Appendix A

Total Dissolved Gas Abatement Plan For Bonneville Dam

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Introduction

The US Army Corps of Engineers (Corps) Federal Columbia River Power System (FCRPS) projects are operated to comply with the Clean Water Act to the extent practicable. The Corps must operate its projects in compliance with the Endangered Species Act (ESA). The Corps has implemented a variety of operational and structural measures to improve the survival of listed stocks. One of these actions involves providing spill for fish during spring and summer migration season to provide an alterative passage route past main stem dams. These fish spills result in the generation of total dissolved gas (TDG) supersaturation at levels that may exceed state and federal standards. The state of Washington has adopted a criteria adjustment for TDG saturation allowing for spill to occur up to preset TDG levels as long as the elevated TDG levels provide for improved fish passage through the spillway without causing more harm to fish than through other passage routes. This rule exemption is dependent upon a TDG abatement plan approved by Washington State Department of Ecology (WDOE) .

The following document contains the TDG abatement plan for Bonneville Dam. A series of tables have been developed estimating the Total Dissolved Gas (TDG) exchange properties in the Columbia River at Bonneville Dam as a function of alternative structural configurations, spill operations, total river flow rates, and background TDG properties. This document contains a description of the assumptions used to generate these TDG estimates and a series of tables that describe the TDG exchange properties at Bonneville Dam for past, present, and future scenarios.

Project Description

Bonneville is located on the Columbia River about 42 miles east of Portland, Oregon, at river mile 145.5. The project consists of four main structures including, from south to north, the navigation lock, the first powerhouse, the spillway dam, and the second powerhouse. Two islands separate the spillway from the powerhouses. Cascade Island which is located between the first powerhouse and the spillway, and Bradford Island which is located between the second powerhouse and the spillway. The total length of the dam including both islands is 6,353 feet. The Bonneville first powerhouse includes 10 generator units with a maximum total discharge capacity of approximately 166 kcfs. The second powerhouse includes 8 generator units with a maximum total discharge capacity of approximately 160 kcfs. The second powerhouse also includes 2 smaller units that supply flow to the adult fishway collection channel. These 2 units have a total capacity of approximately 6.8 kcfs. The Bonneville spillway is 1,450 feet long with eighteen 50-foot wide spillway bays and seventeen intermediate piers. The spillway discharge is controlled by eighteen two-part vertical lift gates. Each gate is 50 feet wide by 60 feet high. The spillway crest is at elevation 24.0 feet mean sea level (fmsl) with maximum free overflow design capacity of 1,600 kcfs, corresponding with the maximum pool elevation of 82.5 fmsl. The spillway will pass the standard project flow of 1,170,000 cfs with the maximum regulated pool elevation of 75.5 fmsl.

Powerhouse Hydraulic Capacity

The Bonneville powerhouse unit hydraulic capacity during the fish passage season was estimated assuming the standard-length submersible traveling screens are installed, a total head of 58 ft, and each unit is operated at the upper limit of the peak efficiency constraint as described in the yearly Fish Passage Plan (FPP, 2010). The unit hydraulic capacity for these conditions was estimated to equal 10.08 kcfs for units 1-8, 10, 12.38 kcfs for unit 9, and 17.97 kcfs for units 11-18 with submersible traveling screens installed. The two fish turbines located in the 2nd powerhouse have a hydraulic capacity of approximately 2.5 kcfs apiece. The total hydraulic capacity of the Bonneville powerhouse with all units (standard and fish turbines) available is 251.9 kcfs. If one of the turbine units in the 1st powerhouse is not available, the hydraulic capacity of the Bonneville powerhouse falls to 241.8 kcfs. In general, turbine maintenance and repair activities are scheduled to provide for maximum capacity during peak flow periods during each year. A minimum powerhouse discharge of 30 kcfs required to meet generation requirements was assumed throughout this evaluation.

Summary of Columbia River Flow at Bonneville Dam

The daily average total river flow, generation flow, and spillway flow was compiled for Bonneville Dam as contained in the Corps of Engineers CROHMS database (http://www.nwd-wc.usace.army.mil/perl/dataquery.pl) for the time period of October 1974 to October 2009. The time centered seven-day moving average of daily flow was computed throughout this 35 year period. This time period was chosen to correspond with the completion of major storage projects in the Columbia River Basin. This period of record was partitioned into two seasons: fish passage season April 1-August 31 for a total of 5 months; and non-fish passage season January 1-March 31 and September 1-December 31 for a total of 7 months. A tabular summary of Columbia River flows at Bonneville Dam within and outside of the fish passage season are found in Table A1 for river flows up to the 7Q10 flow.

The percent exceedences characteristics for the seven-day moving average of daily average flows for the Columbia River at Bonneville Dam during the fish passage season from 1975-2009 are shown in Figure A1. The median river flow during this period is about 205 kcfs. The frequency that the Columbia River flow will exceed 300 kcfs is 15.4 percent and 400 kcfs is only 2.2 percent. The likelihood that the Columbia River flow will exceed the powerhouse capacity of 251.9 kcfs was 31.0 percent of the time.

Outside the fish passage season from 1974-2009, the percent exceedance characteristics for the seven-day moving average of daily average flows for the Columbia River at Bonneville Dam are shown in Figure A2. The median river flow during this period is about 145 kcfs. The frequency that the Columbia River flow will exceed 300 kcfs is 2.5 percent and 400 kcfs is 0.0 percent. The likelihood that the Columbia River flow will exceed the powerhouse capacity of 251.9 kcfs was 5.0 percent of the time outside of the fish passage season.

The Washington water quality standards for TDG are applicable during river flows up to the high seven-day average flow with a return period of 10 years (7Q10). The 7Q10 is the average peak annual flow for seven consecutive days that has a recurrence interval of ten years. The WDOE estimated this discharge for the Columbia River at Bonneville Dam at 467 kcfs as described in the Total Maximum Daily Load for Lower Columbia River Total Dissolved Gas (TMDL, 2002). The period of record used in the TMDL analysis was from 1975-2000. The 7Q10 flow was estimated using the extended period of record from 1975-2009 using the methodology described in Bulletin #17B (USGS, 1982). The resultant mean 7Q10 high flow was estimated to equal 454 kcfs with a 80 percent confidence interval ranging from 416.5 to 514.6 kcfs. This evaluation did not correct the skew coefficient of the station record as was assumed in the Lower Columbia River Temperature TMDL. A review of the historic records show that the 7Q10 flow of 454 kcfs cited in the LCR Temperature TMDL was exceeded in only 1 out of the past 35 water years which infers a return period of once every 35 years. This observation is consistent with the wide confidence interval found in the estimation of the mean 7Q10 flow.

Water Quality Standards

The current Washington water quality standards allow for operations resulting in TDG levels of up to 120 percent at tailwater monitoring stations and 115 percent at the forebay of the next downstream dam based on a 12 hour moving average of consecutive observations. This criteria adjustment is for the purpose of aiding the passage of ESA listed species during their migration season from April 1 through August 31. The hourly maximum TDG saturation is not to exceed 125 percent of saturation during the fish passage season. The Washington water quality TDG standard outside of the fish passage season is 110 percent of saturation.

TDG Abatement Activities

The TDG loading of the Columbia River is influenced by both operations and the structural configuration of the Dam. Operational strategies to aid guidance of fish past the dam may have a direct influence on the TDG conditions in the river. An alternative spill pattern that more effectively guides fish during spillway operations and at lower spill volumes will also lower the TDG pressures in the receiving waters. Alternatively, a reduction in the injury rate of juvenile passing through the powerhouse may also reduce the reliance on spill for fish guidance resulting in an enhancement in TDG conditions.

The general approach for TDG abatement activities in spillway flows focuses on limiting the entrainment of air into the water column, the water flow rate that encounters the bubble plume and thirdly, the effective depth of the air that does become entrained. Spillway flow deflector commonly referred to as flip lips, redirect the spill jet from a plunging flow that transports air bubbles deep into the stilling basin to a horizontal jet that maintains entrained air much closer to the water surface. The spillway flow deflectors also transports highly aerated flow conditions well downstream of the stilling basin into the tailrace channel, promoting the exchange of atmospheric gasses at the local

depths. The effectiveness of spillway flow deflectors in abating TDG production has been consistently demonstrated at Corps of Engineers projects from Bonneville Dam to Chief Joseph Dam on the Columbia River and from Ice Harbor Dam to Lower Granite Dam on the Snake River. Other methodologies to reduce TDG loading below main-stem dams involve minimizing the use of spillways for involuntary spill. Limiting the entrainment of powerhouse flows into the turbulence bubbly flow in the stilling basin can also be an effective method of TDG abatement. A spill pattern that widely distributes spillway flows uniformly across the entire spillway has been found to lower TDG exchange rates.

It is recognized that a potential outcome of implementing gas abatement measures at a project is for greater reliance on spill to achieve fish passage goals. This is accomplished through increasing the spill discharge capacity associated with acceptable TDG levels. The ability to spill significantly larger volumes of water at or below the tailwater TDG criteria of 120 percent has resulted in a net increase in the TDG loading on the Columbia River during voluntary flow conditions. This increase in TDG loading results from a higher percentage of the river spilled at safe levels below the TDG criterion causing an increase in the cross sectional average TDG pressures. The following sections will discuss both the operational and structural configuration at Bonneville Dam that influences TDG loading in the Columbia River during the fish passage season.

Structural Alternatives

Spillway flow deflectors were constructed on 13 of the 18 spill bays at Bonneville Dam in the early 1970s. The spill bays deflectors were located in bays 4 – 15, and bay 18. These deflectors were constructed at an elevation of 14 ft and were designed for involuntary spillway releases when tailwater elevations provide sufficient submergence of the deflectors. This structural configuration will be labeled “Base-13 deflectors” throughout the remainder of this report. However, during involuntary spill the tailwater elevation can reduce the submergence of the flow deflectors below optimal conditions and can even result in a plunging flow regime. The spill pattern for this structural spillway configuration relied on a bulk spill pattern on the outside spill bays without flow deflectors. The higher unit discharge on bays without flow deflectors coupled with deep tailrace channel conditions downstream of the stilling basin caused higher TDG generation at Bonneville when compared to other projects with spill flow deflectors.

In order to address the higher levels of TDG generation at Bonneville Dam, spillway flow deflectors were constructed in bays 1, 2, 3, 16, 17, and 18 during the winter of 2001-2002. The original flow deflector in spill bay 18 was removed and replaced with the updated deflector design. The new spillway deflectors were constructed at elevation 7 ft providing for much greater submergence of these deflectors during voluntary spill conditions. Revised spill patterns were established for the new configuration of deflectors resulting in a much more uniform distribution of spill over the entire spillway. The spill pattern later was modified to restrict the minimum spillgate opening to 2 ft. This causes the closure of selected spill bays for spill discharges less than 85 kcfs. This structural configuration will be labeled “18 deflectors”.

An alternative juvenile passage route was constructed at Bonneville Dam providing access from the forebay of the Bonneville 2nd powerhouse to a release point at the downstream tip of Cascade Island. The corner collector, ogee chute, and outfall (B2CC) were completed prior to the 2004 fish passage season. The B2CC outfall consists of a gated release from the forebay of the 2nd Bonneville Powerhouse over an ogee section and into a 15 ft wide rectangular chute that has an exit at an elevation of 16 ft near the tip of Cascade Island. The B2CC has a discharge operating range of 4.4 to 5.9 kcfs as determined by the forebay elevation. The B2CC discharges into a plunge pool with a minimum elevation of –70 ft and a maximum depth of 86 ft for a tailwater stage of 16 ft. This structural alternative will be called "18 Deflectors and B2CC) throughout the remainder of this document.

The forth structural alternative "18 Deflectors/B2CC/Powerhouse Bypass (Sluiceway)" consisted of the existing spillway with 18 flow deflectors, the B2CC and a powerhouse surface bypass using a sluiceway with a hydraulic capacity of 5 kcfs. This passageway was assumed to discharge into the tailrace channel downstream from the 1st powerhouse. The sluiceway modifications are in the proposed configuration and operational plan for Bonneville to optimize surface flow outlet to improve fish passage efficiency (FPE) and reduce forebay delay.

The final proposed alternative involves the potential spillway operation or structure (e.g., spillway deflectors) modification to reduce injury and improve spillway fish survival ; and to improve conditions for upstream migrants. Although the details of this structural alternative are in development, one of the potential alternatives could involve the redesign of the spillway flow deflectors with associated benefits to TDG generation. This alternative will be referred to "18 Modified Deflectors/B2CC/Powerhouse Bypass".

Spill Operation Alternatives

This study also considered the influence of six different spill operations that govern the operations of Bonneville Dam and resultant generation of TDG supersaturation. The spill operations for the Federal Columbia River Power System are described in the Fish Operations Plan that are devised each year based on the Biological Opinion adaptive management strategy. The first spill operation called for an instantaneous spill equal to 30 percent of the total river flow ("spill 30 %"). The second spill operation required the instantaneous spill to equal 100 kcfs ("spill 100 kcfs"). The third operation assumed a constant spill of 85 kcfs subject to powerhouse minimum hydraulic capacity constraints ("spill 85 kcfs"). The fourth spill operation called for spilling up to the capacity as limited by the 120 percent total dissolved gas saturation criterion at the tailwater fixed monitoring station ("spill to capacity @ 120 %"). The fifth spill operation of no net increase in TDG loading of the Columbia River called for flows to be limited by the either the 110 percent criteria or background TDG level in the Columbia River ("spill to capacity @ 110% or TDGfb"). The final spill operation called for "no voluntary spill" excluding the discharge through the powerhouse surface bypass system or the B2CC.

TDG Properties

The TDG exchange properties at Bonneville Dam have been influenced by the spill operation, spillway flow deflectors, B2CC, and the associated spill pattern. The location of the tailwater fixed monitoring station was moved from a mixed waters station located 6 miles below the dam at Warrendale (WRNO) to the spillway exit channel on Cascade Island in 2005. The spill operation has changed significantly over the past five years. The spill pattern has transitioned from a spillway operation bulking spill on bays without flow deflectors to a more uniform pattern using all 18 spill bays. A minimum gate opening of 2 ft has been imposed that reduces the number of spill bays operating for lower flow conditions.

The TDG saturation observed at the tailwater fixed monitoring station from 2004 to 2007 as a function of spillway discharge is shown in Figure A3. Prior to 2004, the TDG observations at the tailwater fixed monitoring station were at a station (WRNO) influenced from both powerhouse and spillway flows. The TDG saturation observations associated with constant spill operations longer than 2 hours were grouped for spillway discharges in increments of 10 kcfs. The mean value of TDG saturation is shown as a red symbol within each spill discharge grouping and the standard deviation is indicated by the cross hairs. The minimum and maximum observations are also indicated by a short dash in Figure A3. The linear regression model between spillway discharge and TDG saturation at Bonneville Dam is shown Figure A3 with a slope of 0.083 percent/kcfs. This relationship indicates that a 10 kcfs increase in spill will result in a 0.8 percent increase in TDG saturation. The mean value of the spillway capacity as limited by the 120 percent tailwater TDG criteria is about 120 kcfs.

The estimates of TDG exchange in the Columbia River at Bonneville Dam were based on applying a set of empirical equations that describe the TDG exchange as a function of the effective depth of flow and specific spillway discharge. The relationship between TDG saturation and spillway discharge using the standard spill pattern prior to addition of spillway flow deflectors on bays 1-3, 16-18 in 2002 was determined from a site specific field study of TDG exchange conducted during 1999 (Schneider, 1999) as shown in Equation 1. These findings were based on five spill events with a duration of about 2 hours.

Equation 1

$$\Delta P = 8.24 q_s + 118 \qquad (1)$$

N = 5
r^2= 0.96

Where

$$q_s = \frac{Q_{sp}}{N_{eff}} \qquad \text{(kcfs/ft)}$$

N_{eff} = Effective number of active spill bays 1-18.
Q_{sp}= Total spill discharge (kcfs)

$TDG_{sat} = (P_{atm}+\Delta P)/P_{atm} \times 100$ Total Dissolved Gas Saturation (%)
P_{atm} = Local Atmospheric Pressure (mm Hg)

$$N_{eff} = \frac{\sum_{i=1}^{nbays} Q_i \sum_{i=1}^{nbays} Q_i^{C_w - 1}}{\sum_{i=1}^{nbays} Q_i^{C_w}}$$ = Effective number of active spill bays 1-8.

Q_i = Spill discharge in bay i.
Nbays = active number of spill bays.
c_w = 1 spill pattern weighting coefficient

The limitation of the relationship listed in equation 1 was the number of events and limited range in tailwater elevation. The influence of both tailwater elevation and specific discharge for a wide range of spill conditions was developed from observed TDG data collected during the 1997 spill season. This evaluation of the TDG exchange properties prior to the deflectors added in 2002 was based on back calculating the TDG added by spillway flows given the project operations, TDG levels in the forebay, and TDG levels in the Columbia River as measured at the Warrendale and Skamania fixed monitoring stations. The data was filtered to include only constant spill events with a duration of 4 hours and longer. The bilinear least squares regression equation generated from 2079 observations is show in equation 2 below. The standard error was based on predictions and observations of TDG levels in a mixed river as observed at the Warrendale and Skamania gauging stations.

Equation 2

$$\Delta P = 10.59 q_s + 0.37 TWE + 96.70 \qquad (2)$$

N = 2079
r^2= 0.98
Std Error = 8.05 mm Hg

A post deflector TDG exchange study was conducted during 2002 after the construction of new flow deflectors on six spill bays. The TDG sampling throughout the spillway exit channel was conducted throughout much of the fish passage season. The TDG pressures across the spillway exit channel were maintained at five auxiliary sampling stations. The TDG pressures generated during spillway operations at Bonneville Dam were found to be a bilinear function of both the effective depth of flow and specific spillway discharge. The findings from this investigation can be found in (Schneider, 2002) as shown in Equation 3. These findings were based on a total of 167 spill events with a duration of about 2 hours or longer.

Equation 3

$$\Delta P = 13.66 q_s + 1.56 TWE + 23.03 \qquad (3)$$

N = 167

r^2= 0.986

Std Error = 4.01 mm Hg

Where

TWE = Columbia River stage at Bonneville tailwater (ft)

The sensitivity of TDG exchange as a function of a change in the tailwater stage from 20 to 21 ft will result in an increase in TDG pressure of 1.6 mm Hg. Alternatively, an increase in the specific spillway discharge from 6 to 7 kcfs/bay will result in a 13.7 mm Hg increase in TDG pressure. This equation also illustrates the influence of bulking spill in several bays. A total spillway discharge of 100 kcfs uniformly distributed over 18 spill bays will result in a TDG pressure of 890 mm Hg (117.1%) at a tailwater elevation of 20 ft. The same 100 kcfs spilled uniformly over 12 bays will result in a TDG pressure of 928 mm Hg (122.1%) for an increase in TDG saturation of 5 percent over the uniform 18 bay spill pattern. An average local atmospheric pressure of 760 mm Hg was applied to estimate the total dissolved gas saturation.

The average flow weighted TDG saturation below Bonneville Dam was determined for each combination of structural and operational alternative.
A simple mass conservation statement can be developed for computing the flow-weighted average TDG saturation exiting the dam by associating a TDG saturation with the powerhouse and spillway flows as shown in Equation 4.

Equation 4

$$TDG_{avg} = \frac{Q_{sp} TDG_{sp} + Q_{aux} TDG_{aux} + Q_{gen} TDG_{gen}}{Q_{tot}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where:

Q_{tot} = Total River Flow (kcfs)

Q_{sp} = Spillway discharge (kcfs)

Q_{gen} = Generation discharge (kcfs)

Q_{aux} = Auxiliary discharge (B2CC and/or Powerhouse Surface bypass)

TDG_{gen} = TDG saturation of generation discharges (percent)

TDG_{avg} = Average cross sectional TDG saturation in the Columbia River (percent)

TDG_{sp} = TDG saturation of spillway discharges (percent)

TDG_{aux} = TDG saturation of auxiliary discharge (percent)

The location of Bradford and Cascade islands prohibits the interaction of powerhouse and aerated spillway flows below Bonneville Dam and the powerhouse entrainment coefficient is assumed to be zero.

The TDG exchange associated with the B2CC outfall was evaluated during seven release events ranging from 4.5-6.0 kcfs during total river flows of 123-170 kcfs in February of 2004. The spillway was closed throughout this investigation that limited the TDG production to the B2CC flows. The operation of the B2CC resulted in the elevation of average TDG pressures of 0.8 to 2.3 percent saturation for background TDG saturation ranging from 100.0-101.4 percent . The maximum TDG saturation was generally observed in the B2CC plunge pool and ranged from 103 percent to 118 percent during the testing period. The average effective TDG pressure of the B2CC outfall of 1063 mm Hg (140 percent) and was found to remain relatively constant for all flow conditions. A strong entrainment flow about 4 times the B2CC discharge was observed to interact with the releases from the B2CC in the plunge pool. These findings were determined for a limited number of operating conditions where the tailwater elevations ranged from 12.8-16.2 ft.

The return of diverted flow associated with the powerhouse surface bypass alternatives has the potential to generate elevated TDG pressures in the Columbia River. The experience of TDG exchange associated with the ice and trash (IT) chute at The Dalles Dam has been evaluated and was found to cause an increase TDG pressure in the Columbia River by several percent for low background TDG conditions. Th1s outfall does provide some reference for estimating the TDG exchange for surface bypass flows at Bonneville Dam. For this study a constant TDG saturation of 119.8 percent was applied to all powerhouse surface bypass flows. The basis for this estimate was the observed level of TDG exchange associated with surface bypass flows at Bonneville and The Dalles dams and the additional influence of designing a surface collector outfall that would limit the amount of TDG exchange during operation. The design attributes would involve the receiving channel depth of flow, trajectory, chute width, invert elevation, and proximity to other project flows.

A comprehensive evaluation of TDG exchange at Bonneville Dam should consider the existence of elevated background TDG levels from upstream sources. The presence of elevated background TDG levels at Bonneville Dam is caused by the voluntary spill at upstream projects to aid fish passage or voluntary spill resulting from river flows exceeding powerhouse capacity or the presence of surplus generation capacity in the system. The forebay TDG levels at Bonneville Dam are summarized from 1995-2007 as a function of total river flow in Figure A4. The observed daily average TDG saturation in the forebay of Bonneville Dam was summarized for 10 kcfs ranges in total river flow

from 80 to 560 kcfs. The average forebay TDG saturation is indicated by the red circle and the standard deviation in TDG saturation is indicated by the range bars. A well defined linear relationship was evident between observed TDG saturation in the forebay of Bonneville Dam and total river flow. This figure shows that when river flows are approaching the 7Q10 level of 454 kcfs, the background TDG saturation typically range from 120 to 125 percent of saturation. The elevated TDG levels during high river flow are caused by spill from main-stem dams on the Columbia and Snake River.

The contribution of TDG loading of the Columbia River by Bonneville Dam will be a closely related to background TDG levels transported to the tailwater unaltered by powerhouse flows. As an example, the mean TDG saturation associated with a spill discharge of 150 kcfs was about 122 percent saturation as determined from Figure A3. If a total powerhouse discharge of 250 kcfs is maintained the total river flow would approach 400 kcfs. The summary of forebay TDG levels for total river flows of 400 kcfs (Figure A4) shows the range of forebay TDG saturations exceeding 122 percent (note: median+ standard deviation = 122.7 percent. Although not a common occurrence, the spillway operations at Bonneville Dam can result in a reduction in the TDG loading of the Columbia River.

The accuracy of TDG exchange estimates during spillway releases at Bonneville Dam based on Equations 2-3 can be evaluated by conducting a hind caste of historic operations and comparing the calculated TDG pressures to observed conditions at the tailwater fixed monitoring station. Figure A5 shows the tailwater TDG saturation at Bonneville as a function of spillway discharge filtered for constant spill events of 3 hours and longer for the 2008 spill season. One interesting feature of these data is the large range in TDG pressures corresponding with a given spill discharge less than 20 kcfs. The variation in TDG pressure for small spill discharges is likely related to the encroachment of the mixing zone at the tailwater fixed monitoring station. The estimated TDG pressures are consistent with observed conditions with the exception of consistently overestimating TDG pressures for spillway flows greater than 110 kcfs. The spill capacity limited by 120 percent saturation ranged from 60 to 70 kcfs for the 2008 spill season. The variability of TDG saturation for a given spill discharge is chiefly attributed to the variation in the tailwater elevation.

A hind cast of TDG saturation below Bonneville Dam for a wide range of observed historic operations (spillway flow ranged from 20 to 145 kcfs) during May of 2008 were conducted using the relationship shown in Equations 2-3. The hourly total river and spillway flow are shown in Figure A6 along with the TDG saturation as observed and calculated at the tailwater fixed monitoring station. The TDG production model described by equations 3-4 does a good job of estimating both the peak levels of TDG saturation produced during peak forced spill events as well as simulating the voluntary TDG pressures in response to the bulk spill patterns.

Results

A series of estimates of TDG exchange were generated for a matrix of conditions impacting TDG exchange in the Columbia River at Bonneville Dam. This matrix consisted of the structural configuration, spill operation, total river flow, forebay TDG levels, and powerhouse capacity. This large matrix of conditions provides a comprehensive summary of past, present, and potential future configurations at Bonneville Dam. The type of summary also provides for a comparison of TDG exchange conditions for controlled system components. Often times observed historical data is used as the basis for evaluating the progress of a TDG management program. However, the influence of the runoff hydrograph, changes to spill operation or the structural layout of the dam introduces variables that cloud the assessment of TDG abatement progress.

A master table of TDG estimates was developed in an Excel spreadsheet called BONTDGest.xls summarizing the effects of 5 different structural configurations, six different spill operations, two powerhouse capacities, 9 different river flow rates, and five background TDG saturations. A summary of the discrete conditions listed in this table are summarized in Table A2. This table consists of 2700 different cases that provide a comprehensive summary of the TDG management program at Bonneville Dam. The interpretation of data in the master table is more manageable when selecting a smaller subset of conditions to review. It is useful to hold all but one case component constant when reviewing these results. The spreadsheet utility "file/filter/auto" allows the user to reduce this master table into a more meaningful format by allowing the selection of a narrower range of case components. The following discussion provides a general overview of the past, present, and potential future prospects of TDG exchange at Bonneville Dam.

Structural Configuration

The TDG exchange across the five structural configurations investigated at Bonneville Dam for a spill operation of spilling 100 kcfs during total river flows of 150, 300, and 454 kcfs were examined as shown in Table A3. The Base-13 Deflectors structural conditions utilized a bulk spill pattern involving 16 of the 18 spill bays as was the spill operation prior to 2002. The total river flow of 150 kcfs reflects a below average flow condition during the fish passage season. The 300 kcfs is a 15.4 percent exceedance flow and falls into a category of flow in excess of the powerhouse capacity but generally below the TDG compliance thresholds at the tailwater station. The river flow of 454 kcfs represents the 7Q10 high Columbia River discharge that can be expected to occur once every ten years on average. The background TDG levels were assumed to be 110 percent of saturation which would be typical for lower summer flow conditions caused by the generation of TDG supersaturation at upstream projects. A full powerhouse capacity of 251.9 kcfs was assumed for these conditions.

All four structural cases with 18 flow deflectors were able to spill 100 kcfs without exceeding the TDG criteria of 120 percent in spillway flows. The exception was the Base-13 deflectors scenario where a small spill caused spillway TDG levels to reach 120 percent of saturation. The TDG levels in spill ranged from 114.8 to 120.0 percent because of differences in the spill pattern and structural alternative. The small spill for the Base-

13 deflectors condition resulted in only a small increase in the average TDG loading of the Columbia River. The influence of the B2CC outfall with its deep plunge pool and affinity for entraining the surrounding river flows caused a measurable increase in average TDG saturation of about 2 percent saturation. The addition of the powerhouse surface bypass discharge also caused a small increase in the average TDG loading of the Columbia River from 116.1 percent to a level of 116.4 percent saturation. The modification of the spillway flow deflectors was anticipated to achieve a modest reduction in TDG levels in spillway flows at 100 kcfs spill.

The intermediate river flow condition of 300 kcfs resulted in TDG levels in spill that remained at or below 120 percent for all conditions listed in Table A3 with the exception of the Base-13 Deflector scenario which generated spillway TDG levels of 122.6 percent for a forced spill of 47.4 kcfs. The average TDG saturation for the Columbia River with a 300 kcfs flow was smaller than calculated for a river flow of 150 kcfs for all structural conditions except the Base-13 Deflector condition. The average TDG levels at 300 kcfs were caused by the smaller percentage of river spilled. These conditions suggest higher TDG levels in the Columbia River will occur during voluntary spill conditions at the lower flow conditions.

The high flow conditions during the 454 kcfs river flows required powerhouse capacity flows with the remainder of the river spilled in excess of 200 kcfs. The high spill discharges during this flood flow resulted in TDG levels in spill water greater than 125 percent for all structural conditions. The low background TDG levels of 110 percent were responsible for diluting the impacts from spill resulting in the cross sectional average TDG saturation which was maintained at or below 120 percent. During flood flows, the impact of spilling water overwhelms the TDG contribution from the B2CC, and powerhouse surface bypass. The influence of modified deflectors was projected to decrease for increasing spillway discharges.

The addition of the spillway flow deflectors (18 Deflectors) allowed greater flexibility in scheduling voluntary spill although the average Columbia River TDG loading was increased for this flow range. The reduction in TDG loading was realized during involuntary spill conditions where TDG levels in spill were significantly reduced. The addition of the B2CC provided an alternative downstream route of passage with a small increase in TDG loading. The powerhouse surface bypass facility can be designed to have a minimal TDG loading impact.

Spill Operation

The influence of spill operation on TDG exchange was explored for the current condition 18 deflectors/B2CC scenario for three river flow conditions 150, 300, and 454 kcfs. The maximum powerhouse capacity and forebay TDG level of 110 percent were also held constant for this evaluation as listed in Table A4. The spill operation has considerable influence over the TDG exchange during voluntary spill conditions that exist for 150 and 300 kcfs flows. The spill to the 120 percent TDG criteria resulted in the highest TDG levels for these two river flow conditions. This spill operation resulted in a spill

discharge of 114.8 kcfs and resulted in an increase in TDG saturation above background levels of 7.8 percent. The no voluntary spill operation resulted in a small increase in the TDG loading of 1.9 percent saturation caused by the B2CC outfall. The forced spill conditions during a total river flow of 454 kcfs trumps the voluntary spill operation and the TDG generation is identical for all cases exceeding 129 percent.

The "No voluntary spill" or "Spill capacity at 110 or TDGfb" resulted in less than a 2.2 percent saturation increase in TDG levels in the Columbia River for 150 and 300 kcfs. The more aggressive "Spill to capacity at 120 percent" caused largest increases of 7.8 and 4.9 percent in average river TDG levels for the 150 and 300 kcfs river condition. The current spring spill operation of "Spill 100 kcfs" yielded much lower TDG conditions than with the previously applied "Spill to capacity at 120%" operation. At a total river flow of 300 kcfs, the "Spill 30 Percent" operation resulted in an average cross sectional TDG saturation of 113.1 percent compared to the TDG production of the "Spill to capacity at 120 percent operation" of 114.9 percent. The spill operations resulting in higher percent spill conditions generated higher TDG pressures but not above the 120 percent criteria for the 150 and 300 kcfs flows.

The 7Q10 flow resulted in a spill of 196.9 kcfs attaining a TDG saturation of 129 percent in spillway flow and 118.9 percent as a cross sectional average. The powerhouse discharge provided significant dilution with spillway flows for these scenarios. The influence of spill operation is not important during these high forced spill conditions.

Total River Flow

The influence of total river flow on TDG exchange at Bonneville Dam for a spill operation of spill 30 percent of the river is shown in Table A5. All these conditions assumed a forebay TDG saturation of 110 percent. In a separate computation, the total river flow where TDG levels begin to exceed the tailwater criteria of 120 percent assuming the capacity powerhouse discharge of 108 kcfs for current condition was estimated to be 161 kcfs and occurs less than 5 percent of the time (Figure A1). The cross sectional average TDG saturation exceeds 120 percent during a total river flow of 175 kcfs. The spill operations during the total river flows less than 75 kcfs resulted in a net increase in TDG saturation of less than 1 percent saturation in the Columbia River. The spill conditions at Bonneville Dam during the 7Q10 event result in TDG in excess of 129 percent for the existing structural condition.

Forebay TDG Levels

Forebay TDG conditions are important in shaping the average conditions below Bonneville dam when spill is a small component of total river flow. The TDG exchange at Bonneville Dam during a total river flow of 300 kcfs for a structural configuration of 18 deflectors with B2CC for alternative spill operations are listed in Table A6. When forebay levels approach and exceed 115 percent of saturation, the TDG levels in waters released from Bonneville will remain above 115 percent for all spill operations considered. Forebay TDG levels will have little to no influence on determining the spill

capacity as limited by TDG criteria at the tailwater fixed monitoring station. However, if the TDG criteria of 115 percent at the Camas/Washougal fixed monitoring station relevant, high forebay TDG levels and powerhouse flows will play an important part in determining the TDG levels in the Columbia river below Bonneville Dam.

Bonneville Dam 2009 configuration TDG and Flow Summary

The TDG saturation in Columbia River below Bonneville Dam was estimated for 6 different river flows assuming the 2009 spillway configuration for a uniform spill pattern and a forebay TDG saturation of 115 percent. In case 1, the total river flow conditions was chosen to correspond with the hydraulic capacity of the powerhouse will all turbines operating at the upper 1 percent range of best gate with fish screens in place. Cases 2-5 correspond with maximum river flows with the spillway capacity limited by TDG saturations of 110, 115, and 120 percent. The final two cases correspond with high river flows of 400 kcfs and the updated mean 7Q10 flow of 454 kcfs. An auxiliary project discharge of 0 kcfs was also assumed in this analysis. The frequency of exceeding the total river flow for each case within the fish passage season (Apr-Aug) and during the non-fish passage season (Sep-Mar) based on observed flows at Bonneville Dam from 1974-2009 are also listed in Table A7.

The frequency for spilling water above the maximum powerhouse capacity during the fish passage season is slightly above 31 percent of the time at Bonneville Dam but only 4.6 percent of the time outside of the fish passage season. The powerhouse operations will simply pass the background TDG levels to the receiving pool resulting in no change to the TDG conditions. A uniformly distributed spill of 54 kcfs will generate TDG levels at 110 percent of saturation or 5 percent lower than the background conditions. This critical spill discharge was determined from observations during a uniform spill of 3 kcfs/bay over bay 4-15 and extrapolated to a full 18 bays (Wilhelms, 1997). Outside of the fish passage season a river flow of 306 kcfs and greater occurs only about 2 percent of the time. This spill to the 110 percent capacity operation will result in a net decrease in the average TDG conditions of the river to 114.1 percent when forebay levels are 115 percent. The spillway discharges up to 70 kcfs will either reduce or cause no change in the TDG loading of the Columbia River. The spillway flows at Bonneville Dam up to 115 kcfs will result in TDG levels of 120 percent and less which corresponds to a total river discharge of 367 kcfs and a frequency of occurrence of 4.5 percent during the fish passage season. The worst case conditions will be associated with the 7Q10 flows and a spill discharge of 202 kcfs resulting in TDG saturation in spillway flows of 129.6 percent and result in an average TDG saturation of 121.5 percent.

Conclusions

Bonneville spillway was retrofitted with flow deflectors on 13 of the 18 spill bays during the 1970's. These spillway flow deflectors were designed to function efficiently during forced spill conditions where the tailwater elevation was well above 20 ft. The spill pattern for this spillway configuration was designed to pass a considerable amount of flow through spill bays without flow deflectors to generate suitable flow conditions

throughout the exit channel. Bonneville spillway releases were found to generate considerable levels of TDG supersaturation with these conditions. The bulk spill over bays without flow deflectors and deep tailwater channel conditions cause TDG levels to exceed 120 percent of saturation at modest spill discharges.

Spillway flow deflectors are recognized as being the most effective means of reducing the TDG production during aerated spillway flows. The Bonneville spillway was modified in 2002 where Type II flow deflectors at an elevation of 7 ft were installed on spill bays 1-3, and 16-18. These deflectors were positioned 7 ft deeper than the original flow deflectors on bays 4-15 to function more effectively for voluntary spill conditions where the tailwater is typically less than 20 ft.

Bonneville Dam is unique in that the tailwater elevation experiences a wide range of conditions ranging from 10 ft during low flow conditions to upwards of 35 ft during flood flows. This tailwater property results in a wide range of jet flow regimes over the two different style deflectors at Bonneville spillway. The 14 ft elevation deflectors on the interior spill bays function poorly during low flow and tailwater conditions. However in contrast, during high flow and tailwater conditions the effectiveness of the new 7 ft elevation deflectors will diminish as the tailwater deeply submerges these structural elements.

A spill pattern has been developed at Bonneville Dam that is designed to effectively guide fish during voluntary spill events over the spillway and minimize the generation of TDG pressures. This pattern is based around maintaining near-shore velocities to limit predation in the littoral zone while providing for a uniform distribution of flow over all active spill bays during high forced spill conditions.

A third applied element of reducing the TDG generation at Bonneville Dam involves the adoption of a spill operation that accommodates both fish passage goals and water quality objectives. Previous spill operations at Bonneville Dam called for spilling as much water as possible without exceeding the TDG criteria at the downstream tailwater FMS (120%) or at the next forebay station located at Camas/Washougal (115%). This operation routinely caused spillway flows to exceed 150 kcfs during the voluntary fish passage season. The spill operation calling for spill to capacity conditions (gas cap) during the 2008 and 2009 spill seasons was limited to summer night time operations. (Spring spill was set at 100 kcfs for 24 hours per day). The constant rate spill operation causes higher percent spill conditions during the low flow summer months where average river TDG levels can exceed 115 percent. An operating plan of spilling to the TDG capacity will result in the highest TDG loading below Bonneville Dam.

The current structural and spill operation result in TDG levels of about 129 percent saturation when spill is forced during the 7Q10 flood flow. The frequency of flow at this magnitude is only once during a 10 year period.

The modified spillway flow deflectors are not expected to significantly change the TDG generation for large spill discharges compared to the existing conditions. The influence

of the powerhouse surface bypass system on TDG generation at Bonneville is small because of the limited flow capacity.

The TDG levels at the tailwater fixed monitoring station generally remain within the TDG criteria during voluntary spill conditions for spill discharges up 119 kcfs.

Measures to improve the efficiency and effectiveness of fish passageways at Bonneville Dam will continue to be developed with the potential of reducing the reliance on spillway flows and TDG loading. The potential modification of spillway flow deflectors was further investigated in the Bonneville Dam Spillway and Stilling Basin Reconfiguration of Fish Passage Alternative Report (CE, 2009). In this report an adjustable flow deflector was proposed with a permanent concrete deflector located at elevation 5 with a secondary movable deflector at elevation 15.

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Table A1

Percent of time the seven-day moving average of daily average flows exceed the reference Columbia River Flow at Bonneville Dam, 1975-2009 water years

Columbia River Flow (kcfs)	Fish Passage Season April-Aug (%)	Non-Fish Passage Season Sept.-March (%)	Comments
100	96.70%	93.30%	
150	74.40%	42.10%	
200	52.20%	15.00%	
241.8	35.50%	5.50%	Powerhouse capacity 1 unit down
250	32.20%	4.90%	
251.9	31.40%	4.60%	Powerhouse capacity all units
300	15.80%	2.30%	
350	6.50%	0.80%	
400	2.30%	0	
450	0.80%	0	
454	0.70%	0	Updated 7Q10 flow
500	0.40%	0	

Table A2

Configuration Matrix for TDG Estimates in the Columbia River at Bonneville Dam

Structural Alternative	Spill Operation	$Q_{ph\text{-}Max}$ (kcfs)	Q_{total} (kcfs)	TDG_{fb} (%)
Base-13 Deflectors	No Voluntary Spill	251.9	100	105
18 Deflectors	Spill to Capacity @ 110% or TDG Forebay	241.8	150	110
18 Deflectors/B2CC	Spill 85 Kcfs		200	115
18 Deflectors/B2CC/PH Surface Bypass	Spill 100 kcfs		250	120
18 Modified Deflectors/B2CC/PH Surface Bypass	Spill 30 Percent		300	125
	Spill to Capacity @ 120%		350	
			400	
			450	
			454	

Table A3

Summary of Total Dissolved Gas Exchange at Bonneville Dam for Columbia River flow of 150, 300, and 454 kcfs, Forebay TDG level of 110% by Structural alternative and spill operation of spill 100 kcfs

Case	Structural Alternative	Spill Operation	$Q_{ph\text{-}max}$ (kcfs)[1]	Q_{total} (kcfs)	Q_{gen} (kcfs)	Q_{spill} (kcfs)	Q_{aux} (kcfs)	TDG_{fb} (%)	TDG_{sp} (%)	TDG_{aux} (%)	TDG_{avg} (%)	ΔTDG (%)
145	Base-13 Deflectors	Spill 100 kcfs	251.9	150.0	144.6	4.7	0.7	110	120.0	110.0	110.3	0.3
685	18 Deflectors	Spill 100 kcfs	251.9	150.0	49.3	100.0	0.7	110	116.3	110.0	114.2	4.2
1225	18 Deflectors/B2CC	Spill 100 kcfs	251.9	150.0	44.8	100.0	5.2	110	116.3	164.5	116.1	6.1
1765	18 Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	150.0	41.0	100.0	9.0	110	116.3	146.1	116.4	6.4
2305	18 Modified Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	150.0	41.0	100.0	9.0	110	114.8	146.1	115.4	5.4
149	Base-13 Deflectors	Spill 100 kcfs	251.9	300.0	251.9	47.4	0.7	110	122.6	110.0	112.0	2.0
689	18 Deflectors	Spill 100 kcfs	251.9	300.0	199.3	100.0	0.7	110	118.2	110.0	112.7	2.7
1229	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	110	118.2	164.5	113.7	3.7
1769	18 Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	300.0	191.0	100.0	9.0	110	118.2	146.1	113.8	3.8
2309	18 Modified Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	300.0	191.0	100.0	9.0	110	118.2	146.1	113.8	3.8
153	Base-13 Deflectors	Spill 100 kcfs	251.9	454.0	251.9	201.4	0.7	110	127.4	110.0	117.7	7.7
693	18 Deflectors	Spill 100 kcfs	251.9	454.0	251.9	201.4	0.7	110	129.5	110.0	118.7	8.7
1233	18 Deflectors/B2CC	Spill 100 kcfs	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1773	18 Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	454.0	251.9	193.1	9.0	110	128.7	146.1	118.7	8.7
2313	18 Modified Deflectors/B2CC/PH surface Bypass	Spill 100 kcfs	251.9	454.0	251.9	193.1	9.0	110	128.7	146.1	118.7	8.7

[1] Powerhouse capacity of 251.9 kcfs based on all turbines at 58 ft of head, with STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Bonneville master TDG management plan.

$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Bonneville powerhouse (kcfs)

$\mathbf{Q_{total}}$ = Columbia River Flow at Bonneville Dam (kcfs)

$\mathbf{Q_{gen}}$ = Powerhouse Flow (kcfs)

$\mathbf{Q_{spill}}$ = Spillway Flow (kcfs)

$\mathbf{Q_{aux}}$ = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)

$\mathbf{TDG_{sp}}$ = Total Dissolved Gas Saturation in spillway flows (%)

$\mathbf{TDG_{fb}}$ = Total Dissolved Gas Saturation in forebay (%)

TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)

$\mathbf{TDG_{avg}}$ = Flow weighted Total Dissolved Gas Saturation below Dam (%)

ΔTDG = Change in average cross sectional Columbia River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table A4

Summary of Total Dissolved Gas Exchange at Bonneville Dam for Columbia River flow of 150, 300, and 454 kcfs, Forebay TDG level of 110% for the 18 Deflector/B2CC Structural alternative and various spill operations

Case	Structural Alternative	Spill Operation	$Q_{ph\text{-}max}$ (kcfs)[1]	Q_{total} (kcfs)	Q_{gen} (kcfs)	Q_{spill} (kcfs)	Q_{aux} (kcfs)	TDG_{fb} (%)	TDG_{sp} (%)	TDG_{aux} (%)	TDG_{avg} (%)	ΔTDG (%)
1091	18 Deflectors/B2CC	No Voluntary Spill	251.9	150.0	144.8	0.0	5.2	110	105.9	164.5	111.9	1.9
1136	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	150.0	106.0	38.8	5.2	110	111.3	164.5	112.2	2.2
1181	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	150.0	59.8	85.0	5.2	110	114.9	164.5	114.6	4.6
1226	18 Deflectors/B2CC	Spill 100 kcfs	251.9	150.0	44.8	100.0	5.2	110	116.3	164.5	116.1	6.1
1271	18 Deflectors/B2CC	Spill 30 Percent	251.9	150.0	99.8	45.0	5.2	110	111.3	164.5	112.3	2.3
1316	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	150.0	30.0	114.8	5.2	110	117.7	164.5	117.8	7.8
1094	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	110	113.2	164.5	111.4	1.4
1139	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	251.9	42.9	5.2	110	113.2	164.5	111.4	1.4
1184	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	110	116.8	164.5	112.9	2.9
1229	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	110	118.2	164.5	113.7	3.7
1274	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	110	117.3	164.5	113.1	3.1
1319	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	110	120.0	164.5	114.9	4.9
1098	18 Deflectors/B2CC	No Voluntary Spill	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1143	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1188	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1233	18 Deflectors/B2CC	Spill 100 kcfs	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1278	18 Deflectors/B2CC	Spill 30 Percent	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9
1323	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9

[1] Powerhouse capacity of 251.9 kcfs based on all turbines at 58 ft of head, with STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Bonneville master TDG management plan.

$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Bonneville powerhouse (kcfs)

$\mathbf{Q_{total}}$ = Columbia River Flow at Bonneville Dam (kcfs)

$\mathbf{Q_{gen}}$ = Powerhouse Flow (kcfs)

$\mathbf{Q_{spill}}$ = Spillway Flow (kcfs)

$\mathbf{Q_{aux}}$ = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)

$\mathbf{TDG_{sp}}$ = Total Dissolved Gas Saturation in spillway flows (%)

$\mathbf{TDG_{fb}}$ = Total Dissolved Gas Saturation in forebay (%)

TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)

$\mathbf{TDG_{avg}}$ = Flow weighted Total Dissolved Gas Saturation below Dam (%)

ΔTDG = Change in average cross sectional Columbia River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table A5

Summary of Total Dissolved Gas Exchange at Bonneville Dam for Columbia River flows ranging from 100 to 454 kcfs, Forebay TDG level of 110% for the 18 Deflector/B2CC Structural alternative and spill operation of Spill 100 kcfs

Case	Structural Alternative	Spill Operation	$Q_{ph\text{-}max}$ (kcfs)[1]	Q_{total} (kcfs)	Q_{gen} (kcfs)	Q_{spill} (kcfs)	Q_{aux} (kcfs)	TDG_{fb} (%)	TDG_{sp} (%)	TDG_{aux} (%)	TDG_{avg} (%)	ΔTDG (%)
1225	18 Deflectors/B2CC	Spill 100 kcfs	251.9	100.0	30.0	64.8	5.2	110	112.2	164.5	114.2	4.2
1226	18 Deflectors/B2CC	Spill 100 kcfs	251.9	150.0	44.8	100.0	5.2	110	116.3	164.5	116.1	6.1
1227	18 Deflectors/B2CC	Spill 100 kcfs	251.9	200.0	94.8	100.0	5.2	110	117.0	164.5	114.9	4.9
1228	18 Deflectors/B2CC	Spill 100 kcfs	251.9	250.0	144.8	100.0	5.2	110	117.6	164.5	114.2	4.2
1229	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	110	118.2	164.5	113.7	3.7
1230	18 Deflectors/B2CC	Spill 100 kcfs	251.9	350.0	244.8	100.0	5.2	110	118.8	164.5	113.3	3.3
1231	18 Deflectors/B2CC	Spill 100 kcfs	251.9	400.0	251.9	142.9	5.2	110	123.2	164.5	115.4	5.4
1232	18 Deflectors/B2CC	Spill 100 kcfs	251.9	450.0	251.9	192.9	5.2	110	128.6	164.5	118.6	8.6
1233	18 Deflectors/B2CC	Spill 100 kcfs	251.9	454.0	251.9	196.9	5.2	110	129.1	164.5	118.9	8.9

[1] Powerhouse capacity of 251.9 kcfs based on all turbines at 58 ft of head, with STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Bonneville master TDG management plan.

$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Bonneville powerhouse (kcfs)

$\mathbf{Q_{total}}$ = Columbia River Flow at Bonneville Dam (kcfs)

$\mathbf{Q_{gen}}$ = Powerhouse Flow (kcfs)

$\mathbf{Q_{spill}}$ = Spillway Flow (kcfs)

$\mathbf{Q_{aux}}$ = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)

$\mathbf{TDG_{sp}}$ = Total Dissolved Gas Saturation in spillway flows (%)

$\mathbf{TDG_{fb}}$ = Total Dissolved Gas Saturation in forebay (%)

TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)

$\mathbf{TDG_{avg}}$ = Flow weighted Total Dissolved Gas Saturation below Dam (%)

ΔTDG = Change in average cross sectional Columbia River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table A6

Summary of Total Dissolved Gas Exchange at Bonneville Dam for Columbia River flow of 300 kcfs, Forebay TDG levels ranging from 105 to 125 % for the 18 Deflector/B2CC Structural alternative and various spill operations.

Case	Structural Alternative	Spill Operation	$Q_{ph\text{-}max}$ (kcfs)[1]	Q_{total} (kcfs)	Q_{gen} (kcfs)	Q_{spill} (kcfs)	Q_{aux} (kcfs)	TDG_{fb} (%)	TDG_{sp} (%)	TDG_{aux} (%)	TDG_{avg} (%)	ΔTDG (%)
1085	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	105	113.2	164.5	107.2	2.2
1094	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	110	113.2	164.5	111.4	1.4
1103	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	115	113.2	164.5	115.6	0.6
1112	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	120	113.2	164.5	119.8	-0.2
1121	18 Deflectors/B2CC	No Voluntary Spill	251.9	300.0	251.9	42.9	5.2	125	113.2	164.5	124.0	-1.0
1130	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	251.9	42.9	5.2	105	113.2	164.5	107.2	2.2
1139	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	251.9	42.9	5.2	110	113.2	164.5	111.4	1.4
1148	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	227.6	67.2	5.2	115	115.0	164.5	115.9	0.9
1157	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	175.7	119.1	5.2	120	120.0	164.5	120.8	0.8
1166	18 Deflectors/B2CC	Spill to Capacity @ 110% or TDG Forebay	251.9	300.0	122.5	172.3	5.2	125	125.0	164.5	125.7	0.7
1175	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	105	116.8	164.5	109.4	4.4
1184	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	110	116.8	164.5	112.9	2.9
1193	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	115	116.8	164.5	116.4	1.4
1202	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	120	116.8	164.5	119.9	-0.1
1211	18 Deflectors/B2CC	Spill 85 Kcfs	251.9	300.0	209.8	85.0	5.2	125	116.8	164.5	123.4	-1.6
1220	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	105	118.2	164.5	110.4	5.4
1229	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	110	118.2	164.5	113.7	3.7
1238	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	115	118.2	164.5	116.9	1.9
1247	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	120	118.2	164.5	120.2	0.2
1256	18 Deflectors/B2CC	Spill 100 kcfs	251.9	300.0	194.8	100.0	5.2	125	118.2	164.5	123.4	-1.6
1265	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	105	117.3	164.5	109.7	4.7
1274	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	110	117.3	164.5	113.1	3.1
1283	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	115	117.3	164.5	116.5	1.5
1292	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	120	117.3	164.5	119.9	-0.1
1301	18 Deflectors/B2CC	Spill 30 Percent	251.9	300.0	204.8	90.0	5.2	125	117.3	164.5	123.4	-1.6
1310	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	105	120.0	164.5	112.0	7.0
1319	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	110	120.0	164.5	114.9	4.9
1328	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	115	120.0	164.5	117.8	2.8

Case	Structural Alternative	Spill Operation	$Q_{ph\text{-}max}$ (kcfs)[1]	Q_{total} (kcfs)	Q_{gen} (kcfs)	Q_{spill} (kcfs)	Q_{aux} (kcfs)	TDG_{fb} (%)	TDG_{sp} (%)	TDG_{aux} (%)	TDG_{avg} (%)	ΔTDG (%)
1337	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	120	120.0	164.5	120.8	0.8
1346	18 Deflectors/B2CC	Spill to Capacity @ 120%	251.9	300.0	175.7	119.1	5.2	125	120.0	164.5	123.7	-1.3

[1] Powerhouse capacity of 251.9 kcfs based on all turbines at 58 ft of head, with STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Bonneville master TDG management plan.

$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Bonneville powerhouse (kcfs)

$\mathbf{Q_{total}}$ = Columbia River Flow at Bonneville Dam (kcfs)

$\mathbf{Q_{gen}}$ = Powerhouse Flow (kcfs)

$\mathbf{Q_{spill}}$ = Spillway Flow (kcfs)

$\mathbf{Q_{aux}}$ = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)

$\mathbf{TDG_{sp}}$ = Total Dissolved Gas Saturation in spillway flows (%)

$\mathbf{TDG_{fb}}$ = Total Dissolved Gas Saturation in forebay (%)

TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)

$\mathbf{TDG_{avg}}$ = Flow weighted Total Dissolved Gas Saturation below Dam (%)

ΔTDG = Change in average cross sectional Columbia River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table A7. Columbia River Flow at Bonneville Dam and associated Total Dissolved Gas Saturation for 2009 Spillway Configuration assuming a uniform spill pattern and forebay TDG saturation of 115 percent.

Case	Description	Q_{river}	Q_{gen} [+]	Q_{sp}	TDG_{sp} [#]	TDG_{avg} [*]	Frequency (Apr-Aug)	Frequency (Sep-May)
1	Qriver=Qphmax	252	252	0	na	115.0	31.40%	4.60%
2	Q_{sp}@110%	306	252	54	110	114.1	14.80%	2.00%
3	Q_{sp}@115%	322	252	70	115	115	11.70%	1.60%
4	Q_{sp}@120%	367	252	115	120	116.6	4.50%	0.50%
5	Q_{river}=400	400	252	148	123.7	118.2	2.30%	0.00%
6	7Q10-mean	454	252	202	129.6	121.5	0.80%	0.00%

[+] Total powerhouse flow with all turbines operation at upper 1% of best gate with fish screens in place.
[#] Total dissolved saturation in spillway flows undiluted by powerhouse flows.
[*] Average flow weighted total dissolved gas saturation in the Columbia River below Bonneville Dam.
Case 1= Total river flow is at powerhouse hydraulic capacity with no voluntary spill
Case 2= Total river flow with maximum powerhouse flow and spill capacity at 110%.
Case 3= Total river flow with maximum powerhouse flow and spill capacity at 115%
Case 4= Total river flow with maximum powerhouse flow and spill capacity at 120%
Case 5= Total river flow with maximum powerhouse flow at 400 kcfs
Case 6= Total river flow at 7Q10 flow rate.

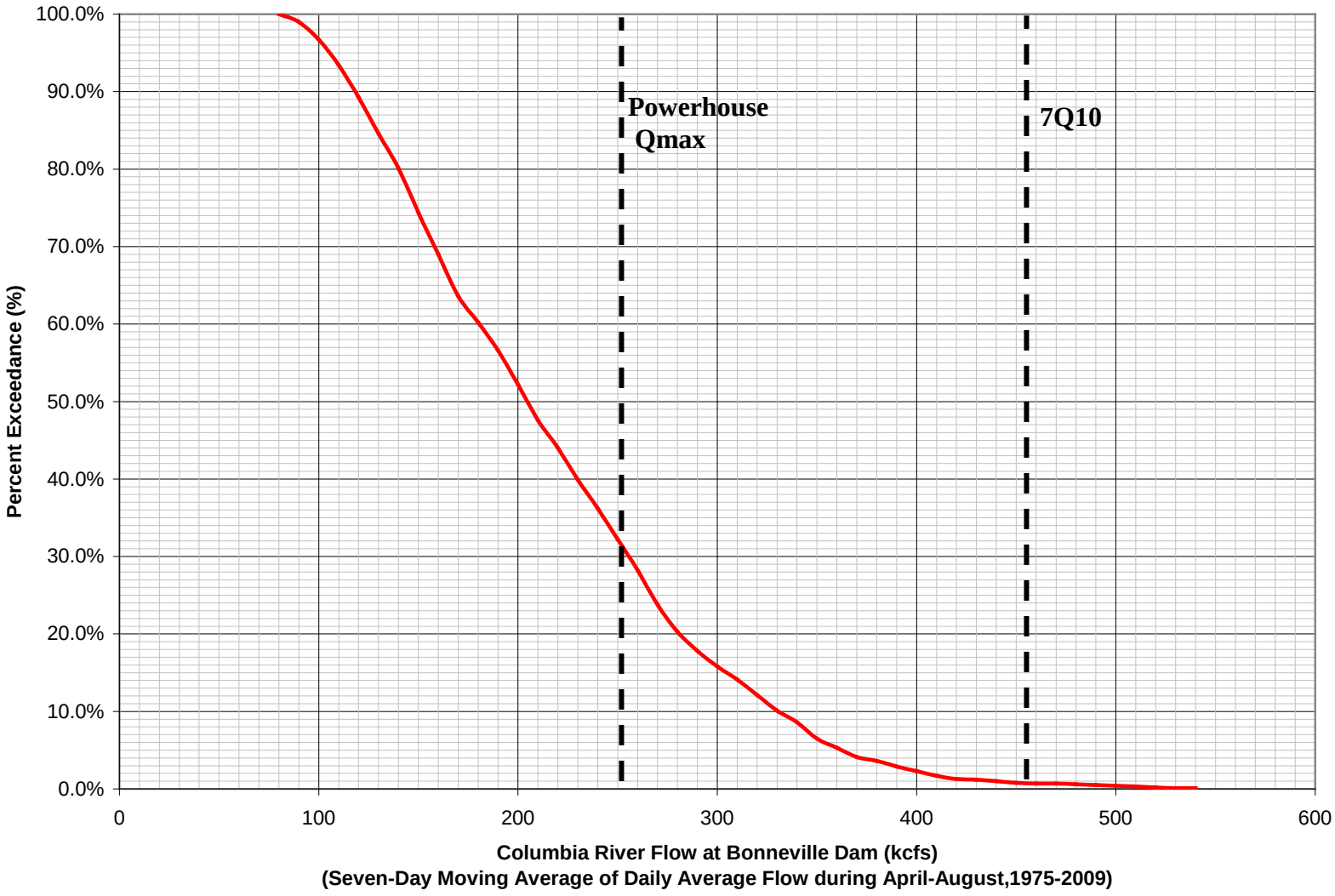

Figure A1. Percent Exceedance versus Columbia River Flow at Bonneville Dam during April-August 1975-2007.

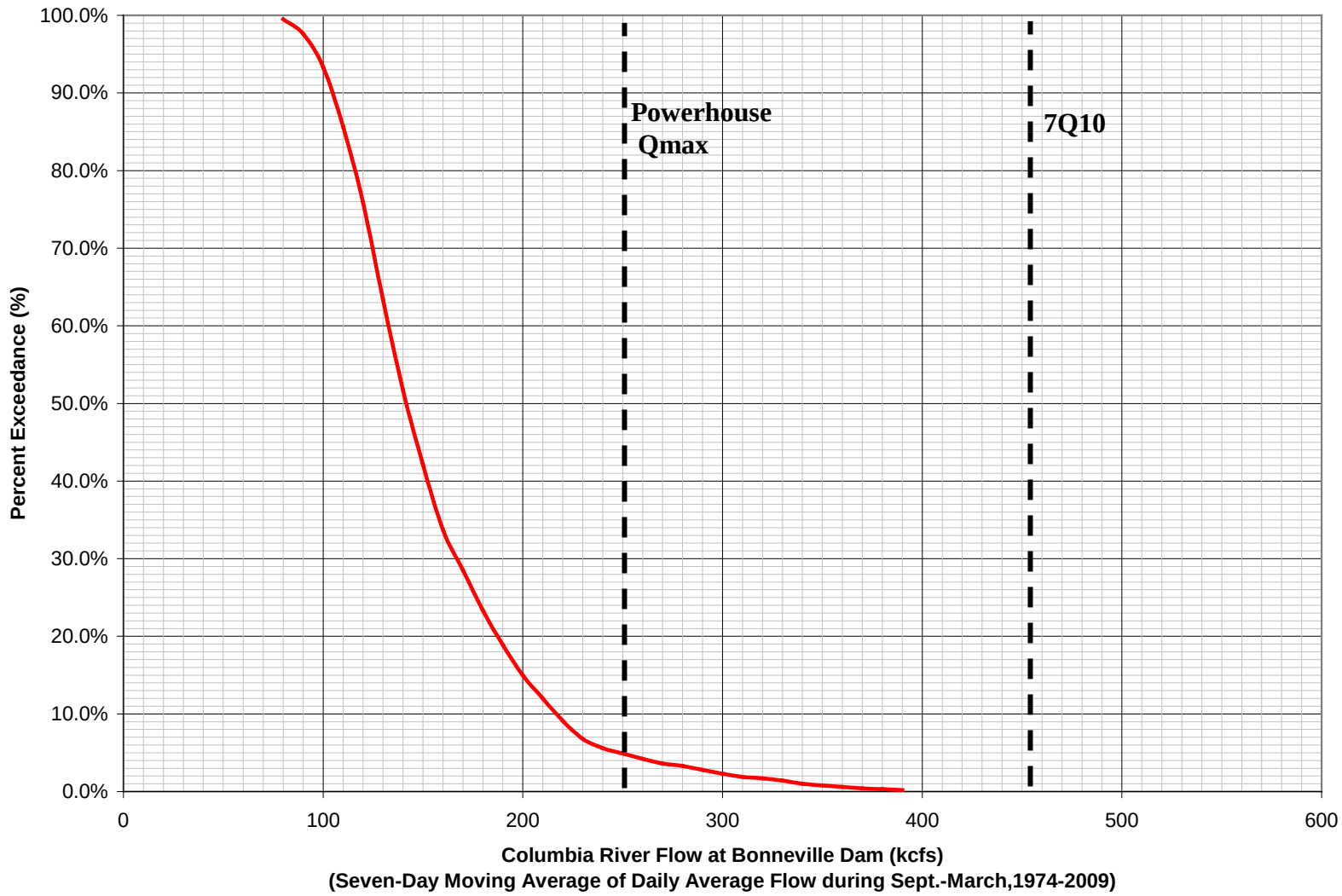

Figure A2. Percent Exceedance versus Columbia River Flow at Bonneville Dam during Sept.-March, 1974-2007.

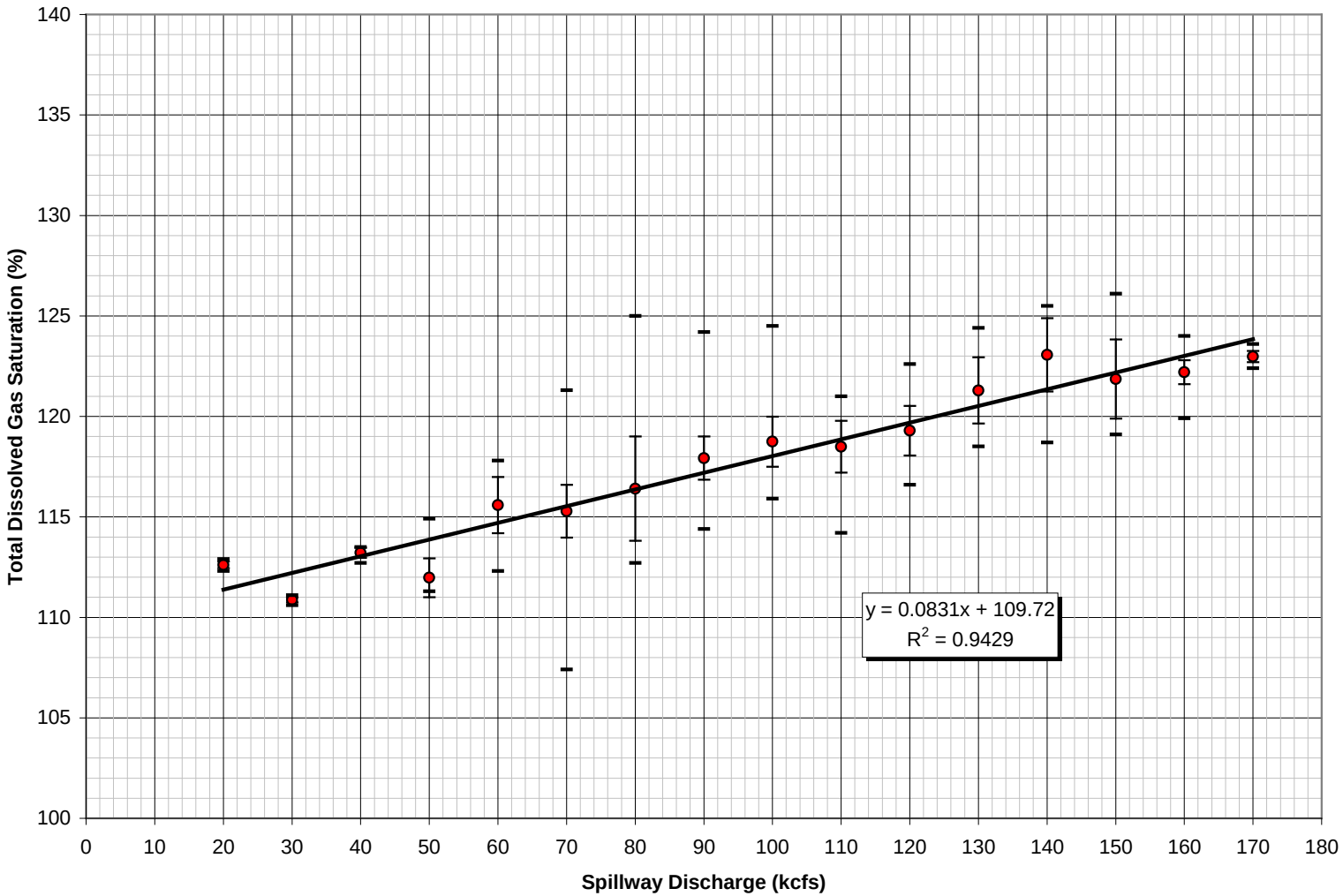

Figure A3. Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at Bonneville Dam (CCIW) as a function of Spillway Discharge, 2004-2007

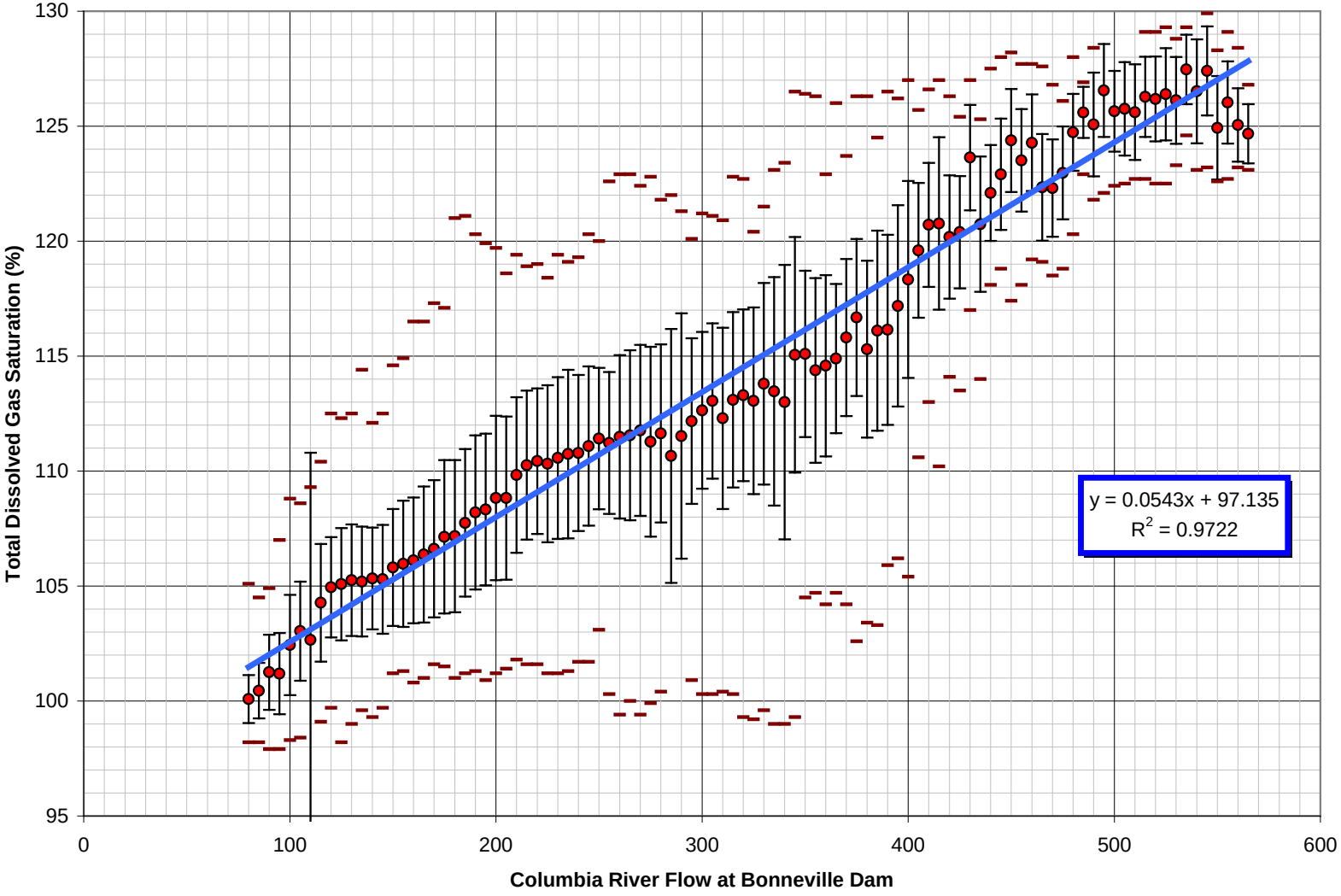

Figure A4. Total Dissolved Gas Saturation in the Forebay of Bonneville Dam as a function of Total Columbia River Flow, 1995-2007

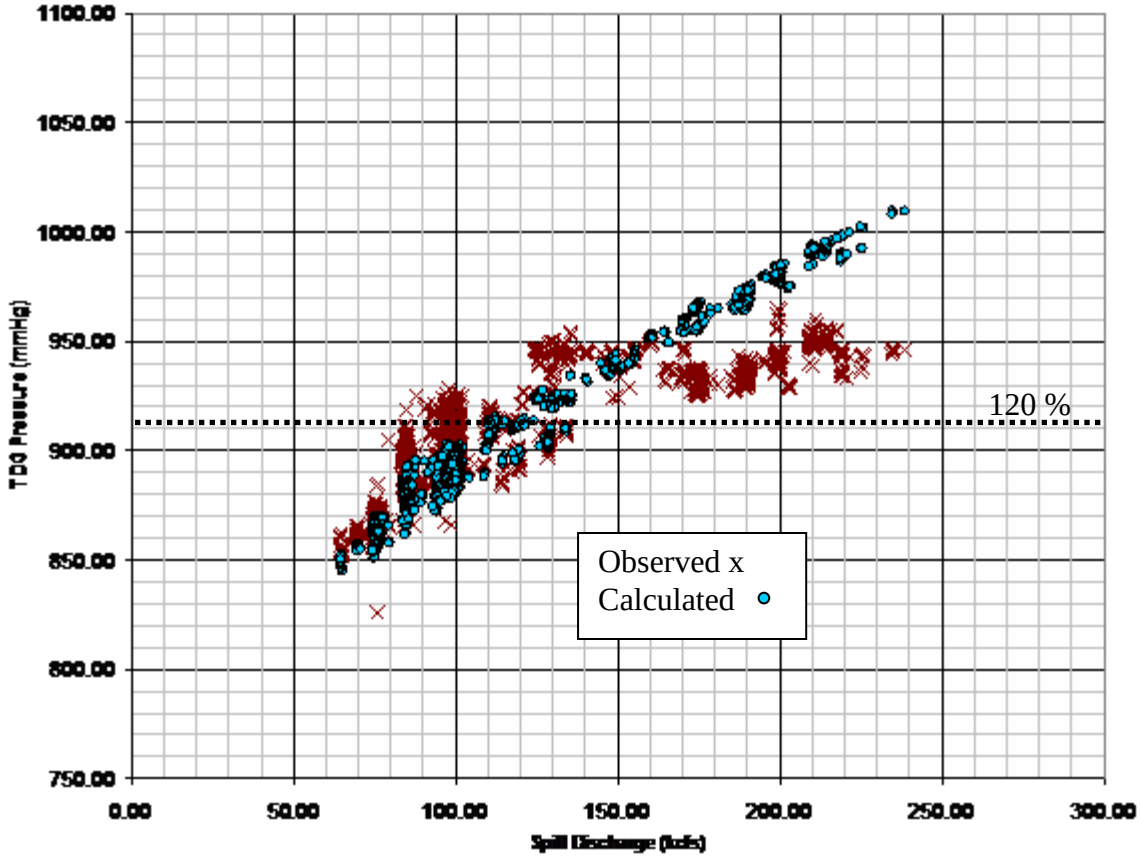

Figure A5. Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at Bonneville as a function of Spillway Discharge, 2008 (Observed and Calculated)

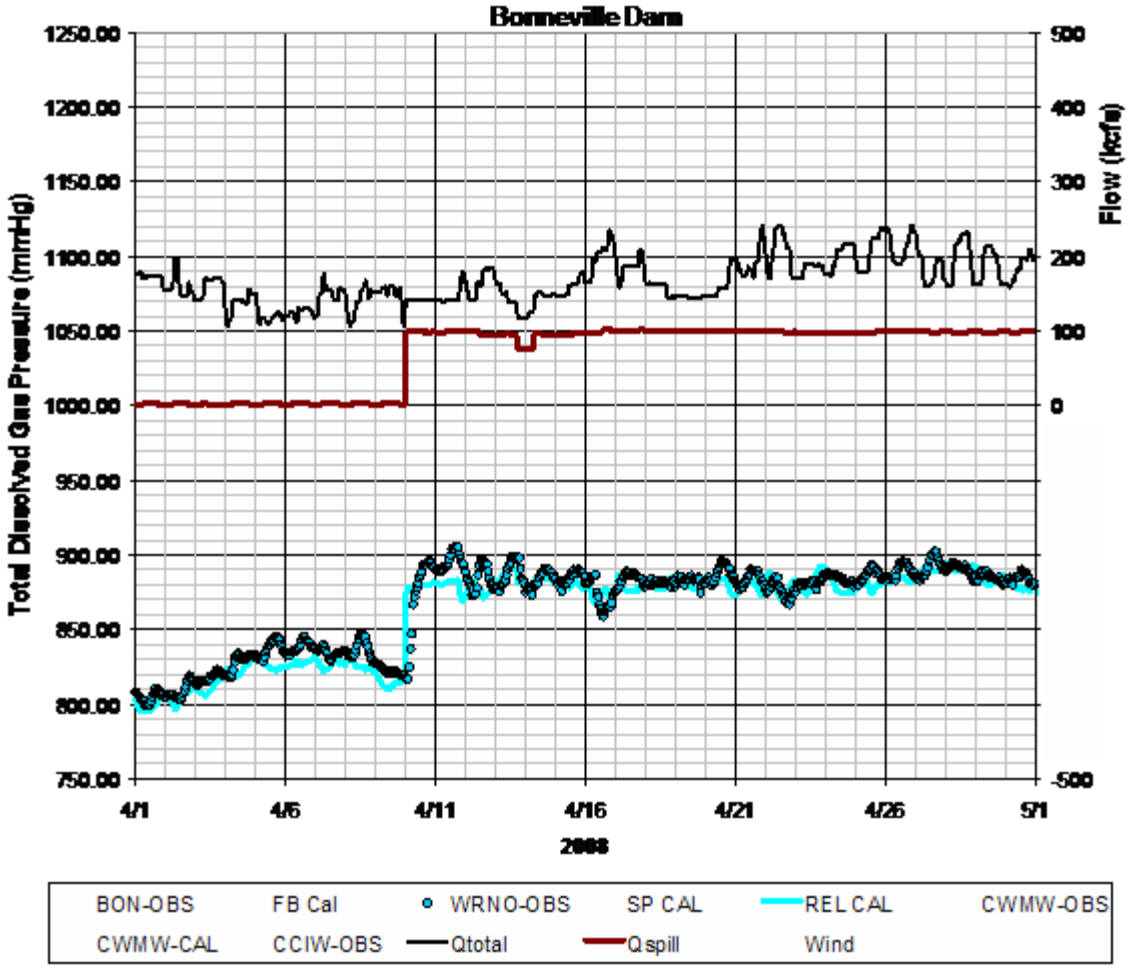

Figure A6 Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Warrendale fixed monitoring station downstream of Bonneville Dam, April 2008 (Rel Cal=Calculated TDG saturation from Equations 3-4, CCIW=Tailwater Fixed Monitoring Station)