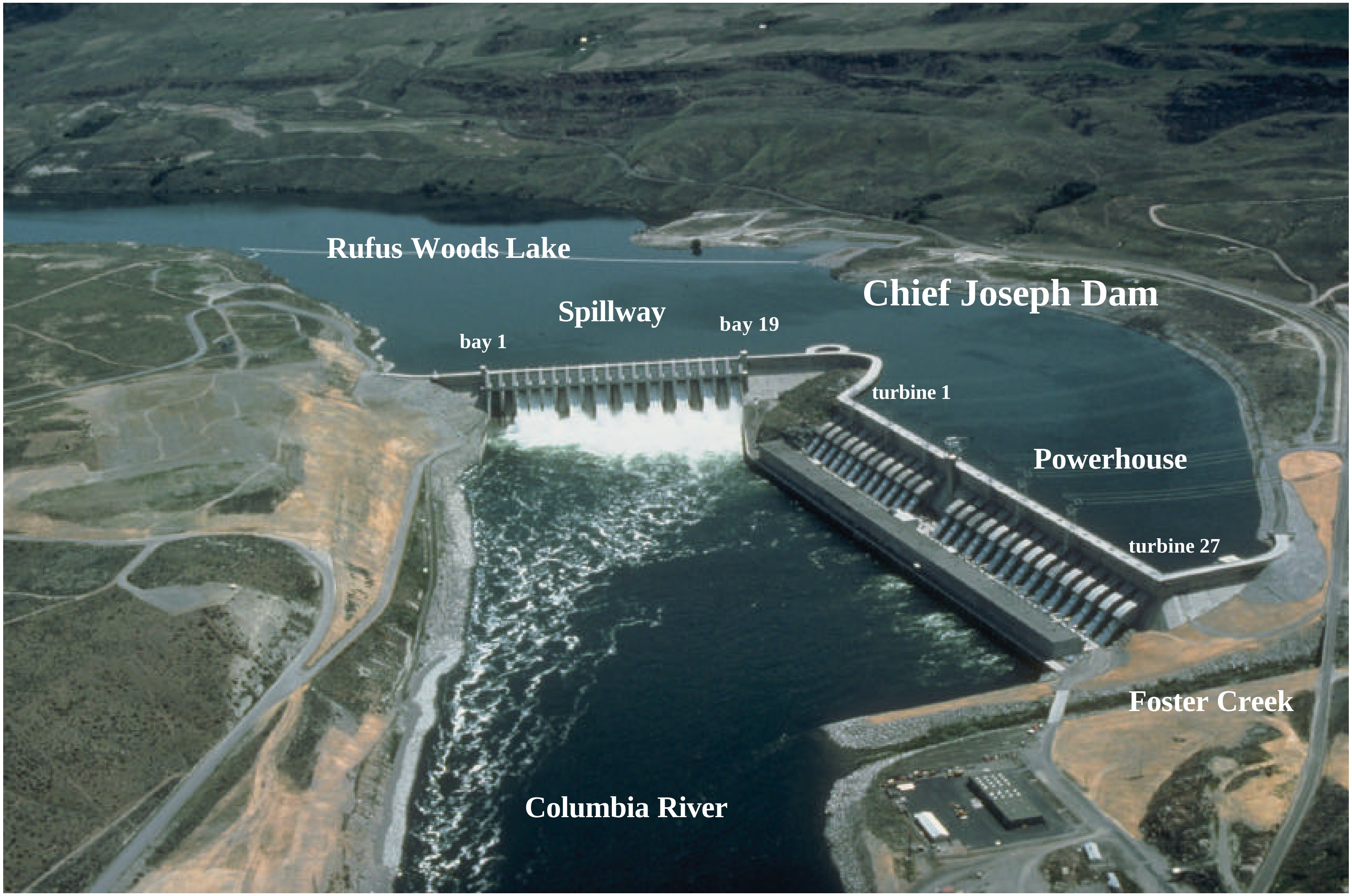

Figure 1. Aerial Photograph of Chief Joseph Dam, Rufus Woods Lake, and the Columbia River.

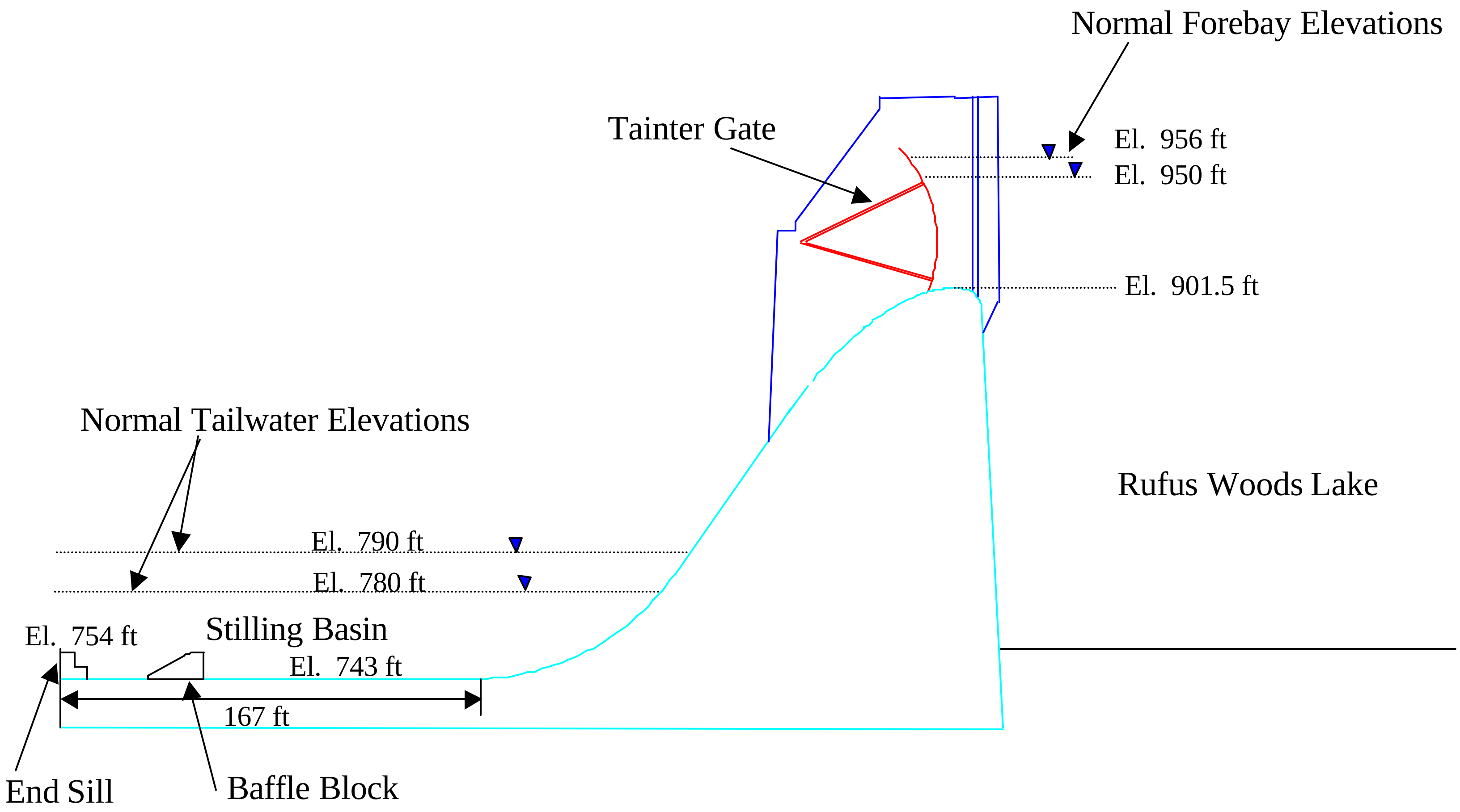

Figure 2. Profile View of Chief Joseph Spillway with Typical Water Surface Elevations.

Figure 3. Tailrace Channel Bathymetry Below the Spillway at Chief Joseph Dam, 1998 Survey.

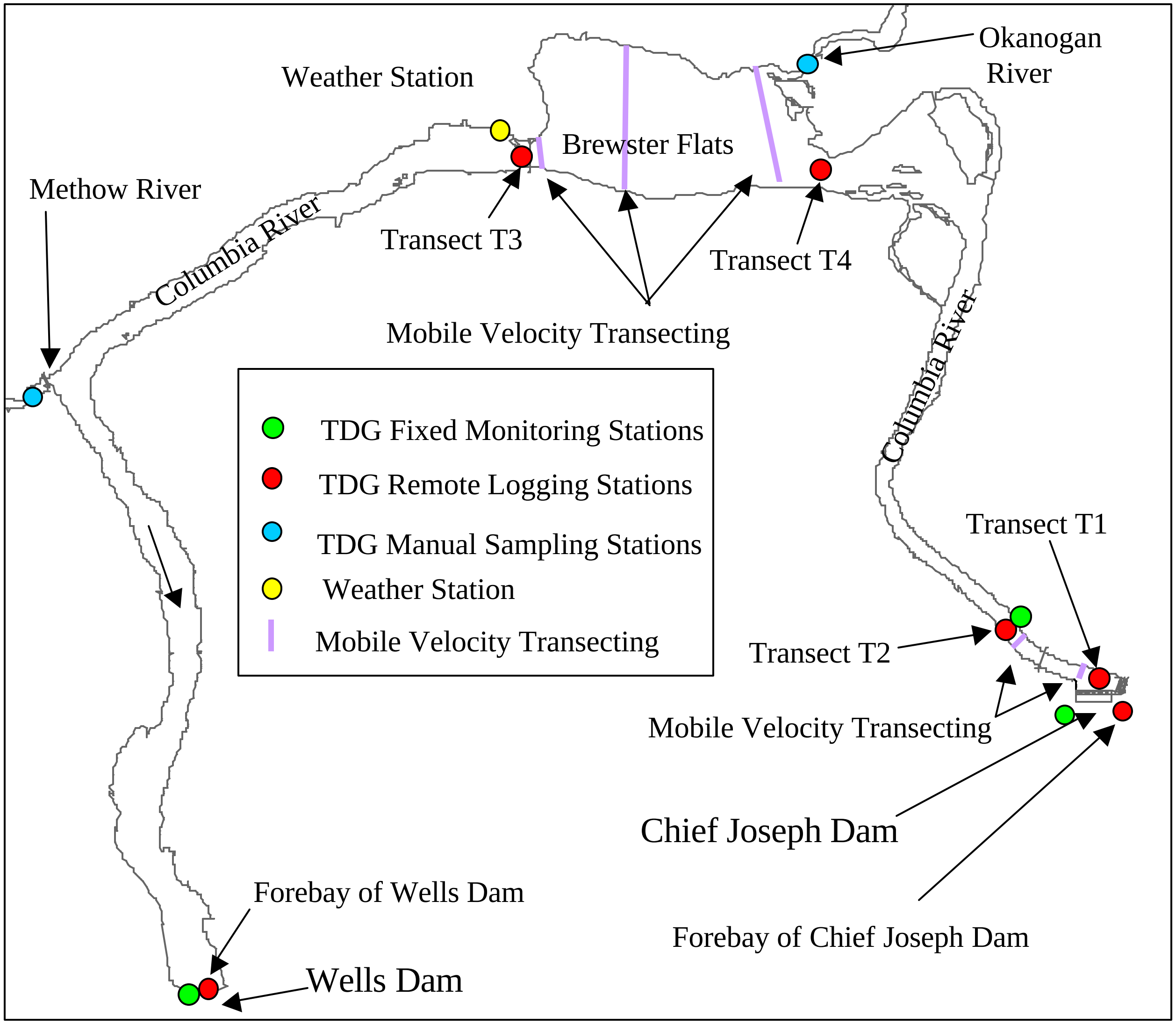

Figure 4. Total Dissolved Gas, Weather, and Velocity Monitoring Locations in Columbia River, June 6-10, 1999.

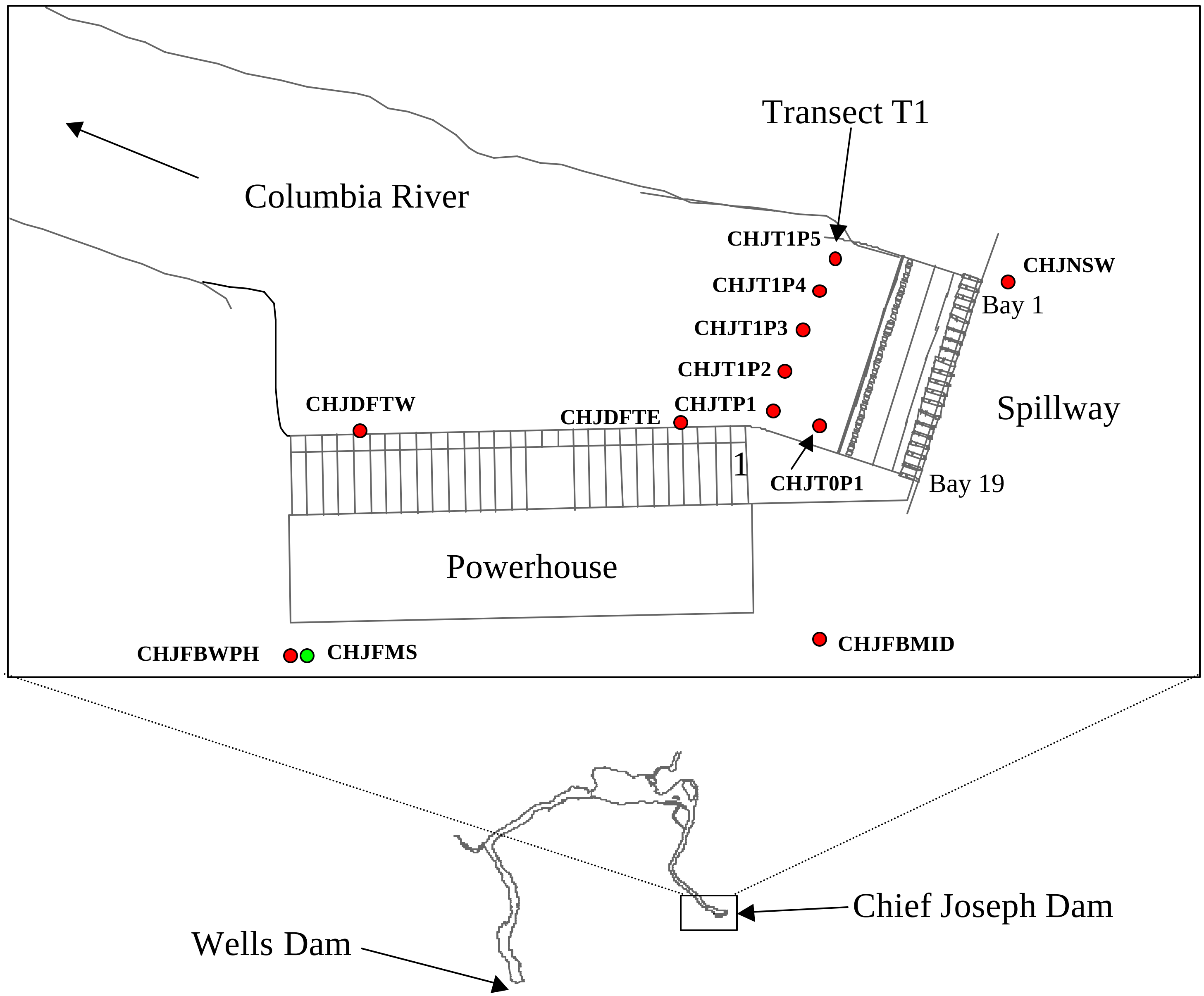

Figure 5. Total Dissolved Gas Monitoring Stations in the Forebay and Downstream of Chief Joseph Dam, June 6-10, 1999.

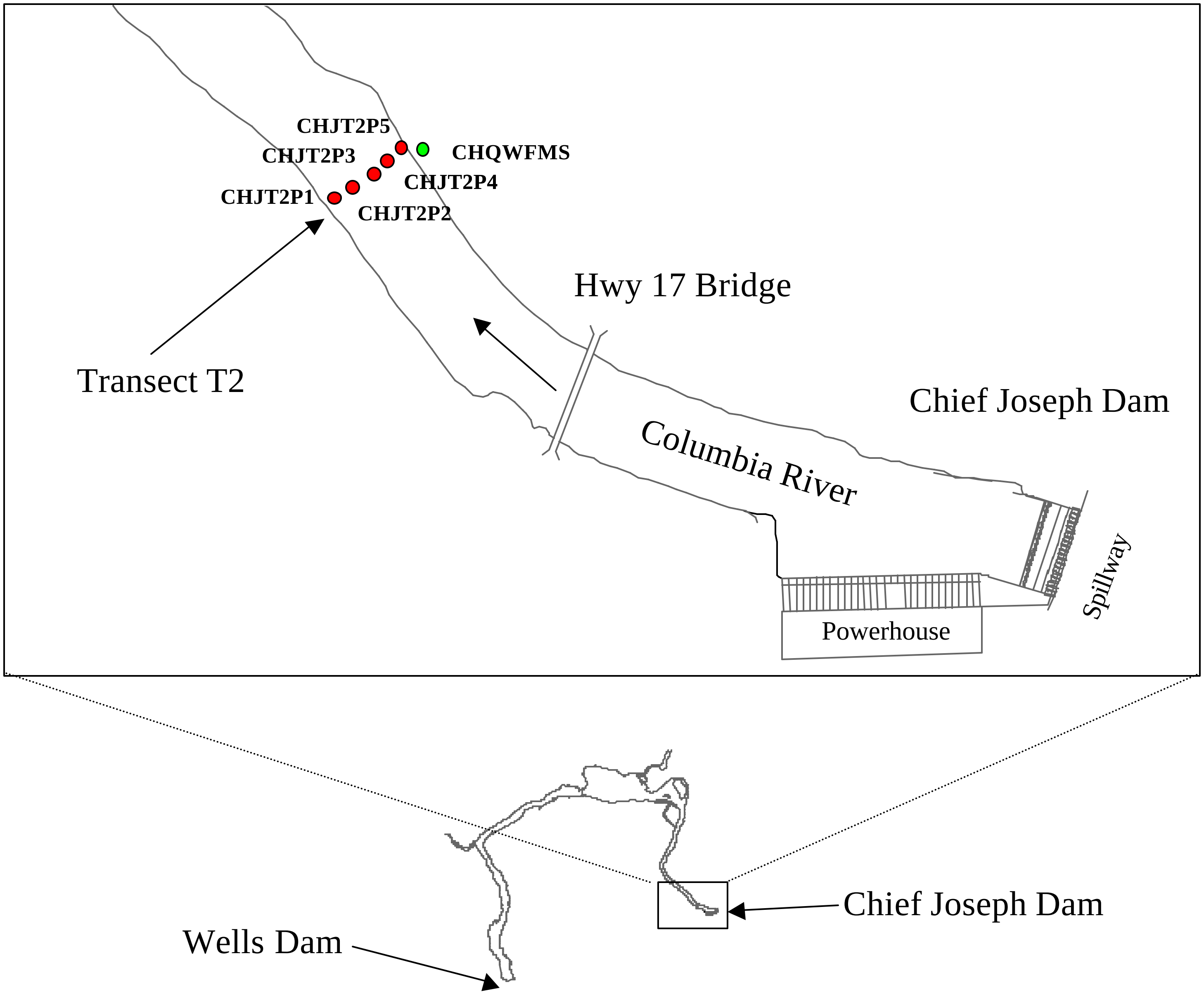

Figure 6. Total Dissolved Gas Monitoring Stations on Transect T2 Downstream of Chief Joseph Dam, June 6-10, 1999.

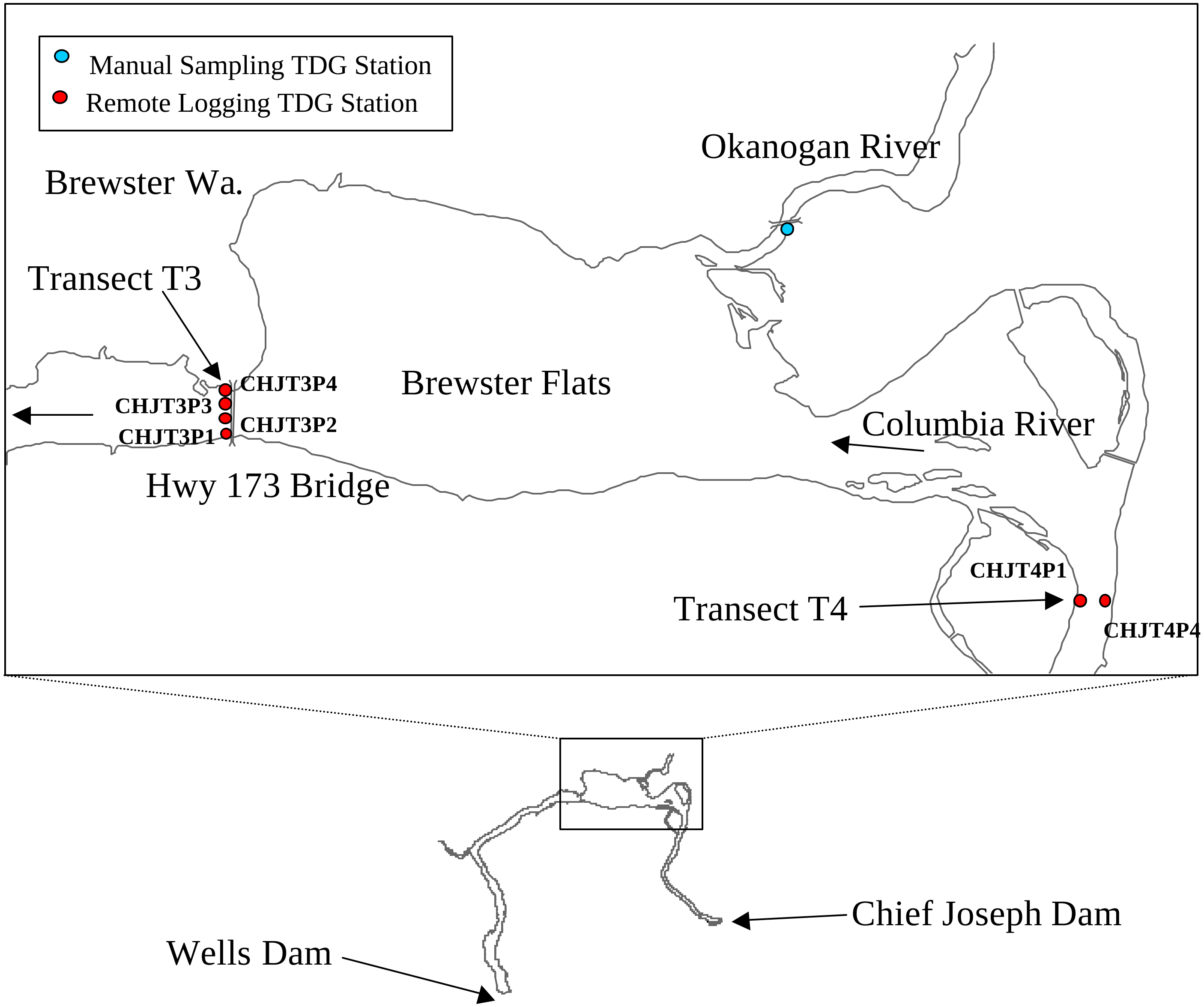

Figure 7. Total Dissolved Gas Monitoring Stations in the Brewster Flats Reach of the Columbia River, June 6-10, 1999.

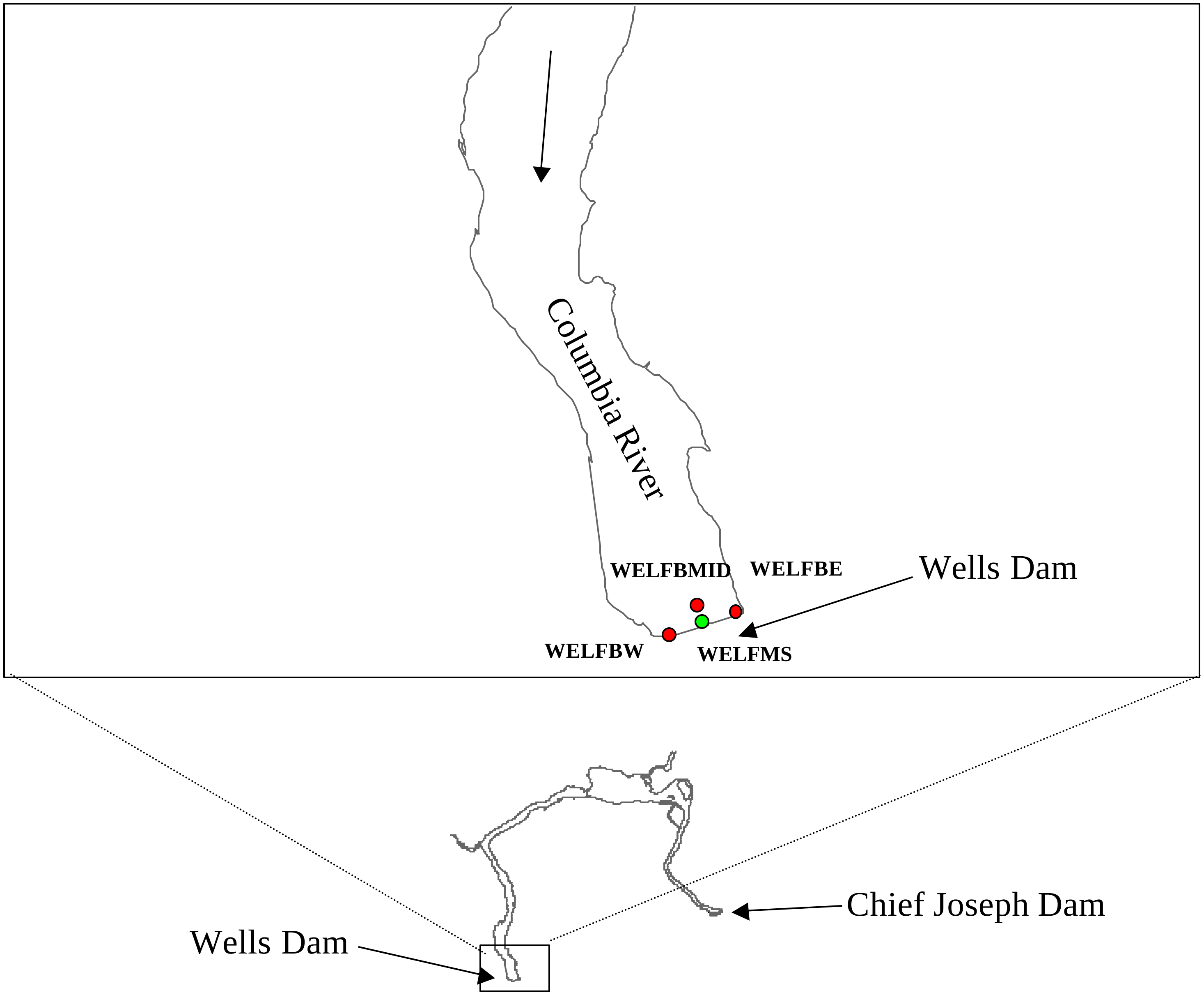

Figure 8. Total Dissolved Gas Monitoring Stations in Forebay of Wells Dam, June 6-10, 1999.

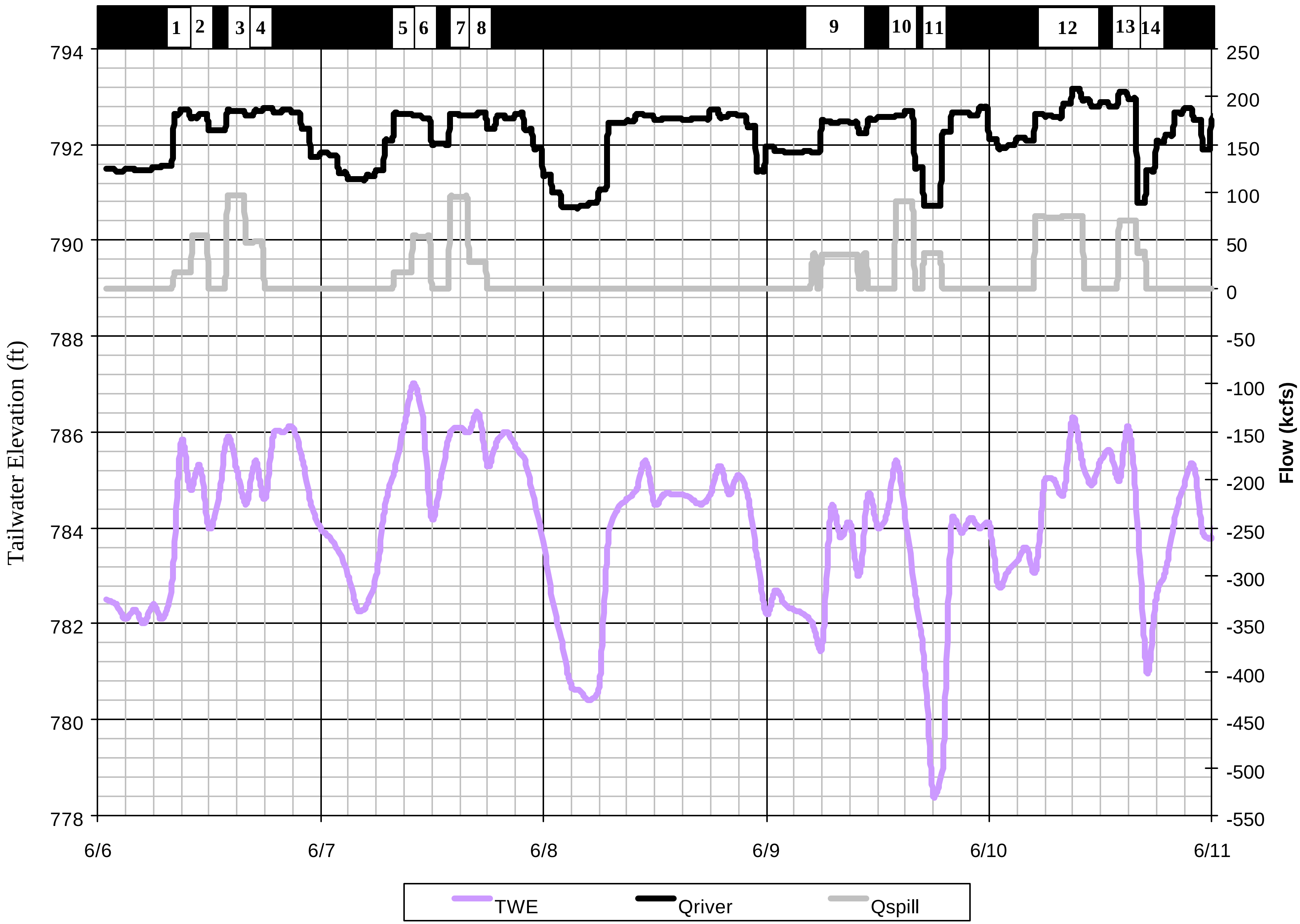

Figure 9. Tailwater Elevation below Chief Joseph Dam, June 6-11, 1999.

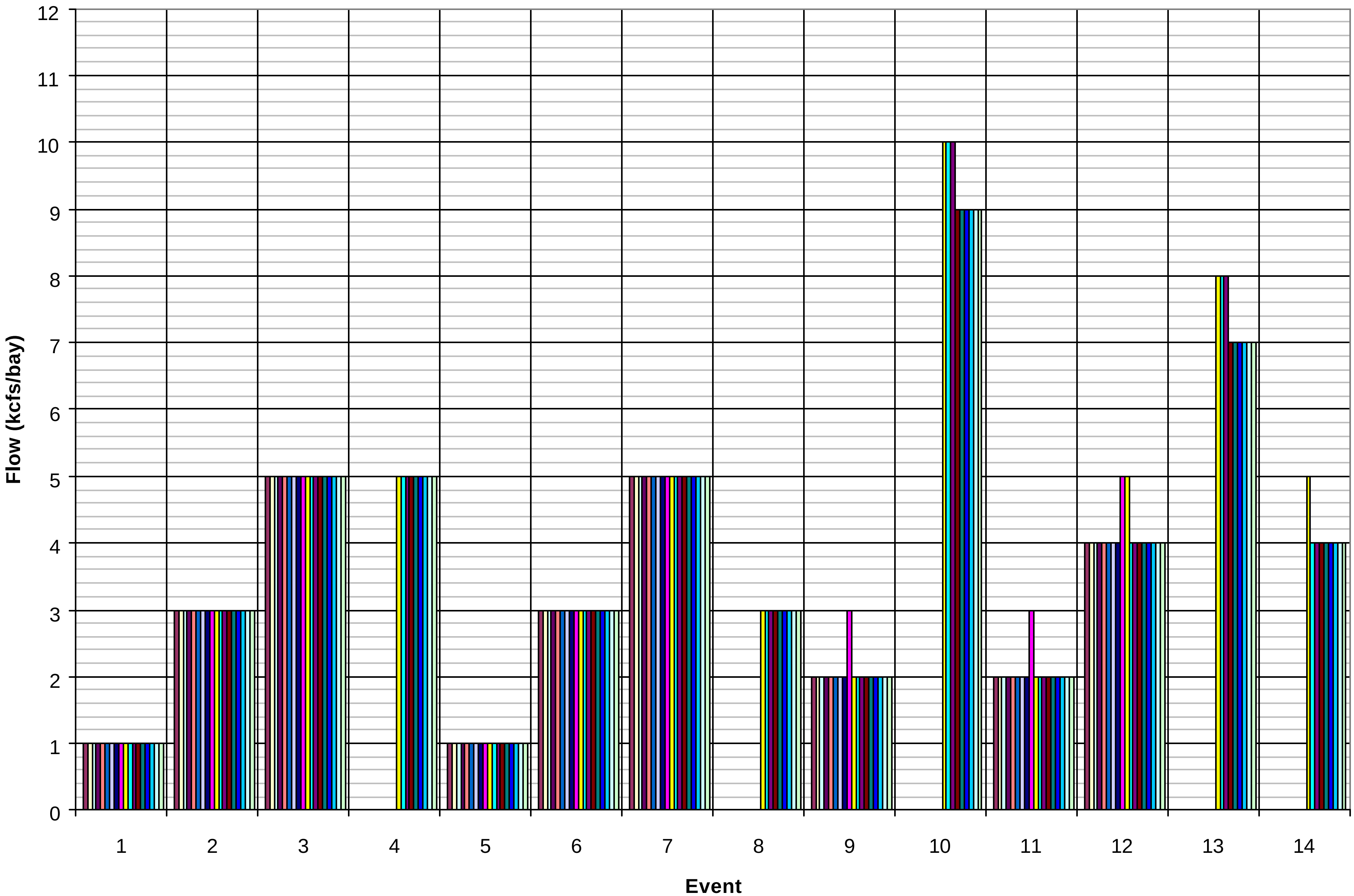

Figure 10. Spill Patterns During the Total Dissolved Gas Exchange Study at Chief Joseph Dam, June 6-10, 1999.

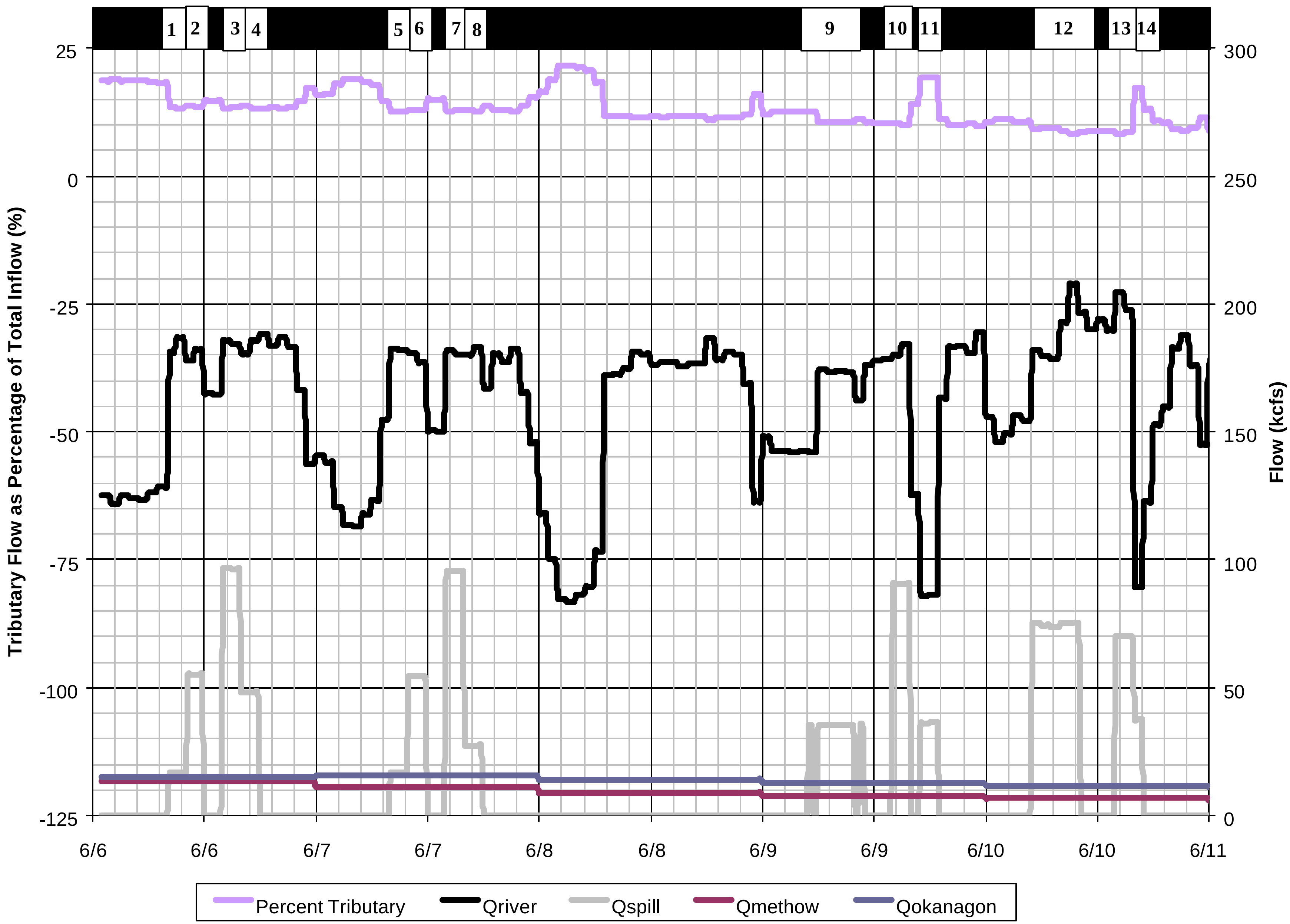

Figure 11. Inflow Hydrograph for Wells Pool, June 6-11, 1999.

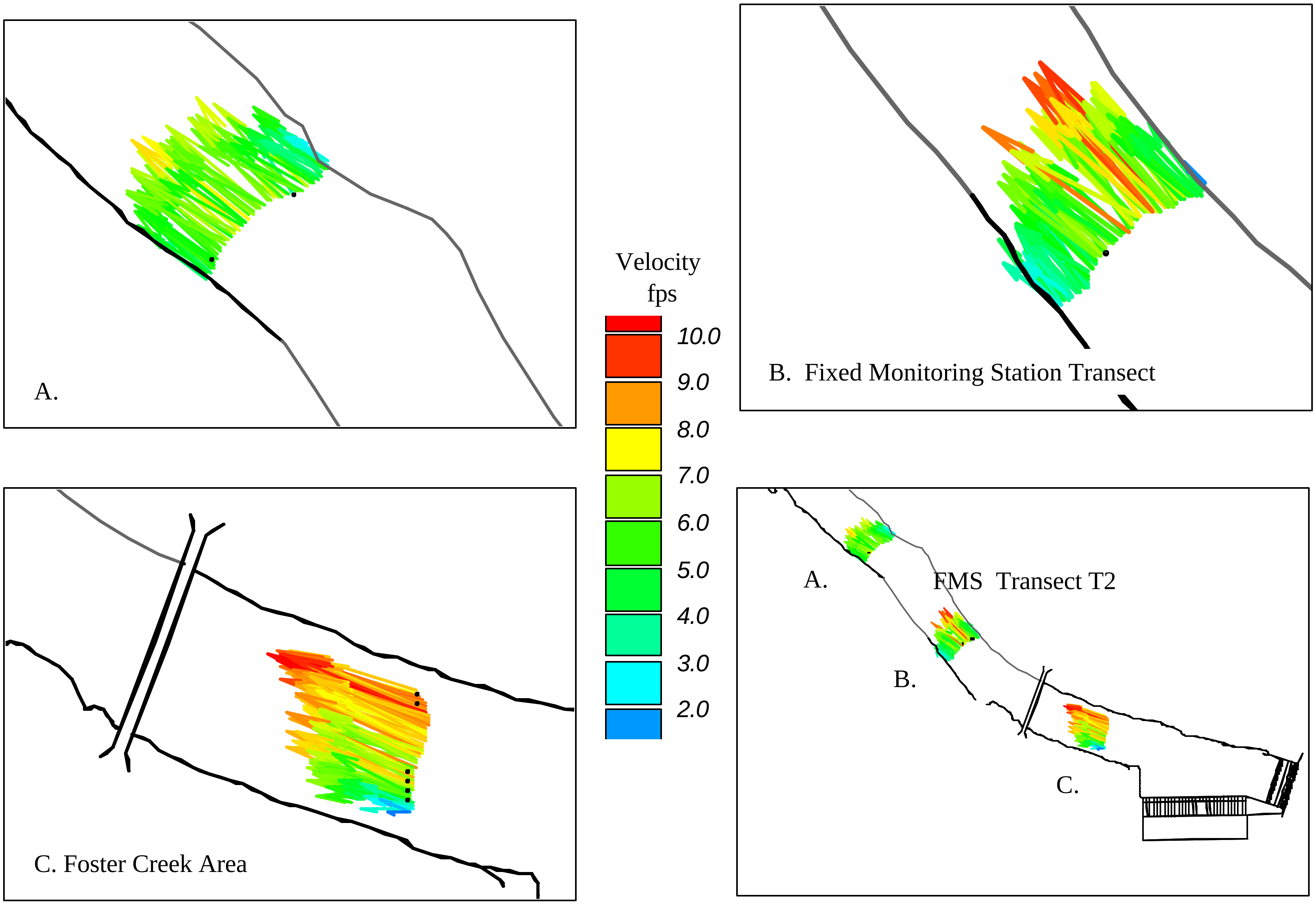

Figure 12. Depth-Averaged Velocities Below Chief Joseph Dam, June 6, 1700 hrs
(Event 4, Qriver=185 kcfs, Qspill=48 kcfs, TWE=784.8 ft)

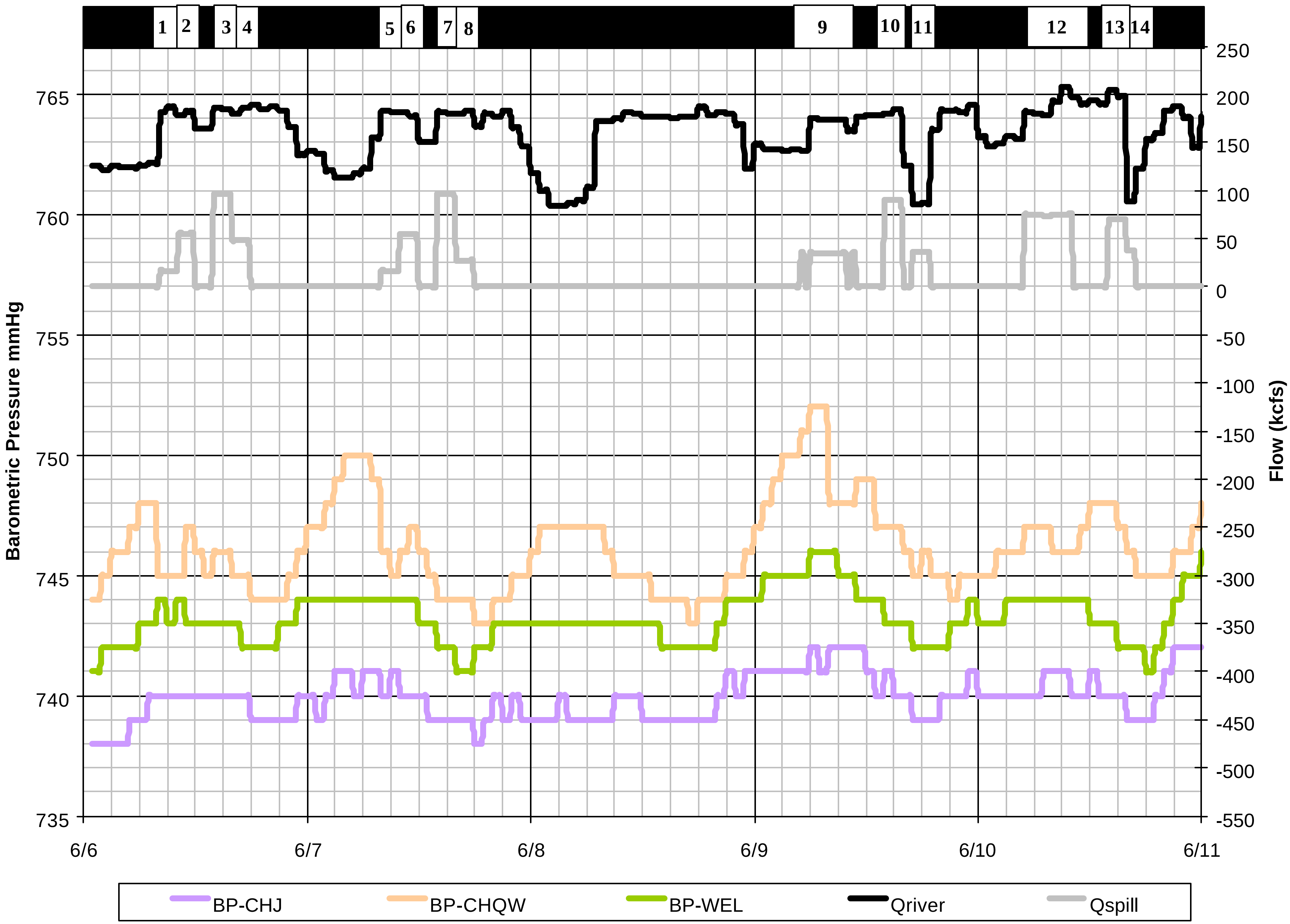

Figure 13. Barometric Pressure at Fixed Monitoring Stations, June 6-11, 1999.

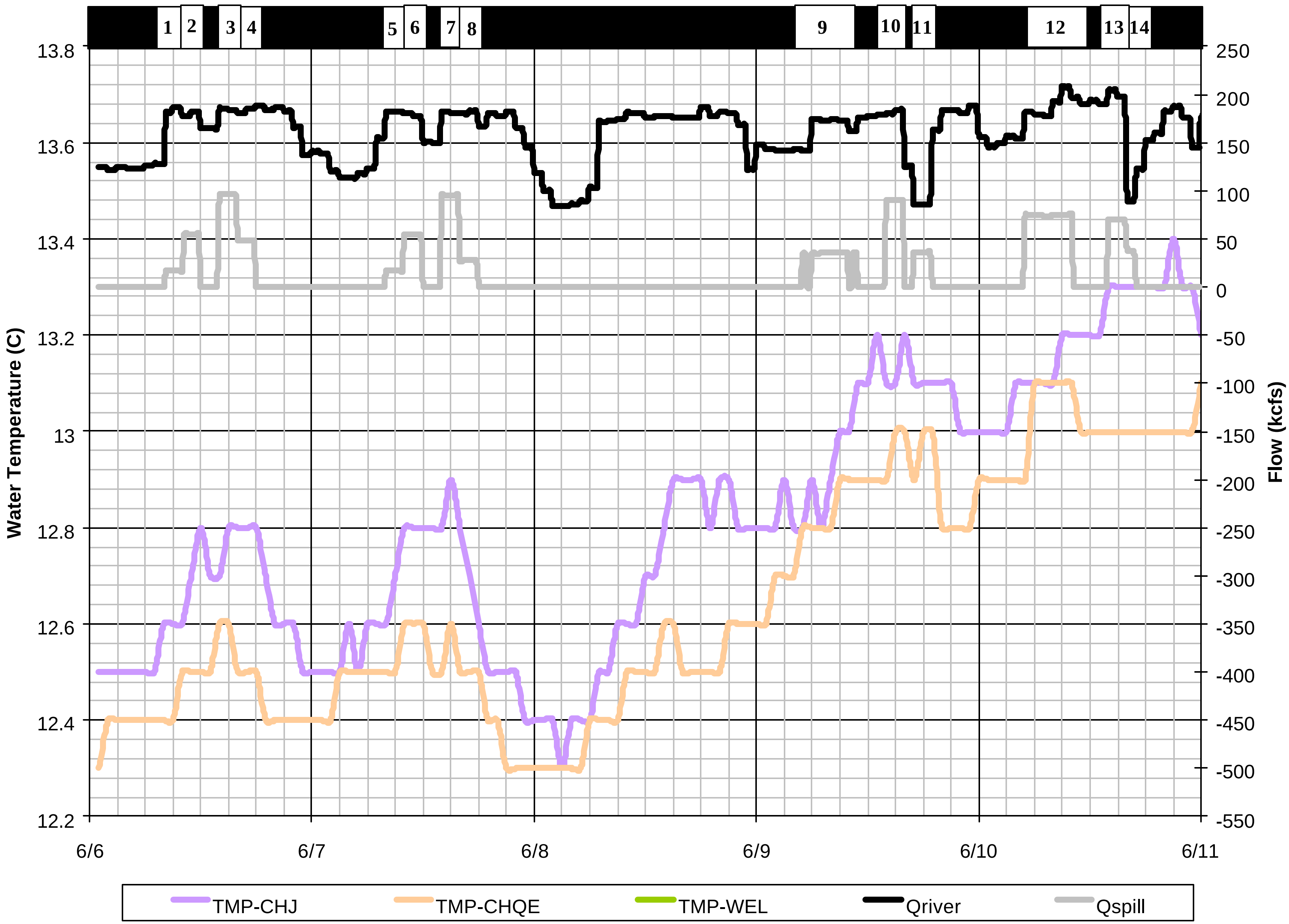

Figure 14. Water Temperatures at Fixed Monitoring Stations, June 6-11, 1999.

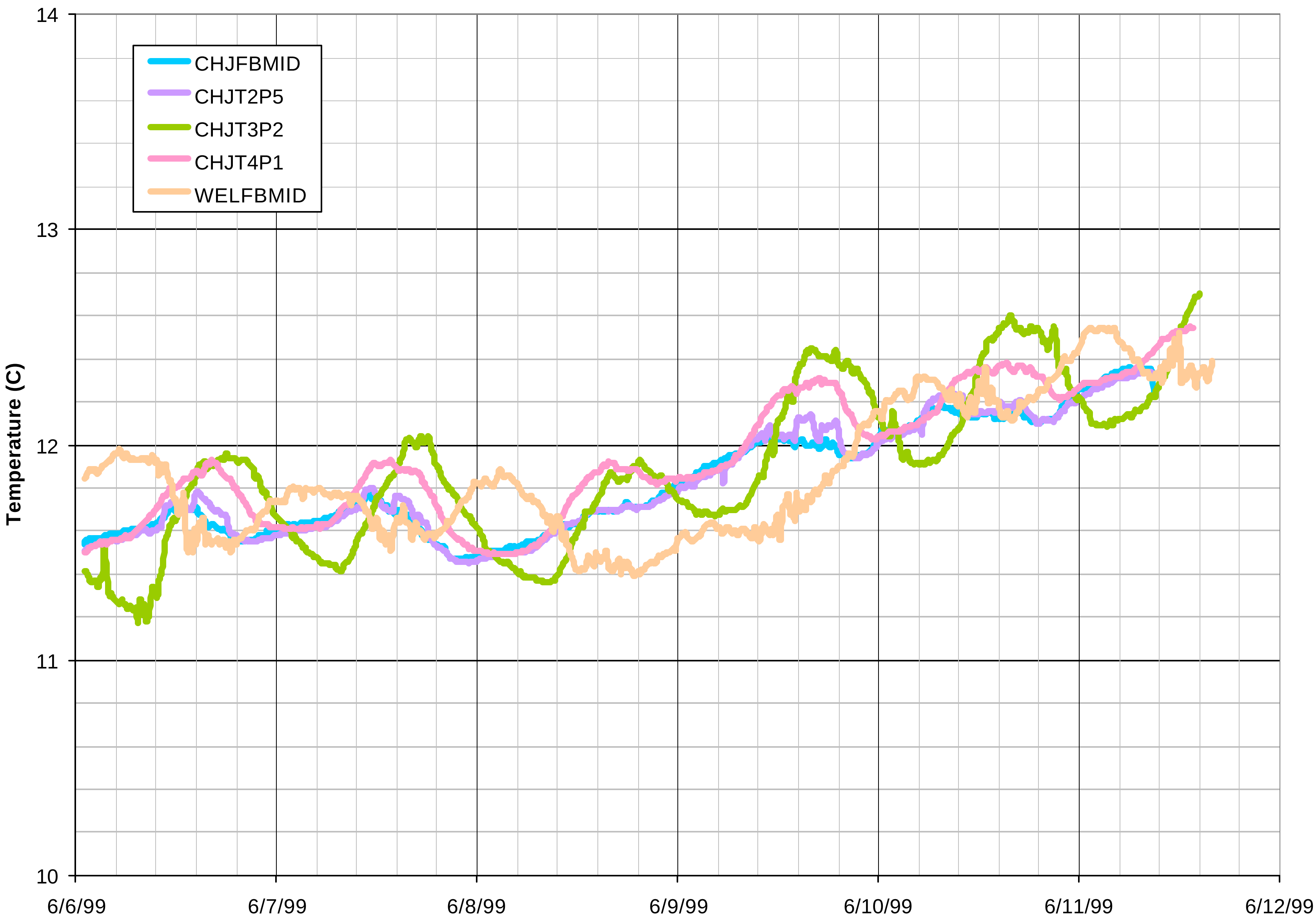

Figure 15. Water Temperatures at Selected Stations Throughout Lake Pateros and the Forebay of Chief Joseph Dam, June 6-11, 1999.

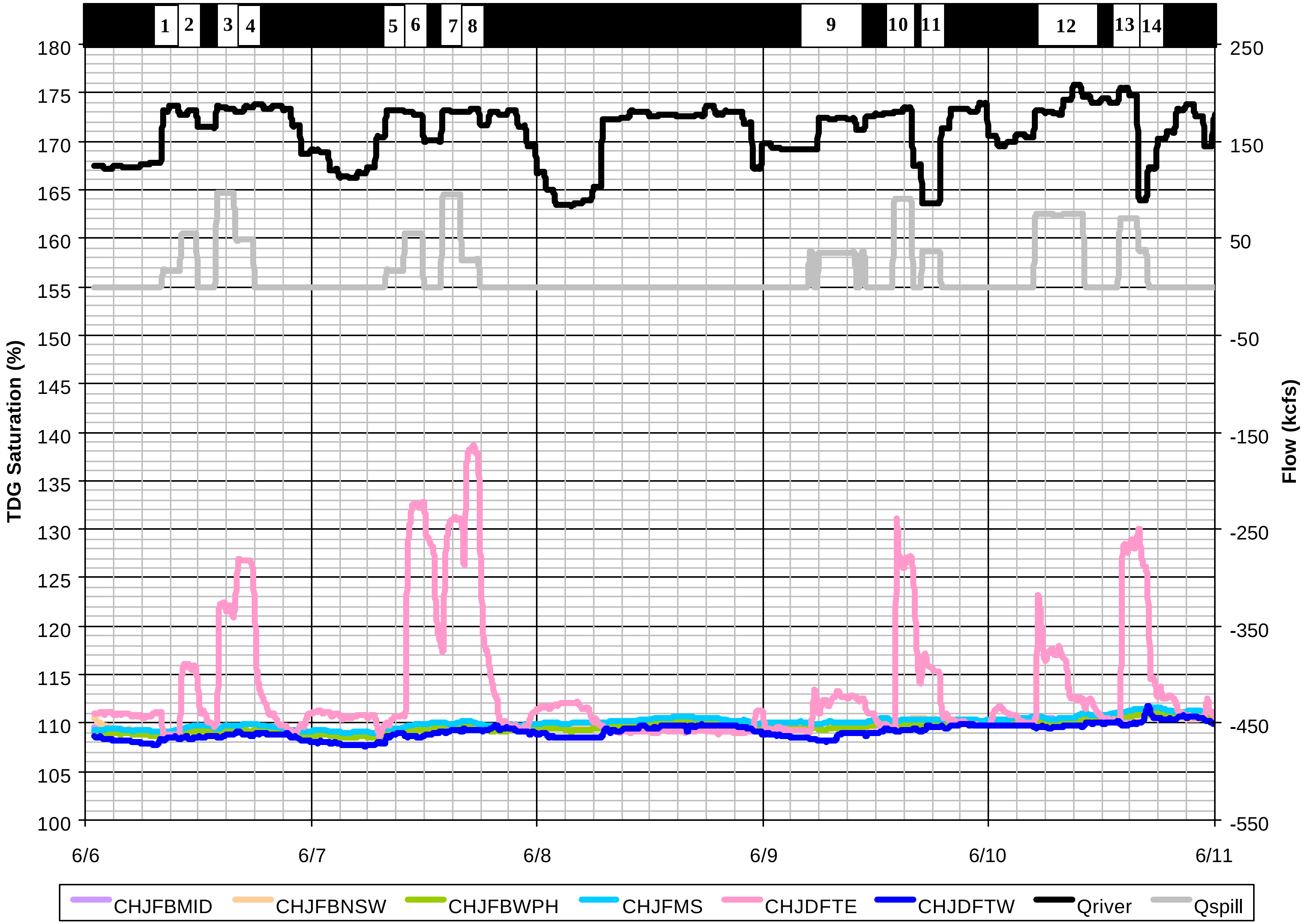

Figure 16. Project Operation and Total Dissolved Gas Saturation in the Forebay and Downstream of the Powerhouse at Chief Joseph Dam, June 6-10, 1999.

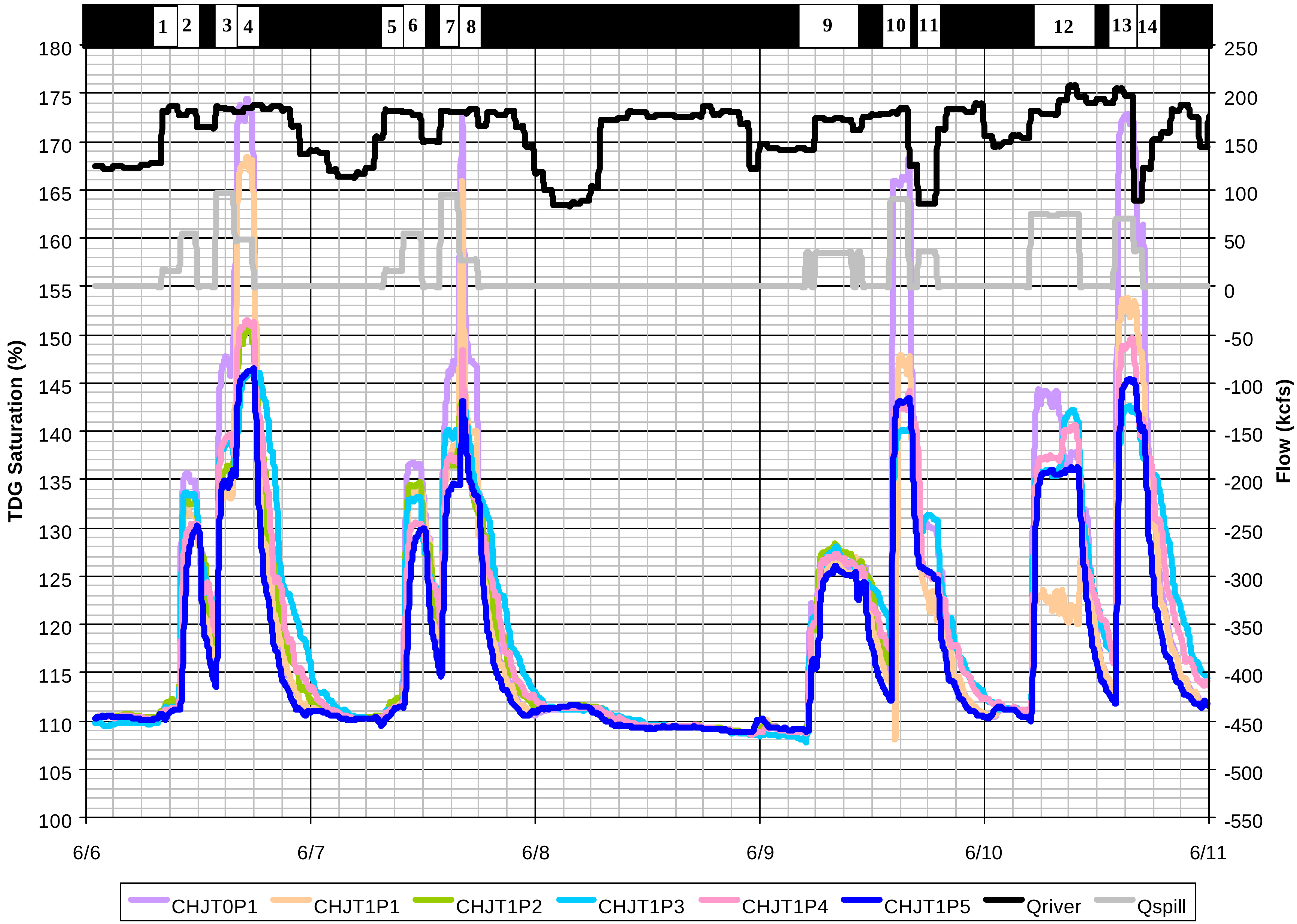

Figure 17. Project Operation and Total Dissolved Gas Saturation on Transect T1 at Chief Joseph Dam, June 6-10, 1999.

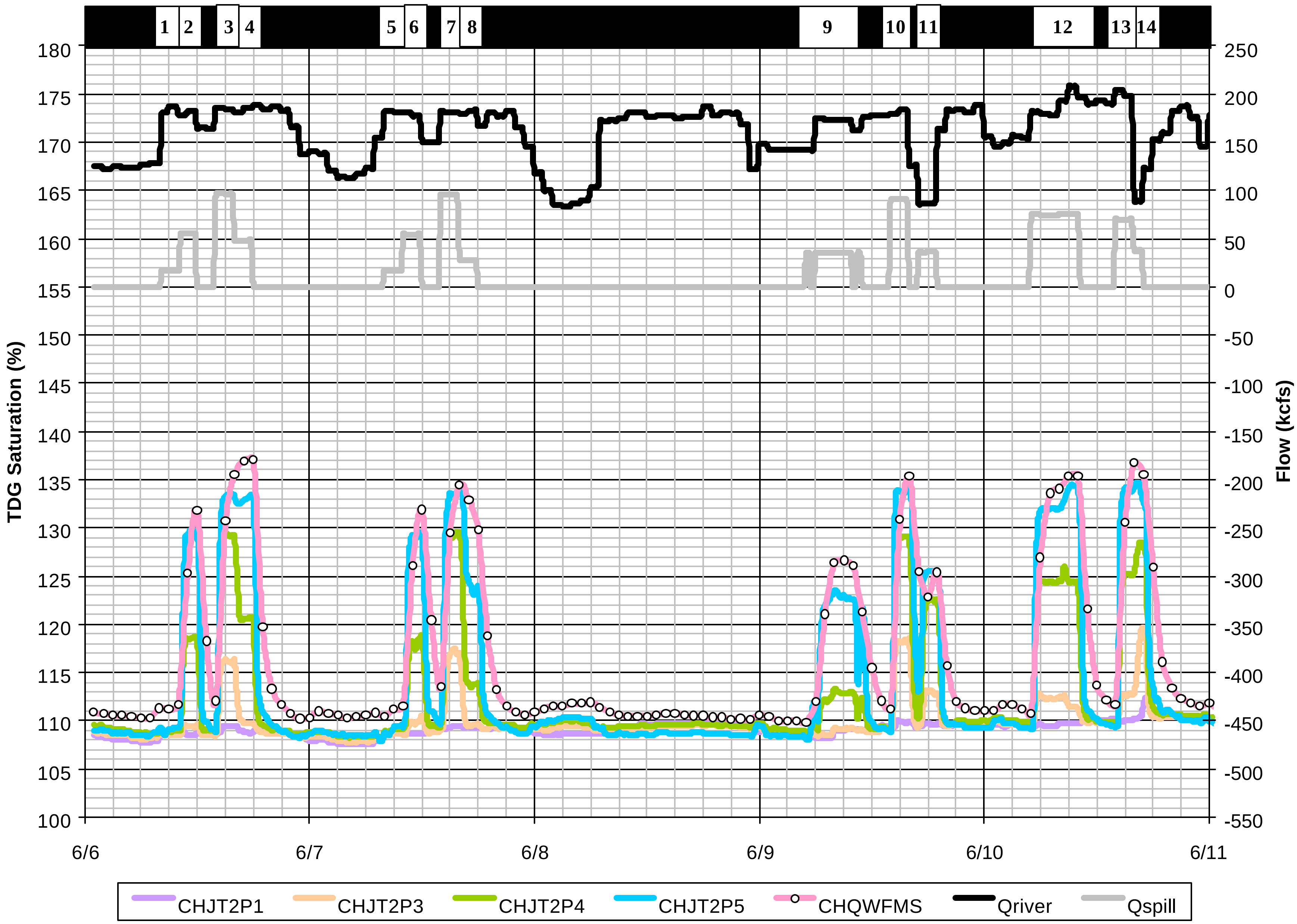

Figure 18. Project Operation and Total Dissolved Gas Saturation on Transect T2 at Chief Joseph Dam, June 6-10, 1999.

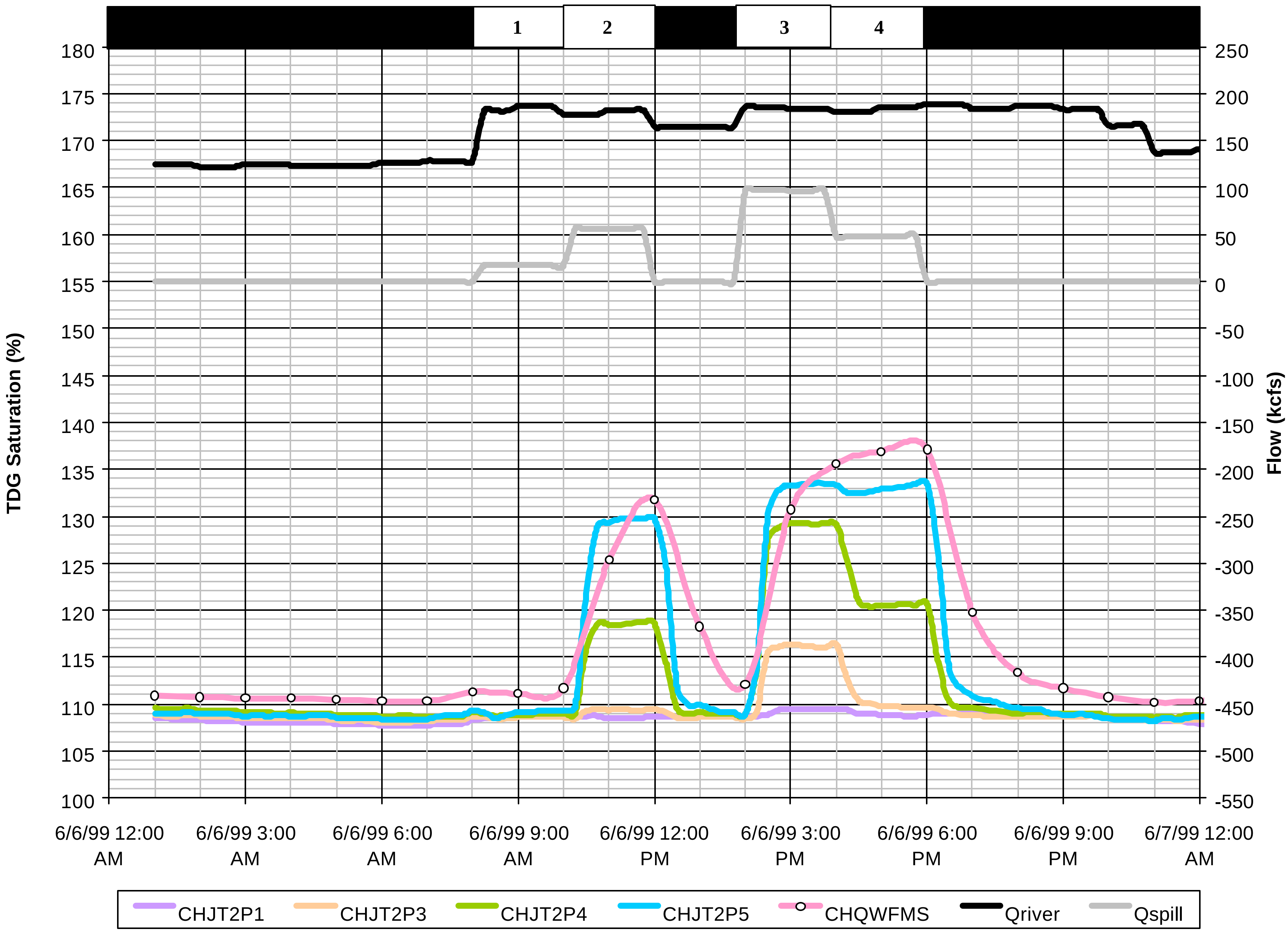

Figure 19. Project Operation and Total Dissolved Gas Saturation on Transect T2 at Chief Joseph Dam, June 6, 1999.

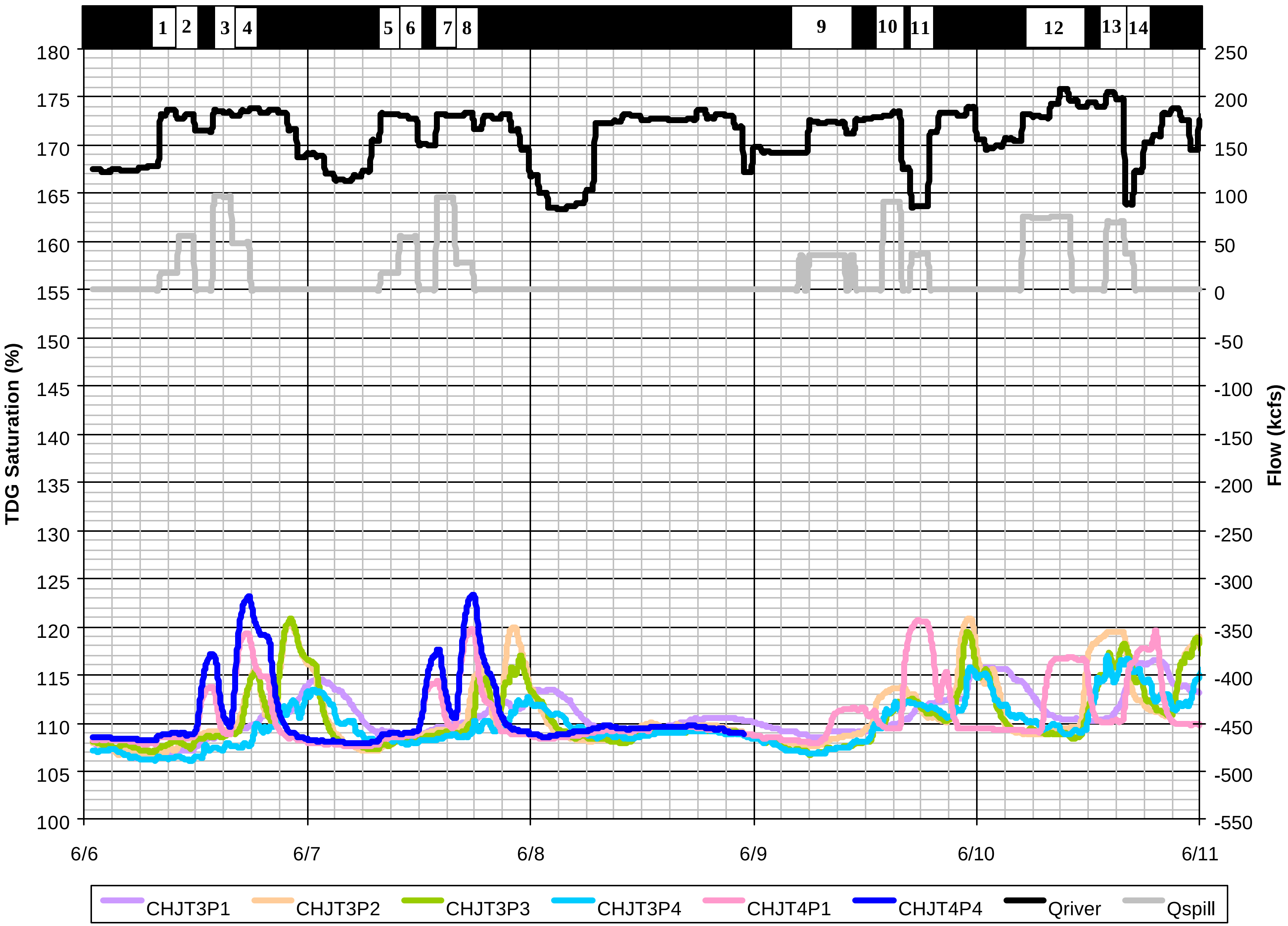

Figure 20. Project Operation and Total Dissolved Gas Saturation on Transect T3 and T4 below Chief Joseph Dam, June 6-10, 1999.

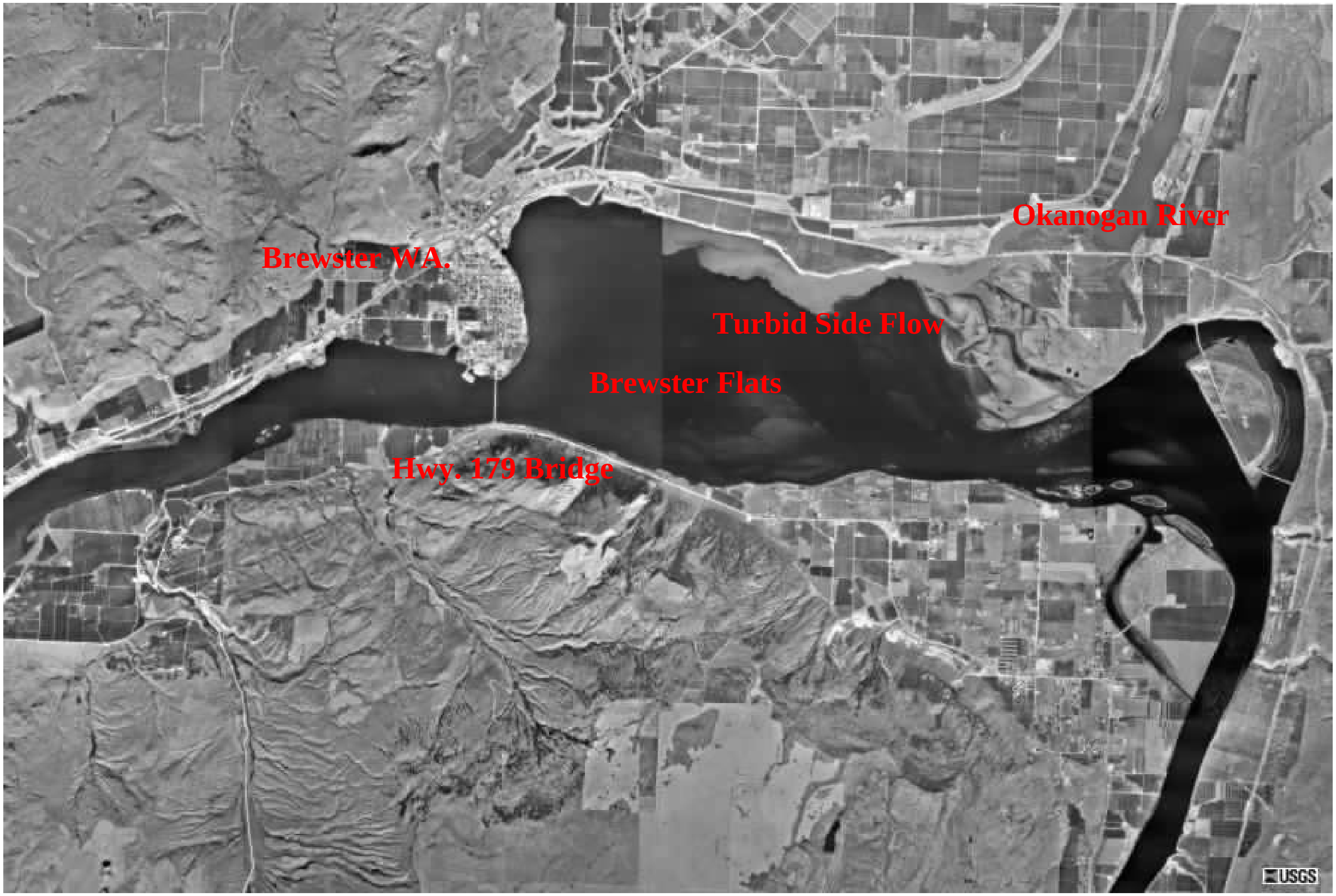

Figure 21. Aerial Photograph of Brewster Flats with Turbid Okanogan Side Flow.

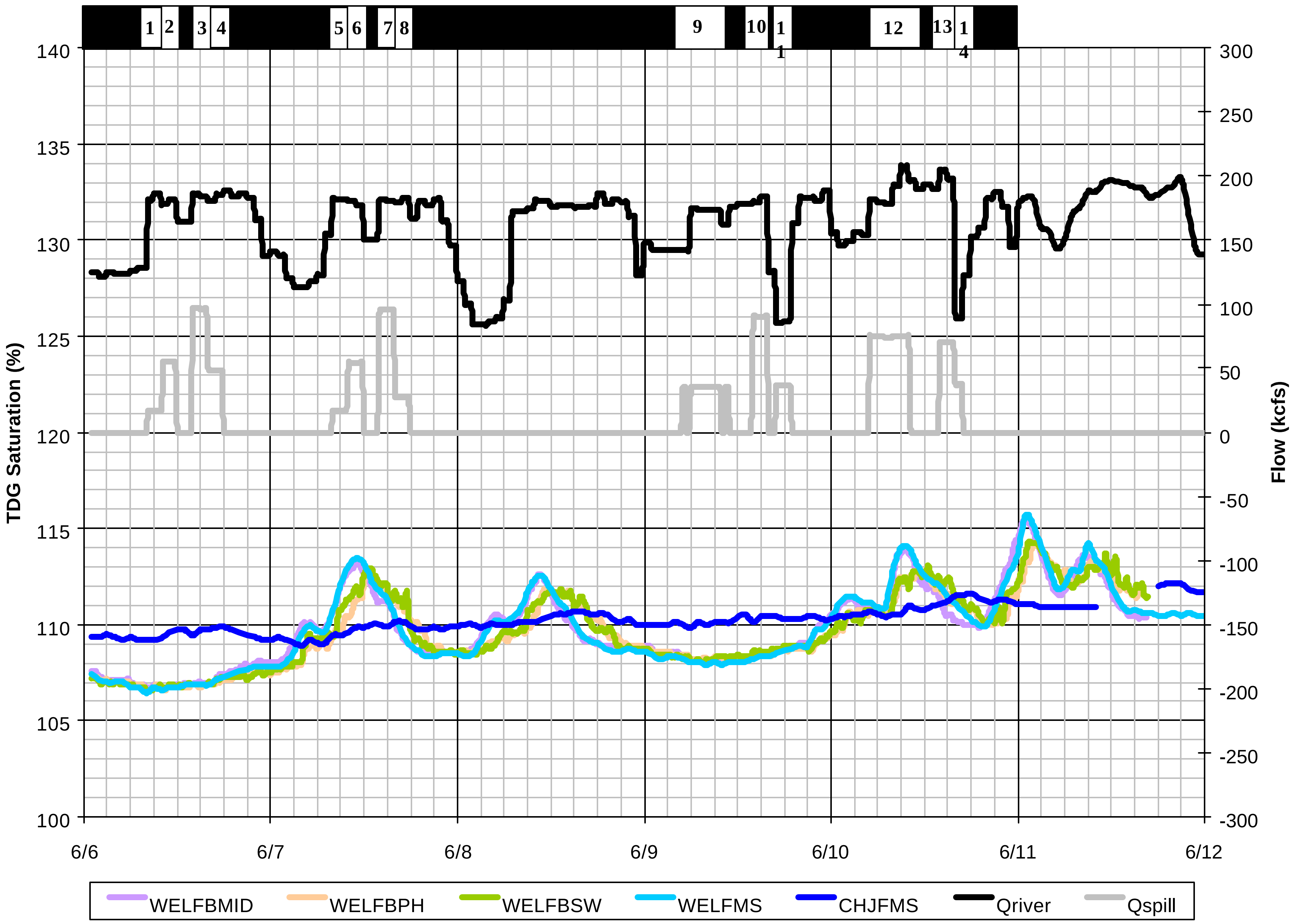

Figure 22. Project Operation and Total Dissolved Gas Saturation at Wells Dam, June 6-12, 1999.

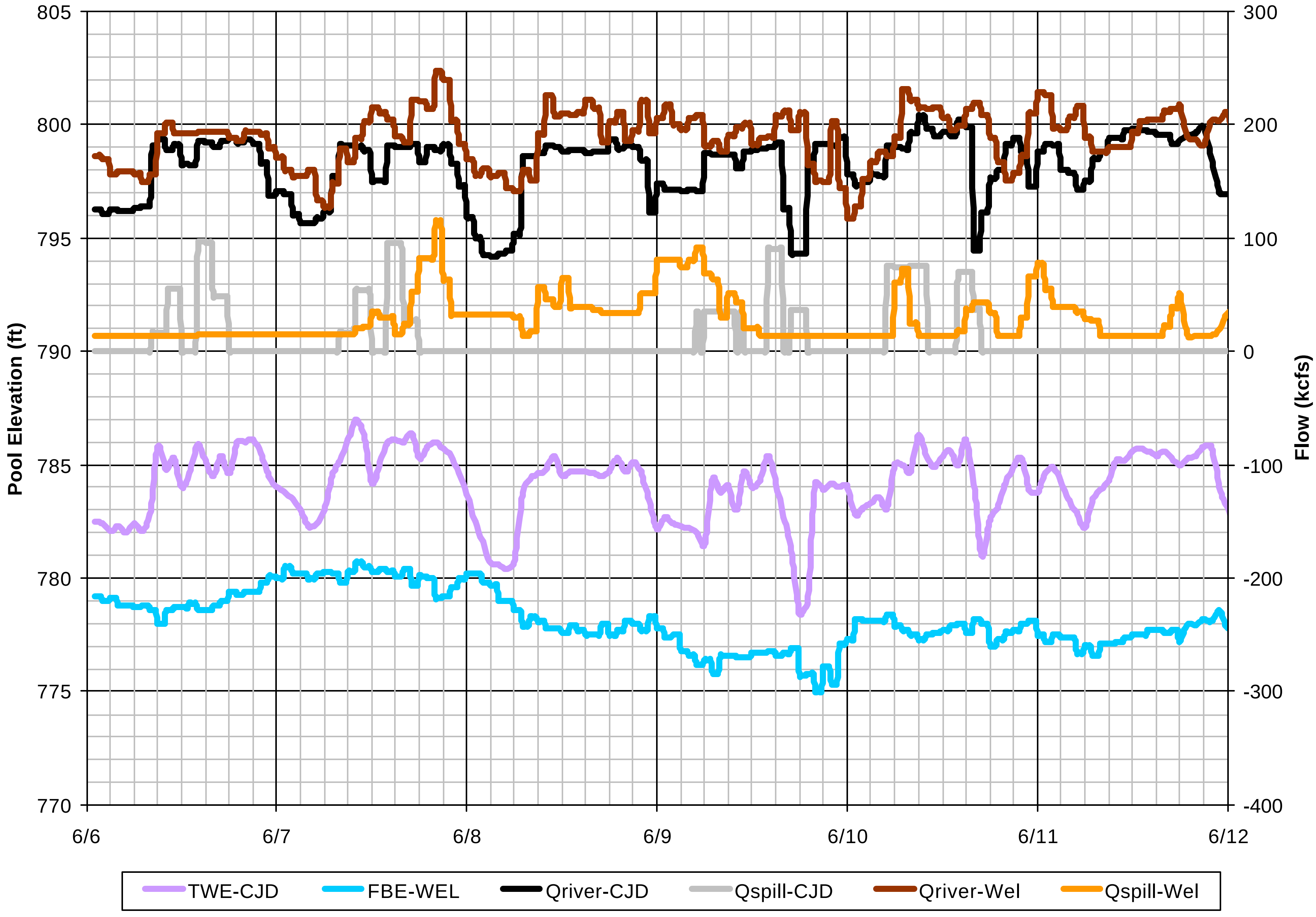

Figure 23. Project Operation and Water Surface Elevation at Chief Joseph and Wells Dams, June 6-12, 1999.

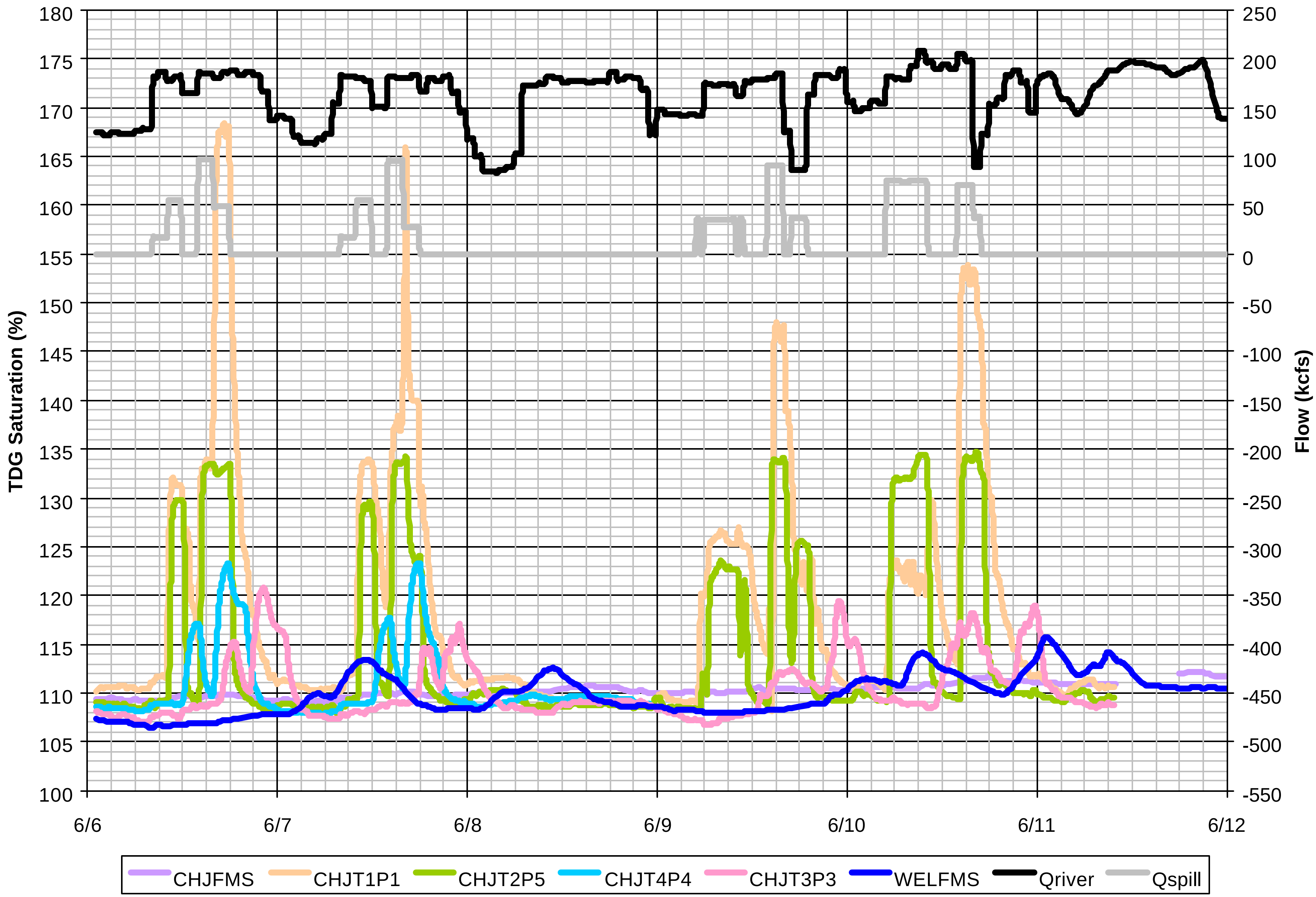

Figure 24. Project Operation and Total Dissolved Gas Saturation in Mid-Channel Throughout Wells Pool, June 6-12, 1999.

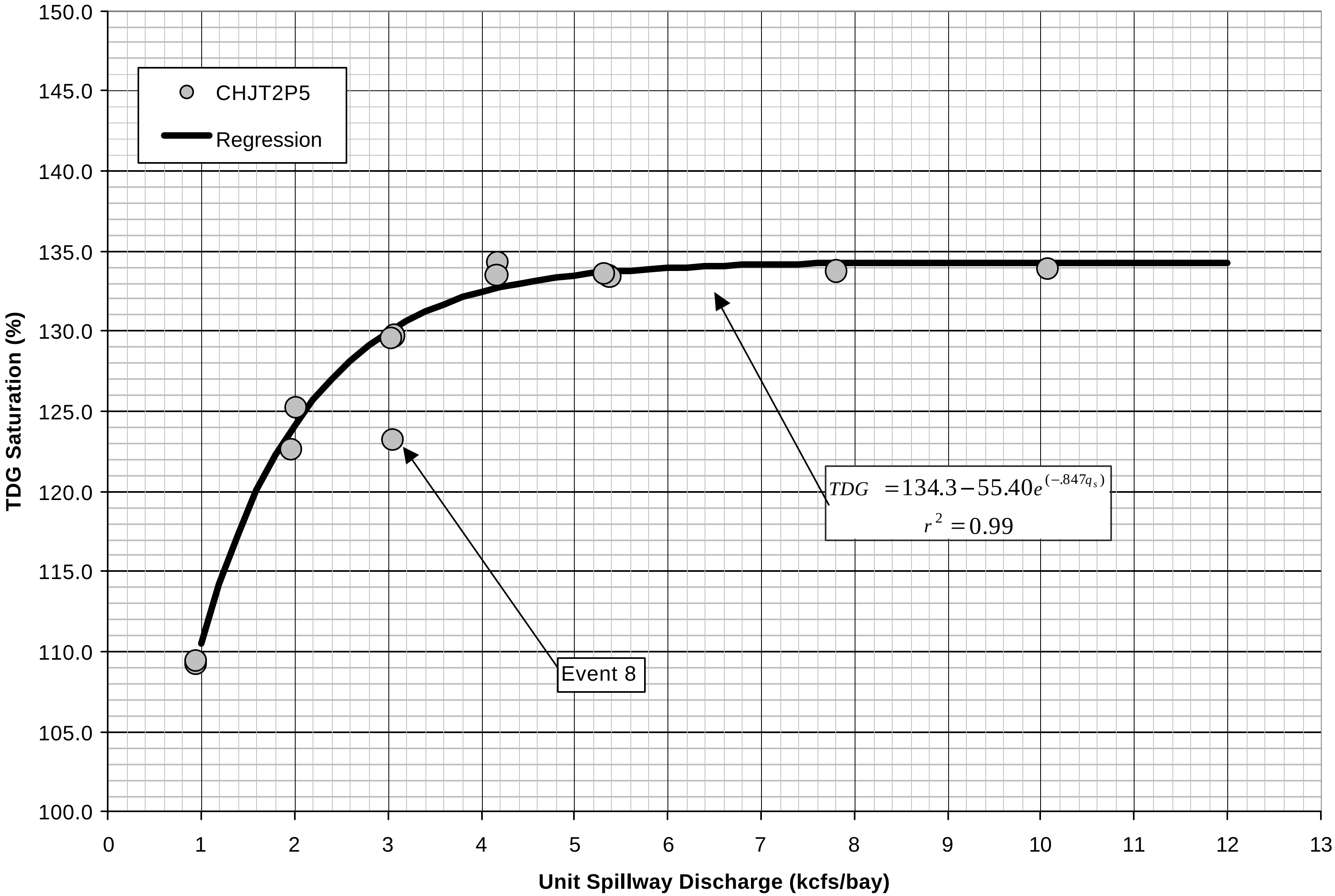

Figure 25. Total Dissolved Saturation at CHJT2P5 as a Function of Unit Spillway Discharge at Chief Joseph Dam, June 6-12, 1999.

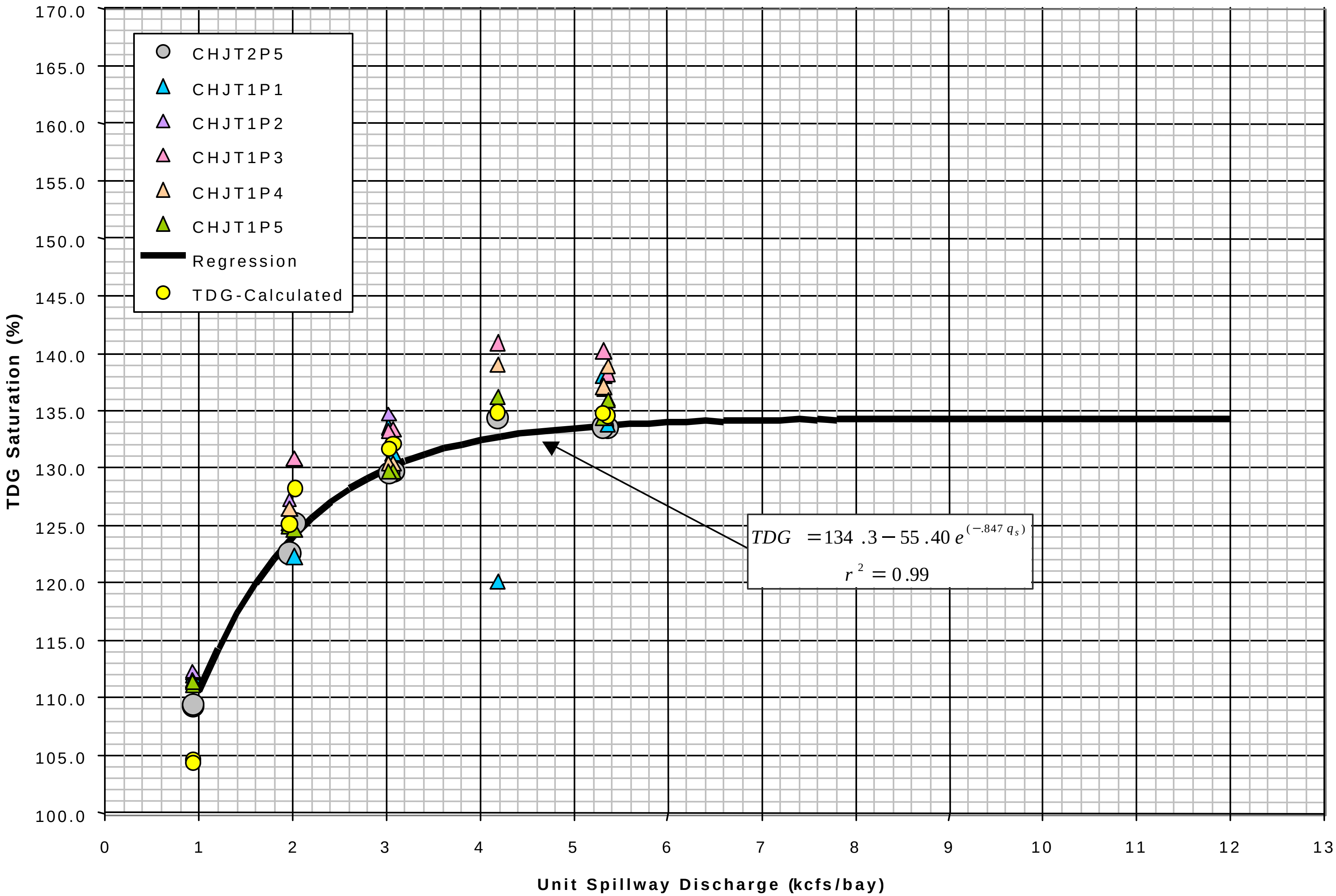

Figure 26. Total Dissolved Gas Saturation as a Function of Unit Spillway Discharge at Chief Joseph Dam, June 6-10, 1999 (Stations CHJT2P5 and CHQW).

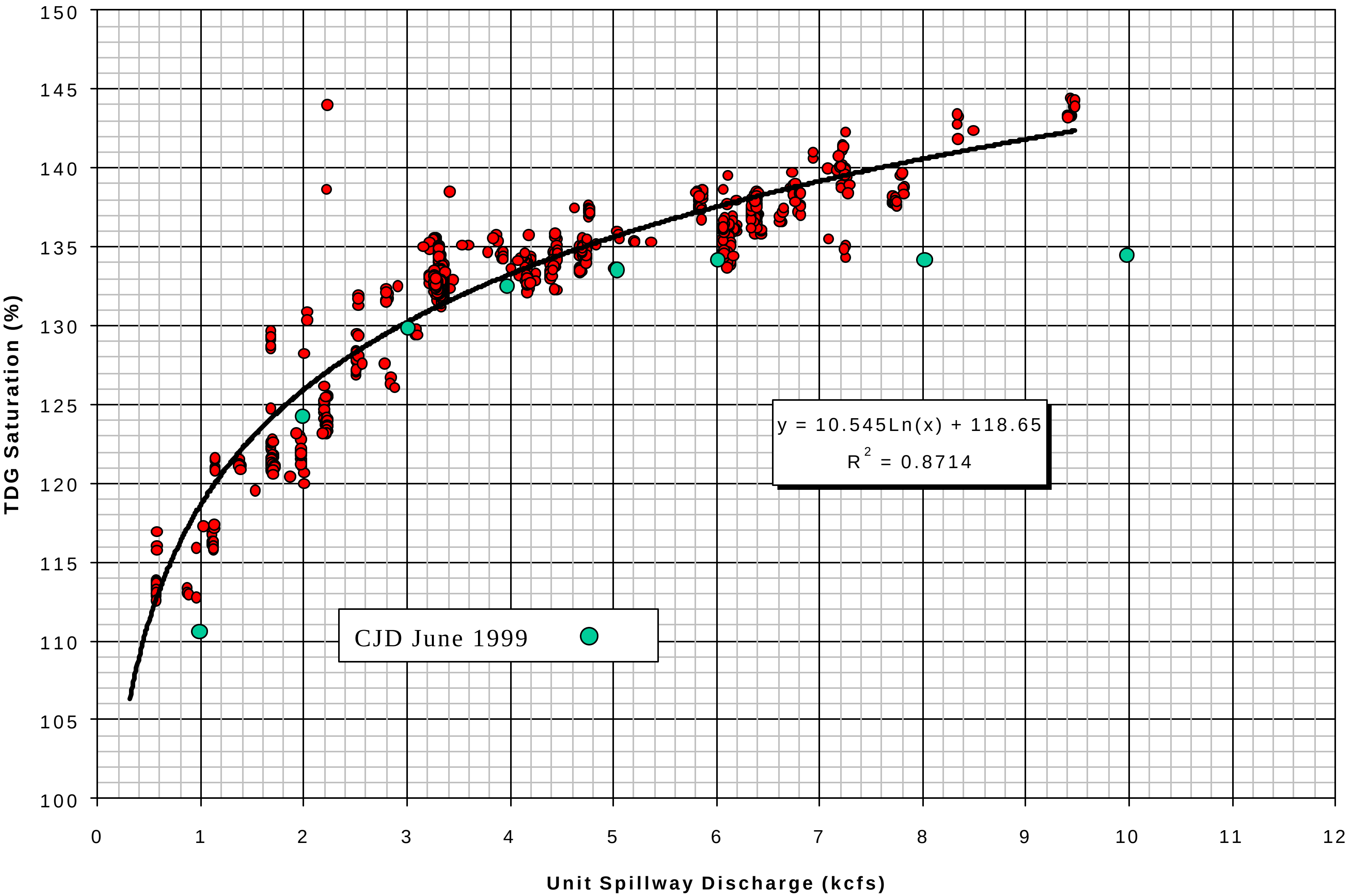

Figure 27. Total Dissolved Gas Saturation as Measured as a Function of Unit Spillway Discharge at the Tailwater Fixed Monitoring Station at Chief Joseph Dam, 1997 and June 1999.

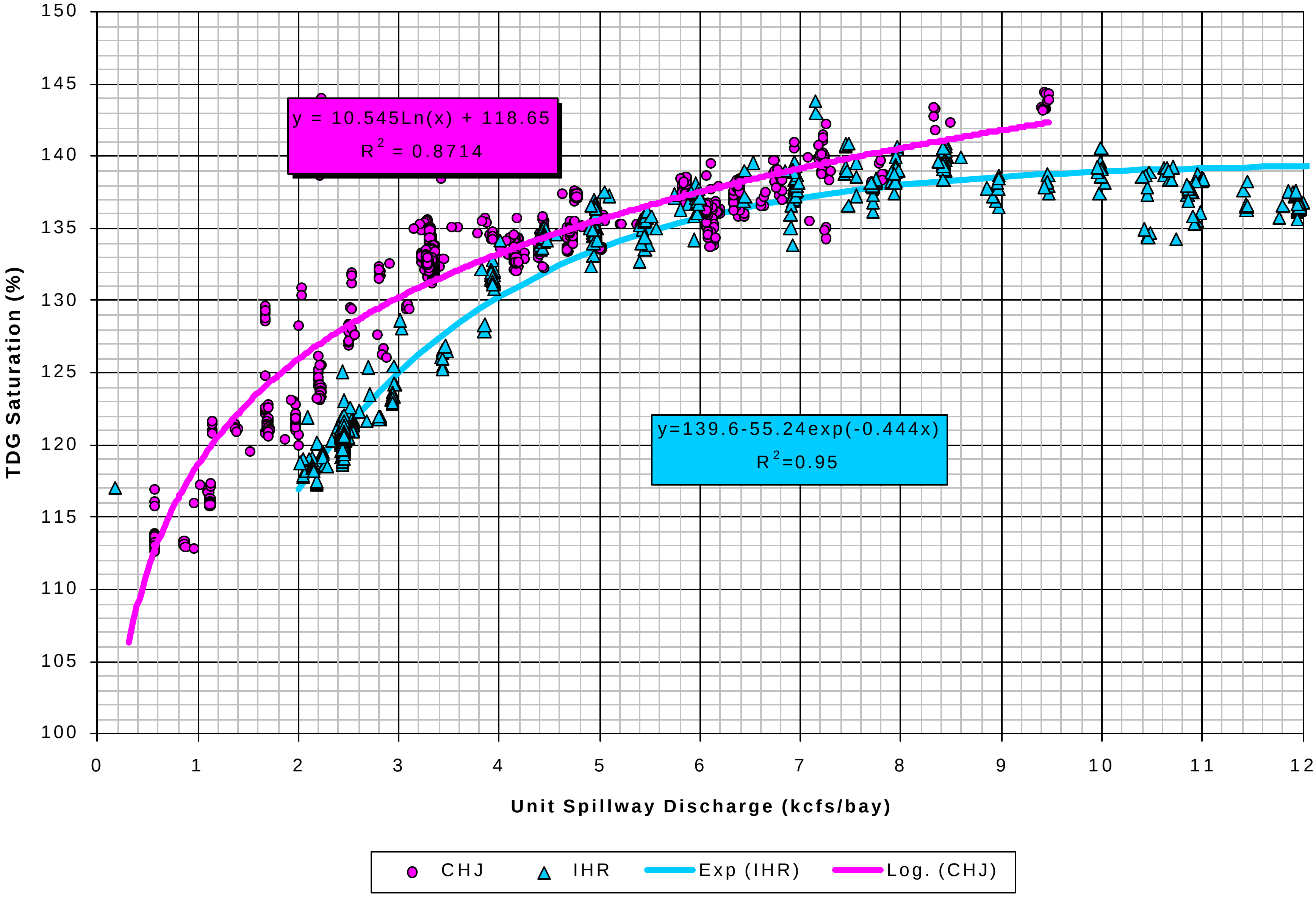

Figure 28. Total Dissolved Gas Saturation as Measured as a Function of Unit Spillway Discharge at the Tailwater Fixed Monitoring Station at Chief Joseph Dam, 1997 and Ice Harbor Dam, 1996.

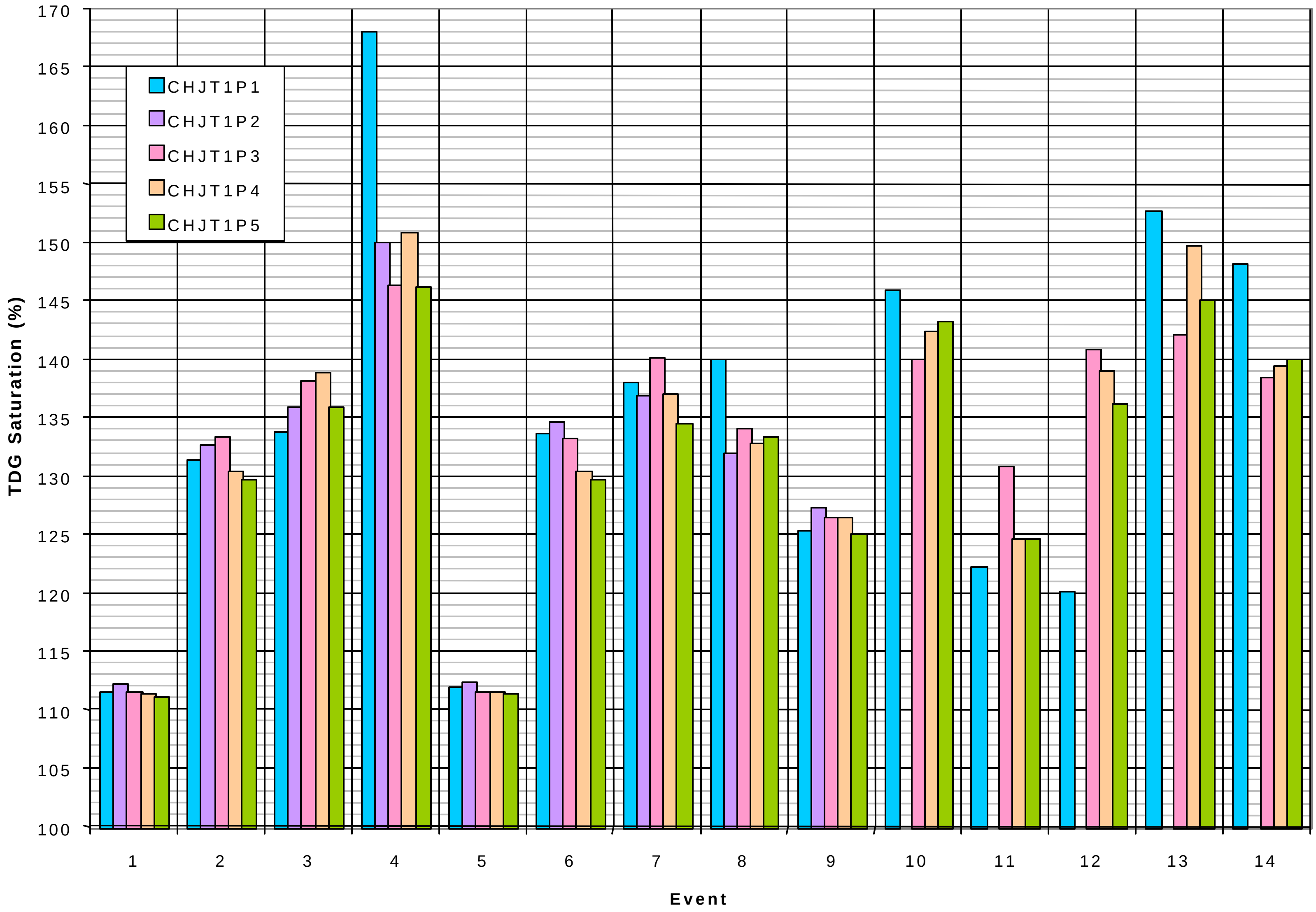

Figure 29. Total Dissolved Gas Saturation on Transect T1 at the End of Each Spill Event at Chief Joseph Dam, June 6-10, 1999.

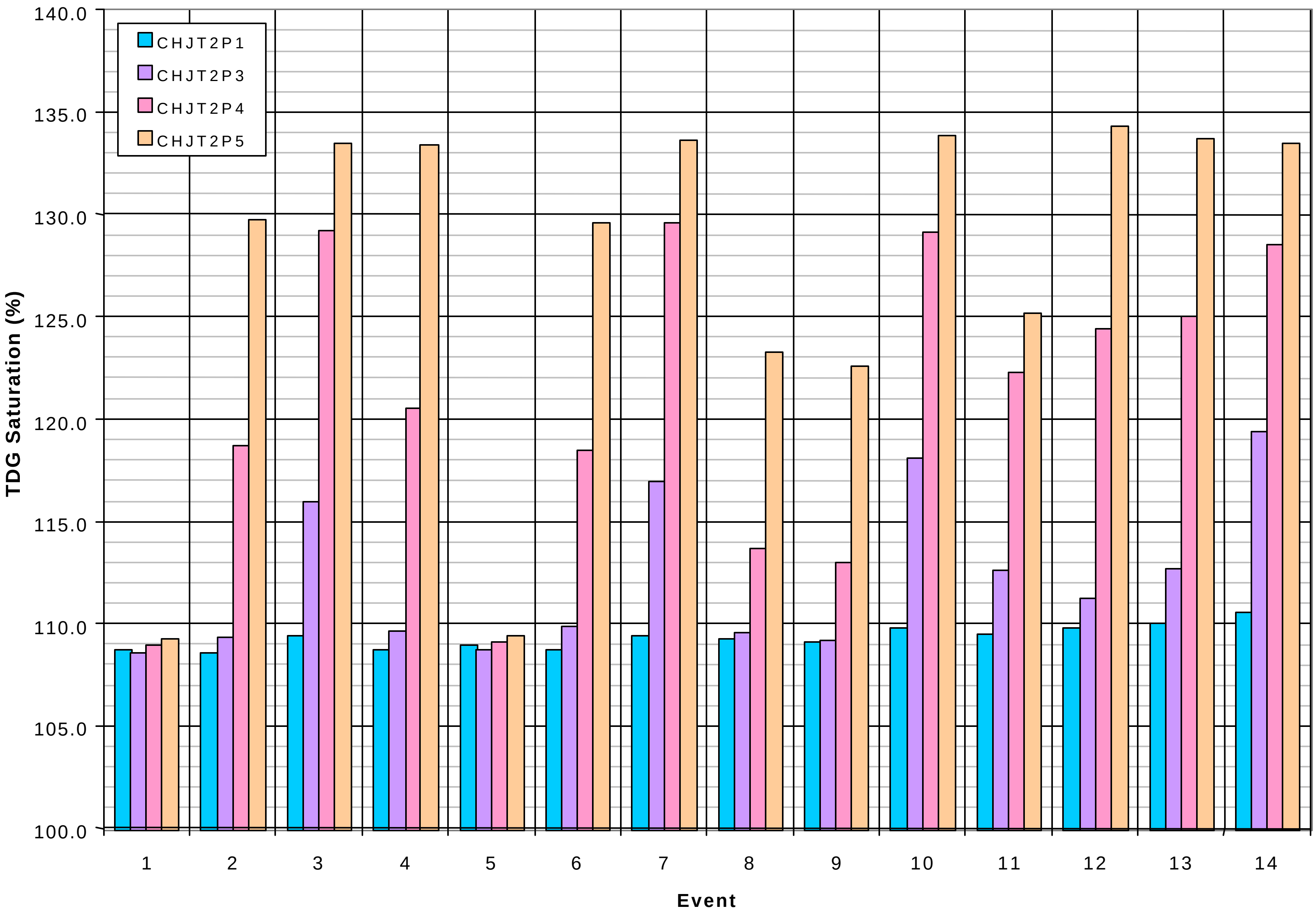

Figure 30. Total Dissolved Gas Saturation on Transect T2 at the End of Each Spill Event at Chief Joseph Dam, June 6-10, 1999.

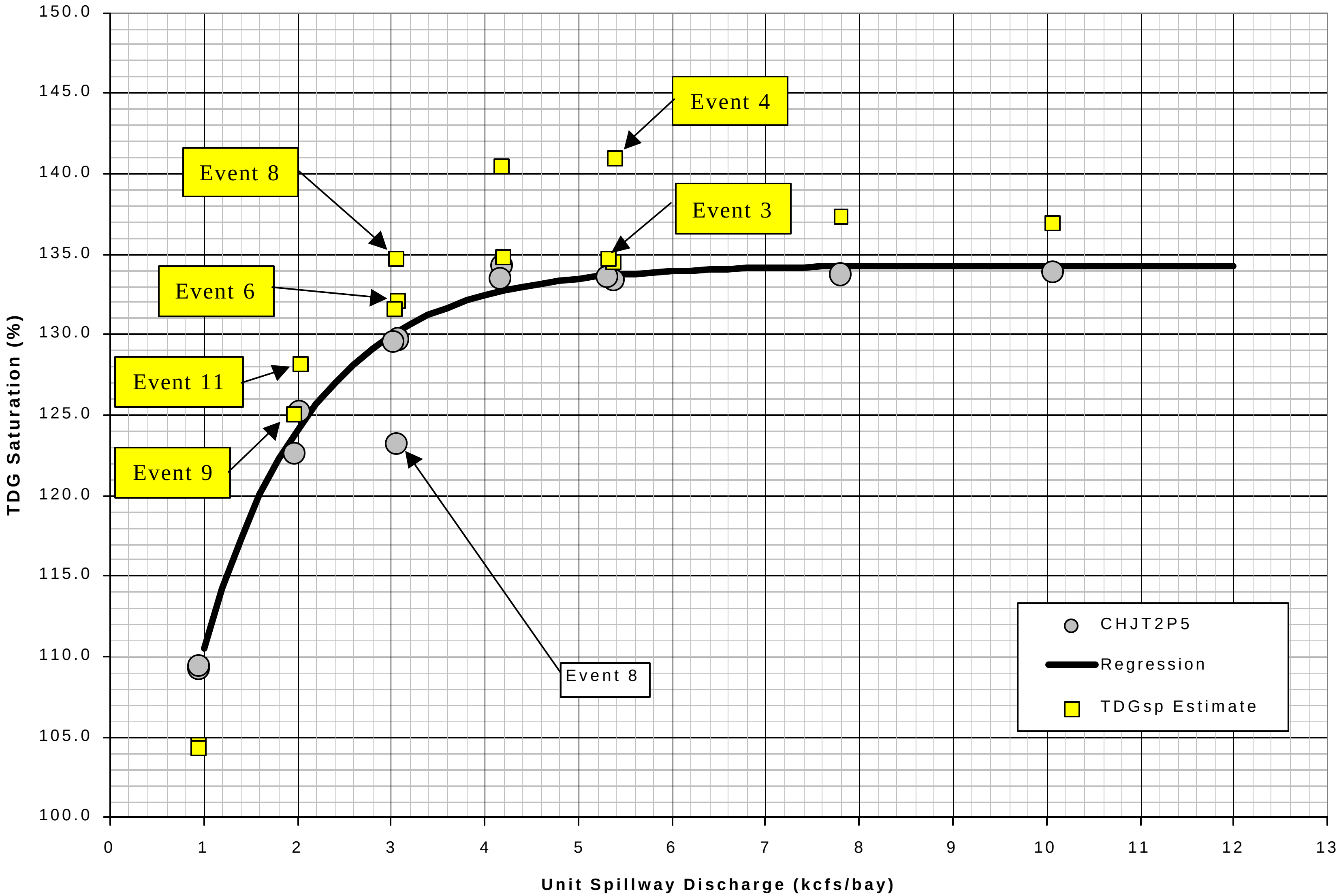

Figure 31. Total Dissolved Saturation at CHJT2P5 as a Function of Unit Spillway Discharge at Chief Joseph Dam, June 6-12, 1999.

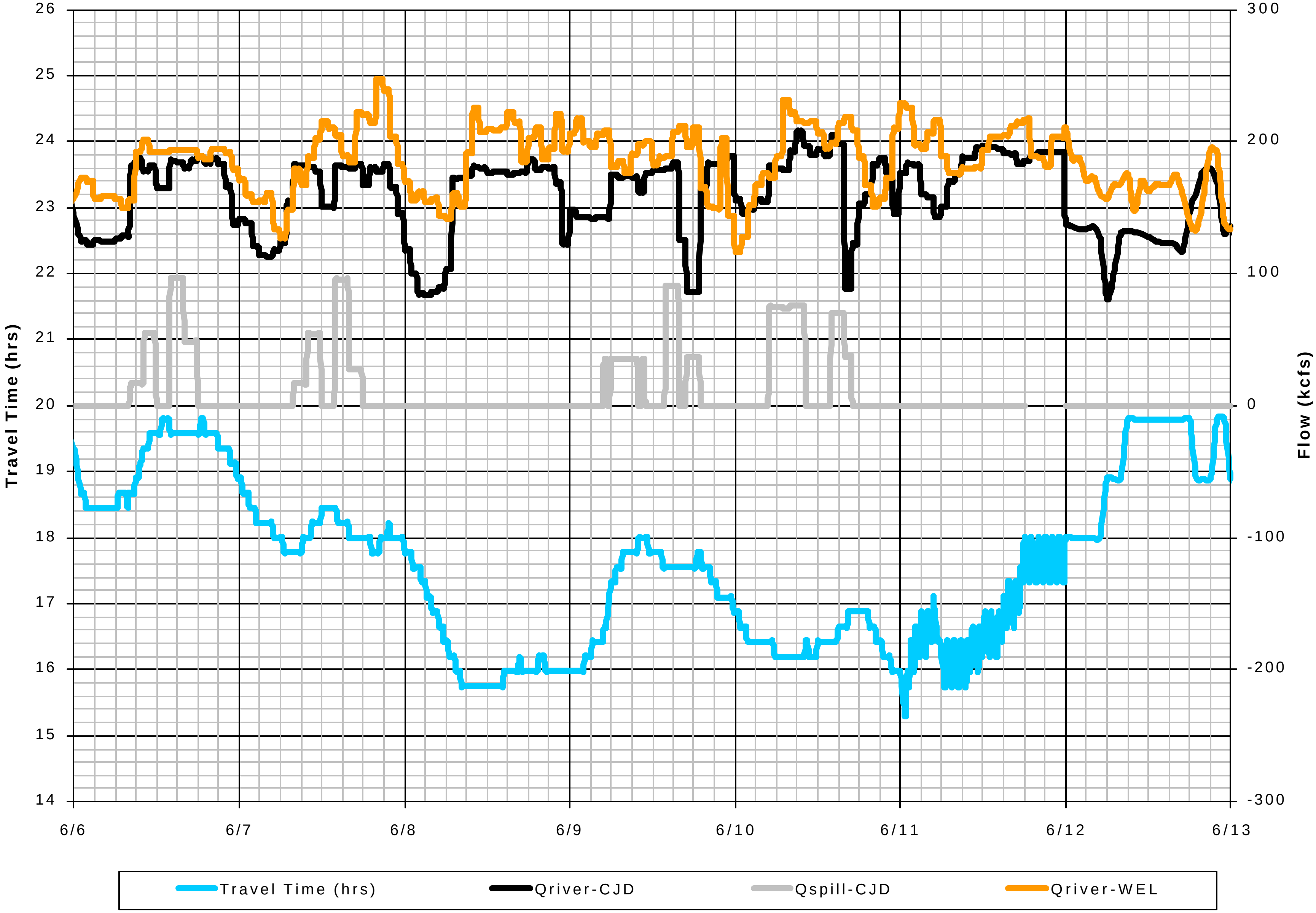

Figure 32. Estimated Travel Time Through Lake Pateros and Project Operations at Chief Joseph and Wells Dams, June 6-12, 1999.

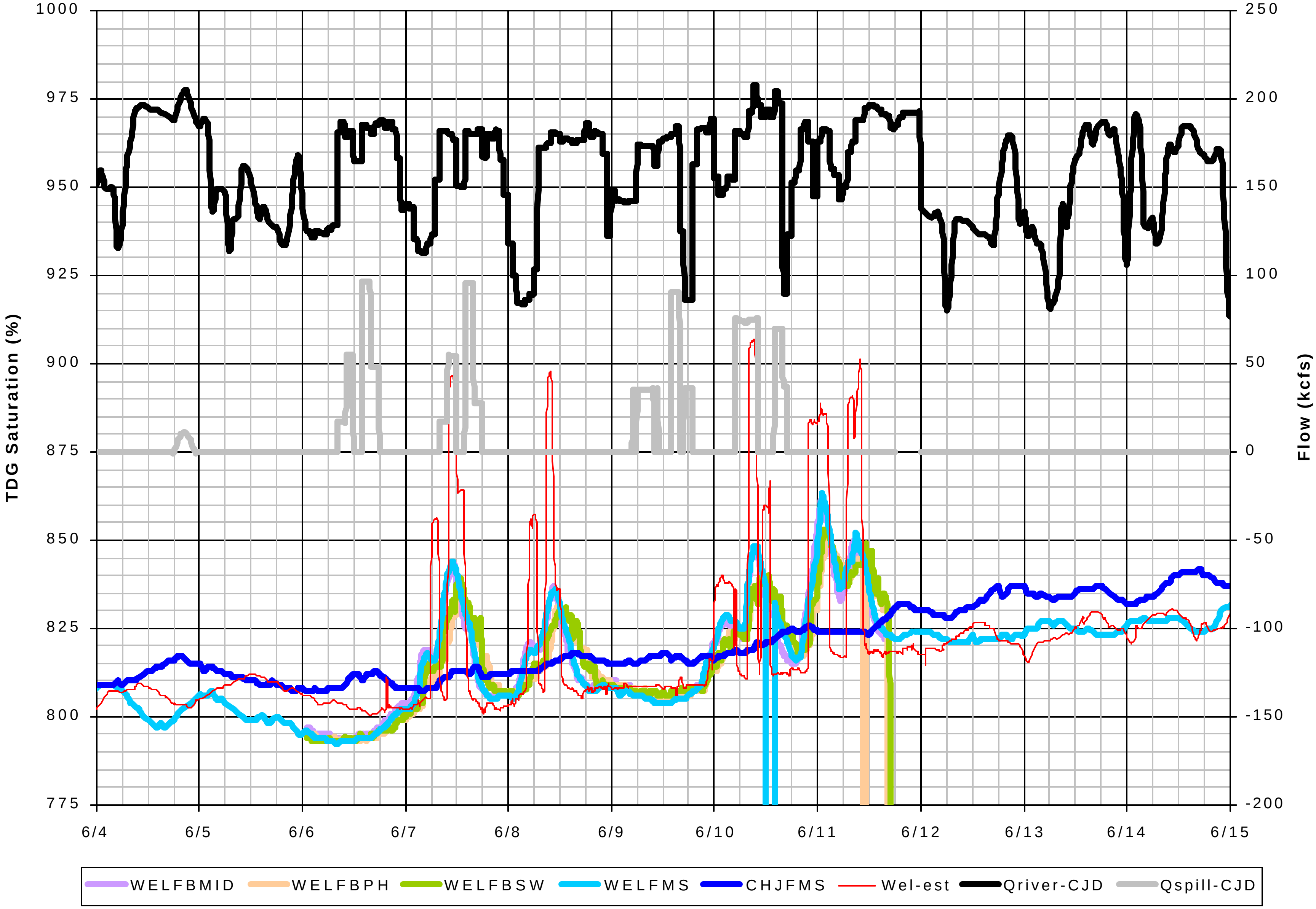

Figure 33. Routing of TDG Plume Through Lake Pateros with No Dispersion, June 4-15, 1999.

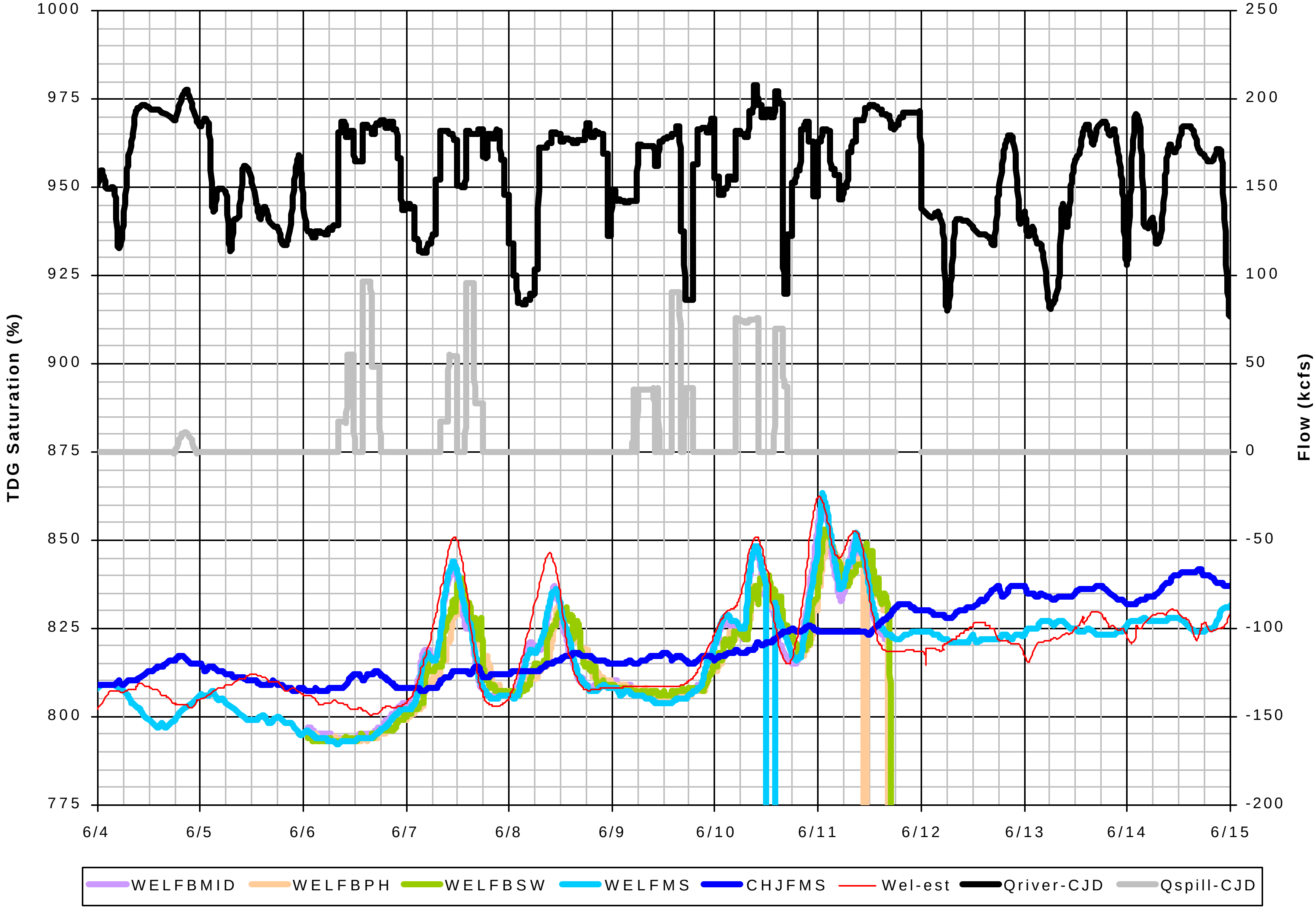

Figure 34. Routing of TDG Plume Through Lake Pateros with Normally Distributed Dispersion, June 4-15, 1999.