Total Dissolved Gas Exchange at Bonneville Dam, 2002 Spill Season

Prepared For

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Preface

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The following document summarizes the impacts of spillway releases at Bonneville Dam during April 10- September 5, 2002 on the total dissolved gas (TDG) saturation in the Columbia River. The document refers to several digital video clips of flow conditions and to an animation of data collected during this study. This referenced material can be viewed only in the digital version of this report, available in Adobe Acrobat format on the enclosed CD-ROM.

Executive Summary

During the winter of 2001-2002, six new spillway flow deflectors were constructed at Bonneville Dam to reduce the production of TDG saturation during spillway releases. The new flow deflectors in spill bays 1-3, 16-18 were placed 7 ft deeper than the existing flow deflectors located in spill bays 4-15. A new spill pattern was also implemented in conjunction with the addition of the new flow deflectors. A study was conducted throughout the 2002 spill season to determine the TDG exchange characteristics of spill operations at Bonneville Dam. The purpose of the study was to determine the impacts of spill on the TDG pressures in the Columbia River downstream from Bonneville Dam. The relative TDG exchange performance of the new and old spillway flow deflectors was a secondary objective. The major water quality findings from this study are as follows:

The addition of six new flow deflectors and the corresponding change in spill pattern resulted in a significant reduction in the TDG saturation when compared to similar spill rates observed prior to the 2002 spill season. The degree of improvement over pre-2002 conditions declined for increasing discharge. The estimated reduction in TDG saturation for a spill discharge of 75 kcfs was 10 percent of saturation.

For low tailwater elevations, ranging from 10.2 to 13.7, the new flow deflectors generated considerably lower TDG pressures than the old deflectors. The difference in the mean TDG saturation (old deflector minus new deflector) for a specific discharge of 7 kcfs/bay was 6.1 percent. At higher tailwater elevations and discharges, the measurements were insufficient to determine the differences in TDG resulting from different deflector designs.

In general, for standard spill patterns during these measurements, the TDG exchange in spillway releases from Bonneville Dam were found to be directly related to the specific spillway discharge and weakly related to the tailwater stage. A family of multivariate linear regression equations was developed to predict the TDG exchange as a function of the specific discharge and tailwater elevation.

A spillway discharge of about 120 kcfs resulted in a cross sectional average TDG saturation exiting the Bonneville spillway channel of 120 percent +/- 1.9 percent. A spillway discharge of 50 kcfs resulted in a cross-sectional average TDG saturation of 110 percent +/- 0.3 percent, which is the Oregon and Washington state water quality criteria for TDG saturation outside of the spill season.

The TDG pressures exiting the Bonneville spillway channel were generally considerably higher than the TDG pressures observed at the tailwater fixed monitoring station (FMS) located at Warrendale. The TDG pressures observed at the Warrendale gage are more closely approximated by the flow-weighted average of both spillway and powerhouse releases from Bonneville Dam.

The TDG saturation observed at the Camas/Washougal FMS is influenced by Bonneville Dam operations and in-river processes influencing heat and mass exchange. The TDG criteria (115 percent) applied at the Camas/Washougal FMS is more restrictive on project operations than is the TDG criteria (120 percent) applied to the Warrendale station.

The average net change in the TDG saturation between Bonneville Dam and the

Camas/Washougal FMS, located 24.1 miles downstream of the dam at river mile 121.6 near the Washington shore, was about –2.2 percent.

An approach to calculate the spill capacity at Bonneville Dam as limited by TDG saturation criteria, was developed as a function of forebay TDG saturation, total river flow, barometric pressure and the TDG margin of safety. The implementation of this spill management algorithm should reduce the likelihood of unwanted excursions above the TDG saturation criteria.

The tailwater FMS at Bonneville Dam should be moved into the spillway exit channel. This location would provide for the consistent and equitable management of spill between dams in the Columbia River basin and provide a better estimate of peak and average TDG pressures generated as a consequence of Bonneville operations.

The potential gas abatement benefits of the new flow deflector design should be determined for intermediate (tailwater elevation 18 ft) and high tailwater elevations (tailwater elevation 23.5 ft). The findings from these additional tests would support any decision to update the deflector design for the entire Bonneville spillway.

Background

Bonneville Dam was recognized as being one of the biggest TDG producers in the Columbia River basin prior to the construction of additional spillway flow deflectors in 2002. The high production of TDG pressure was evident below Bonneville in spite of the relatively low head and the existence of spillway flow deflectors on 13 of the 18 spill bays. Several factors were thought to contribute to the high production of TDG pressure at Bonneville. The depth of flow below the spillway at Bonneville becomes increasingly deeper. The maximum depth of flow immediately below the stilling basin can approach 90 ft for high river flow conditions. The open river conditions below Bonneville produce a wide range of tailwater elevations, which limit the effectiveness of spillway flow deflectors. The baffle block locations in the Bonneville stilling basin are very close to the spillway and influence flow patterns and energy dissipation throughout the tailwater channel. The spill pattern prior to 2002 was highly non-uniform and was biased toward spill bays without flow deflectors. The outside spill bays 1 and 18 were used to pass only minimal discharges. All of these factors contributed to the high TDG levels produced during spill at Bonneville Dam. A high priority was placed on developing an effective gas abatement program at Bonneville Dam. A number of laboratory studies were initiated to study and design structural and operational gas abatement measures. The structural alternatives studied involved spillway flow deflectors, raised stilling basin, and modified radial gates. A series of field studies were also conducted to determine the TDG exchange properties of the existing spillway at Bonneville for the purpose of determining background conditions and aid in the selection of effective TDG abatement measures.

The first detailed field investigation of the TDG exchange in the Bonneville tailwater was conducted during February 17-18, 1997 (Wilhelms and Schneider, 1997). A detailed array of 37 instruments was used to describe the TDG exchange ranging from 40 to 245 kcfs[1] for the standard spill pattern and a uniform pattern over bays 4-15. The average TDG saturation exiting the Bonneville tailwater channel exceeded 120 percent of saturation during all of the test conditions with the exception of the 40 kcfs event. The standard spill pattern involved a flow distribution that was highly non-uniform with the highest unit discharges through spill bays without flow deflectors. Consequently, the average TDG saturation associated with the standard spill pattern was generally about 125 percent for spill discharges up to 135 kcfs and reached a maximum saturation of 138 percent during a spill of 245 kcfs. In general, absorption of TDG occurred in the stilling basin where the TDG saturation approached 170 percent, while desorption occurred in the tailwater channel. The large depths of flow immediately below the stilling basin were thought to contribute to the high TDG pressures generated during this test. One unexpected result from this study was the generation of higher TDG pressures for comparable high specific discharges for the uniform pattern over spill bays with flow deflectors when compared to the standard spill pattern. This observation lead to the conclusion that the addition of flow deflectors may result in higher gas levels for some lower-frequency high-volume spill events. Results from the supplemental study suggest that TDG production associated with current flow deflectors at Bonneville Dam is relatively insensitive to tailwater elevation. Potential modifications of flow deflectors at Bonneville include a larger toe radius and lower elevation, which may provide additional dissolved gas abatement at the margin.

[1] kcfs is thousand feet per second

A second detailed investigation of TDG exchange was conducted during February 1-4, 1999 to address the influence of non-deflectored bays on TDG exchange at Bonneville Dam (Schneider, 1999). The test conditions involved spillway flows distributed uniformly over non-deflected bays, deflected bays, a combination of both deflected and non-deflected bays, and the standard spill pattern. The total spillway discharged ranged from 12 to 278 kcfs. A total of 23 TDG stations were deployed during this study from the forebay spillway channel downstream to Ives Island. The TDG exchange was found to be very sensitive to both the spill pattern and specific discharge. The TDG saturation associated with the non-deflectored spill bays was greater than observed for the other spill pattern for specific discharges up to 10 kcfs/bay. The TDG saturation of the non-deflectored bays quickly reached an upper limit of 132 percent for a specific discharge of 6.7 kcfs/bay and greater. The TDG exchange associated with spill over the deflectored bays 8-15 was found to be an exponential function of the specific discharge and was greater than 132 percent of saturation for specific discharges of 13.8 kcfs/bay and higher. The standard spill pattern again produced an average TDG saturation of 125 percent of saturation for spillway flows up to 163 kcfs and reached a maximum TDG saturation of 133.2 percent for a spill of 278 kcfs. The TDG exchange associated with the standard spill pattern was found to be well approximated by the additive performance of individual spillbays with and without flow deflectors. Once again, the highest TDG pressures were observed in the bubbly flow downstream from the stilling basin with local TDG saturations as high as 163 percent. The lateral mixing of spill and degassing associated with the venting of entrained air resulted in a reduction in the peak TDG saturation as a function of distance from the spillway.

Six new spillway flow deflectors were constructed at the Bonneville spillway in bays 1-3, and 16-18 during the fall and winter months of 2001-2002. The purpose of these flow deflectors is to reduce the amount of TDG exchanged during spillway operations. A second design criterion involves providing for safe passage and effective guidance of juvenile fish past Bonneville Dam.

The design of the new spillway flow deflectors is considerably different from the existing flow deflectors in bays 3-15. The new flow deflectors are located 7 ft deeper than the older flow deflectors and provide a larger radius of curvature for the transition from the spillway face to the flow deflector. Post-construction evaluation of these newly installed flow deflectors is designed to assess both the water quality and biological properties associated with the new spillway structure and associated operational policy. The following report outlines the water quality evaluation of the modified spillway.

Objective

The main object of the post-construction water quality study was to quantify the TDG exchange associated with the modified spillway consisting of the original flow deflectors at elevation 14 ft[2], and new flow deflectors at elevation 7 ft. To accomplish this, the Bonneville spillway was operated under a wide range of conditions involving the spill pattern, discharge, and tailwater elevation. The TDG evaluation will provide information regarding the impacts of added flow deflectors and the associated spill pattern on TDG exchange below the Bonneville spillway. The reduction in TDG saturation afforded by the new structural configuration and operation as compared to the pre-2002 conditions will be determined by this study. This detailed TDG exchange information can be used to quantify the water quality benefits associated with the modified structure, provide operational direction for the spillway, and help identify the relative TDG exchange properties associated with the new and old spillway flow deflector designs. The decision to fully implement the new flow deflectors at the Bonneville spillway will be dependent upon the additional TDG abatement benefits, flexibility in spill management, and improved fish guidance associated with this modified structure and its operation. The study will provide detailed descriptions of the TDG habitat in the spillway exit channel. The TDG properties within and downstream of the highly aerated flow conditions were examined as were the conditions near the entrances to the adult fish ladders. This information can also be used to assess the adequacy of the existing FMS in terms of compliance with state water quality criteria and the total daily maximum load for TDG in the Lower Columbia River. The influence of spillway flows at Bonneville Dam will constitute the primary source for elevated TDG pressures in Columbia River from the dam to the Pacific Ocean. The relatively shallow nature of the river reach below Bonneville will cause a much larger percentage of this water body to reside above the compensation depth when compared to impounded river reaches and thereby pose a greater risk to aquatic ecology. The results from this study will provide critical information for determining the TDG loading introduced into the open river reach below Bonneville and help determine the fate of dissolved gases during mixing and transport throughout this river reach.

[2] All elevations (el) referenced to the National Geodetic Vertical Datum (NGVD). To convert feet to meters, multiply by 0.3048.

Approach

This study primarily focused on determining the TDG exchange characteristics associated with routine spillway operations using the standard spill pattern identified in the fish passage plan and for a series of test spill patterns designed to determine the performance of specific spill bays. An array of TDG sensors was deployed above and below the spillway at fixed locations to measure the net change in TDG content of spill. The TDG instruments were aligned along sampling transects to capture the prominent cross sectional properties in TDG pressure across the spillway exit channel. The automated TDG instruments recorded TDG pressure on a 15-minute frequency to document the time histories of TDG pressures in response to changing project operations. The variation of the spillway channel topography together with the non-uniform standard spill pattern likely contributed to prominent lateral gradient in TDG pressure throughout the spillway exit channel. Both spillway and powerhouse discharges were varied during the spill season to provide a wide range of project spill and tailwater elevations. Both the specific discharge or discharge per width of the spillway and deflector submergence have been identified in laboratory investigations as being critical properties in determining the potential TDG exchange of spillway releases. The instrument depths were recorded through the study to provide a local estimate of the tailwater elevation. An hourly powerhouse log was also maintained to provide a record of the hourly gate setting and unit discharges.

A second objective of this study was to determine the relative TDG exchange performance associated with both the new and old spillway flow deflectors. This objective was to be addressed in a series of paired test spill patterns involving a uniform spill over the six bays with the new deflector design and a uniform spill over six bays with the old deflector design. A corresponding series using the standard spill pattern with a comparable aggregate specific discharge to the uniform spill patterns was also scheduled. A rigorous investigation of deflector performance requires a wide range of tailwater elevations and specific discharges. The deflector performance testing for only the low tailwater conditions were executed. The tests scheduled for intermediate and high tailwater conditions were canceled due to concerns involving the disruption of the standard fish passage plan. The TDG sampling array was expanded to provide greater coverage throughout the spillway exit channel. The instrument array consisted of four primary sampling transects located upstream of the spillway, immediately below the stilling basin, at the tailwater restricted access line, and near the exit of the spillway channel. The instruments recorded the time history of TDG pressures in response to the scheduled 3-hour spill events. Hence, lateral and longitudinal gradients in TDG pressures were investigated downstream of the spillway. The local barometric pressure was recorded throughout the sampling period. Water temperatures were also routinely recorded at each of the TDG sampling stations.

Total Dissolved Gas Properties and Processes

This section provides background information regarding the properties and processes governing TDG exchange at main-stem dams found in the Columbia River Basin. This summary is based on properties of the gas laws, mass transfer theory, and observations at other projects in the basin. This information is provided to clarify the interpretation of data observed at Bonneville Dam during this investigation.

TDG Properties

The TDG pressure in water is composed of the sum of the partial pressures of atmospheric gases dissolved in the water. The primary gases making up TDG pressure in water are oxygen, nitrogen, argon, and carbon dioxide. The atmospheric compositions of these gases are 20.95, 78.09, 0.93, and 0.03 percent, respectively. Henry's Law is an equation of state that relates the solubility of a given gas to the partial pressure. The constant of proportionality is called Henry's constant or the Bunsen coefficient. This equation relates the mass concentration of a constituent gas to the partial pressure at equilibrium. The constant of proportionality is a function of barometric pressure, temperature, and salinity. The mass concentration of dissolved gases in water can be determined from estimates of the TDG pressure, water temperature, and barometric pressure assuming atmospheric composition of gases in solution. Thus, for constant temperature and pressure conditions, the TDG can be represented as either a concentration or pressure in conservation statements.

The solubility of a gas in water is dependent on the ambient pressure of the gas, water temperature, and salinity. The total pressure experienced by entrained air bubbles in the water column is composed of barometric pressure and hydrostatic pressure. Thus, the solubility of gas in water doubles at a depth of about 33 ft in response to a doubling of the total pressure. The compensation depth is where the total pressure is equal to partial pressure of the TDG. At this depth, the saturation concentration is equal to the ambient concentration in the water. The solubility of gas in water is inversely proportional to the temperature. If the TDG concentration of 30 mg/l (907 mmHg, 110.0 percent) is held constant in a water sample at one-atmosphere of pressure, and the temperature is raised from 20^o to 21^o C, the TDG pressure will increase by 17 mmHg (924 mmHg, 112.0 percent). Under these conditions, an increase in temperature of one degree will result in an increase in the TDG saturation of 2 percent.

TDG Exchange Processes

The TDG exchange characteristics at a hydraulic structure are closely coupled to the system hydrodynamics. As the flow conditions are altered by structural or operational means, the TDG exchange is also modified. The following general description of processes governing TDG exchange at hydropower dams has been formulated based in part upon the theory of mass exchange, laboratory studies, and near-field TDG studies conducted as part of the Dissolved Gas Abatement Study (DGAS) (USACE 1997). This discussion focuses upon the hydrodynamic and mass exchange characteristics in four regions: forebay, spillway/turbine passage, stilling basin, and tailwater channel.

Forebay

The TDG properties in the immediate forebay of a dam have generally been well mixed, when no thermal stratification is present. Thermal stratification can limit the influence of air/water exchange of gasses to the near-surface layers of a pool. The heating or cooling of an impoundment can cause TDG pressure responses that result in changes to supersaturated conditions (Colt 1984). Biological activity involving the production or consumption of oxygen will influence the TDG pressure. Therefore, under stratified conditions, the initial TDG pressure of spillway releases may be different from those associated with hydropower releases. TDG levels in the forebay can change rapidly in response to operations of upstream projects, tributary inflows, and meteorological conditions. The flow under a spillway gate or into a turbine intake may spawn vortices that provide a vehicle for air entrainment. In general, the TDG concentrations are not significantly altered by near-field flow conditions in the forebay.

Spillway

The depth of flow and water velocities change rapidly as flow passes under the spillway gate onto the face of the spillway. The roughness of the spillway piers and gates may generate sufficient surface turbulence and water spray to entrain air. Flow on the spillway may become aerated for smaller specific discharges as a consequence of the development of the turbulent boundary layer. However, the short time of travel down the spillway will limit the exposure of water to entrained air bubbles to only a few seconds and thereby limit the amount of gas exchange. The entrained air and shallow flow on the spillway may cause desorption of dissolved gases if forebay levels are elevated.

Turbine passage

There is little opportunity for entrained air to be introduced into the confined flow path through a turbine, except during turbine start-up or shutdown, when air may be aspirated into the turbine. Under some conditions it may be advantageous to introduce air into a turbine to prevent cavitation or for smooth operation. When air is introduced into a turbine, the opportunity exists for mass transfer to occur resulting in TDG supersaturation. The extent of TDG transfer in a turbine will be dependent upon the amount of air introduced and the total pressures encountered. In most cases where no air is introduced, there is no appreciable change in TDG pressure as flows pass through the penstock, turbine, and draft tube. The powerhouse simply conveys the TDG properties withdrawn from the forebay pool to the tailwater and does not directly contribute to higher TDG loading.

Entrainment of powerhouse releases

The high energy content and dissipation rate of spillway flows has the potential to entrain large volumes of water into highly aerated flow contributing to the TDG loading of project releases. Powerhouse discharge may either be entrained into spillway flows in the stilling basin, or mixed with spillway releases in the river channel downstream. When the spillway is adjacent to the powerhouse, a portion of this entrainment flow is supplied directly from powerhouse releases. This entrained flow is exposed to entrapped air bubbles in the spillway flow causing uptake of dissolved gas. The fate of powerhouse discharges varies from project to project and depends upon operating conditions, structural features such as training walls and energy dissipation features, and tailwater channel properties. The findings from the Little Goose spillway performance test (Schneider and Wilhelms 1998) showed that nearly all of the powerhouse flow was entrained into spillway releases and gassed to comparable pressures.

Stilling basin

The flow conditions in the stilling basin are often highly three-dimensional and are shaped by the presence of spillway flow deflectors, spill pattern, spillway piers, training walls, baffle blocks, end sill, tailwater elevation, project head, and spillway geometry. In general, however, the flow conditions downstream of a standard spillway are characterized by highly aerated flow plunging to the bottom of the stilling basin. The baffle blocks and end sill redistribute the bottom-oriented discharge jet throughout the water column. Because of the high air entrainment and the transport of air to depth, a rapid and substantial absorption of atmospheric gases takes place in the stilling basin below the spillway. These flow conditions result in maximum TDG pressures experienced below the dam.

The function of spillway flow deflectors is to prevent the plunging of a spillway discharge and the entrained air to depth in the stilling basin. In previous laboratory studies of spillway flow deflectors (USAEWES 1998), hydraulic performance in the stilling basin was classified into several categories. The categories were identified to help characterize the trajectory of the spillway jet throughout the adjoining stilling basin. These flow regimes were also hypothesized to have certain dissolved gas transfer characteristics. The categories and associated hydraulic actions are described below:

a. *Plunging flow* includes *aerated plunging flow,* which occurred when the underside of the surface jet was vented at the downstream end of the deflector; *unstable aerated plunging flow,* which occurred when the underside venting of the surface was inconsistent; and *non-aerated plunging flow,* which occurred when the underside aeration ceased, but there was sufficient momentum to still cause a plunging flow off of the deflector. Also included in this category was *oscillating or surging flow,* which was an unstable condition with the flow alternately attempting to ride the surface of the tailwater, but then plunging to the stilling basin floor with tailwater surging over the plunging flow.

b. *Skimming flow or surface jet* occurred when the spillway jet remained along the surface of the tailwater with a relatively flat water surface with no plunging action and little downwelling.

c. *Undulating flow or an undulating surface jet* occurred when the spillway jet coming off of the deflector would "ramp up" on the downstream water surface forming an undulating surface with standing waves under some conditions.

d. Ramped surface jet occurred when the spillway jet would "ramp" up on the tailwater as it left the deflector, causing large standing waves and significant downwelling. For the ramped surface jet, the lift angle of the jet coming off the deflector was greater than 25 degrees.

e. *Surface jump or submerged surface jump* occurred when a hydraulic roller formed at the deflector, and with higher tailwater, the spillway jet was inundated on the deflector, resulting in a submerged hydraulic jump that was elevated off the stilling basin floor. This includes an *unstable surface jump*, which occurs when the sloping upstream face of the surface jet attempts to break over into a “surface jump,” but retreats and starts again.

Tailwater channel

A rapid and substantial desorption of supersaturated dissolved gas takes place in the tailwater channel immediately downstream of the stilling basin. As the entrained air bubbles are transported downstream, they rise above the compensation depth in the shallow tailwater channel. While above the compensation depth, the air bubbles strip dissolved gas from the water column. The entrained air content decreases as the flow moves downstream as the air bubbles rise and escape to the atmosphere. The desorption of dissolved gas appears to be quickly arrested by the loss of entrained air within 200-500 ft of the stilling basin. The reduction of TDG pressures downstream from the aerated flow regime is generally the result of dilution, temperature change, surface exchange, and chemical/biological processes.

The depth of the tailwater channel appears to be a key parameter in determining TDG levels entering the downstream pool (USACE, 2002). If a large volume of air is entrained for a sufficient time period, the TDG saturation will approach equilibrium conditions dictated primarily by the depth of flow. Thus, mass exchange in the tailwater channel has the greatest influence on TDG levels delivered downstream during high spill discharges. This process may account for the upper limit on TDG exchange observed at many Corps of Engineers (CE) projects at high spillway discharges.

Mixing Zone Development

The TDG content of powerhouse and spillway releases often contains very different TDG pressures. The interaction of project powerhouse and spillway flows establishes a mixing zone. As discussed previously, hydropower releases entrained into the aerated spillway flows will often be exposed to similar levels of TDG exchange as experienced by spillway releases. The entrained hydropower releases are mixed with spillway releases and effectively add to the spillway discharge from a project. As a consequence, the amount of hydropower releases available for dilution of spillway releases in the mixing zone downstream is reduced.

The development of the mixing zone below a project will influence the spatial distribution of TDG properties in the downstream pool. The understanding of mixing zone development is critical to the interpretation of observed downstream TDG pressures. In regions where the mixing between powerhouse and spillway releases is incomplete, lateral gradients in TDG pressure will be present and point observations of TDG pressure will be biased by local project releases. The properties of the mixing zone will be dependent upon the tailwater channel features, the location of powerhouse and spillway structures, hydrodynamic conditions in the river, spillway and powerhouse operations, and the entrainment of powerhouse flows into the aerated spillway flows.

Riverine TDG Exchange Processes

The inflow from tributaries to the main stem can change the water quality properties in the study area through transport and mixing processes. Shallow, steep gradient streams generally will have a TDG content approaching 100 percent of saturation and will dilute the higher TDG levels in the main stem river generated from spillway releases. The water temperature of tributaries can also be different from conditions in the main stem influencing both average main stem temperatures and TDG pressures.

The heat exchange within the river systems can result in rising and falling water temperatures that influence TDG pressures. The exchange of energy will be governed by meteorological conditions influencing long wave and short-wave radiation, evaporation, and conductive heat exchange processes. The hydraulic and topographic features of a pool will also influence the responsiveness of a river reach to external energy forcing processes. Shallow channel reaches of slowly flowing water will respond much more quickly to external energy inputs than deeper, more swiftly flowing sections. Lateral gradients in TDG pressure can be generated from the differential heat exchange in a river reach fed by uniform water quality.

The development of vertical gradients in water temperature can also develop on a diurnal basis in pools or near-dam areas where vertical mixing is limited by slack water and calm winds. These vertical gradients in temperature can also develop in areas where tributary inflows contain water temperatures that are significantly different from the primary river. These processes can result in forebay water temperatures significantly higher than tailwater water temperatures and TDG pressures influenced by these thermal differences.

The TDG levels generally increase during spillway operations at main-stem dams due to the entrainment of bubbles in the stilling basin. Once most of the air bubbles are vented back to the atmosphere, exchange of TDG pressure at the air-water interface is driven towards equilibrium with atmospheric conditions. Where the in-pool degassing rates exceed to addition of TDG pressures at a dam, the TDG pressures will undergo a net reduction over the length of a pool.

The mass exchange at the water surface can be greatly accelerated where surface waves increase the air-water interface, entrain bubbles, and promote the movement of water to the surface layer. The roughening of the water surface can be generated by surface winds or channel features such as rapids or falls.

The interaction of nutrients, algae, and dissolved oxygen (DO) can impact TDG concentrations in a river. The diurnal cycling of photosynthesis and respiration is chiefly responsible for fluctuations in DO concentrations. A 1 mg/l variation in DO will result in a variation of TDG pressure ranging from 12 to 17 mm Mercury (Hg) depending upon water temperature.

Site Characterization

Bonneville Dam is about 6400 ft long and includes two powerhouses, a spillway, two navigation locks, multiple fish ladders, and three islands (Figure 1). The spillway is bounded by Bradford Island to the south and Cascades Island to the north. The first powerhouse is located to the south of Bradford Island and the second powerhouse is located to the north of Bradford Island. A total of six 59-megawatt units and eight 77-megawatt turbines reside in Powerhouse No. 1 and Powerhouse No. 2, respectively. The current operating policy places a priority for generation through the second powerhouse during the fish passage season.

The 18-bay spillway is approximately 1100 ft long, and has twelve 50.75-ft-high vertical lift gates and six 60-ft-high wheel gates (Figure 2). The spillway crest is located at elevation 24 with a normal forebay pool elevation ranging from 71.5 to 76.5. Spillway bays 4 through 15 and 18 have deflectors that are 12 ft long and are located at el 14. The stilling basin is a horizontal apron-type with a double row of sloping baffle blocks (Figure 3). The stilling basin is 147 ft long with an invert elevation of -16 for the first 71 ft and drops to el -24 for the remaining length. An irregular concrete apron is at the end of the stilling basin and usually slopes downward to the tailrace topography. The operation of the spillway gates was fully automated in 2002 allowing a much finer adjustment in the gate setting to be selected. Spillway flow deflectors were constructed on bays 4-15 (Figure 4) and 18 during the 1970's at elevation 14 with a 12 ft length and a 6-ft toe curve. Six new flow deflectors were constructed in spill bays 1-3, and 16-18 during the winter of 2001-2002. The new deflectors were constructed at elevation 7 with a 12-ft length and a 15 ft toe curve.

The old lock is 76 ft wide by 500 ft long. It discharges into a navigation channel that joins the releases from Powerhouse No. 1 approximately 1200 ft downstream of the lock. The new lock is 86 ft wide by 675 ft long and discharges into a channel that joins the discharge from the remainder of the project about 2600 ft downstream of the lock. Powerhouse discharges and lock operation only indirectly influence the spillway flow conditions by changing the local tailwater elevation.

The bathymetry of the channel downstream of the spillway (Figure 5) is highly irregular ranging in elevation from near zero to -60. The typical tailwater pool elevation ranges from 7.8 to 30.4 ft during the spill season resulting in an average depth in the stilling basin of about 40 ft. The tailrace channel is about 80 ft deep in two locations on each side of the exit channel (directly downstream of bays 5 and 17) for typical discharge conditions. The largest expanse of deep water is directly downstream of bay 5. The channel bottom then slopes upward to an elevation of approximately -10 near the mouth of the spillway exit channel with a corresponding channel width of 850 ft. The spillway exit channel then slopes downward to meet the tailrace channel of Powerhouse 2.

Study Design

The characterization of hydraulic flow regimes associated with spillway releases with spillway flow deflectors have been found to be a function of the specific discharge (discharge per unit width or discharge per spill bay) and deflector submergence. A description of the various flow regimes expected below Bonneville Spillway has been summarized in the Draft Data Report dated 20 March 2000 entitled "Modified Bonneville Deflector at Elevations 7 and 10, Bonneville Spillway Section Model" (Wilhelms, 2000). There are two types of flow regimes that have the potential to significantly influence the performance of the spillway flow deflectors from a water quality and biological standpoint. At the lower end of the flow performance spectrum is plunging flow. Aerated plunging flow occurs when the underside of the surface jet is vented at the downstream end of the deflector. A plunging spillway jet acquires a horizontal component directing the jet to the base of the stilling basin and generating a return surface current to the plunge point. The plunging jet carries entrained air bubbles to depth, greatly increasing the potential to transfer atmospheric gasses from the bubbles to the water column. A portion of the plunging jet will encounter the baffle blocks and stilling basin floor. The rate of energy dissipation during plunging flow conditions will also be larger, generating more severe levels of turbulence and shear forces.

At the upper end of the expected flow regimes at the Bonneville spillway, are conditions leading to a submerged hydraulic jump. During these conditions, the tailwater elevation cannot be swept away from the flow deflector causing a submerged hydraulic jump to form at the base of the spillway. The consequences of these hydraulic conditions on TDG exchange and fish passage are not well known. The imparting of vertical momentum in the hydraulic jump on the high velocity jet passing over the deflector will likely influence the rate of energy dissipation, jet trajectory, and amount of air entrainment. These two types of flow conditions (plunging flow and submerged hydraulic jump) have been identified as critical conditions upon which to evaluate spillway flow deflector performance at Bonneville Dam.

The operating conditions that are both necessary and sufficient to quantify the performance of the modified Bonneville Spillway fall into three ranges of flow conditions. The upper quartile of total river flow at Bonneville, based on a flow duration curve using daily average flows from April 1-August 31, 1974-1999, is defined by discharges greater than 300 kcfs and tailwater elevations greater than 23.5 ft. Hourly total river flows exceeding 300 kcfs have occurred during five of the last six years at Bonneville Dam. Low flow conditions defined as being in the lowest quartile of flows can be defined by discharges less than 130 kcfs. During these conditions, the tailwater will generally be 12.5 ft or lower resulting in new and old spillway deflector submergences of 5.5 and –1.5 ft respectively. The range in spillway discharges is greatly limited by the total river flow during low flow conditions. The flow regimes associated with these events are a skimming flow, unstable plunging/skimming flow, and plunging flow. Average total river flow conditions ranging from 170 to 250 kcfs (25 percent of the flow centered around the median total river discharge of 210 kcfs) were identified as the third set of conditions in which to evaluate the TDG exchange characteristics associated with the modified Bonneville spillway. During these moderate flow conditions, the average tailwater was about 18 ft with associated new and old spillway deflector submergences of 11 and 4 ft, respectively. The flow regimes associated with moderate flow events are a ramped surface jet, skimming flow, unstable plunging/skimming flow, and plunging flow.

The original test plan called for monitoring of the TDG saturation in the approach and exit spillway channel for the routine operations during the fish passage season. This type of sampling would capture the TDG exchange associated with the standard spill pattern over a wide range of spill discharges, and tailwater elevations. However, to address the specific question concerning the TDG exchange performance of the different types of spillway flow deflectors, special spill patterns calling for a uniform spill over six spill bays with the same deflector design was required. These paired spill events were required for a wide range of specific discharges and tailwater elevations to develop a comprehensive evaluation of the different deflector designs. The flow conditions associated with high, moderate, and low river discharges were identified as necessary conditions to compare the different deflector TDG exchange performance. The only deflector specific TDG testing executed during the 2002 spill season was for low flow conditions. The additional test conditions for moderate and high river discharges were canceled because of conflicts with biological studies and impacts on fish passage.

Two separate arrays of TDG instruments were deployed during the 2002 spill season at Bonneville Dam. The first deployment consisted of five stations located on the left channel bank on Bradford Island (BONTWP1), right bank on Cascade Island (BONTWP5), and at the quarter points across the channel (BONTWP2, BONTWP3, BONTWP4) as shown in Figure 6. The instruments deployed from the channel banks were located in permanently positioned steel conduits, which allowed access to these instruments from shore. The instruments deployed away from the channel bank were on the channel bottom in a steel housing and could not be accessed during spillway releases because of safety concerns. This instrument transect was located about 1400 to 1617 ft below the spillway with the average depths of deployment ranging from 10 to 21.8 ft, as listed in Table 1. The instruments at the shore-based stations were maintained throughout the spill season from April 11 through August 31. The instruments located away from the channel bank were deployed on April 8 and retrieved on July 6. The high spillway releases during the first week in June of over 200 kcfs caused the instruments at stations BONTWP2, BONTWP3, and BONTWP4 to move downstream several hundred feet. Theses stations remained in spill waters near the mouth of the exit channel but downstream of the original positions.

The second deployment of instruments was conducted on August 24 where spill was shut down for a period of 3 hours to accommodate the positioning of instruments throughout the Bonneville exit spillway channel. This instrument array consisted of 20 stations positioned upstream, within, and downstream of the highly aerated flow conditions which develop during spillway releases at Bonneville Dam. The purpose of the detailed sampling array was to capture the spatial and temporal TDG exchange characteristics associated with test spill events isolating the performance of the different deflector designs. An array of sampling stations consisting of four major transects was deployed in the forebay (FB), below the stilling basin at transect T1, 800 ft below the stilling basin at transect T2, and aligned with the fixed shored-based stations (BONTWP1 and BONTWP5) at transect T3, as shown in Figure 6.

Two stations were deployed from shore in the forebay of the spillway entrance channel on the left (FBP1) and right banks (FBP2). The station on the right bank was positioned next to the permanent fixed monitoring station (BON).

Transect T1 was located just downstream of the stilling basin at distances ranging from 300 to 400 ft below the spillway in depths ranging from 37 to 68 ft on average (Table 1). Two stations were located just downstream from the entrances to the fish ladders on Bradford and Cascade Islands and were suspended in the water column. The five stations located immediately below the stilling basin (T1P1, T1P2, T1P3, T1P4, and T1P5) were generally aligned with spill bays 18, 14, 9, 5, and 2, respectively. The instrument located at station T1P5 was not recovered after the completion of the spill season. This instrument was located in one of the deepest holes below the north end of the spillway and the attached buoys and rigging were lost during testing. Instruments were lost at this location during previous TDG testing below Bonneville Dam.

The second downstream transect, T2, consisted of four stations (T2P1, T2P2, T2P3, T2P4) and was positioned about 809 to 1017 ft below the spillway. The first (T2P1) and fourth (T2P4) stations were generally aligned with spill bays with new flow deflectors while the interior stations were positioned downstream from spill bays with the old flow deflector design. The average depths on this transect ranged from 11.3 ft at station T2P1, to 39 ft at station T2P3 (Table 1).

The third downstream transect, T3, was positioned downstream of the highly aerated flow conditions generated during spillway releases at Bonneville Dam. This transect consisted of both the shore based stations (BONTWP1, and BONTWP5) with five additional station (T3P2, T3P3, T3P4, T3P5, T3P6) positioned away from the channel banks on channel bottom and were distributed across the channel. This transect was positioned downstream from the spillway at distances that ranged from 1400 to 1617 ft and the average instrument depths ranged from 10.1 to 29 ft (Table 1).

Two additional permanent fixed monitoring stations located downstream of Bonneville Dam during the 2002 spill season were the Warrendale (WRNO) and Camas\Washougal (CWMW) stations. The Warrendale station is located on the Oregon side of the river 6 miles downstream of Bonneville Dam at river mile 140.2. The CWMW station is 24.1 miles downstream of the dam at river mile 121.6 near the Washington shore as shown in Figure 7. The Warrendale station is considered the Bonneville tailwater station for compliance purposes with water quality standards, where the average of the highest 12-hour daily observations is restricted to 120 percent of saturation. The Camas/Washougal station is treated as the downstream compliance location where the average of the highest 12 hourly observations is not to exceed 115 percent of saturation.

Project Operation

The initiation of spill at Bonneville Dam began on April 10 and was maintained through August 31 with the exception of a 3-hour stoppage on August 24 to install TDG instrumentation. The average total river flow of 236 kcfs during this five-month period was above average, ranking the 9th highest out of 28 years since 1975. The average hourly spill during this period was 108.7 kcfs or about 46 percent of the total river flow. The hourly spill discharge consisted of either 75 kcfs, spilling to the TDG capacity as dictated at the downstream fixed monitoring stations, or forced spill. The hourly project operations are shown in Figure 8 for the 2002 spill season. The red line shows the upper boundary for the hydraulic capacity powerhouse releases at Bonneville Dam. River discharges above the hydraulic capacity of both powerhouses require spill. The statistical summary of project operations at Bonneville during the 2002 spill season is listed in Table 2.

The daylight spill of 75 kcfs was part of a management plan to limit the fallback of adults during the daylight hours in spillway discharges. The 75 kcfs spill events were generally scheduled in blocks of 2 to 4 days with nighttime spill to capacity as determined at the downstream fixed monitoring stations. The spillway discharge of about 75 kcfs was scheduled about 27 percent of the time during the active spill season.

The spill to capacity discharge as limited by the TDG numerical criteria resulted in a wide range of operations. In almost every case during the 2002 spill season, the TDG conditions of 115 percent at the Camas/Washougal FMS was the limiting factor for the spillway discharge at Bonneville Dam. The Warrendale station is located 6 miles below the dam where powerhouse and spillway flows are nearly well-mixed and the 120 percent TDG criteria applies. Therefore, since the loss in TDG saturation in the Columbia River between Warrendale and the Camas/Washougal monitoring station was well less then 5 percent, the downstream TDG constraint of 115 percent was most frequently reached. The spill to capacity discharges ranged from about 90-160 kcfs and varied as a function of the total river flow and forebay TDG saturation.

The total river flow and power market dictated periods of forced spill well above the TDG capacity spill. During the first week of June and again in July, the hourly spill discharge exceeded 200 kcfs. The highest hourly spill of 248.7 kcfs occurred on June 5 during a total river discharge of about 320 kcfs. The maximum powerhouse discharge was 227 kcfs during this period. The hourly total river flow exceeded the maximum powerhouse capacity about 56 percent of the time during the 2002 spill season (Figure 8). However, the spill discharge exceeded 160 kcfs, the upper end of the spill to capacity range, only about 8 percent of the time.

The standard spill pattern was applied for all but 24 hours during the spill season when special test spills were conducted. The standard spill pattern consisted of distributing the flow over all 18 bays in a nearly uniform pattern. The standard spill pattern is shown in Figure 9 for spill discharges of 75, 128, 180, and 230 kcfs. The spill pattern for discharges up to 130 kcfs calls for slightly higher specific discharge on the bays with new deflectors (bays 1-3, 16-18). The higher spill discharges associated with forced spill conditions limits the flow through bays 1 and 18 to about 8 kcfs, while distributing the remaining flow evenly across the spillway.

A series of special spill patterns were scheduled during the last week in August. A uniform spill of 10, 19, 31, and 42 kcfs were scheduled over just bays with the new spillway flow deflectors (bays 1-3, 16-18) for a 3-hour duration. Four additional spill events called for a uniform spill of 10, 19, 31, and 42 kcfs over 6 bays (bays 4-9) with the old spillway flow deflector. These paired spill events provided a head to head comparison of the performance of the different flow deflector designs for tailwater conditions present at the end of August.

The standard spill pattern was also scheduled for discharges of 25, 50, 75, and 100 kcfs during the end of August to provide spill events with comparable unit discharge for the non-standard spill patterns described above. The lower end spill discharges using the standard spill pattern were also intended to provide an estimate of the spill capacity at the state and federal water quality standard of 110 percent saturation.

The forebay water surface elevation was generally held within 1 ft of the forebay pool elevation of 75 ft. The forebay elevation exceeded 76 ft less than 1 percent of the time as listed in Table 2.

The tailwater elevation varied widely as a function of total river flow throughout the fish passage season. The fluctuation in the tailwater elevation is much greater at Bonneville Dam than observed at most other main-stem dams because of the open river conditions below the project. The tailwater elevation was recorded below each powerhouse and at the Tanner Creek gage as shown in Figure 10. The tailwater elevation averaged 18.7 ft and ranged from 9.9 to 28 ft as observed at the Tanner Creek gage. A positive submergence on the old spillway flow deflectors was maintained 83.4 percent of the time and all the time for the new flow deflectors.

The tailwater elevation was also estimated in the exit spillway channel at stations BONTWP1 and BONTWP5 throughout the spill season. The Tanner Creek stage was similar to the spillway channel stage most of the year but underestimated the spillway channel stage during high spillway flows. The spillway channel tailwater elevation, as observed at the BONTWP1 station, was used in all subsequent analyses of TDG exchange at Bonneville during the 2002 spill season.

Hydrodynamics

The hydrodynamic properties of the modified spillway and spill patterns are critical components for characterizing the TDG exchange properties observed during the 2002 spill season. The hydraulic conditions in the stilling basin are responsible for the entrainment and transport of bubbles throughout this region and into the adjoining tailwater channel. The design considerations of the new deflectors were based heavily on the categorization of flow regimes observed in the laboratory models of the Bonneville spillway and receiving basin and the hypothesized TDG exchange characteristics associated with these conditions. The resulting three-dimensional flow patterns that developed below Bonneville spillway influence the transport of downstream migrants, and flow conditions encountered by upstream migrants. These larger scale velocity patterns also influence the flow distribution across TDG sampling transects which are used to estimate the average TDG loading introduced to the Columbia River below the dam.

The standard spill pattern, as characterized by a flow-weighted specific discharge and tailwater elevation observed in the Bonneville spillway exit channel, experienced four different discharge jet flow regimes as identified in the laboratory investigations for the flow deflectors located at elevation 14 ft: plunging flow, skimming surface jet, undulating surface jet, and surface jump. The hydraulic performance regimes, as determined in the laboratory models as a function of tailwater elevation or deflector submergence and specific discharge are shown in Figure 11. The envelope of operating conditions experienced during the 2002 spill season is also illustrated in this figure (blue transparent region). Although the changes in flow regimes are shown as distinct changes in Figure 11, the reality of three-dimensional flow patterns and transient water surface perturbations are likely to result in the transition of flow regimes over a much broader set of conditions. From a dissolved gas transfer standpoint, the skimming flow region has been viewed as the optimal flow conditions minimizing the mean depth to which entrained bubbles are transported and the resultant TDG pressures generated. The plunging flow regime has been identified as producing the highest TDG pressures caused by the vertical transport of water and entrained air in the stilling basin and adjoining tailwater channel. The interpretation of the expected gas transfer associated with the undulating surface jump was thought to be less effective than a skimming flow but substantially better than plunging flow. In general, the gas abatement characteristics for a given flow were thought to drop off for increasing deflector submergence conditions outside of the skimming and plunging flow regimes.

The previous efforts to directly measure the flow distribution in the Bonneville spillway exit channel have encountered a number of difficulties. An acoustic doppler current profiler (ADCP) was applied in a mobile transecting application near the exit of the Bonneville spillway exit channel during the 1999 field study. The high velocities in this region along with the concentration of micro-bubbles in the flow limited the utility of this type of sampling. The lack of a direct measure of the flow distribution near the sampling transect at the exit of the spillway channel required the estimation of the flow distribution at this location based on the channel conveyance properties relative to the position of the sampling stations. In general, the shore-based stations were assumed to represent a smaller percentage of the total spill discharge. The shallow local depths of flow coupled with the channel roughness associated with the riprap reduces the flow rate in the near shore areas. A symmetric weighting of the data collected on stations BONTWP1, BONTWP2, BONTWP3, BONTWP4, and BONTWP5 of 0.125, 0.25, 0.25, 0.25, and 0.125, respectively, was used to estimate the average cross sectional TDG pressures exiting the spillway channel. When the lateral gradient in the TDG saturation is small (<3 percent) the uncertainty introduced by these coefficients is also small. However, for the high discharges when the lateral gradients in the TDG saturation can approach 10 percent of saturation, the uncertainty in the average TDG pressure can grow.

The surface flow conditions were observed on a periodic basis to note prominent features of water circulation and entrainment of air. These prototype observations were supported by observations of the general circulation patterns observed in the 1:40-scale general model of the Bonneville tailwater channel. During normal tailwater conditions where both types of flow deflectors are submerged by 6 ft or greater, the visual behavior at the water surface of the spill jet derived from passage over the deflectors looks similar. The only difference in the water surface appearance was a bit more turbulence and wave generation associated with the spill over the interior bays (4-15). There is some development of regions of concentrated flow where velocities tend to be higher and the extent of the white water associated with entrained air extends further downstream. These flow features are likely related to topographic steering caused by the variation in channel bathymetry and edge effects. The flow distribution downstream of the aerated flow regime was generally well ordered and with surface velocities approaching a uniform distribution.

The surface flow conditions looked quite different during the low tailwater conditions observed during the last week in July and August. During this time period, the tailwater elevation remained slightly above and below elevation 14, placing the flow deflectors in bays 4-15 near the tailwater surface. The agitation of the water surface was slightly greater downstream of the spill bays with the old flow deflectors as shown in the video clip linked to Figure 12. However, the movement of water downstream from these bays stalled outside of the stilling basin and was redirected laterally into the near shore regions of the tailwater channel. Note the upstream transport of foam in the darker water located near mid-channel. The zone of highly aerated flow also mimicked this pattern with the milky white water extending much further downstream of the exterior bays near the channel shoreline than for the interior portion of the spillway. An upstream directed or return current was visually apparent in the middle of the spillway exit channel downstream of the stilling basin. The upstream movement of water can be seen in the video clip linked to Figure 13. The flow distribution near the exit of the spillway exit channel was highly non-uniform with strong shore based currents on both sides of the channel and much smaller velocities located in the middle of the channel. The time-lapse video of flow conditions in Figure 14 near the exit of the spillway channel clearly shows a vigorous shore-based current flanking much slower moving water in the middle of the channel. The extent of this non-uniformity in velocity varied as a function of both spill discharge and tailwater elevation.

Results

Barometric Pressure

The barometric pressure plays a central role in the calculation of the TDG saturation and the absolute pressure exerted on the entrained air during spillway releases. The barometric pressure downstream from Bonneville Dam at the Warrendale FMS averaged 765 mmHg and ranged from 756 to 776 mmHg during the 2002 fish passage season. The TDG saturation at all the monitoring stations was determined by normalizing the observed TDG pressure by the local barometric pressure observed at the Warrendale gage. The delta TDG pressure was determined by subtracting the total pressure from the barometric pressure. The barometric pressure at sub-hourly intervals was estimated by linearly interpolating between the hourly barometric pressure observations. The time history of barometric pressure is shown in Figure 15 along with the forebay TDG pressure and project operations. The passage of a strong weather front can change the local barometric pressure by as much as 9 mmHg and result in a change in the TDG saturation of about 1.4 percent. This change in barometric pressure can result in the TDG saturation exceeding the downstream TDG numeric criteria unrelated to project operations or current river TDG pressure conditions.

Water Temperature

The water temperature can influence such properties as water viscosity, molecular diffusivity of atmospheric gasses, and the TDG saturation concentration. The water temperature ranged from a low of 6.8 ^{o}C during the first week in April to 21 ^{o}C during late July and August as shown in Figure 16 for station BON in the forebay. The temperatures were nearly uniform across the sampling array in the exit spillway channel. There was no evidence of vertical stratification in the forebay or lateral gradients in temperature across the approach spillway channel. The most significant influence of water temperature on the TDG saturation involves the heat exchange that occurs between the dam and the downstream fixed monitoring station located at Camas/Washougal. A change in temperature will induce a corresponding change in TDG saturation when the concentration of gasses remains constant. In general, a one-degree increase/decrease in water temperature will result in a 2-3 percent increase/decrease in the TDG saturation assuming the gas concentrations remain constant. The hourly time history of water temperatures at the fixed monitoring stations BON (forebay of Bonneville Dam), WRNO (tailwater station at Warrendale), and CWMW (downstream station at Camas/Washougal) are shown in Figure 17 for July 16-31, 2002. The water temperatures observed at BON and WRNO were virtually identical over this time period given the short time of travel between these sampling locations. A daily cycle in water temperature was observed at these two stations with afternoon temperatures as much as 0.5 ^{o}C higher than early morning conditions. The daily temperature cycle at the Camas/Washougal gage was much more pronounced with a daily temperature range of over 1 ^{o}C in many instances. Taking into account the travel time between the project and CWMW station of 12 to 20 hours, the increase in water temperature can approach over 2 ^{o}C and the corresponding increase in TDG pressure exceed 20 mmHg. The in-river process influencing the TDG saturation between Bonneville Dam and the Camas/Washougal station can be found in a report entitled “Water Quality Study of TDG, Temperature, and Dissolved Oxygen Spatial and Temporal Variations Downstream of Bonneville Dam, June 8-22, 2001” (Carroll and Schneider, 2001).

Total Dissolved Gas

The TDG pressure was monitored in the approach and exit spillway channel at Bonneville Dam throughout the fish passage season of 2002. The number of active stations above and below the spillway varied throughout the season. The spill at Bonneville was initiated on April 10 at 1800 hours when three stations (BONTWP2-BONTWP4) were in the water and logging data. The two shore-based stations BONTWP5 and BONTWP1 were added on April 11 and 12, respectively and were maintained throughout the spill season. The instrument at station BONTWP2 malfunctioned on June 3. The three interior stations were retrieved on July 6. Instruments were redeployed on August 24 in the forebay, and on three transects below the spillway to sample low tailwater conditions for prescribed spill patterns intended to determine the performance of both new and old spillway flow deflectors. The instrument at station T1P5 was deployed but not recovered after the testing period. The instruments at stations T3P6 and FEP2 malfunctioned with no data recovered. Partial data records were recovered from instruments at stations FEP1 and T1P2. A statistical summary of all data recorded at the fixed monitoring stations and study sampling stations during spillway releases from April 10 – August 31 is listed in Table 3.

Forebay TDG Saturation

The TDG in the forebay of Bonneville Dam varied widely from day to day as a function of production from upstream projects and moderated by degassing at the air-water interface. The hourly variation in the total dissolved saturation at the forebay station (BON) is shown in Figure 18 along with project operations at The Dalles Dam, TDG saturation at The Dalles tailwater station (TDDO), and hourly average wind speed at The Dalles airport. The TDG saturation at The Dalles tailwater station are generally well mixed and reflect the average TDG saturation in the Columbia River below The Dalles Dam. The difference between the TDG saturation at TDDO and BON reflects the change in TDG saturation between these two projects. The change in TDG saturation ranged from 0 to 8 percent saturation taking, into account the travel time between these two sampling stations. The degree of change in TDG saturation was highly correlated with the wind field observed at The Dalles airport. Strong sustained winds generally result in large reductions in TDG saturation as releases from The Dalles Dam are transported through Bonneville pool. On the other hand, slack winds generally result in increasing TDG saturations arriving at Bonneville Dam as the TDG loading introduced at The Dalles Dam is transported unchanged through Bonneville Pool (Figure 18).

The TDG saturation in the forebay of Bonneville Dam averaged about 111.1 percent during the 2002 spill season. The TDG saturation ranged from a high of 119.0 percent to a low of 102.7 percent. The TDG saturation exceeded 110 percent about 65 percent of the time between April 10 and August 31. The TDG saturation exceeded the forebay numeric waiver criteria of 115 percent about 16.6 percent of the hourly observations. The large daily variation in forebay TDG levels introduces a significant challenge when managing spill as constrained by the TDG variance criteria at downstream sampling stations. On numerous occasions, the forebay TDG saturation changed by over 7 percent during a 24-hour period greatly influencing the TDG saturation released by powerhouse operations to the Columbia River below Bonneville Dam.

There was no indication of strong vertical or lateral variations in TDG pressure in the forebay of Bonneville Dam. Auxiliary forebay stations FBP1 and FBP2 were added to the left and right channel banks during the August deployment of water quality stations (Figure 6). The station FBP2 replicated the TDG pressures observed at the FMS forebay station BON, as shown in Figure 19. The station on the opposite bank FBP1 was generally about 0-5 mmHg less than conditions observed at the other forebay stations. The approach flow conditions coupled with strong winds prevent vertical thermal stratification from developing in the forebay approach channel to the spillway.

Spillway Exit Channel TDG Saturation

The TDG conditions exiting the spillway channel were monitored throughout the spill season at Bonneville Dam and were found to be significantly higher than the TDG saturation observed at both the upstream and downstream fixed monitoring stations for most of the year. The instantaneous TDG saturation at the exit of the spillway channel and in the forebay (BON) is shown with project operations at Bonneville Dam throughout the fish passage season in Figure 20. The contents of Figure 20 are repeated with an expanded time scale (monthly Figures 20a-20e, weekly Figures 20f-20y, and daily Figures 20z-20ad) to highlight the details of the TDG response to project operations. In the digital version of this report, the time axis of Figure 20 can be expanded by clicking on the appropriate time period. The TDG saturation in the exit channel ranged from 106.3 percent during a 10 kcfs spill over bays 4-9 to 140.9 percent during a spill of 248 kcfs. The TDG saturation was generally higher on interior sampling stations for spill discharges greater than 100 kcfs. The TDG production was highly correlated with spill discharge with higher spill rates generating higher TDG levels in the exit channel. The shore-based station BONTWP5 was active throughout the spill season with TDG levels exceeding 110, 115, and 120 percent saturation 98.4, 70.9, and 16.7 percent of the time (Table 3). The sampling station located at mid-channel BONTWP3 resulted in TDG levels exceeding 110, 115, and 120 percent saturation 99.2, 77.1, and 51.3 percent of the time from April 10-July 6.

The change in spill discharge was accompanied by a distinctive change in TDG saturation on the sampling transect near the exit of the spillway exit channel. A clear example of the high correlation between spill discharge and TDG production is shown in Figure 20m for the week of June 1-8. On June 3, a spill discharge of 75 kcfs resulted in the TDG saturation at all five sampling stations near 115 percent (114-116). Later in the day on June 3 the spill discharge was increased to about 120 kcfs resulting in an increase in the TDG saturation to about 120 percent on average (118-121.5). The variation in TDG saturation across the sampling transect was greater for the 120 kcfs spill than for the 75 kcfs spill. The spill discharge was increased over 100 kcfs to 230 kcfs on the afternoon of June 3 with TDG saturation ranging from 124 to 135 percent saturation for an average of about 132 percent. The TDG saturation on the interior stations was considerable higher (11 percent) than the shore-based samples during the 230 kcfs spill. The total river flow (300-340 kcfs) and tailwater elevation (23-25 ft) remained relatively constant during this time period.

The influence of tailwater elevation on TDG exchange at Bonneville involves the trajectory of the spill jet exiting the flow deflector and the total depth of flow throughout the spilling basin and adjoining tailwater channel. It was difficult to see a consistent correlation between tailwater elevation and TDG production for the standard spill pattern for any given event. There were several events where the spill pattern and discharge were held constant while the total river flow and corresponding tailwater elevation were changed significantly. On April 27, event 21 spilling 75.6 kcfs was held constant while the total river flow increased from 210 to 280 kcfs. The tailwater elevation ranged from 16.6 ft to 20.2 ft. The TDG saturation on station BONTWP2-P5 remained constant during this event while the TDG saturation on station BONTWP1 increased from 114.5 to 117.5 as the tailwater elevation was raised. Similar events

(43 and 62) on May 13 and 27 did not demonstrate any relationship between tailwater elevation and TDG exchange.

On May 1-3, event 27 spilling 109 kcfs was held constant while the total river flow ranged from 200 to 290 kcfs. The tailwater elevation ranged from 16.6 to 19.5 ft during this event. The TDG saturation at several of the sampling stations tended to fluctuate in direct proportion to changes in tailwater elevation. The range of tailwater elevation within an event was generally small compared to the seasonal change in tailwater elevations. The relationship between tailwater elevation and TDG exchange can also be evaluated by pooling the results of events conducted throughout the sampling period for a range of tailwater elevations.

The influence of the initial TDG saturation in the forebay, on the resultant TDG saturation exiting the tailwater channel was explored during several events during the 2002 spill season. During April 12-14, spill event 2 with a discharge of 76 kcfs was maintained while the forebay TDG saturation ranged from 104 to 117 percent. The TDG saturation exiting the spillway channel remained constant during this period. The large volume of air entrained during spillway releases coupled with the turbulence and pressure time history of bubbles, resulted in the establishment of new equilibrium conditions independent of the initial conditions.

There were several events where the TDG saturation exiting the spillway exit channel was less than the initial conditions in the forebay. On July 7, during a spill of 75 kcfs (event 150), the forebay TDG saturation averaged 117.8 percent while the TDG saturation exiting the spillway channel was about 3 percent less at 114.8 percent. Out of the 264 events sampled during the 2002 spill season, 13 events resulted in a net decrease in the TDG saturation associated with spillway flows. The average TDG content in the Columbia River is reduced a small degree when TDG exchange associated with spillway flows produces lower TDG levels than is contained in powerhouse releases.

The small unit discharges scheduled during events 257-259 resulted in TDG pressures similar to conditions observed in the forebay. During August 29 and 30, a total spill discharge of 10.5 kcfs was scheduled over bays 1-3, 16-18 (Event 259), and bays 4-9 (Event 258) for a combined duration of six hours as shown in Figure 20ab. The TDG saturation in the forebay continuously declined during this six-hour period with the average TDG saturation below the spillway tracking the general decline in TDG saturation. The conditions in the stilling basin during these conditions of low unit discharge may not have been sufficient to change the TDG content of spill.

TDG Lateral Distribution

The lateral distribution of TDG saturation varied widely as a function of spill discharge, pattern and tailwater elevation. For a spill discharge of 75 kcfs, the spill pattern consists of specific spill discharges of 5 to 6 kcfs/bay over bays 1-3 and 16-18 while ranging from 3-4 kcfs/bay on bays 4-15 (bays with el. 14 ft deflector) as shown in Figure 21. The TDG distribution for a tailwater elevation of 11 ft ranged from 111 percent on station BONTWP1 to 116 percent at station BONTWP4. The TDG saturation increased at the near-shore stations BONTWP1-P5 for a tailwater elevation of 17.7 ft. The TDG saturation was nearly uniform for a 75 kcfs spill during a tailwater elevation of 17.7 ft. For a high tailwater elevation of 22.8 ft, the highest TDG saturation (116 percent) was observed near the channel banks at stations BONTWP1 and P5 while the minimum TDG saturation of 113.5 percent was observed near mid-channel. The difference distributions of TDG saturation are likely related to the flow regimes associated with the difference deflector designs and the variation in the depths of flow. At low tailwater elevations the end bays with the deflector at elevation 7 ft will perform better (generate lower TDG levels) than flow over bays with the old deflector design (14. ft).

The lateral distribution of TDG saturation for a spill discharge of 120 kcfs resulted in higher average conditions for high tailwater elevations, as shown in Figure 22. The TDG saturation near the right channel bank increased from 115 during the low tailwater conditions to 120 percent for the higher tailwater conditions. The local minimum TDG saturation was consistently observed in the middle of the channel and may correspond with the lower specific discharge of bays near the middle of the spillway.

The TDG saturation near mid-channel for a spill discharge of 145 was significantly higher than observed near the channel shore. The peak TDG saturation during a 145 kcfs spill was 123.8 percent near mid-channel compared with 120 percent near the left bank as shown in Figure 23. The higher TDG saturation at stations away from the channel banks occurred despite the lower specific discharges over the interior bays. The deeper channel located below the middle section of the spillway may account for the shift in higher TDG saturation for higher spill discharges.

The TDG saturation by station was plotted against the total spill discharge, as shown in Figure 24. The TDG saturation on the right channel bank (BONTWP5) was much more variable when compared to the TDG response observed near the left channel bank at station BONTWP1. The TDG response across the interior stations generally was greater than the near-shore observation for spill discharges of 120 kcfs and higher as shown in Figure 25. The highest TDG saturation was generally observed near the middle of the exit channel for higher spillway discharges. The variation in the lateral distribution of TDG saturation is important if a permanent fixed monitoring station is moved into the spillway exit channel at Bonneville. The relocation of a fixed monitoring station to the spillway exit channel will provide a direct measure of project operations impacts on the change in TDG saturation in the Columbia River below Bonneville Dam. This location would also meet the monitoring objectives set out in the Lower Columbia River TMDL for TDG and would provide direct information for managing the spillway operations as constrained by the TDG variance criteria.

TDG Saturation Animation April 8-September 4, 2002

The presentation of the spatial and temporal patterns of the TDG exchange in the Bonneville spillway channel were summarized on a 30-minute time interval from April 8 – September 4, 2002 in a data animation. The data animation is simply the compilation of over 7000 figures containing 100,000 observations depicting the instantaneous TDG saturation and corresponding spill pattern throughout the study period as presented in the movie file bontdg02.avi. This type of display illustrates the spatial variation in the TDG saturation throughout the exit channel as shown in the upper left hand portion of Figure 26. The lateral position in the spillway exit channel for each TDG sampling station (symbols) was normalized by the channel width. The normalized distance used to present these finding ranged from 0 (left bank) to 1 (right bank). The lateral distribution of TDG saturation at all sampling transects on August 26, at 0730 hrs are shown in Figure 26. The blue line highlights the TDG distribution near the exit of the spillway channel (BONTW). The TDG saturation in the forebay (BONFB) is shown as a vertical line (pink). The TDG saturation on Transect T1 (below the stilling basin), and Transect T2 (midway between T1 and BONTW) are shown by the triangular and square symbols, respectively. The blue dashed line indicates the TDG saturation distribution across Transect (BONTW) three hours earlier than the current time. The current time, total river flow (Qtotal, kcfs), spill discharge (Qspill, kcfs), and tailwater elevation (TWE, ft) are listed in the legend to the right of the lateral

TDG saturation distribution plot.

The bar chart in the lower left hand corner of Figure 26 shows the instantaneous spill pattern or spill bay discharge in kcfs. The operations records are recorded hourly and reflect the hourly average spill bay discharge. Any gate changes made at some intermediate point within an hour will be averaged based on the length of operation. The bars representing the discharge in bays with the new flow deflectors (bays 1-3, 16-18) are highlighted in gold while the bars representing the discharge of bays with old flow deflectors (bays 4-15) are cross hatched.

The graph on the right-hand portion of Figure 26 shows the 12-hour time history of project operations and the TDG response at selected monitoring stations. The red arrow points to the current time. The total river flow and spillway discharge are shown in the upper portion of this figure with the discharge scale located on the right-hand y-axis. The TDG saturation for all stations near the exit of the spillway channel (Transect BONTW and T3) is shown in this figure. The forebay TDG saturation is indicated by the station labeled BON. This figure shows recent and upcoming operational changes and the corresponding response in TDG saturation near the exit of the spillway channel.

The TDG conditions on August 26, at 0730 are in response to a spill discharge of 117 kcfs for a tailwater elevation of 12.2 ft. The spill pattern called for slightly high discharges (7.8 kcfs) through bays 2, 3, 16, and 17 with the lowest discharges of 5 kcfs through bays 9 and 11. The lateral distribution of TDG saturation mimics this spill pattern with slightly lower TDG saturation in the center of the channel and near the channel banks. The highest TDG saturation was observed on Transect T1 in bubbly flow. The distribution of TDG saturation on the T1 Transect is similar to the lateral distribution observed downstream. The stripping of dissolved gas from the water column is likely the cause for the reduction in the TDG saturation between the T1 and BONTW transects. The dashed blue line indicates the TDG saturation on the BONTW transect during a 55 kcfs spill at August 26 at 0430 hours. The doubling of the spill discharge resulted in an increase of 6 to 10 percent saturation at each sampling station. The TDG response to a constant spill of 117 kcfs can be seen in the time-history window in the right-hand side of the figure. The TDG saturation remains nearly constant across the downstream transect during this event.

In viewing the entire period of record contained in the data animation linked to Figure 26, many of the observations characterizing TDG exchange discussed previously are reinforced. The responsiveness of the TDG saturation in the spillway channel to spill discharge change is shown throughout the spill season. The TDG saturation remains nearly constant across the sampling array for constant discharge conditions within each event. However, the TDG response for different events with the same spill discharge and spill pattern can look very different depending upon the tailwater elevation. The TDG saturation in the spillway exit channel appears to be independent from the forebay TDG saturation. Even during periods with no spill discharge, the TDG saturation in the exit channel was considerably different from conditions in the forebay. The elevated TDG saturation in the exit channel during these periods was likely shaped by water discharged from the fish ladders and the spill associated with attraction flow releases from spill bays 1 and 18. It is hard to generalize about the lateral distribution of TDG saturation in the spillway exit channel. It is inappropriate to map the TDG saturation at a downstream sampling stations to the discharge from a particular spill bay. The three-dimensional flow patterns and lateral mixing associated with the large scale turbulent eddies yields this type of evaluation ineffectual. The most effective means of determining the TDG exchange associated with the new and old spillway flow deflectors was through the scheduling of special test spill patterns during the last week in August.

TDG Exchange 2002 versus pre-2002

The TDG exchange during the standard spill pattern during the 2002 spill season was significantly less than previous years for spillway discharge less than 160 kcfs based on the TDG exchange studies conducted in 1997 and 1999. The difference in the TDG exchange can be attributed to the new spill pattern and the added spillway flow deflectors on spill bays 1-3, and 16-18. The reduction in the average cross sectional TDG saturation in the Bonneville spillway exit channel ranged from 15 percent saturation for a spill discharge of 42 kcfs, to 10 percent saturation for a spill discharge of 75 kcfs, to 5 percent saturation for a spill discharge of 110 kcfs, and 2 percent saturation for a spill discharge of 150 kcfs, as shown in Figure 27. The range in the average TDG saturation for specific monitoring stations are shown by the error bars associated with the specific events in this figure. The degree of TDG reduction between the 2002 conditions and the previous spillway conditions was likely underestimated at discharges greater than 100 kcfs due to the limited range in tailwater stage represented by the 1997 and 1999 tests. The TDG saturation for previous spillway conditions would likely have been greater for higher tailwater conditions.

The change in TDG exchange associated with specific bays can be estimated by comparing the 2002 and 1999 test pattern results with and without flow deflectors. The reduction in the TDG exchange associated with individual bays is important since the aggregate TDG loading can be reasonably approximated by the additive composition of individual bays. The TDG response curve for unit discharge ranging from 3 to 17 kcfs/bay is shown in Figure 28 for spillbays without flow deflectors. The range in TDG saturation observed across the sampling transect nearest to the exit of the spillway channel are indicated by the error bar at each event. The TDG saturation with flow deflectors at elevation 7 as a function of unit discharge ranging from 1.7 to 7 kcfs/bay is also shown in Figure 28. The TDG saturation associated with a 7 kcfs/bay discharge with the flow deflector was up to 17 percent saturation (117.8 versus 134.8 percent) less than the original spillway design. It is likely that the difference between these TDG exchange characteristics would be smaller for higher tailwater and specific discharges conditions tested in 2002.

The added reduction in TDG exchange caused by the additional spillway flow deflectors must also consider the change in spill pattern. The spill pattern was changed from a highly non-uniform distribution with much of the discharge through spill bays without flow deflectors, to a pattern weakly non-uniform with modestly higher flows through the exterior bay with the new flow deflectors. The old and new spill patterns for a total spill discharge of 110 kcfs are shown in Figure 29. The old spill pattern shown in the upper portion of this figure has about 44 percent of the spill passing through bays without flow deflectors. The highest spill bay discharge was 13.8 kcfs through bays 2 and 17 without flow deflectors prior to 2002. Spill bays 1 and 18 were generally set to a constant discharge of 1 kcfs for all spill conditions reducing the active width of the spillway by a factor of 1/8th. The new pattern utilizes the entire width of the spillway with the discharge distribution slightly higher toward the outer most bays. The highest unit discharge for the new pattern was about 8 kcfs on bays 2 and 17. The installation of a fully automated gate control sequence for the 2002 spill season allowed for greater flexibility in distributing flow across the spillway.

The highest TDG pressures generated by spill have routinely been observed just downstream of the end sill in highly aerated flow conditions. The reduction in the maximum TDG saturation generated within the aerated flow regime was significantly reduced with the introduction of spillway flow deflectors and the modification of the spill pattern. During the 1999 testing of standard spill bays during a 6.7 kcfs/bay discharge, the maximum TDG saturation observed below the stilling basin was 135.5 percent of saturation. During a similar discharge event in 2002 over spill bays with the new flow deflectors, the maximum TDG saturation observed in bubbly flow below the stilling basin was only 119.3 percent.

Data Analysis-TDG Exchange

There are many ways of summarizing the TDG exchange associated with spillway flow at Bonneville Dam. These alternative analyses involve the aggregation of observed TDG information using various criteria. All these approaches aggregate data spatially to approximate the cross sectional average conditions exiting the spillway channel. One approach is to aggregate the TDG exchange by groupings of spillway discharge. This approach is relevant to determining the spillway capacity subject to the water quality waiver as defined by the Oregon and Washington water quality regulations. A second approach aggregates data by spill discharge event as defined by a continuous spillway release with duration of one hour or longer. The advantage of this approach is the ability to investigate multiple casual parameters involved in TDG exchange during Bonneville spillway releases. The aggregation of data reduces the random variability associated with the TDG exchange and the sampling of these flows. The third approach uses the instantaneous raw data. This approach yields the largest number of observations and widest range of project operations and related environmental properties.

Spillway Discharge Approach

One data analysis approach involved calculating the hourly cross sectional average of TDG saturation exiting the spillway exit channel. The TDG saturation was calculated using a weighted average of the TDG pressure and divided by a constant barometric pressure of 760 mmHg. A constant barometric pressure was used instead of the actual barometric pressure to remove the additional variance of TDG saturation estimates associated with changing barometric pressure. The TDG observations with less than 4 recording stations at the downstream transect were excluded from this evaluation because of the potential sampling bias with the shore-based stations. The observations associated with spillway discharges of 1.5 hours and longer were considered for this evaluation to retain only TDG observations during steady-state operations. Only spill conditions using the standard spill pattern were included in this data summary. The remaining sub-set of observations was then grouped by spillway discharge in 5 kcfs increments and a statistical summary generated. The results from this analysis are listed in Table 4.

The spillway discharge associated with 120 kcfs in this table summarizes all observations meeting the previously discussed criteria for sustained spill discharges ranging from 117.5 to 122.5 kcfs. A total of 250 hourly observations were summarized in this discharge range with an average TDG saturation of 120.3 percent, a maximum TDG saturation of 121.5 percent and a minimum TDG saturation of 117.8 percent. The median TDG saturation (percentile 0.50) was estimated to be 120.5 percent. A total of 76.9 percent of the observations in this flow range exceeded 120 percent of saturation during the 2002 spill season.

This evaluation only summarizes the TDG exchange at Bonneville in terms of the total spillway discharge. The potential cause for the variability within a given spill discharge range was not explored explicitly by this analysis. Within each narrow spill discharge grouping, the estimated average TDG saturation associated with spillway flows can range up to 4.7 percent of saturation (120 kcfs). The range of the 0.05 and 0.95 percentile saturation within discharge groups with over 100 observations ranged from 1.5 percent saturation to 3.0 percent saturation. The different number of observations associated with the discharge grouping does limit the utility of the statistical summary.

The median TDG saturation was found to be a linear function of the total spillway discharge for flows ranging from 25 to 250 kcfs. The median hourly cross-sectional average TDG saturation in the Bonneville spillway exit channel is shown as a function of total spillway discharge, as shown in Figure 30. The error bars associated with the median value represent the 25^{th} and 75^{th} percentile. The 5^{th} and 95^{th} percentile are also shown in Figure 30 along with the minimum and maximum values for each discharge grouping, as listed in Table 4. A linear regression between the median cross-sectional average TDG saturation and spillway discharge resulted in a slope of 0.12 percent/kcfs and an intercept of 106.0 as shown in Figure 30. This relationship implies an increase in spillway discharge of 10 kcfs will result in an increase in the average TDG saturation of 1.2 percent.

Spill Event Approach

The TDG exchange data were aggregated by spill event to identify the causal relationships with project operation and environmental conditions. A spill event was identified by constant spillway releases with a duration of 2 hours or longer. The change in spill discharge between hourly records of less than 3 kcfs was chosen as the criteria for defining spill events. The data during the first hour of an event was not used in calculating the average conditions because it was generally a period of transition. A total of 264 spill events were identified between the initiation of spill on April 10 and the termination of spill on August 31, 2002. The total spill discharge ranged from 25 kcfs to 248 kcfs for the standard spill pattern. The tailwater elevation ranged from 11.1 ft to 27.4 ft for the summarized events. The operational summary of the spill events is listed in Table 5. The summary of the TDG response by station and event for the transect near the exit of the spillway channel is listed in Table 6 and 7. The events summary of the TDG saturation on Transects T1, T2, and FB are listed in Tables 8, 9, and 10, respectively.

A simple linear regression analysis was conducted using the spill event aggregation of observed conditions during the 2002 spill season. Only events using the standard spill pattern with 4 or more active tailwater channel sampling stations were included in this evaluation. The inclusion of events when only the 2 shore-based stations were active was found to provide a biased estimate of average conditions exiting the spillway channel. A total of 166 observations were retained in this evaluation. The cross sectional average delta TDG pressure was regressed against the unit spillway discharge as aggregated by spill event as listed in Equation 1.

$$\Delta P = c_1 q_s + c_2 \qquad (1)$$

where: ?P = delta TDG pressure =TDG pressure minus barometric pressure (mmHg)
q_s = flow weighted specific spillway discharge (kcfs/bay)
c1,c2 = regression coefficients

The delta TDG pressure was found to be a linear function of the specific spillway discharge. The regression Equation 1 resulted in a standard error of 7.01 mmHg with an R^2 correlation of 0.958. The slope of the regression equation was determined to be equal to 15.59 (mmHg/kcfs/bay). The relationship between delta TDG pressure and specific discharge implies a 10 kcfs increase in spill discharge will result in a 1.14 percent saturation increase in TDG saturation. The spill discharges resulting in a TDG saturation of 110, 115, 120, and 125 percent are 38.4, 82.3, 126.2, and 170.1 kcfs respectively assuming a standard barometric pressure of 760 mmHg and the relationship expressed in Equation 1. The regression results and variation of the calculated (equation 1) and observed delta TDG pressure as a function the specific discharge is shown in Figure 31. The same results stated in terms of the TDG saturation are shown in Figure 32.

The influence of tailwater elevation on TDG exchange was explored by conducting a multivariate regression of the event-averaged observations. A bilinear functional formulation was found to provide the best fit to the observed data. The delta TDG pressure was described as a linear function of the specific spillway discharge and the tailwater elevation as shown in Equation 2. The tailwater elevation calculated at station T3P1 was used in this evaluation of the data.

$$\Delta P = c_1 q_s + c_2 twe + c_3 \qquad (2)$$

The delta TDG pressure was found to be a linear function of the specific spillway discharge and tailwater elevation. The regression Equation 2 resulted in a standard error of 4.10 mmHg with an R^2 correlation of 0.986. The specific spill discharge coefficient (C1) was determined to be equal to 13.66 (mmHg/kcfs/bay). The relationship between delta TDG pressure and specific discharge implies a 10 kcfs increase in spill discharge will result in a 1.00 percent saturation increase in TDG saturation. Holding the spillway discharge constant, a 1 ft rise in the tailwater elevation will result in a 0.2 percent saturation (1.56 mmHg increase) in the result TDG saturation. The regression results and variation of the calculated (equation 2) and observed delta TDG pressure as a function the specific discharge is shown in Figure 33. The same results stated in terms of the TDG saturation are shown in Figure 34.

The tailwater elevation in the spillway exit channel is influenced by the total flow discharged at Bonneville. Hence, the TDG saturation generated during a 120 kcfs spill will depend weakly on the tailwater elevation or the total project discharge at Bonneville Dam. For instance, for a total river flow of 150 kcfs with a corresponding tailwater elevation of about 14 ft, the spill discharges resulting in a TDG saturation of 110, 115, and 120 percent are 41.0, 91.0, and 141.1 kcfs respectively, assuming a standard barometric pressure of 760 mmHg and the relationship expressed in Equation 2. For a total river flow of 300 kcfs with a corresponding tailwater elevation of about 23.4 ft, the spill discharges resulting in a TDG saturation of 110, 115, and 120 percent are estimated to equal 21.7, 71.7, and 121.8 kcfs, respectively, or about 20 kcfs less than conditions at 150 kcfs.

Instantaneous Response Approach

The raw TDG exchange data collected on a 15-minute sampling interval were used to identify the causal relationships with project operation and environmental conditions. Using the instantaneous data enables the influence of changing tailwater elevation during constant spillway releases to be factored into the regression evaluation. The data associated with constant spillway releases greater than one hour in duration were used to eliminate observations during transitional periods. The spill discharge was assumed to change when the difference in hourly spill discharge exceeded 3 kcfs. Observations were also excluded from this evaluation when less than 4 stations were active due to a bias in the estimated cross sectional average.

A total of 6874 observations were identified between the initiation of spill on April 10 and the termination of spill on August 31, 2002. The total spill discharge ranged from 27.4 kcfs to 248.7 kcfs for the standard spill pattern. The tailwater elevation ranged from 10.0 ft to 29.3 ft for the summarized events. The cross sectional average TDG saturation ranged from 107.7 to 135.2 percent.

A simple linear regression analysis was conducted using the instantaneous cross sectional average delta TDG pressure as the dependent variable and unit spillway discharge and tailwater depth as independent variables, as shown in Equations 1 and 2. The delta TDG pressure was found to be a linear function of the specific spillway discharge. The linear regression resulted in a standard error of 6.64 mmHg with a coefficient of determination R^2 of 0.952. The slope of the regression equation was determined to be equal to 15.13 (mmHg/kcfs/bay). The relationship between delta TDG pressure and specific discharge implies a 10 kcfs increase in spill discharge will result in a 1.11 percent saturation increase in TDG saturation.

The addition of tailwater elevation as an independent variable (Equation 2) resulted in a small improvement to the prediction of TDG exchange. The regression Equation 2 resulted in a standard error of 4.16 mmHg with an R^2 correlation of 0.981. The specific spill discharge coefficient (C1) was determined to be equal to 13.40 (mmHg/kcfs/bay). The relationship between delta TDG pressure and specific discharge implies a 10 kcfs increase in spill discharge will result in a 0.98 percent saturation increase in TDG saturation. Holding the spillway discharge constant, a 1 ft rise in the tailwater elevation will result in an increase of 0.2 percent saturation (1.59 mmHg increase). The exchange relationships determined for both the events based and instantaneous data analysis was nearly identical. The regression results and variation of the calculated (Equation 2) and observed delta TDG pressure as a function the specific discharge is shown in Figure 35. The same results stated in terms of the TDG saturation are shown in Figure 36.

The fit of the regression equations to the observed data is best determined by reviewing the time-history of the observed and calculated cross sectional average TDG saturation exiting the tailwater channel. The two-component model shown in Equation 2 based on the raw instantaneous observations was used to hindcast the calculated average TDG saturation exiting the spillway channel. This equation was based on about two-thirds of the qualified observations recorded during the 2002 spill season. The project operations with observed and calculated TDG saturation are shown in Figures 37a-37u. This simple two-component model closely tracks the calculated conditions throughout the year. The high spill discharges of 200 kcfs were closely predicted as shown in Figures 37i, 37l, and 37m. The subtle variation in the observed TDG saturation to changes in tailwater stage were also closely predicted as shown in Figure 37e. There are some notable events where the regression model did not closely reproduce the observed data. The initial 50 kcfs spill during April was over-estimated by 1-2 percent as shown in Figure 37a. The observed average TDG saturation during much of July and the first three weeks in August were consistently over-estimated (Figure 37n-37t). The observed average TDG saturation was based on the two shore based stations during this period resulting in a biased estimate of the cross sectional average conditions. And finally, the special test spill events in the last week of August were not always predicted within 1-2 percent (Figure 37u). The regression equation applies for the standard spill pattern for discharges ranging from 50 to 250 kcfs and tailwater elevations ranging from 8 to 29 ft.

TDG exchange and Hydraulic Models

An important component of the design of spillway flow deflectors has been the characterization of different flow regimes as a function of unit discharge and deflector submergence as observed in scaled physical models. The selection of a final deflector design elevation, length, and toe curve for the purpose of TDG abatement has been based on the development of these relationships (Figure 11). What is not possible to measure in the laboratory is the TDG exchange for various deflector designs and flow conditions. The results from the 2002 spill season sampling for TDG pressures in the spillway channel at Bonneville does allow some exploration of the linkage between the identified spill jet flow regimes as identified in the laboratory and the resultant TDG exchange observed in the field. There are some clear limitations between pairing up observations made in the laboratory and the dissolved gas exchange as observed in the field. The laboratory model contains only several spill bays and will not replicate the three-dimensional flow field properties characterizing the prototype. The TDG exchange observed in the prototype will be a composite of the performance of both new and old spillway deflector designs. Two-thirds of the spill bays have the old deflector design while the remaining 6 bays or one-third of the spillway contain the deeper new deflector design. The non-uniformity of the spill pattern and adjoining tailwater channel will make a significant contribution to flow conditions and the resultant TDG exchange in the prototype.

The utility in comparing the hydraulic model findings with field observations of TDG exchange is to further develop the connection between hydraulic flow features and the associated TDG exchange. The average cross sectional TDG saturation relative to a constant barometric pressure of 760 mmHg was selected for evaluation subject to four or more active sampling stations. A contour plot of TDG saturation was generated as a function of the flow-weighted unit spillway discharge and tailwater elevation as shown in Figure 38. The contours of TDG saturation shown in Figure 38 were based on a simple linear interpolation of TDG saturation between the individual event outcomes. The hydraulic flow regimes, as identified in the laboratory (Wilhelms and Schneider, 1999) for the old flow deflector design at elevation 14 ft is also shown on Figure 38. One important aspect of these results is the sensitivity between the aggregate TDG exchange to specific discharge and insensitivity of TDG exchange to deflector submergence. The TDG exchange contours are nearly vertical implying the TDG exchange remains relatively constant for a given specific discharge despite a large change in deflector submergence. The TDG exchange for a specific discharge of 7 kcfs/bay varied from 119 percent for plunging flow conditions to 121 percent for the surface jump flow regime. These results were also evident in the bivariate regression analyses. What is not apparent in this figure is a distinct change in TDG exchange as a function of change in flow regime. The TDG exchange in the plunging flow regime was complicated by the significant difference in TDG exchange conditions of the old and new flow deflectors. It is likely that the TDG exchange properties of the old deflectors degrade as the tailwater elevation drops below elevation 14 while the performance of the new deflectors improves as a skimming jet regime becomes well developed.

TDG Exchange of New and Old Spillway Flow Deflectors

A series of 12 test spill conditions were scheduled during the period of August 25-30, 2002 to investigate the TDG exchange associated with the new spillway flow deflectors (bays 1-3, 16-18), the old spillway flow deflectors (bays 4-9), and the combined operation of both new and old spillway flow deflectors (bays 1-18). These findings apply only for the range of discharge and tailwater elevations tested. The specific discharge ranged from 1.7 kcfs/bay to 7.0 kcfs/bay, as shown in Table 5. The tailwater elevation ranged from 10.2 ft to 13.7 ft, which was below the elevation of spillway flow deflectors on bays 4-15. The spill discharges of about 42, 32, 20, and 9.0 kcfs were uniformly distributed over spill bays 1-3, 16-18, and bays 4-9 for a duration of three hours each during the end of August. This test plan resulted in 4 paired events to compare the TDG exchange of the old deflector design (el. 14 ft) and the new deflector design (el. 7 ft). The TDG pressure was logged on a 5-minute time interval throughout the sampling array downstream from the spillway. The observations in TDG pressure were averaged over the second and third hours of each event across transect 3 to provide an average cross sectional TDG saturation to be used to compare the TDG exchange attributes.

The TDG saturation generated from spilling water over just the old spillway flow deflectors (bays 4-9) was significantly higher than comparable discharges over the new spillway flow deflectors (bays 1-3, 16-18) for discharges greater than 10 kcfs. The TDG saturation corresponding with spill over bays 4-9 (old deflectors), bays 1-3, 16-18 (new deflectors), and standard pattern (old and new deflectors) are shown in Figure 39 as a function of the total discharge. The error bars associated with each event indicate the standard deviation about the mean value. The TDG saturation associated with a discharge of 10 kcfs was about 107 percent saturation for both the old and new deflector spill patterns. The difference between the TDG production of new and old deflectors increased for increasing discharge. The 20 kcfs spill over the old deflectors generated a mean TDG saturation of 110 percent compared to 108 percent for the new defectors. The 31 kcfs spill generated an average TDG saturation of 116 percent compared to 111.5 percent for the new deflectors. The TDG saturation associated with a 122.3 percent for a 42 kcfs spill compared to 116 percent for the new deflectors.

The three response curves converge with one-another when the discharge relationship with TDG saturation is represented as the specific discharge as shown in Figure 40. The slope of the TDG saturation versus specific discharge relationship was 3.0 for the test spill pattern over bays 4-9 (old defectors) compared to only 1.74 for the test spill pattern over bays 1-3, 16-18 (new deflectors). Another means of comparing the old and new deflector performance is to estimate the specific discharge associated with 110, 115, and 120 percent saturation. The linear regression equations listed in Figure 40 were used to estimate the corresponding specific discharge for a given TDG saturation. The spill pattern using the old deflectors resulted in an average TDG saturation of 110, 115, and 120 percent for specific discharges of 3.0, 4.7, and 6.35 kcfs/bay. The spill pattern using only new deflectors resulted in an average TDG saturation of 110, 115, and 120 percent for 4.8, 6.7, and 9.6 kcfs/bay. If it is assumed that all 18 spillbays performed similarly to the test spill events, the 120 percent spill capacity for a spillway with 18 bays located at elevation 14 ft would equal 117 kcfs compared to 172.8 for a spillway with 18 bays located at elevation 7 ft for a tailwater elevation ranging from 10.2 to 13.7 ft.

The paired test spill pattern for the old and new deflectors for a discharge of 42 kcfs (7 kcfs/bay) scheduled back to back on August 26-27 clearly illustrates the difference in TDG exchange. The time history of TDG levels across Transect T3 for events 246 (old deflectors) and 247 (new deflectors) are shown in Figure 20aa. In both cases, the TDG saturation reached steady conditions after about one hour of operation. The lateral gradient in TDG saturation on Transect T3 was weak for both spill events. The spillway discharge of 42 kcfs corresponding to a specific discharge of about 7 kcfs/bay resulted in an average TDG pressure of 941.2 mmHg when the old deflectors were active (Event 247) compared to 895.2 mmHg for the new deflectors (Event 246). The TDG response at each sampling station experienced a significant increase in response to the change in the spill pattern from new to old flow deflectors. In terms of TDG saturation, a spill discharge of 42 kcfs (7 kcfs/bay) over the old flow deflectors generated an average TDG saturation of about 122.3 percent compared to 116.1 percent for the new flow deflectors for a difference of about 6 percent saturation.

A statistical comparison of the mean value of the cross sectional average TDG saturation for the four paired test spill events involving the old and new flow deflectors was conducted. The independent-samples T test procedure was used to compare the mean TDG saturation of the old and new spillway flow deflectors. For each of the paired events, the mean, standard deviation, and standard error mean were calculated as listed in Table 11. The TDG pressure associated with the old flow deflector pattern was greater than the corresponding new deflector spill for three of the four conditions. The difference in the mean TDG pressure (old deflector minus new deflector) for spills of 42, 32, 20, and 9.0 kcfs were 46, 24.4, 12.3, and -3.5 mmHg, respectively. The mean difference in TDG pressure for each paired test was significantly different from zero at the 95 percent confidence level. The 95 percent confidence interval was generally less then 2 mmHg in range. This statistical evaluation supports the conclusion that the TDG pressures generated by spilling over the old deflectors were significantly greater than comparable spill over the new deflectors for a uniform six bay spill greater than 10.0 kcfs during tailwater elevations ranging from 10.2 to 13.7 ft.

The TDG saturation generated for the standard spill pattern was determined to be a linear function of the specific discharge for events observed during August 25-31. The specific discharge for the standard spill pattern was determined by calculating the flow-weighted discharge per bay. The linear response of the standard spill pattern to specific discharge is compared with the response of both old and new flow deflector spill patterns in Figure 40. The TDG exchange associated with the standard spill pattern falls between the response of old and new flow deflectors. The TDG saturation produced by a 7 kcfs/bay spill over the new deflectors, old deflectors, and combination of new and old deflectors (standard spill patterns) was 115.5, 122, and 118 percent, respectively, based on the least squared linear regression equations shown in Figure 40.

The deflector specific TDG production equation (Figure 40) was used to estimate the TDG exchange associated with the standard pattern. This approximation assumes that the TDG exchange of individual bays are additive and vary linearly as a function of only the spillbay discharge. The average TDG saturation was estimated using the following conservation statement:

$$TDG_{avg} = \frac{\sum_{i=1}^{18} Q_i TDG_i}{\sum_{i=1}^{18} Q_i} \qquad (3)$$

where TDG_i =TDG saturation for bay i

$TDGi=(\Delta P+BP)/BP*100$

$\Delta P=c_1 Q_i+c_2$

Q_i = Discharge through bay i (kcfs)

TDG_{avg}=Cross sectional average TDG saturation

c1, c2 = Parameters describing TDG exchange for old and new deflectors

The predictive error of the average cross sectional TDG saturation associated with the standard spill pattern during the period of August 25-30 using Equation 3 averaged –0.04 with a standard deviation of 1.12 percent and ranged from -2.23 percent to 1.52 percent. A total of 16 standard spill events were identified during this time period corresponding with the refined August sampling array. The predictive error was determined by the subtracting the estimate of TDG saturation as defined by Equation 3 from the observed average cross section TDG saturation. The predictive error using the linear regression equation defined in Equation 2 was also determined for this same time period. The two component lumped model resulted in an average predictive error of –0.06 percent with a standard deviation of 0.58 percent and ranged from –1.33 percent to 0.75 percent. The observed versus predicted TDG saturation for the individual spill bay approach (Equation 3) and the aggregate spillway approach (Equation 2) are shown in Figure 41. The aggregate spillway approach provided a marginally better estimate of the observed cross sectional TDG saturation exiting the spillway channel for the standard spill pattern.

The test results clearly show that the new flow deflectors at elevation 7 ft generated significantly lower TDG pressures when compared to the old flow deflectors at elevation 14 ft. The lower TDG saturation associated with the bays 1-3 and 16-18 were generated even though the depth of flow in the tailwater channel downstream from these spill bays were on average, greater than those found below bays 4-9 (Figure 5). The tailwater elevation during the last week in August was consistently lower than the elevation of the old flow deflectors. The un-submerged flow deflectors (el. 14) generated a plunging flow condition resulting in higher rates of exchange of TDG when compared to the new deflectors (elevation 7 ft) operating under a submergence of 3 to 6 feet. The small positive submergence on the new flow deflectors generated a skimming flow regime creating a vigorous current hugging both channel banks. The different flow regimes downstream from the bays with new and old flow deflectors were evident in both the downstream extent of highly aerated flow and the lateral flow distribution at the downstream sampling transect. A non-uniform pattern of highly aerated flow was evident during the standard spill pattern at lower tailwater elevations in August with bubbly flow extending further downstream of spill bays with the deeper deflectors. The discharge downstream of the central portion of the spillway was observed to stall resulting in a return current directed upstream toward the spillway. The greater energy contained in the surface jets associated with the deeper deflectors likely created a strong entrainment demand drawing flow released from the central portion of the spillway.

It is unlikely that the TDG exchange response for the different flow deflectors determined in this study is applicable for higher tailwater conditions or specific discharges. The tailwater elevation during most of the spill season was higher than elevation 14 ft, creating a positive submergence on the flow deflectors in bays 4-15. A tailwater elevation ranging from 14 to 20 feet will result in a small positive submergence across spill bays 4-15 resulting in a discharge jet with a horizontal trajectory or skimming flow that is likely to generate smaller TDG pressures than observed in this study. At the same time, the deeper flow deflectors will transition away from a skimming flow regime for higher submergences and into an undulating flow regime (Wilhelms and Schneider, 1999). The TDG exchange performances during a skimming or undulating flow regime are thought to be comparable. The original experimental design called for the evaluation of the TDG exchange performance of the new and old flow deflectors over a range (low, medium, and high) of tailwater elevations. Only the performance at low tailwater conditions was executed due to concerns with the potential disruption of ongoing biological tests and of in-season fish passage at Bonneville.

The TDG exchange performance of the old and new flow deflectors during the low tailwater conditions in 2002 were compared to the performance of the old flow deflectors as observed in the 1997 (Wilhelms and Schneider, 1997) and 1999 (Schneider and Carroll, 1999) field tests. The tailwater elevations during the 1997 test ranged from 20.1 to 22 ft during uniform spill over bays 4-15. The tailwater elevations ranged from 19.9 to 20.9 ft during the 1999 testing where spill was uniformly distributed over bays 8-15. The TDG saturation was normalized by a standard barometric pressure of 760 mmHg for all test results to eliminate any bias introduced by the variation in barometric pressure observed during testing. The mean cross sectional TDG saturation and range in individual sampling station TDG saturation are shown in Figure 42 for the test conditions observed in 1997, 1999, and 2002. The specific discharge associated with about 3 kcfs/bay and 7 kcfs/bay affords a direct comparison between the three test results. At 3 kcfs/bay, all the test results are similar, generating a mean TDG saturation ranging from 108 to 110 percent. For the 7 kcfs/bay specific discharge conditions, the TDG saturation generated over spillbays with an elevation of 14 ft during the low tailwater conditions in 2002 resulted in a mean TDG saturation higher than observed during the previous testing conditions in 1997 and 1999 on the order of 1.5 to 3.0 percent saturation. The deflector submergence of the 1997 and 1999 test conditions (5.9-8.0 ft) over the old deflectors were similar to the submergence (3.2-6.7 ft) of the new deflectors during the 2002 study. However, the TDG saturation associated with the new deflectors was less than observed for the old deflectors in the 1997 and 1999 studies by up to 6 percent for a specific discharge of 7 kcfs/bay. The larger depths of flow in the stilling basin couple with the variation in spill patterns and deflector submergences probably contributed to the size of the difference between these spill events. The relationship between TDG generation and specific discharge for spill over the old deflectors during the 1997 and 1999 tests were non-linear as evidenced by the reduction in slope of this relationship for higher discharges (Figure 42). The variance in response at individual sampling stations also increased for high specific discharges which likely is related to the variation in depth of flow across the tailwater channel below the stilling basin.

Spillway capacity as limited by state water quality criteria

The Oregon and Washington state water quality criteria for TDG is 110 percent of saturation. However, special exceptions to this criteria have been adopted by the states during the fish passage season to accommodate spillway discharges designed to aid endangered salmonids and steelhead fish passage at Columbia River basin dams. These variances from the 110 percent criteria generally allow instantaneous levels to reach 125 percent of saturation in the Columbia River. Furthermore, the daily average of the highest 12 hourly observations in the tailwater of a dam is not allowed to exceed 120 percent of saturation. A third constraint prohibits the exceedance of 115 percent of saturation based on the daily average of the highest 12 hourly observations in the forebay of the next downstream dam or at the Camas/Washougal FMS below Bonneville Dam.

A network of fixed monitoring stations have been sited throughout the Columbia River basin to determine the compliance with the state water quality criteria, monitor the habitat in the Columbia River with regards to water temperature and TDG pressure, and to aid in supporting the management of voluntary and involuntary spill events. The TDG properties observed at fixed monitoring stations are very sensitive to the location of these stations relative to the source for supersaturated conditions in the Columbia River, mainly spillway discharges. The spatial gradients in TDG pressure can be very large in the tailwater region of a dam (US Army Corps of Engineers, 2001). These heterogeneities in TDG pressure can be generated within the region of aerated flow caused by structural differences between spill bays, topographic variance, hydrodynamic conditions, and spill patterns. A second source for variation in TDG properties below a dam is the development of the mixing zone between spillway and powerhouse discharges. The influence of heat exchange and degassing at the air/water interface also contribute to TDG properties in the Columbia River. As a general rule, the TDG saturation measured at a sampling station will be inversely related to the distance from the aerated flow associated with spillway releases.

The fixed monitoring stations in the Columbia River influenced by spillway releases at Bonneville Dam consist of the tailwater FMS located at Warrendale (WRNO) located about 6 miles downstream of the dam near the Oregon shore, and the Camas/Washougal FMS located about 24 miles downstream of Bonneville Dam near the Washington shore (Figure 7). The 120 percent of saturation criteria is applied at the Warrendale FMS while the 115 percent of saturation is applied at the Camas/Washougal FMS. The TDG data collected during the 2002 spill season in the Bonneville dam spillway exit channel provided a means of evaluating the TDG saturation observed at both of these downstream sampling stations and to develop guidance regarding the capacity of spillway releases as constrained by the site-specific water quality criteria.

During the 2002 spill season at Bonneville Dam, spillway operations contributed to the frequency and extent of TDG saturation excursions of the Washington and Oregon State TDG waiver criteria. A review of the TDG saturation data at the Bonneville forebay (BON), Bonneville tailwater (WRNO), and downstream forebay station (CWMW) during spill from April 10 through August 31 of 2002 found that the TDG saturation observed in the Bonneville forebay was outside of the waiver criteria during 22.6 percent of the days (33 days out of 144 days). This compares with 13 and 18 days of excursions above TDG criteria at the forebay stations at The Dalles and John Day Dams.

The TDG saturation at the tailwater compliance station (WRNO) of Bonneville Dam was above the waiver criteria during 13.3 percent of the time (20 days out of 144 days). The tailwater FMS stations at WRNO do not directly monitor spillway releases as occur below John Day and McNary Dams. This tailwater stations is located near the left channel bank, six miles downstream of the spillway. The location of the spillway, centered between the 1st and 2nd powerhouse, influences the lateral distribution of TDG pressures at the tailwater station with the maximum levels are often located away from the channel bank. In general, the powerhouse and spillway releases were nearly well-mixed at the Warrendale station located downstream of Bonneville Dam based on estimates of average river TDG conditions from upstream sampling stations.

The number of days above TDG compliance criteria was greatest at the FMS at Camas/Washougal where the TDG saturation was found to be above the waiver criteria during 45.4 percent of the days (65 days out of 144 days). The Camas FMS is located about 24.1 miles downstream of the dam near the right descending bank. The time of travel between the dam and the Camas station generally ranges from 14 to 20 hours. The open channel river reach below Bonneville significantly influences the in-river processes that affect TDG pressure. The Columbia River just above Camas has numerous shallow flats that can significantly influence the exchange of both energy and mass. The relatively shallow flow conditions throughout this reach will influence channel velocities, time of travel, and water surface exchange rates. The relatively shallow flow conditions will also impact the characteristics of habitat as influenced by TDG pressure. The fraction of the volume of water in this reach above the compensation depth can be much greater than would occur in pooled river reaches having the same TDG conditions.

Spillway Exit channel

The maximum and average TDG saturation generated in the Bonneville Dam spillway exit channel during the 2002 spill season was summarized in terms of the spillway discharge resulting in 110, 115, 120, and 125 percent of saturation. The average cross sectional TDG observations on a 15 minute interval were grouped in 5 kcfs blocks starting at 25 kcfs for spill events with a duration of one hour or longer. A statistical summary was conducted on each grouping of observations generating estimates of mean, minimum, maximum, and frequency of occurrence within the groupings. The results from this summary are shown in Figure 30 where the error bars represent a 95 percent confidence interval with each discharge group. Based on a linear regression of the mean values within each group, the total spillway discharge associated with 110, 115, 120, and 125 percent of saturation was 35, 75, 120, and 160 kcfs, respectively. This data summary also indicates the average TDG saturation exiting the spillway channel can exceed 120 percent for a spillway discharge of 110 kcfs. More specific estimates of the average TDG saturation generated in the Bonneville spillway exit channel must take into account the contribution of both the spill discharge, as represented by specific discharge, and tailwater elevation.

An alternative means of summarizing the TDG exchange properties at Bonneville Dam involves the response of individual sampling stations over a range of operating conditions. The average TDG saturation was determined for each sampling station by spill event for the period of April 10 through August 24 as shown in Figure 23. The lateral variation in TDG saturation increases with discharge and was observed to be as high as 11 percent saturation for a discharge of 250 kcfs. The highest TDG saturation was generally observed away from the channel bank during higher spill events. The spillway discharges resulting in the cross sectional maximum TDG saturation of 110, 115, 120, and 125 percent were 50, 65, 110, and 150 kcfs, respectively.

Warrendale

The findings from earlier sampling studies found that the TDG saturation in the Columbia River were nearly well mixed. The estimated TDG saturation at the Warrendale station (WRNO) can be estimated from the following conservation equation.

$$TDG_{wrno} = \frac{(TDG_{spill} Q_{spill} + TDG_{fb} Q_{ph})}{(Q_{spill} + Q_{ph})} \qquad (4)$$

where TDG_{wrno}=TDG saturation at Warrendale FMS (percent)
TDG_{spill} = TDG saturation generated in the Bonneville spillway exit channel (percent)
TDG_{fb} = TDG saturation observed in the forebay of Bonneville Dam (percent)
Q_{spill} = Total spillway discharge (kcfs)
Q_{ph} = Total powerhouse 1 and 2 discharge (kcfs)

This formulation neglects auxiliary project discharges at Bonneville such as fish ladders and bypass channels. In most cases, the auxiliary project discharge is a small contribution to total river flows. Equation 4 was applied to estimate the average TDG saturation in spillway flows. The estimated TDG saturation at Warrendale using Equation 4 closely reproduced the observed TDG saturation at Warrendale, as shown in Figure 43. The predictive error (observed minus calculated) was estimated assuming a 4-hour lag time between the release from the dam and detection at the Warrendale station. The average TDG pressure error of estimate from April 10 – August 31 was 4.9 mmHg and the root-mean-squared estimate was 14.8 mmHg. There were several instances where the observed conditions at Warrendale changed abruptly unrelated to operations at Bonneville Dam. The data following these events were erroneous and likely attributed to instrument malfunction. The removal of these observed data from estimates of the predictive error resulted in an average error of estimate of 2.9 mmHg and the root-mean-squared estimate of 12.6 mmHg. This analysis indicates the utility of predictive TDG equations in scrutinizing the observations gathered from the FMS. In many cases, instrument malfunctions result in subtle changes to the recorded TDG pressure. The inconsistency with the TDG loading as estimated from these predictive relationships can help identify erroneous and misleading data.

The spillway discharge resulting in TDG saturation of 120 percent at the Warrendale FMS can be estimated by rearranging Equation 4 and solving for the spillway discharge. The spillway discharge can be estimated as a fraction (f) of the total river flow ranging from 0 to 1 (Q_{spill}=f Q_{total}). The two-component Equation 2 can be used to estimate the TDG saturation generated from a spillway discharge. The specific spillway discharge can be estimated by dividing the total spillway discharge by the number of active spill bays (18 in most cases) assuming that the discharge is distributed evenly over all 18 bays. The three inputs to this solution involve the forebay TDG saturation, the total river flow, and the barometric pressure. The tailwater elevation can be estimated from the total river discharge. The unknown to be determined is the fraction (f) of the river spilled. The quadratic equation derived from this formulation is as follows:

$$f^2 \frac{(100 c_1 Q_{tot}^2)}{18 Bp} + f\left(\frac{100 c_2 TWE}{Bp} + \frac{c_3 100}{Bp} + 100 - TDG_{fb} \right) Q_{tot} + TDG_{fb} Q_{tot} - TDG_{wrno} Q_{tot} = 0 \quad (5)$$

where:
f = fraction of the total river flow spilled
Q_{tot} = total river flow (kcfs)
Q_{spill} = f Q_{tot} (kcfs)
TDG_{fb} = TDG saturation in the forebay (percent)
TDG_{wrno} = TDG saturation at Warrendale (percent)
TWE = tailwater elevation (ft)
Bp = Barometric pressure (mmHg)
c_1,c_2,c_3 = TDG exchange coefficients (13.4, 1.60, 23.9)

The Equation 5 was solved for TDG forebay levels ranging from 105-120 percent for total river flows ranging from 80 to 420 kcfs as listed in Table 12. This table can be divided into three regions. The first region 1 (blue highlight) is where 100 percent of the river can be spilled without exceeding 120 percent of saturation. This typically can occur for low total river discharges where the smaller tailwater depths limit the amount of TDG pressure produced during spillway releases. The total river flows up to 140 kcfs fall into this region. The second region (no highlight) is defined by spilling a volume of water that produces exactly 120 percent of saturation for the flow- weighted discharge from Bonneville Dam. In most cases, the TDG produced during spill is greater than 120 percent of saturation exiting the Bonneville spillway exit channel. However, when these waters mix with powerhouse releases that are typically less than 120 percent, the average TDG pressures fall to 120 percent. The table clearly demonstrates that as the forebay TDG saturation increases, the spill capacity constrained by the 120 criteria at Warrendale must be reduced. For example, if the total river flow is 260 kcfs and the forebay TDG saturation is equal to 112 percent, the spillway capacity for these conditions yielding 120 percent at the Warrendale FMS is estimated to equal 170 kcfs. If the forebay TDG saturation increases to 115 percent saturation, the spillway discharge must be reduced to 159 kcfs to achieve an average TDG saturation release of 120 percent. The third region (beige highlight) is for forced spill conditions where the powerhouse release is constrained by the powerhouse discharge capacity assumed to equal 210 kcfs where the residual flow is spilled. The average TDG saturation will exceed 120 percent during involuntary spill conditions.

The information contained in Table 12 should be used as a general guide for selecting spillway releases generating an average river TDG saturation of 120 percent. As will be seen in the next section, the TDG criteria imposed at the Camas/Washougal FMS, is the critical constraint governing spillway discharges at Bonneville Dam. Therefore, generating average river conditions of 120 percent will result in the observed TDG saturation exceeding 115 percent at the Camas/Washougal FMS for most river conditions. A degree of uncertainty is inherent in the estimation TDG pressure in spillway flows, forebay TDG saturation, current barometric pressure, and degree of mixing with powerhouse releases. A factor of safety should be considered in selecting a spill discharge if the intent is not to exceed the water quality criteria. Reducing the spillway discharge by 5-10 percent of the amount listed in Table 12 should be sufficient to limit the frequency of excursions above water quality criteria.

Tailwater fixed monitoring stations are inconsistently located throughout the Columbia River basin. This inconsistent citing of tailwater stations causes biased spill management decisions to consistently take place. At some projects, the tailwater instrument is located directly in spill waters undiluted from powerhouse releases. The tailwater station below John Day Dam is an example of a station directly in waters released from the spillway. At Bonneville Dam, the tailwater station is located well downstream of the spillway exit channel in a reach of river that is nearly well mixed in terms of TDG pressure. The mixing of powerhouse and spillway flows prior to arriving at the tailwater stations masks the extreme TDG pressures generated during spillway flows and present throughout most of the spillway exit channel. Maintaining a tailwater monitoring station near the mouth of the Bonneville spillway exit channel would provide a direct measure of the TDG pressures produced during spillway releases, monitor the extreme TDG pressures encountered by fish residing or migrating through this region, provide a sampling station that is consistent with the intent of the state water quality variance for fish passage and the Lower Columbia River TMDL for TDG, and provide information sufficient to estimate the TDG pressures within and downstream of the mixing zone between powerhouse and spillway flows.

Camas/Washougal

Bonneville Dam operations modified by in-river processes of dispersion, heat exchange, and degassing is responsible for the TDG pressures sampled at the Camas/Washougal (CWMW) FMS. The time of travel from Bonneville Dam to the Camas/Washougal station typically ranges from 14 to 20 hours depending on the river discharge. The open river reach below Bonneville is shallow and wide in places promoting the surface exchange of energy, momentum, and mass. The TDG pressure discharged from Bonneville Dam was routed conservatively to the Camas/Washougal monitoring stations using the SYSTDG model (Schneider, 2001). The generation of TDG saturation in spillway flows was approximated using Equation 2. The calculated and observed TDG saturation at the Camas/Washougal FMS is shown in Figure 44 and the net change in TDG pressure was summarized for these hourly estimates. The calculated TDG saturation at the CWMW station assumed no change due to temperature or surface degassing. The mean change in TDG pressure from the dam to CWMW for the 2002 spill season was -2.2 percent of saturation as determined from the difference between the calculated and observed TDG saturation at CWMW. The estimated change in TDG saturation corresponding to the 10th and 90th percentile were -0.8 and -3.3 percent as shown in Figure 45. The influence of temperature and off-gassing at the air/water interface are counteracting processes accounting for the total change in TDG saturation. Since the change in TDG pressure between the dam and the CWMW FMS is generally less than 5 percent saturation, the 115 percent TDG criteria at CWMW is a more restrictive criteria than the 120 percent TDG criteria imposed at the WRNO station.

The simulation of TDG generation and transport from Bonneville Dam to the Camas/Washougal station was repeated taking into account the influence of water temperature and air/water exchange or degassing. The calculated and observed TDG saturation at the CWMW stations are shown in Figure 46. The mean and root-mean-square (rms) predictive errors were determined for the 2002 spill season at the CWMW station and found to equal 1.4 mmHg and 6.3 mmHg, respectively. This rms error at the CWMW station was only slightly greater than determine for the TDG saturation exiting the spillway.

The challenge of managing the spillway releases at Bonneville based on the TDG saturation measured at the Camas/Washougal station involves the stochastic nature of the in-river processes. The net reduction in TDG pressure is closely linked to river flows (time of travel) and the meteorology (wind and heat exchange) imposed on this river reach. Both of these properties can change significantly from hour to hour. A spillway management strategy for a given river flow condition or set of conditions, can be devised by knowing the TDG exchange associated with spillway operations, TDG saturation to be delivered by powerhouse flows, and the change in TDG pressure from the dam to the compliance station. A risk-based spillway management strategy is proposed for Bonneville Dam based upon the concept of a target release TDG saturation that has associated with it some probability of resulting in an excursion above the water quality criteria. The TDG release target is a function of the compliance TDG numeric criteria plus a TDG margin of safety. In this case, the target release TDG saturation reflects the average cross-sectional or flow-weighted TDG saturation exiting the dam from all sources. If no change in the TDG pressure occurs between the dam and the compliance station, the target release TDG saturation would simply equal the TDG waiver criteria and spillway discharge could be calculated from the following relationship:

$$Q_{spill} = \frac{(Q_{total} TDG_{Target} - Q_{ph} TDG_{fb} - Q_{aux} TDG_{aux})}{TDG_{spill}}$$

where

Q_{ph} = Total Powerhouse Discharge (kcfs)
Q_{sp} = Spillway Discharge (kcfs)
Q_{aux} = Auxilary Discharge (kcfs)
Q_{total}= Qspill + Qph + Qaux (kcfs)
TDG_{fb}= TDG Saturation in forebay (percent)
TDG_{sp}=TDG Saturation in spillway releases (percent)
TDG_{Target} = TDG_{Waiver} + TDG_{MOS} Target TDG Saturation (percent)
TDG_{Waiver} = TDG Saturation Waiver Criteria (percent)
TDG_{MOS} = TDG Saturation Margin of Safety (percent)

However, the TDG saturation is known to change during passage between the dam and the limiting TDG monitoring station at Camas/Washougal. The assimilative capacity or change in TDG saturation in the Columbia River was summarized as a probability distribution (Figure 45). The central task surrounding spill management can be reduced to the decision involving the acceptable level of risk that a decision to spill will result in an excursion above the water quality criteria. What level of risk should be the basis for managing spill volumes when the directive is to spill up to the water quality criteria; (50 percent of the time, 25 percent of the time, or 1 percent of the time)? For instance, if a TDG saturation margin of safety of 2.2 percent or 16.8 mmHg (50^{th} percentile in Figure 45) is used to develop a target TDG saturation of 115+2.2=117.2 percent based on criteria imposed at the Camas/Washougal gage, then according to the summary of the change in TDG saturation for the 2002 spill season, the likelihood of exceeding 115 percent at CWMW would be 50 percent. To reduce the likelihood of exceeding the 115 percent criteria at CWMW to 10 percent, a margin of safety closer to 0.8 percent or 6.4 mmHg (10th percentile in Figure 45) would be appropriate. Inherent in this type of risk based management strategy is the basic conclusion that reducing the risk of exceedance of water quality criteria can be accomplished by reducing spill in the system.

An example of the spill management strategy described above for Bonneville Dam is illustrated in the example shown in Figure 47. A forebay TDG saturation of 113 percent will allow some level of spill to occur without exceeding the compliance TDG waiver below the dam. The amount of spill that can be accommodated will depend upon the total river flow and TDG loss rate in the Columbia River in route to the compliance sampling stations. In this case, a target release TDG saturation of 116.6 percent was selected without causing conditions exceeding the 120 percent saturation criteria at the tailwater fixed monitoring station and 115 percent saturation at the Camas/Washougal station. This example shows the TDG saturation in undiluted spill water well above 120 percent but through dilution and degassing, the TDG saturation at the Warrendale station registers an average value closer to 116.2 percent. A constant flow and degassing rate were applied to this example resulting in an average TDG saturation of 114.8 percent at the Camas/Washougal station or just below the compliance standard of 115 percent. If the target TDG saturation was slightly higher than 116.6 percent, the remaining TDG saturation at the Camas/Washougal station would likely have been greater than the 115 percent standard. A direct estimation of spill discharge as a function of the forebay TDG saturation, total river flow, barometric pressure, and target TDG saturation can be determined by substituting the TDG_{target} for TDG_{wrno} in Equation 5.

Bonneville Dam TDG Exchange Comparison With Other Projects

The TDG exchange at Bonneville Dam can be compared to conditions observed at other projects in the Columbia River Basin. The TDG properties generated at Bonneville Dam under the standard spill pattern produced a TDG saturation in the exit spillway channel of 115 percent at a spill discharge of about 75 kcfs (4.3 kcfs/bay), and a TDG saturation of 120 percent at a spill discharge of 120 kcfs (7 kcfs/bay) based on the regression presented in Figure 30. The Dalles Dam, located at River Mile 191.5 on the Columbia River, has a standard spillway and stilling basin design. The stilling basin depths of 25 ft at The Dalles Dam are shallower than those found at Bonneville Dam. During continuous sampling below The Dalles spillway during the 2000 spill season, the TDG saturation was never found to be less than 120 percent (Schneider, 2001). The spill discharges ranged from 20 to 250 kcfs during this sampling period at The Dalles Dam.

Lower Granite Dam is located on the Snake River at river mile 107.5. The spillway has 8 spillbays with flow deflectors on each bay. The stilling basin at Lower Granite Dam is of conventional design with a typical depth of flow of 32 ft. Powerhouse and spillway releases interact strongly at Lower Granite Dam as a large portion of the powerhouse releases are entrained into the aerated flow in the stilling basin. During the 2002 spill season, the TDG saturation in spillway releases reached 115 percent of saturation for a spill discharge of about 32 kcfs (4 kcfs/bay), and 120 percent for a spillway discharge of about 53 kcfs (~7kcfs/bay) as reported by Schneider (2002). The TDG response at Bonneville Dam during the 2002 spill season was similar to conditions observed at Lower Granite Dam with spillway flow deflectors when expressed in terms of specific spill discharge.

Conclusions

The addition of six new flow deflectors at spill bays 1-3, and 16-18 at the Bonneville spillway were completed for the 2002 spill season. The new flow deflectors were installed at an elevation of 7 ft in comparison to flow deflectors on bays 4-15 located at an elevation of 14 ft. A new spill pattern was also developed to provide suitable flow conditions to aid fish passage. The new spill pattern provides for a much more uniform distribution of spill compared to the old spill pattern. The change in TDG saturation in the spillway channel at Bonneville Dam was monitored throughout the 2002 spill season. The main objective of this monitoring study was to quantify the TDG exchange associated with spillway operations at Bonneville Dam. A second objective was to determine the TDG exchange properties of the new and old spillway flow deflectors. The following conclusions were derived from the TDG sampling during the 2002 spill season.

The TDG exchange in spillway releases from Bonneville Dam were found to be directly related to the specific spillway discharge and only weakly related to the tailwater stage. A 10 kcfs increase in the spillway discharge resulted in an increase in the TDG saturation of 1.0 percent. Conversely, a 1 ft rise in the tailwater elevation resulted in an increase in the TDG saturation of 0.2 percent. These relationships were determined by a bilinear regression evaluation of project operations and the TDG saturation response.

A spillway discharge of about 120 kcfs resulted in a cross sectional average TDG saturation of 120 percent exiting the Bonneville spillway channel. The influence of other factors such as tailwater stage and the barometric pressure can cause a range of TDG responses for the same discharge. The maximum TDG pressures exiting the spillway channel at 120 kcfs are 1 to 2 percent higher than the average saturation.

A spillway discharge of 50 kcfs resulted in a cross sectional average TDG saturation of 110 percent which is the Oregon and Washington state water quality criteria for TDG saturation outside of the spill season. The spill discharge and TDG saturation relationships are dependent upon the 2002 spill pattern. This property will be important in planning spill at Bonneville outside of the fish passage season like the spring creek spill typically scheduled in March.

A spillway discharge of about 165 kcfs resulted in a cross-sectional average TDG saturation of 125 percent exiting the Bonneville spillway channel. A maximum TDG saturation exiting the Bonneville spillway channel of 125 percent was found to be generated for spill discharges as low as 150 kcfs.

The TDG pressures established in the spillway channel during spill were independent from the initial TDG pressure observed in the forebay. The aerated flow conditions in the stilling basin and adjoining tailwater channel establishes a new equilibrium conditions for TDG pressure dependent on the pressure time history of entrained air. Most of the time, spill resulted in a net increase in TDG pressure in spill water above conditions observed in the forebay. In a limited number of cases, spillway discharges resulted in a net decrease in the TDG saturation of spill waters.

The addition of six new flow deflectors and the corresponding change in spill pattern resulted in a significant reduction in the TDG saturation for comparable spill discharge prior to 2002. The estimated reduction in TDG saturation for discharges of 42, 75, 110, and 150 kcfs was 15, 10, 5, and 2 percent of saturation. The degree of improvement over pre-2002 conditions declined for increasing discharge. The estimates of gas abatement benefits are conservative for the higher discharges because of the limited conditions for the pre-2002 testing. The new spillway configuration also reduced the maximum TDG pressures generated within the bubbly flow region downstream of the spillway.

The new flow deflectors generated considerably lower TDG pressures than the old deflectors for low tailwater conditions ranging from 10.2 to 13.7 ft. The difference in the mean TDG pressure (old deflector minus new deflector) for spills of 42, 32, 20, and 9.0 kcfs were 46 (6.1), 24.4 (3.2), 12.3 (1.6), and -3.5 (-0.4) mmHg (percent saturation), respectively. The vertical plunge from the elevation 14 deflector to the tailwater likely contributed to the higher dissolved gas exchange with the old flow deflectors. There is insufficient evidence to determine the TDG exchange performance of the different deflector designs at higher tailwater elevations or specific discharges.

The lateral distribution of TDG saturation near the exit of the Bonneville spillway channel becomes increasingly non-uniform for higher spill discharges. The maximum TDG saturation generally is located away from the near-shore area. The difference between the maximum and minimum TDG saturation can exceed 10 percent of saturation for spill discharges of 200 kcfs and higher.

The events-based average TDG exchange was compared to the hydraulic flow regimes observed in the scaled physical models of the Bonneville spillway. The change in TDG levels were highly correlated with the change in spillway discharge and weakly related to deflector submergence. A distinct change in TDG exchange as a function of a change in flow regime was not apparent in this relationship.

The TDG pressures exiting the Bonneville spillway channel were generally considerably higher than the TDG pressures observed at the tailwater fixed monitoring station located at Warrendale. The TDG pressures observed at the Warrendale gage are more closely represented by the flow-weighted average of both spillway and powerhouse releases from Bonneville Dam. Inconsistencies in the observed TDG pressures at the Warrendale gage were identified on several occasions during the 2002 spill season. These erroneous values were identified by measurements in the entrance and exit to the spillway channel.

The TDG saturation observed at the Camas/Washougal FMS is influenced by Bonneville Dam operations and in-river processes influencing heat and mass exchange. The TDG criteria (115 percent) applied at the Camas/Washougal FMS is more restrictive on project operations than is the TDG criteria (120 percent) applied to the Warrendale station. The TDG saturation was above the water quality criteria 45.4 percent of the time during the 2002 fish passage season. The reduction in TDG saturation between Bonneville Dam and the Camas/Washougal station averaged 2.2 percent during the 2002 spill season.

The results from this study characterizing the exchange of TDG saturation at Bonneville Dam and its fate in the Columbia River, allows the consideration of a risk-based management strategy when the policy is to spill up to the TDG criteria. An approach to estimate the spill capacity at Bonneville Dam limited by TDG saturation criteria was developed as a function of forebay TDG saturation, total river flow, barometric pressure and the TDG margin of safety. The selection of the acceptable risk of excursion above the WQ criteria will determine the TDG margin of safety, TDG target saturation, and associated spill discharge to be released from Bonneville Dam. The probability distribution for net change in TDG saturation between Bonneville Dam and the Camas/Washougal station observed during the 2002 spill season was recommended as the basis for selecting the TDG margin of safety. The acceptable risk of excursion above the TDG criteria is the critical component of this management policy.

Recommendations

The following recommendations were generated from the 2002 TDG study at Bonneville Dam.

The tailwater FMS at Bonneville should be moved into the spillway exit channel. This location would provide a better estimate of the peak and average TDG saturation generated by Bonneville Dam operations than the current station at Warrendale. A tailwater station located in spill water would be consistent with most of the other tailwater stations located below main-stem dams operated by the Corps of Engineers. This sampling location would be consistent with the monitoring recommendations identified in the Lower Columbia total maximum daily load (TMDL) for TDG. The TDG saturation measured in the spillway channel is a direct consequence of spillway operations at Bonneville Dam. The TDG saturation at the Warrendale station is influenced by both the spillway discharge and powerhouse discharge magnitude and distribution. The influence of the TDG generated at upstream projects plays a prominent role in determining the TDG saturation at the Warrendale FMS. The location of the tailwater station in spillway releases at Bonneville undiluted by powerhouse releases would allow for the more consistent and equitable management of spill between dams in the Columbia River basin.

A decision support algorithm was developed to identify the spill capacity at Bonneville limited by the TDG criteria at the downstream fixed monitoring stations. The implementation of this spill management algorithm should reduce the likelihood of unwanted excursions above the TDG saturation criteria. A critical component in applying this algorithm is the acceptable frequency of choosing a spill discharge that will result in an excursion of the water quality criteria due to the stochastic nature of in-river heat and dissolved gas exchange. The decision support algorithm could be quickly updated each day as a function of total river flow, forebay TDG saturation, barometric pressure, and metoerologic forecasts.

The potential gas abatement benefits of the new flow deflector design should be determined for intermediate (tailwater elevation 18 ft) and high tailwater elevations (tailwater elevation 23.5 ft). The new flow deflectors produced significantly lower TDG saturation (6 percent during a 7 kcfs/bay spill) when compared to the old flow deflectors for low tailwater conditions (10.8-13.7 ft). The required tests would involve a minimal disruption to the fish passage program at Bonneville or could be conducted outside of the fish passage season. The scheduling of 8 test spill patterns for the intermediate and high tailwater elevation would require only 48 hours of spill. The findings from these additional tests would support any decision to update the deflector design for the entire Bonneville spillway.

Appendix A References

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Appendix B Tables

Table 1. Total dissolved gas sampling stations in the Columbia River near Bonneville Dam, 2002.

Site	Latitude	Longitude	Depth Average (ft)	Distance Downstream Spillway (ft)	Distance from Left Bank (ft)	Comments
BONTWP1	45.643417	121.9471	10.1	1617	15	Deployed in conduit from left bank of spillway exit channel
BONTWP2	45.644081	121.946505	20.8	1577	220	Deployed on bottom at 1/4 point from left bank
BONTWP3	45.64454	121.946305	16.1	1508	441	Deployed on bottom at mid-point
BONTWP4	45.645186	121.946	14.0	1455	662	Deployed on bottom at 3/4 point from left bank
BONTWP5	45.645767	121.946267	15.6	1400	870	Deployed in conduit from right bank of spillway exit channel
FBP1	45.642974	121.940751	20.8	-46	0	Suspended from railing in forebay left bank
FBP2	45.646370	121.940618	31.0	-34	1050	Suspended from railing in forebay right bank
FEP1	45.642920	121.942091	11.7	282	0	Suspended from railing in front of south fish ladder, malfunctioned
FEP2	45.646000	121.941317		230	1145	Suspended from railing in front of north fish ladder entrance
T1P1	45.6432167	121.942333	47.5	400	155	Deployed on bottom downstream from bay 18
T1P2	46.6437833	121.9420667	63.7	327	360	Deployed on bottom downstream from bay 14, malfunctioned
T1P3	45.64465	121.9419667	36.8	300	678	Deployed on bottom downstream from bay 9
T1P4	45.6451167	121.942	67.7	311	847	Deployed on bottom downstream from bay 5
T1P5	45.645617	121.941317		305	1029	Deployed on bottom downstream from bay 2, Instrument lost
T2P1	45.6433833	121.944767	11.3	1014	152	Deployed on bottom downstream from bay 17
T2P2	45.643967	121.944333	29.5	903	388	Deployed on bottom downstream from bay 13
T2P3	45.6449	121.944033	39.0	830	735	Deployed on bottom downstream from bay 7
T2P4	45.645567	121.94395	19.4	809	975	Deployed on bottom downstream from bay 2
T3P2	45.643717	121.94705	20.2	1604	110	Deployed on bottom 110 ft from left bank
T3P3	45.64425	121.946533	27.7	1467	337	Deployed on bottom 337 ft from left bank
T3P4	45.64455	121.94645	25.9	1447	445	Deployed on bottom 445 ft from left bank
T3P5	45.645	121.94625	29.0	1395	617	Deployed on bottom 617 ft from left bank
T3P6	45.64535	121.946267	14.8	1400	736	Deployed on bottom 736 ft from left bank, malfunctioned
BON	45.38	121.57	N/a			Forebay fixed monitoring station
WRNO	45.608026	122.039111	N/a			Tailwater fixed monitoring station at Warrendale
CWMW	45.4	122.2	N/a			Downstream fixed monitoring station at Camas/Washougal

Table 2. Statistical summary of hourly Bonneville Dam operations, April-August 2002.								
		Q_{total} (kcfs)	Q_{ph1} (kcfs)	Q_{ph2} (kcfs)	$Q_{ph1@2}$ (kcfs)	Q_{spill} (kcfs)	FBE (ft)	TWE (ft)
Average		236.1	30.6	90.	119.4	108.7	75.4	18.7
Maximum		404	94.7	145.5	227.5	248.7	76.4	28
Minimum		109.7	0	0	0	0	73.7	9.9
Std Dev		67.8	31.2	32.8	60.1	45.0	0.51	4.3
Percentile (%)	1	122.2	0	29.2	12.4	0	73.9	11.8
	10	155.4	0	32.2	31.6	74.6	74.9	13.5
	25	188.4	0	77.3	76.4	75.8	75.4	16.1
	50	242.8	26.6	101.8	135.6	118.9	75.6	19.2
	75	296.3	64.8	115.3	175.95	141.3	75.7	22.45
	90	330.5	76	126.4	194.1	155.1	75.9	24.5
	99	376.7	87	139.2	215.6	216.3	76	26.8

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Table 3. Statistical Summary of Total Dissolved Gas Saturation in the approach and exit spillway channel at Bonneville Dam, April 10-August 31, 2002

Site	Date/Time	Date/Time	N	TDG Saturation / Percent Exceedance (%)									
				Avg[1]	Max[2]	Min[3]	Stdev[4]	110[5]	115[5]	120[5]	125[5]	130[5]	135[5]
BONTWP1	4/12/02 10:45	8/31/02 23:45	14954	117.4	127.5	105.5	2.8	98.4	78.0	15.1	0.1	0.0	0.0
BONTWP2	4/10/02 18:00	6/3/02 19:00	5189	119.1	132.5	107.4	4.3	97.6	71.1	47.5	4.2	0.5	0.0
BONTWP3	4/10/02 18:00	7/6/02 13:30	8335	120.2	137.9	107.3	5.4	99.2	77.1	51.4	13.3	6.6	0.6
BONTWP4	4/10/02 18:00	7/6/02 13:30	8335	120.1	140.9	107.4	4.2	98.4	85.5	59.2	7.9	1.6	0.6
BONTWP5	4/11/02 16:45	8/31/02 23:45	15012	116.8	125.8	106.0	3.2	98.4	70.9	16.7	0.1	0.0	0.0
FBP1	8/24/02 21:00	8/31/02 23:55	2052	105.2	108.8	102.2	1.9	0.0	0.0	0.0	0.0	0.0	0.0
FBP2	8/24/02 21:00	8/31/02 23:55	2052	105.7	109.3	102.7	1.9	0.0	0.0	0.0	0.0	0.0	0.0
FEP1	8/24/02 21:00	8/31/02 20:00	1624	123.1	147.6	111.0	8.7	100.0	77.7	56.8	34.4	22.2	12.8
FEP2													
T1P1	8/24/02 21:00	8/31/02 23:55	2052	121.2	131.9	106.8	5.9	93.4	88.1	54.8	31.4	1.2	0.0
T1P2	8/24/02 21:00	8/26/02 13:00	481	117.7	127.7	112.0	4.8	100.0	49.5	36.7	17.1	0.0	0.0
T1P3	8/24/02 21:00	8/31/02 23:55	2052	116.5	125.6	106.8	4.3	93.2	60.8	28.3	0.7	0.0	0.0
T1P4	8/24/02 21:00	8/31/02 23:55	2052	119.6	128.6	106.9	4.9	93.7	87.7	51.5	13.8	0.0	0.0
T1P5			2052										
T2P1	8/24/02 21:00	8/31/02 23:55	2052	117.5	124.7	106.3	4.0	91.5	86.9	32.8	0.0	0.0	0.0
T2P2	8/24/02 21:00	8/31/02 23:55	2052	114.4	121.3	106.4	3.4	91.7	47.5	1.6	0.0	0.0	0.0
T2P3	8/24/02 21:00	8/31/02 23:55	2052	115.8	126.7	106.4	3.5	93.7	60.1	11.8	1.4	0.0	0.0
T2P4	8/24/02 21:00	8/31/02 23:55	2052	117.1	123.5	106.8	3.7	91.2	77.5	21.9	0.0	0.0	0.0
T3P2	8/24/02 21:00	8/31/02 23:55	2052	116.7	123.1	106.6	3.5	92.1	67.8	10.4	0.0	0.0	0.0
T3P3	8/24/02 21:00	8/31/02 23:55	2052	114.6	122.6	106.5	2.8	91.9	42.1	1.9	0.0	0.0	0.0
T3P4	8/24/02 21:00	8/31/02 23:55	2052	114.4	123.4	106.5	3.1	92.6	41.4	3.0	0.0	0.0	0.0
T3P5	8/24/02 21:00	8/31/02 23:55	2052	115.9	123.8	106.8	3.1	92.2	80.2	3.0	0.0	0.0	0.0
T3P6													
BON	4/1/02 0:00	8/31/02 23:00	3431	111.1	119.0	102.7	3.7	64.8	16.6	0.0	0.0	0.0	0.0
WRNO	4/1/02 0:00	8/31/02 23:00	3405	115.6	128.9	104.0	3.6	96.8	59.0	7.7	0.9	0.0	0.0
CWMW	4/1/02 0:00	8/31/02 23:00	3434	113.3	125.1	103.5	3.5	83.7	32.6	2.4	0.1	0.0	0.0

[1] Average total dissolved gas saturation
[2] Maximum total dissolved gas saturation
[3] Minimum total dissolved gas saturation
[4] Standard deviation total dissolved gas saturation
[5] Percent exceedance of total dissolved gas saturation in column header

Table 4. Summary of Hourly Average Total Dissolved Gas Saturation by Spill Discharge Grouping in the Bonneville Spillway Exit Channel

Qspill (kcfs)	q_s (kcfs/bay)	n	TDG Saturation (%)				TDG Saturation percentile (%)					Percent Occurrence Greater than TDG Criteria (%)				
			Avg	Max	Min	St Dev	.05	.25	.50	.75	.95	110	115	120	125	130
25	2.1	3	108.1	108.3	107.8	0.2	107.8	108.0	108.1	108.2	108.3	0.0	0.0	0.0	0.0	0.0
55	3.2	3	111.4	111.5	111.4	0.1	111.4	111.4	111.4	111.5	111.5	100.0	0.0	0.0	0.0	0.0
75	4.4	454	115.3	117.0	114.0	0.7	114.3	114.6	115.2	115.8	116.7	100.0	55.9	0.0	0.0	0.0
80	4.6	3	116.5	117.1	116.1	0.5	116.1	116.3	116.4	116.7	117.0	100.0	100.0	0.0	0.0	0.0
85	4.9	4	116.5	116.6	116.4	0.1	116.5	116.5	116.5	116.5	116.6	100.0	100.0	0.0	0.0	0.0
90	5.2	10	116.6	117.5	115.4	1.0	115.4	115.5	117.3	117.4	117.5	100.0	100.0	0.0	0.0	0.0
100	5.7	104	118.3	119.6	116.4	1.1	116.5	117.1	118.8	119.1	119.4	100.0	100.0	0.0	0.0	0.0
105	5.9	2	117.1	117.5	116.7	0.5	116.8	116.9	117.1	117.3	117.4	100.0	100.0	0.0	0.0	0.0
110	6.2	102	119.6	121.2	117.9	1.0	118.0	118.9	119.5	120.6	121.0	100.0	100.0	30.8	0.0	0.0
115	6.6	20	119.6	121.3	118.2	1.0	118.2	118.8	119.3	120.7	120.9	100.0	100.0	42.0	0.0	0.0
120	6.7	250	120.3	121.5	117.8	0.9	118.2	119.9	120.5	120.9	121.2	100.0	100.0	76.9	0.0	0.0
125	7.0	21	120.6	121.6	119.4	0.8	119.5	119.6	121.0	121.2	121.3	100.0	100.0	68.7	0.0	0.0
130	7.2	195	121.4	122.6	119.5	0.8	120.0	120.8	121.6	122.0	122.5	100.0	100.0	94.3	0.0	0.0
135	7.5	27	120.9	122.5	119.7	0.8	119.8	120.1	121.1	121.4	122.2	100.0	100.0	80.3	0.0	0.0
140	7.9	65	121.9	124.4	120.2	1.1	120.2	121.4	121.6	122.3	123.9	100.0	100.0	100.0	0.0	0.0
145	8.1	106	122.7	124.1	122.0	0.5	122.1	122.3	122.6	123.0	123.6	100.0	100.0	100.0	0.0	0.0
150	8.4	175	123.6	124.7	122.6	0.5	123.0	123.3	123.5	124.0	124.5	100.0	100.0	100.0	0.0	0.0
155	8.6	59	123.6	124.2	122.6	0.4	122.9	123.4	123.7	123.9	124.1	100.0	100.0	100.0	0.0	0.0
160	8.9	22	124.7	125.0	124.2	0.2	124.3	124.5	124.7	124.8	125.0	100.0	100.0	100.0	0.0	0.0
165	9.2	34	125.2	126.0	124.6	0.4	124.7	124.8	125.2	125.4	125.9	100.0	100.0	100.0	67.2	0.0
170	9.5	28	126.4	127.1	125.4	0.6	125.5	125.9	126.4	126.9	127.0	100.0	100.0	100.0	100.0	0.0
180	10.0	11	127.0	127.3	126.9	0.1	126.9	126.9	126.9	127.1	127.2	100.0	100.0	100.0	100.0	0.0
185	10.3	4	127.2	127.3	127.2	0.0	127.2	127.2	127.2	127.2	127.3	100.0	100.0	100.0	100.0	0.0
195	11.0	1	129.2	129.2	129.2	na	129.2	129.2	129.2	129.2	129.2	100.0	100.0	100.0	100.0	0.0
200	11.2	21	129.4	130.1	128.9	0.4	128.9	129.1	129.4	129.9	130.1	100.0	100.0	100.0	100.0	13.1
205	11.5	27	129.7	130.9	127.3	0.8	128.7	129.3	129.6	130.1	130.8	100.0	100.0	100.0	100.0	30.3

Table 4. Summary of Hourly Average Total Dissolved Gas Saturation by Spill Discharge Grouping in the Bonneville Spillway Exit Channel																	
Qspill (kcfs)	**q_s (kcfs/bay)**	**n**	**TDG Saturation (%)**				**TDG Saturation percentile (%)**					**Percent Occurrence Greater than TDG Criteria (%)**					
			Avg	**Max**	**Min**	**St Dev**	**.05**	**.25**	**.50**	**.75**	**.95**	**110**	**115**	**120**	**125**	**130**	
210	11.7	3	130.8	130.9	130.7	0.1	130.7	130.8	130.9	130.9	130.9	100.0	100.0	100.0	100.0	100.0	
215	12.0	14	131.3	131.7	130.7	0.3	130.9	131.1	131.2	131.6	131.7	100.0	100.0	100.0	100.0	100.0	
220	12.2	12	131.7	132.3	131.1	0.4	131.2	131.3	131.7	131.9	132.3	100.0	100.0	100.0	100.0	100.0	
230	12.9	6	133.2	133.3	133.0	0.1	133.0	133.2	133.2	133.3	133.3	100.0	100.0	100.0	100.0	100.0	
245	13.8	1	135.0	135.0	135.0	na	135.0	135.0	135.0	135.0	135.0	100.0	100.0	100.0	100.0	100.0	
250	13.9	3	134.9	135.6	134.5	0.6	134.5	134.6	134.8	135.2	135.5	100.0	100.0	100.0	100.0	100.0	

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	**Starting Date-Time**	**Ending Date-Time**	**Duration (hrs)**	**Q_{total} (kcfs)**	**Q_{sp} (kcfs)**	**Q_{sp}/Q_{tot} (%)**	**FBE (ft)**	**TWE (ft)**	**Spill[+] Pattern**	**qs (kcfs/bay)**
1	4/10/02 19:00	4/12/02 9:00	38	206.6	51.4	25.0	76.0	17.0	std	3.00
2	4/12/02 11:00	4/15/02 9:00	70	234.5	76.1	32.8	75.8	19.3	std	4.44
3	4/15/02 15:00	4/15/02 17:00	2	301.0	89.9	29.9	75.5	23.2	std	5.17
4	4/16/02 1:00	4/16/02 3:00	2	314.0	90.1	28.7	75.9	24.1	std	5.21
5	4/16/02 6:00	4/16/02 8:00	2	341.5	121.1	35.5	75.7	25.5	std	6.84
6	4/16/02 14:00	4/17/02 2:00	12	352.7	150.7	42.7	75.7	26.2	std	8.45
7	4/17/02 4:00	4/17/02 8:00	4	343.0	130.2	38.0	75.8	25.9	std	7.26
8	4/17/02 9:00	4/17/02 13:00	4	352.0	140.7	40.0	75.7	26.3	std	7.90
9	4/17/02 14:00	4/18/02 11:00	21	335.2	169.8	50.8	75.6	25.9	std	9.48
10	4/18/02 13:00	4/20/02 4:00	39	311.2	150.3	48.5	75.6	24.4	std	8.45
11	4/20/02 6:00	4/20/02 18:00	12	269.7	76.6	28.4	75.9	21.8	std	4.48
12	4/20/02 20:00	4/21/02 4:00	8	318.3	152.9	48.0	75.6	23.9	std	8.56
13	4/21/02 5:00	4/21/02 18:00	13	298.6	76.7	25.7	75.9	22.9	std	4.48
14	4/21/02 20:00	4/24/02 3:00	55	268.0	149.0	55.8	75.6	21.5	std	8.39
15	4/24/02 5:00	4/24/02 13:00	8	278.4	75.7	27.2	75.9	21.2	std	4.39
16	4/24/02 20:00	4/25/02 4:00	8	268.7	149.0	55.6	75.6	21.4	std	8.40
17	4/25/02 6:00	4/25/02 19:00	13	251.8	75.5	30.0	75.8	19.8	std	4.38
18	4/25/02 21:00	4/26/02 4:00	7	240.0	152.7	63.7	75.7	20.1	std	8.54
19	4/26/02 6:00	4/26/02 18:00	12	253.5	75.5	29.9	75.8	20.0	std	4.38
20	4/26/02 20:00	4/27/02 4:00	8	205.8	134.3	65.5	75.8	18.1	std	7.54
21	4/27/02 5:00	4/27/02 19:00	14	258.4	75.6	29.5	75.8	20.0	std	4.38
22	4/27/02 21:00	4/28/02 7:00	10	218.8	134.1	61.9	75.7	18.7	std	7.54
23	4/28/02 8:00	4/29/02 11:00	27	197.6	141.4	71.6	75.4	17.3	std	7.95
24	4/29/02 12:00	4/30/02 4:00	16	218.7	129.5	59.4	75.6	18.2	std	7.25
25	4/30/02 6:00	4/30/02 18:00	12	242.0	74.5	30.8	75.8	19.1	std	4.28
26	4/30/02 20:00	5/1/02 4:00	8	228.4	119.4	52.4	75.8	18.8	std	6.75
27	5/1/02 5:00	5/1/02 18:00	13	235.1	75.0	32.0	75.8	18.7	std	4.33
28	5/1/02 20:00	5/3/02 13:00	41	230.6	109.0	47.9	75.7	18.7	std	6.21
29	5/3/02 15:00	5/4/02 3:00	12	241.8	119.5	49.9	75.8	19.5	std	6.75
30	5/4/02 5:00	5/4/02 18:00	13	239.6	76.3	32.0	75.7	19.1	std	4.46
31	5/4/02 20:00	5/5/02 4:00	8	259.7	134.1	51.7	75.9	20.2	std	7.52
32	5/5/02 5:00	5/5/02 19:00	14	252.8	75.5	30.0	75.8	19.8	std	4.38
33	5/5/02 21:00	5/6/02 11:00	14	197.7	145.7	73.8	75.5	17.5	std	8.18
34	5/6/02 15:00	5/7/02 13:00	22	236.0	155.4	66.5	75.7	19.2	std	8.69
35	5/7/02 14:00	5/8/02 13:00	23	258.1	149.1	58.4	75.6	20.5	std	8.40
36	5/8/02 14:00	5/10/02 4:00	38	222.8	143.7	64.9	75.6	19.0	std	8.06
37	5/10/02 5:00	5/10/02 19:00	14	193.8	76.6	39.6	75.9	16.5	std	4.45
38	5/10/02 20:00	5/11/02 2:00	6	197.5	129.3	65.5	75.9	16.4	std	7.22
39	5/11/02 4:00	5/11/02 19:00	15	225.2	75.4	33.5	75.8	17.5	std	4.37
40	5/11/02 21:00	5/12/02 3:00	6	235.0	128.7	54.9	75.7	18.4	std	7.21
41	5/12/02 4:00	5/12/02 19:00	15	194.5	76.0	39.3	75.9	16.0	std	4.41
42	5/12/02 21:00	5/13/02 2:00	5	179.5	128.5	71.6	75.6	15.3	std	7.21

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	**Starting Date-Time**	**Ending Date-Time**	**Duration (hrs)**	**Q_{total} (kcfs)**	**Q_{sp} (kcfs)**	**Q_{sp}/Q_{tot} (%)**	**FBE (ft)**	**TWE (ft)**	**Spill+ Pattern**	**qs (kcfs/bay)**
43	5/13/02 4:00	5/13/02 19:00	15	227.3	74.8	33.6	75.4	17.5	std	4.34
44	5/13/02 21:00	5/13/02 23:00	2	233.8	128.4	55.0	75.6	18.5	std	7.21
45	5/14/02 0:00	5/14/02 13:00	13	197.0	139.0	71.1	75.5	16.9	std	7.83
46	5/14/02 14:00	5/15/02 12:00	22	211.7	128.3	60.7	75.6	17.5	std	7.20
47	5/15/02 14:00	5/17/02 13:00	47	206.2	119.3	58.3	75.7	17.4	std	6.74
48	5/17/02 14:00	5/18/02 3:00	13	241.1	109.2	45.6	75.8	18.6	std	6.22
49	5/18/02 4:00	5/18/02 19:00	15	223.8	75.4	34.0	76.0	17.9	std	4.36
50	5/18/02 21:00	5/19/02 3:00	6	215.0	109.2	50.8	75.8	17.3	std	6.22
51	5/19/02 4:00	5/19/02 19:00	15	228.5	75.8	33.2	75.9	17.8	std	4.40
52	5/19/02 21:00	5/20/02 3:00	6	234.5	99.6	42.6	75.8	18.3	std	5.71
53	5/20/02 4:00	5/20/02 19:00	15	237.0	75.4	31.9	75.7	18.4	std	4.37
54	5/20/02 21:00	5/21/02 3:00	6	250.3	90.0	36.0	75.8	19.0	std	5.17
55	5/21/02 4:00	5/21/02 17:00	13	267.7	75.8	28.3	75.9	20.0	std	4.39
56	5/21/02 19:00	5/22/02 14:00	19	287.8	99.9	34.7	75.9	21.3	std	5.74
57	5/22/02 16:00	5/23/02 13:00	21	283.8	148.5	52.5	75.6	21.8	std	8.36
58	5/23/02 14:00	5/24/02 14:00	24	270.7	154.0	56.9	75.5	21.2	std	8.62
59	5/24/02 15:00	5/25/02 10:00	19	271.7	146.5	54.1	75.6	21.3	std	8.21
60	5/25/02 11:00	5/25/02 23:00	12	257.8	128.4	49.9	75.5	20.5	std	7.21
61	5/27/02 0:00	5/27/02 2:00	2	208.8	130.3	62.4	76.0	17.9	std	7.28
62	5/27/02 4:00	5/27/02 19:00	15	249.6	75.5	30.5	75.8	19.3	std	4.38
63	5/27/02 21:00	5/28/02 3:00	6	279.3	129.5	46.4	75.6	21.1	std	7.26
64	5/28/02 5:00	5/28/02 9:00	4	283.0	75.7	26.7	75.9	21.2	std	4.38
65	5/28/02 19:00	5/30/02 13:00	42	305.2	129.2	42.6	75.4	23.0	std	7.24
66	5/30/02 14:00	5/30/02 22:00	8	302.9	119.6	39.5	75.6	22.9	std	6.76
67	5/31/02 1:00	5/31/02 22:00	21	311.3	119.3	38.4	75.6	23.3	std	6.75
68	6/1/02 0:00	6/1/02 14:00	14	333.6	119.2	35.8	75.6	24.3	std	6.74
69	6/1/02 17:00	6/1/02 20:00	3	381.6	148.7	39.0	75.1	26.6	std	8.35
70	6/1/02 22:00	6/2/02 8:00	10	314.8	199.3	63.8	75.7	24.5	std	11.14
71	6/2/02 11:00	6/2/02 13:00	2	309.0	159.8	51.7	75.6	23.8	std	8.93
72	6/2/02 17:00	6/2/02 19:00	2	308.5	160.5	52.0	75.8	23.8	std	8.94
73	6/2/02 20:00	6/2/02 23:00	3	327.1	119.3	36.5	75.9	24.0	std	6.75
74	6/3/02 9:00	6/3/02 17:00	8	310.2	117.3	37.8	75.6	23.1	std	6.64
75	6/4/02 0:00	6/4/02 6:00	6	321.0	229.7	71.6	75.7	23.8	std	12.87
76	6/4/02 12:00	6/4/02 15:00	3	327.4	164.7	50.3	75.6	24.5	std	9.18
77	6/4/02 17:00	6/4/02 19:00	2	311.3	133.8	43.0	75.6	23.8	std	7.50
78	6/4/02 20:00	6/4/02 22:00	2	349.0	165.3	47.4	75.4	25.1	std	9.20
79	6/5/02 1:00	6/5/02 5:00	4	326.8	248.0	76.0	75.5	24.6	std	13.86
80	6/5/02 12:00	6/5/02 15:00	3	370.6	180.0	48.6	75.1	26.3	std	10.04
81	6/5/02 18:00	6/6/02 6:00	12	385.0	218.4	56.8	74.9	27.3	std	12.22
82	6/6/02 15:00	6/6/02 17:00	2	387.8	216.5	55.9	74.7	27.4	std	12.09
83	6/6/02 18:00	6/7/02 5:00	11	361.9	207.5	57.4	74.7	26.8	std	11.64
84	6/7/02 7:00	6/7/02 9:00	2	327.2	140.1	42.8	74.9	25.1	std	7.89
85	6/7/02 11:00	6/7/02 14:00	3	377.2	170.8	45.3	74.3	26.8	std	9.53
86	6/7/02 15:00	6/7/02 21:00	6	340.9	140.1	41.1	74.4	25.4	std	7.86

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	**Starting Date-Time**	**Ending Date-Time**	**Duration (hrs)**	**Q_{total} (kcfs)**	**Q_{sp} (kcfs)**	**Q_{sp}/Q_{tot} (%)**	**FBE (ft)**	**TWE (ft)**	**Spill+ Pattern**	**qs (kcfs/bay)**
87	6/7/02 23:00	6/8/02 5:00	6	338.1	214.8	63.5	74.3	25.4	std	11.97
88	6/8/02 8:00	6/8/02 12:00	4	373.2	184.3	49.4	73.8	26.7	std	10.26
89	6/8/02 14:00	6/8/02 16:00	2	365.2	168.8	46.2	73.9	26.6	std	9.45
90	6/8/02 18:00	6/8/02 20:00	2	344.5	144.9	42.1	74.4	25.6	std	8.15
91	6/8/02 22:00	6/9/02 4:00	6	328.7	213.5	65.0	74.9	25.0	std	11.94
92	6/9/02 6:00	6/9/02 16:00	10	309.3	129.0	41.7	75.4	23.8	std	7.22
93	6/9/02 23:00	6/11/02 9:00	34	305.5	118.5	38.9	75.3	23.1	std	6.70
94	6/11/02 15:00	6/11/02 23:00	8	360.6	180.4	50.0	75.3	25.9	std	10.04
95	6/12/02 3:00	6/12/02 5:00	2	286.2	119.5	41.8	75.3	22.8	std	6.75
96	6/12/02 8:00	6/12/02 11:00	3	266.7	75.6	28.3	75.4	21.5	std	4.38
97	6/12/02 19:00	6/13/02 0:00	5	334.2	143.7	43.0	75.5	24.0	std	8.08
98	6/13/02 2:00	6/13/02 4:00	2	295.5	119.0	40.3	75.5	22.6	std	6.73
99	6/13/02 9:00	6/13/02 12:00	3	300.9	98.8	32.8	75.4	22.4	std	5.70
100	6/13/02 14:00	6/13/02 16:00	2	316.4	119.7	37.8	75.5	23.0	std	6.75
101	6/13/02 18:00	6/14/02 4:00	10	326.4	144.8	44.4	75.6	23.9	std	8.14
102	6/14/02 7:00	6/14/02 17:00	10	269.6	74.8	27.8	75.4	21.3	std	4.34
103	6/15/02 2:00	6/15/02 16:00	14	295.2	99.0	33.6	75.4	22.1	std	5.69
104	6/16/02 2:00	6/17/02 3:00	25	273.9	100.3	36.6	75.7	21.1	std	5.74
105	6/17/02 7:00	6/17/02 9:00	2	308.3	114.4	37.1	75.7	22.2	std	6.53
106	6/17/02 11:00	6/17/02 14:00	3	313.4	129.9	41.4	75.7	22.9	std	7.26
107	6/17/02 17:00	6/17/02 19:00	2	333.0	160.8	48.3	75.5	24.0	std	8.97
108	6/17/02 20:00	6/17/02 23:00	3	318.1	143.6	45.2	75.4	23.4	std	8.07
109	6/18/02 5:00	6/18/02 9:00	4	271.0	84.4	31.1	75.4	21.3	std	4.86
110	6/18/02 10:00	6/18/02 12:00	2	277.5	75.1	27.1	75.6	21.2	std	4.36
111	6/18/02 16:00	6/19/02 7:00	15	328.1	130.9	39.9	75.8	23.7	std	7.32
112	6/19/02 10:00	6/19/02 13:00	3	343.5	149.4	43.5	75.7	24.7	std	8.41
113	6/19/02 16:00	6/20/02 13:00	21	357.6	164.7	46.1	75.5	25.7	std	9.17
114	6/20/02 16:00	6/21/02 0:00	8	354.4	164.7	46.5	75.5	25.7	std	9.18
115	6/21/02 1:00	6/21/02 6:00	5	343.2	149.2	43.5	75.6	25.2	std	8.41
116	6/21/02 7:00	6/21/02 23:00	16	352.7	159.2	45.2	75.4	25.7	std	8.88
117	6/22/02 1:00	6/22/02 4:00	3	338.7	139.4	41.2	75.6	25.1	std	7.83
118	6/22/02 5:00	6/23/02 2:00	21	316.1	129.6	41.1	75.6	23.9	std	7.25
119	6/23/02 4:00	6/23/02 16:00	12	284.5	75.5	26.5	75.7	21.9	std	4.38
120	6/23/02 18:00	6/24/02 3:00	9	341.3	128.0	37.5	75.3	24.3	std	7.19
121	6/24/02 6:00	6/24/02 10:00	4	295.6	76.2	25.8	75.8	22.5	std	4.42
122	6/23/02 23:37	6/24/02 16:00	16.375	340.2	119.8	35.2	75.9	24.0	std	6.77
123	6/24/02 18:00	6/24/02 21:00	3	353.8	145.5	41.1	75.8	25.0	std	8.15
124	6/24/02 23:00	6/25/02 2:00	3	305.1	145.2	47.6	75.7	23.6	std	8.16
125	6/25/02 4:00	6/25/02 18:00	14	286.5	75.0	26.2	75.5	21.9	std	4.35
126	6/25/02 19:00	6/25/02 21:00	2	312.8	98.6	31.5	75.7	22.7	std	5.66
127	6/25/02 23:00	6/26/02 3:00	4	280.8	145.2	51.7	75.8	21.9	std	8.14
128	6/26/02 4:00	6/26/02 19:00	15	285.9	75.2	26.3	75.6	21.6	std	4.36
129	6/26/02 21:00	6/27/02 9:00	12	300.9	123.9	41.3	75.7	22.4	std	6.96
130	6/27/02 10:00	6/27/02 22:00	12	322.7	110.3	34.2	75.8	23.4	std	6.28

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	Starting Date-Time	Ending Date-Time	Duration (hrs)	Q_{total} (kcfs)	Q_{sp} (kcfs)	Q_{sp}/Q_{tot} (%)	FBE (ft)	TWE (ft)	Spill[+] Pattern	qs (kcfs/bay)
131	6/28/02 0:00	6/28/02 5:00	5	311.5	204.3	65.6	75.7	23.6	std	11.42
132	6/28/02 7:00	6/28/02 15:00	8	321.3	108.2	33.7	75.3	23.7	std	6.18
133	6/28/02 18:00	6/28/02 20:00	2	325.6	124.1	38.1	75.7	23.9	std	6.98
134	6/28/02 23:00	6/29/02 8:00	9	366.2	203.0	55.5	75.4	26.1	std	11.36
135	6/29/02 10:00	6/29/02 12:00	2	359.2	148.4	41.3	75.4	25.9	std	8.35
136	6/29/02 13:00	6/29/02 15:00	2	339.7	130.0	38.3	75.8	25.2	std	7.26
137	6/29/02 17:00	6/30/02 0:00	7	350.4	149.5	42.7	75.7	25.5	std	8.40
138	6/30/02 2:00	7/1/02 0:00	22	305.6	109.2	35.8	75.7	23.2	std	6.23
139	7/1/02 8:00	7/1/02 15:00	7	352.3	201.2	57.5	74.9	25.1	std	11.26
140	7/1/02 19:00	7/2/02 0:00	5	300.1	119.0	39.6	75.4	23.1	std	6.73
141	7/2/02 2:00	7/2/02 8:00	6	306.7	202.7	66.1	74.6	23.4	std	11.35
142	7/2/02 11:00	7/2/02 15:00	4	335.9	129.2	38.5	74.3	24.4	std	7.25
143	7/2/02 16:00	7/2/02 22:00	6	321.5	120.0	37.3	74.7	23.9	std	6.74
144	7/3/02 0:00	7/3/02 4:00	4	306.0	203.8	66.6	75.0	23.5	std	11.44
145	7/3/02 6:00	7/4/02 1:00	19	300.0	118.4	39.6	75.2	22.8	std	6.69
146	7/4/02 2:00	7/4/02 4:00	2	308.4	169.7	55.0	75.3	23.4	std	9.43
147	7/4/02 5:00	7/5/02 3:00	22	311.0	119.1	38.4	75.5	23.2	std	6.74
148	7/5/02 4:00	7/5/02 20:00	16	281.2	75.5	26.9	75.4	21.4	std	4.40
149	7/5/02 22:00	7/6/02 3:00	5	270.5	128.7	47.7	75.3	21.0	std	7.23
150	7/6/02 4:00	7/6/02 20:00	16	249.7	75.3	30.6	75.6	19.5	std	4.37
151	7/7/02 0:00	7/7/02 3:00	3	276.7	130.2	47.2	75.8	21.1	std	7.27
152	7/7/02 5:00	7/7/02 20:00	15	240.3	75.0	31.4	75.5	19.0	std	4.35
153	7/7/02 23:00	7/8/02 3:00	4	288.9	124.2	43.0	75.5	21.2	std	6.97
154	7/8/02 5:00	7/8/02 20:00	15	239.1	74.8	31.3	75.3	18.9	std	4.34
155	7/8/02 22:00	7/10/02 13:00	39	215.1	109.4	51.5	75.5	17.6	std	6.24
156	7/11/02 1:00	7/12/02 13:00	36	239.4	122.8	51.8	74.8	18.9	std	6.92
157	7/12/02 14:00	7/13/02 2:00	12	282.0	116.3	41.5	74.8	21.2	std	6.57
158	7/13/02 4:00	7/13/02 20:00	16	242.5	74.1	30.7	74.9	19.3	std	4.30
159	7/13/02 22:00	7/14/02 3:00	5	259.5	113.4	43.7	75.6	20.0	std	6.47
160	7/14/02 4:00	7/14/02 20:00	16	243.3	75.1	31.0	75.5	19.0	std	4.36
161	7/14/02 22:00	7/15/02 13:00	15	246.5	119.5	48.8	75.7	19.3	std	6.75
162	7/15/02 14:00	7/16/02 12:00	22	240.5	124.5	52.5	75.7	18.8	std	7.01
163	7/16/02 14:00	7/17/02 3:00	13	208.2	132.6	63.8	75.1	17.3	std	7.44
164	7/17/02 5:00	7/17/02 21:00	16	241.6	75.9	31.7	75.4	18.4	std	4.44
165	7/17/02 23:00	7/18/02 3:00	4	254.1	144.3	56.8	75.8	19.9	std	8.08
166	7/18/02 5:00	7/18/02 20:00	15	258.1	75.4	29.3	75.7	19.7	std	4.10
167	7/18/02 22:00	7/19/02 3:00	5	229.7	149.2	65.7	75.6	18.9	std	8.40
168	7/19/02 5:00	7/19/02 21:00	16	224.8	75.8	34.0	75.5	17.8	std	4.43
169	7/19/02 23:00	7/20/02 3:00	4	225.5	159.1	70.6	75.5	18.9	std	8.87
170	7/20/02 5:00	7/20/02 20:00	15	198.3	76.0	38.6	75.5	17.0	std	4.44
171	7/20/02 22:00	7/21/02 13:00	15	236.0	168.5	71.8	75.5	19.4	std	9.40
172	7/21/02 14:00	7/22/02 9:00	19	219.3	159.7	73.0	75.3	18.2	std	8.90
173	7/22/02 12:00	7/23/02 12:00	24	211.6	145.3	70.0	75.5	17.8	std	8.16
174	7/23/02 13:00	7/24/02 6:00	17	192.3	140.9	73.3	75.8	16.2	std	7.93

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	Starting Date-Time	Ending Date-Time	Duration (hrs)	Q_{total}l (kcfs)	Q_{sp} (kcfs)	Q_{sp}/Q_{tot} (%)	FBE (ft)	TWE (ft)	Spill[+] Pattern	qs (kcfs/bay)
175	7/24/02 8:00	7/25/02 :00	20	208.0	130.1	62.8	75.8	17.0	std	6.92
176	7/25/02 5:00	7/25/02 20:00	15	203.9	75.4	37.4	75.8	16.8	std	4.38
177	7/25/02 22:00	7/26/02 4:00	6	181.4	130.2	72.1	75.6	16.0	std	7.30
178	7/26/02 6:00	7/26/02 20:00	14	169.8	74.4	43.8	75.2	14.2	std	4.32
179	7/26/02 22:00	7/28/02 9:00	35	165.1	138.7	84.4	74.9	14.3	std	7.80
180	7/28/02 10:00	7/28/02 12:00	2	157.3	143.6	91.3	74.6	13.6	std	8.04
181	7/28/02 15:00	7/29/02 4:00	13	176.1	139.2	79.0	74.2	14.6	std	7.82
182	7/29/02 6:00	7/29/02 21:00	15	157.4	76.2	48.6	74.8	12.9	std	4.41
183	7/29/02 22:00	7/30/02 4:00	6	201.7	144.3	71.5	75.0	16.0	std	8.09
184	7/30/02 6:00	7/30/02 21:00	15	200.0	76.2	38.2	75.0	15.6	std	4.43
185	7/30/02 23:00	7/31/02 4:00	5	180.7	142.9	79.1	74.9	15.5	std	8.04
186	7/31/02 6:00	7/31/02 20:00	14	159.8	75.6	47.5	75.1	13.3	std	4.39
187	7/31/02 22:00	8/1/02 4:00	6	195.8	159.2	81.3	75.4	15.8	std	8.88
188	8/1/02 5:00	8/1/02 20:00	15	168.8	75.2	44.6	75.6	13.8	std	4.37
189	8/1/02 22:00	8/2/02 3:00	5	179.3	143.5	80.1	75.5	15.0	std	8.06
190	8/2/02 5:00	8/2/02 20:00	15	161.3	123.2	76.4	75.3	13.7	std	6.93
191	8/2/02 23:00	8/3/02 6:00	7	177.6	139.0	78.3	75.5	14.6	std	7.84
192	8/3/02 7:00	8/3/02 19:00	12	166.8	128.5	77.1	75.6	14.1	std	7.21
193	8/3/02 20:00	8/4/02 4:00	8	173.7	135.8	78.2	75.5	14.4	std	7.61
194	8/4/02 5:00	8/4/02 20:00	15	146.8	76.4	52.4	75.7	12.6	std	4.46
195	8/5/02 2:00	8/5/02 4:00	2	168.8	129.6	76.8	75.6	13.0	std	7.25
196	8/5/02 6:00	8/5/02 21:00	15	184.7	75.1	41.0	75.6	14.4	std	4.36
197	8/5/02 23:00	8/6/02 0:00	1	180.5	143.9	79.7	75.6	15.2	std	8.08
198	8/6/02 1:00	8/6/02 4:00	3	191.4	154.1	80.5	75.2	15.6	std	8.61
199	8/6/02 6:00	8/6/02 17:00	11	170.9	133.0	77.8	74.9	14.7	std	7.48
200	8/6/02 19:00	8/7/02 0:00	5	156.9	120.1	76.6	75.2	13.6	std	6.74
201	8/7/02 2:00	8/7/02 23:00	21	148.0	109.9	74.3	75.4	12.8	std	6.28
202	8/8/02 0:00	8/8/02 8:00	8	158.7	120.0	75.6	75.5	13.4	std	6.77
203	8/8/02 10:00	8/8/02 12:00	2	173.1	134.1	77.5	75.4	14.6	std	7.54
204	8/8/02 13:00	8/9/02 21:00	32	183.6	145.6	79.3	75.4	15.5	std	8.22
205	8/9/02 22:00	8/10/02 0:00	2	158.4	121.4	76.7	75.5	14.2	std	6.83
206	8/10/02 1:00	8/10/02 3:00	2	149.3	111.2	74.5	75.4	13.5	std	6.35
207	8/10/02 5:00	8/10/02 20:00	15	151.2	75.1	49.8	75.5	12.8	std	4.36
208	8/10/02 22:00	8/11/02 4:00	6	161.9	123.6	76.4	75.5	13.8	std	6.95
209	8/11/02 5:00	8/11/02 20:00	15	173.9	75.2	43.6	75.6	14.1	std	4.37
210	8/11/02 22:00	8/12/02 4:00	6	127.9	90.5	70.7	75.5	11.9	std	5.20
211	8/12/02 5:00	8/12/02 20:00	15	166.4	76.1	46.5	75.6	13.3	std	4.44
212	8/13/02 0:00	8/13/02 4:00	4	151.9	114.0	75.1	75.6	13.4	std	6.50
213	8/13/02 5:00	8/13/02 20:00	15	175.2	75.0	44.0	75.5	14.0	std	4.35
214	8/14/02 0:00	8/14/02 10:00	10	152.3	114.3	75.1	75.5	13.2	std	6.52
215	8/14/02 14:00	8/15/02 1:00	11	172.2	133.6	77.6	75.5	14.5	std	7.52
216	8/15/02 3:00	8/15/02 6:00	3	148.7	110.2	74.1	75.3	13.6	std	6.30
217	8/15/02 7:00	8/15/02 13:00	6	151.7	115.2	75.9	75.4	13.2	std	6.57
218	8/15/02 14:00	8/15/02 19:00	5	171.1	133.4	78.0	75.7	14.2	std	7.48

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	Starting Date-Time	Ending Date-Time	Duration (hrs)	Q_{total} (kcfs)	Q_{sp} (kcfs)	Q_{sp}/Q_{tot} (%)	FBE (ft)	TWE (ft)	Spill[+] Pattern	qs (kcfs/bay)
219	8/15/02 20:00	8/16/02 0:00	4	187.1	139.2	74.4	75.7	15.1	std	7.83
220	8/16/02 6:00	8/16/02 18:00	12	182.0	75.2	41.5	74.6	14.7	std	4.37
221	8/16/02 20:00	8/17/02 2:00	6	189.4	149.4	78.9	74.2	15.5	std	8.38
222	8/17/02 5:00	8/17/02 18:00	13	137.9	75.4	54.8	74.2	12.0	std	4.40
223	8/17/02 20:00	8/18/02 1:00	5	146.2	110.3	75.4	74.2	12.3	std	6.28
224	8/18/02 3:00	8/18/02 20:00	17	137.2	99.6	72.6	74.0	11.8	std	5.68
225	8/18/02 21:00	8/19/02 1:00	4	147.1	110.6	75.2	74.1	12.3	std	6.30
226	8/19/02 2:00	8/19/02 6:00	4	162.2	124.5	76.7	74.0	13.5	std	7.01
227	8/19/02 8:00	8/19/02 18:00	10	136.2	98.0	72.0	74.1	11.9	std	5.62
228	8/19/02 20:00	8/20/02 19:00	23	156.5	119.0	76.0	73.8	13.3	std	6.68
229	8/20/02 20:00	8/21/02 6:00	10	168.0	129.7	77.2	73.9	14.1	std	7.30
230	8/21/02 7:00	8/21/02 21:00	14	157.9	120.5	76.3	74.1	13.6	std	6.78
231	8/21/02 22:00	8/22/02 0:00	2	173.1	134.9	77.9	74.0	14.5	std	7.58
232	8/22/02 2:00	8/22/02 4:00	2	155.0	117.1	75.6	74.1	13.3	std	6.63
233	8/22/02 5:00	8/22/02 18:00	13	151.5	76.3	50.4	74.2	12.9	std	4.44
234	8/22/02 20:00	8/23/02 0:00	4	146.3	109.5	74.8	74.7	12.7	std	6.28
235	8/23/02 1:00	8/23/02 4:00	3	156.7	119.4	76.2	74.5	13.2	std	6.73
236	8/23/02 5:00	8/23/02 18:00	13	157.1	75.0	47.8	74.1	13.1	std	4.38
237	8/23/02 20:00	8/24/02 4:00	8	157.9	119.5	75.6	74.1	13.1	std	6.72
238	8/24/02 6:00	8/24/02 16:00	10	164.3	75.1	45.9	74.1	13.4	std	4.38
239	8/24/02 20:00	8/25/02 3:00	7	165.5	127.4	76.9	73.9	13.9	std	7.15
240	8/25/02 6:00	8/25/02 18:00	12	126.4	74.8	59.4	73.9	11.1	std	4.38
241	8/25/02 20:00	8/25/02 22:00	2	135.7	98.6	72.7	74.0	11.2	std	5.65
242	8/25/02 23:00	8/26/02 1:00	2	133.8	74.7	55.9	74.1	11.2	std	4.36
243	8/26/02 2:00	8/26/02 4:00	2	119.6	56.3	47.2	74.1	10.2	std	3.13
244	8/26/02 6:00	8/26/02 12:00	6	156.4	117.8	75.3	73.8	12.5	std	6.65
245	8/26/02 14:00	8/26/02 18:00	4	137.5	100.0	72.7	74.2	11.1	std	5.68
246	8/26/02 20:00	8/26/02 22:00	2	137.3	41.8	30.5	74.5	11.6	unew6	7.00
247	8/26/02 23:00	8/27/02 1:00	2	136.3	41.7	30.6	74.6	12.1	uold6	6.88
248	8/27/02 2:00	8/27/02 4:00	2	128.0	32.2	25.2	74.6	11.5	unew6	5.10
249	8/27/02 5:00	8/27/02 13:00	8	134.1	98.0	73.1	74.5	11.3	std	5.92
250	8/27/02 14:00	8/27/02 18:00	4	150.2	114.9	76.5	75.3	12.4	std	6.54
251	8/27/02 23:00	8/28/02 4:00	5	156.1	119.4	76.5	75.9	13.0	std	6.74
252	8/28/02 6:00	8/28/02 19:00	13	156.0	76.3	49.2	75.8	12.5	std	4.48
253	8/28/02 20:00	8/28/02 22:00	2	173.6	32.5	18.7	75.8	13.7	uold6	5.10
254	8/28/02 23:00	8/29/02 1:00	2	150.1	27.5	18.4	75.8	12.9	std	2.08
255	8/29/02 2:00	8/29/02 4:00	2	122.8	19.1	15.6	75.8	11.7	uold6	3.16
256	8/29/02 6:00	8/29/02 19:00	13	144.1	75.3	52.3	75.7	11.9	std	4.37
257	8/29/02 20:00	8/29/02 22:00	2	127.3	20.7	16.3	75.8	11.1	unew6	3.20
258	8/29/02 23:00	8/30/02 1:00	2	123.0	10.5	8.5	75.8	11.3	unew6	1.77
259	8/30/02 2:00	8/30/02 4:00	2	112.9	10.8	9.5	75.8	10.8	uold6	1.69
260	8/30/02 5:00	8/30/02 13:00	8	138.0	99.8	72.3	75.7	11.2	std	5.72
261	8/30/02 19:00	8/30/02 21:00	2	157.9	118.9	75.3	75.9	12.3	std	6.69
262	8/30/02 23:00	8/31/02 3:00	4	137.6	99.7	72.4	75.8	11.4	std	5.71

Table 5. Events Summary for Spillway Operations at Bonneville Dam.										
Event	**Starting Date-Time**	**Ending Date-Time**	**Duration (hrs)**	**Q_{total} (kcfs)**	**Q_{sp} (kcfs)**	**Q_{sp}/Q_{tot} (%)**	**FBE (ft)**	**TWE (ft)**	**Spill+ Pattern**	**qs (kcfs/bay)**
263	8/31/02 5:00	8/31/02 16:00	11	157.4	118.4	75.3	75.7	12.3	std	6.71
264	8/31/02 18:00	8/31/02 23:00	5	179.0	139.3	77.8	75.5	14.0	std	7.85

+Spill Pattern key std = Standard spill pattern
unew6 = Uniform distribution over bays with new deflectors 1-3, 16-18
uold6 = Uniform distribution over bays with old deflectors (4-9)
Highlight indicates test spill conditions

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
1	206.6	51.4	17.0	std	104.6		109.7	109.9	109.6	109.6	109.7	5.2
2	234.5	76.1	19.3	std	111.3	115.1	113.9	113.5	114.5	114.9	114.2	2.9
3	301.0	89.9	23.2	std	110.5	116.2	115.5	114.3	115.6	116.4	115.4	4.9
4	314.0	90.1	24.1	std	111.4	117.0	116.0	113.3	115.9	117.3	115.6	4.2
5	341.5	121.1	25.5	std	111.9	118.8	121.1	119.9	121.9	120.3	120.6	8.7
6	352.7	150.7	26.2	std	114.7	121.7	124.9	121.6	124.0	123.4	123.2	8.5
7	343.0	130.2	25.9	std	113.8	119.0	122.1	120.6	120.5	119.5	120.6	6.8
8	352.0	140.7	26.3	std	113.9	121.6	123.0	120.8	122.3	121.4	121.9	8.0
9	335.2	169.8	25.9	std	113.4	120.8	128.1	126.2	124.2	122.3	125.0	11.6
10	311.2	150.3	24.4	std	112.3	120.1	123.5	122.6	121.7	121.9	122.2	9.9
11	269.7	76.6	21.8	std	111.2	115.6	114.0	113.1	114.7	115.3	114.3	3.1
12	318.3	152.9	23.9	std	112.4	120.1	124.4	124.7	121.3	121.8	122.9	10.5
13	298.6	76.7	22.9	std	110.6	116.1	114.7	113.4	114.8	115.9	114.7	4.1
14	268.0	149.0	21.5	std	110.3	119.9	123.2	121.5	122.0	119.8	121.6	11.2
15	278.4	75.7	21.2	std	110.6	115.5	113.3	112.8	114.2	115.0	113.9	3.3
16	268.7	149.0	21.4	std	114.8	119.9	123.4	121.5	121.9	119.9	121.7	6.9
17	251.8	75.5	19.8	std	115.0	115.5	113.9	113.2	114.4	115.2	114.2	-0.8
18	240.0	152.7	20.1	std	116.2	119.8	122.5	121.8	122.9	119.6	121.7	5.5
19	253.5	75.5	20.0	std	114.7	115.6	113.9	113.3	114.3	114.9	114.2	-0.5
20	205.8	134.3	18.1	std	113.4	119.8	120.2	119.6	121.6	116.9	119.9	6.5
21	258.4	75.6	20.0	std	112.0	116.5	113.9	113.2	114.3	114.7	114.2	2.3
22	218.8	134.1	18.7	std	111.7	119.6	120.3	119.3	121.3	116.9	119.8	8.1
23	197.6	141.4	17.3	std	112.1	119.9	120.1	120.4	121.6	117.3	120.2	8.1
24	218.7	129.5	18.2	std	114.9	119.0	120.2	119.9	120.3	116.6	119.6	4.6
25	242.0	74.5	19.1	std	115.1	114.6	113.4	113.3	114.5	114.9	114.0	-1.2

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
26	228.4	119.4	18.8	std	113.0	118.0	119.7	118.1	119.8	116.7	118.8	5.8
27	235.1	75.0	18.7	std	112.0	114.2	113.6	113.3	114.2	114.2	113.8	1.8
28	230.6	109.0	18.7	std	110.1	117.4	118.2	118.2	118.6	116.3	118.0	7.9
29	241.8	119.5	19.5	std	109.4	117.7	119.6	118.6	119.5	117.3	118.8	9.4
30	239.6	76.3	19.1	std	109.9	114.7	113.8	113.1	114.5	114.5	114.0	4.1
31	259.7	134.1	20.2	std	109.9	119.4	121.2	121.2	119.8	118.1	120.2	10.3
32	252.8	75.5	19.8	std	110.8	115.3	113.7	113.0	114.2	115.0	114.0	3.2
33	197.7	145.7	17.5	std	110.5	119.7	121.5	121.0	122.3	117.4	120.8	10.3
34	236.0	155.4	19.2	std	110.5	119.4	122.4	122.5	122.8	118.4	121.6	11.2
35	258.1	149.1	20.5	std	110.0	120.1	122.4	120.8	122.4	119.2	121.3	11.3
36	222.8	143.7	19.0	std	113.2	118.9	121.8	120.5	122.6	118.2	120.9	7.7
37	193.8	76.6	16.5	std	112.6	114.8	114.8	114.2	114.9	113.2	114.5	1.9
38	197.5	129.3	16.4	std	109.8	117.9	119.5	119.0	120.8	115.4	119.0	9.2
39	225.2	75.4	17.5	std	111.6	114.1	114.5	114.0	114.5	113.3	114.2	2.6
40	235.0	128.7	18.4	std	111.6	118.7	120.4	120.0	119.9	116.6	119.5	7.9
41	194.5	76.0	16.0	std	111.9	114.3	115.0	114.0	115.0	113.1	114.4	2.5
42	179.5	128.5	15.3	std	114.3	118.4	119.9	118.8	120.5	115.1	119.0	4.7
43	227.3	74.8	17.5	std	112.9	114.4	114.5	113.8	114.6	113.6	114.2	1.4
44	233.8	128.4	18.5	std	110.4	118.5	120.4	120.3	119.9	116.7	119.5	9.1
45	197.0	139.0	16.9	std	110.2	119.2	120.6	120.5	121.7	117.1	120.2	10.1
46	211.7	128.3	17.5	std	110.7	119.6	119.6	119.5	120.5	116.3	119.4	8.6
47	206.2	119.3	17.4	std	112.0	117.9	119.5	118.4	120.5	116.4	118.9	6.8
48	241.1	109.2	18.6	std	114.3	117.8	119.0	119.2	119.8	116.8	118.8	4.5
49	223.8	75.4	17.9	std	114.6	114.3	114.5	114.9	115.2	114.0	114.7	0.1
50	215.0	109.2	17.3	std	114.2	117.5	118.5	118.0	119.4	115.9	118.2	3.9
51	228.5	75.8	17.8	std	115.6	114.7	115.1	114.5	115.2	113.9	114.8	-0.8
52	234.5	99.6	18.3	std	114.6	116.8	118.5	118.9	118.5	115.5	118.0	3.4

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
53	237.0	75.4	18.4	std	115.4	114.8	114.9	114.3	114.9	114.0	114.6	-0.9
54	250.3	90.0	19.0	std	113.2	116.2	117.2	117.1	118.0	115.6	117.1	3.9
55	267.7	75.8	20.0	std	111.4	116.4	114.3	113.9	115.4	116.9	115.1	3.6
56	287.8	99.9	21.3	std	109.9	117.8	117.9	117.7	118.0	117.4	117.8	7.9
57	283.8	148.5	21.8	std	110.2	120.0	123.8	122.6	122.1	120.1	122.1	11.9
58	270.7	154.0	21.2	std	112.1	120.0	123.9	123.9	123.4	119.8	122.8	10.6
59	271.7	146.5	21.3	std	116.1	120.1	124.2	123.3	122.3	119.7	122.4	6.3
60	257.8	128.4	20.5	std	115.9	119.2	122.1	123.2	119.9	118.4	121.0	5.2
61	208.8	130.3	17.9	std	116.1	119.1	120.3	120.0	121.2	116.8	119.9	3.8
62	249.6	75.5	19.3	std	115.8	115.6	114.8	114.3	115.3	114.9	114.9	-0.9
63	279.3	129.5	21.1	std	114.7	119.1	122.5	124.2	119.7	118.6	121.3	6.6
64	283.0	75.7	21.2	std	116.0	116.4	114.6	113.9	115.5	115.6	115.0	-1.0
65	305.2	129.2	23.0	std	114.9	119.2	122.5	123.5	119.7	118.9	121.2	6.3
66	302.9	119.6	22.9	std	113.9	118.5	120.7	119.9	120.5	119.0	120.0	6.0
67	311.3	119.3	23.3	std	113.3	118.4	120.6	119.7	120.7	118.9	119.9	6.6
68	333.6	119.2	24.3	std	113.7	118.6	120.8	119.5	121.5	119.4	120.2	6.5
69	381.6	148.7	26.6	std	114.2	120.3	124.5	122.2	123.7	121.1	122.8	8.5
70	314.8	199.3	24.5	std	111.7	121.7	129.7	133.2	128.0	122.4	128.2	16.6
71	309.0	159.8	23.8	std	111.6	120.1	125.0	126.7	122.7	122.2	123.9	12.3
72	308.5	160.5	23.8	std	112.3	120.0	125.2	127.0	122.9	122.2	124.0	11.7
73	327.1	119.3	24.0	std	112.0	118.8	120.4	119.1	121.3	120.1	120.1	8.1
74	310.2	117.3	23.1	std	115.0	118.6	120.6	119.4	121.1	120.1	120.1	5.1
75	321.0	229.7	23.8	std	115.7	124.3		133.3	136.1	123.9	132.0	16.3
76	327.4	164.7	24.5	std	114.4	120.0		127.1	124.1	122.2	124.5	10.1
77	311.3	133.8	23.8	std	115.7	118.9		122.6	121.1	120.6	121.3	5.7
78	349.0	165.3	25.1	std	116.2	120.0		127.0	124.9	122.1	124.7	8.5
79	326.8	248.0	24.6	std	115.6	125.7		136.3	136.6	124.8	133.6	18.0

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..												
Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
80	370.6	180.0	26.3	std	116.4	121.3		129.2	125.5	120.9	125.8	9.4
81	385.0	218.4	27.3	std	115.9	122.7		134.7	129.8	122.8	129.9	14.0
82	387.8	216.5	27.4	std	116.8	123.0		134.0	129.1	122.5	129.3	12.5
83	361.9	207.5	26.8	std	116.6	122.1		133.5	129.0	123.8	129.2	12.6
84	327.2	140.1	25.1	std	116.5	121.3		122.4	124.2	123.4	123.1	6.6
85	377.2	170.8	26.8	std	116.6	121.8		126.3	124.7	121.5	124.5	8.0
86	340.9	140.1	25.4	std	114.9	120.9		122.1	123.6	122.6	122.5	7.6
87	338.1	214.8	25.4	std	114.7	123.0		134.4	130.6	124.1	130.2	15.5
88	373.2	184.3	26.7	std	114.1	120.1		129.5	125.9	121.6	126.0	11.9
89	365.2	168.8	26.6	std	114.6	120.5		126.0	124.5	121.1	124.2	9.6
90	344.5	144.9	25.6	std	112.6	121.0		122.7	123.1	120.4	122.4	9.8
91	328.7	213.5	25.0	std	113.4	122.6		134.3	129.7	124.1	129.9	16.5
92	309.3	129.0	23.8	std	113.5	119.4		122.7	120.2	119.7	121.0	7.5
93	305.5	118.5	23.1	std	114.5	118.3		120.1	120.9	120.1	120.2	5.7
94	360.6	180.4	25.9	std	117.4	121.6		130.0	126.0	123.1	126.6	9.1
95	286.2	119.5	22.8	std	116.5	118.4		121.2	120.9	120.2	120.6	4.1
96	266.7	75.6	21.5	std	116.2	116.1		114.9	116.3	115.8	115.7	-0.5
97	334.2	143.7	24.0	std	118.3	119.5		123.3	123.1	122.9	122.7	4.4
98	295.5	119.0	22.6	std	118.2	118.3		120.5	121.1	120.1	120.4	2.2
99	300.9	98.8	22.4	std	116.9	118.1		118.0	119.4	119.8	118.7	1.8
100	316.4	119.7	23.0	std	117.2	118.1		120.7	121.1	119.7	120.4	3.2
101	326.4	144.8	23.9	std	118.2	120.1		123.8	122.6	121.7	122.6	4.5
102	269.6	74.8	21.3	std	116.7	116.4		114.8	116.4	116.0	115.7	-1.0
103	295.2	99.0	22.1	std	112.4	117.7		117.6	118.5	118.9	118.1	5.8
104	273.9	100.3	21.1	std	111.0	117.5		118.3	118.9	118.1	118.4	7.4
105	308.3	114.4	22.2	std	111.3	118.3		119.0	120.5	119.1	119.5	8.2
106	313.4	129.9	22.9	std	112.0	118.7		123.5	120.1	119.2	121.1	9.1

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
107	333.0	160.8	24.0	std	113.3	120.1		127.7	123.8	123.1	124.7	11.5
108	318.1	143.6	23.4	std	114.4	119.3		123.9	122.7	121.5	122.5	8.2
109	271.0	84.4	21.3	std	112.7	118.6		115.1	116.2	115.3	116.0	3.3
110	277.5	75.1	21.2	std	112.1	115.6		114.8	115.5	115.4	115.2	3.1
111	328.1	130.9	23.7	std	112.7	118.8		123.0	120.5	120.5	121.2	8.5
112	343.5	149.4	24.7	std	112.6	120.7		123.4	123.4	123.1	123.1	10.4
113	357.6	164.7	25.7	std	114.2	120.3		127.0	124.3	121.6	124.5	10.3
114	354.4	164.7	25.7	std	115.4	120.0		127.0	124.5	122.2	124.6	9.2
115	343.2	149.2	25.2	std	115.4	121.0		124.2	123.7	123.7	123.5	8.1
116	352.7	159.2	25.7	std	116.9	120.7		126.5	124.1	122.7	124.4	7.5
117	338.7	139.4	25.1	std	115.7	120.8		122.9	123.8	123.8	123.1	7.3
118	316.1	129.6	23.9	std	113.7	119.4		123.1	120.6	119.8	121.3	7.6
119	284.5	75.5	21.9	std	110.5	115.8		115.0	116.1	116.1	115.7	5.1
120	341.3	128.0	24.3	std	112.3	118.9		122.1	120.4	118.6	120.6	8.3
121	295.6	76.2	22.5	std	112.5	116.0		115.2	116.8	116.6	116.0	3.6
122	340.2	119.8	24.0	std	113.2	117.7		120.2	120.7	118.9	119.9	6.7
123	353.8	145.5	25.0	std	114.2	120.5		122.8	123.9	123.4	123.0	8.8
124	305.1	145.2	23.6	std	114.6	119.3		124.1	122.5	121.5	122.6	8.0
125	286.5	75.0	21.9	std	115.7	116.4		115.3	117.1	116.6	116.3	0.6
126	312.8	98.6	22.7	std	117.3	117.9		117.7	119.4	119.4	118.6	1.3
127	280.8	145.2	21.9	std	118.4	119.4		124.1	122.7	120.3	122.5	4.1
128	285.9	75.2	21.6	std	118.1	116.4		115.4	117.3	116.6	116.4	-1.7
129	300.9	123.9	22.4	std	115.7	117.8		122.1	120.7	119.6	120.7	5.1
130	322.7	110.3	23.4	std	112.9	118.3		118.6	120.0	119.4	119.2	6.3
131	311.5	204.3	23.6	std	112.9	121.6		133.2	129.4	122.7	129.0	16.1
132	321.3	108.2	23.7	std	113.4	118.9		118.5	120.9	121.3	119.8	6.4
133	325.6	124.1	23.9	std	114.6	119.1		121.4	121.6	120.7	121.1	6.5

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
134	366.2	203.0	26.1	std	115.4	122.2		133.7	128.2	122.8	128.8	13.4
135	359.2	148.4	25.9	std	114.1	121.4		123.3	124.2	121.1	123.1	9.0
136	339.7	130.0	25.2	std	115.2	121.0		122.6	121.3	119.6	121.5	6.3
137	350.4	149.5	25.5	std	116.3	120.9		123.4	124.3	123.6	123.5	7.2
138	305.6	109.2	23.2	std	115.5	117.5		118.8	121.0	121.0	119.7	4.2
139	352.3	201.2	25.1	std	111.7	122.4		133.3	126.9	121.8	128.1	16.4
140	300.1	119.0	23.1	std	113.3	117.6		120.1	120.9	119.5	120.0	6.7
141	306.7	202.7	23.4	std	114.9	122.2		133.1	128.3	122.8	128.6	13.8
142	335.9	129.2	24.4	std	116.4	120.4		122.0	121.5	119.2	121.3	4.9
143	321.5	120.0	23.9	std	116.4	118.3		120.3	120.9	118.8	120.1	3.7
144	306.0	203.8	23.5	std	115.0	122.5		134.0	128.2	122.8	129.0	14.0
145	300.0	118.4	22.8	std	112.2	118.1		120.3	120.9	119.3	120.1	7.9
146	308.4	169.7	23.4	std	111.2	119.5		127.8	124.4	121.8	124.7	13.5
147	311.0	119.1	23.2	std	111.6	117.9		120.0	121.1	119.5	120.1	8.5
148	281.2	75.5	21.4	std	112.4	115.8		114.9	116.4	115.6	115.6	3.2
149	270.5	128.7	21.0	std	116.3	118.4		123.3	120.4	118.6	121.0	4.8
150	249.7	75.3	19.5	std	117.9	115.8		114.9	116.0	115.1	114.6	-3.2
151	276.7	130.2	21.1	std	118.1	118.4				118.4	118.4	0.3
152	240.3	75.0	19.0	std	116.1	114.9				114.9	114.9	-1.2
153	288.9	124.2	21.2	std	112.5	117.8				118.4	118.1	5.6
154	239.1	74.8	18.9	std	110.6	114.4				114.3	114.4	3.8
155	215.1	109.4	17.6	std	111.9	117.2				115.8	116.5	4.6
156	239.4	122.8	18.9	std	114.0	118.5				117.0	117.8	3.7
157	282.0	116.3	21.2	std	113.0	118.3				118.3	118.3	5.2
158	242.5	74.1	19.3	std	112.2	114.9				114.3	114.6	2.4
159	259.5	113.4	20.0	std	110.8	117.8				117.1	117.4	6.6
160	243.3	75.1	19.0	std	108.8	115.1				114.2	114.6	5.9

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
161	246.5	119.5	19.3	std	108.9	117.5				117.0	117.2	8.3
162	240.5	124.5	18.8	std	109.8	117.4				116.8	117.1	7.3
163	208.2	132.6	17.3	std	110.2	119.0				116.5	117.7	7.5
164	241.6	75.9	18.4	std	109.6	114.6				114.0	114.3	4.8
165	254.1	144.3	19.9	std	109.0	119.2				118.6	118.9	9.9
166	258.1	75.4	19.7	std	110.0	115.7				114.1	114.9	4.9
167	229.7	149.2	18.9	std	110.1	119.3				118.4	118.8	8.7
168	224.8	75.8	17.8	std	109.5	114.3				113.8	114.1	4.6
169	225.5	159.1	18.9	std	108.6	119.3				118.9	119.1	10.4
170	198.3	76.0	17.0	std	108.3	114.2				113.3	113.8	5.5
171	236.0	168.5	19.4	std	109.4	120.0				119.2	119.6	10.2
172	219.3	159.7	18.2	std	112.1	119.9				118.7	119.3	7.2
173	211.6	145.3	17.8	std	114.1	120.0				117.5	118.7	4.6
174	192.3	140.9	16.2	std	111.2	119.7				116.6	118.1	7.0
175	208.0	130.1	17.0	std	109.9	118.4				115.9	117.1	7.2
176	203.9	75.4	16.8	std	107.9	114.2				113.1	113.7	5.7
177	181.4	130.2	16.0	std	106.6	117.7				115.9	116.8	10.2
178	169.8	74.4	14.2	std	105.9	113.7				112.4	113.0	7.2
179	165.1	138.7	14.3	std	104.2	118.4				116.8	117.6	13.4
180	157.3	143.6	13.6	std	103.4	118.9				117.0	117.9	14.5
181	176.1	139.2	14.6	std	103.9	118.5				117.3	117.9	14.0
182	157.4	76.2	12.9	std	104.1	113.7				112.3	113.0	8.9
183	201.7	144.3	16.0	std	105.2	119.3				116.9	118.1	12.9
184	200.0	76.2	15.6	std	105.1	114.1				112.8	113.4	8.4
185	180.7	142.9	15.5	std	105.3	119.1				117.2	118.1	12.8
186	159.8	75.6	13.3	std	105.2	113.6				112.6	113.1	8.0
187	195.8	159.2	15.8	std	106.5	119.3				116.7	118.0	11.5

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)							
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
188	168.8	75.2	13.8	std	106.8	113.4				112.6	113.0	6.1
189	179.3	143.5	15.0	std	107.1	119.1				117.4	118.3	11.2
190	161.3	123.2	13.7	std	106.3	117.8				114.7	116.3	10.0
191	177.6	139.0	14.6	std	106.6	117.9				117.2	117.6	11.0
192	166.8	128.5	14.1	std	107.0	118.2				114.5	116.3	9.3
193	173.7	135.8	14.4	std	106.5	118.7				115.9	117.3	10.9
194	146.8	76.4	12.6	std	105.6	112.9				112.7	112.8	7.2
195	168.8	129.6	13.0	std	105.9	117.3				114.6	115.9	10.0
196	184.7	75.1	14.4	std	105.9	114.5				112.8	111.8	5.9
197	180.5	143.9	15.2	std	106.1	119.8				118.1	119.0	12.9
198	191.4	154.1	15.6	std	106.7	120.2				117.3	118.7	12.0
199	170.9	133.0	14.7	std	106.6	119.3				115.9	117.6	11.0
200	156.9	120.1	13.6	std	106.4	116.3				114.7	115.5	9.1
201	148.0	109.9	12.8	std	107.0	116.7				116.0	116.4	9.4
202	158.7	120.0	13.4	std	106.0	117.2				114.8	116.0	10.0
203	173.1	134.1	14.6	std	106.3	119.2				116.4	117.8	11.5
204	183.6	145.6	15.5	std	107.4	120.1				117.5	118.8	11.4
205	158.4	121.4	14.2	std	109.2	116.7				114.9	115.8	6.6
206	149.3	111.2	13.5	std	109.8	116.9				115.8	116.3	6.6
207	151.2	75.1	12.8	std	108.2	113.4				113.1	113.3	5.1
208	161.9	123.6	13.8	std	107.9	117.6				115.1	116.3	8.5
209	173.9	75.2	14.1	std	106.5	114.5				112.8	113.7	7.1
210	127.9	90.5	11.9	std	106.7	113.5				113.8	113.6	6.9
211	166.4	76.1	13.3	std	107.6	114.2				113.1	113.7	6.1
212	151.9	114.0	13.4	std	107.8	117.5				115.4	116.5	8.7
213	175.2	75.0	14.0	std	109.8	114.2				113.0	113.6	3.8
214	152.3	114.3	13.2	std	111.3	116.3				115.9	116.1	4.8

Table 6. Events based project operations and total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 10- August 24 2002..													
Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)								
					BON	BONTWP1	BONTWP2	BONTWP3	BONTWP4	BONTWP5	BONTW-AVG	ΔTDG
215	172.2	133.6	14.5	std	110.3	119.4				116.6	118.0	7.7
216	148.7	110.2	13.6	std	109.2	118.5				115.8	117.1	8.0
217	151.7	115.2	13.2	std	108.4	117.6				115.3	116.4	8.0
218	171.1	133.4	14.2	std	108.5	119.3				116.9	118.1	9.6
219	187.1	139.2	15.1	std	107.7	119.4				117.4	118.4	10.7
220	182.0	75.2	14.7	std	105.5	114.5				112.8	113.6	8.1
221	189.4	149.4	15.5	std	107.2	119.9				117.1	118.5	11.3
222	137.9	75.4	12.0	std	107.1	113.5				113.2	113.4	6.2
223	146.2	110.3	12.3	std	106.4	117.4				115.9	116.7	10.3
224	137.2	99.6	11.8	std	107.6	116.6				115.9	116.3	8.7
225	147.1	110.6	12.3	std	107.8	117.6				116.1	116.8	9.0
226	162.2	124.5	13.5	std	106.1	118.5				114.9	116.7	10.6
227	136.2	98.0	11.9	std	106.4	117.0				115.9	116.4	10.0
228	156.5	119.0	13.3	std	105.1	117.0				114.8	115.9	10.8
229	168.0	129.7	14.1	std	103.8	119.1				116.3	117.7	13.9
230	157.9	120.5	13.6	std	103.2	116.8				114.8	115.8	12.6
231	173.1	134.9	14.5	std	103.5	119.1				117.4	118.2	14.7
232	155.0	117.1	13.3	std	104.2	116.9				114.5	115.7	11.5
233	151.5	76.3	12.9	std	104.8	114.6				113.1	113.8	9.0
234	146.3	109.5	12.7	std	105.2	117.9				115.9	116.9	11.6
235	156.7	119.4	13.2	std	105.4	117.3				114.8	116.0	10.6
236	157.1	75.0	13.1	std	107.0	114.9				113.1	114.0	7.0
237	157.9	119.5	13.1	std	107.9	116.7				114.9	115.8	7.9
238	164.3	75.1	13.4	std	109.6	114.1				113.0	113.6	3.9

Table 7. Events based project operations and total dissolved gas saturation on transect T3 in the spillway exit channel at Bonneville Dam, August 25-31, 2002.

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)								
					BON	BONTWP1	T3P2	T3P3	T3P4	T3P5	BONTWP5	BONTW-avg	ΔTDG
239	165.5	127.4	13.9	std	108.3	118.0	119.8	118.3	118.7	119.3	113.7	118.4	10.1
240	126.4	74.8	11.1	std	107.9	111.1	114.3	113.6	112.5	114.9	113.1	113.5	5.6
241	135.7	98.6	11.2	std	106.8	115.1	118.8	114.1	113.6	115.9	115.3	115.5	8.7
242	133.8	74.7	11.2	std	106.0	111.6	114.3	112.9	111.5	114.2	112.3	113.0	7.0
243	119.6	56.3	10.2	std	105.3	106.3	109.5	109.5	110.3	110.9	109.2	109.6	4.3
244	156.4	117.8	12.5	std	104.6	116.9	119.0	116.3	116.9	117.9	114.7	117.2	12.6
245	137.5	100.0	11.1	std	104.3	113.6	117.2	113.7	114.6	115.7	115.0	115.1	10.8
246	137.3	41.8	11.6	unew6	104.0	114.2	115.8	117.2	116.5	116.6	114.0	116.1	12.0
247	136.3	41.7	12.1	uold6	103.9	119.6	121.9	122.3	123.0	123.6	121.7	122.3	18.4
248	128.0	32.2	11.5	unew6	103.9	110.2	111.4	112.1	112.5	111.9	109.0	111.5	7.7
249	134.1	98.0	11.3	std	104.3	115.4	119.0	114.4	114.5	117.7	115.5	116.2	11.9
250	150.2	114.9	12.4	std	105.3	118.3	120.5	116.6	117.1	118.5	115.6	117.9	12.6
251	156.1	119.4	13.0	std	105.8	116.9	118.9	116.4	116.9	118.2	114.9	117.2	11.4
252	156.0	76.3	12.5	std	107.5	113.9	115.1	113.9	112.7	116.0	112.7	114.2	6.7
253	173.6	32.5	13.7	uold6	109.2	115.9	116.3	116.4	116.2	115.8	113.4	115.9	6.7
254	150.1	27.5	12.9	std	109.6	108.3	108.6	108.1	107.8	107.9	108.7	108.2	-1.5
255	122.8	19.1	11.7	uold6	109.6	110.0	110.5	110.4	110.1	109.9	108.9	110.1	0.4
256	144.1	75.3	11.9	std	109.8	113.4	114.9	113.1	112.9	115.2	112.8	113.8	4.1
257	127.3	20.7	11.1	unew6	108.5	107.1	108.2	107.9	107.9	108.1	108.0	107.9	-0.6
258	123.0	10.5	11.3	unew6	107.6	106.5	107.3	107.4	107.3	107.3	106.8	107.2	-0.4
259	112.9	10.8	10.8	uold6	106.4	105.8	106.7	106.7	106.7	106.9	106.1	106.6	0.1
260	138.0	99.8	11.2	std	105.8	114.8	118.8	114.4	113.8	115.6	115.3	115.5	9.7
261	157.9	118.9	12.3	std	106.4	117.2	119.3	116.1	116.3	117.4	114.9	117.0	10.7
262	137.6	99.7	11.4	std	105.1	115.3	119.2	115.0	113.3	115.4	115.2	115.6	10.5
263	157.4	118.4	12.3	std	103.7	117.4	119.3	116.4	116.0	117.1	115.5	117.1	13.3
264	178.5	137.4	14.0	std	104.2	118.9	120.5	118.2	119.1	119.5	116.3	119.0	14.8

Table 8. Events based statistical summary of total dissolved gas saturation on Transect T1 in the exit channel at Bonneville Dam, August 25-31, 2002.

Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)					
					BON	FEP1	T1P1	T1P2	T1P3	T1P4
239	165.5	127.4	13.9	std	108.3	115.1	128.6	125.6	123.3	125.8
240	126.4	74.8	11.1	std	107.9	113.9	118.2	113.6	113.4	116.2
241	135.7	98.6	11.2	std	106.8	115.1	122.8	118.5	116.2	121.5
242	133.8	74.7	11.2	std	106.0	121.6	118.4	114.1	113.7	116.4
243	119.6	56.3	10.2	std	105.3	122.4	111.7	112.6	112.5	112.0
244	156.4	117.8	12.5	std	104.6	123.1	125.6	121.0	120.5	124.1
245	137.5	100.0	11.1	std	104.3	117.1	120.8		115.3	117.2
246	137.3	41.8	11.6	unew6	104.0	125.4	117.9		117.4	116.9
247	136.3	41.7	12.1	uold6	104.0	128.3	120.3		120.1	126.9
248	128.0	32.2	11.5	unew6	103.9	125.7	113.2		113.4	114.7
249	134.1	98.0	11.3	std	104.3	121.2	123.1		118.1	121.5
250	150.2	114.9	12.4	std	105.3	113.9	129.0		120.3	124.7
251	156.1	119.4	13.0	std	105.8	125.7	125.9		121.0	124.9
252	156.0	76.3	12.5	std	107.4	126.5	118.9		114.1	117.6
253	173.6	32.5	13.7	std	109.1	131.7	115.9		115.7	117.4
254	150.1	27.5	12.9	uold6	109.6	133.2	109.0		108.0	109.2
255	122.8	19.1	11.7	uold6	109.7	131.7	110.5		110.1	110.8
256	144.1	75.3	11.9	std	109.7	118.6	118.5		113.6	117.7
257	127.3	20.7	11.1	unew6	108.6	124.2	109.4		109.1	109.8
258	123.0	10.5	11.3	unew6	107.6	123.6	107.3		107.2	107.2
259	112.9	10.8	10.8	uold6	106.5	123.2	108.3		107.0	108.3
260	138.0	99.8	11.2	std	105.8	118.7	123.2		115.7	121.2
261	157.9	118.9	12.3	std	106.3	121.9	128.0		121.2	124.3
262	137.6	99.7	11.4	std	105.1	131.3	124.5		115.3	120.7
263	157.4	118.4	12.3	std	103.8	139.6	127.3		120.1	122.8
264	178.5	137.4	14.0	std	104.2	144.2	128.5		124.3	126.1

Table 10. Events based statistical summary of total dissolved gas saturation in the approach spillway channel at Bonneville Dam, August 25-31, 2002.							
Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	Total Dissolved Gas Saturation (%)		
					BON	FBP1	FBP2
239	165.5	127.4	13.9	std	108.3	106.9	107.4
240	126.4	74.8	11.1	std	107.9	106.6	107.2
241	135.7	98.6	11.2	std	106.8	105.7	106.1
242	133.8	74.7	11.2	std	106.0	105.0	105.4
243	119.6	56.3	10.2	std	105.3	104.3	104.7
244	156.4	117.8	12.5	std	104.6	103.4	103.9
245	137.5	100.0	11.1	std	104.3	103.2	103.6
246	137.3	41.8	11.6	unew6	104.0	103.0	103.4
247	136.3	41.7	12.1	uold6	104.0	103.1	103.4
248	128.0	32.2	11.5	unew6	103.9	102.9	103.3
249	134.1	98.0	11.3	std	104.3	103.3	103.7
250	150.2	114.9	12.4	std	105.3	104.1	104.6
251	156.1	119.4	13.0	std	105.8	104.5	105.0
252	156.0	76.3	12.5	std	107.4	106.2	106.8
253	173.6	32.5	13.7	std	109.1	107.9	108.3
254	150.1	27.5	12.9	uold6	109.6	108.5	108.9
255	122.8	19.1	11.7	uold6	109.7	108.5	108.8
256	144.1	75.3	11.9	std	109.7	108.5	109.0
257	127.3	20.7	11.1	unew6	108.6	107.6	107.9
258	123.0	10.5	11.3	unew6	107.6	106.7	106.9
259	112.9	10.8	10.8	uold6	106.5	105.9	105.9
260	138.0	99.8	11.2	std	105.8	104.7	105.2
261	157.9	118.9	12.3	std	106.3	105.0	105.6
262	137.6	99.7	11.4	std	105.1	104.3	104.7
263	157.4	118.4	12.3	std	103.8	102.7	103.1
264	178.5	137.4	14.0	std	104.2	103.1	103.5

Table 9. Events based statistical summary of total dissolved gas saturation on Transect T2 in the exit channel at Bonneville Dam, August 25-31, 2002.									
Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill+ Pattern	Total Dissolved Gas Saturation (%)				
					BON	T2P1	T2P2	T2P3	T2P4
239	165.5	127.4	13.9	std	108.3	122.2	118.4	120.7	118.7
240	126.4	74.8	11.1	std	107.9	115.3	111.4	113.1	116.0
241	135.7	98.6	11.2	std	106.8	118.1	114.7	116.7	118.4
242	133.8	74.7	11.2	std	106.0	115.7	112.3	113.3	114.7
243	119.6	56.3	10.2	std	105.3	109.7	109.5	111.3	110.2
244	156.4	117.8	12.5	std	104.6	121.0	117.0	118.1	119.6
245	137.5	100.0	11.1	std	104.3	117.4	114.1	114.9	118.0
246	137.3	41.8	11.6	unew6	104.0	119.1	118.5	117.3	117.6
247	136.3	41.7	12.1	uold6	104.0	120.2	120.4	125.4	121.7
248	128.0	32.2	11.5	unew6	103.9	113.0	112.9	115.0	113.0
249	134.1	98.0	11.3	std	104.3	118.4	115.2	116.8	119.9
250	150.2	114.9	12.4	std	105.3	122.1	118.4	118.5	120.4
251	156.1	119.4	13.0	std	105.8	121.2	116.9	118.3	120.0
252	156.0	76.3	12.5	std	107.4	116.7	111.7	114.7	115.6
253	173.6	32.5	13.7	std	109.1	115.8	115.8	119.0	116.1
254	150.1	27.5	12.9	uold6	109.6	109.4	108.7	109.1	110.0
255	122.8	19.1	11.7	uold6	109.7	109.9	110.2	111.8	109.6
256	144.1	75.3	11.9	std	109.7	116.1	111.4	114.1	114.8
257	127.3	20.7	11.1	unew6	108.6	108.8	108.9	109.7	109.0
258	123.0	10.5	11.3	unew6	107.6	107.5	107.1	107.1	107.3
259	112.9	10.8	10.8	uold6	106.5	106.4	106.5	107.1	107.1
260	138.0	99.8	11.2	std	105.8	118.1	114.5	115.1	118.6
261	157.9	118.9	12.3	std	106.3	121.2	117.9	118.4	119.3
262	137.6	99.7	11.4	std	105.1	118.7	116.0	115.3	118.6
263	157.4	118.4	12.3	std	103.8	120.4	117.9	116.3	120.0
264	178.5	137.4	14.0	std	104.2	123.0	118.2	121.2	122.4

Table 11. Statistical comparison of the paired spill events mean value.

									t-test for equality of means						
Event	Q_{total} (kcfs)	Q_{sp} (kcfs)	TWE (ft)	Spill[+] Pattern	N	Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)	Mean Diff	Std. Error Diff	95% Conf Inter of Diff	
246	137.3	41.8	11.6	unew6	23	895.2	0.488	.10178							
247	136.3	41.7	12.1	uold6	23	941.2	1.954	.40756	109.498	24.733	0.00	45.9971	0.42007	-46.86	-45.13
248	128.0	32.2	11.5	unew6	23	858.1	1.731	.36103							
253	173.6	32.5	13.7	uold6	23	882.5	0.778	.16220	-61.656	30.534	0.00	24.4029	.39579	-25.21	-23.60
255	122.8	19.1	11.7	uold6	23	837.6	0.637	.13275							
257	127.3	20.7	11.1	unew6	23	825.3	2.222	.46322	25.59	25.59	0.00	12.334	.4818	11.34	13.33
258	123.0	10.5	11.3	unew6	23	820.5	0.402	.08382							
259	112.9	10.8	10.8	uold6	23	817.1	0.161	.03359	38.388	28.889	0.00	3.4667	.0903	3.28	3.65

Table 12. Bonneville Dam spill capacity as a function of total river flow and total dissolved gas saturation in the forebay as constrained by the 120 percent criteria at Warrendale fixed monitoring station.

Qtotal (kcfs)	Bonneville Dam spillway discharge [+] (kcfs)															
	Total Dissolved Gas Saturation in the forebay of Bonneville Dam															
	105	**106**	**107**	**108**	**109**	**110**	**111**	**112**	**113**	**114**	**115**	**116**	**117**	**118**	**119**	**120**
80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80
90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140
150	147	147	146	146	146	146	146	146	145	145	145	145	144	144	144	143
160	151	151	150	150	149	149	149	148	148	147	146	146	145	144	143	142
170	155	154	154	153	153	152	151	151	150	149	148	146	145	144	142	140
180	159	158	157	157	156	155	154	153	152	150	149	147	146	144	141	138
190	163	162	161	160	159	158	156	155	154	152	150	148	146	143	140	137
200	166	165	164	163	162	160	159	157	156	154	152	149	146	143	140	135
210	170	169	167	166	165	163	161	159	157	155	153	150	147	143	139	134
220	173	172	171	169	167	166	164	162	159	157	154	151	147	143	138	132
230	177	175	174	172	170	168	166	164	161	158	155	152	148	143	138	131
240	180	178	177	175	173	171	168	166	163	160	156	153	148	143	137	129
250	183	182	180	178	175	173	171	168	165	161	158	153	149	143	136	128
260	187	185	183	180	178	176	173	170	166	163	159	154	149	143	136	126
270	190	188	185	183	181	178	175	172	168	164	160	155	150	143	135	125
280	193	191	188	186	183	180	177	174	170	166	161	156	150	143	135	124
290	196	194	191	188	186	182	179	176	172	167	162	157	151	143	134	122
300	199	196	194	191	188	185	181	177	173	169	164	158	151	143	134	121

Table 12. Bonneville Dam spill capacity as a function of total river flow and total dissolved gas saturation in the forebay as constrained by the 120 percent criteria at Warrendale fixed monitoring station.

Qtotal (kcfs)	Bonneville Dam spillway discharge + (kcfs)															
	Total Dissolved Gas Saturation in the forebay of Bonneville Dam															
	105	**106**	**107**	**108**	**109**	**110**	**111**	**112**	**113**	**114**	**115**	**116**	**117**	**118**	**119**	**120**
310	202	199	196	194	190	187	183	179	175	170	165	159	152	143	133	120
320	205	202	199	196	193	189	185	181	177	172	166	160	152	144	133	119
330	208	205	202	198	195	191	187	183	178	173	167	160	153	144	133	120
340	210	207	204	201	197	193	189	185	180	174	168	161	153	144	132	130
350	213	210	207	203	200	196	191	187	181	176	169	162	154	144	140	140
360	216	213	209	206	202	198	193	188	183	177	171	163	155	150	150	150
370	219	215	212	208	204	200	195	190	185	179	172	164	160	160	160	160
380	221	218	214	210	206	202	197	192	186	180	173	170	170	170	170	170
390	224	221	217	213	208	204	199	194	188	181	180	180	180	180	180	180
400	227	223	219	215	211	206	201	195	190	190	190	190	190	190	190	190
410	229	226	222	217	213	208	203	200	200	200	200	200	200	200	200	200
420	232	228	224	220	215	210	210	210	210	210	210	210	210	210	210	210

Entire river spilled without exceeding 120% at tailwater station.
Forced spill conditions and average TDG saturation greater than 120% assuming a powerhouse capacity of 210 kcfs
+ Barometric pressure of 760 mm Hg was assumed.

Figure 1. Columbia River and Bonneville Lock and Dam during power generation and spillway operations.

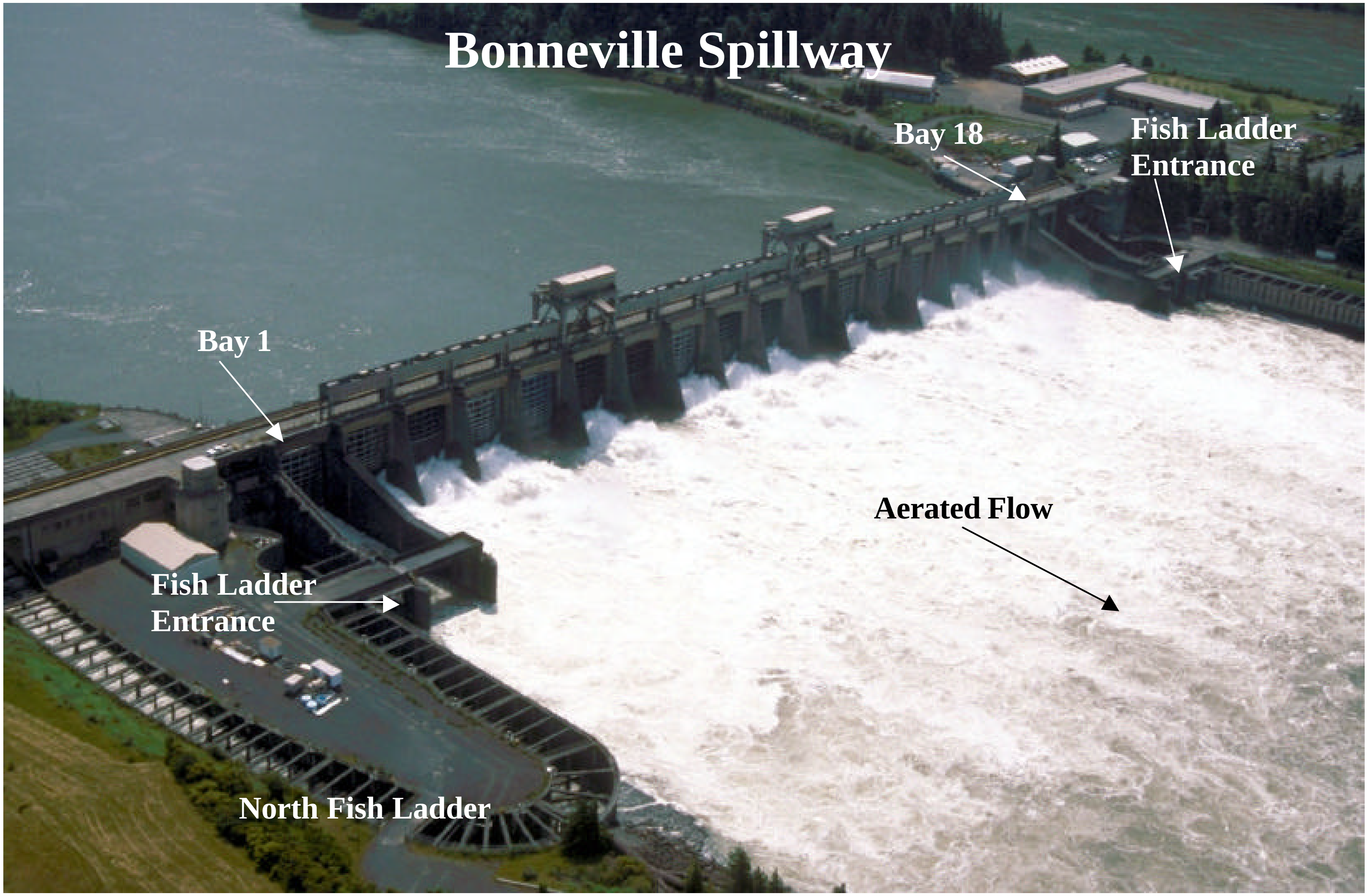

Figure 2. Bonneville Spillway and aerated flow condition

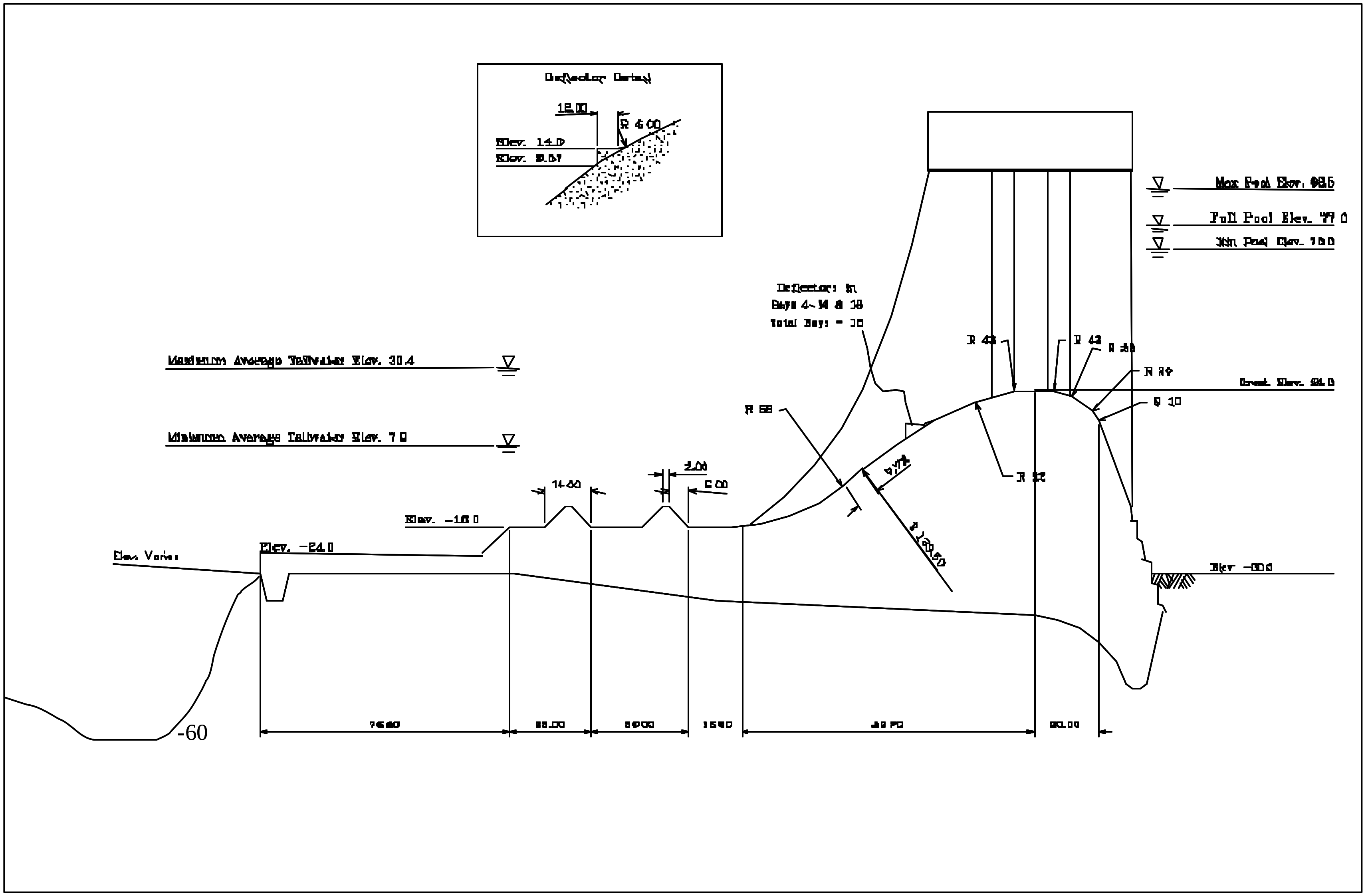

Figure 3. Profile View of Bonneville Spillway, Stilling Basin, and Tailwater Channel

Figure 4. Bonneville spillway flow deflectors in bays 4-15 at an elevation of 14 ft

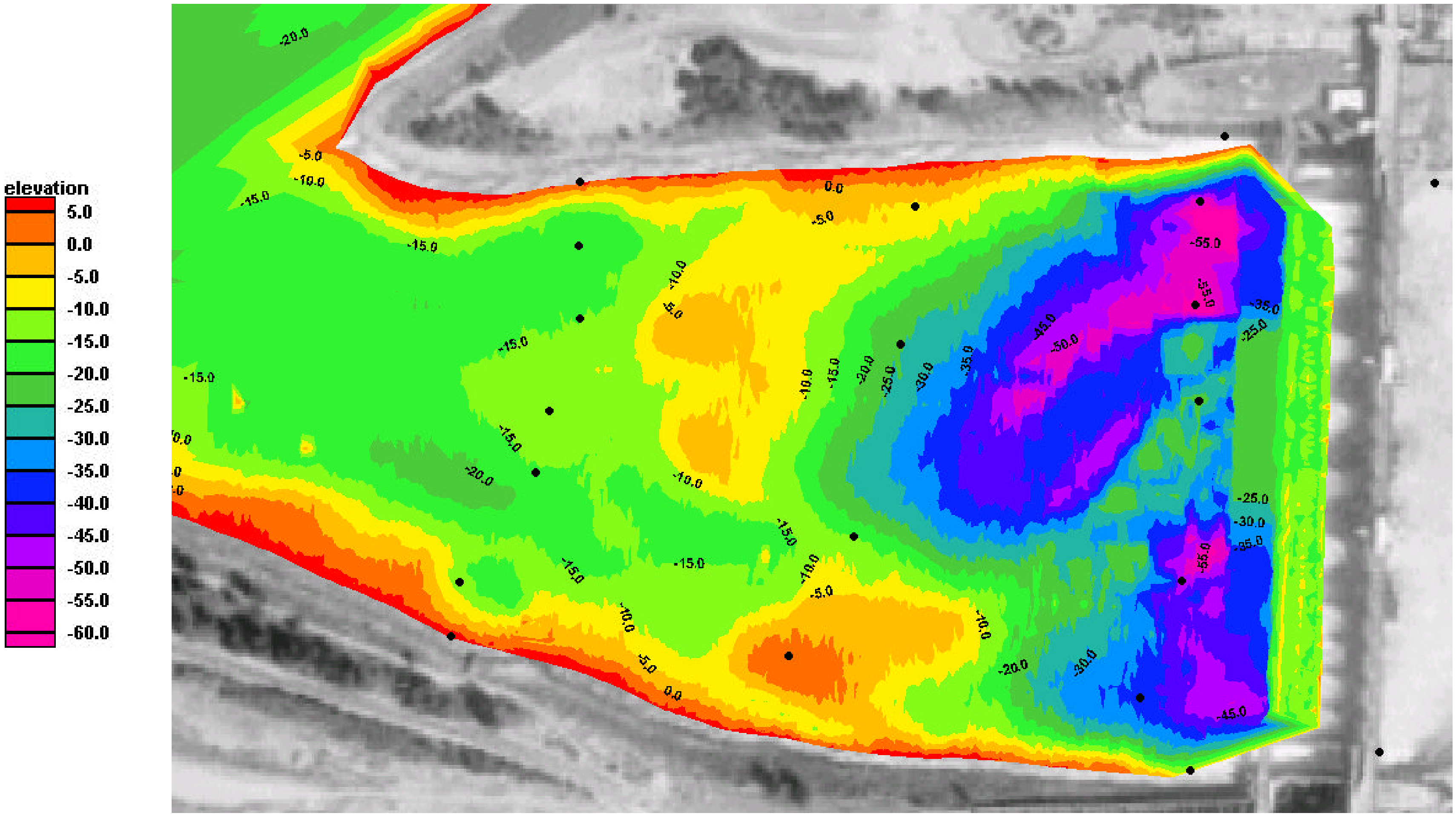

Figure 5. Bonneville spillway exit channel bed elevation contours

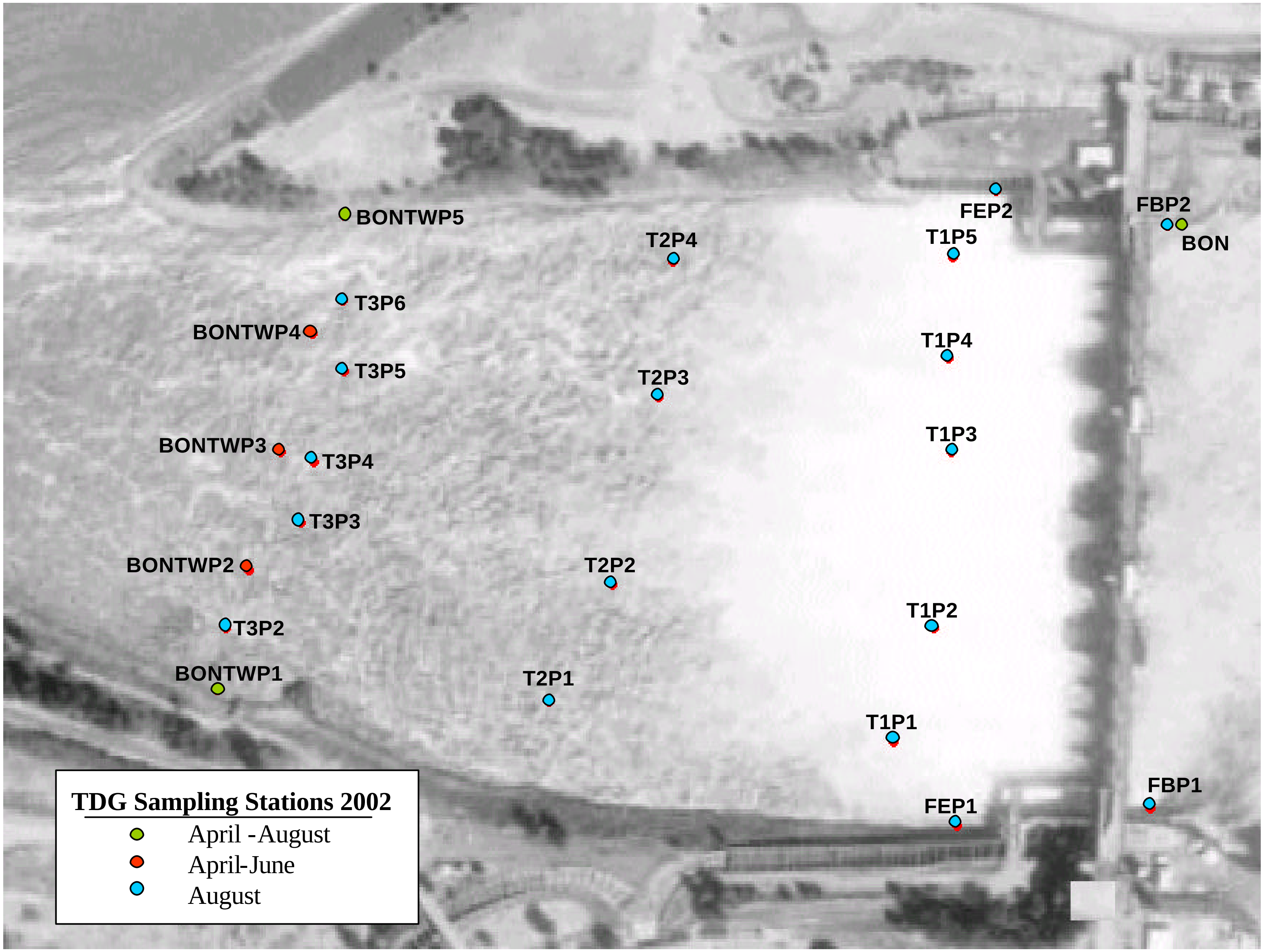

Figure 6. Total dissolved gas sampling stations in the Bonneville entrance and exit spillway channel, 2002

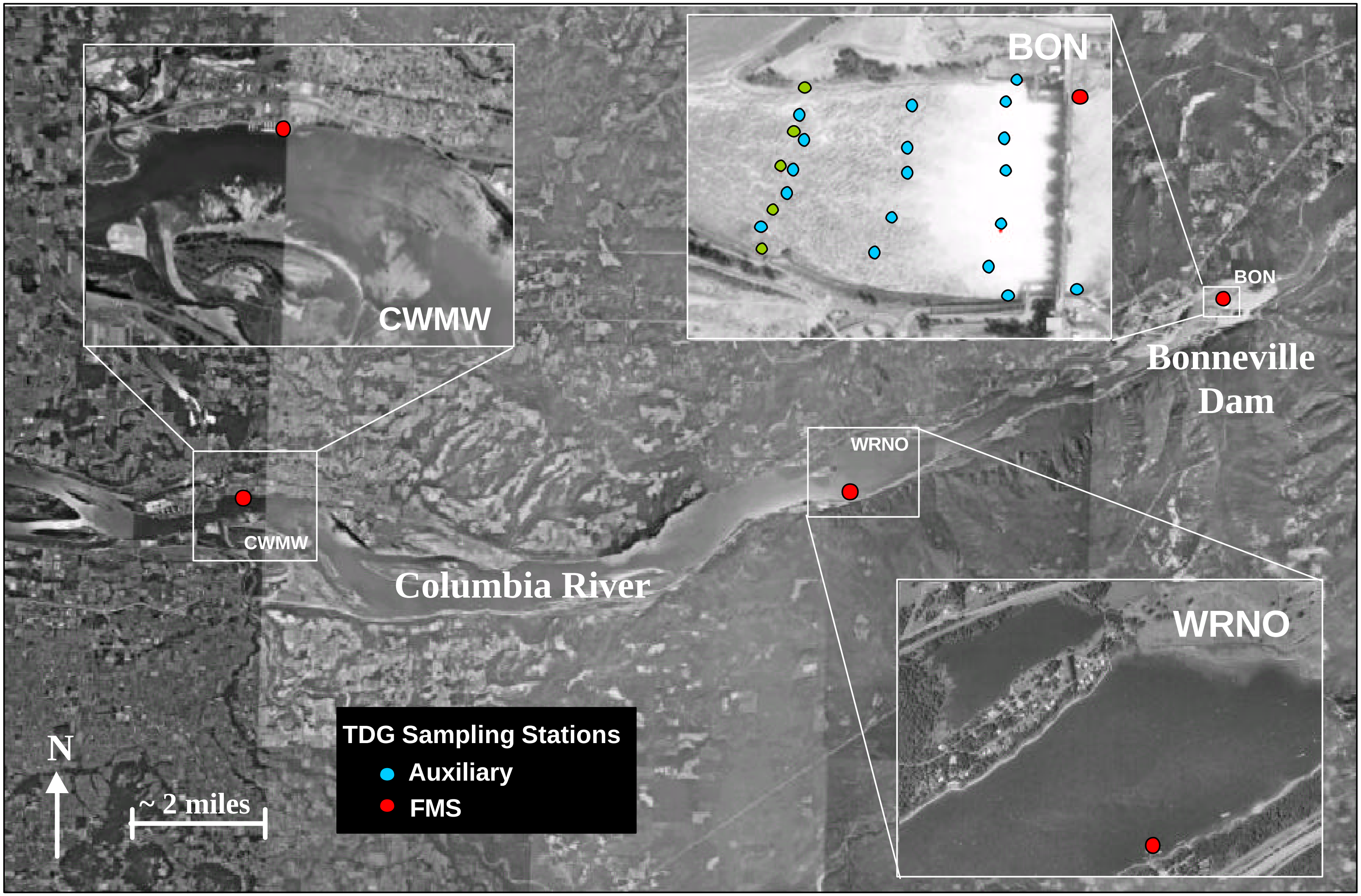

Figure 7. Total dissolved gas sampling stations upstream and downstream of Bonneville Dam, 2002

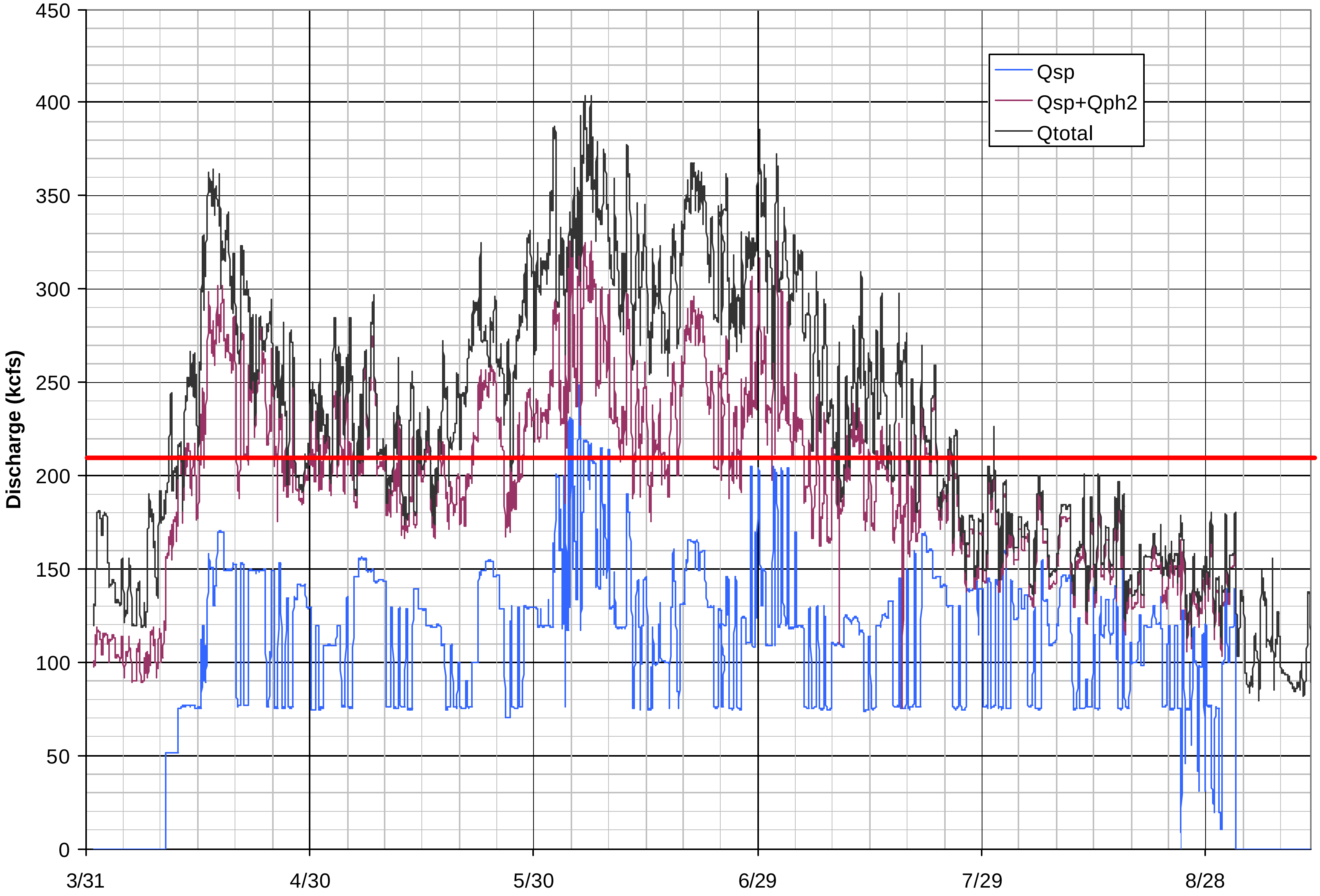

Figure 8. Bonneville Dam powerhouse, spillway, and total project flows, April-August 2002

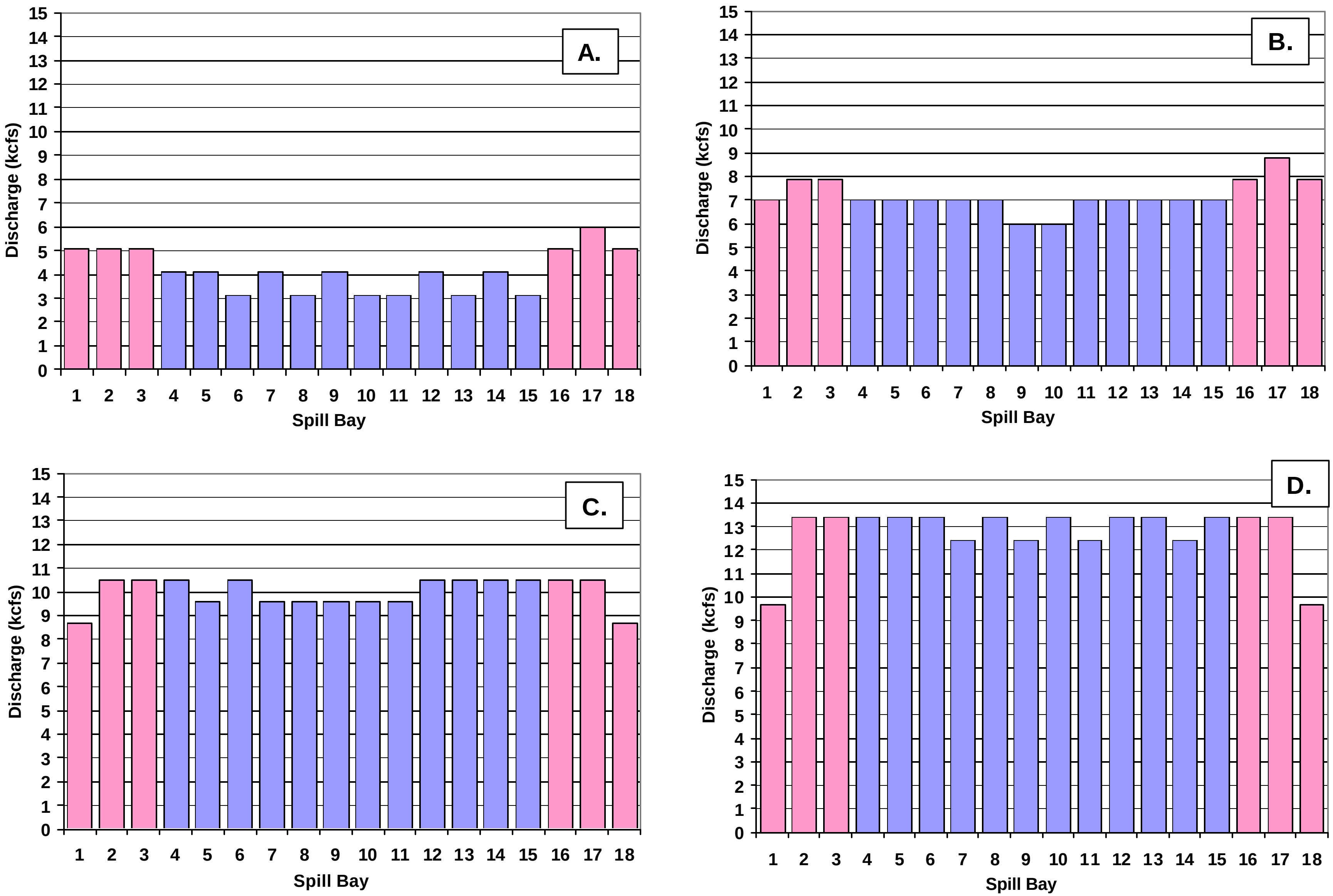

Figure 9. Bonneville Dam standard spill pattern for the 2002 fish passage season, (A=75 kcfs, B=128 kcfs, C=180 kcfs, D=230 kcfs)

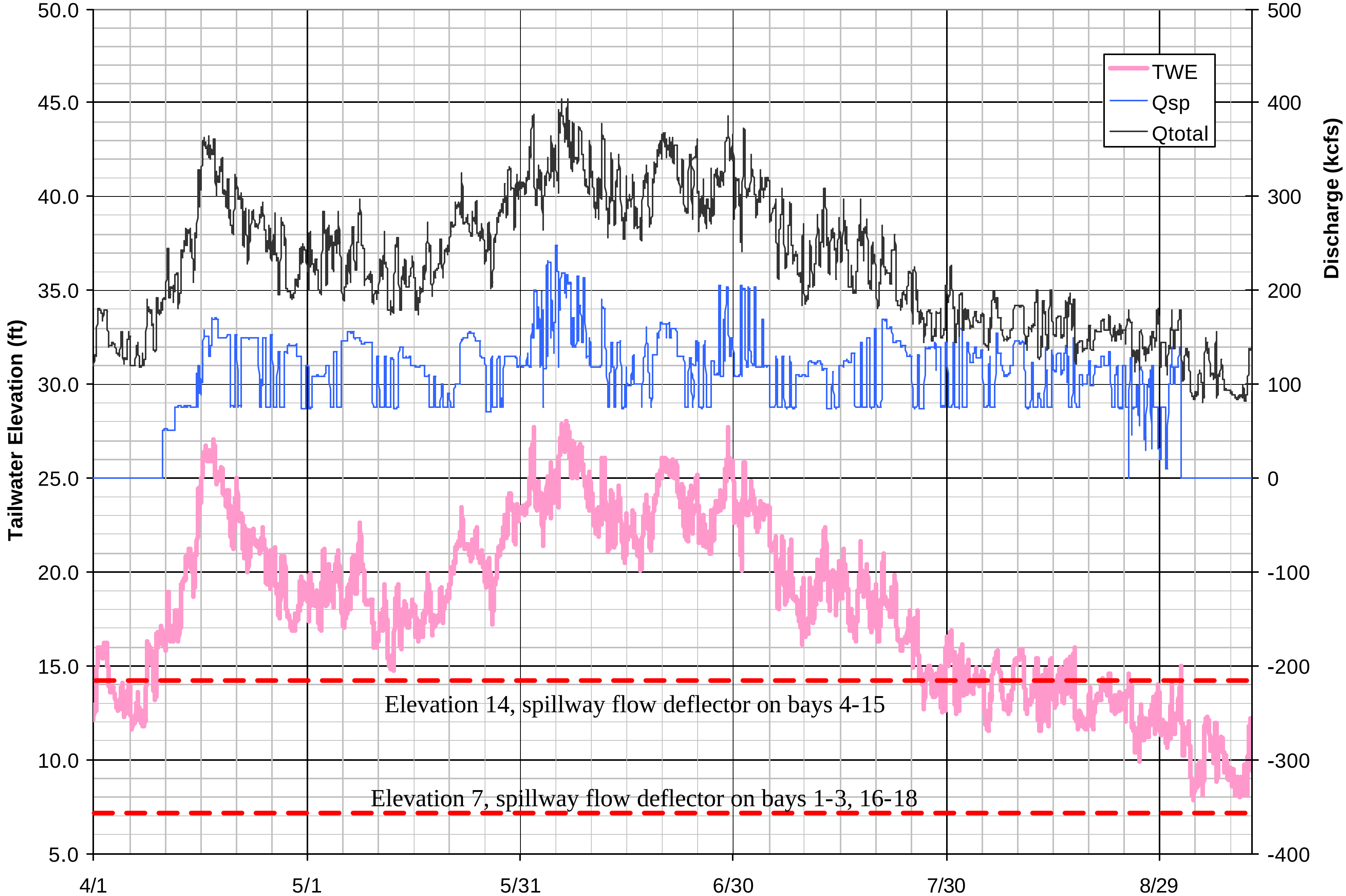

Figure 10. Bonneville Dam operations and tailwater elevation as measured at the Tanner Creek gage, April – August 2002

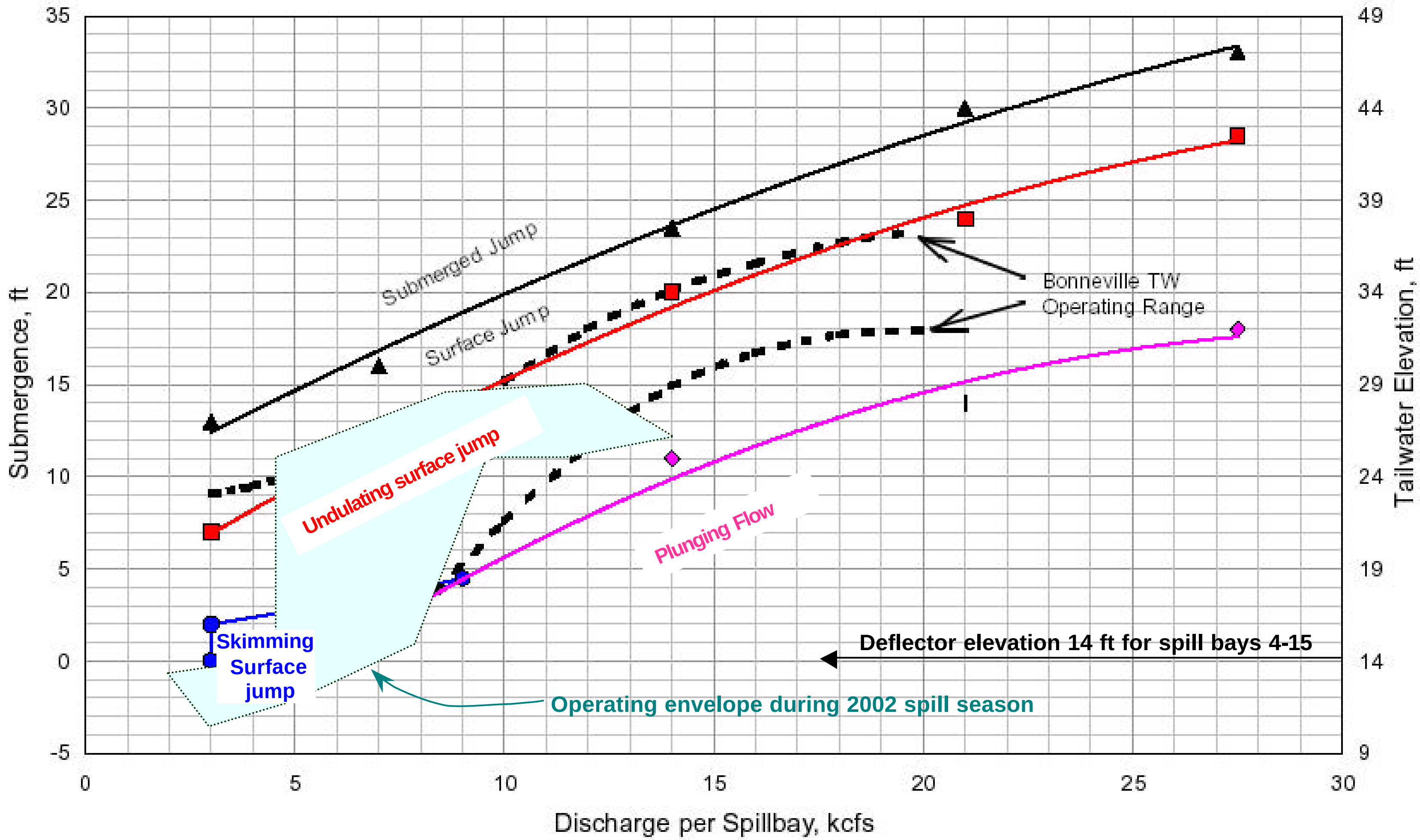

Figure 11. Performance curves, Bonneville Spillway Section Model Modified Deflector at el 14.0

Figure 12. Video clips of flow conditions on the spillway face and stilling basin, July 18, 2002. Event 166, Qspill = 75 kcfs, Tailwater elevation=17.2 ft, standard spill pattern
(click on figure to start video clip, requires file named bon11proc.avi)

Figure 13. Video clips of flow conditions just downstream of the stilling basin in the spillway exit channel, July 18, 2002. Ev ent 166, Qspill = 75 kcfs, Tailwater elevation=17.2 ft, standard spill pattern
(click on figure to start video clip, requires file named bon2proc.avi)

Figure 14. Video clips of flow conditions near the exit of the s pillway exit channel, July 18, 2002. Event 166, Qspill = 75 kcfs, Tailwater elevation=17.2 ft, standard spill pattern
(click on figure to start video clip, requires file named bon8proc.avi)

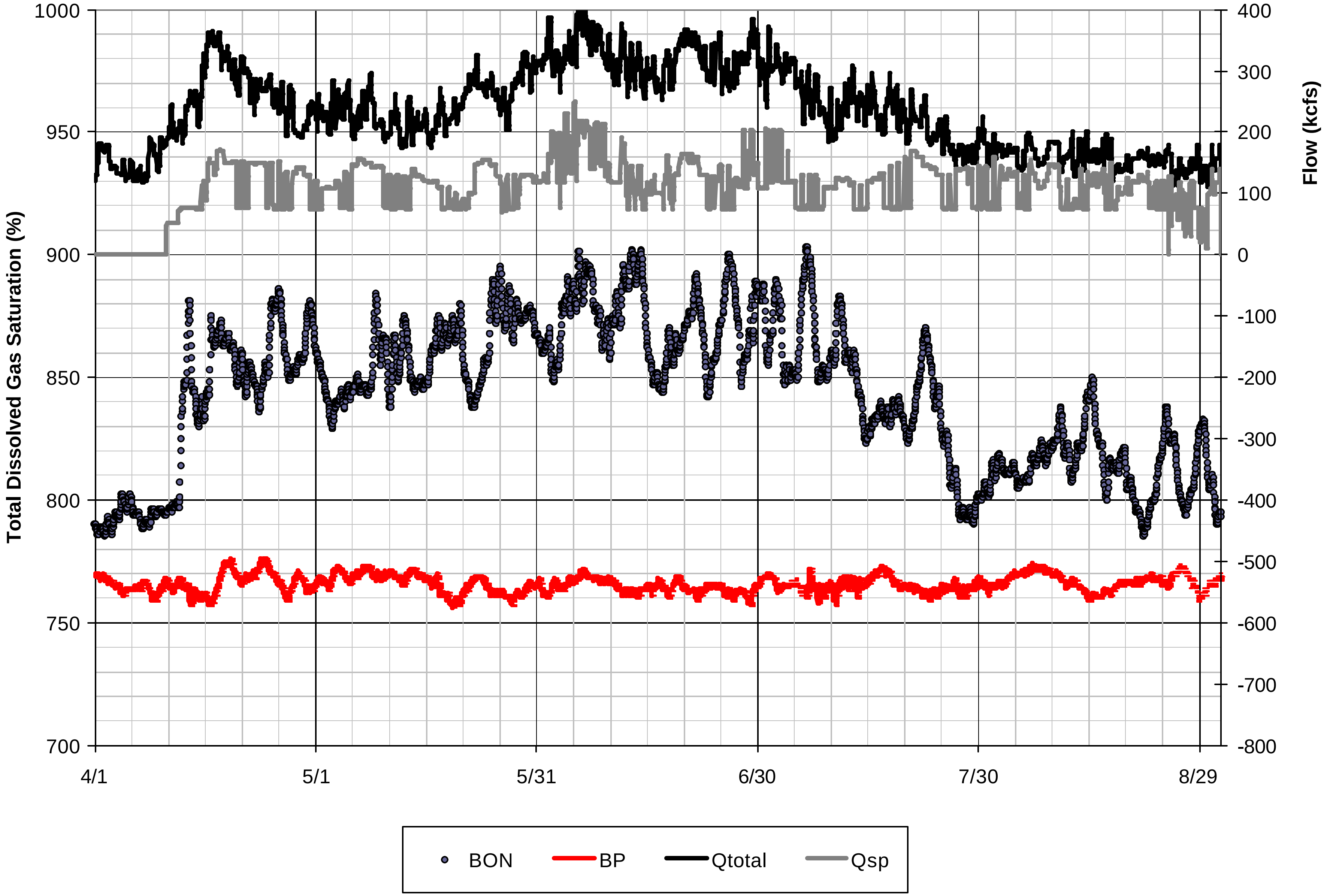

Figure 15. Project operations, forebay total dissolved gas pressure and barometric pressure at the Warrendale fixed monitoring station, April-August 2002

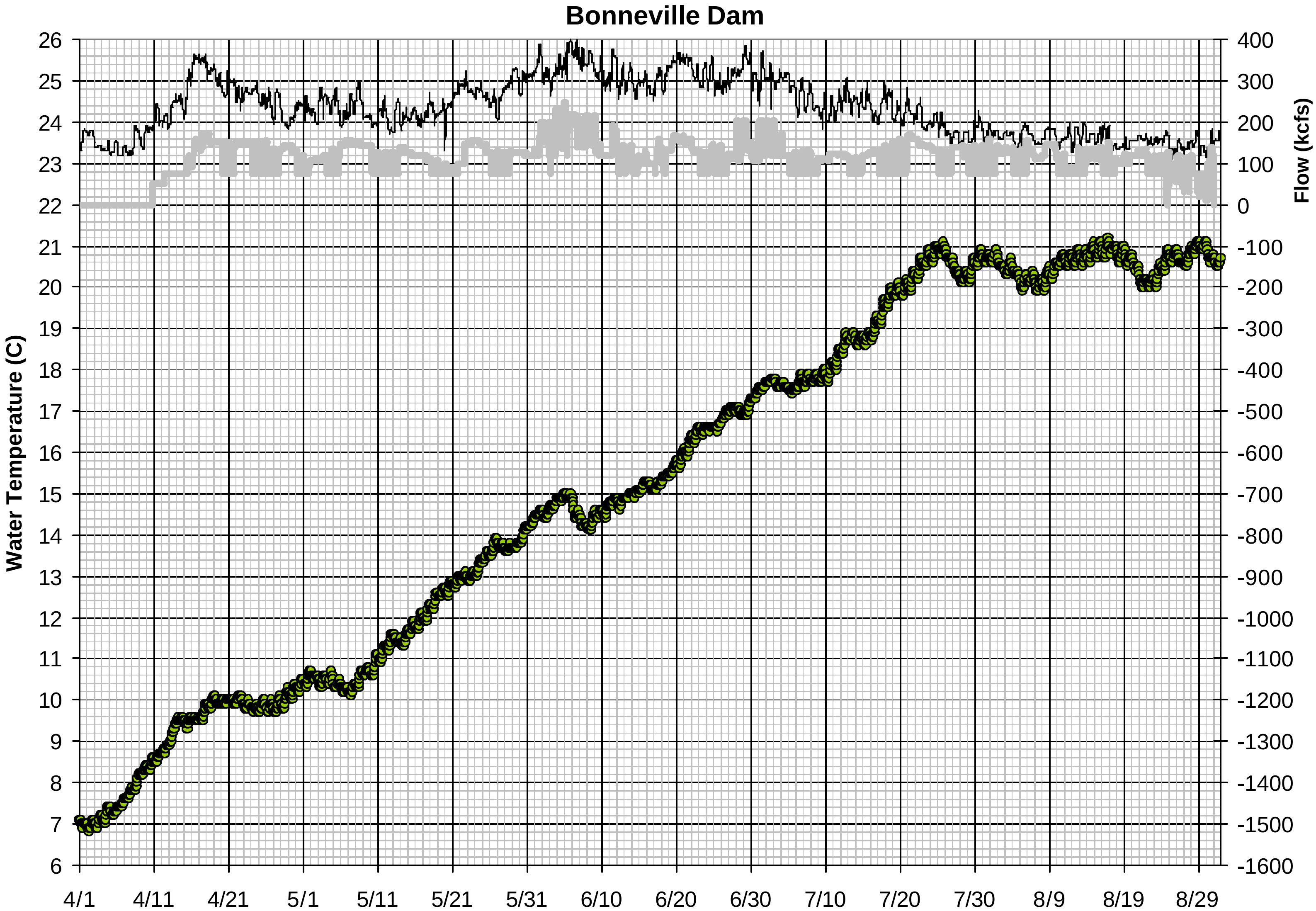

Figure 16. Hourly water temperatures in the forebay (BON) of Bonneville Dam, April 1-August 31, 2002

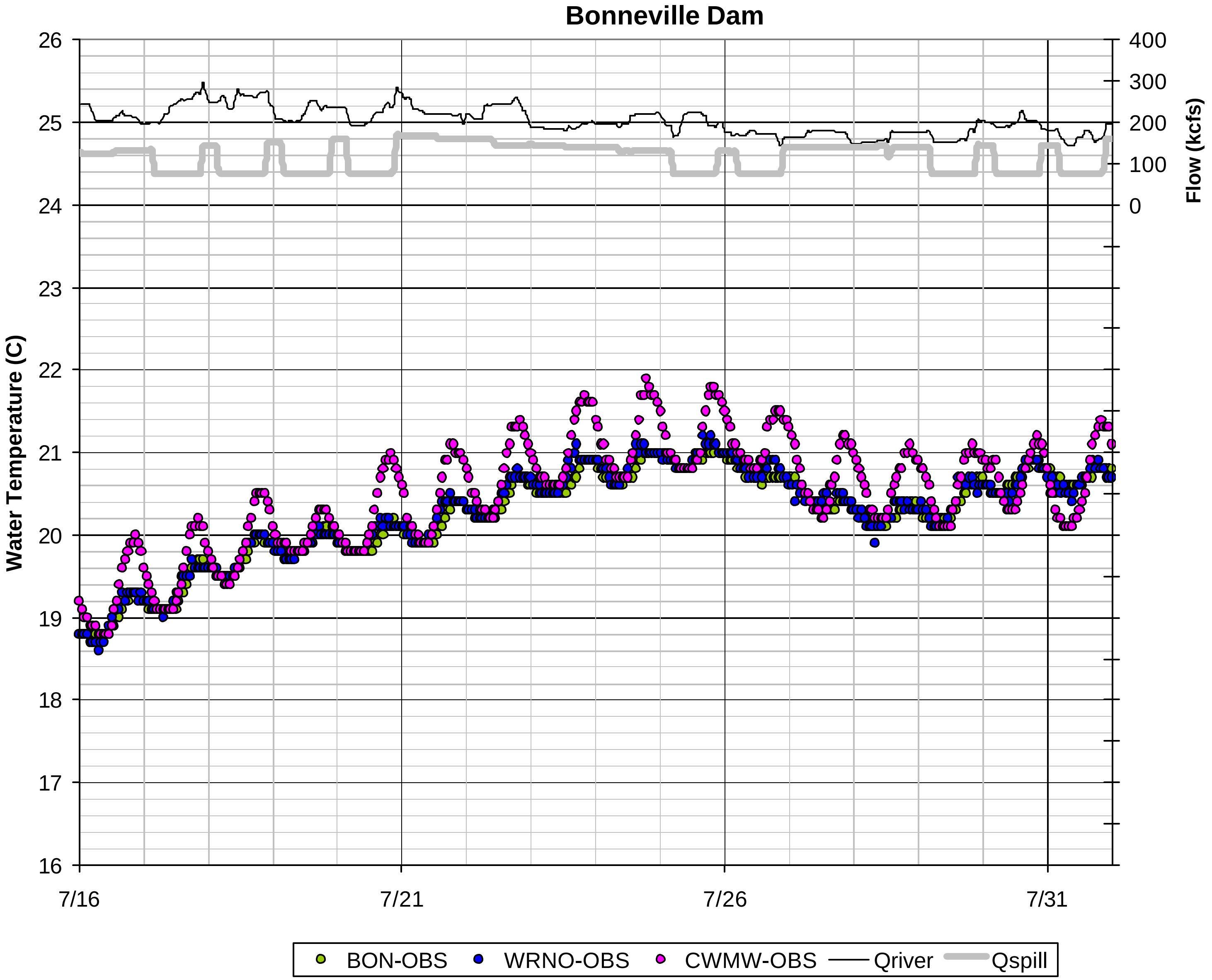

Figure 17. Hourly water temperatures in the forebay of Bonneville Dam (BON), at the tailwater station (WRNO), and downstream at Camas/Washougal (CWMW), July 16- 31, 2002

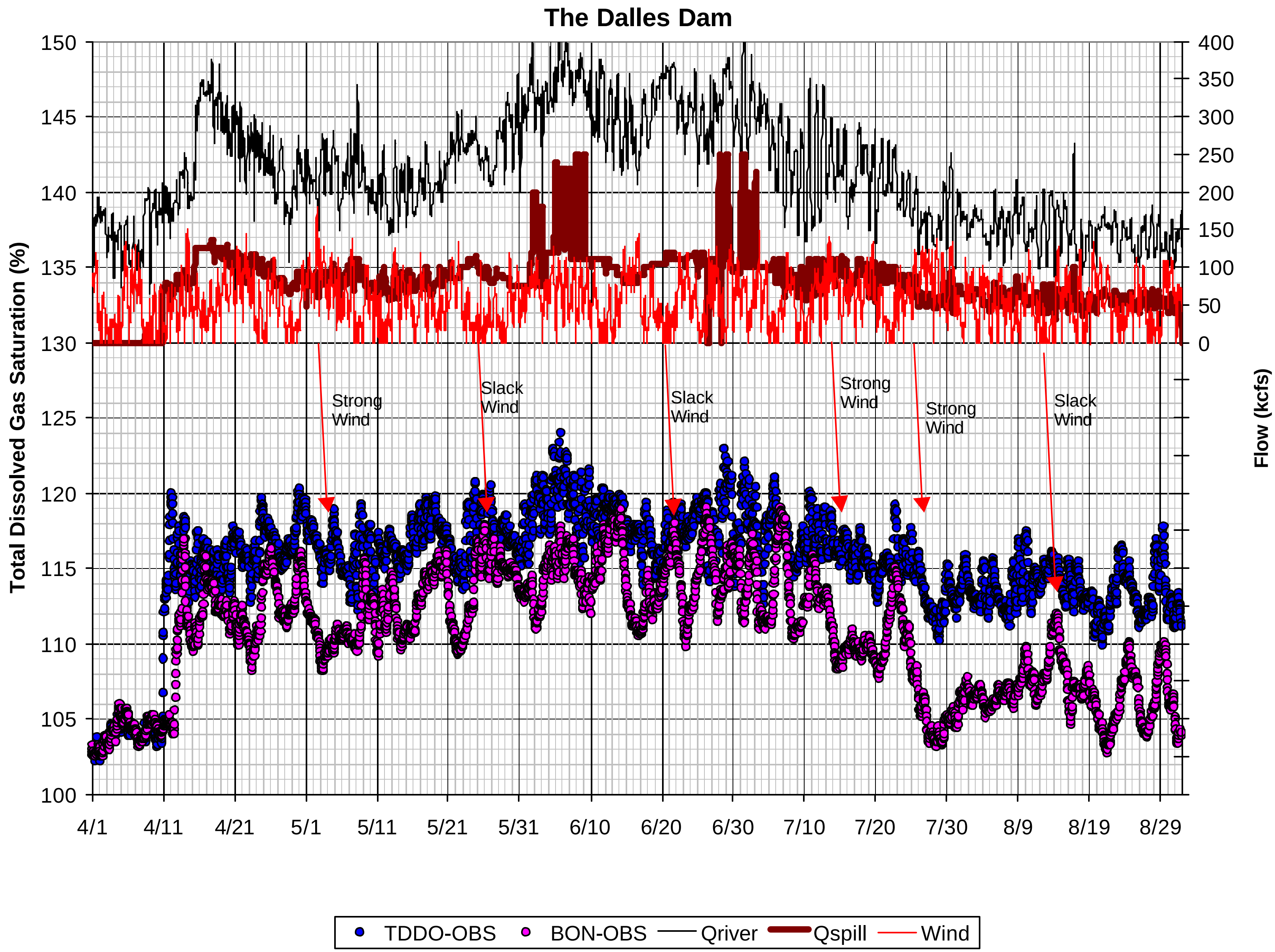

Figure 18. Hourly summary of The Dalles Dam operation, total dissolved gas saturation at The Dalles tailwater FMS (TDDO) and Bonneville forebay (BON), and wind speed at The Dalles Airport, April-August, 2002 (note: wind speed in mps x 10 on flow axis)

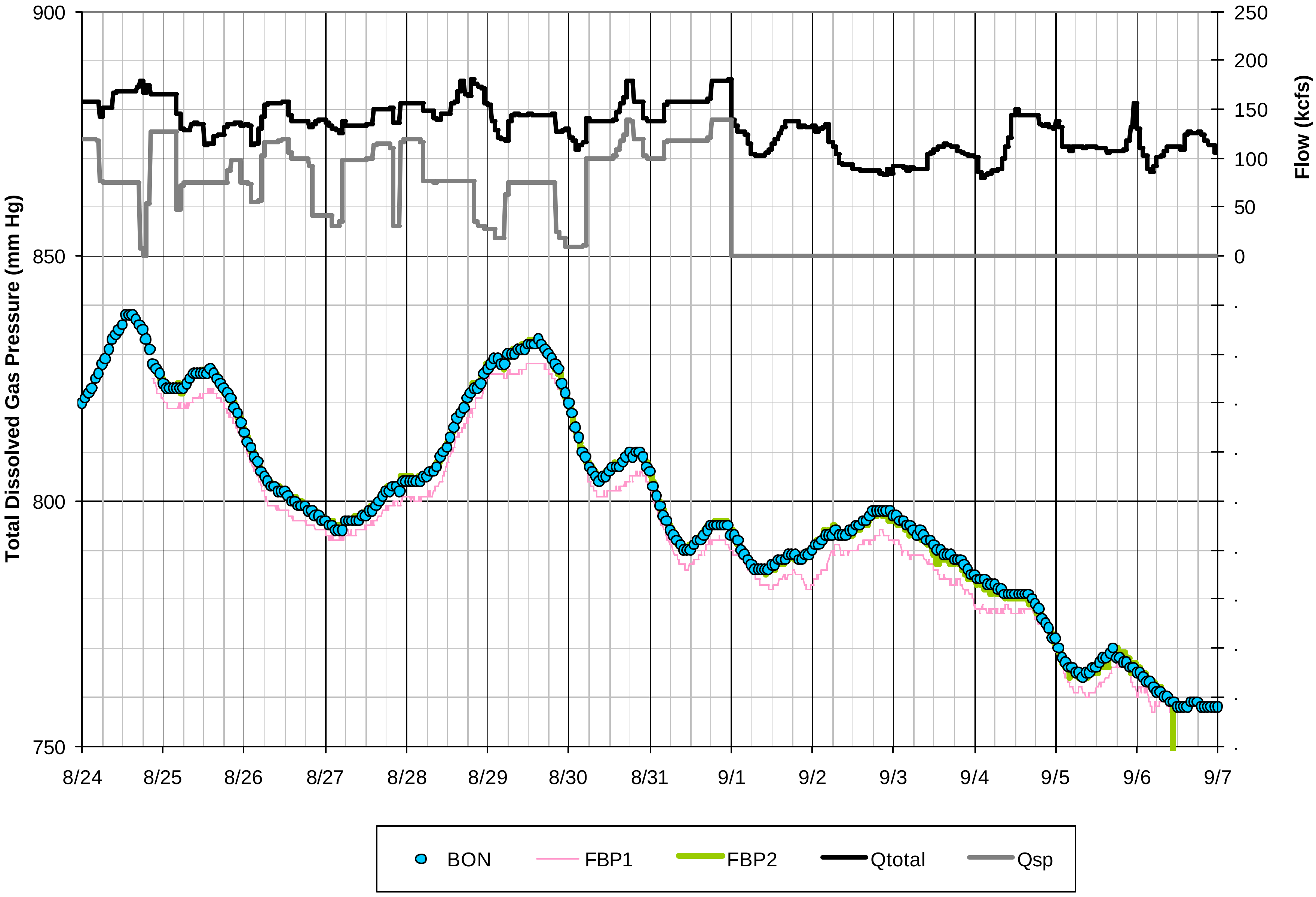

Figure 19. Total dissolved gas pressure in the upstream approach channel to the spillway at Bonneville Dam, August 24-September 6, 2002

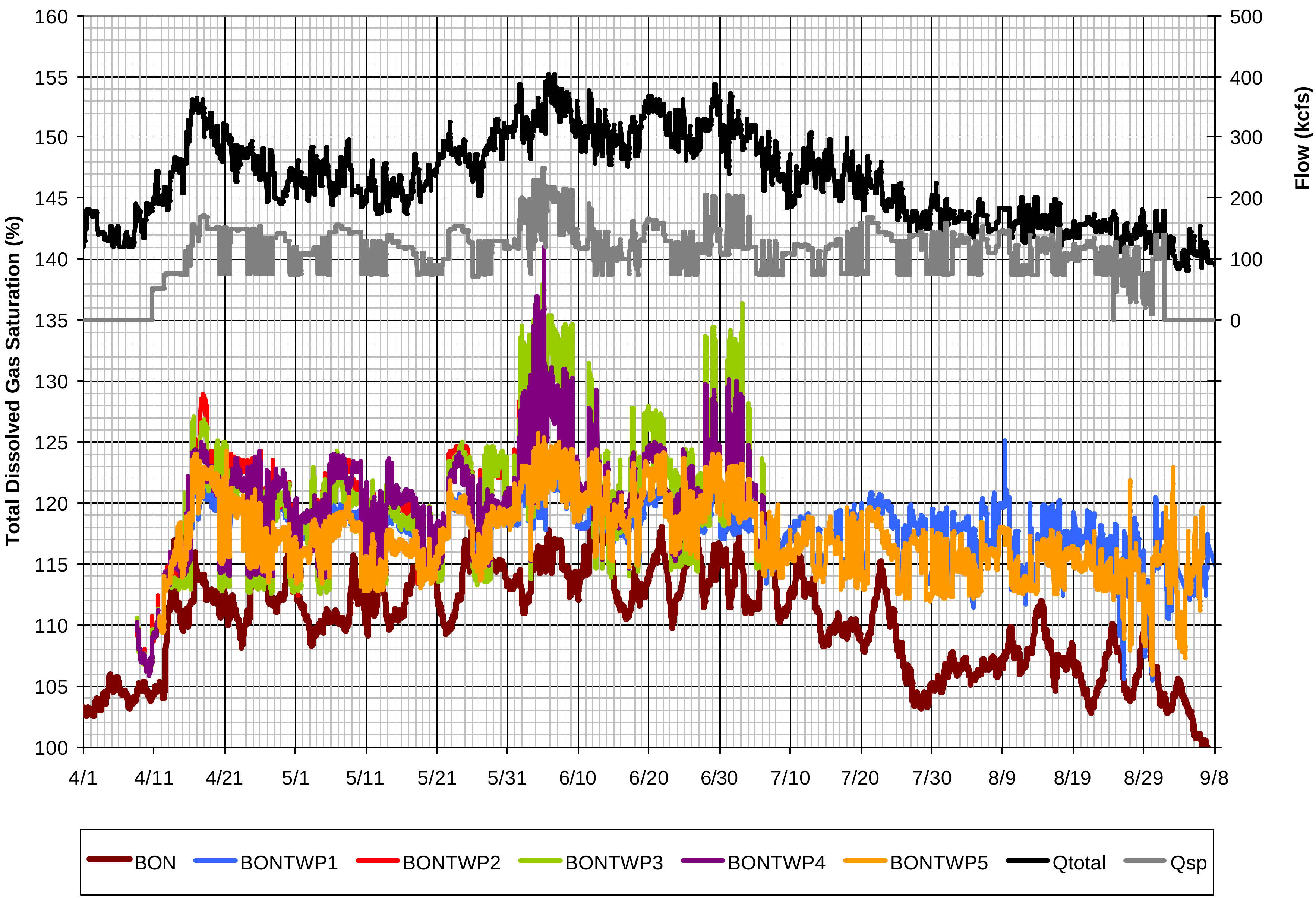

Figure 20. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, 2002

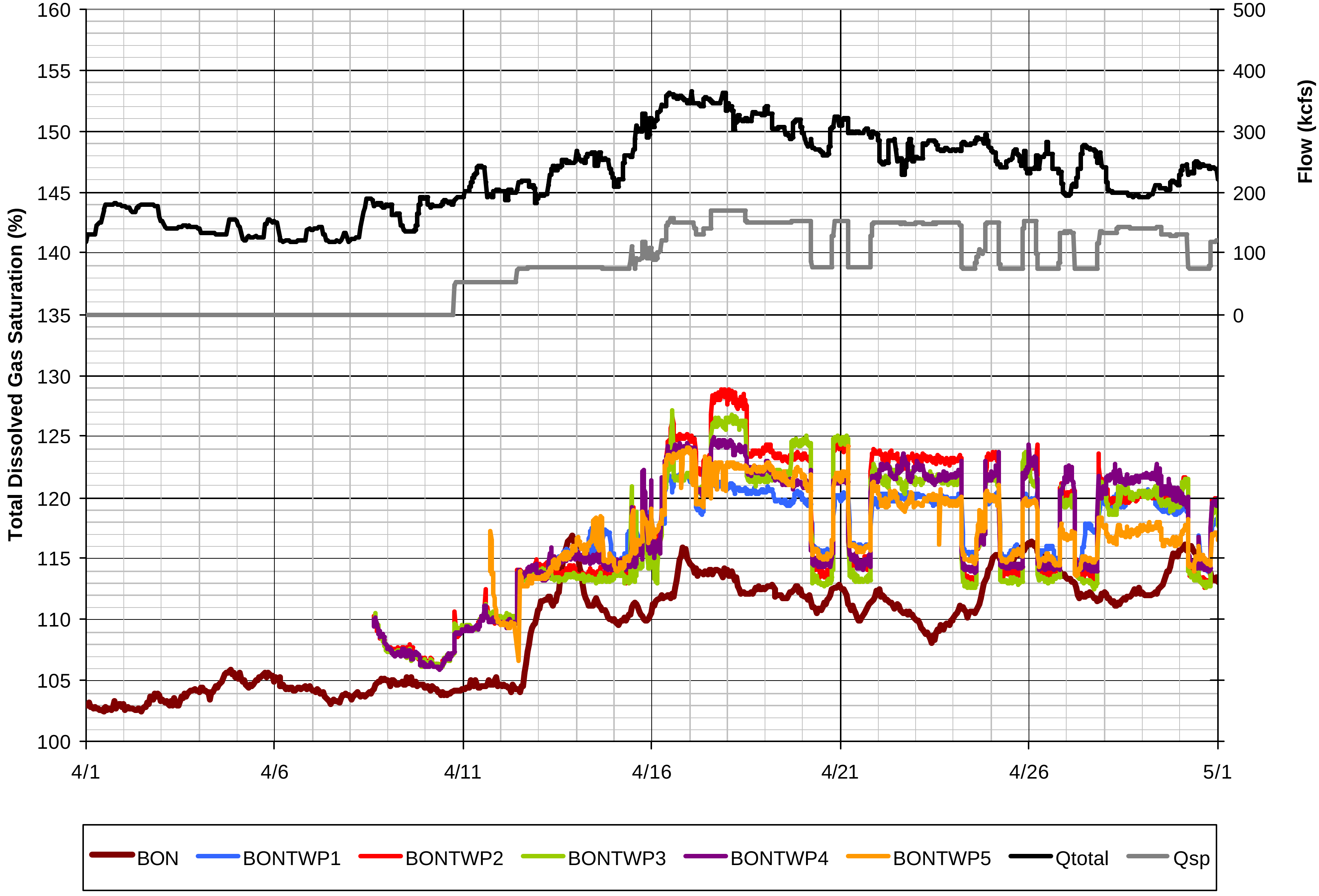

Figure 20a. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, April 2002

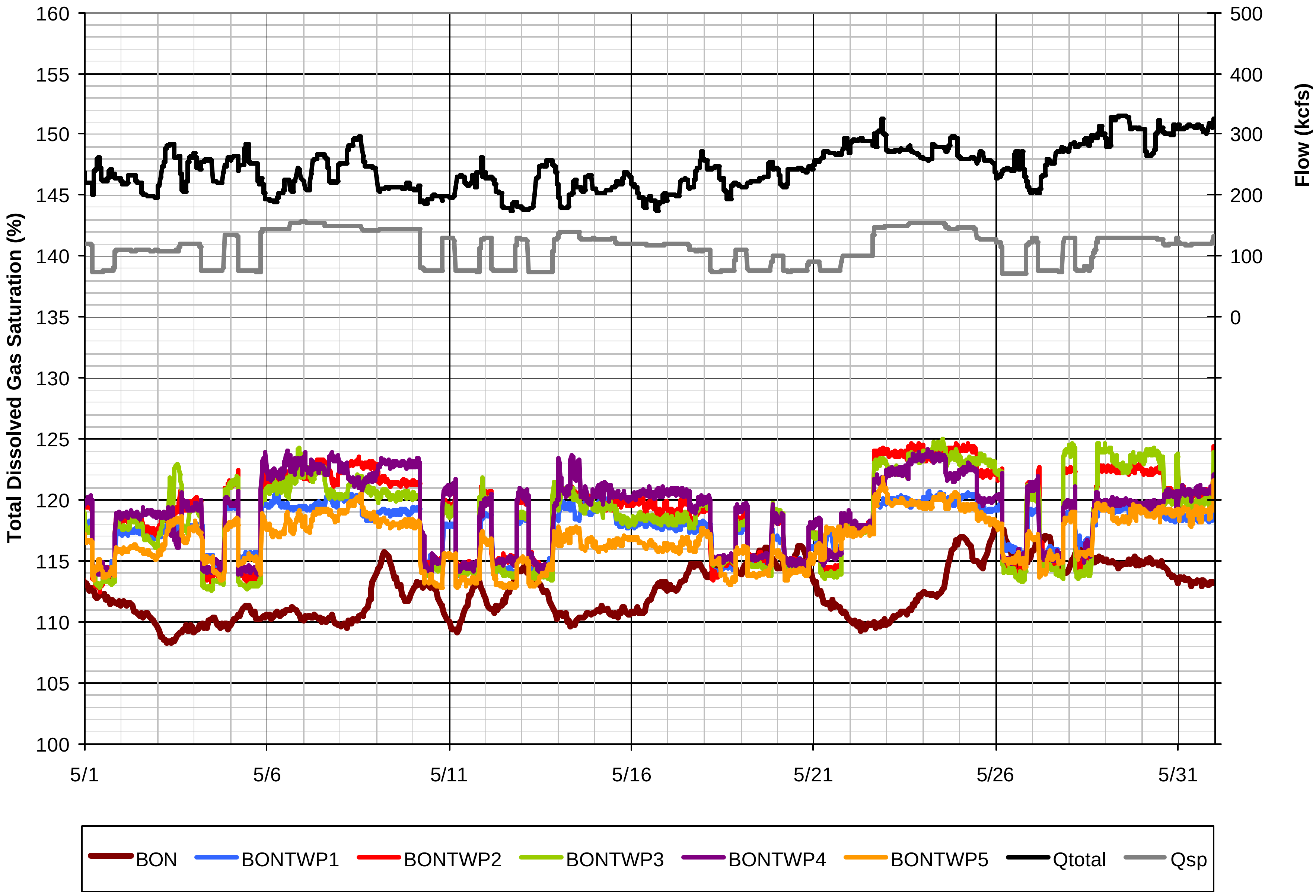

Figure 20b. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, May 2002

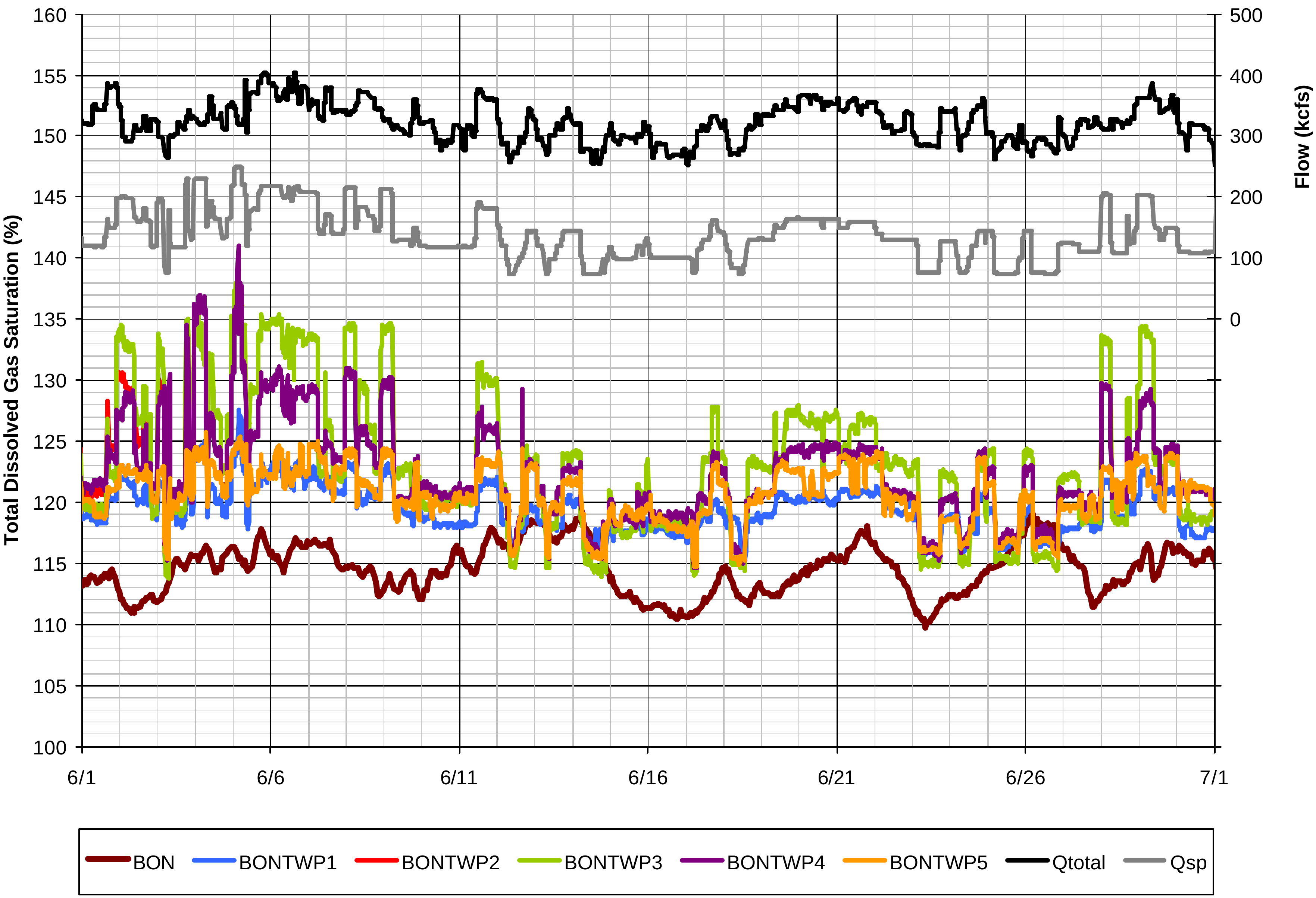

Figure 20c. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 2002

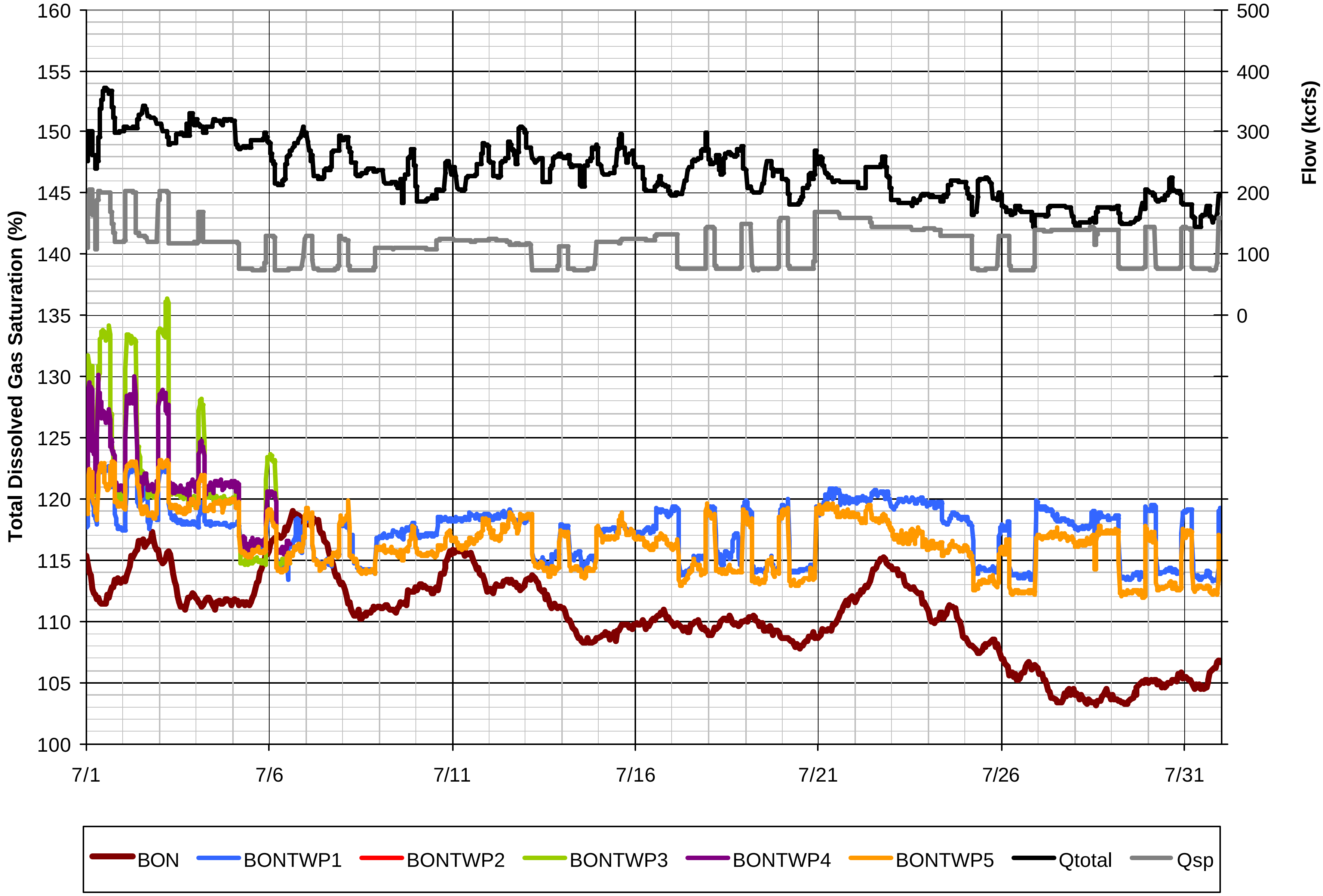

Figure 20d. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, July 2002

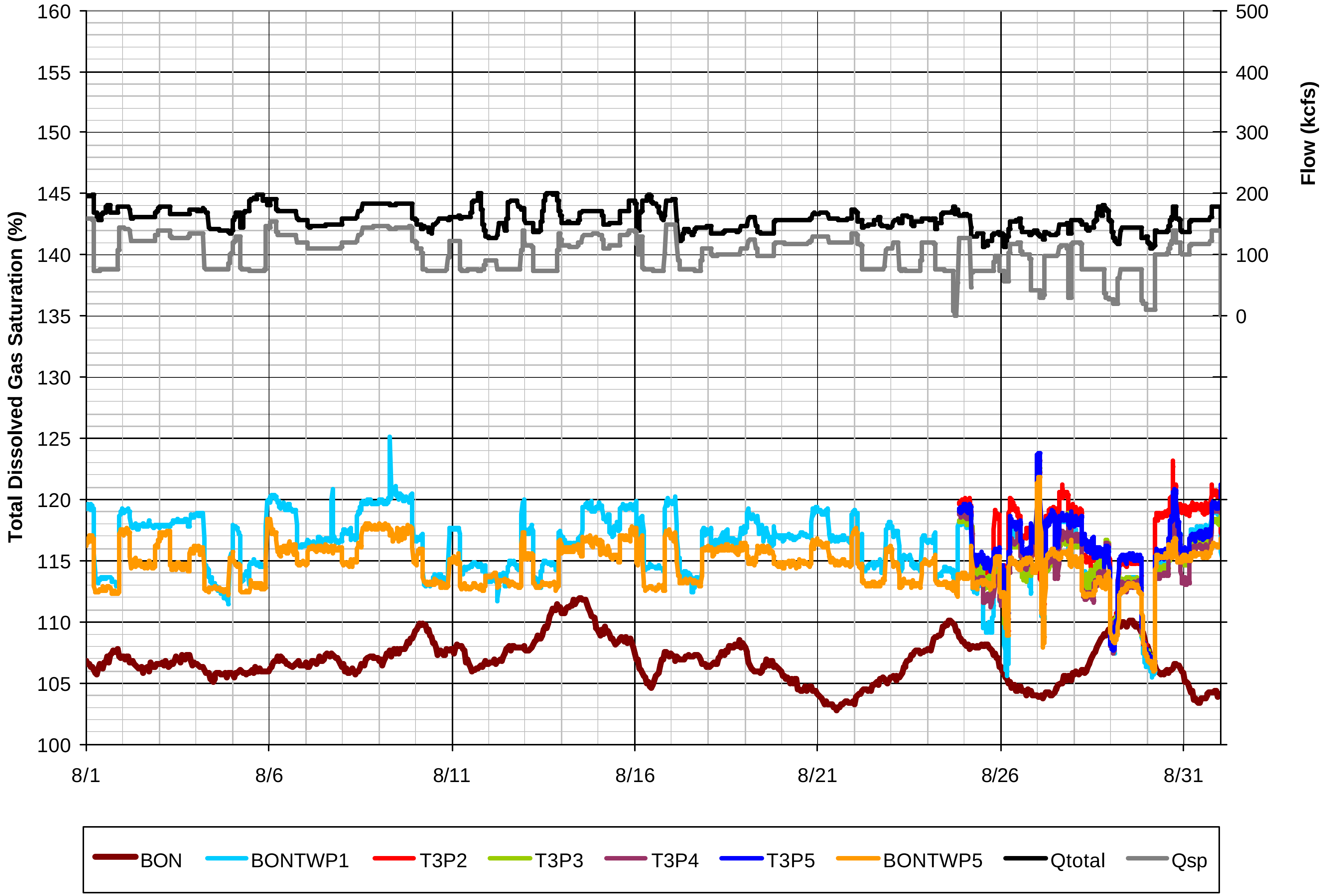

Figure 20e. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 2002

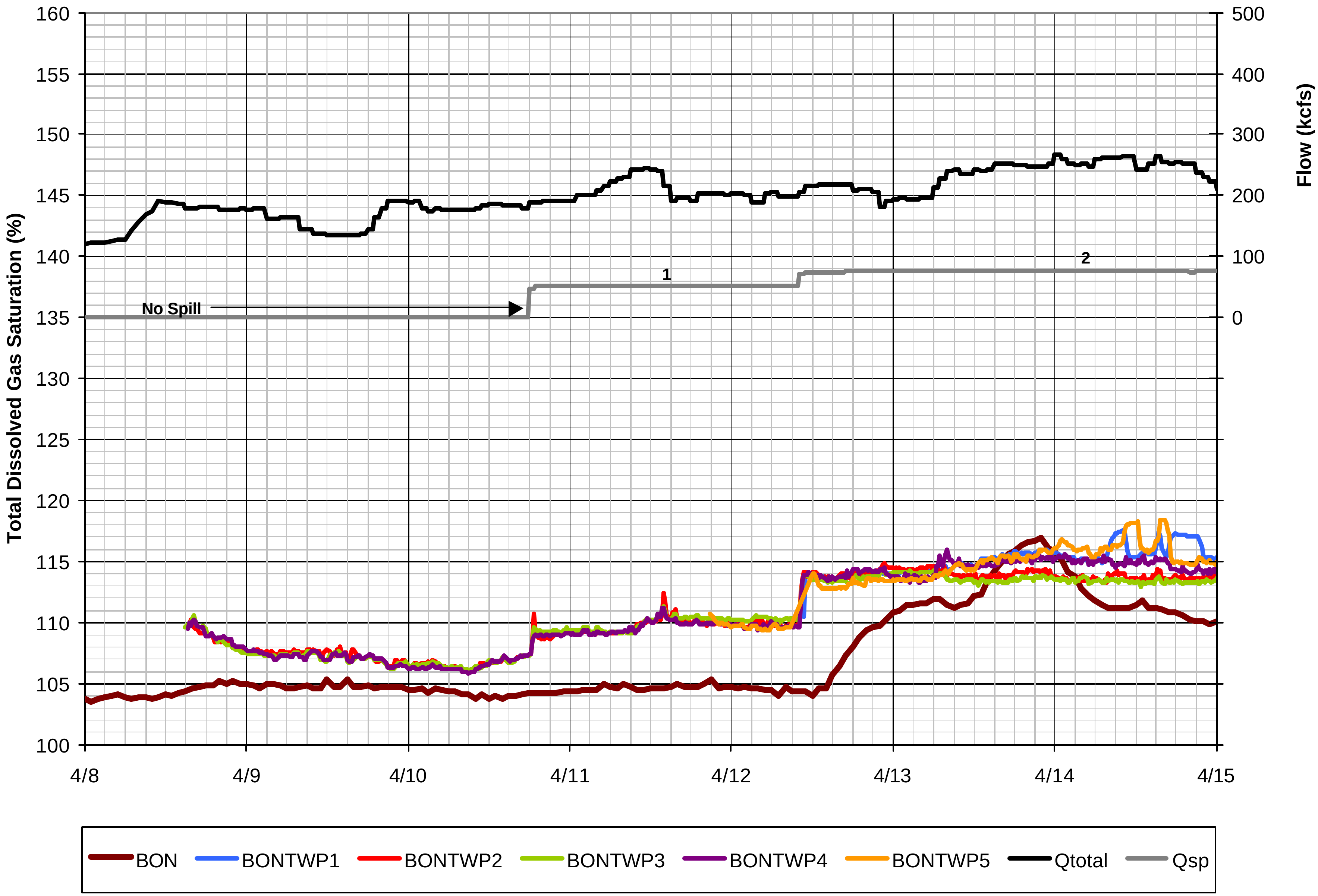

Figure 20f. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, April 8-14 2002

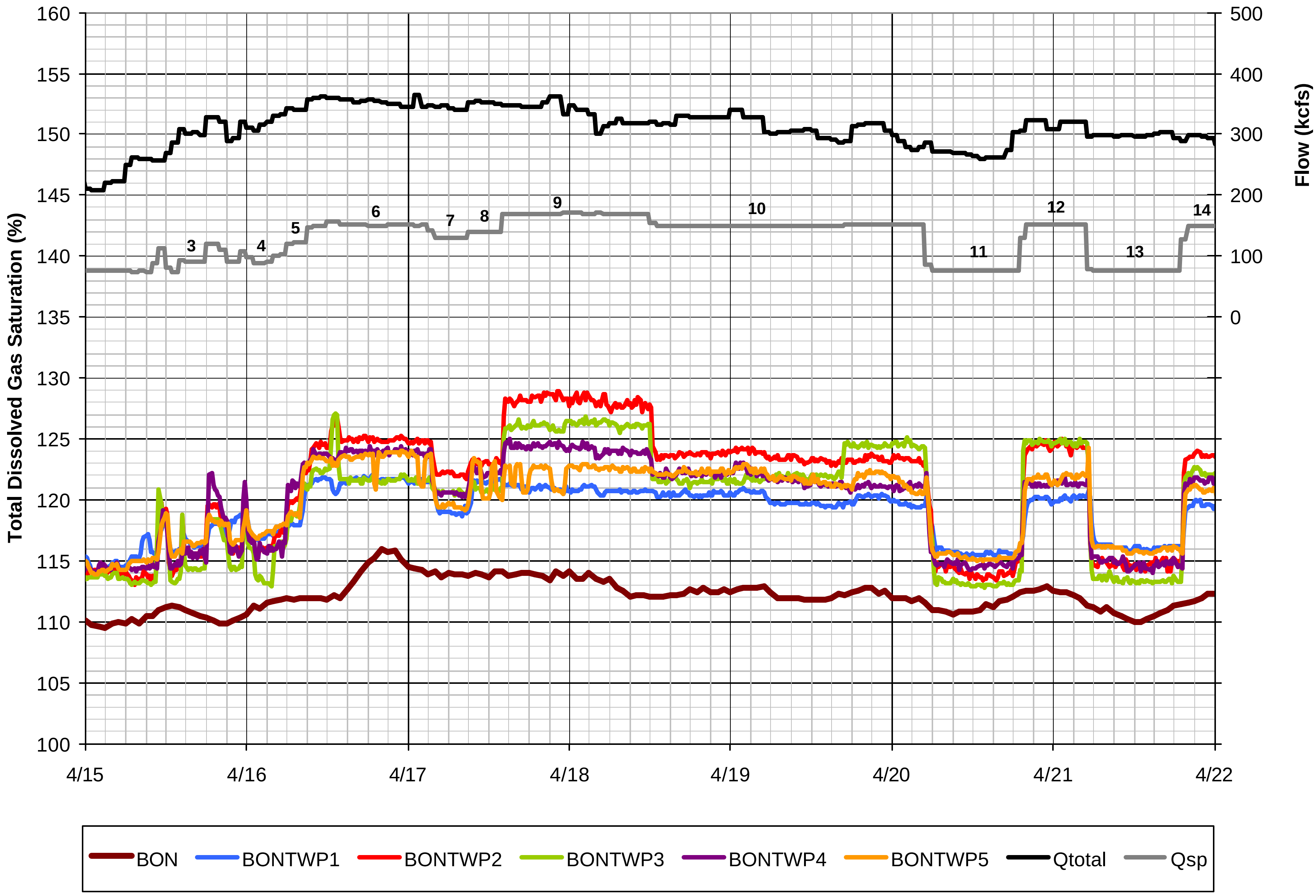

Figure 20g. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, April 15-21 2002

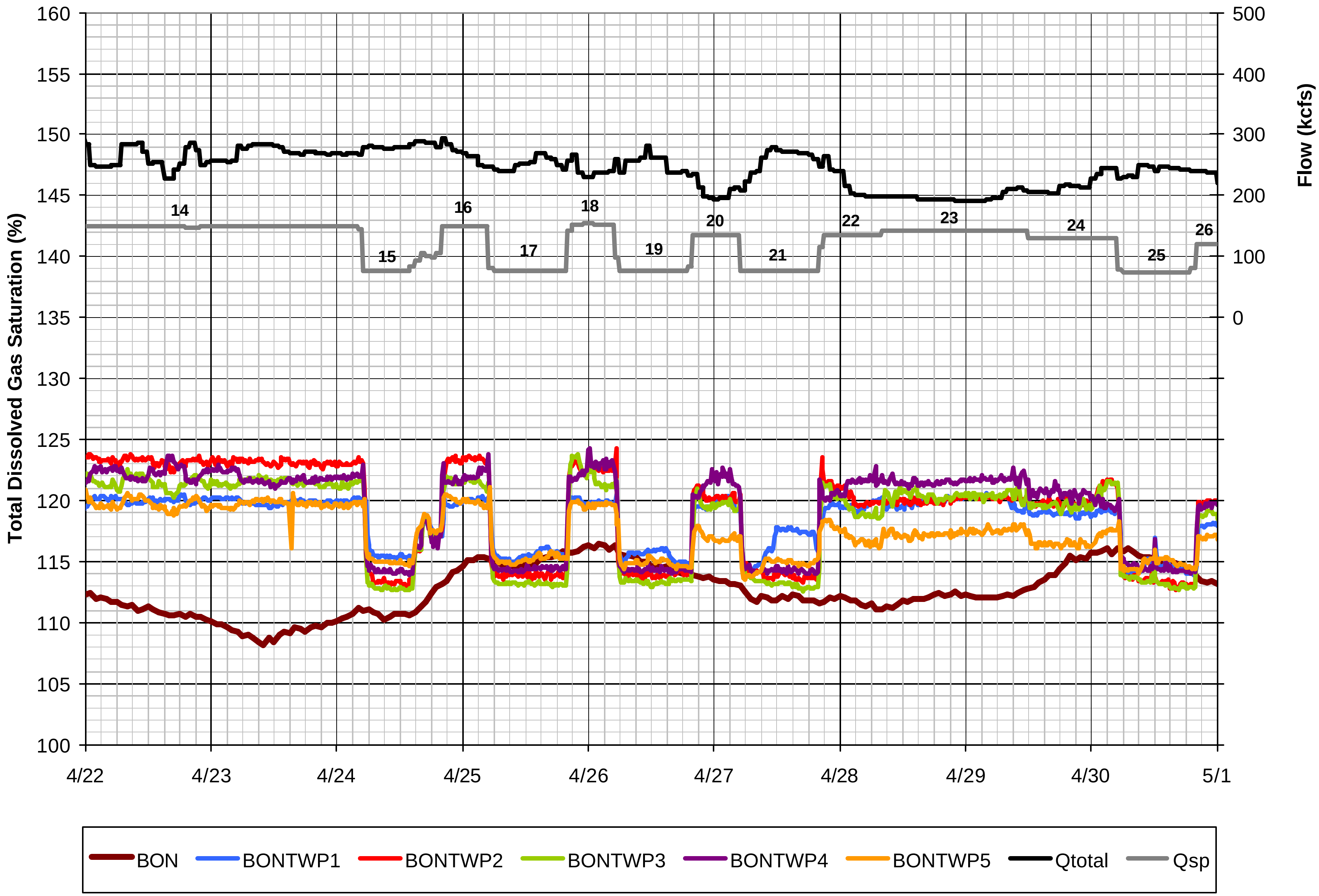

Figure 20h. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, April 22-30, 2002

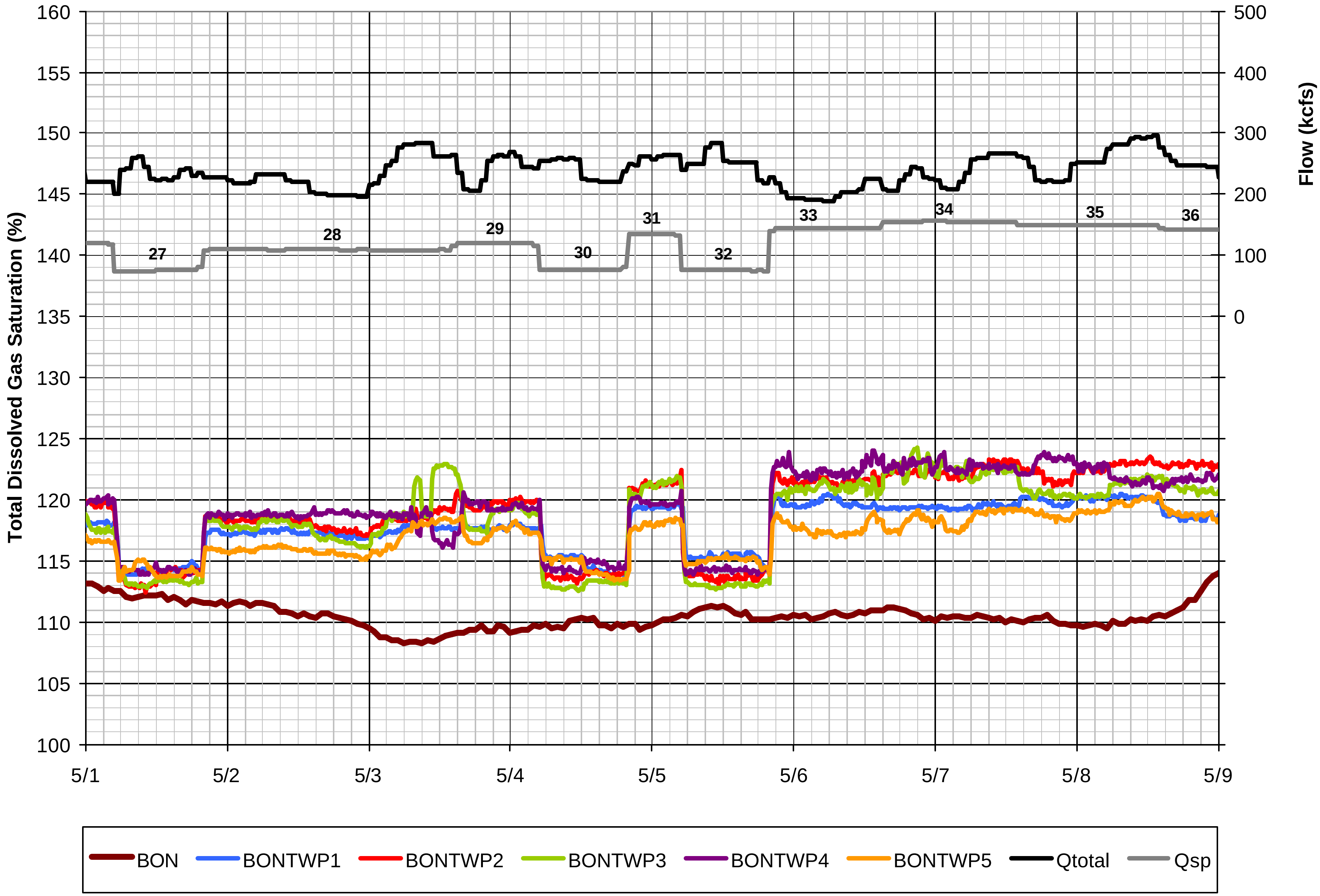

Figure 20i. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, May 1-8 2002

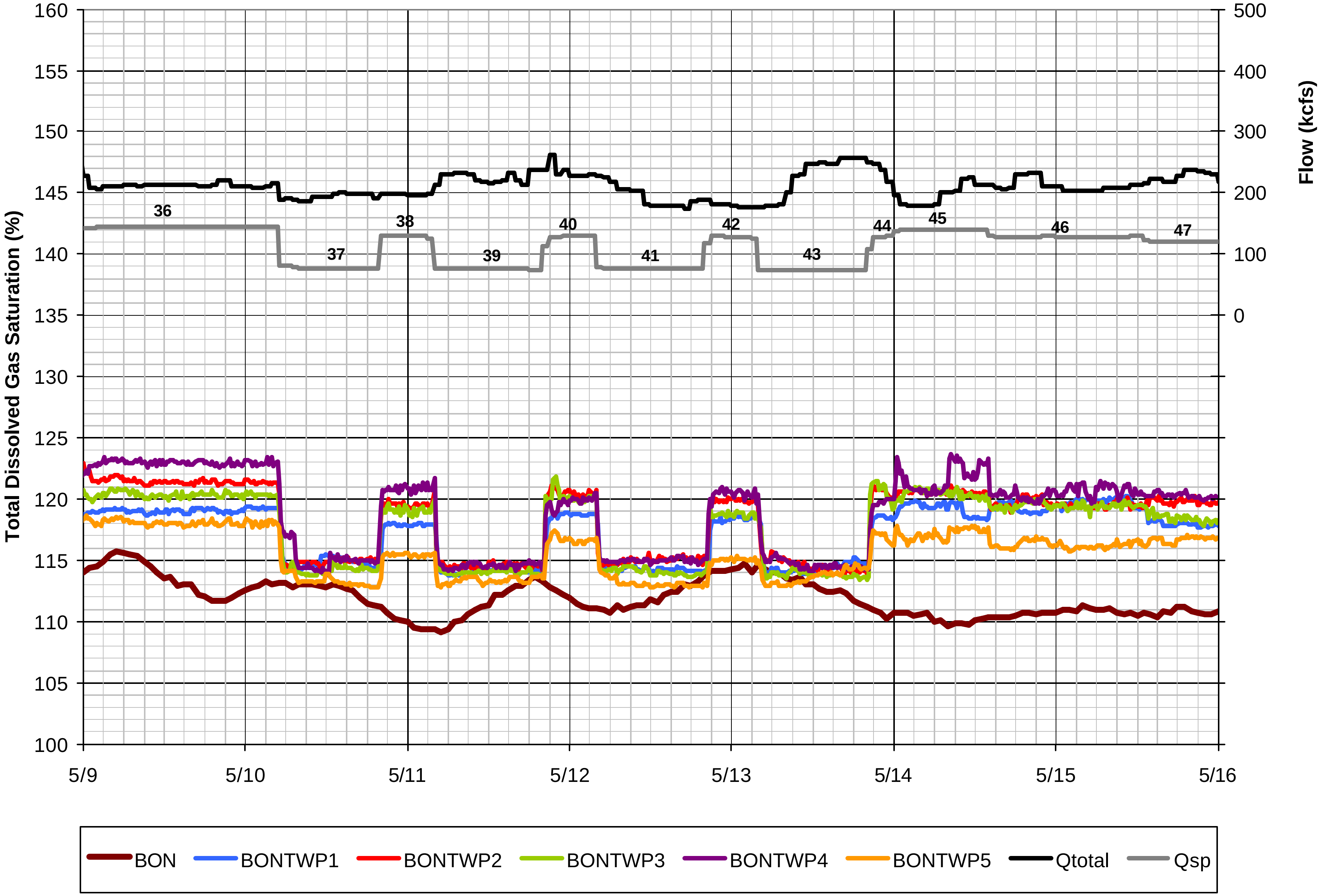

Figure 20j. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, May 9-15, 2002

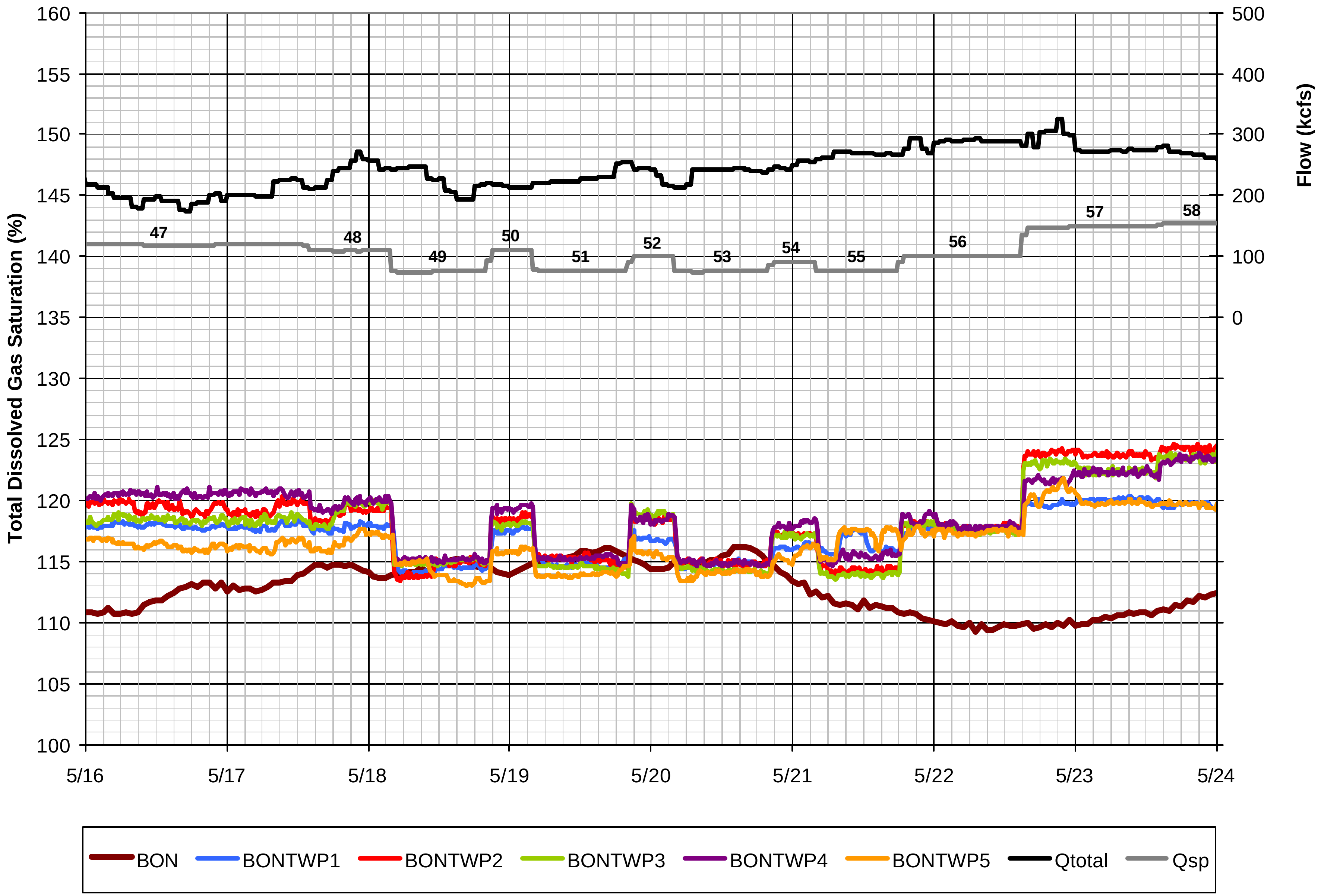

Figure 20k. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, May 16-23, 2002

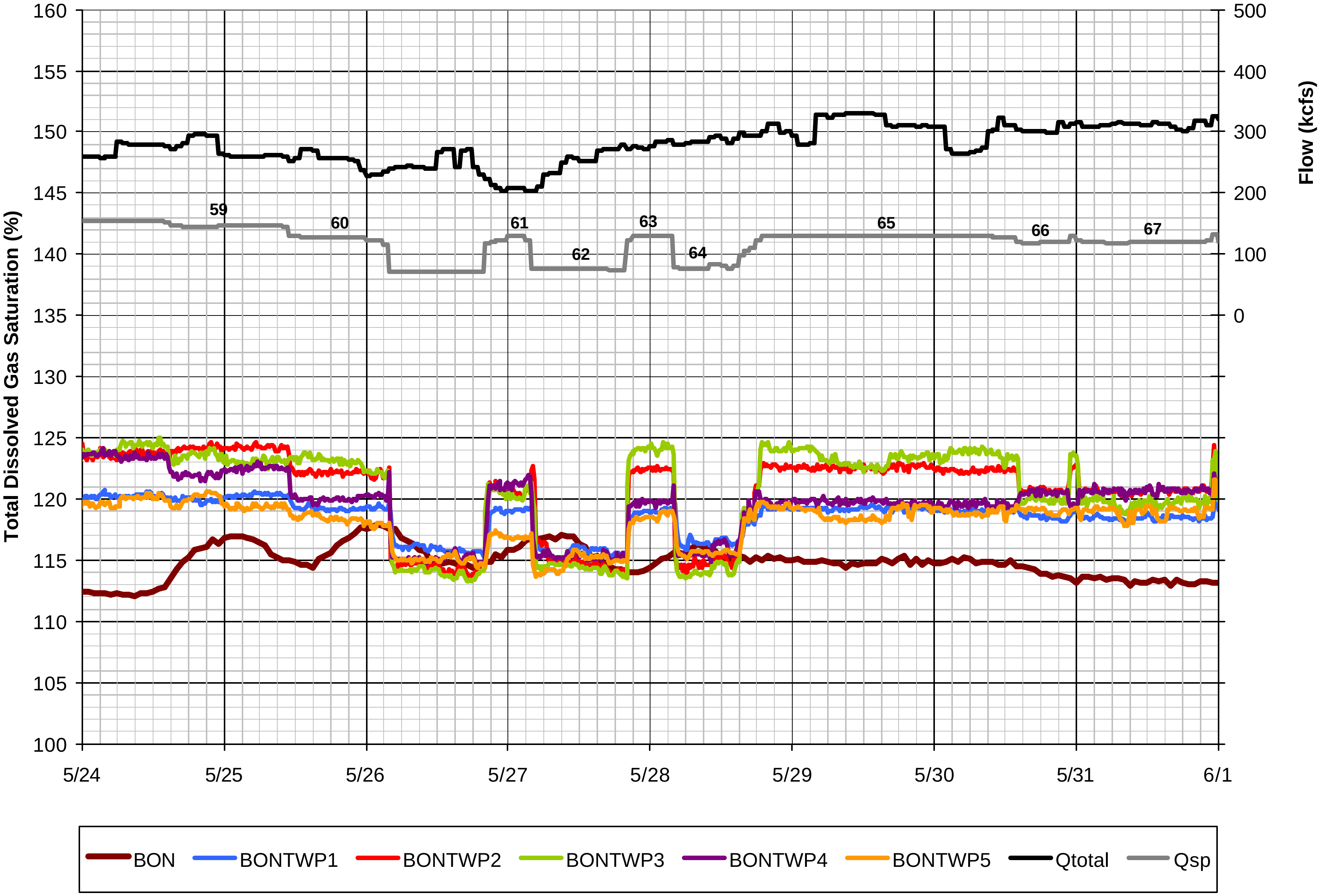

Figure 20l. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, May 24-31, 2002

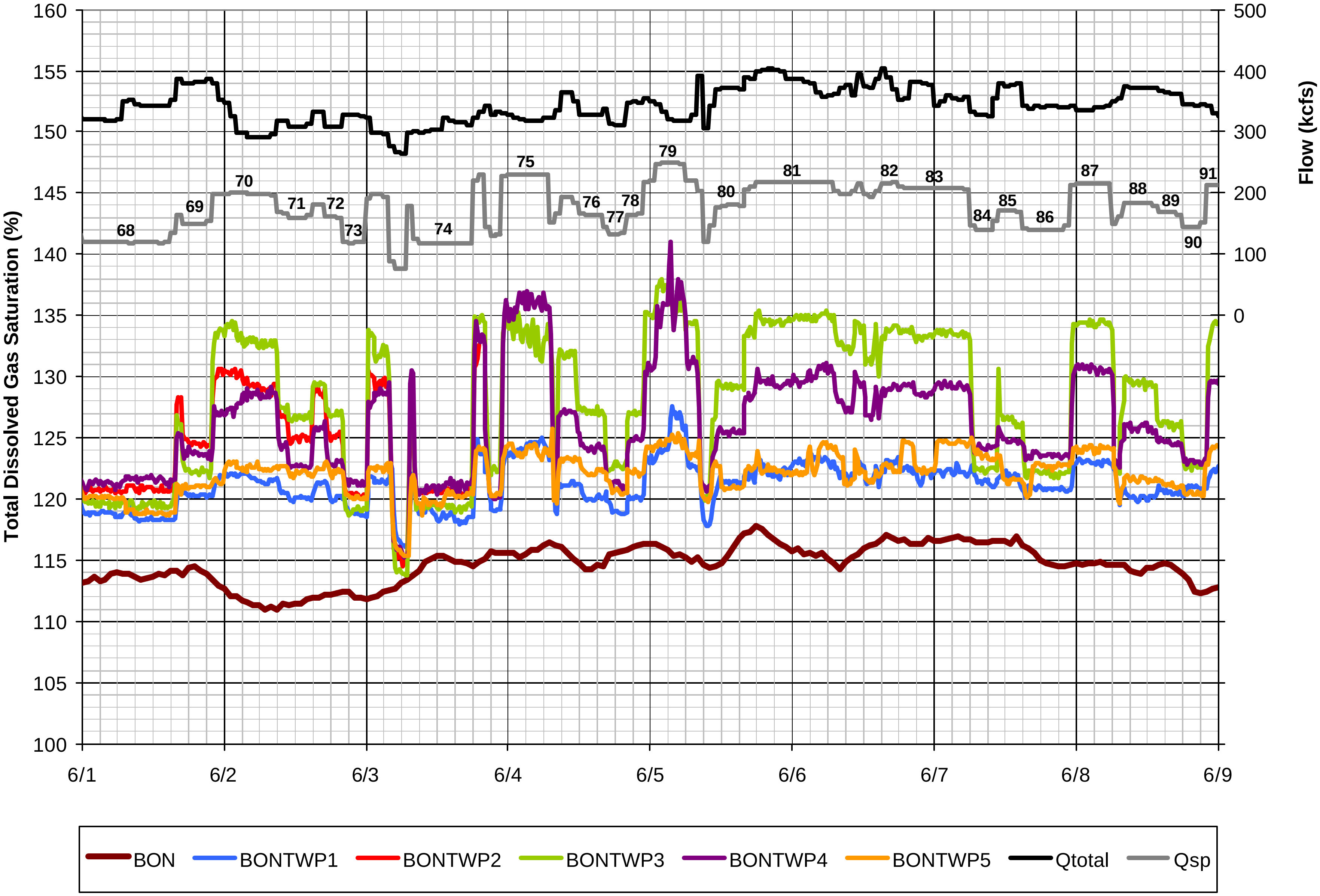

Figure 20m. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 1-8, 2002

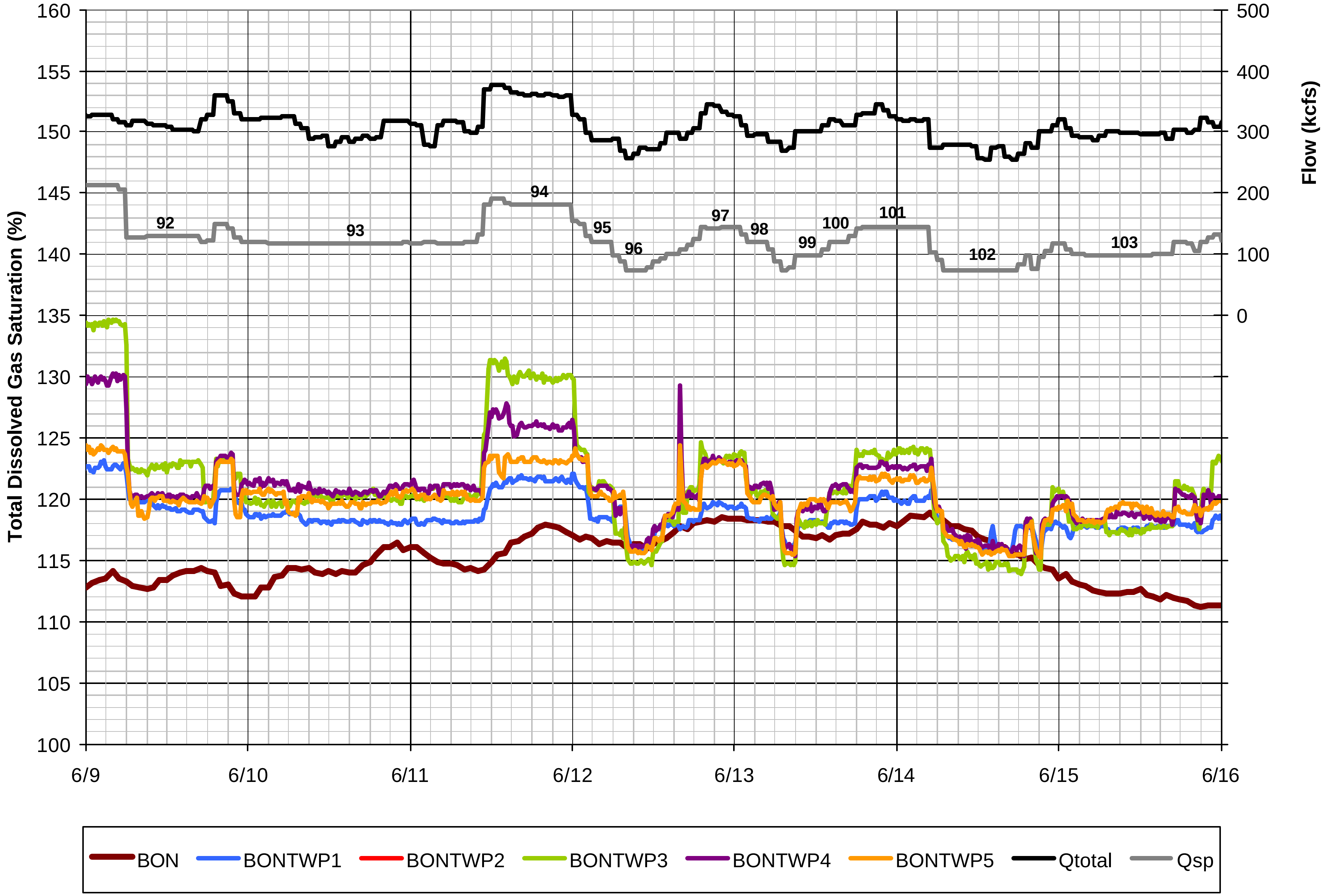

Figure 20n. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 9-15, 2002

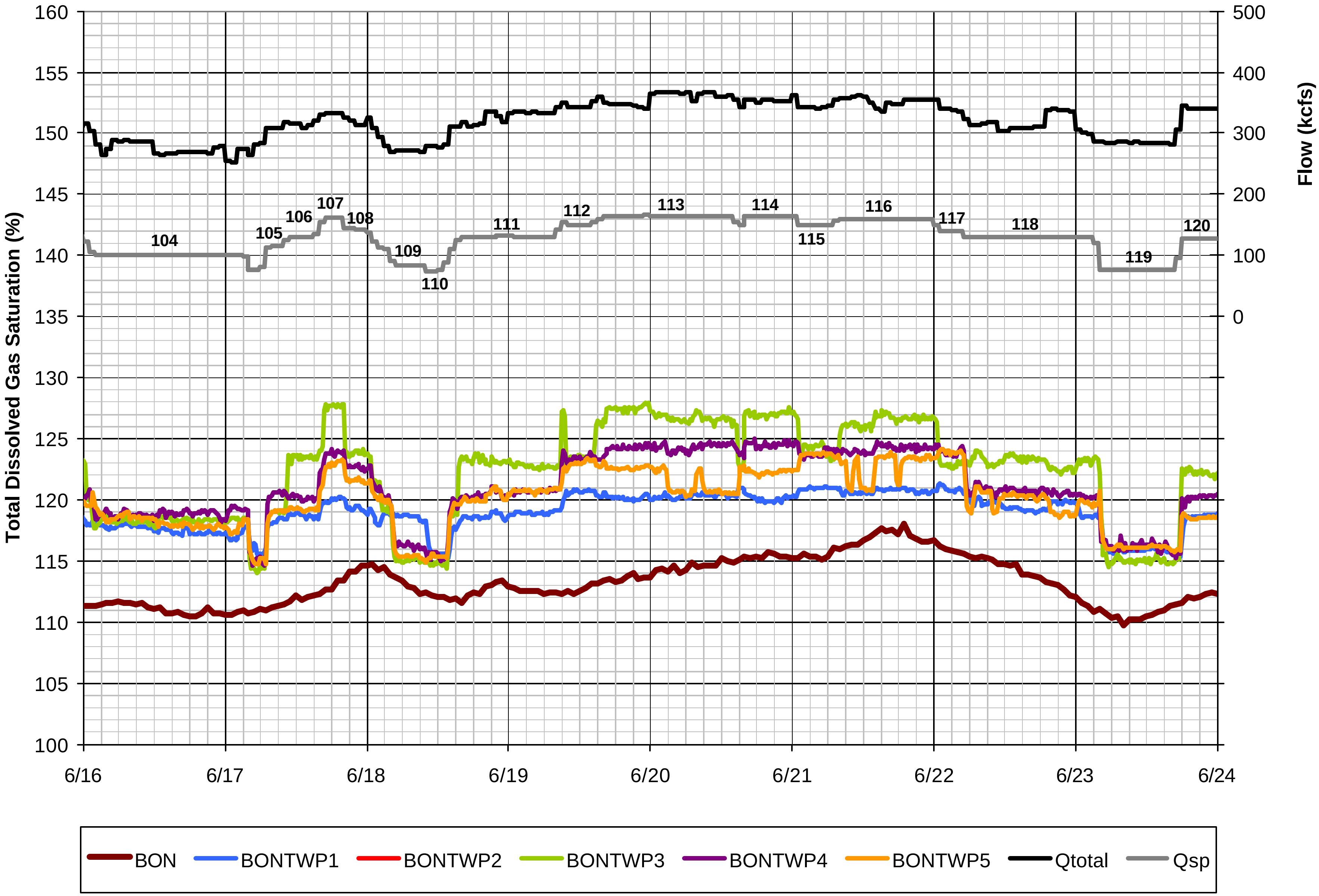

Figure 20o. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 16-23, 2002

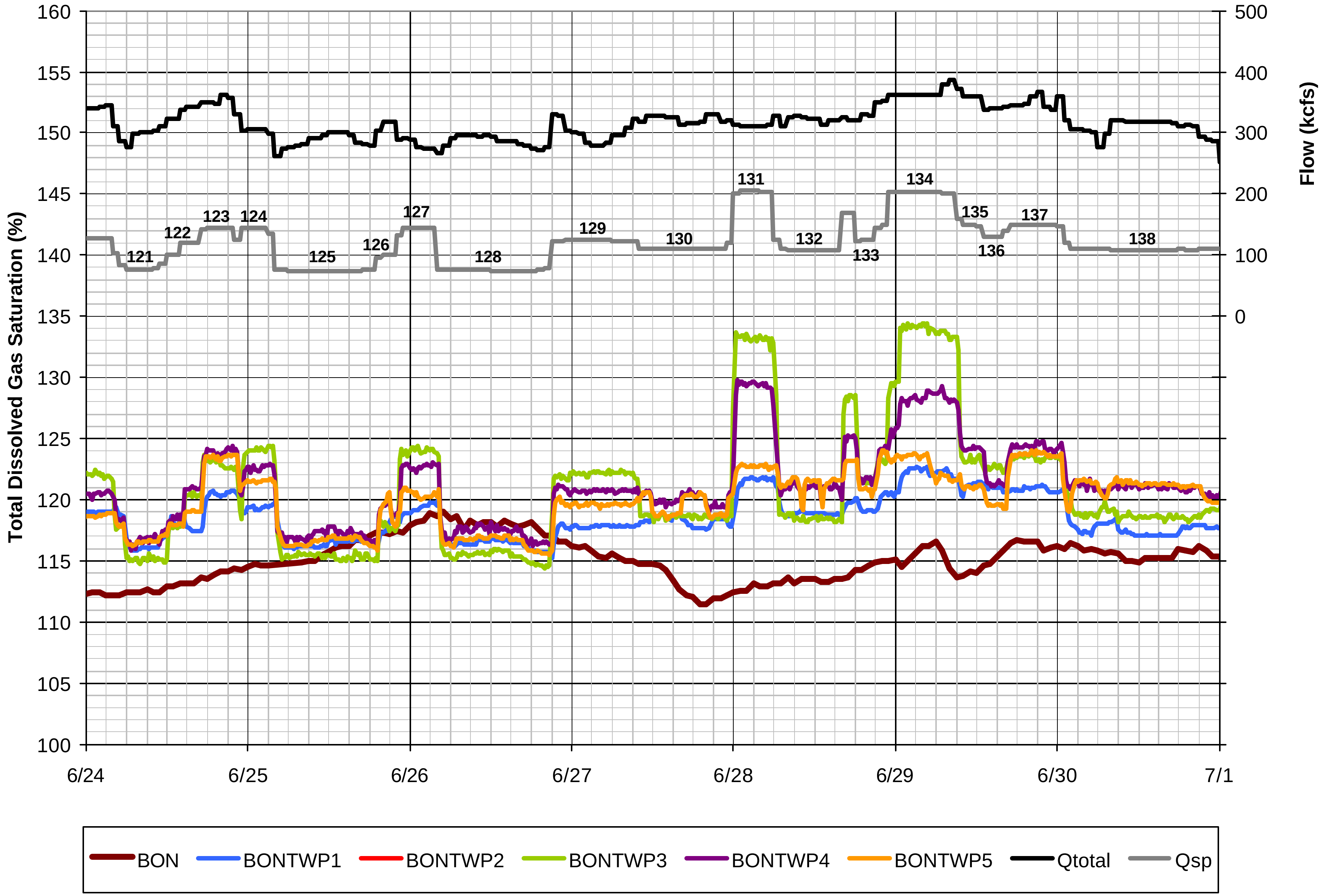

Figure 20p. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 24-30, 2002

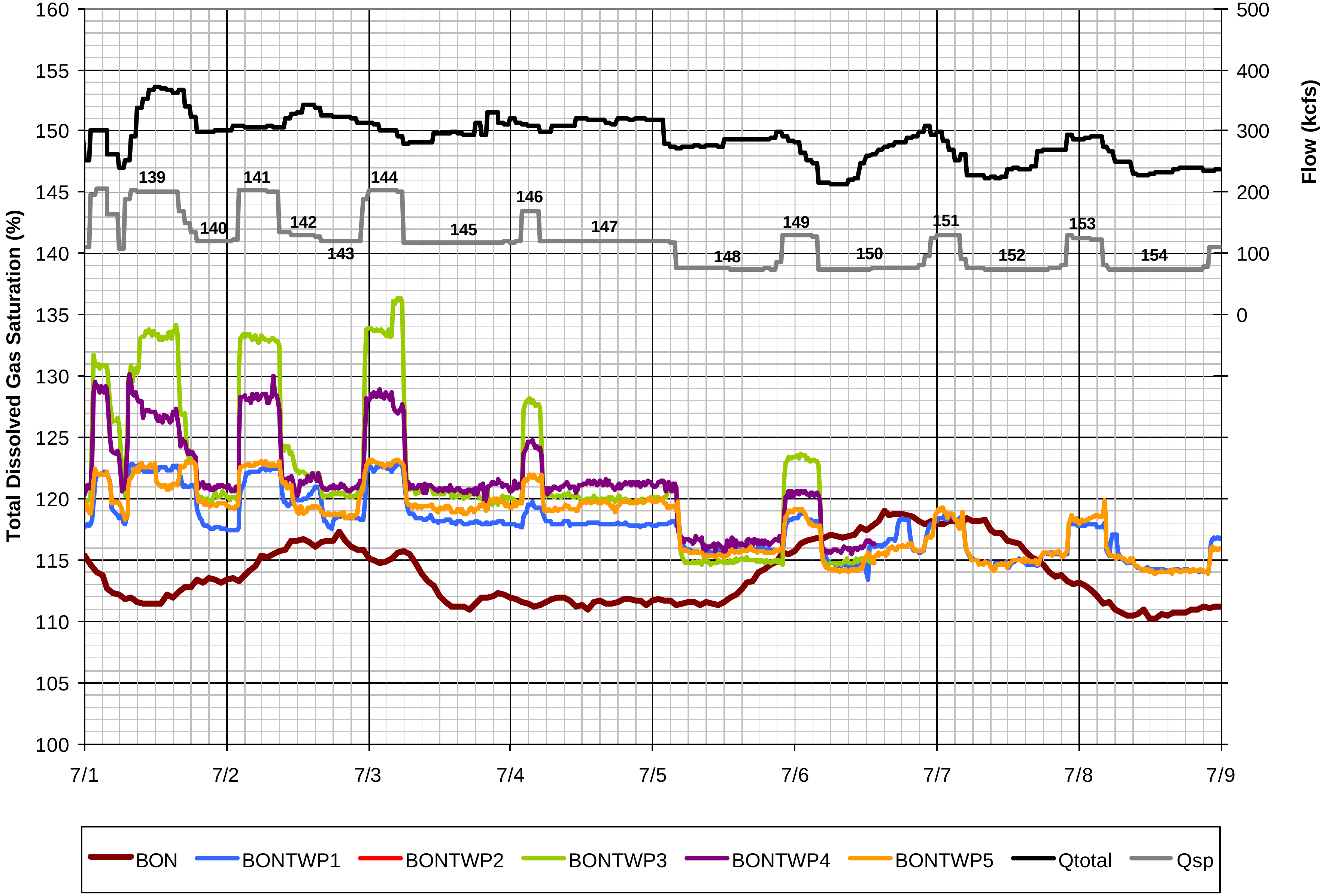

Figure 20q. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, July 1-8, 2002

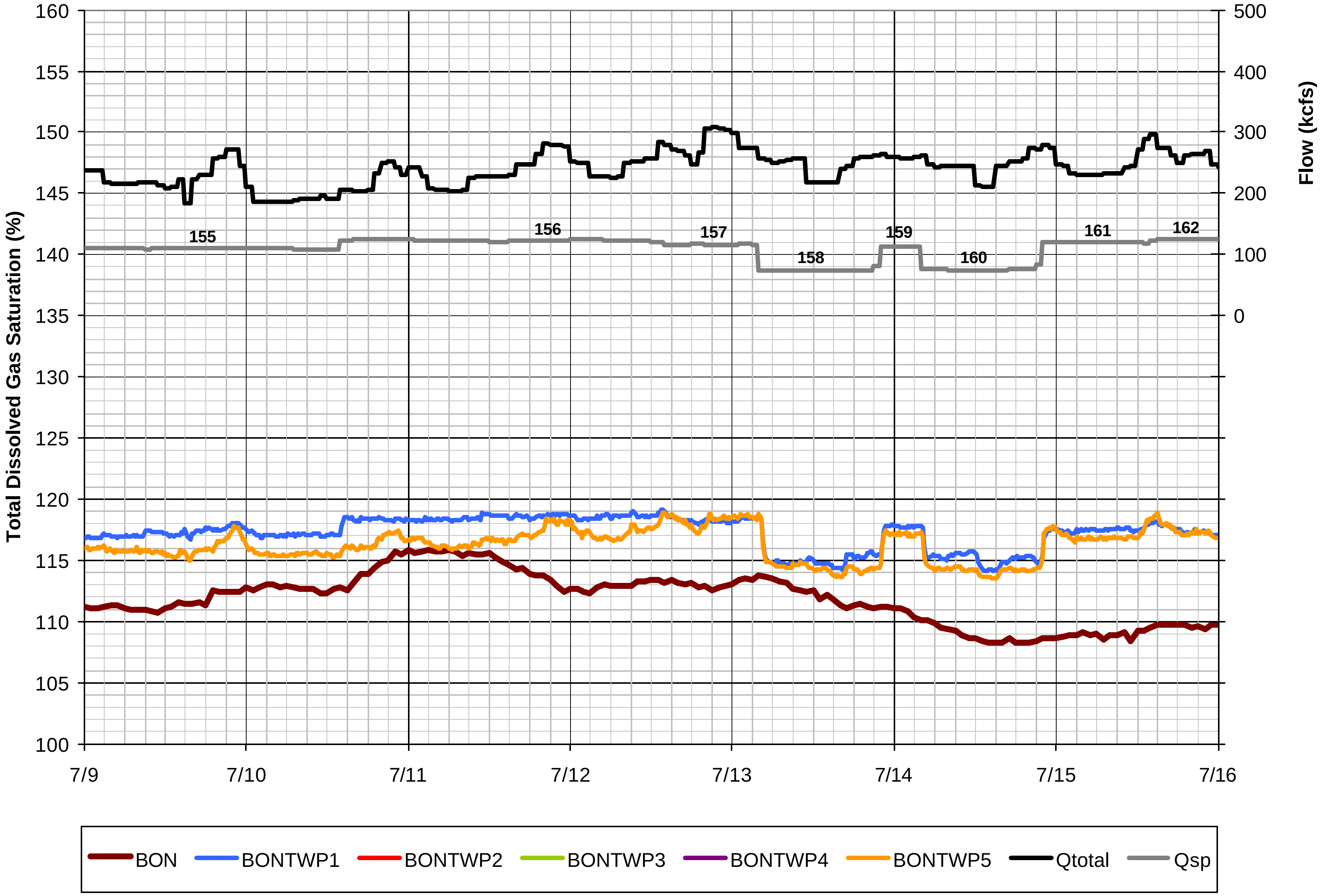

Figure 20r. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 9-15, 2002

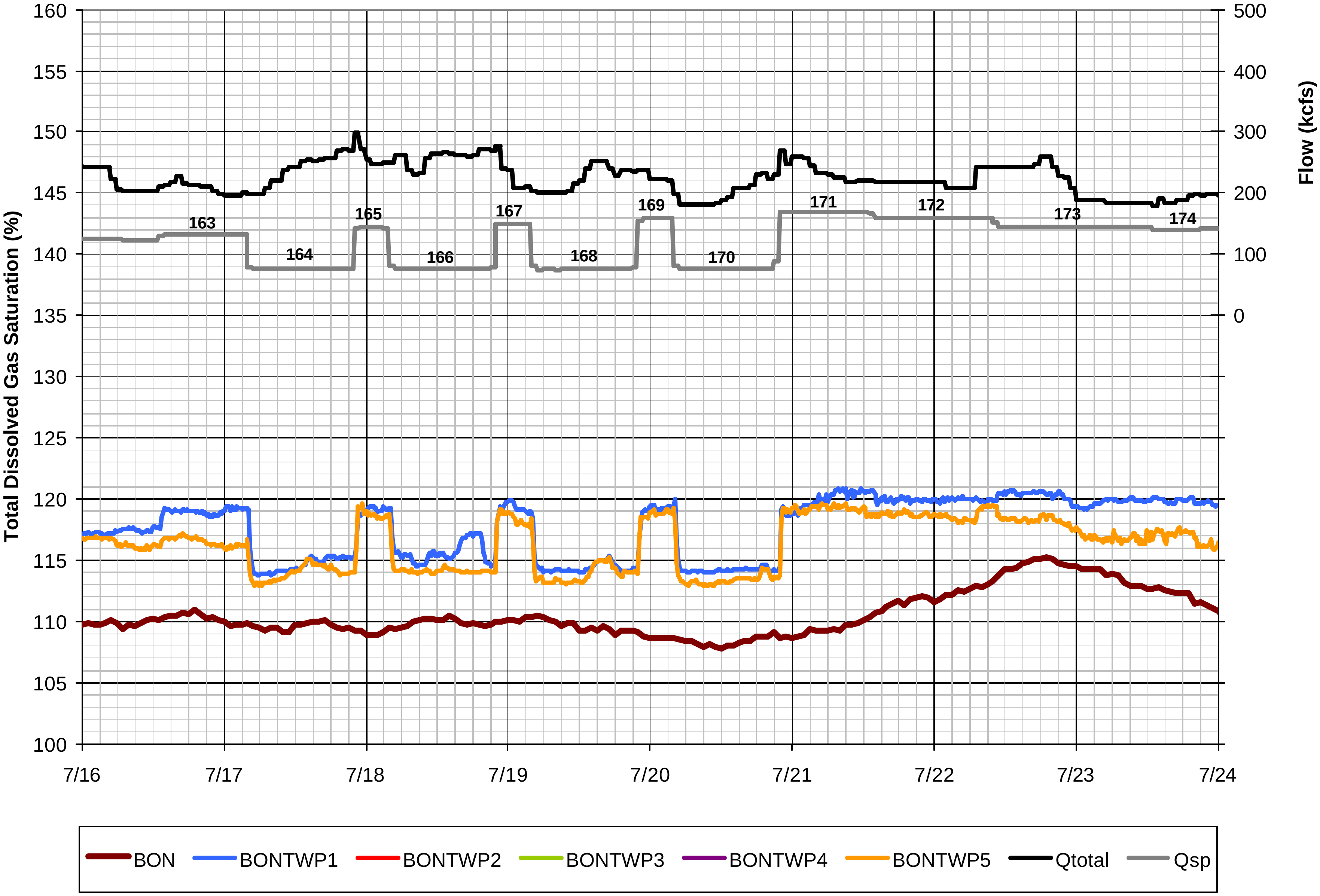

Figure 20s. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, June 16-23, 2002

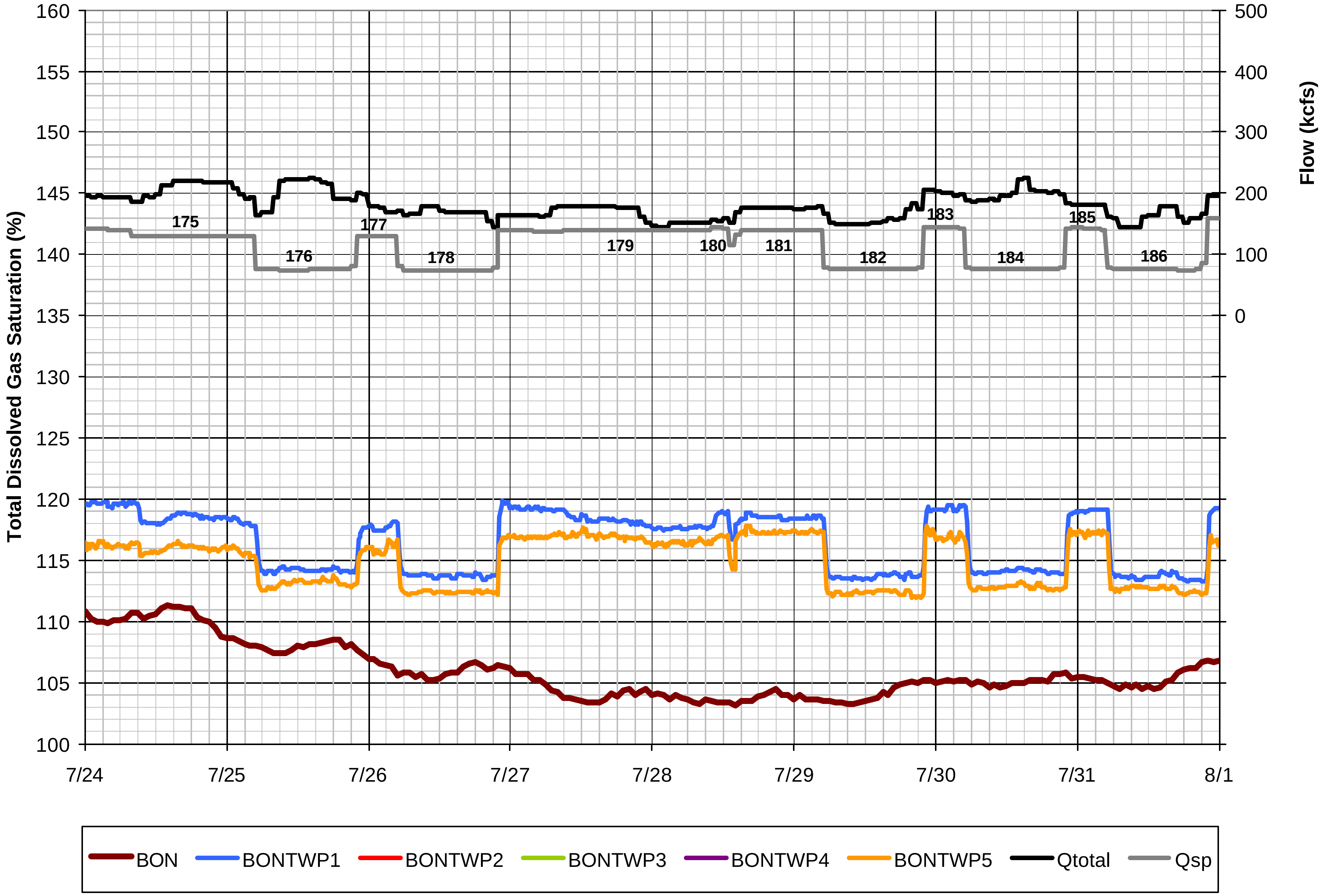

Figure 20t. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, July 24-31, 2002

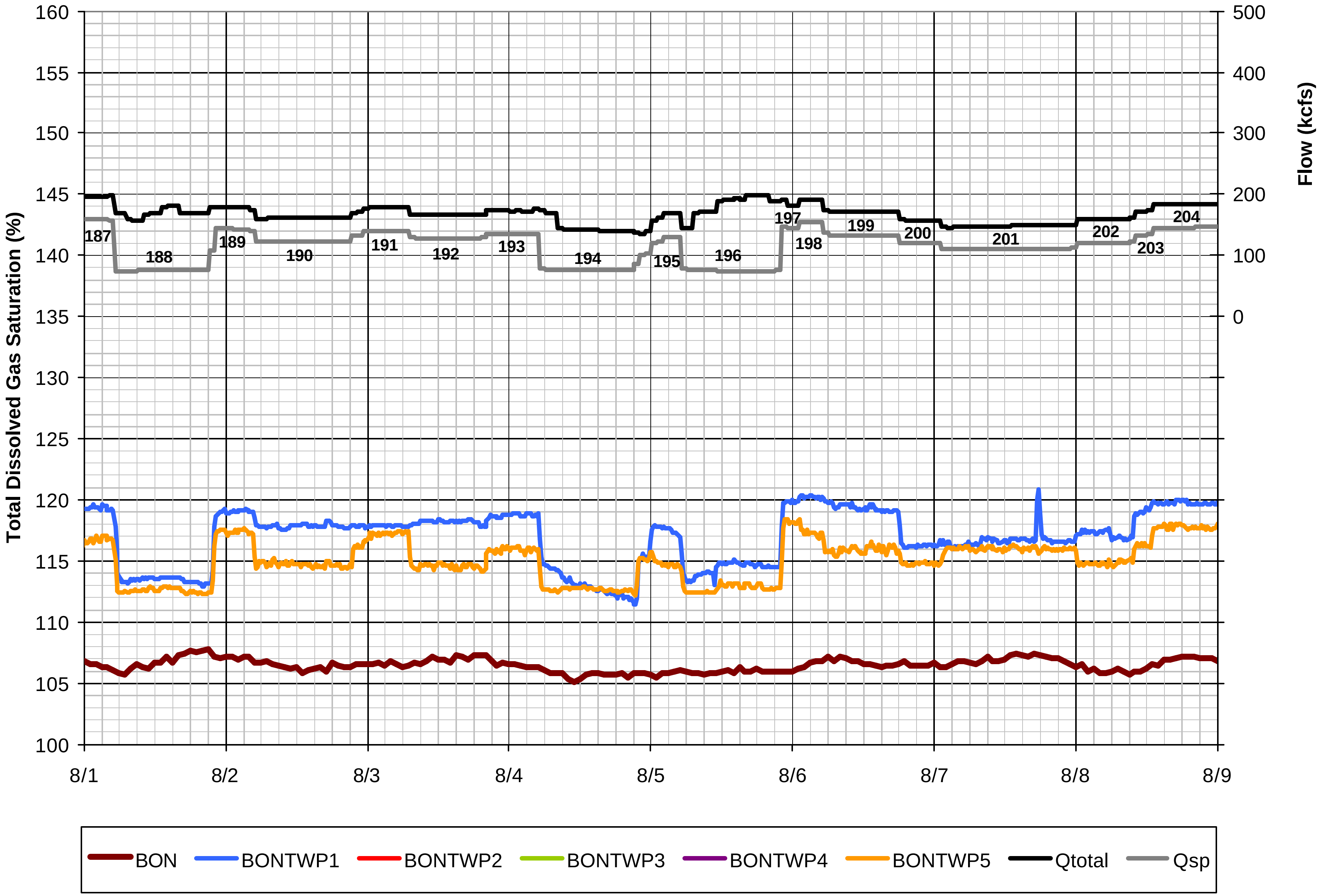

Figure 20u. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 1-8, 2002

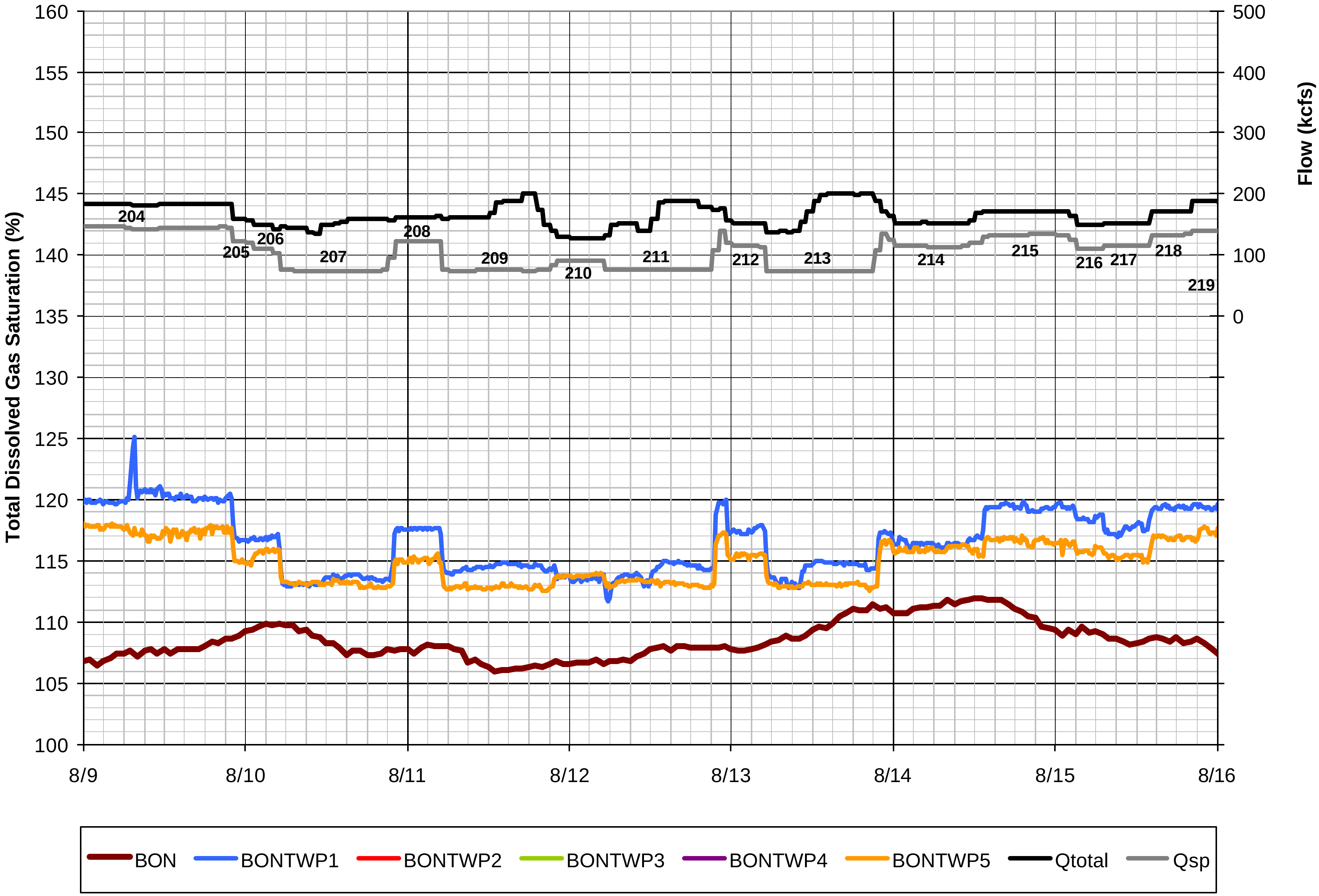

Figure 20v. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 9-15, 2002

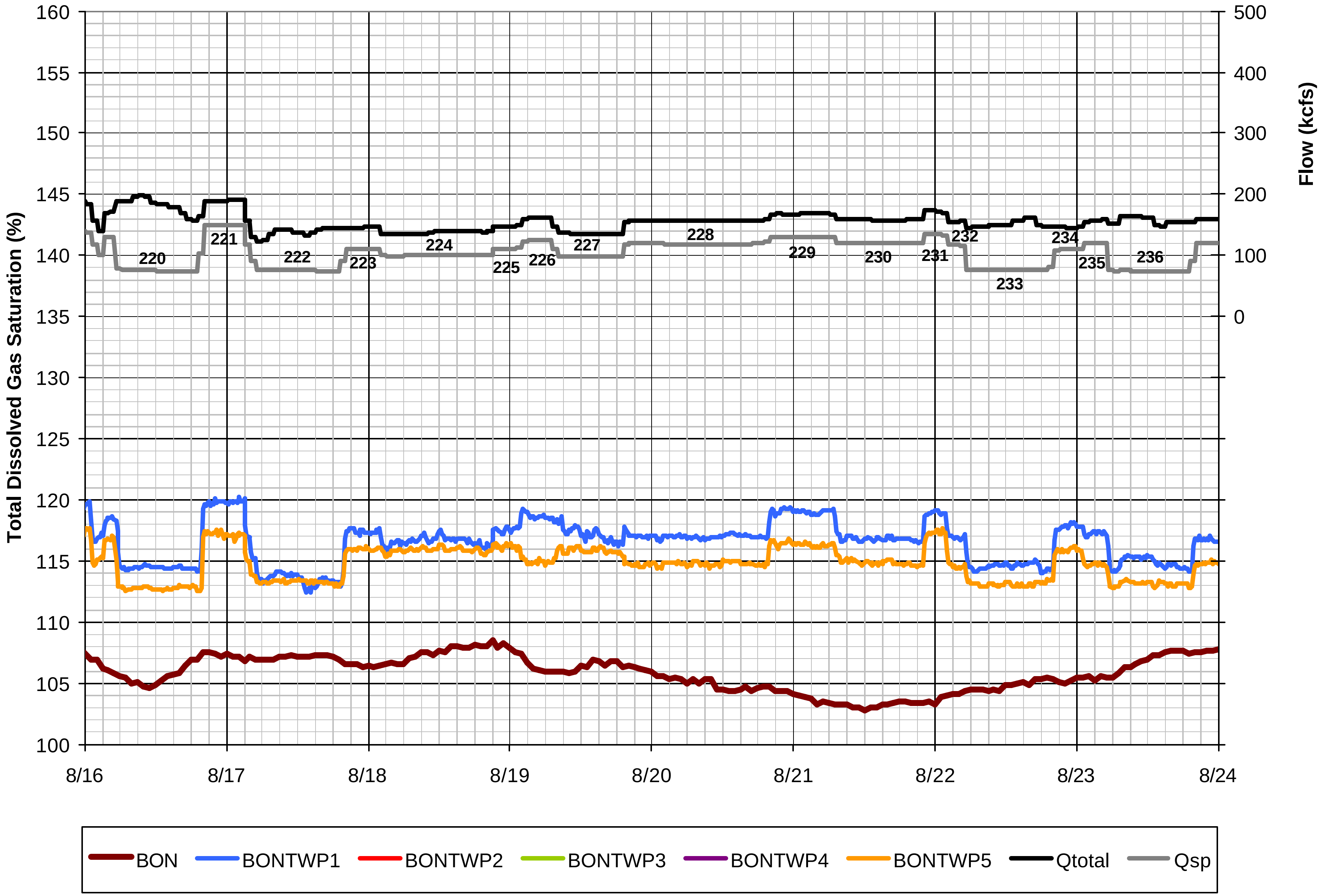

Figure 20w. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 16-23, 2002

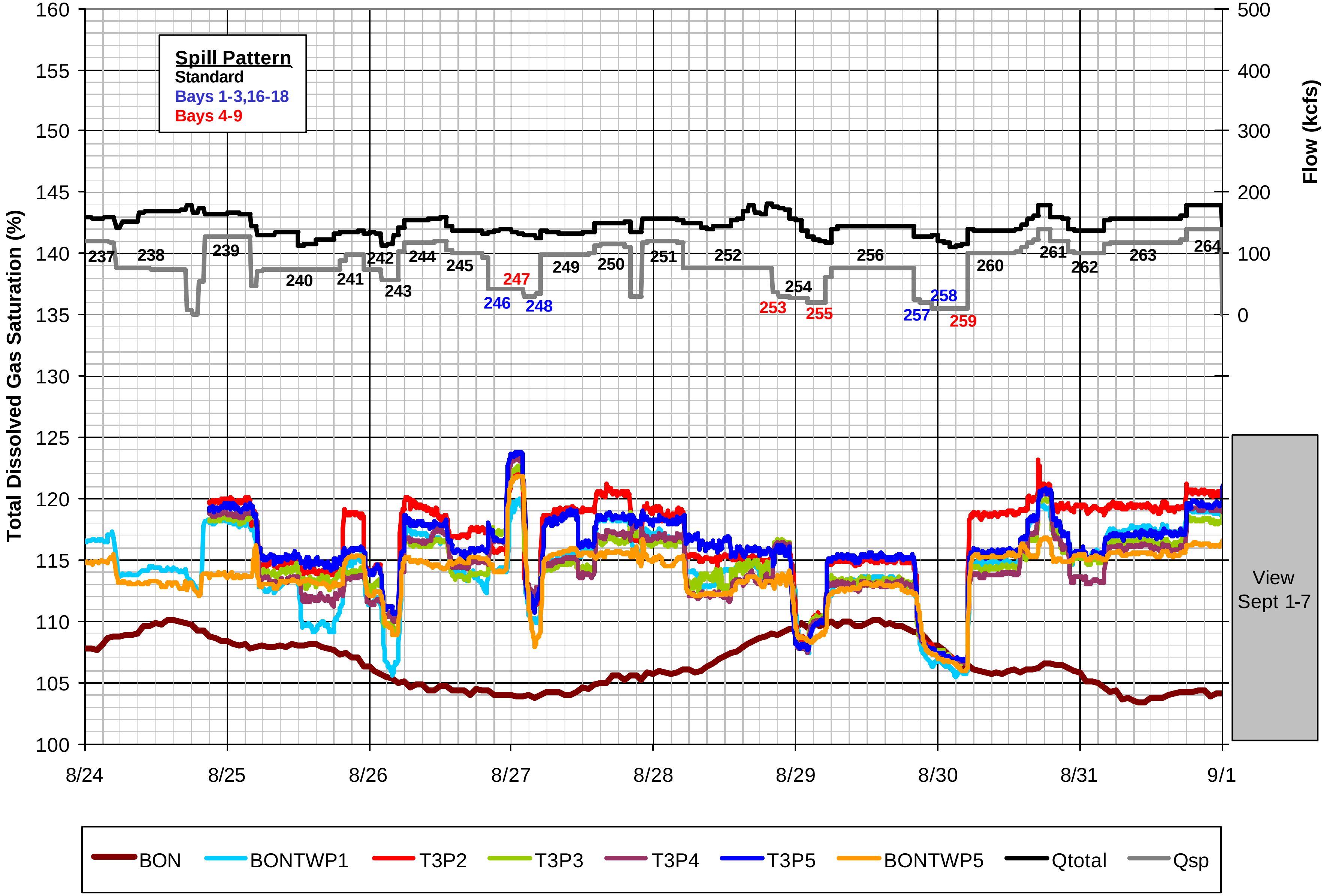

Figure 20x. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 24-31, 2002

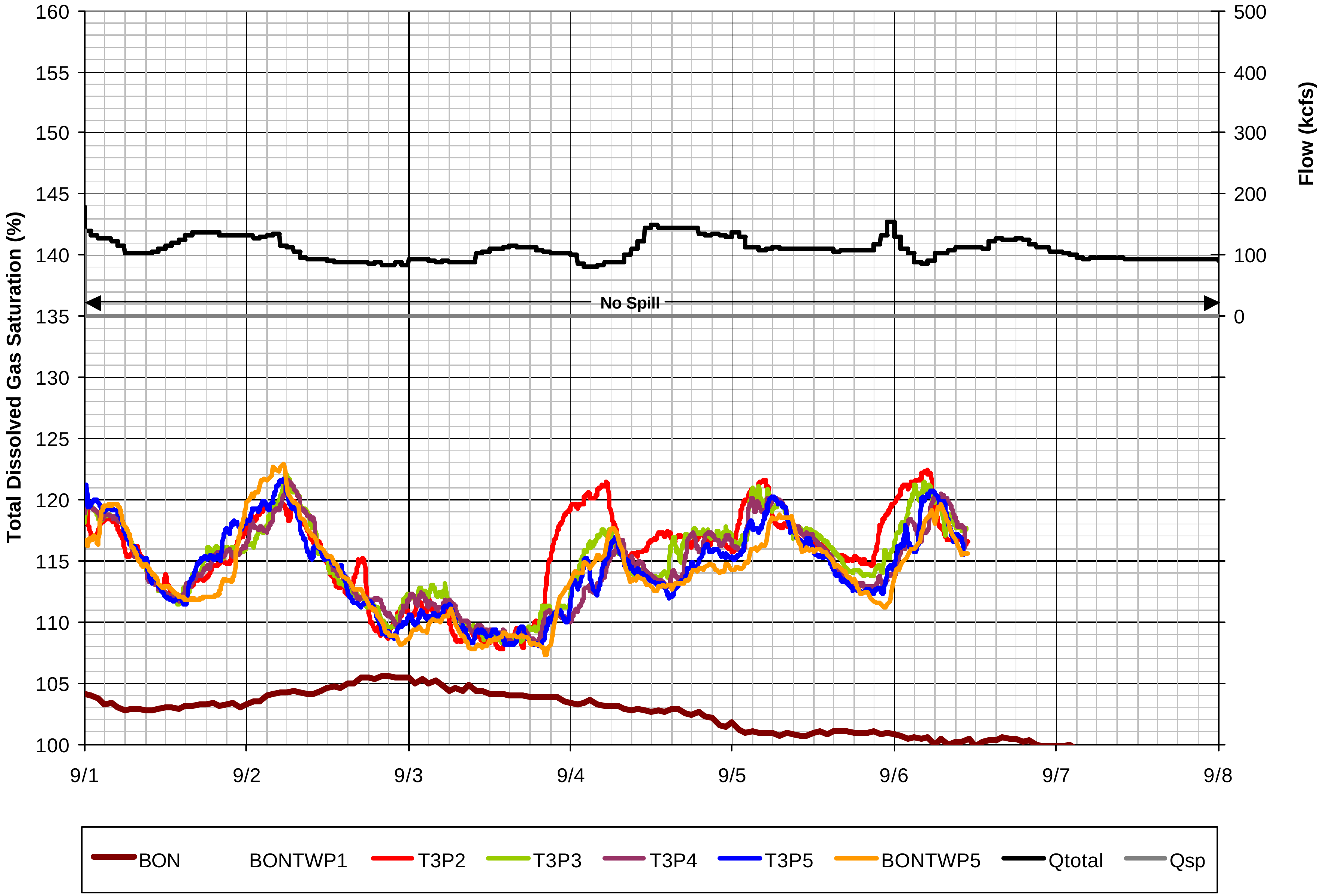

Figure 20y. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, September 1-7, 2002

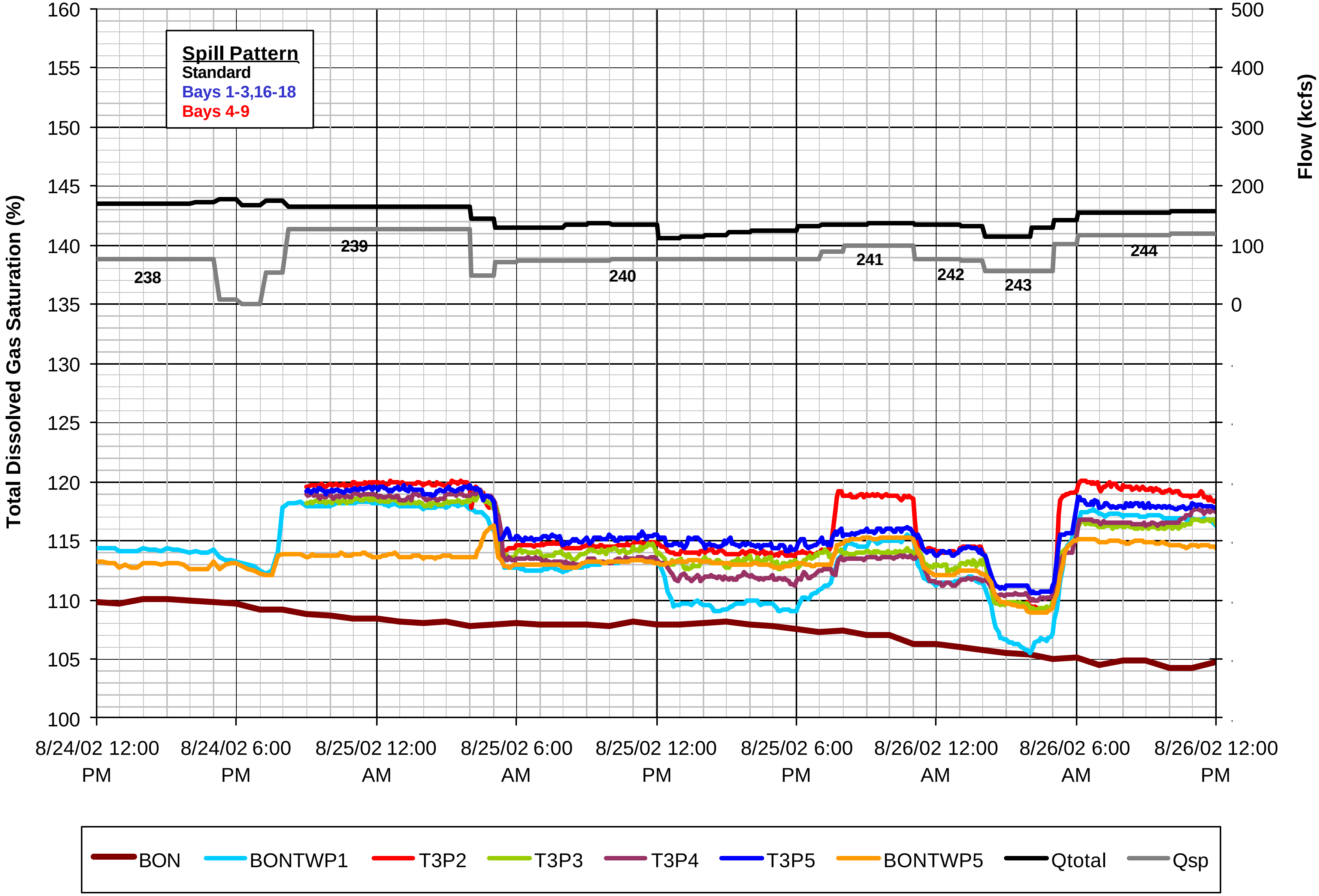

Figure 20z. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 24-26, 2002

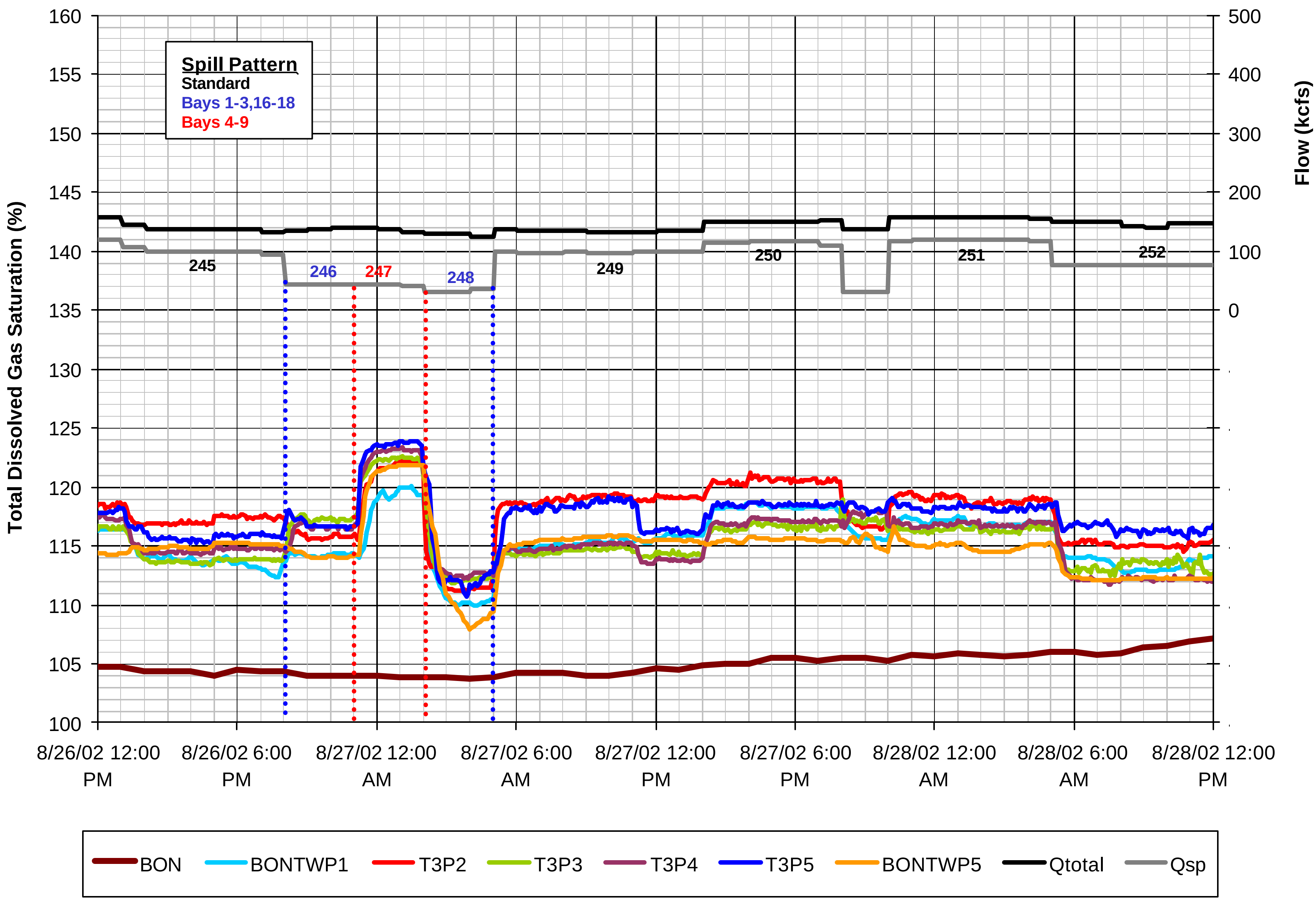

Figure 20aa. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 26-28, 2002

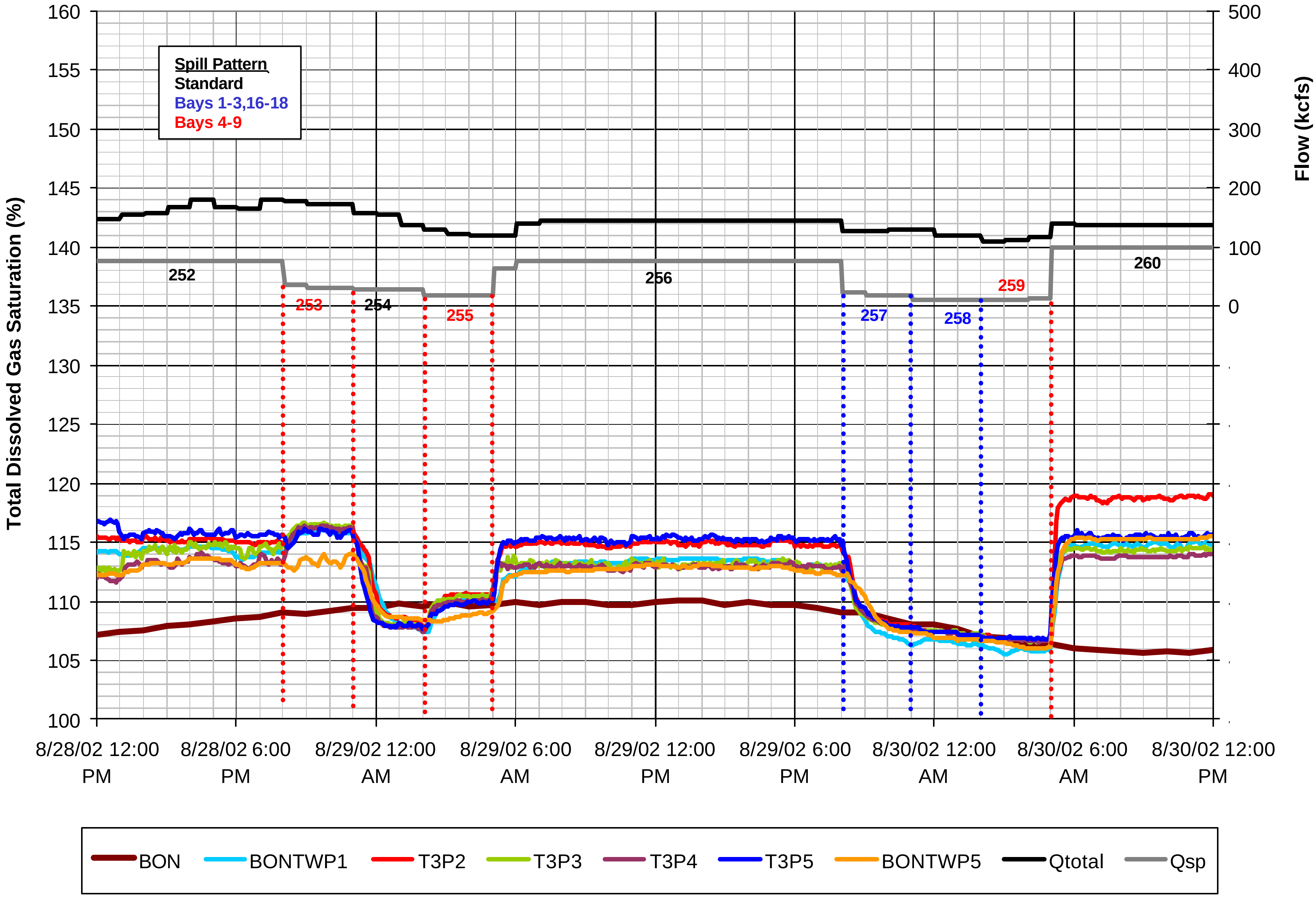

Figure 20ab. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 28-30, 2002

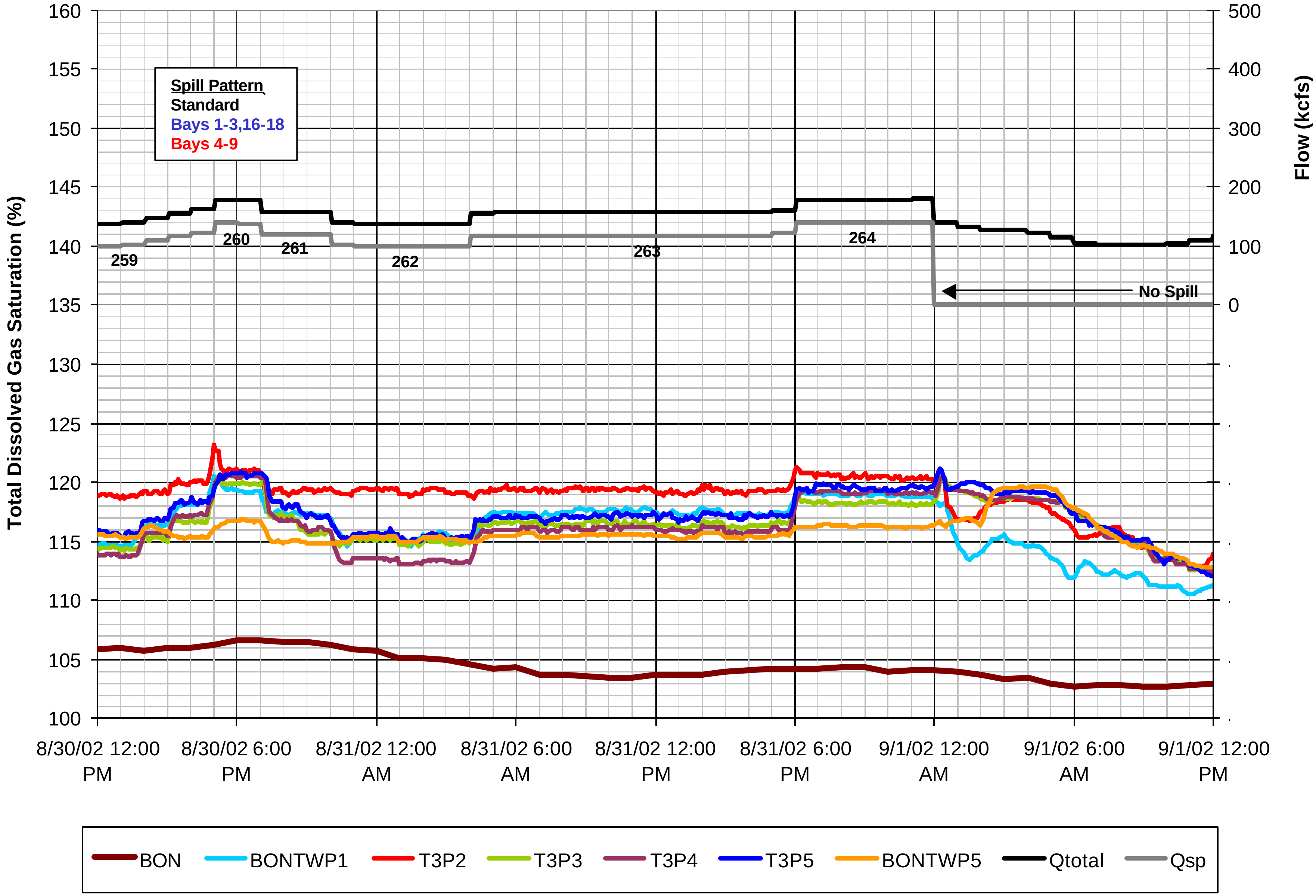

Figure 20ac. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, August 30-September 1, 2002

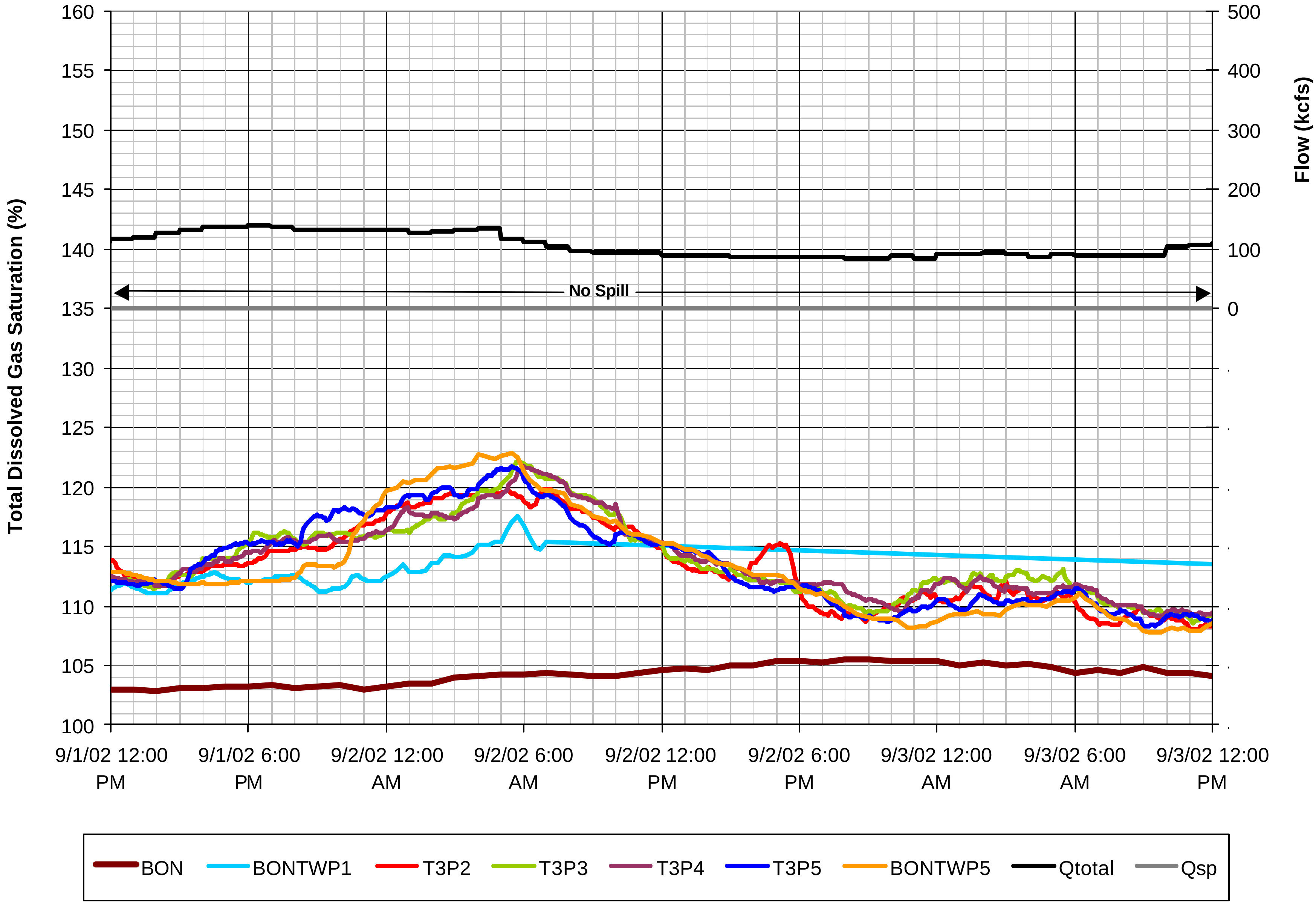

Figure 20ad. Total dissolved gas saturation measured at the forebay fixed monitoring station and various tailwater sites and project operations, September 1-3, 2002

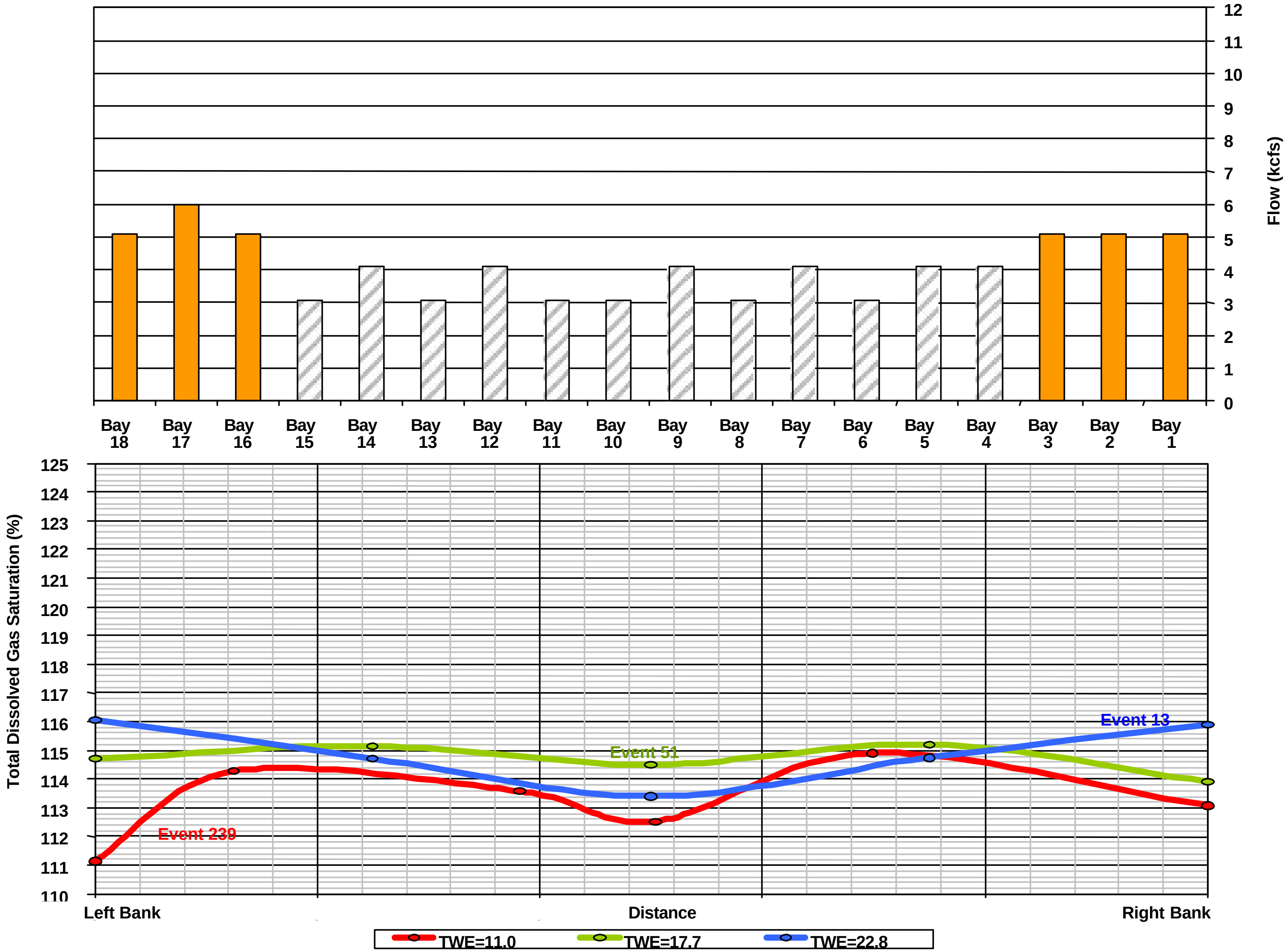

Figure 21. Lateral distribution of total dissolved gas saturation in the Bonneville spillway exit channel and spill pattern for a spill discharge of 75 kcfs and tailwater elevations of 11, 17.7, and 22.8 ft

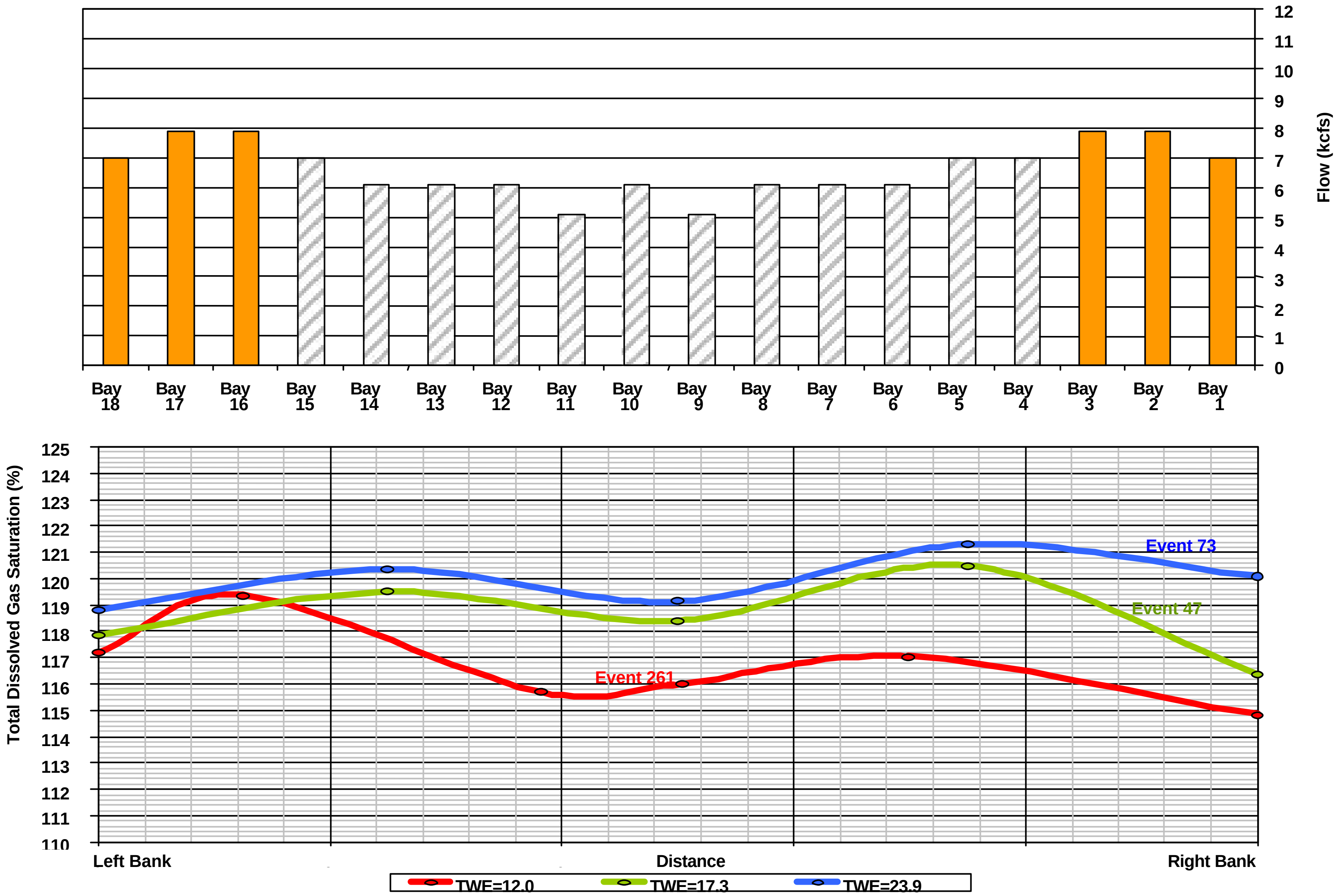

Figure 22. Lateral distribution of total dissolved gas saturation in the Bonneville spillway exit channel and spill pattern for a spill discharge of 118-121 kcfs and tailwater elevations of 12, 17.3, and 23.9 ft

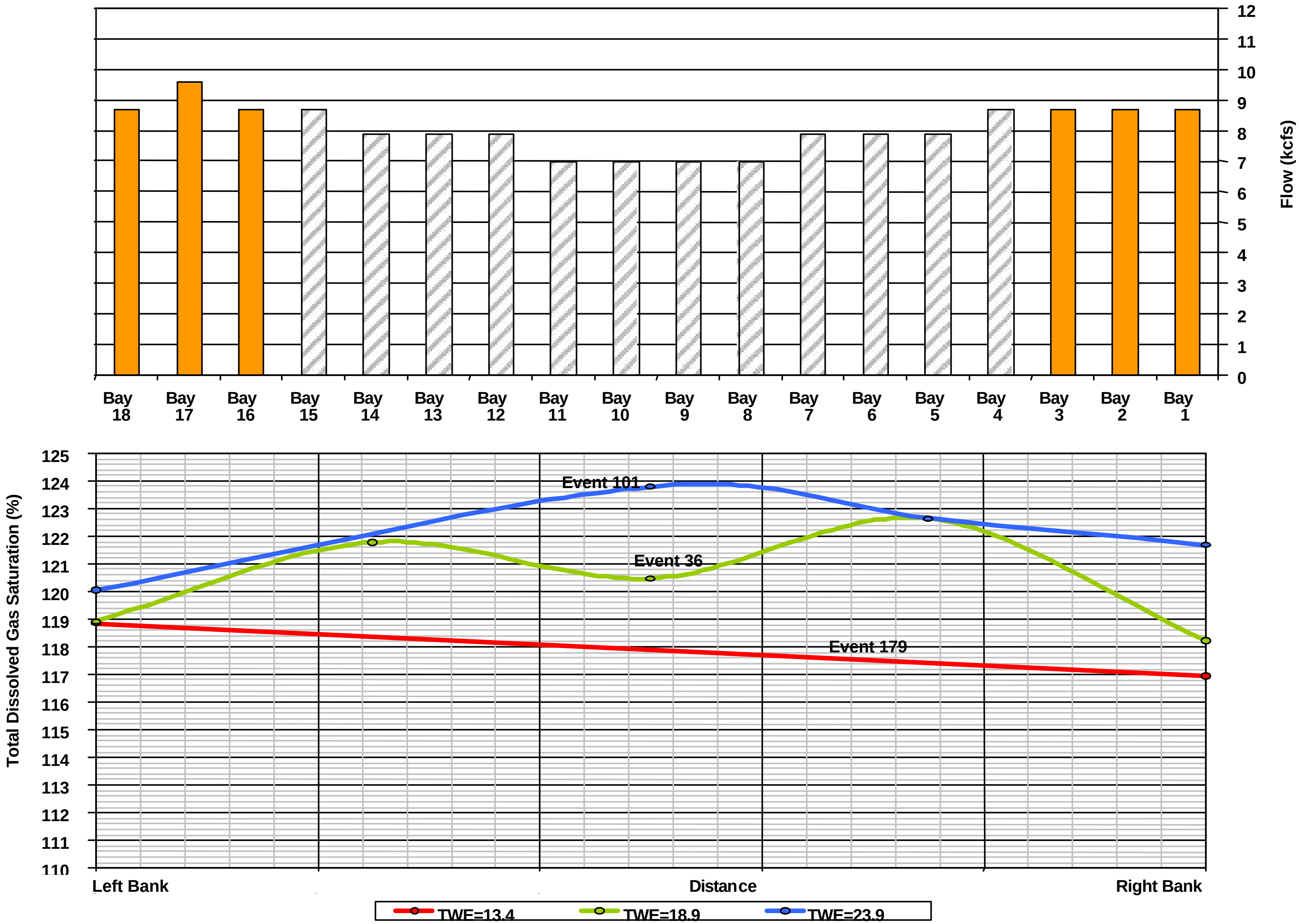

Figure 23. Lateral distribution of total dissolved gas saturation in the Bonneville spillway exit channel and spill pattern for a spill discharge of 143-146 kcfs and tailwater elevations of 13.4, 18.9, and 23.9 ft

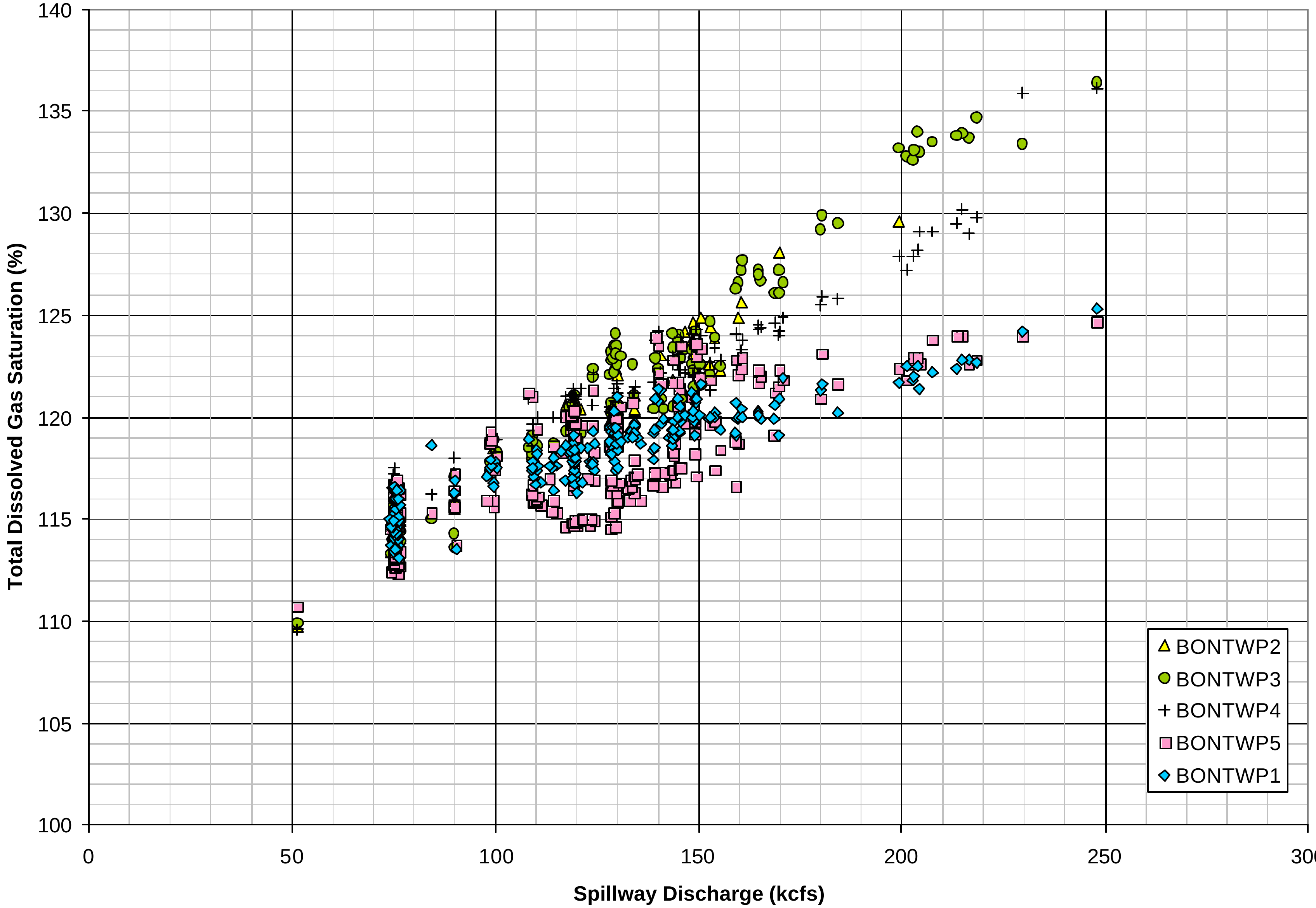

Figure 24. Total dissolved gas saturation in the Bonneville spillway exit channel versus spillway discharge by sampling station, April 10-August 24, 2002

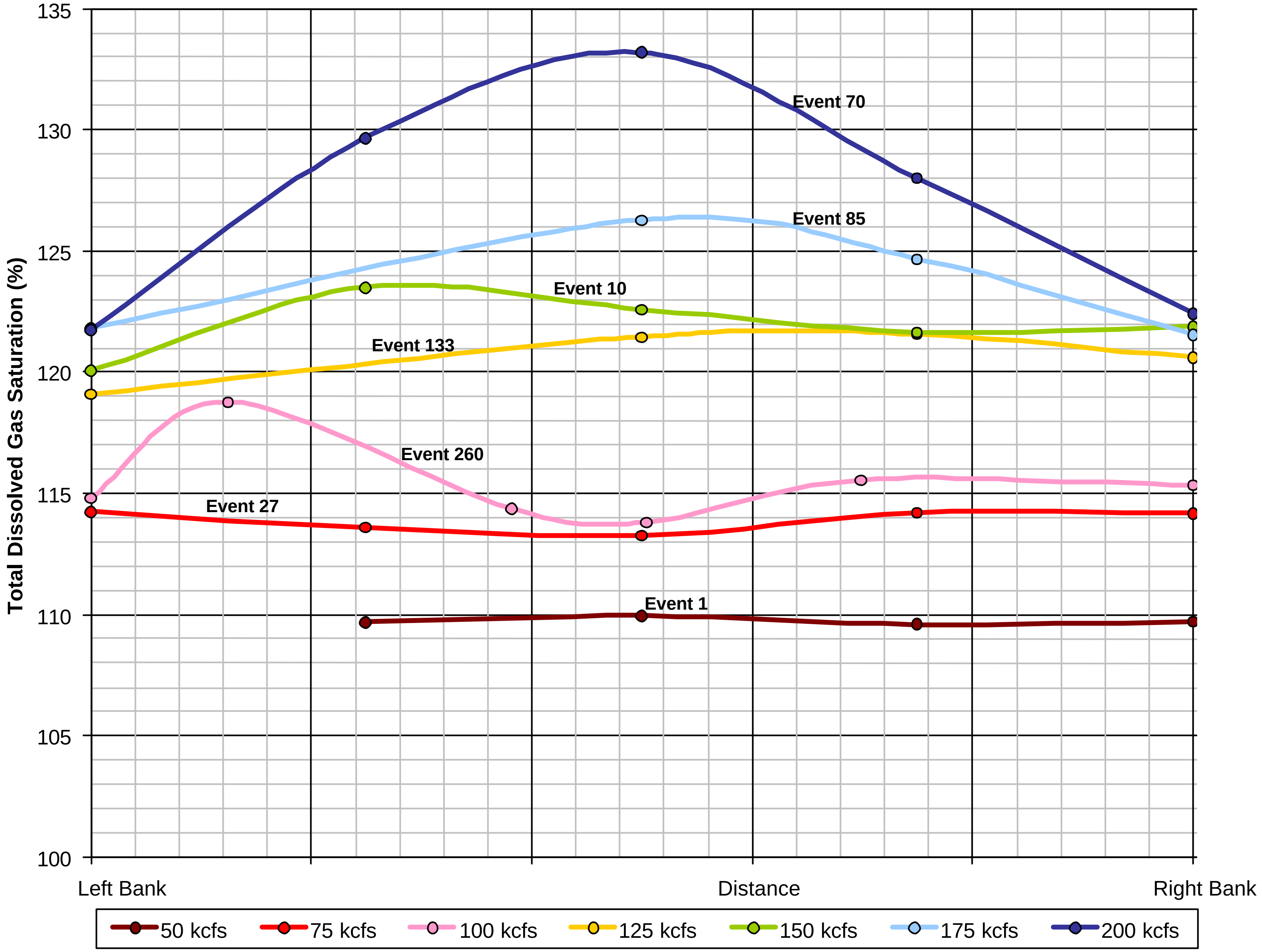

Figure 25. Lateral distribution of total dissolved gas saturation in the Bonneville spillway exit channel over a range of spill discharges (50-250 kcfs)

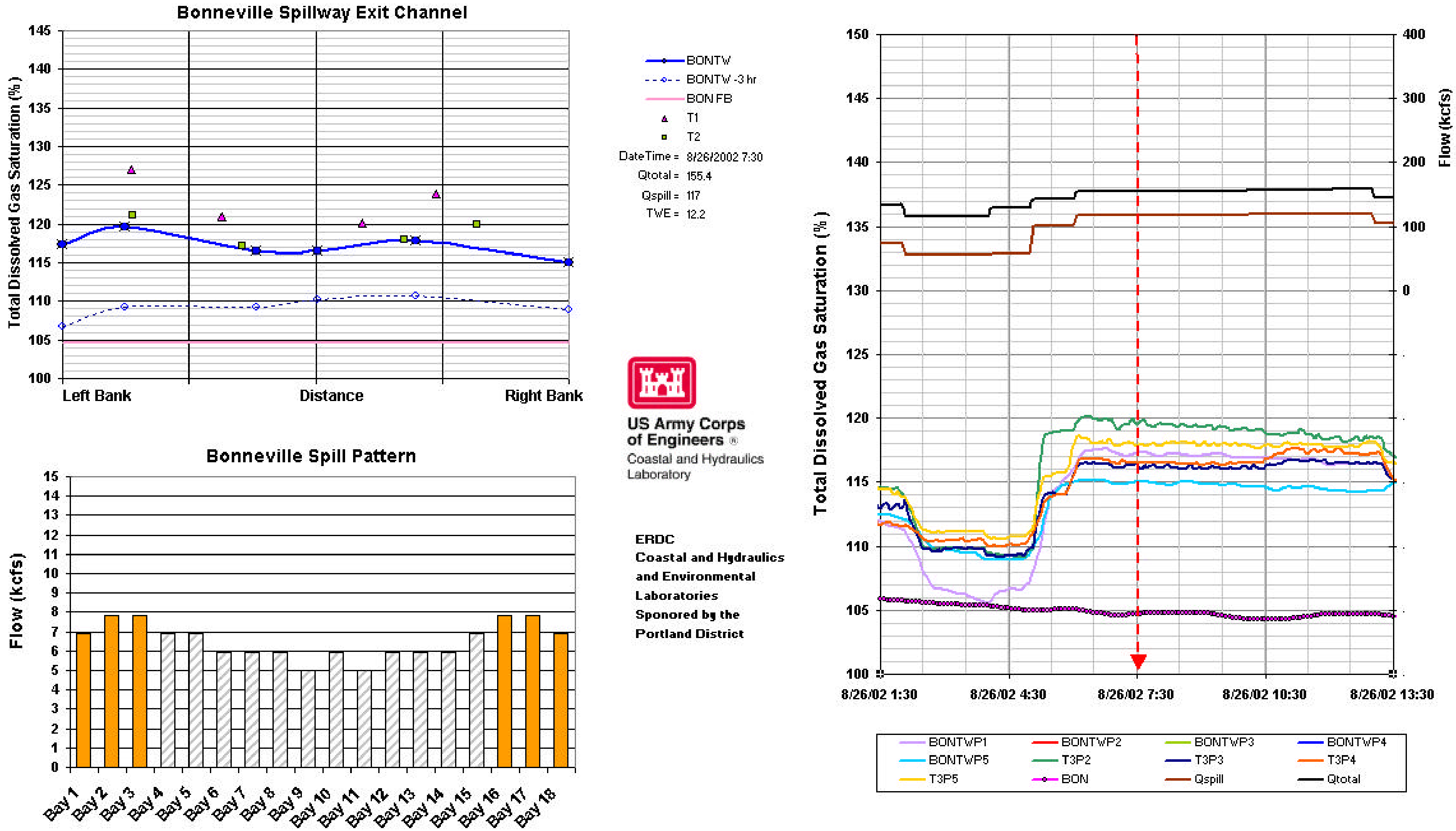

Figure 26. Bonneville spill pattern and total dissolved gas saturation in the spillway approach and exit channel, April 8-September 4, 2002
(Click on figure to view animation of study results, requires file “bontdg02.avi”)

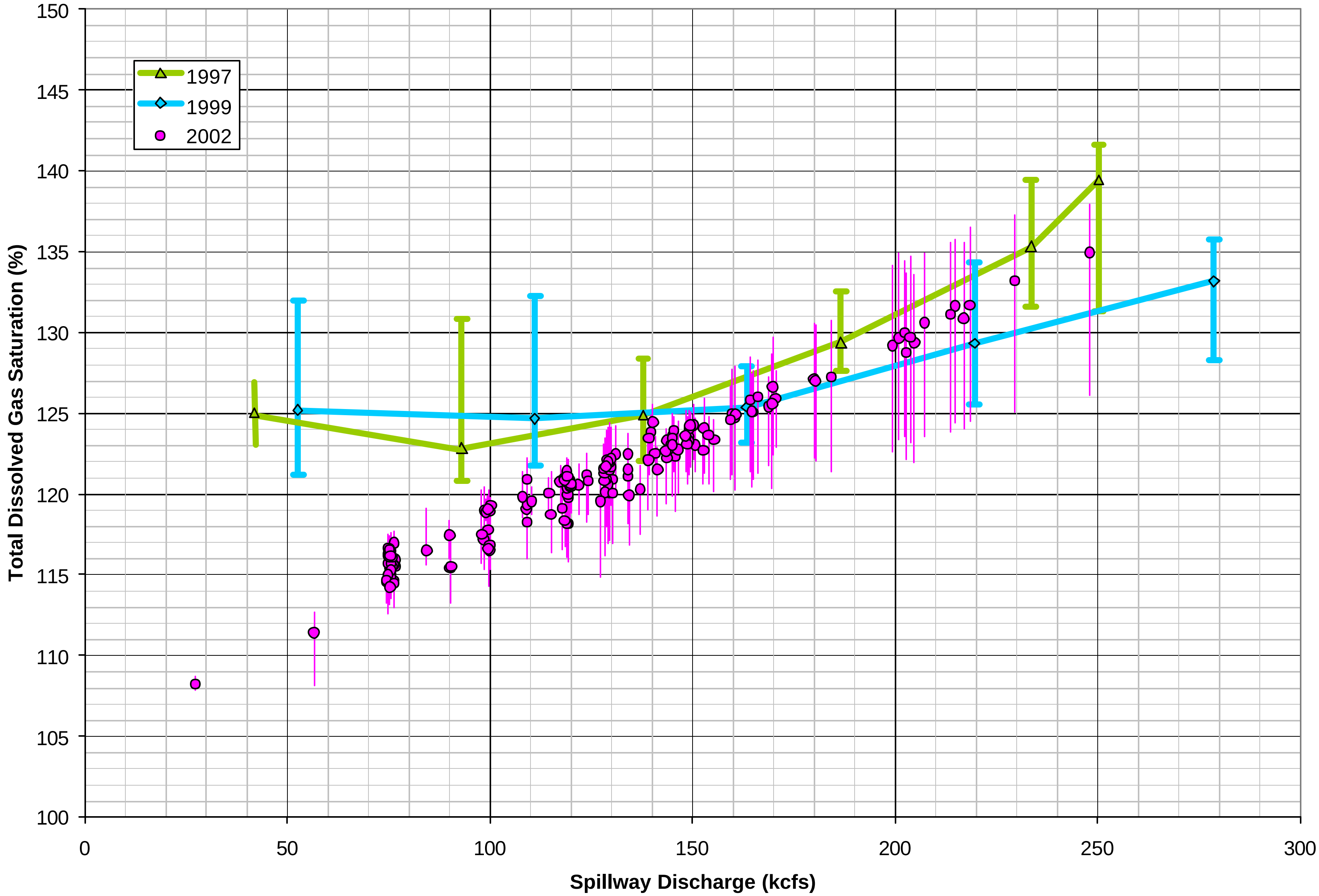

Figure 27. Average cross sectional total dissolved gas saturation in the Bonneville Spillway exit channel versus total spillway discharge
(2002 – standard pattern, 1999 – standard pattern, 1997 – standard pattern without bay 16)

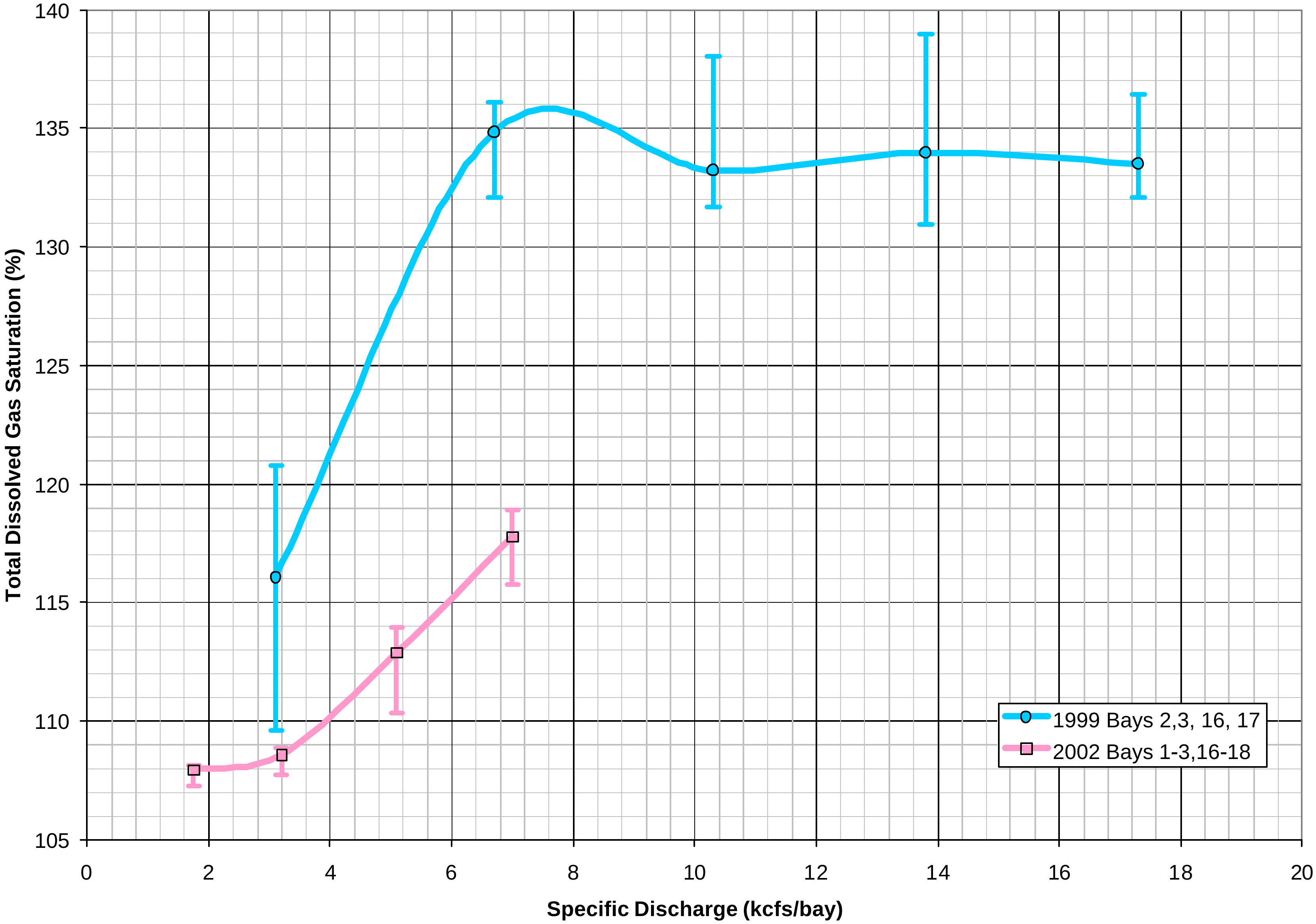

Figure 28. Total dissolved gas saturation as a function of specific spill discharge in the Bonneville spillway exit channel. (1999 – No deflectors, 2002 - El. 7 ft deflectors)

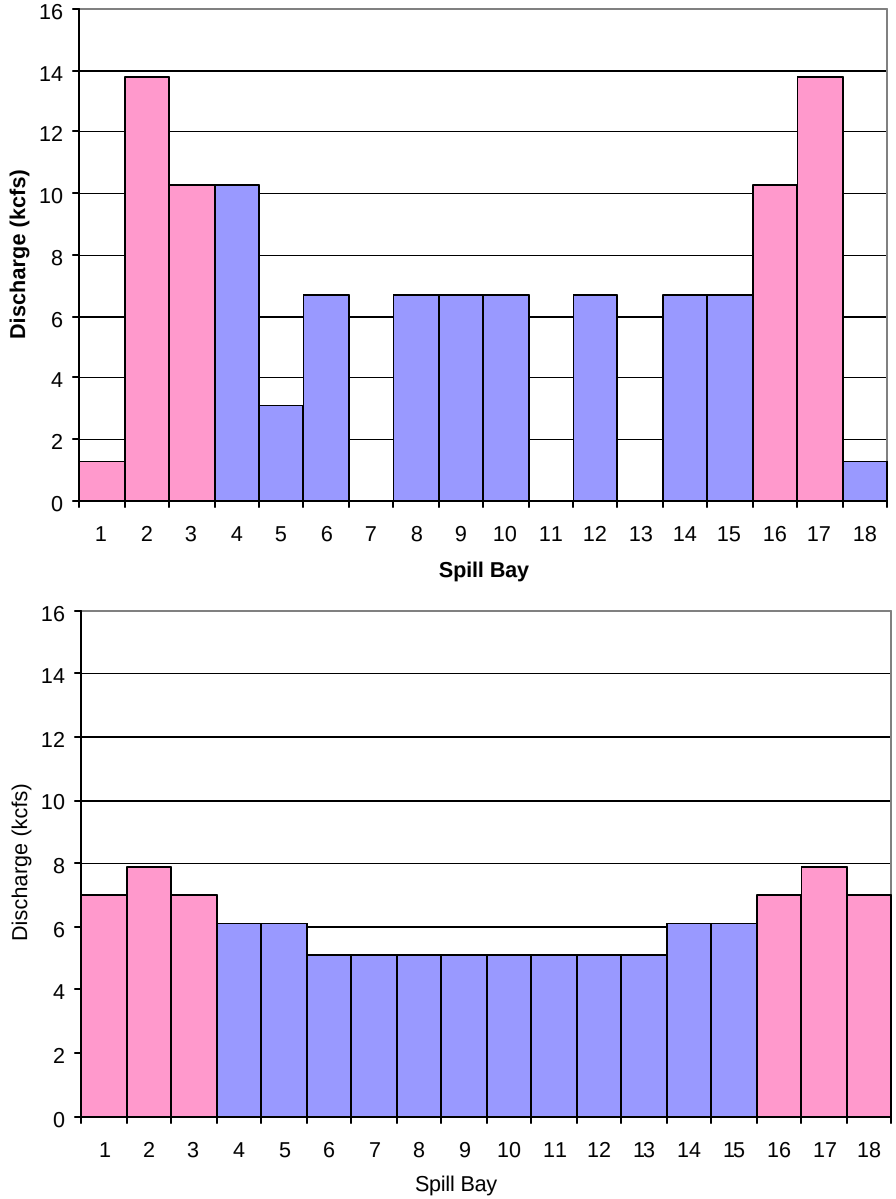

Figure 29. 1999 and 2002 Bonneville standard spill pattern (A. 1999 pattern for Q_{sp}=111.1 kcfs, B. 2002 pattern for Q_{sp}=109.2 kcfs)

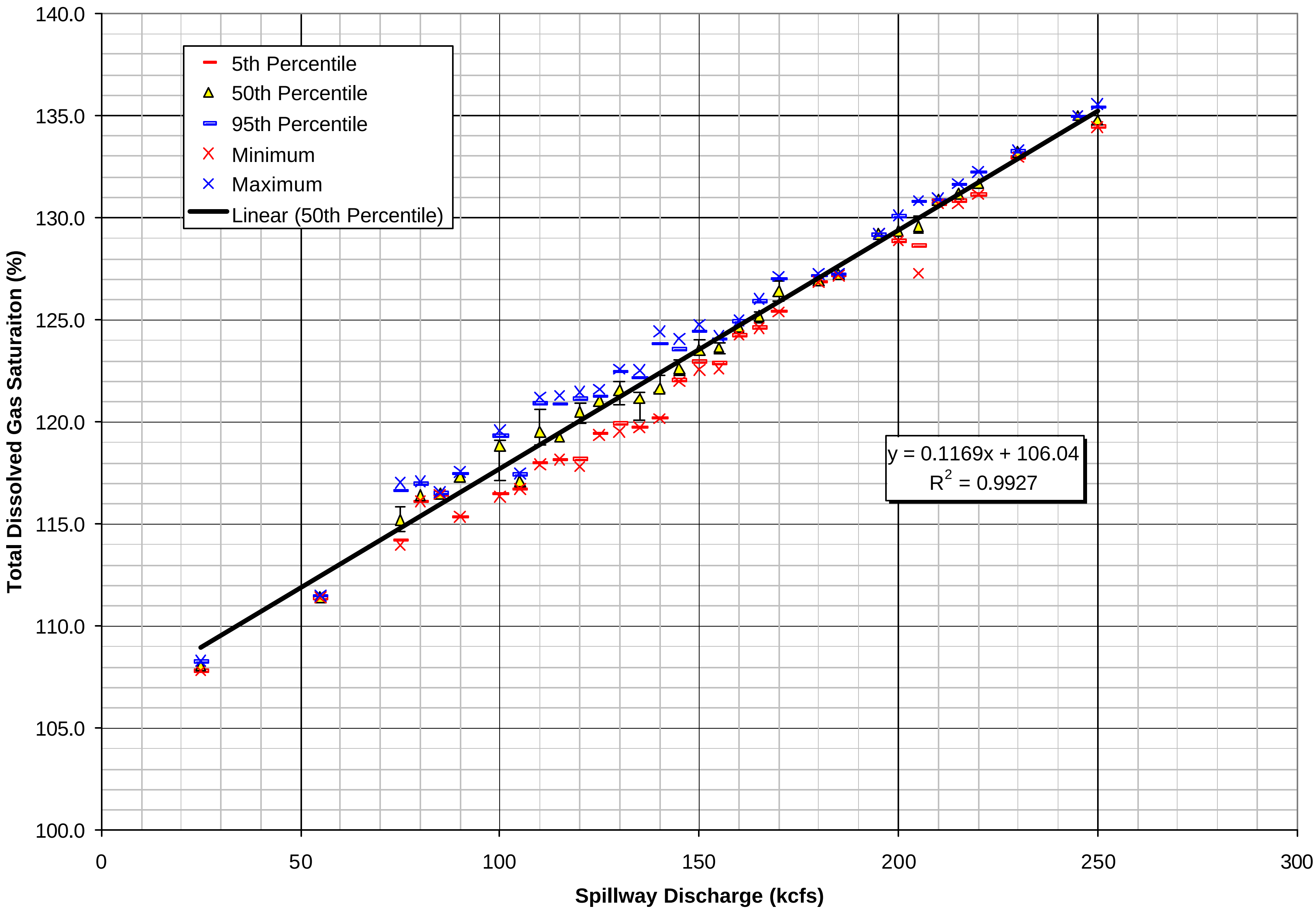

Figure 30. Statistical summary of average cross sectional total dissolved gas saturation in the Bonneville spillway exit channel by spill discharge range (spill range 25-250 kcfs, 5 kcfs increments)

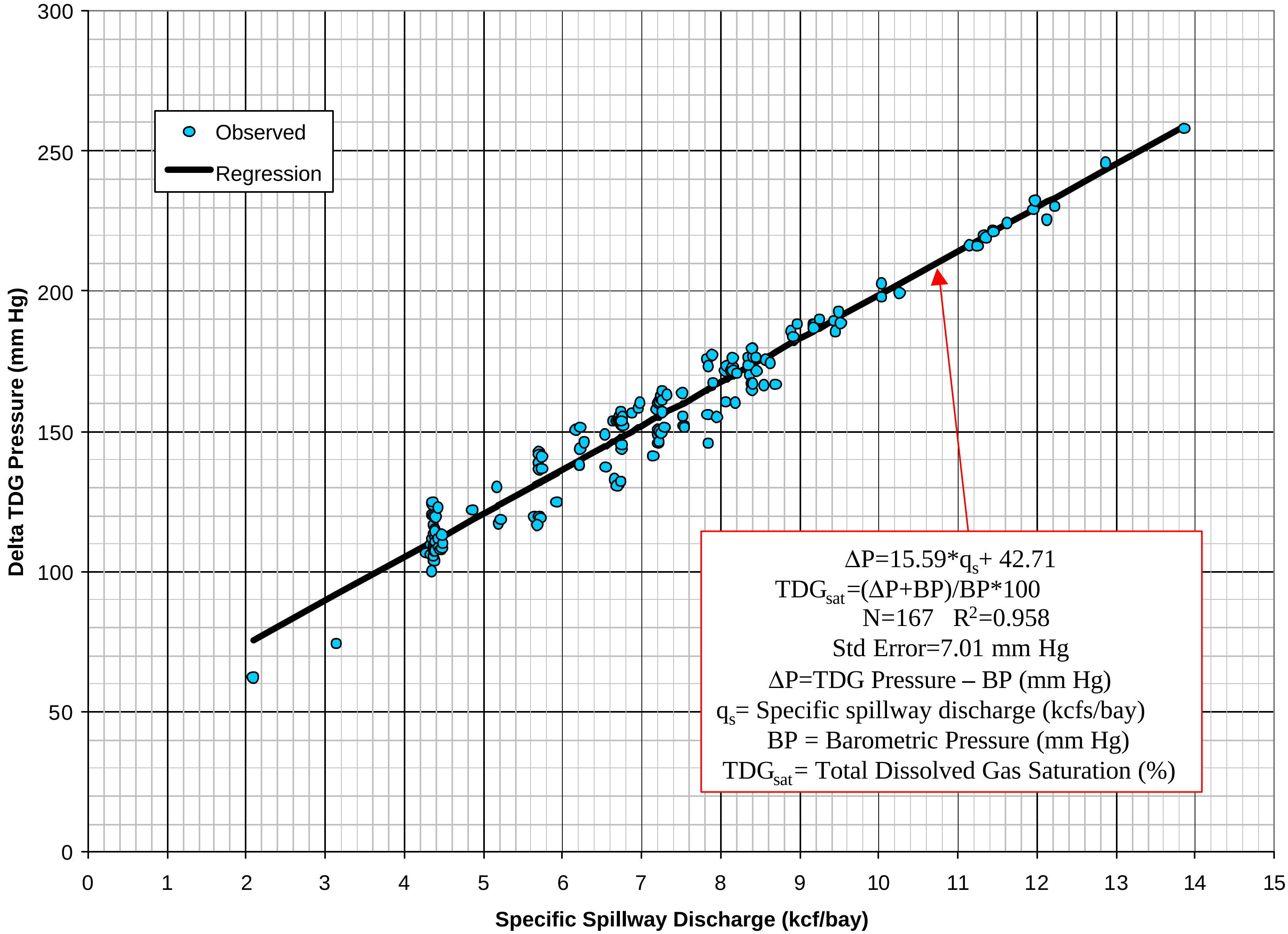

Figure 31. Observed and calculated average cross sectional delta total dissolved gas pressure in the Bonneville spillway exit c hannel as a function of unit spillway discharge by event

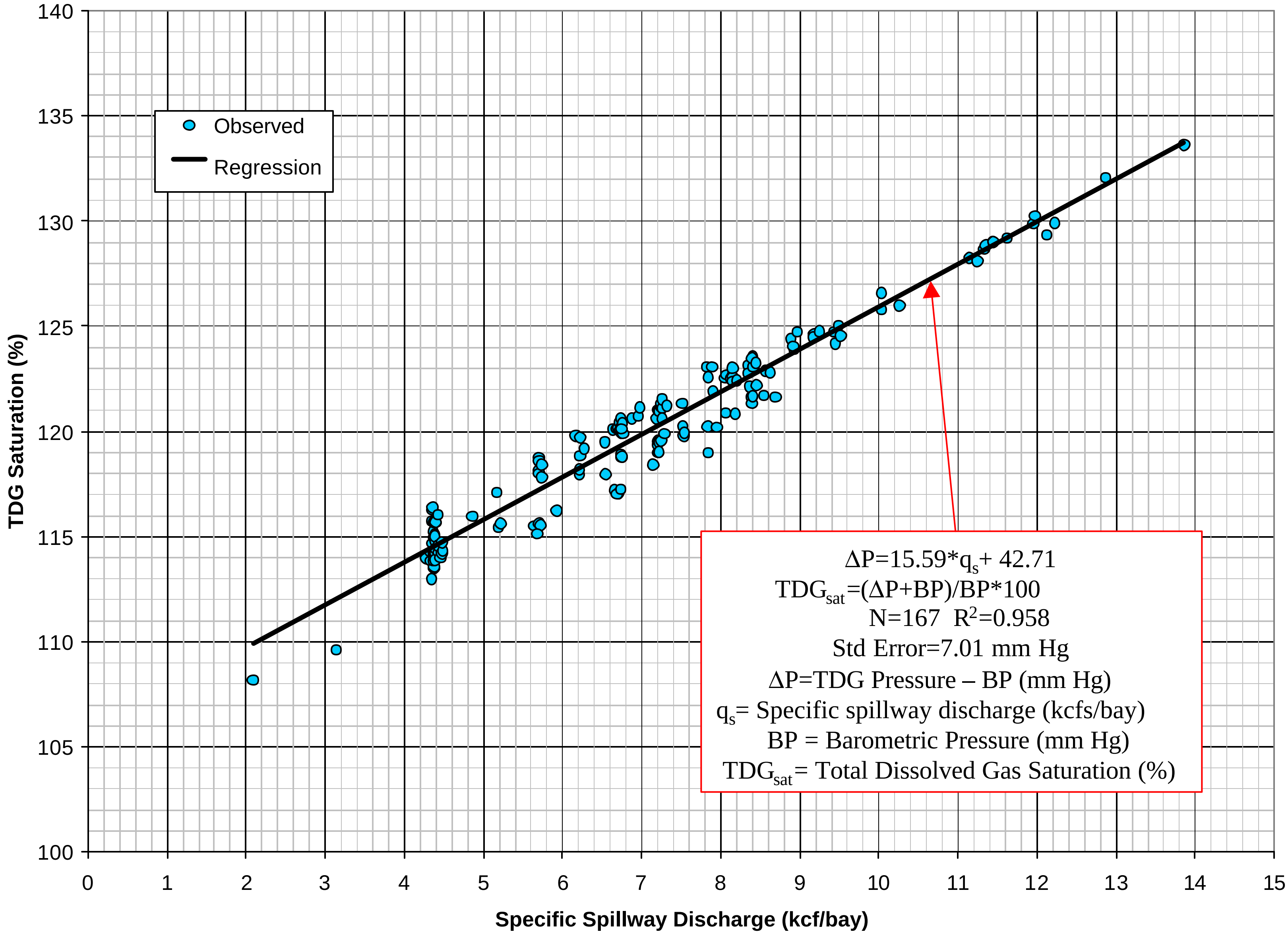

Figure 32. Observed and calculated average cross sectional total dissolved gas saturation in the Bonneville spillway exit channel as a function of unit spillway discharge by event

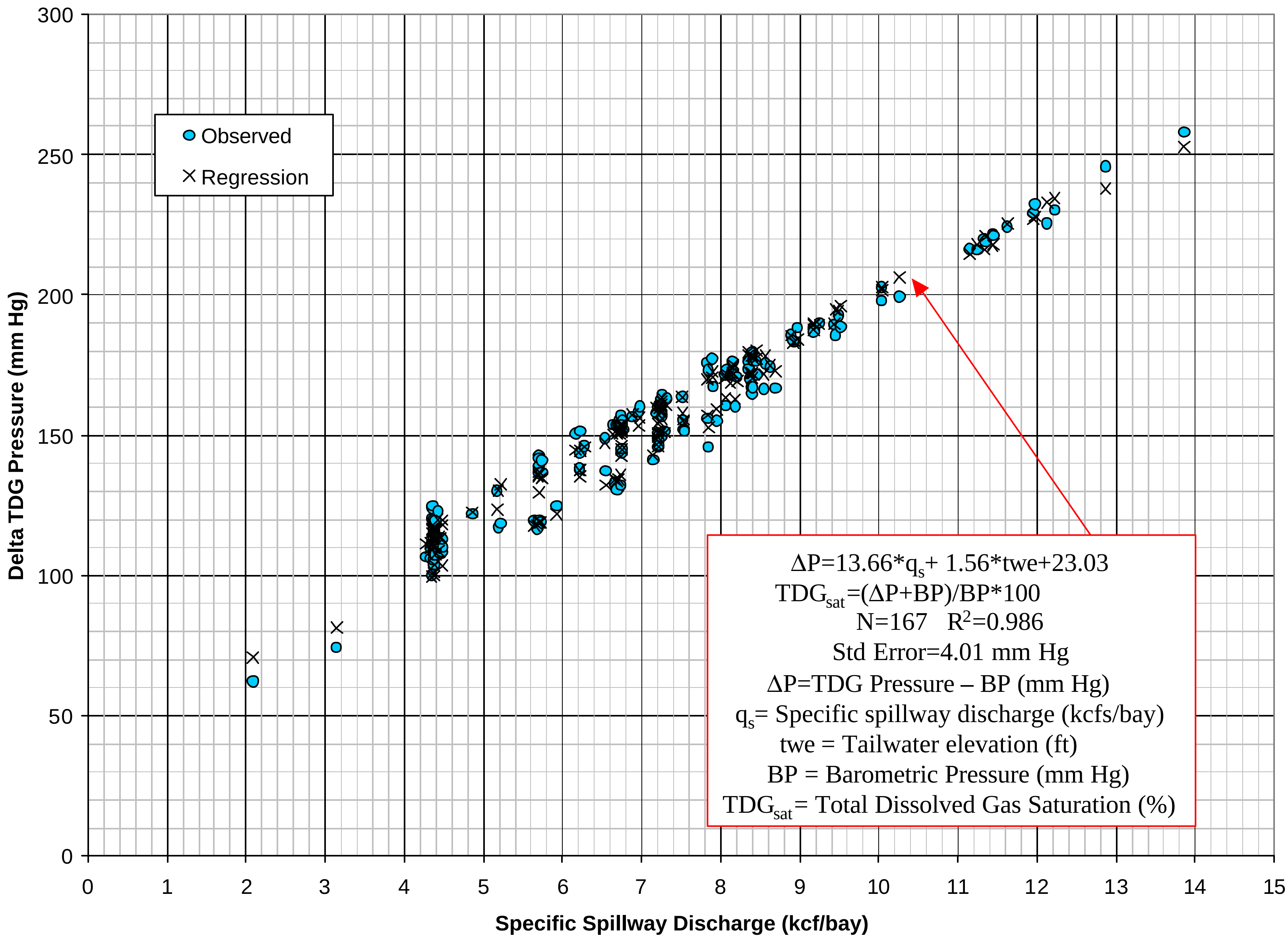

Figure 33. Observed and calculated average cross-sectional delta total dissolved gas pressure in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge by event

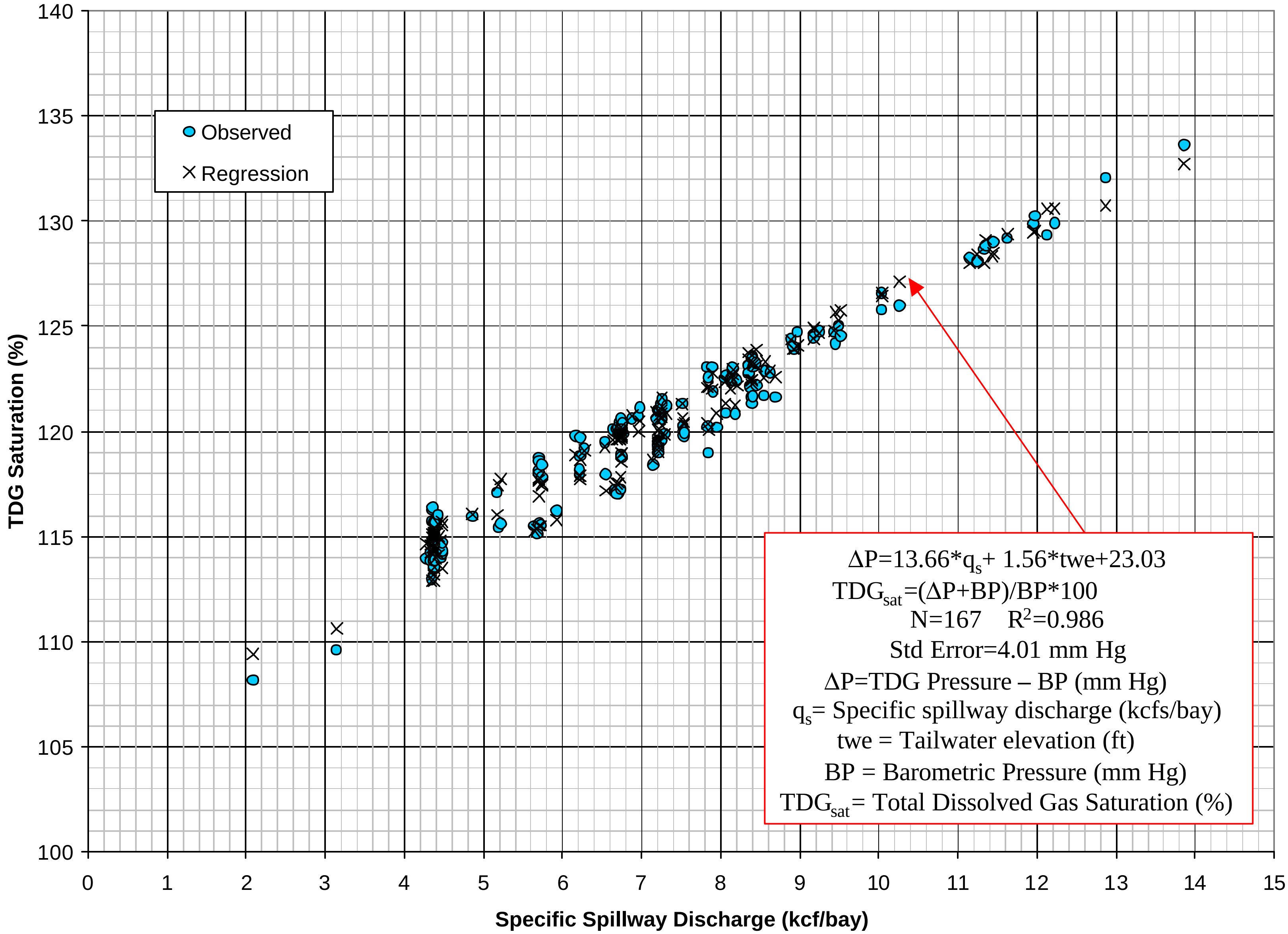

Figure 34. Observed and calculated average cross-sectional total dissolved gas saturation in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge by event

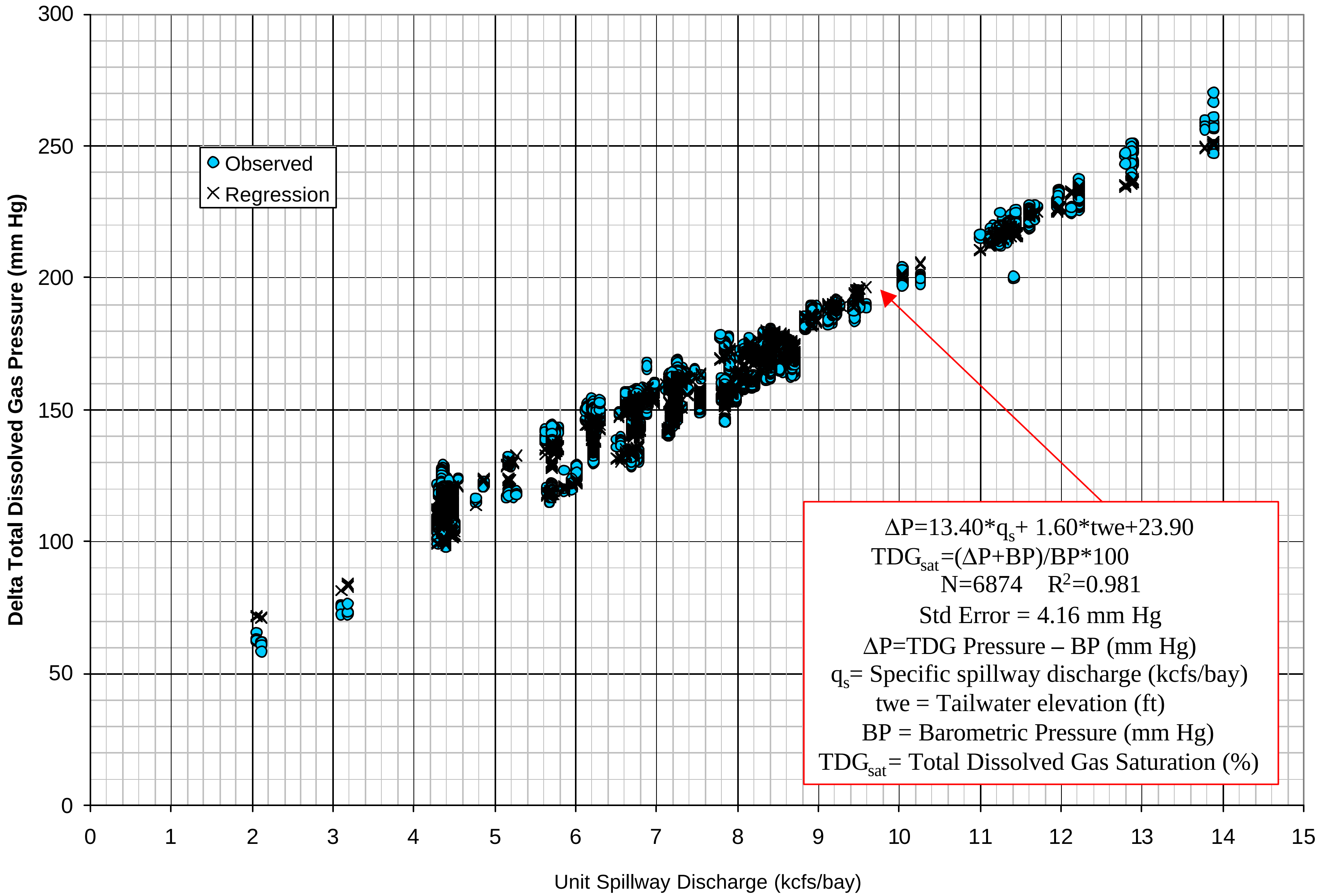

Figure 35. Observed and calculated average cross-sectional delta total dissolved gas pressure in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge (filtered 15-minute observations)

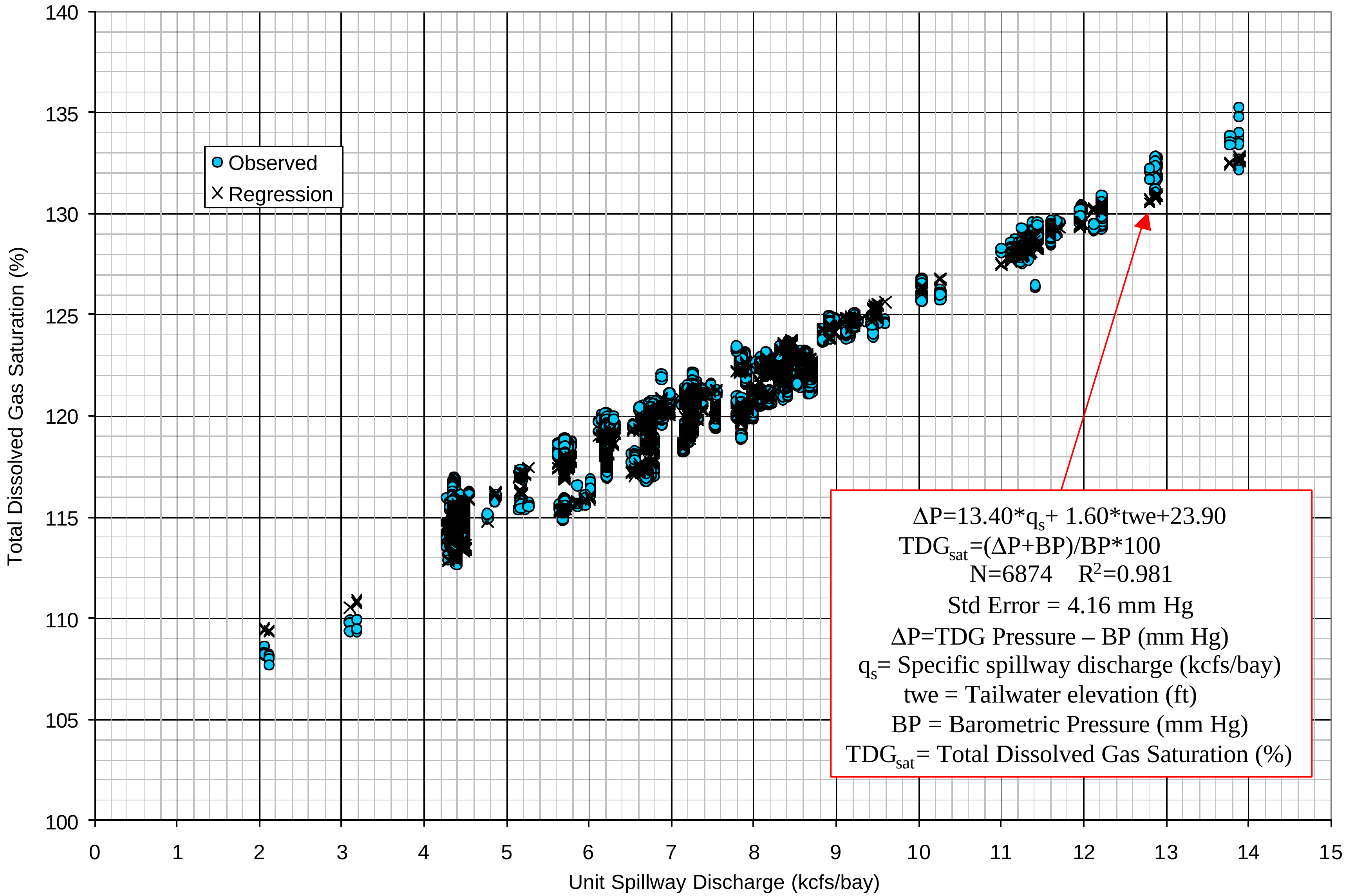

Figure 36. Observed and calculated average cross-sectional delta total dissolved gas pressure in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge (filtered 15-minute observations)

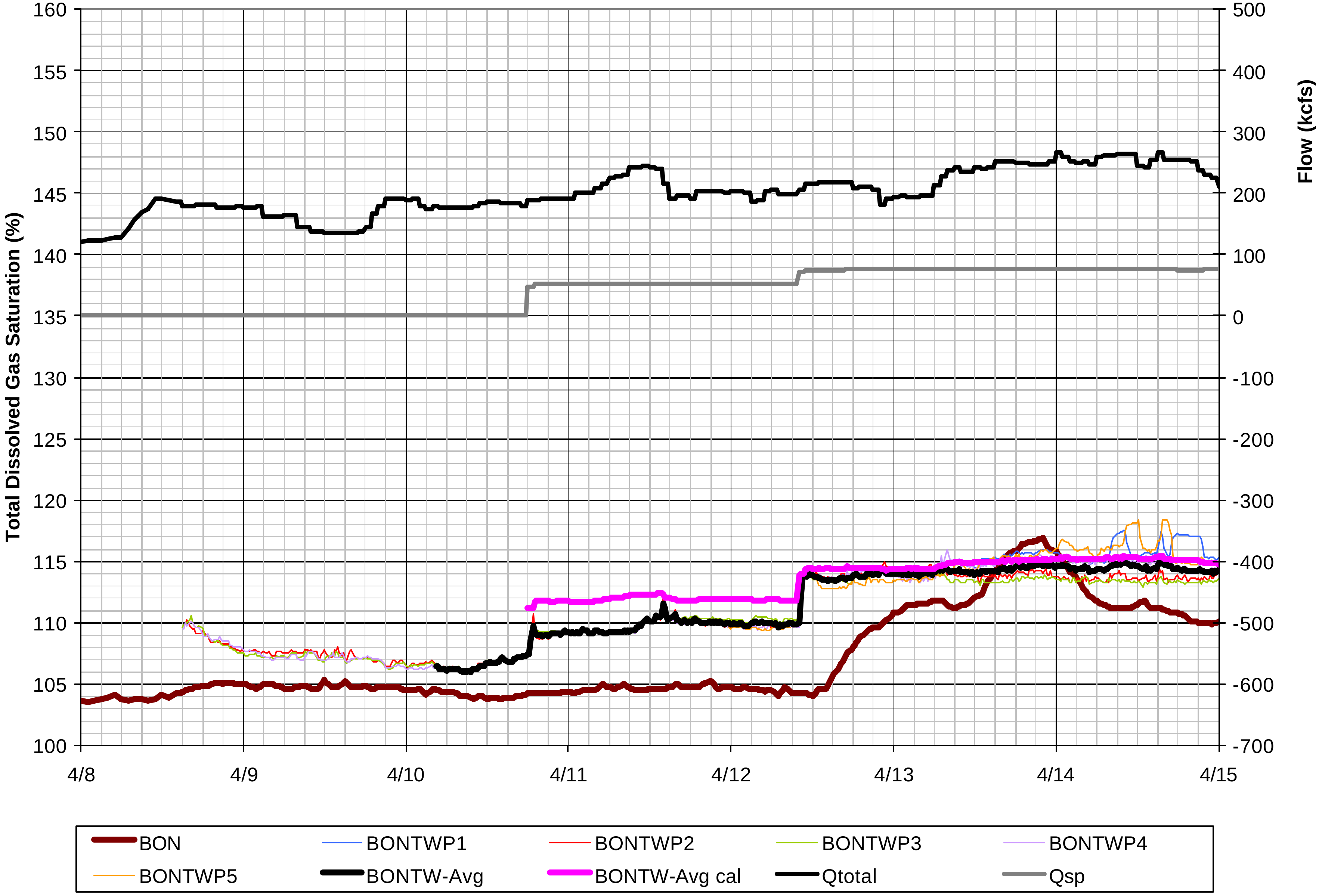

Figure 37a. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 8-14, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

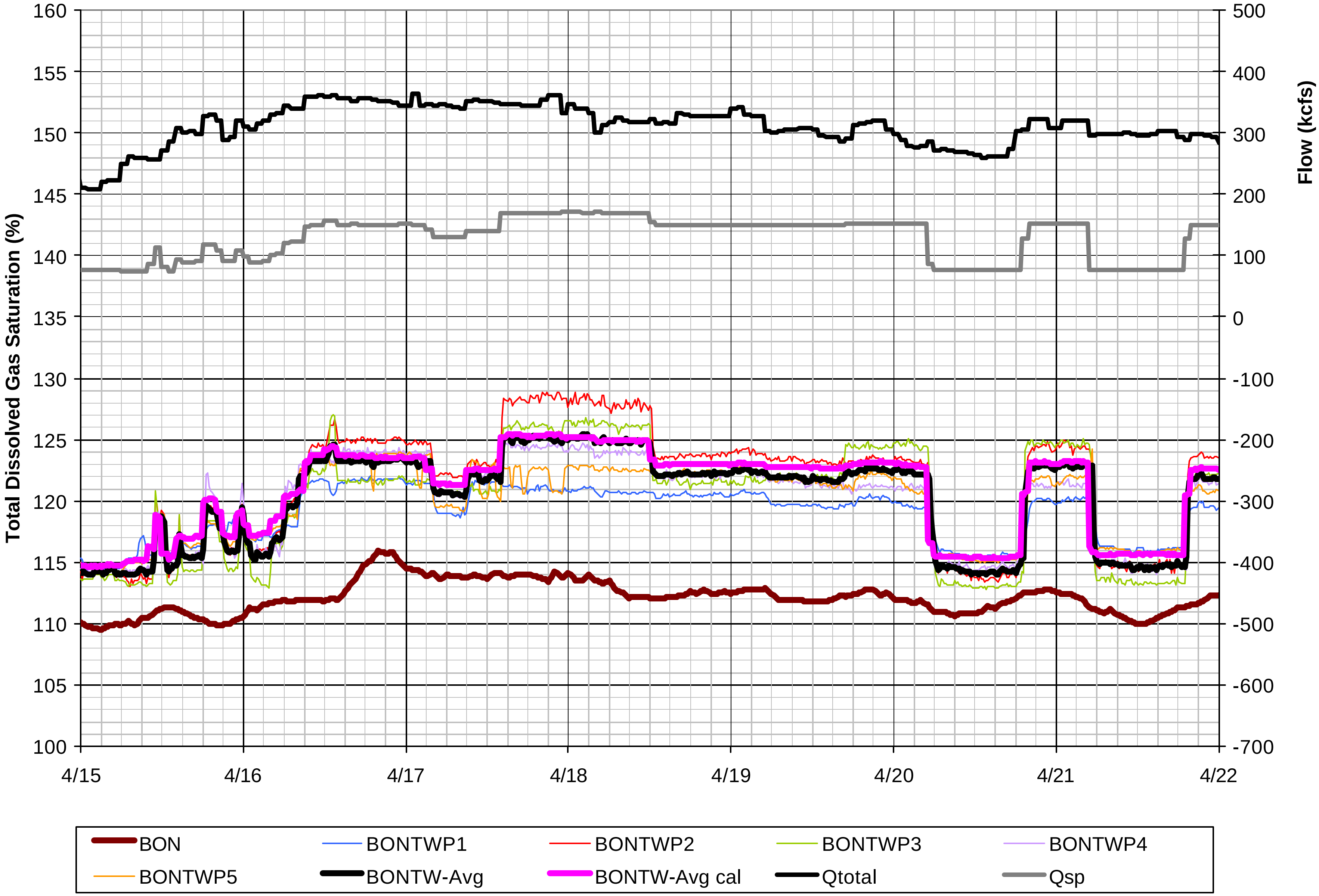

Figure 37b. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 15-21, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage).

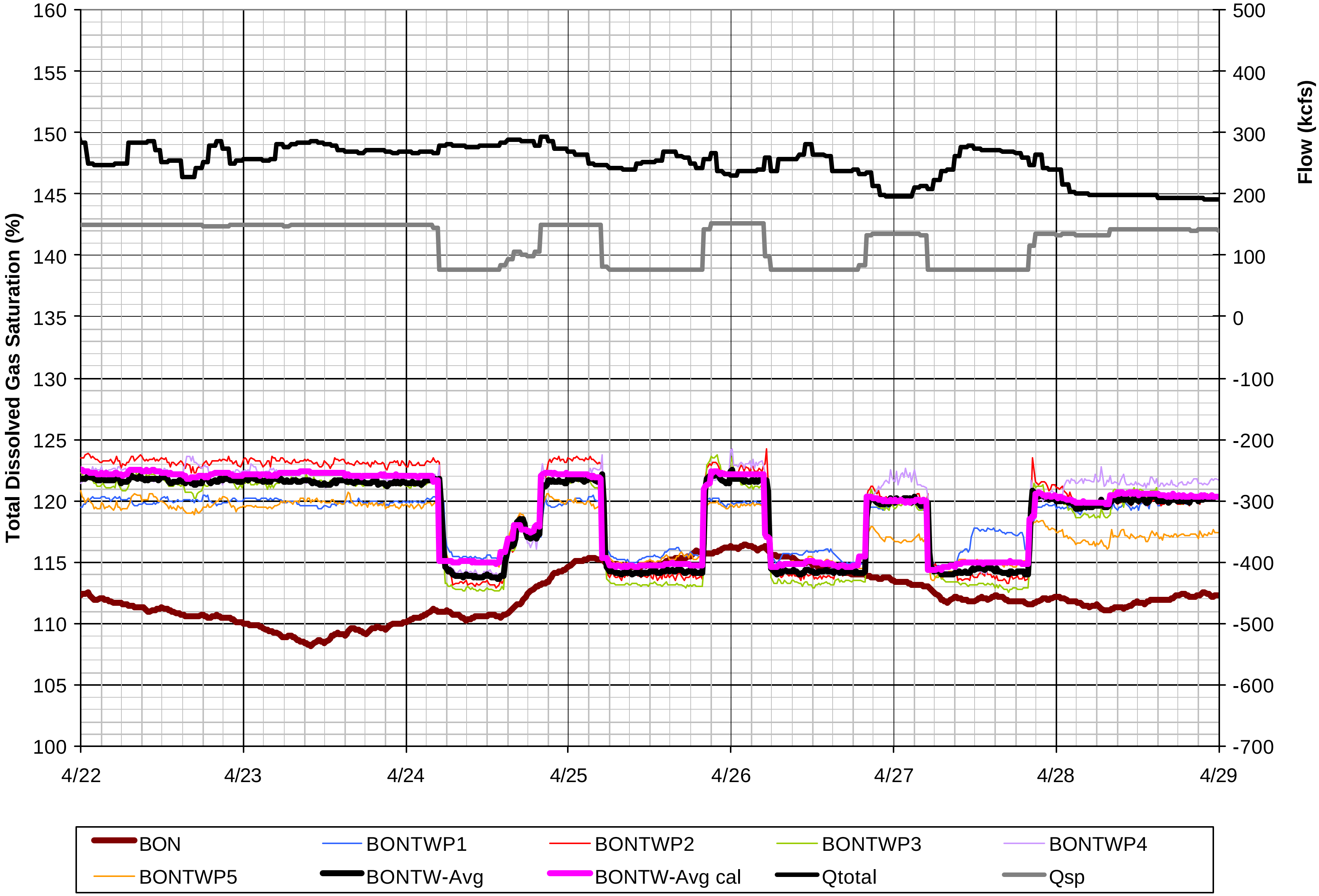

Figure 37c. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, April 22-28, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

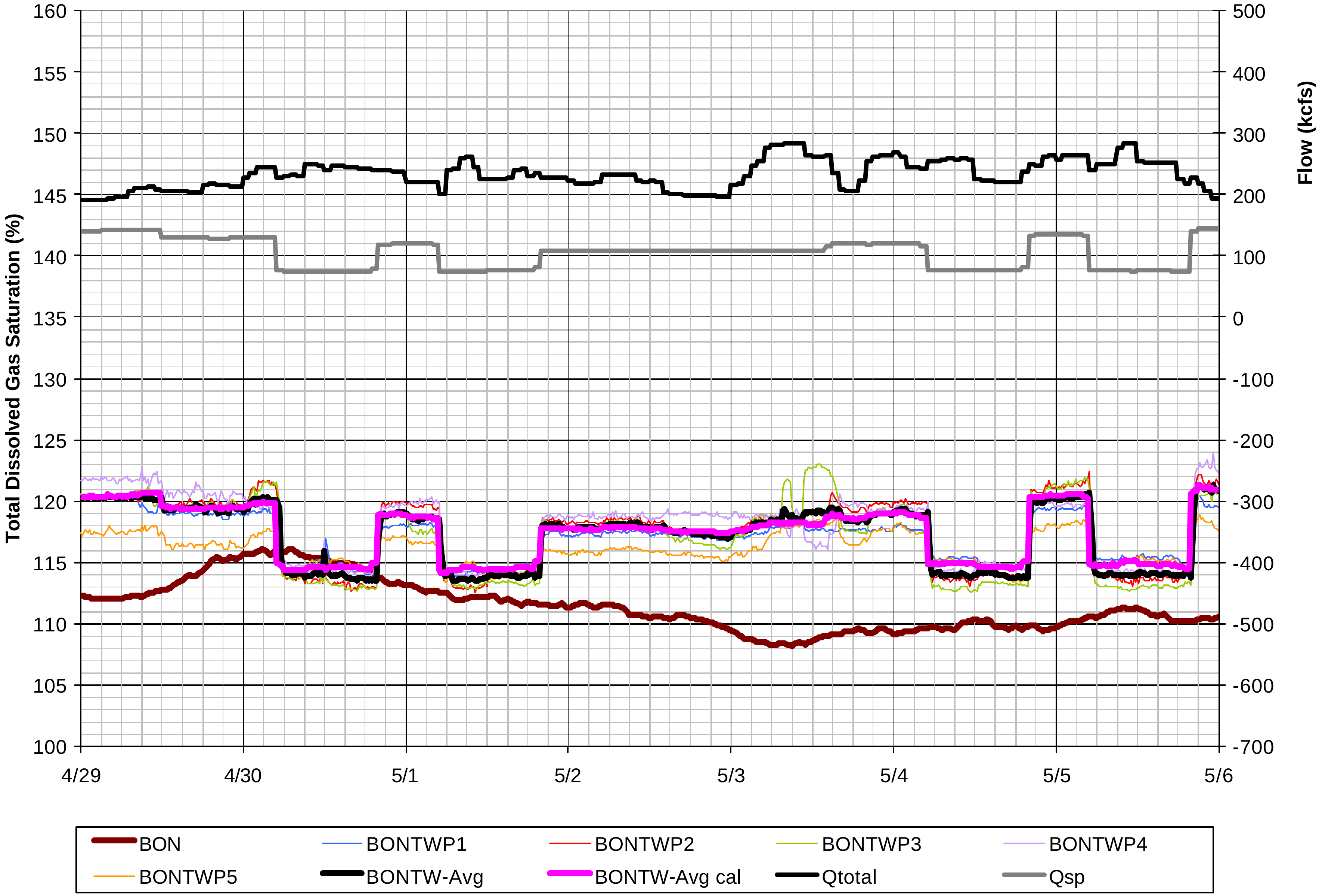

Figure 37d. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, April 29-May 5, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

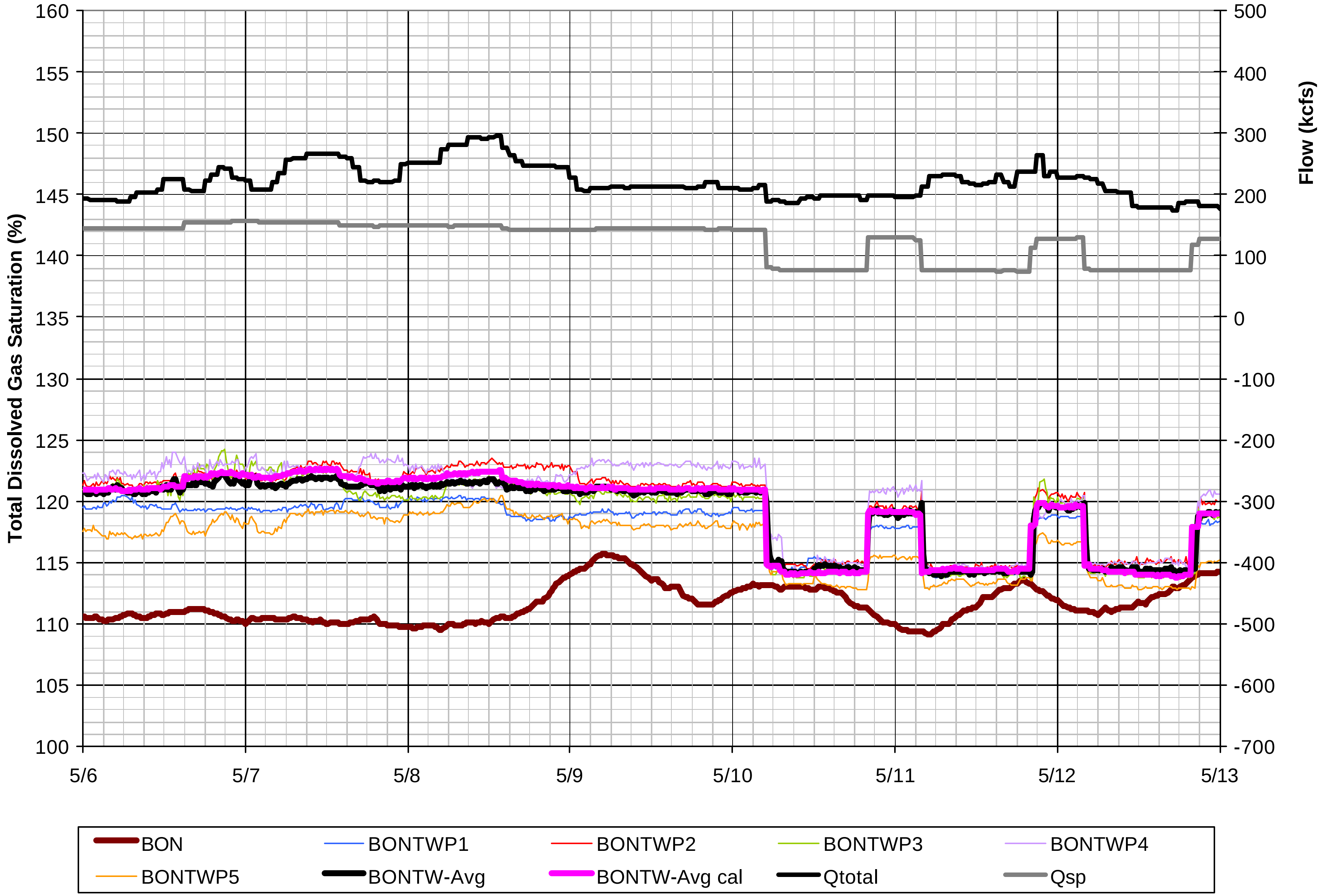

Figure 37e. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, May 6-12, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

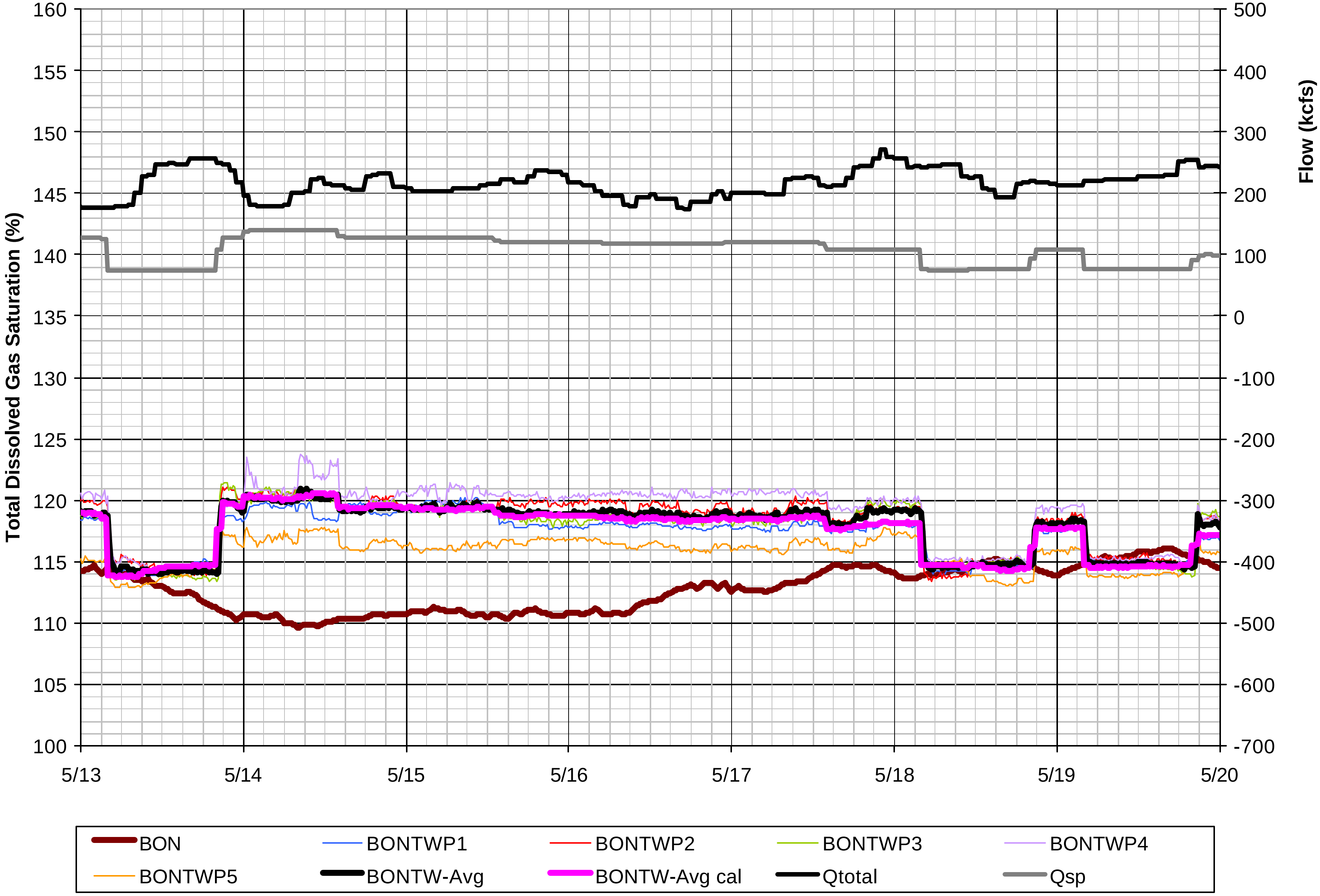

Figure 37f. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, May 13-19, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

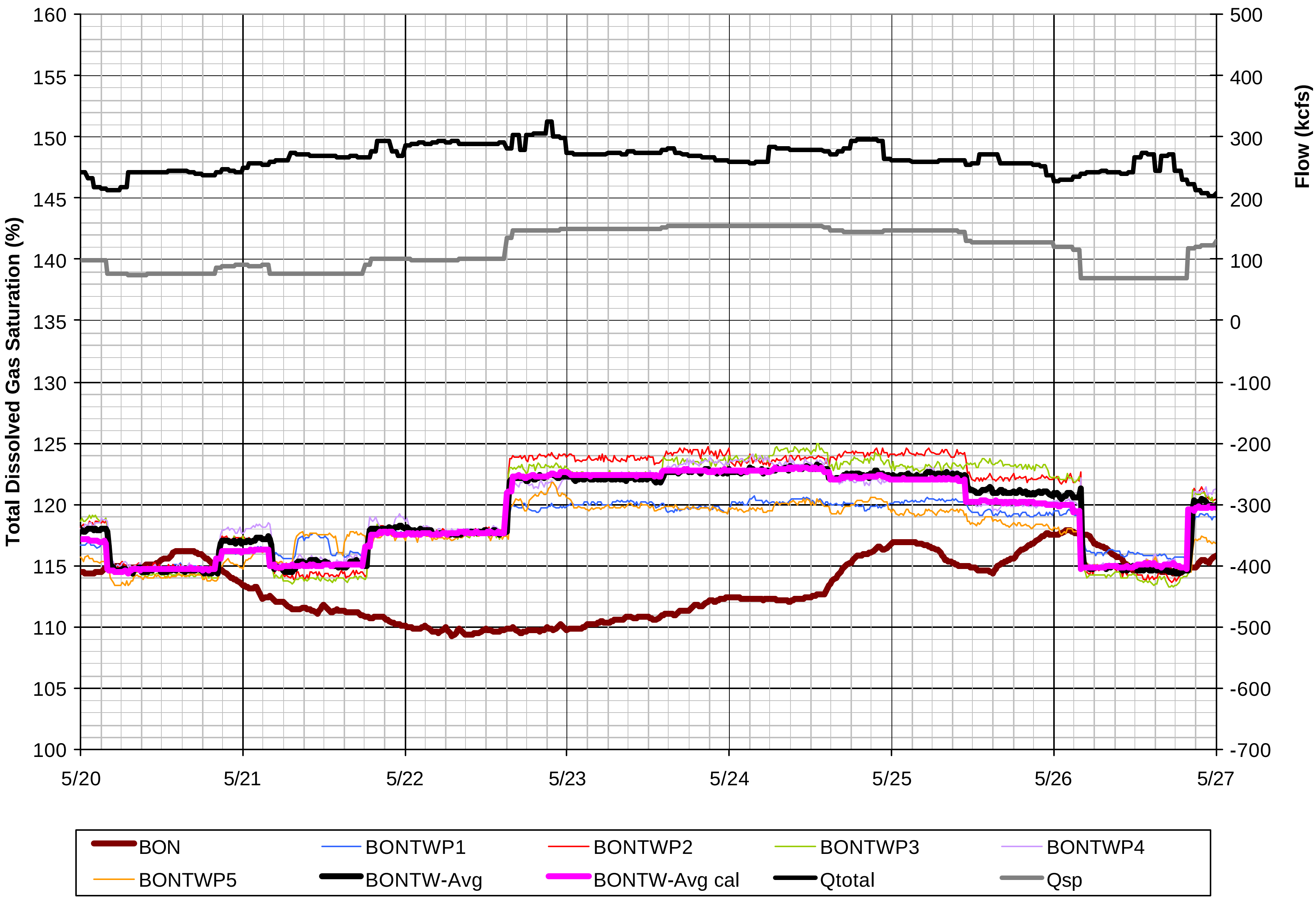

Figure 37g. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, May 20-26, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

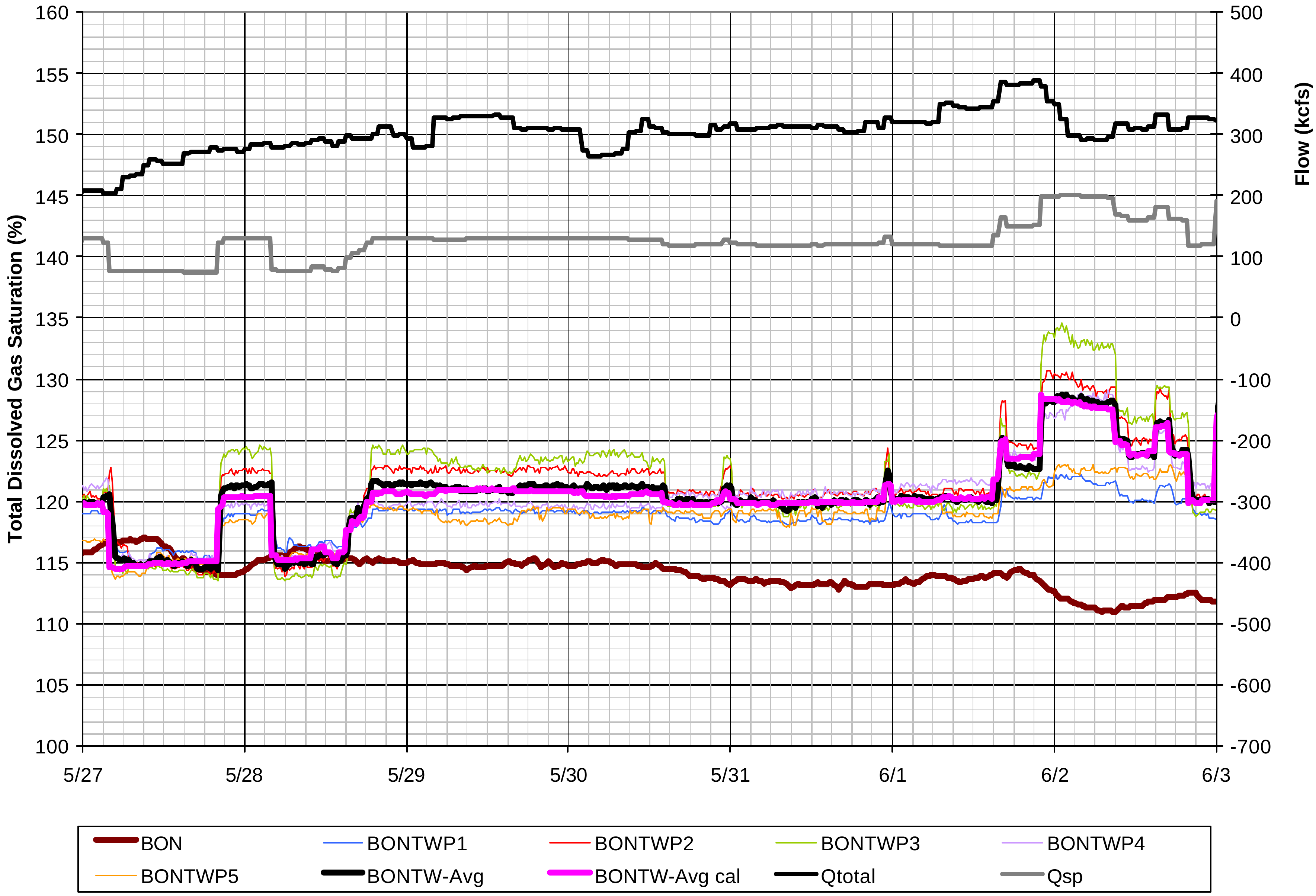

Figure 37h. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, May 27-June 2, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

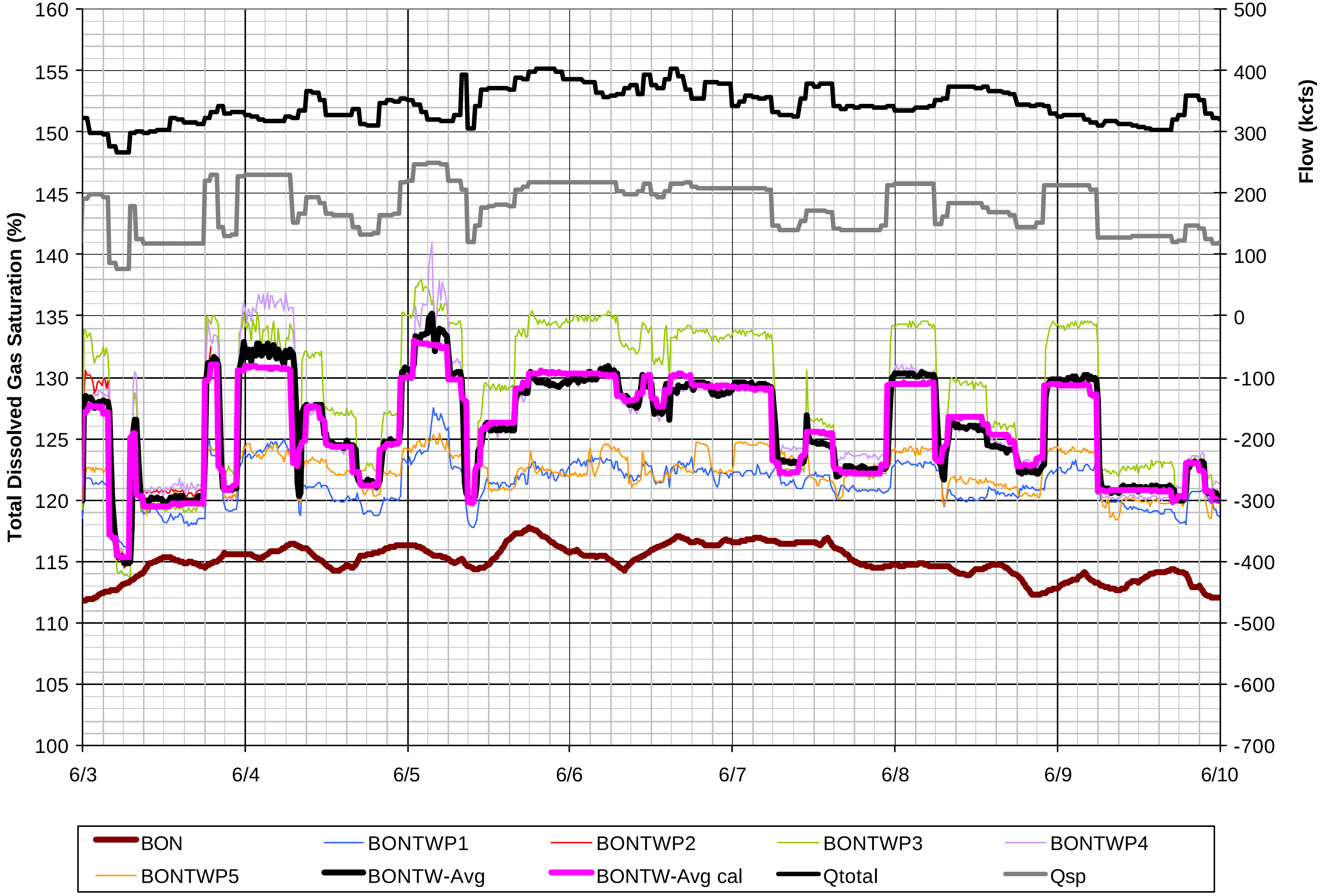

Figure 37i. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, June 3-9, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

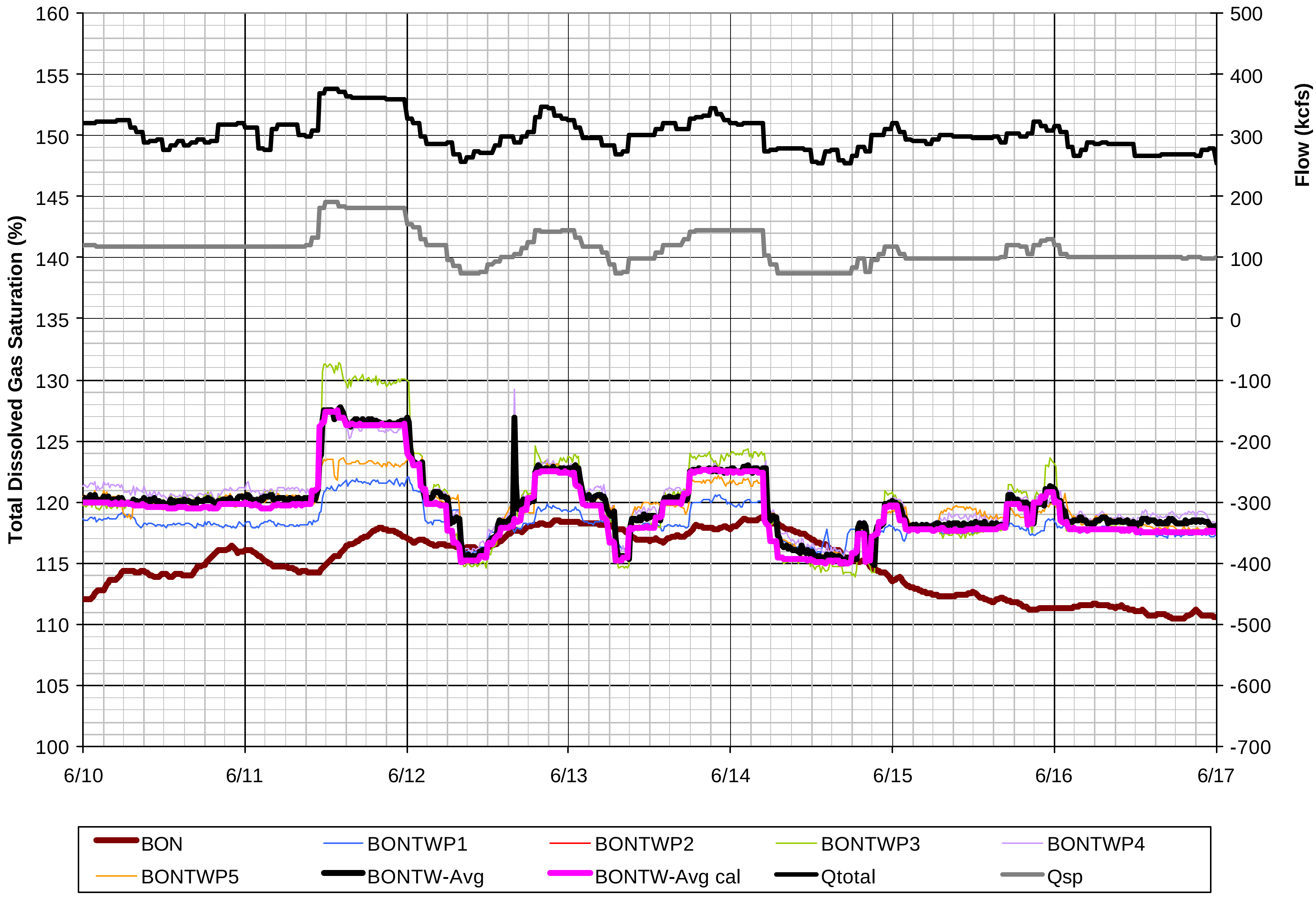

Figure 37j. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, June 10-16, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

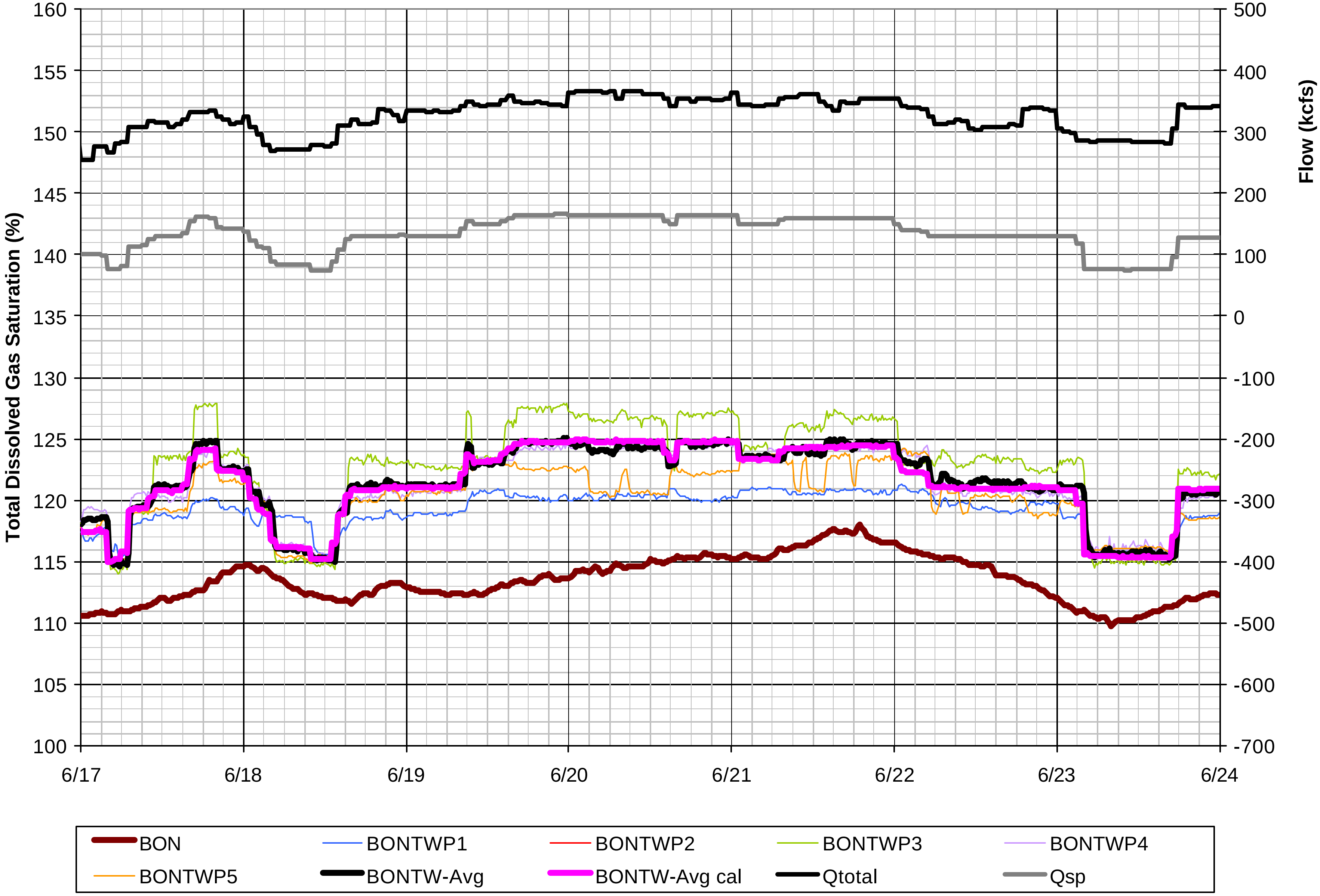

Figure 37k. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, June 17-23, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

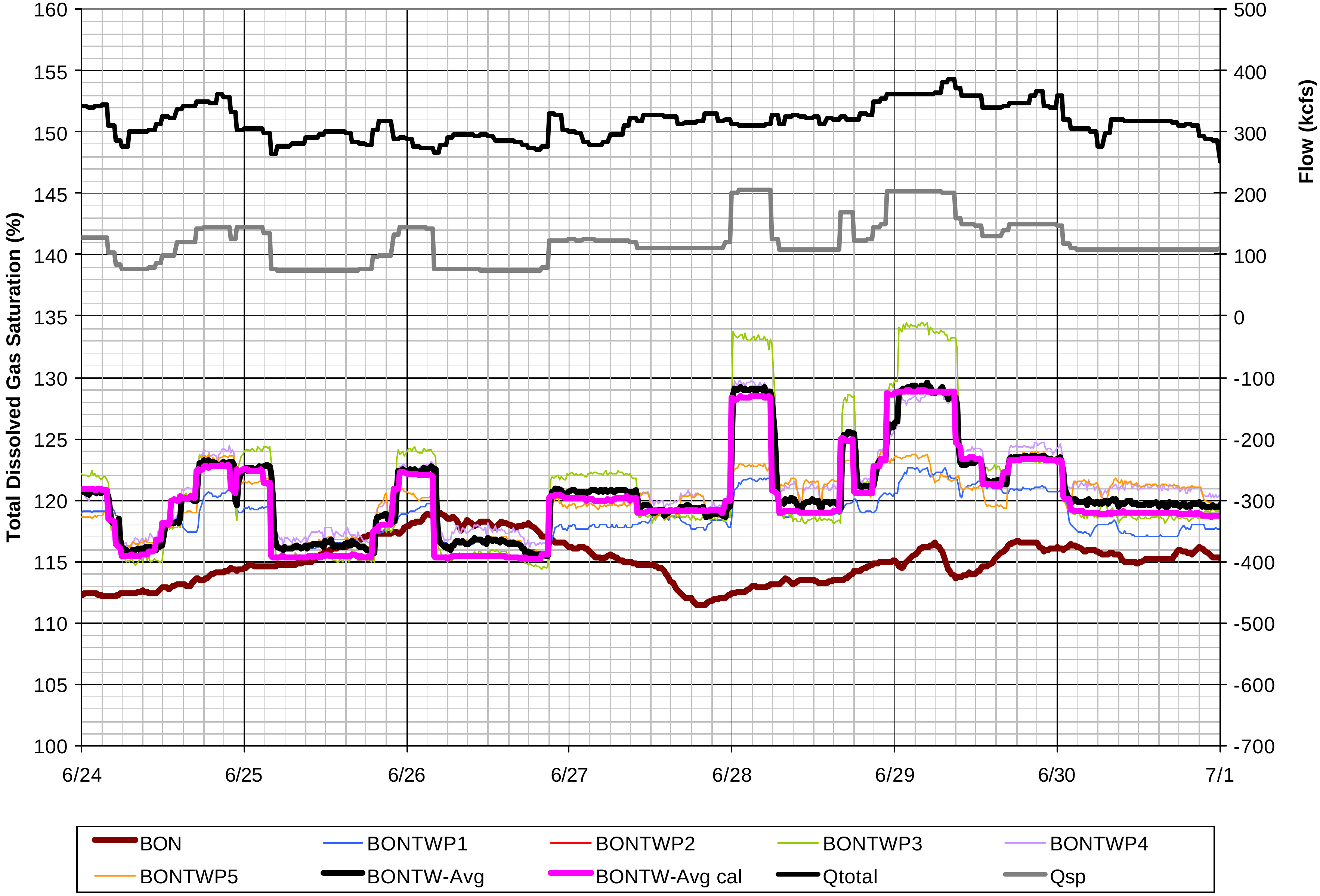

Figure 37l. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, June 24 -30, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

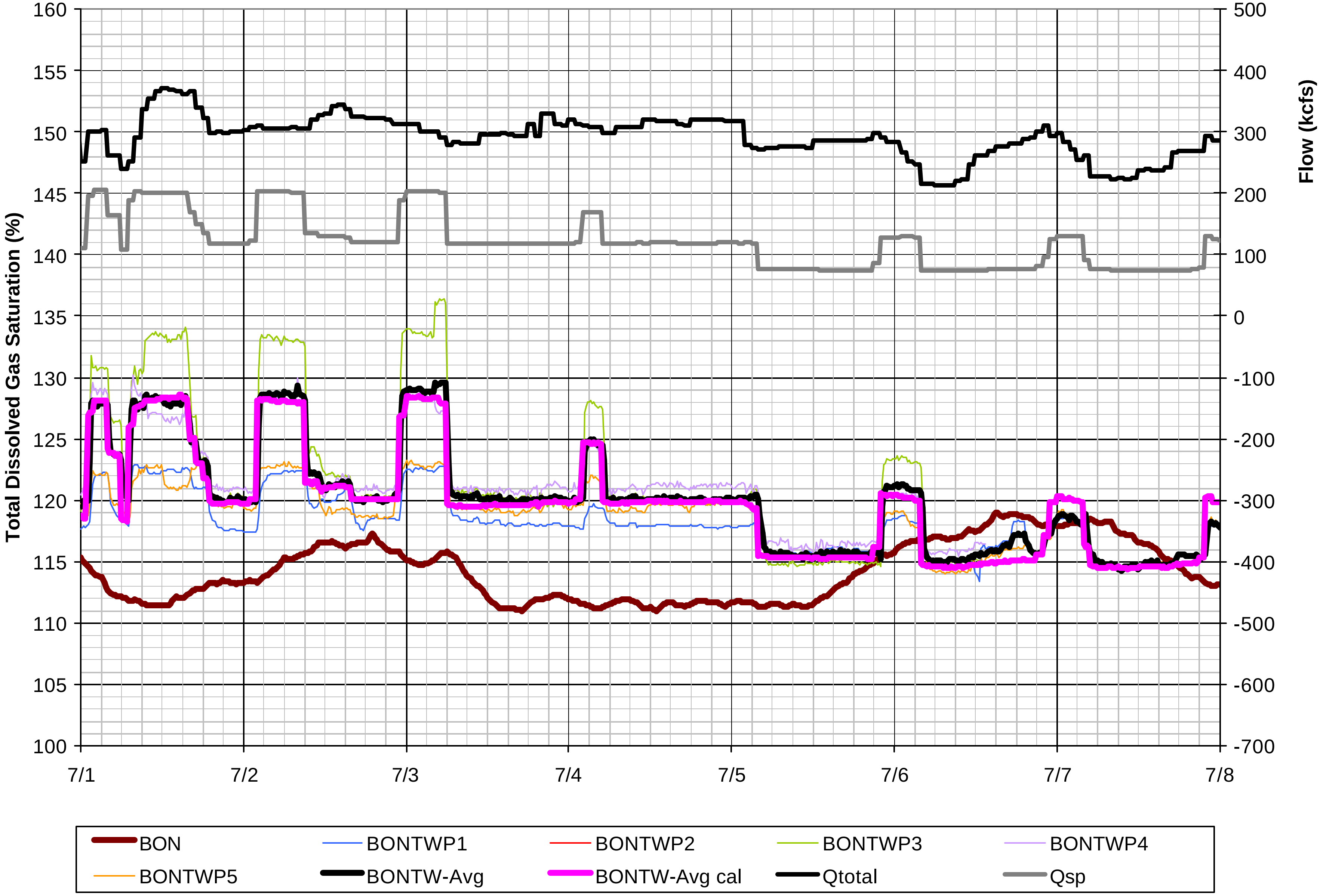

Figure 37m. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, July 1-7, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

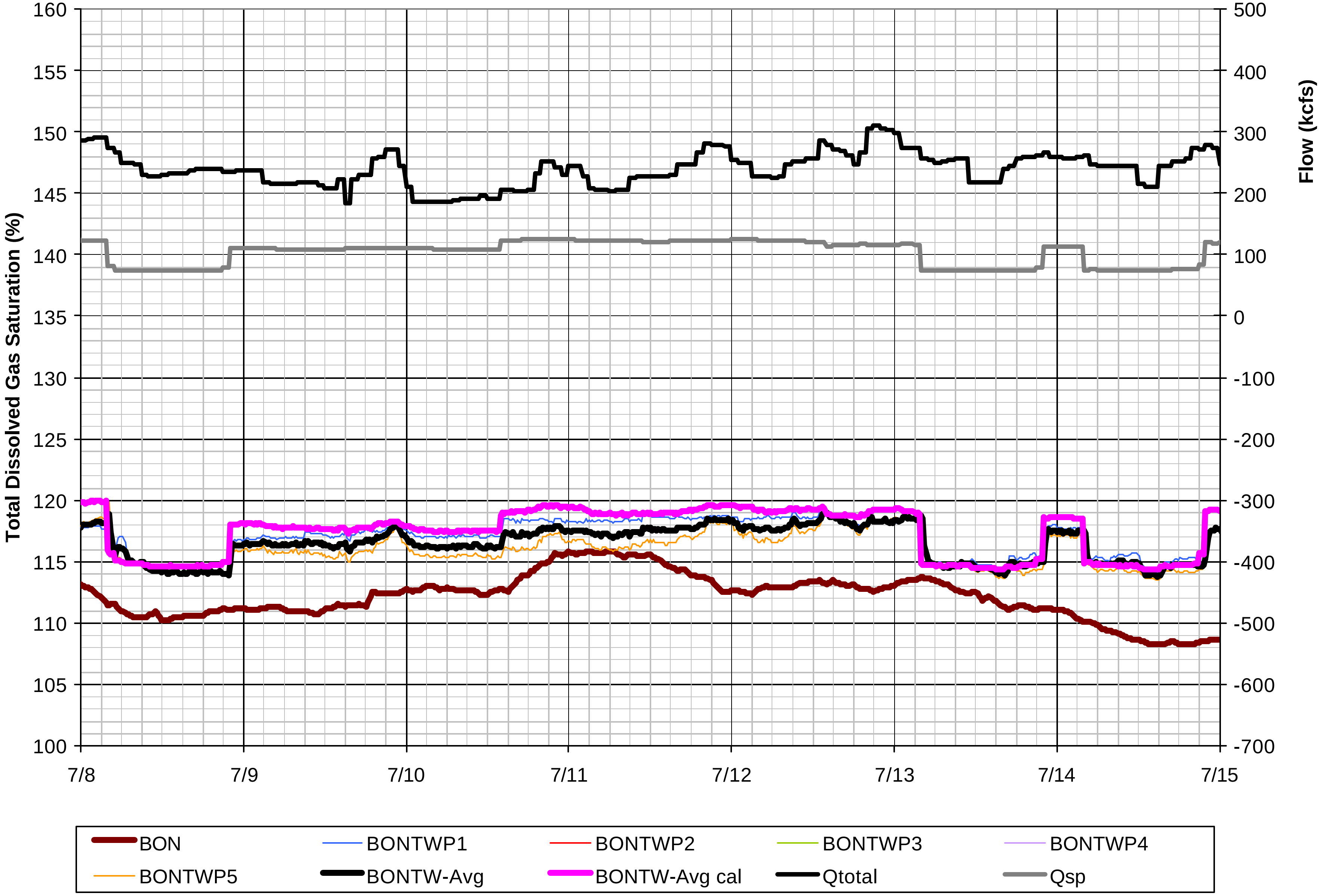

Figure 37n. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, July 8-14, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

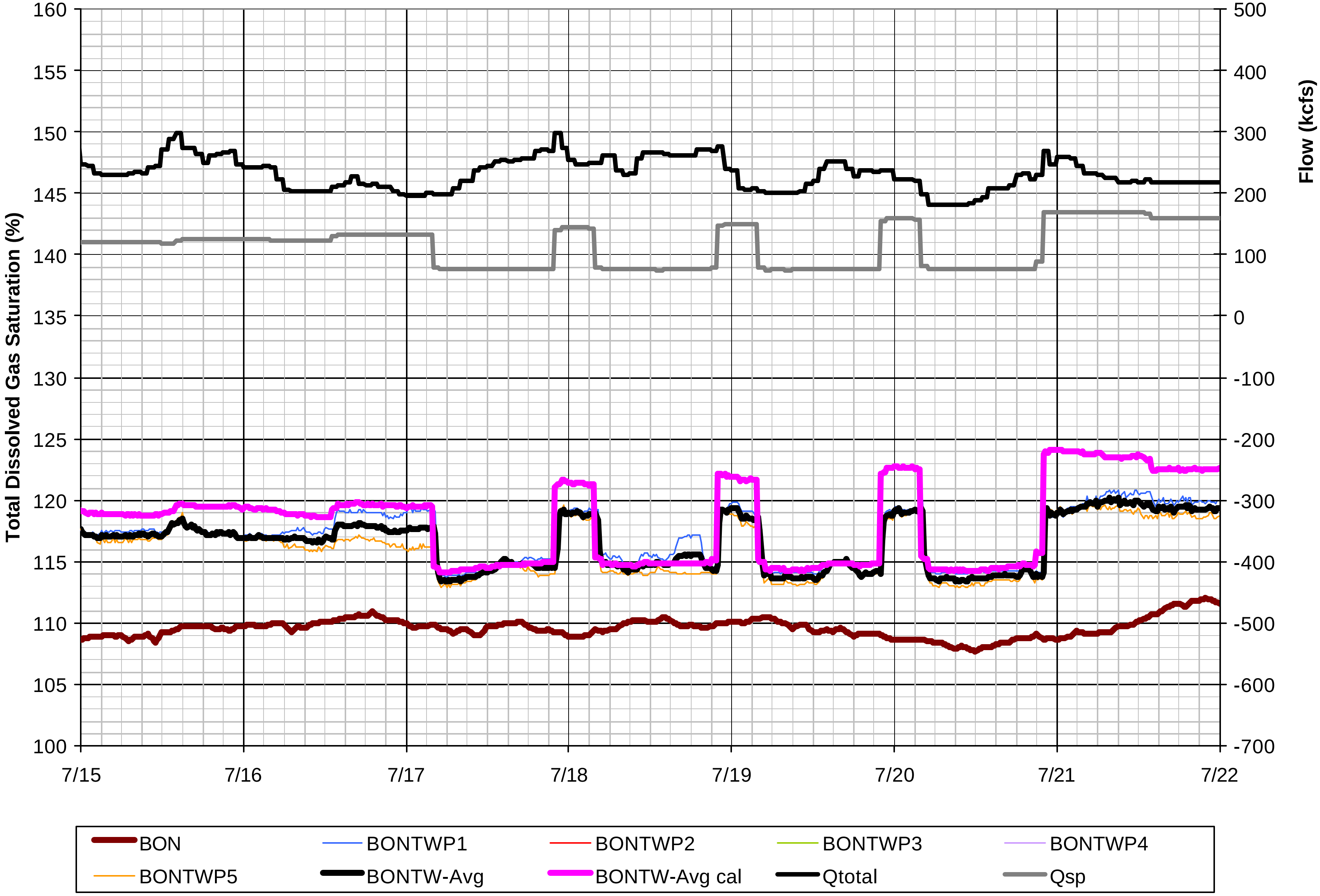

Figure 37o. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, July 15-21, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

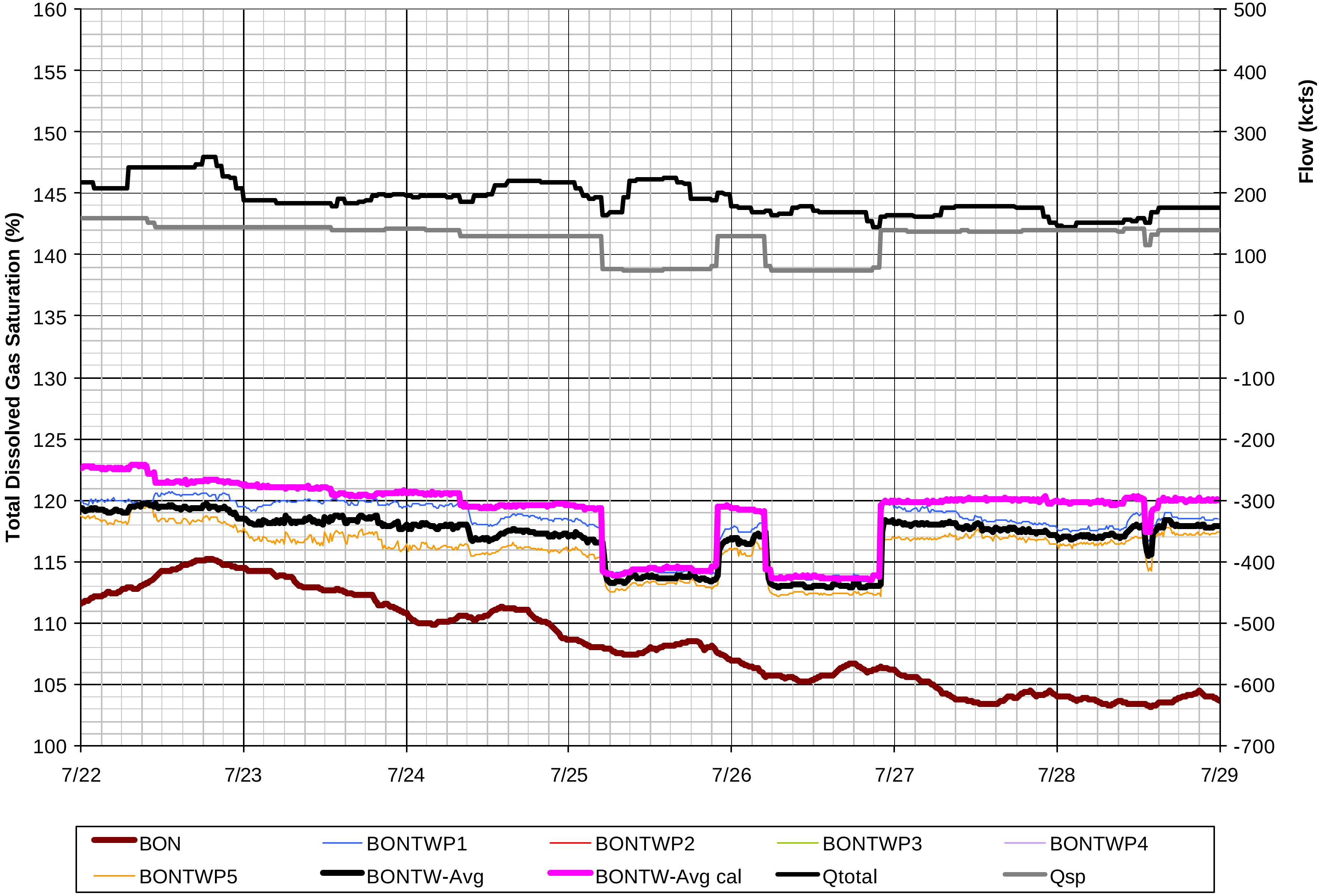

Figure 37p. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, July 22-28, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

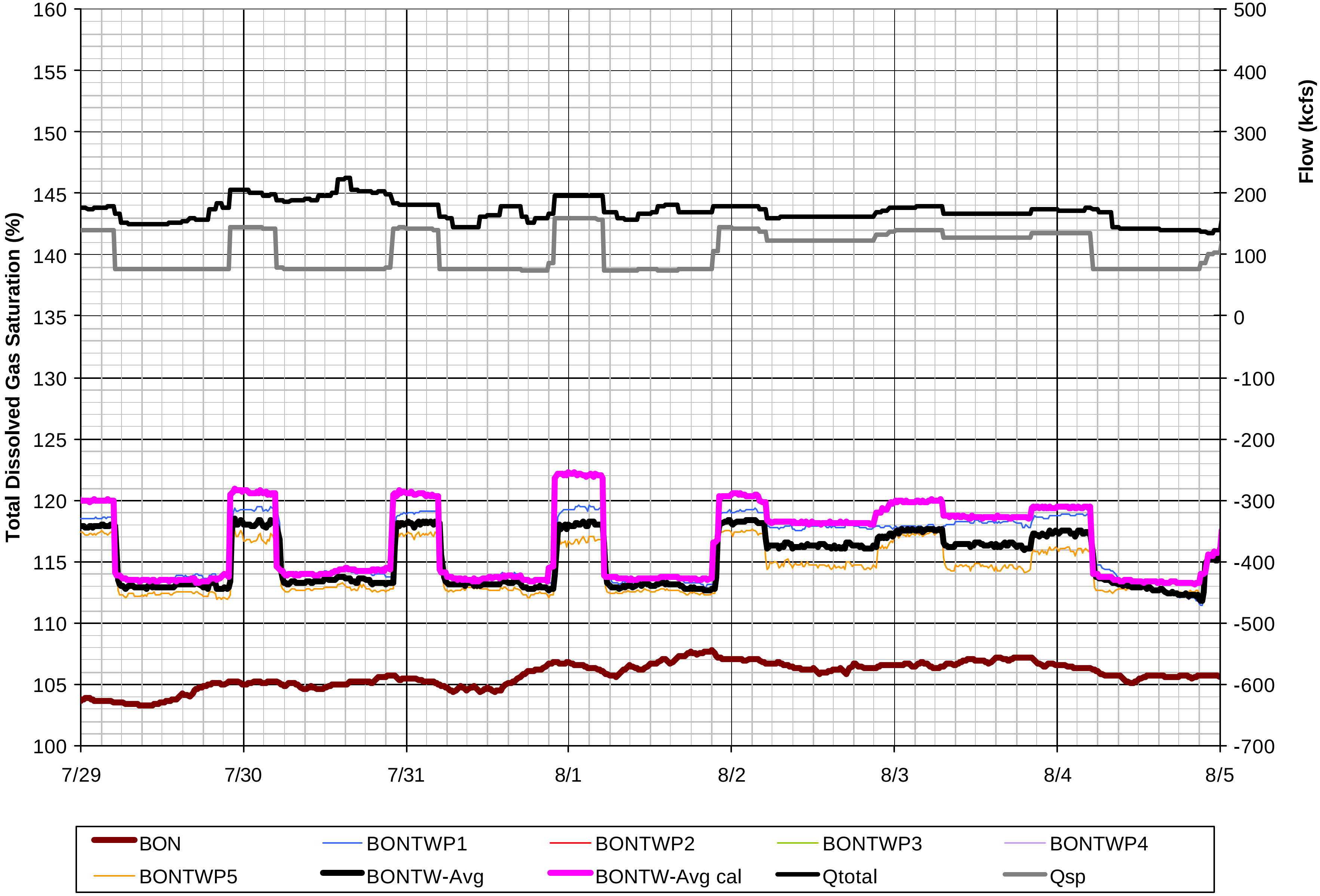

Figure 37q. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, July 29-August 4, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

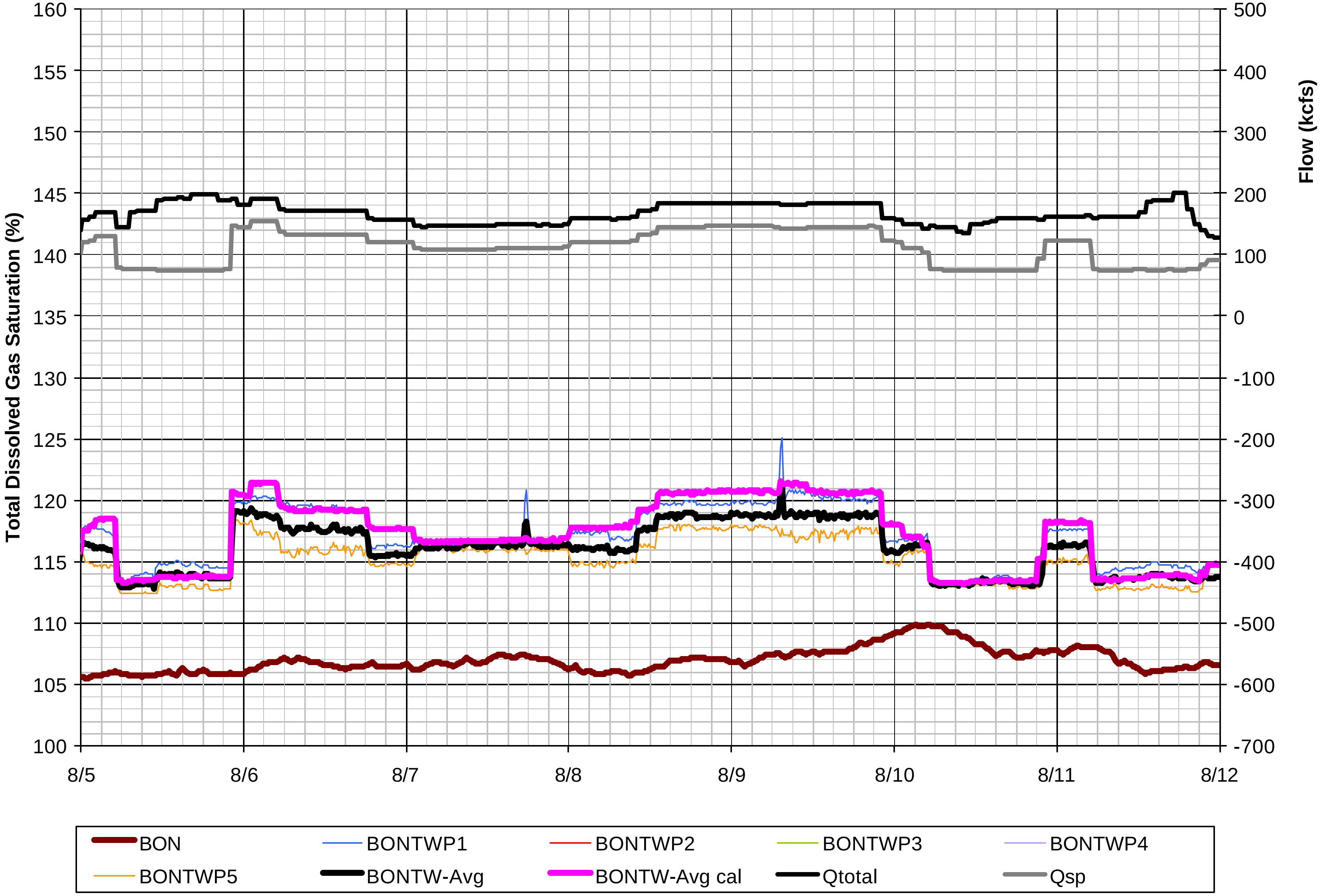

Figure 37r. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, August 5-11, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

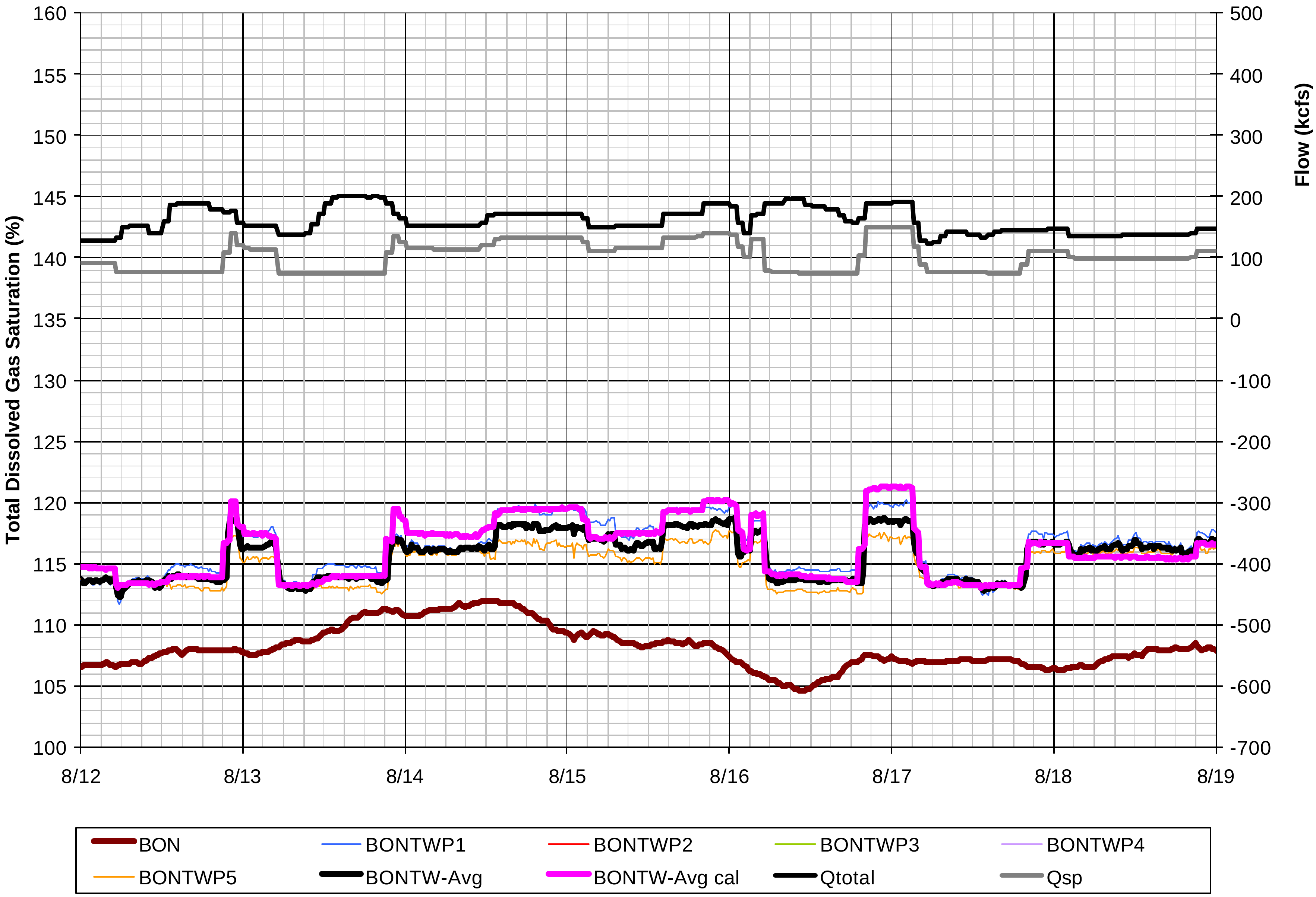

Figure 37s. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillway exit channel at Bonneville Dam, August 12-18, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

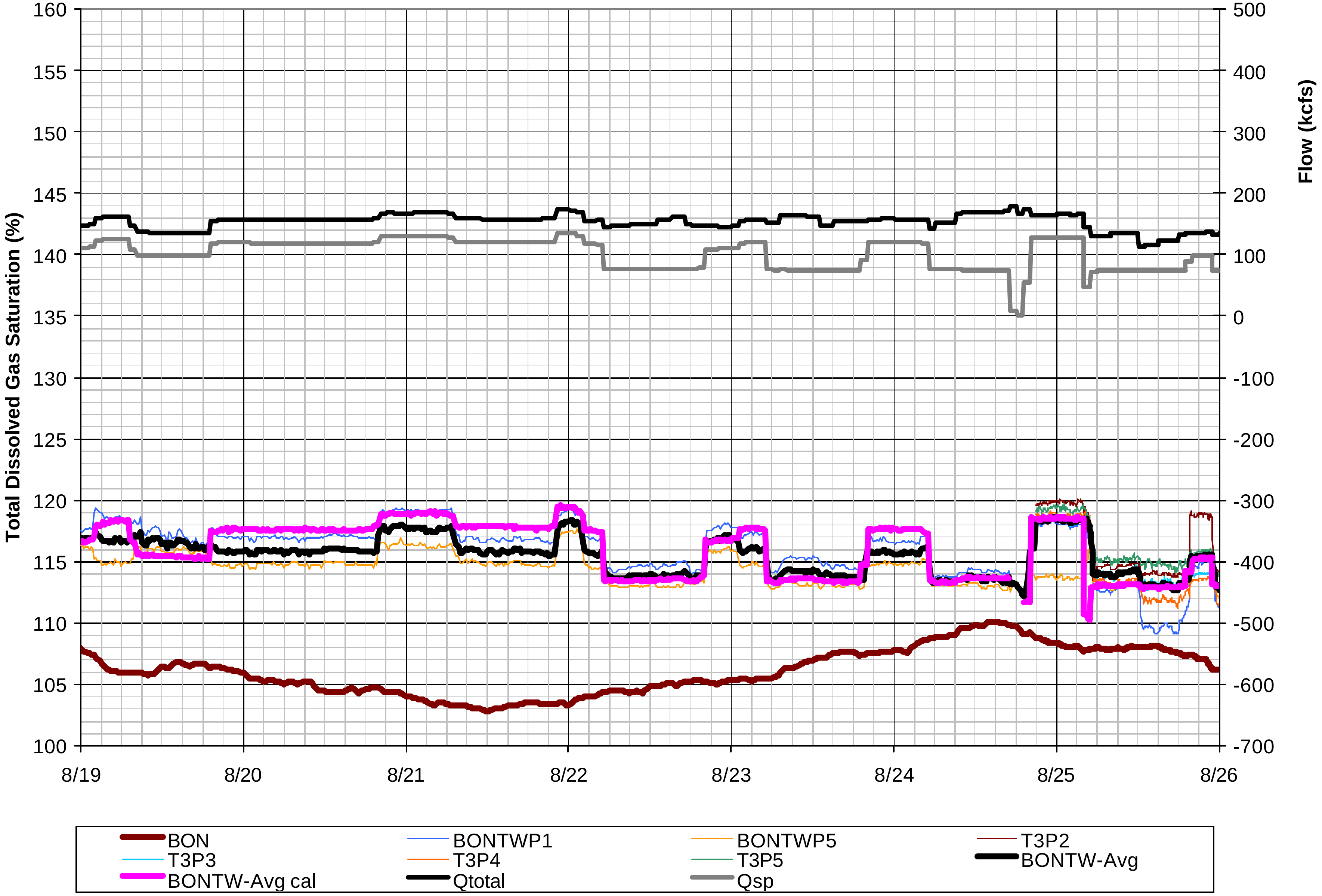

Figure 37t. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, August 19-25, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

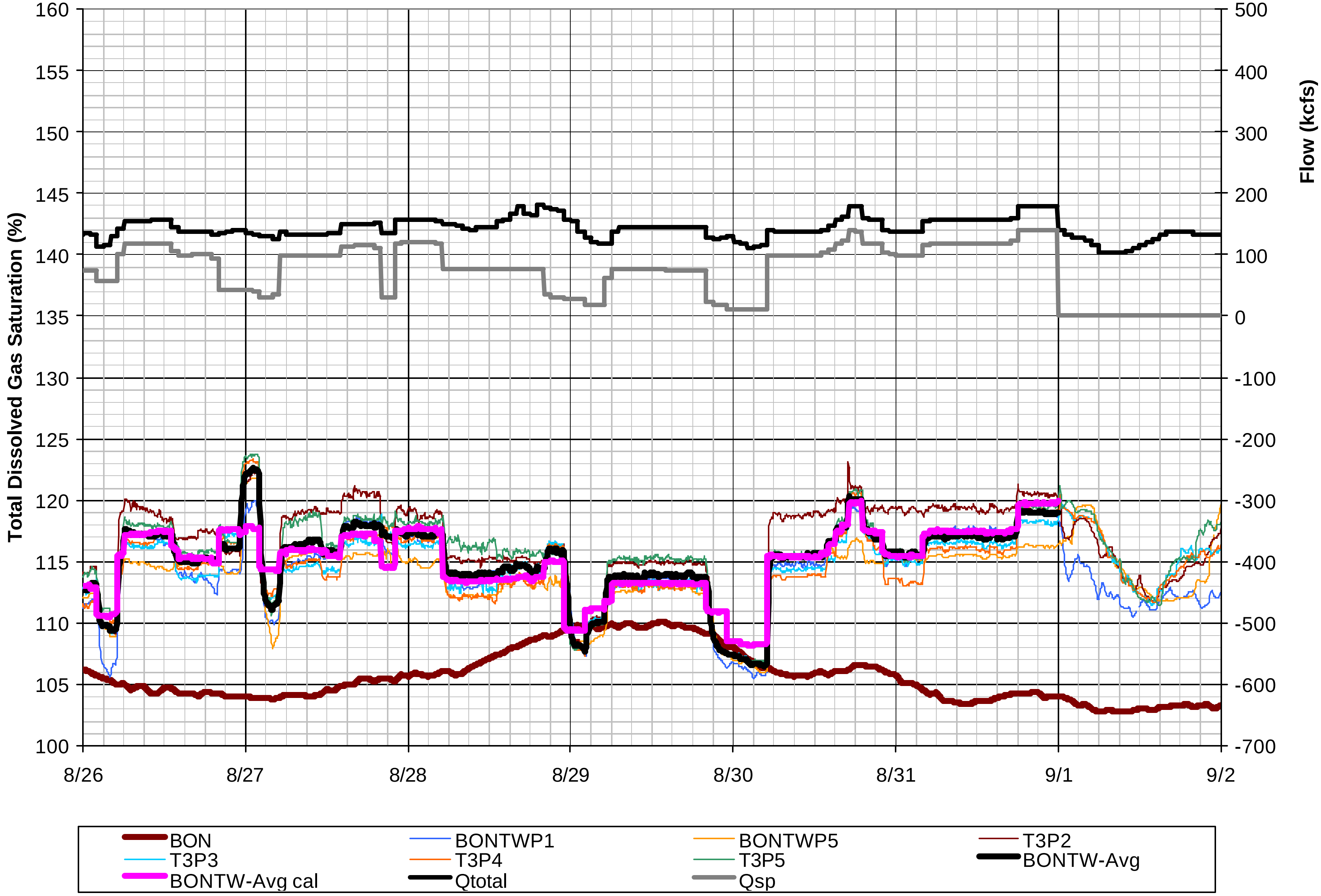

Figure 37u. Project operation with observed and calculated average cross sectional total dissolved gas saturation in the spillw ay exit channel at Bonneville Dam, August 26-September 1, 2002 (BONTW-Avg-cal based variation of specific discharge and tailwater stage)

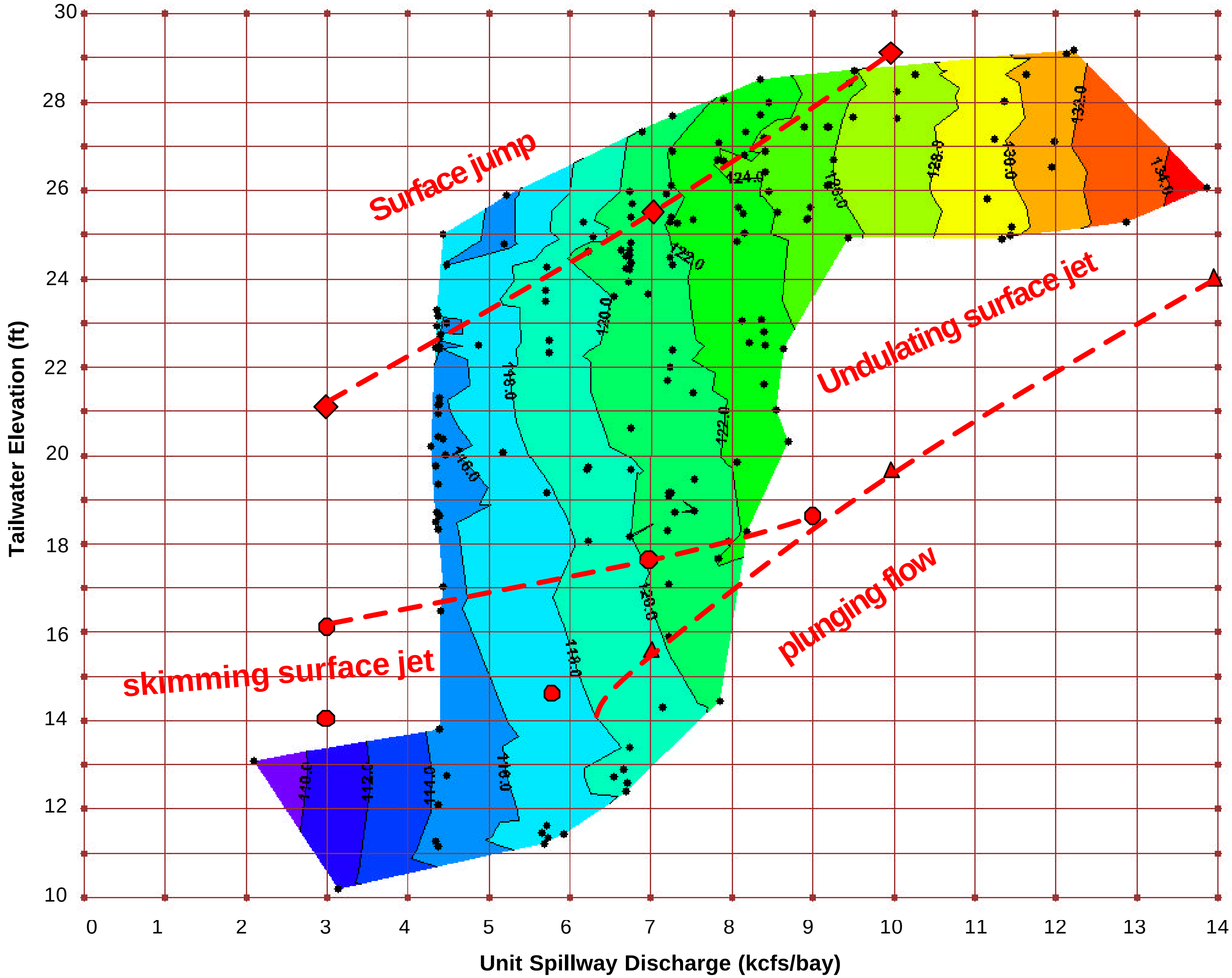

Figure 38. Average cross sectional total dissolved gas saturation in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge

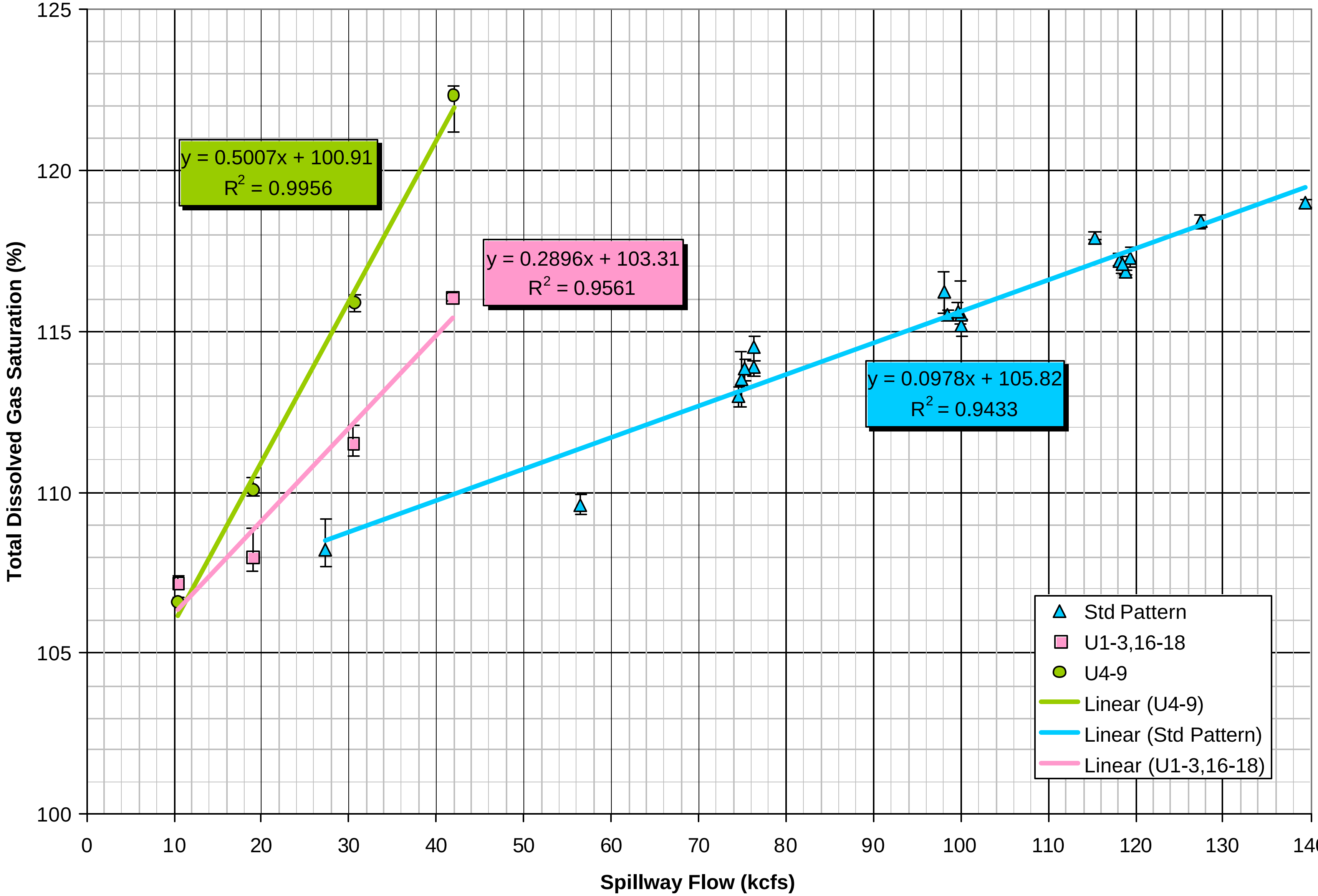

Figure 39. Total dissolved gas saturation as a function of spill discharge for the old deflectors, new deflectors, and standard spill patterns(new deflectors U1-3, 16-18, old deflectors U4-9, standard –Std Pattern)

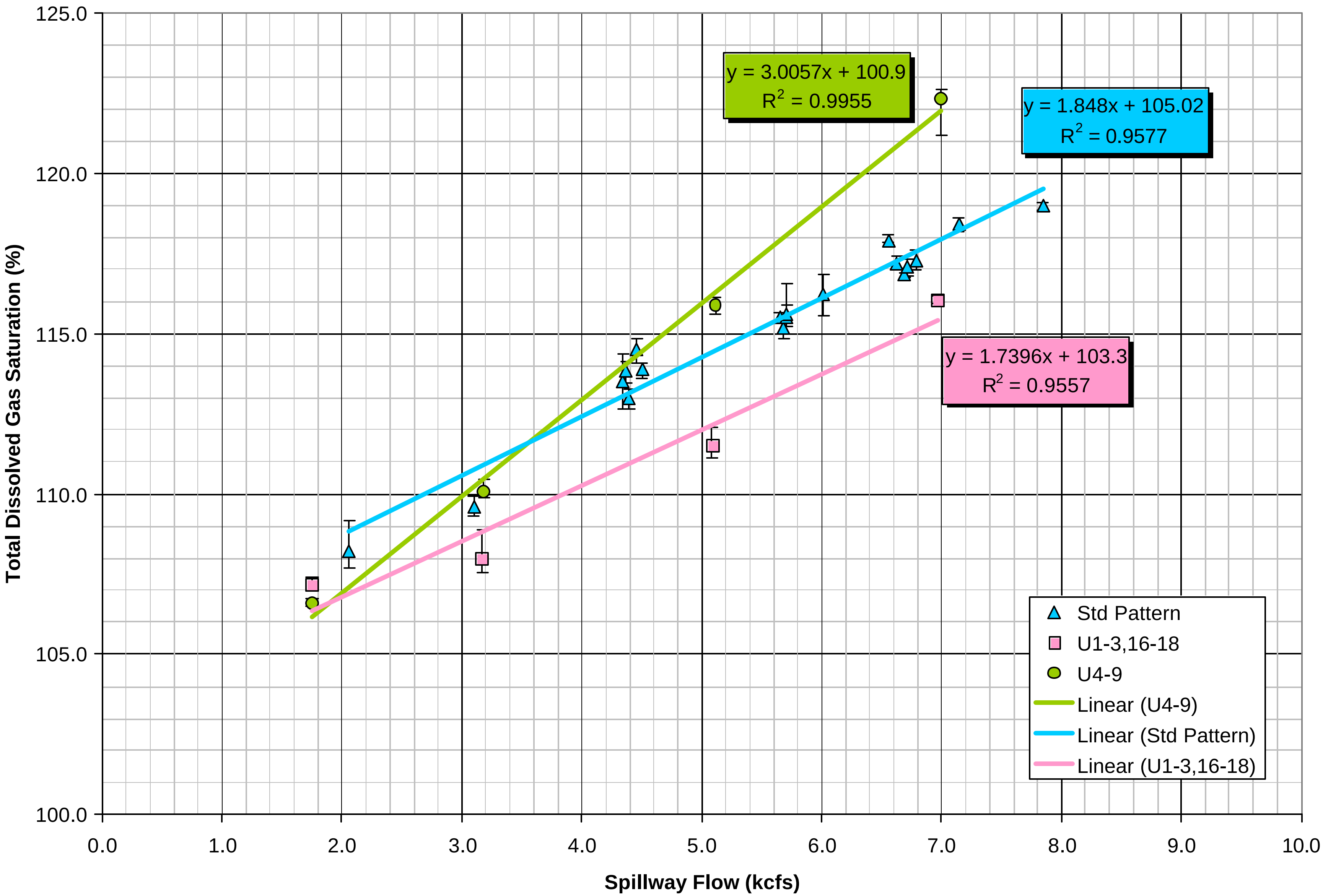

Figure 40. Total dissolved gas saturation as a function of specific spill discharge for the old deflectors, new deflectors, and standard spill patterns (new deflectors U1-3, 16-18, old deflectors U4-9, standard –Std Pattern)

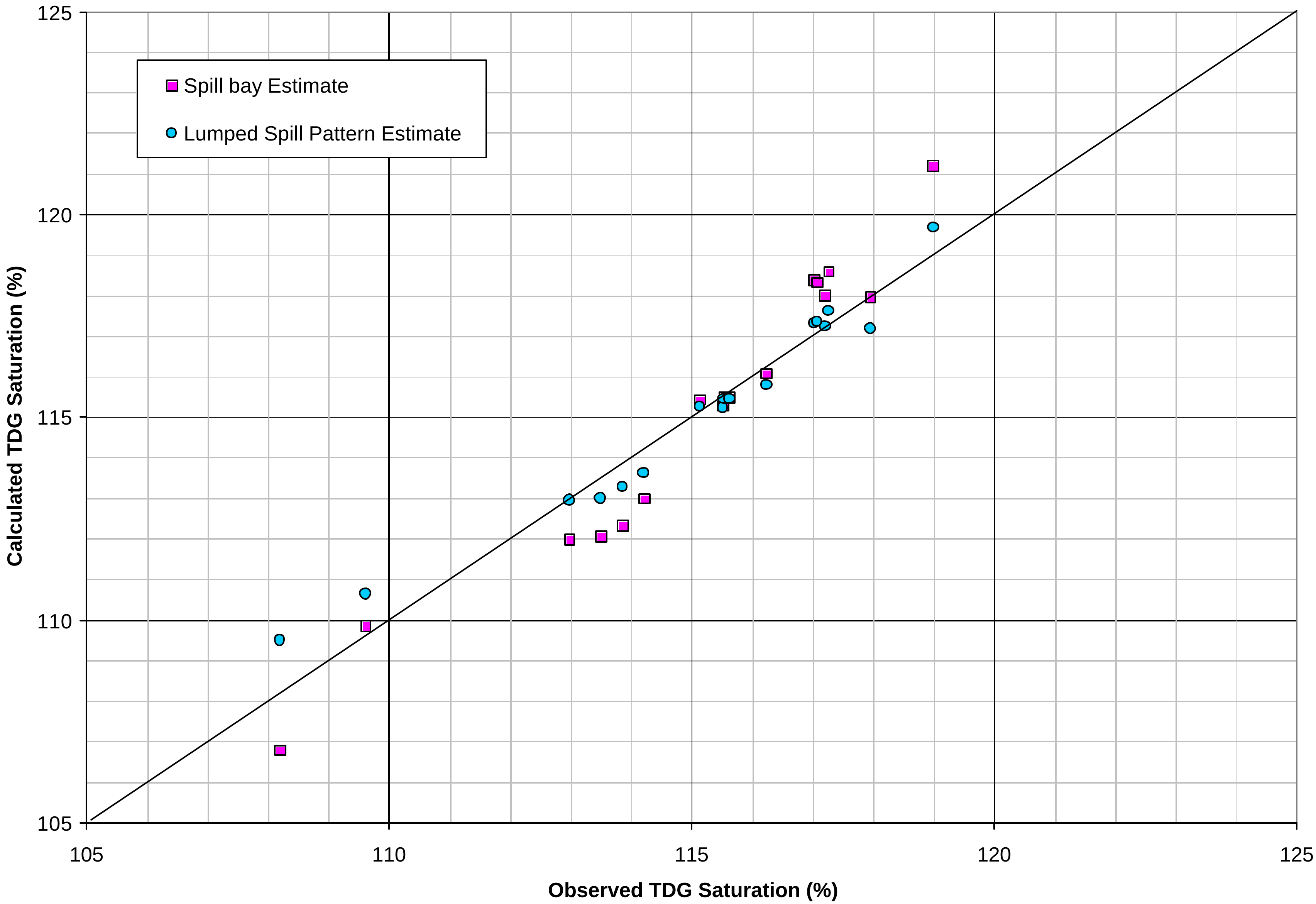

Figure 41. Observed and Calculated Total Dissolved Gas Saturation for standard spill pattern events, August 25-30, 2002 (spill bay estimate based on equation 3, Lumped spill pattern estimate based on equation 2)

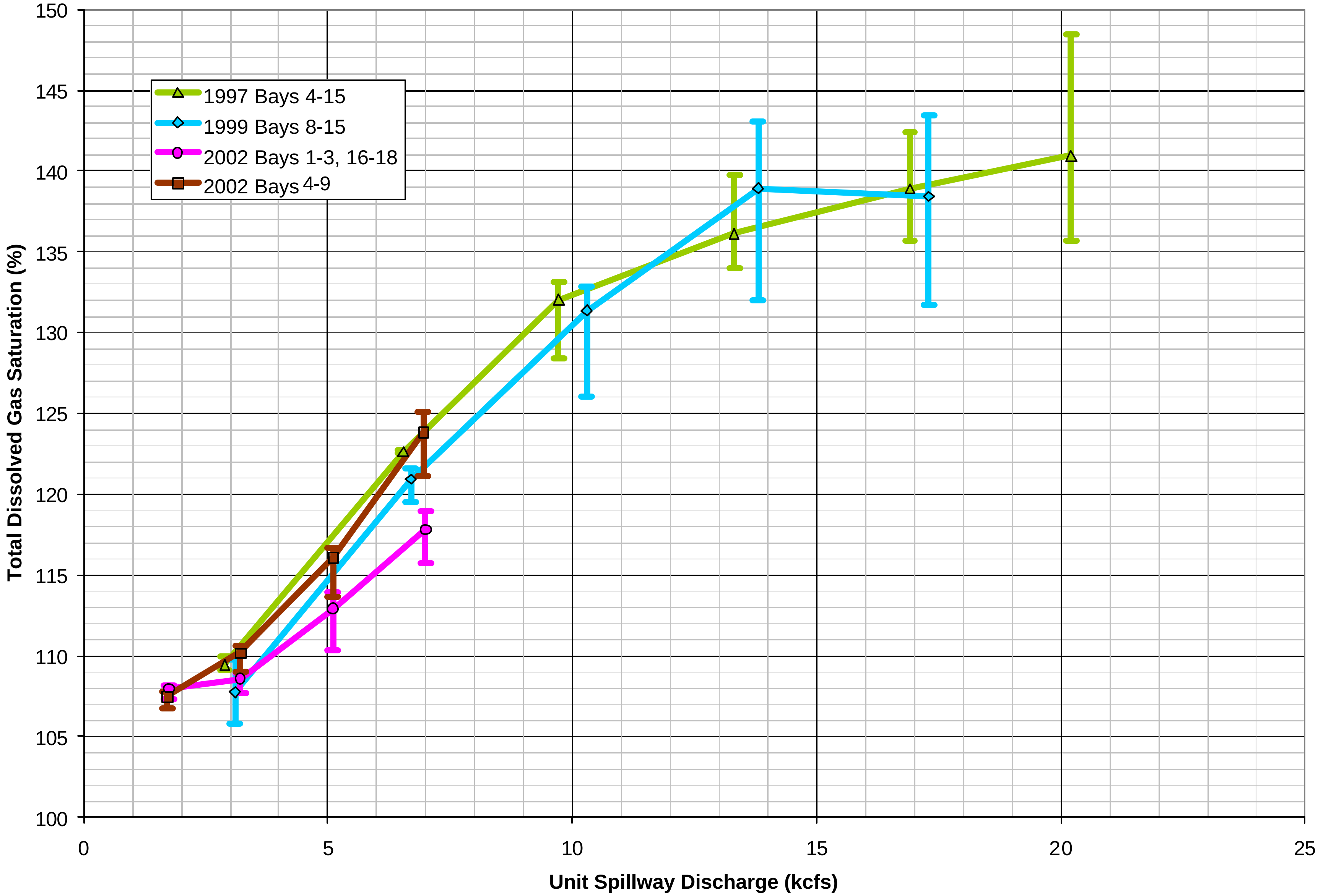

Figure 42. Total Dissolved Gas Saturation versus unit spilway discharge (TDG Saturation based on a standard pressure of 760 mmhg)

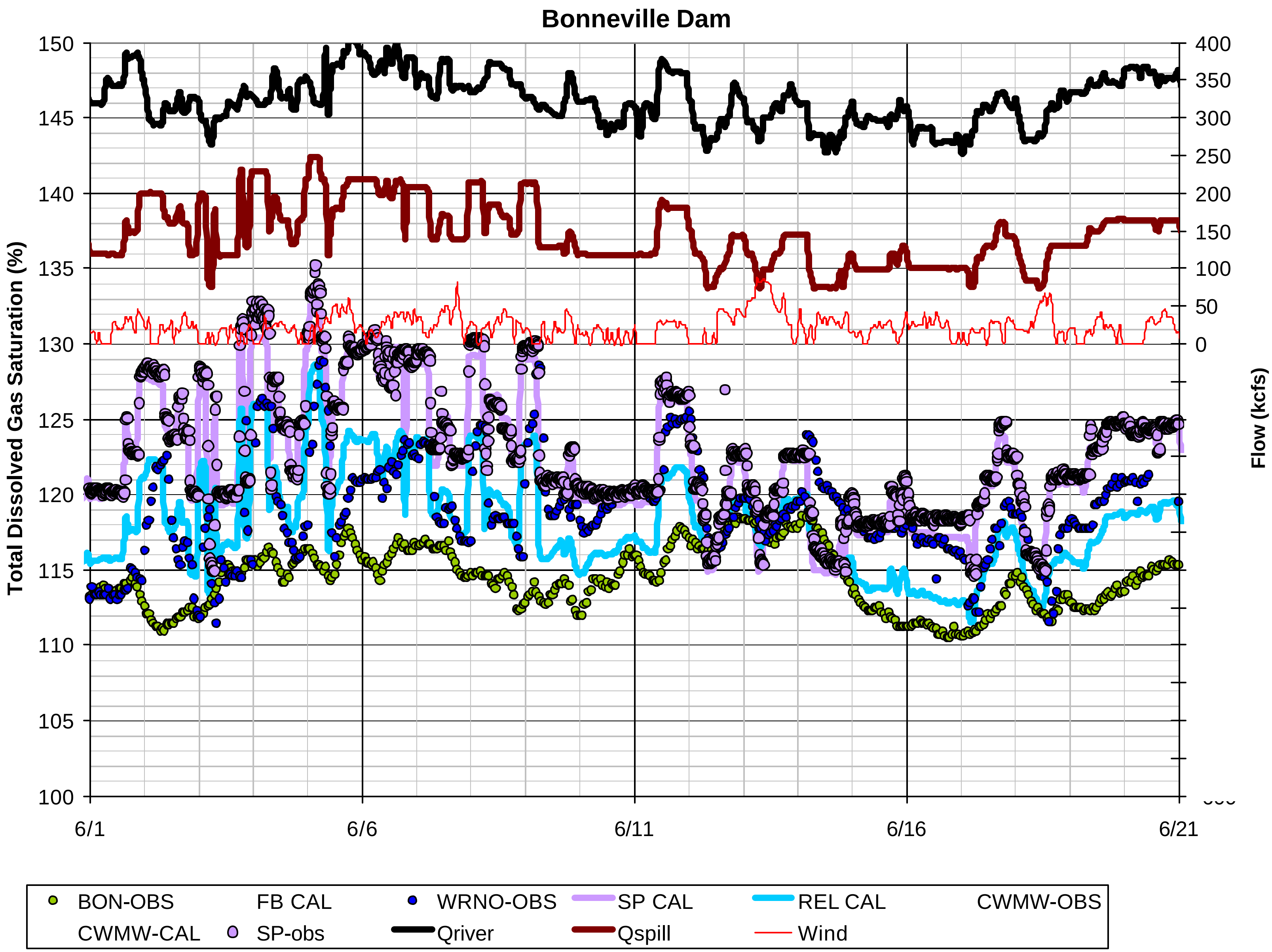

Figure 43. Bonneville project operations and observed and calculated hourly total dissolved gas saturation, June 2002 (SP-Bonneville spillway exit channel, WRNO-Warrendale, CAL-calculated, OBS-observed, REL CAL-flow weighted average)

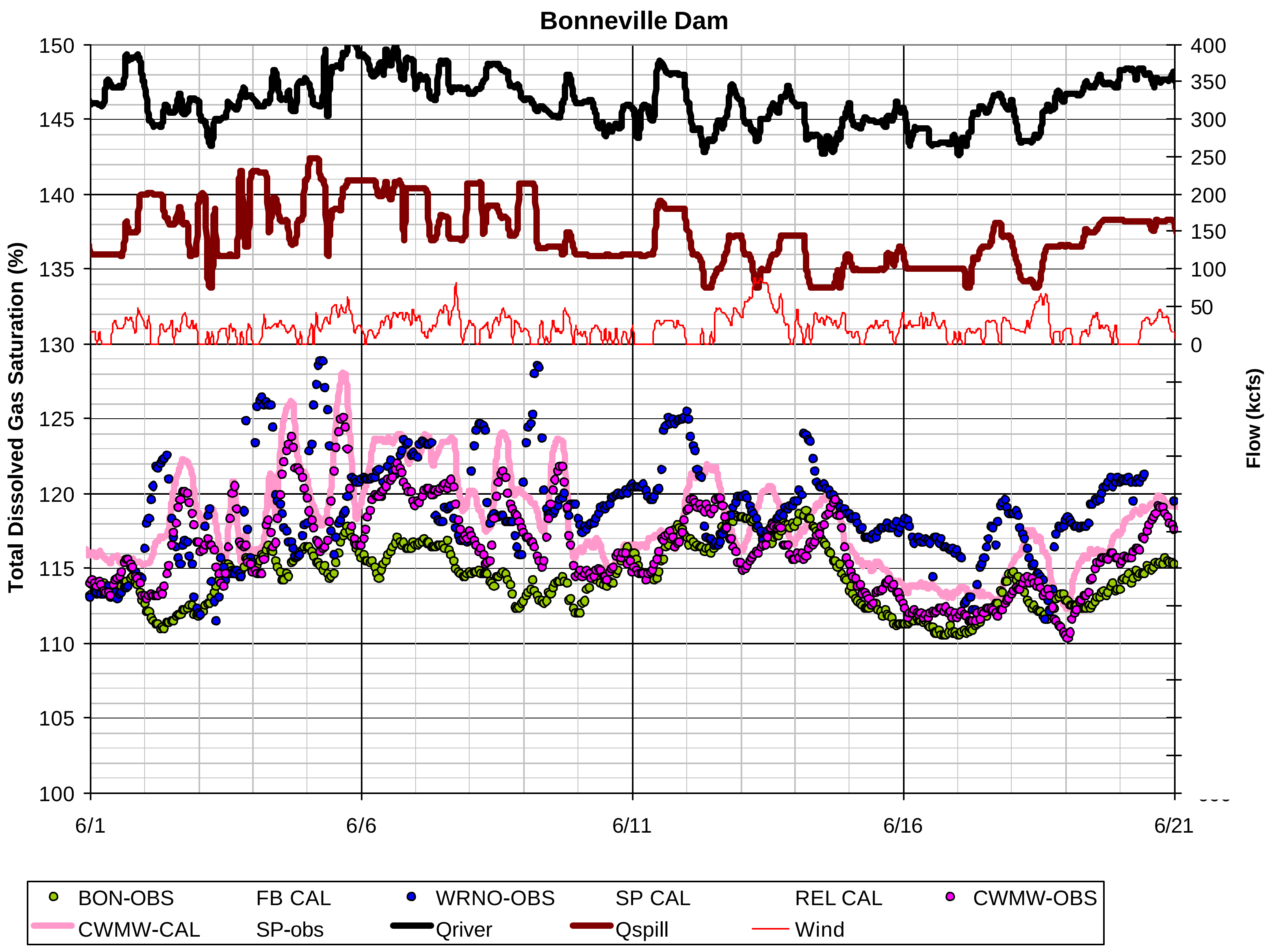

Figure 44. Bonneville project operations and observed and calculated hourly total dissolved gas saturation, June 2002 (CWMW-Camas/Washougal,CWMW-CAL conservative routing, WRNO-Warrendale, CAL-calculated, OBS-observed)

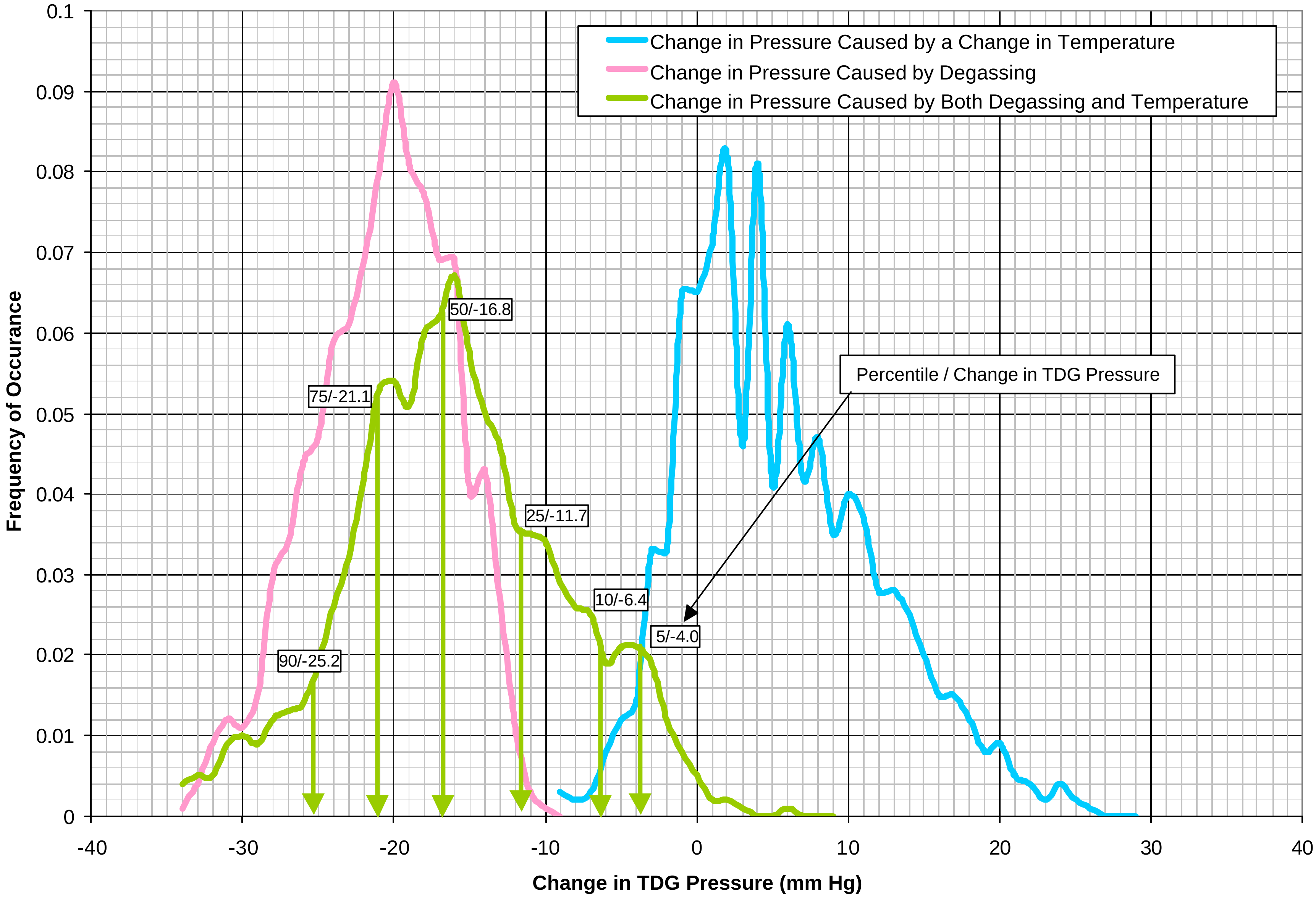

Figure 45. Probability distribution of the change in average cross sectional total dissolved gas pressure in the Columbia River between Bonneville Dam and the Camas/Washougal fixed monitoring station.

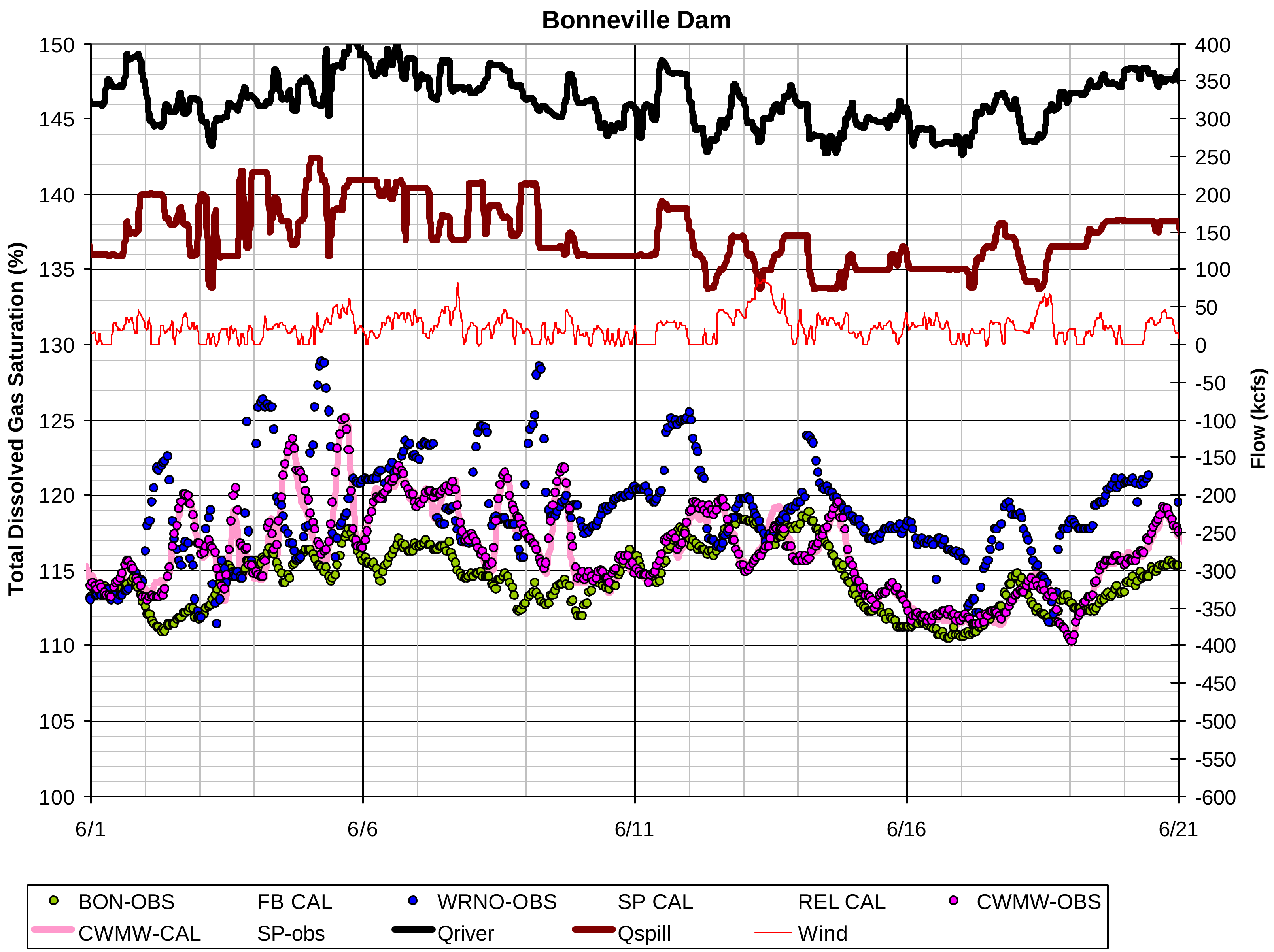

Figure 46. Bonneville project operations and observed and calculated hourly total dissolved gas saturation, June 2002 (CWMW-Camas/Washougal,CWMW-CAL non-conservative routing, WRNO-Warrendale, CAL-calculated, OBS-observed)

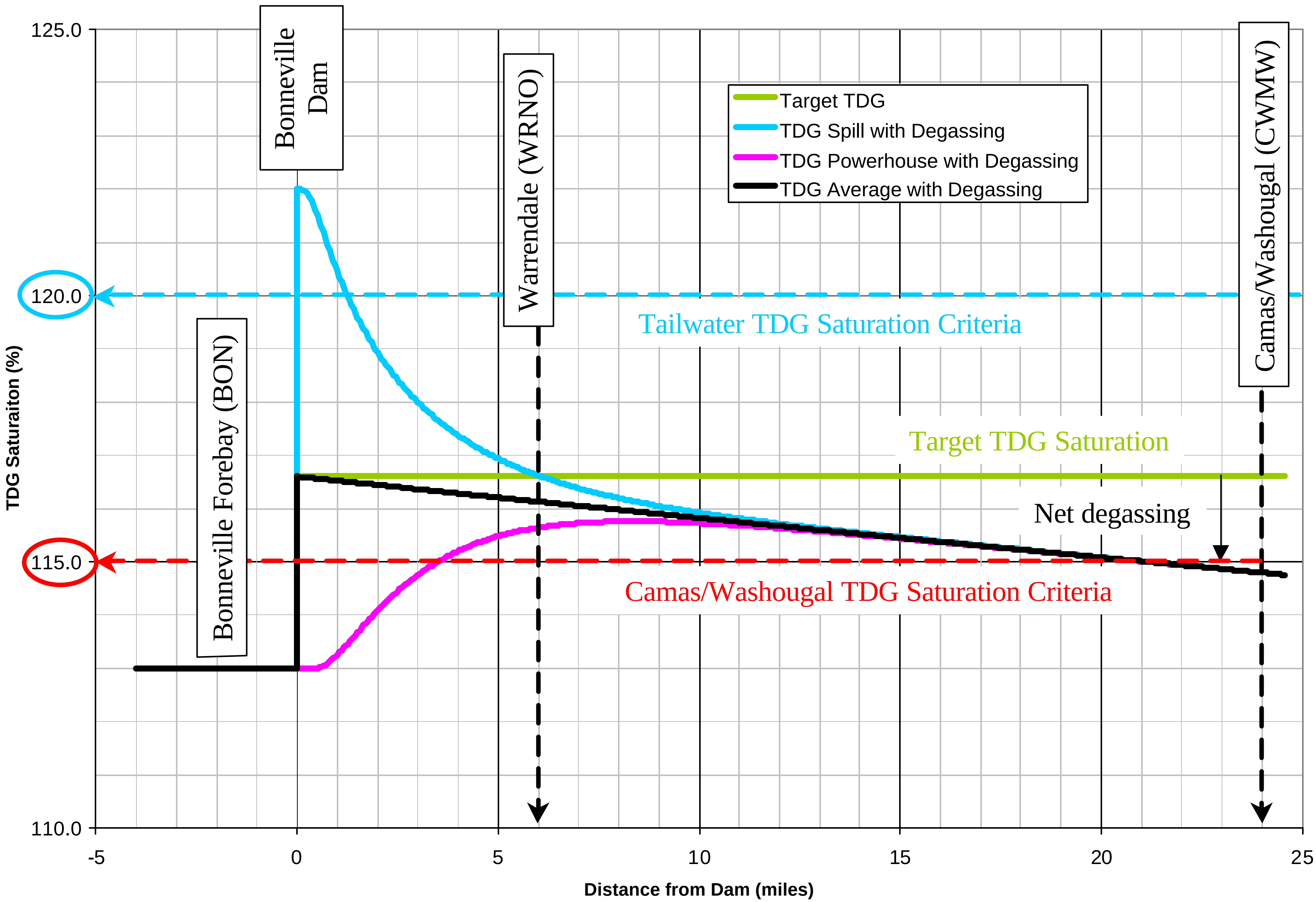

Figure 47. Total Dissolved Gas Exchange and Transport at Bonnev ille Dam and in the Columbia River