Appendix F

Total Dissolved Gas Abatement Plan For Lower Monumental Dam

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Introduction

In its operation of the Federal Columbia River Power System (FCRPS) projects, the U.S. Army Corps of Engineers (Corps) is responsible for providing for the authorized project purposes consistent with applicable laws and regulations. The operation of the Corps FCRPS project has effects on water quality and Endangered Species Act (ESA) listed fish. Accordingly the Corps considers the ecological objectives of the Clean Water Act and the ESA, and complies with the applicable water quality standards to the extent practicable as well conducting operations consistent with applicable Biological Opinions.

The 2008 NOAA Fisheries Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp) relies on spill operations at Corps mainstem projects for listed juvenile salmon and steelhead passage. Currently, the spill operations during the juvenile fish passage season (generally early April into August) at Corps dams are consistent with court-ordered operations and the adaptive management provisions in the 2008 NOAA BiOp as implemented through the Adaptive Management Implementation Plan (AMIP). The intent of the spill operations is to help meet juvenile fish survival performance standards identified in the BiOp. These fish passage spills may result in the generation of total dissolved gas (TDG) supersaturation in the Columbia and lower Snake rivers at levels above current state and federal water quality standards. The states of Washington and Oregon have authorized exceptions to these standards as long as the elevated TDG levels provide for improved fish passage through the spillway without causing more harm to fish populations than through other passage routes. The purpose of this document is to summarize past, present, and future structural and operational TDG abatement as requested by the State of Washington for their criteria adjustment.

The following document contains the TDG abatement plan for Lower Monumental Dam. The Total Dissolved Gas (TDG) exchange properties in the Snake River at Lower Monumental dam have been formulated as a function of alternative structural configurations, spill operations, total river flow rates, background TDG properties and powerhouse hydraulic capacity. The following 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 Lower Monumental Dam for past, present, and future scenarios.

Project Description

Lower Monumental is located 41.6 miles above the Snake and Columbia River confluence and 28.7 miles downstream of the Little Goose project. The main structures include the powerhouse, concrete spillway and stilling basin, navigation lock, fish facilities, and the concrete non-overflow sections with rock-fill embankments on the north and south shores. The dam is 3,791 feet long, including the embankments. The powerhouse includes six generator bays with a maximum total discharge capacity of approximately 135 kcfs. The hydraulic capacity of Lower Monumental is similar to Little Goose and Lower Granite. The Lower Monumental spillway is 498 feet long and consists

of eight 50-foot-wide spillway bays separated by seven 14-foot-wide piers. The spillway bays are numbered consecutively from south to north. The spillway crest elevation is 483.0 fmsl. Eight tainter gates, 50 feet wide by 60.56 feet high, control the spillway discharge. The design capacity of the spillway is 850 kcfs, with a corresponding maximum pool elevation of 548.3 fmsl. At normal full pool elevation 540.0 fmsl, the spillway will pass a maximum of 676 kcfs

Powerhouse Hydraulic Capacity

The Lower Monumental powerhouse unit hydraulic capacity during the fish passage season was estimated assuming the standard-length submersible traveling screens are installed, a total head of 98 ft, and each unit is operated at the upper limit of the peak efficiency constraint as described in the yearly Fish Passage Plan (FPP, 2009). The unit hydraulic capacity for these conditions was estimated to equal 19.4 kcfs for unit 1, 20.0 kcfs for units 2-3, 19.2 kcfs for units. The total hydraulic capacity of the Lower Monumental powerhouse with all 6 units available is 116.8 kcfs. If only 5 units are available the hydraulic capacity of the Lower Monumental powerhouse was estimated as 97.6 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 11.5 kcfs required to meet generation requirements was assumed throughout this evaluation.

Summary of Snake River Flow at Lower Monumental Dam

The daily average total river flow, generation flow, and spillway flow was compiled for Lower Monumental 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 five months; and Non-Fish Passage Season January 1-March 31 and September 1-December 31 for a total of seven months.

The percent exceedance characteristics for the seven-day moving average of daily average flows for the Snake River at Lower Monumental Dam are shown in Figure 1. During the fish passage season from 1975-2009, the median river flow during this period is about 58 kcfs. The frequency that the Snake River flow will exceed 100 kcfs is 22.5 percent and 200 kcfs is only 0.2 percent as listed in Table F1. The TDG exchange characteristics were evaluated for a typical spring operation when total river flows were 94 kcfs (April 7-May 31) and for a typical summer discharge of 57 kcfs (June 1-August 31).

Outside the fish passage season from 1974-2009, the percent exceedance characteristics for the seven-day moving average of daily average flows for the Snake River at Lower Monumental Dam are shown in Figure 2. The median river flow during this period is about 29 kcfs. The frequency that the Snake River flow will exceed 100 kcfs is 2.7 percent and 200 kcfs is 0.0 percent.

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 Snake River at Lower Monumental Dam at 214 kcfs as described in the Total Maximum Daily Load for Lower Snake River Total Dissolved Gas (WDOE, 2002). The period of record used in the TMDL analysis was from 1975-2000. The 7Q10 flow was updated using the extended period of record from 1975-2009 using the methodology described in Bulletin #17B (USGS, 1982) and the data identified in the Lower Snake River TMDL. The updated mean 7Q10 high flow in the Snake River at Lower Monumental Dam was estimated to equal 203 kcfs with a 80 percent confidence limit ranging from 184.4 to 247.6 kcfs. This evaluation did not correct the skew coefficient of the station record. A review of the historic records show that the updated 7Q10 flow of 203 kcfs was exceeded in only 2 of the past 35 water years which infers a return period of once every 17.5 years.

Water Quality Standards

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

TDG Abatement Activities

The TDG loading of the Snake 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 of spill for fish guidance resulting in an enhancement in TDG conditions.

The general approach for TDG abatement activities 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 influence of 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 shallow depths. The effectiveness of spillway flow deflectors in abating TDG production has been consistently demonstrated at Corps of Engineers projects on the Columbia and Snake rivers. Other methodologies to reduce TDG loading below main-stem dam 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 enhancement. 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. 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 Snake 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 Lower Monumental Dam that influences TDG loading in the Snake River during the fish passage season.

Structural Alternatives

The installation of spillway flow deflectors on 6 of the 8 spill bays was included in the original construction of the spillway. The Type I deflector consists of a 12.5-ft-long deflector with a small fillet radius toe curve at an elevation of 434 ft. During the winter of 2003-2004 two additional flow deflectors were added in spill bays 1 and 8 completing this structural gas abatement measure at Lower Monumental Dam. The new deflectors have a Type II design consisting of a 12 ft length and a toe radius providing transition from the spillway face to the horizontally oriented deflector also at elevation 434 ft.

A total of five different structural alternatives were considered in this evaluation of TDG exchange at Lower Monumental Dam. The base condition, “6 Deflectors” consisted of the originally designed spillway with Type I spillway flow deflectors in spill bays 2-6. The second structural configuration “8 Deflectors” includes the spillway with spillway flow deflectors on all eight spill bays. The third configuration “Deflectors and SW” was defined by the existing spillway configuration in 2008 with spillway flow deflectors on all 8 spill bays and a spillway weir (SW) located in spill bay 8. The purpose of this SW structure is to more effectively and efficiency guide juvenile fish past Lower Monumental Dam by providing a surface oriented release over the spillway. The modernization of the Lower Monumental Powerhouse is not expected to change the hydraulic capacity at this project. The fourth structural alternative “Deflectors/SW/Powerhouse Bypass (IT Sluice)” consisted of the existing conditions plus 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 powerhouse. The fifth structural alternative "Deflectors/SW/Powerhouse Bypass with tailrace divider wall" consisted of the a full complement of spillway flow deflectors, SW, plus a Powerhouse surface bypass system and a training wall separating the spillway and powerhouse. This training wall was anticipated to improve fish egress and reduce the entrainment of powerhouse flows into the aerated spillway discharge.

Spill Operation Alternatives

This study also considered the influence of six different spill operations that govern the operations of Lower Monumental 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 the instantaneous voluntary spill equal to 30 percent of the total river flow. The second spill operation required the instantaneous spill to equal 27 kcfs which corresponds with the 2008 operation during the spring. The third operation assumed a constant spill of 17 kcfs subject to powerhouse minimum hydraulic capacity constraints which corresponds with the 2008 spill operation during the summer. 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 (FMS). The fifth spill operation of no net increase in TDG loading of the Snake River called for flows to be limited by the either the 110 percent criteria or background TDG level in the Snake River. The final spill operation called for no voluntary spill excluding the discharge through the powerhouse surface bypass system.

TDG Properties

The TDG exchange properties at Lower Monumental Dam have been influenced by the spillway flow deflectors and the associated spill pattern. The spill operation has changed significantly over the past five years as well. The spill pattern has transitioned from a uniform spill pattern to a bulked spill pattern providing training flow for releases through the SW. The spill operation called for the use of all spill bays during spill operations prior to 1999. The spill pattern was changed for the 2000 fish passage season in an effort to lower TDG production by using only spill bays with flow deflectors. The relationship between TDG saturation and spillway discharge since the installation of spillway flow deflectors in end bays 1 and 8 during the winter of 2003-2004 are shown in Figure 3. The nonlinear relationship between spillway discharge and TDG saturation below 40 kcfs shown in Figure 3 is a result of the implementation of a bulk spill pattern in this operating range. The spillway capacity as limited by the 120 percent tailwater TDG criteria has also declined as a result of this bulked spill operation. The typical spillway capacity as limited by the 120 percent TDG criteria has decreased considerably with the implementation of a bulked spill pattern. The spillway capacity as limited by 120 percent

saturation ranged from 34 to 41 kcfs prior 2003 compared to a range of 23 to 32 kcfs since 2003.

The estimates TDG exchange in the Snake River at Lower Monumental 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. A detailed TDG exchange study was conducted during the 2004 fish passage season at Lower Monumental Dam (Schneider and Wilhelms, 2005). The findings from this investigation of spill up to 44.7 kcfs concluded that the TDG exchange was found to be an exponential function of the specific spillway discharge (kcfs/ft) as shown in Equation 1.

Equation 1

$$\Delta P = 179.97(1 - \exp(-15.07 q_s)) \qquad (mm\,Hg) \qquad (1)$$

r^2=0.95

Std Error = 5.85 mm Hg

Where

$$q_s = \frac{Q_{sp}}{W_{eff}} = \frac{Q_{sp}}{50(N_{sb} + .43(8 - N_{sb}))} \qquad \text{(kcfs/ft)}$$

N_{sb} = Active number of spill bays 1-8.
Q_{sp} = Total spill discharge (kcfs)

The range of spillway flows during the 2004 study limited the applicability of this formulation to higher spill rates experienced during the 2006 and 2008. The equations for TDG production were updated for the existing spillway with flow deflectors with the SW located in spill bay 8 for the current bulked spill pattern based on fixed monitoring data collected during 2008 as presented in Equation 2. The TDG exchange was found to be a product of the exponential function of the specific spillway discharge and the effective tailwater depth of flow.

Equation 2

$$\Delta P = D_{tw}^{1.098} q_s^{0.4986} \qquad (mm\,Hg) \qquad (2)$$

r^2 = 0.91
Std Error = 9.5 mm Hg
D_{tw} = TWE – 405.0 Tailwater Depth of Flow (ft)
TWE = Tailwater elevation (ft)
q_s = Q_{spill}/N_{bays} Specific spillway Discharge (kcfs/bay)
Q_{spill} = total spillway discharge (kcfs)
N_{bays} = Effective number of active spillway bays.
$TDG_{sat} = (P_{atm}+\Delta P)/P_{atm} \times 100$ Total Dissolved Gas Saturation (%)
P_{atm} = Local Atmospheric Pressure (mm Hg)

An increase in the tailwater stage from 440 to 441 ft will result in an increase in TDG pressure of 2.4 mm Hg during a specific spillway discharge of 6 kcfs/bay. Alternatively, an increase in the specific spillway discharge from 6 to 7 kcfs/bay will result in a 6.9 mm Hg increase in TDG pressure for a tailwater elevation of 440 ft. This equation also illustrates the influence of bulking spill in several bays such as the SW with training flow. A total spillway discharge of 45 kcfs uniformly distributed over 8 spill bays will result in a delta pressure of 83 mm Hg (111.0%) at a tailwater elevation of 440 ft. The same 45 kcfs spilled uniformly over 4 bays will result in a delta TDG pressure of 117.4 mm Hg (115.5%) for an increase in TDG saturation of 4.5% over the uniform 8 bay spill pattern. An average local atmospheric pressure of 755 mm Hg was applied to estimate the total dissolved gas saturation.

The TDG properties of powerhouse flows were assumed to retain forebay TDG characteristics. However, the fate of the TDG characteristics of powerhouse releases is complicated by the subsequent entrainment of a portion of this discharge into the highly aerated flow conditions downstream of the spillway. The spillway flow deflectors generate a turbulent surface oriented jet that draws water adjacent to and beneath this jet into this flow feature. The associated TDG exchange of the entrained flow ranges from complete incorporation into the spillway flows within the stilling basin attaining identical TDG saturations as spillway flows to mixing with spillway releases in the tailwater channel where TDG exchange is less prominent due to the air/water ratios and shallower depth of entrained bubbles.

The average flow weighted TDG saturation below Lower Monumental Dam was determined for each combination of structural and operational alternatives.
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 3.

Equation 3

$$TDG_{avg} = \frac{Q_{sp}TDG_{sp} + Q_{gen}TDG_{gen}}{Q_{tot}} \quad \text{.....(3)}$$

where:

Q_{tot}	=	Total River Flow (kcfs)
Q_{sp}	=	Spillway discharge (kcfs)
Q_{gen}	=	Generation discharge (kcfs)
TDG_{gen}	=	TDG saturation of generation discharges (percent)
TDG_{avg}	=	Average cross sectional TDG saturation in the Snake River (percent)

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

To account for the added TDG loading associated with the entrainment of powerhouse releases into the aerated spillway flow, an added mass term was included in the conservation statement as shown in Equation 4. This added mass discharge estimates the effective powerhouse flow entrainment into spillway releases where a portion of powerhouse release encounters the aerated flow conditions caused by spillway flows and experiences a similar level of TDG uptake. This formulation reduces the amount of flow from the powerhouse releases retaining forebay TDG levels available for dilution with spillway releases while increasing the volume of water exposed to highly aerated flow below the spillway.

Equation 4

$$TDG_{avg} = \frac{(Q_{sp} + Q_{ent})TDG_{sp} + (Q_{gen} - Q_{ent})TDG_{gen}}{Q_{tot}} \qquad (4)$$

where:

Q_{tot} = Total River Flow (kcfs)

Q_{sp} = Spillway discharge (kcfs)

Q_{gen} = Generation discharge (kcfs)

Q_{ent} = Effective entrainment discharge (kcfs)

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

TDG_{avg} = Average TDG saturation on transect USGS (percent)

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

A simple functional form for the effective entrainment discharge has been estimated from field studies of TDG exchange at Lower Monumental (Schneider and Wilhelms, 2004) and Lower Granite dams (Schneider, 2003). The effective entrainment discharge was found to be linearly proportional to the spillway discharge in each case where the constant of proportionality is called the effective entrainment coefficient. The functional form for the estimation of the entrainment discharge is shown in equation 5. The entrainment coefficient for Lower Monumental Dam during the field study conducted in 2004 was 0.80.

Equation 5

$$Q_{ent} = C_{ent}Q_{sp} \qquad (4)$$

Where

$$0 < Q_{ent} < Q_{ph}$$

The return of diverted flow associated with the powerhouse surface bypass alternatives has the potential to generate elevated TDG pressures in the Snake 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. The outfall below Bonneville Dam associated with the Bonneville 2nd Powerhouse Corner collector (B2CC) was also found to add to the TDG loading in the Columbia River during low tailwater conditions. The type of outfall flow conditions below these two surface bypass systems are quite different. A plunge pool was constructed at the outfall of the B2CC increasing the potential for aerated flow to experience large hydrostatic pressures and TDG uptake. In contrast, the IT chute at The Dalles Dam discharges into a shallow basin and is directed at an angle to releases from the powerhouse. These outfalls do provide some reference for estimating the TDG exchange for surface bypass flows at Lower Monumental Dam. For this study a constant TDG saturation of 119.8 percent was applied for all 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 Lower Monumental Dam should consider the existence of elevated background TDG levels from upstream sources. The presence of elevated background TDG levels at Lower Monumental Dam is caused by the voluntary spill at upstream projects to aid fish passage or involuntary spill resulting from river flows exceeding powerhouse capacity or the presence of surplus generation capacity in the system. The forebay TDG levels at Lower Monumental Dam are summarized from 1995-2007 as a function of total river flow in Figure 4. The observed daily average TDG saturation in the forebay of Lower Monumental Dam was summarized for 5 kcfs ranges in total river flow from 30 to 245 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 Lower Monumental Dam and total river flow. This figure shows that when river flows are approaching the 7Q10 level of 203 kcfs, the background TDG saturation typically ranges from 119 to 128 percent of saturation.

The reliability of TDG exchange estimates at Lower Monumental Dam as presented in Equation 2 can be evaluated by reviewing historic operations and the associated TDG response as measured at the tailwater fixed monitoring stations. The tailwater TDG saturation at Lower Monumental as a function of spillway discharge filtered for constant spill events of 3 hours and longer for the last three years are shown in Figure 5. One interesting feature of these data are the large range of TDG response for a given spill discharge. The spill capacity limited by 120 percent saturation has ranged from 20 to 60 kcfs. The variability of TDG saturation for a given spill discharge is chiefly attributed to the variation in tailwater elevation. Other factors contributing to the wide spread in the TDG data as a function of spill discharge are variations in spill pattern, local atmospheric pressure, background TDG levels (during small percent spill events), and water temperature influences.

A hind cast of TDG saturation below Lower Monumental Dam for a wide range of observed historic operations (total river flow ranged from 37 to 237 kcfs) during May of 2008 were conducted using the relationship shown in Equation 2. The spill discharge ranged from 9 to 122 kcfs and averaged 35 kcfs during this month. The tailwater elevation also experienced a wide variation from 437.2 to 447.8 ft. The hourly total river and spillway flow are shown in Figure 6 along with the TDG saturation as observed and calculated at the tailwater fixed monitoring station. This simple equation does an adequate job of estimating both the peak levels of TDG saturation produced during peak involuntary spill events as well as simulating the voluntary TDG pressures in response to both bulk and uniform training spill patterns.

Results

A series of estimates of TDG exchange were generated for a matrix of conditions impacting TDG exchange in the Snake River at Lower Monumental 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 Lower Monumental 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 lmnTDGest.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 F2. This table consists of 2694 different cases that provide a comprehensive summary of the TDG management program at Lower Monumental Dam. The utility of this master table is more manageable when selecting a much 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 bay allowing the selection of a narrower range of case components. The following discussion of a small subset of the contents from this analysis.

Structural Configuration

The TDG exchange across the five structural configuration investigated at Lower Monumental Dam for a spill operation of spilling 27 kcfs during total river flows of 50, 125, and 203 kcfs was examined as shown in Tables F3, F4, and F5. The total river flow of 50 kcfs reflects an average flow condition during the fish passage season. The 125 kcfs is a 10 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 203 kcfs represents the high Snake River discharge that can be expected to occur one every ten years on average. The background TDG levels were assumed to be 110 percent of saturation which would be unusual for the flood flow conditions and generation of TDG supersaturation at upstream projects. A full powerhouse capacity of 116.8 kcfs was assumed for these conditions.

All five cases were able to spill 27 kcfs without exceeding the TDG criteria of 120 percent in spillway flows. The TDG levels in spill were similar for all cases except the 8 Deflector configuration (Table F3). A uniform 8 bay spill pattern was assumed for this configuration resulting in a considerably smaller TDG level in both spill and cross sectional average condition. It is informative to contrast the 6 Deflector performance with the 8 Deflector results since both configurations assumed a uniform 8 bay spill pattern. The addition of the two end bay deflectors reduced the TDG saturation from 117.3 to 111.8 percent, a considerable reduction in TDG saturation. The other structural components with the SW used a bulk spill pattern that generates higher TDG levels. The addition of the spillway/powerhouse training wall provided a significant reduction in the cross sectional TDG levels in spite of the higher TDG content in spill.

The higher river flow condition of 125 kcfs resulted in TDG levels in spill slightly exceeding the tailwater criteria of 120 percent for structural configurations with the SW as listed in Table F4. The higher TDG levels are associated with the greater tailwater depth of flow. The range in cross sectional average TDG levels was much smaller for this condition due to the much small percent river spilled and the greater influence of background TDG levels in the forebay. It should be noted that the lower gate settings applied to the 6 and 8 Deflector configurations has been shown to be a source of elevated fish injury at the Bonneville spillway.

The high flow conditions during the 203 kcfs river flows require spill to exceed 90 kcfs for all cases (Table F5). The spill pattern also involves the full spillway for cases at this level of spill. The 6 Deflector configuration generated TDG levels in spill above 130 percent of saturation. The influence of the non-deflected flows from bay 1 and bay 8 were likely the source for these higher TDG levels. This clearly demonstrates the added gas abatement benefits of adding the two end bay deflectors. The large involuntary spill

releases generated TDG levels in excess of 125 percent for all cases in spillway waters and above 120 percent in mixed waters for all conditions except the case with the spillway training wall. The training wall allows for powerhouse releases to dilute the high TDG waters generated in spillway releases which was not the case for the other structural alternatives. The SW was not found to be a detriment to TDG generation at this high spillway flow.

Spill Operation

The influence of spill operation on TDG exchange was explored for the existing 2009 structural configuration of 8 deflectors with SW for three river flow conditions 50, 125, and 203 kcfs. The maximum powerhouse capacity and forebay TDG level of 110 percent was also held constant for this evaluation as listed in Table F6. The SW configuration was only capable of spilling from a non-SW spill bay at a river flow of 50 kcfs because the fixed SW discharge exceeds the 110 percent TDG constraint. It is interesting to note that the highest spill discharge during the 50 kcfs river flow did not generate the highest TDG level. This condition is caused by the change in spill pattern and is consistent with the observed data shown in Figure 5 where the TDG levels decline for flows approaching 40 kcfs. The spill operation has a very important influence on the TDG loading of the Snake River at 50 kcfs with average TDG levels ranging from no change from background conditions to a maximum level of 118 percent for a fixed spill of 27 kcfs. The spill operation of 27 kcfs at low river flow conditions is likely to trigger exceedances of 115 percent in the forebay of Ice Harbor Dam.

The spill operation at 125 kcfs is also an important determinant of TDG loading in the Snake River. A small amount of spill is required at this flow rate because of excess flow above powerhouse capacity. However, the capacity spill constrained by the tailwater TDG criteria of 120 percent resulted in a spill discharge of 63.5 kcfs. This seems to be a large discharge at Lower Monumental Dam as limited by the tailwater TDG criteria but observed data in Figure 5 supports this high capacity estimate. The high entrainment of powerhouse flows is evident in the spill to capacity at 120 percent condition where nearly all the powerhouse flows become entrained into the spillway.

The spill operation influence of TDG exchange is not important at the flood flow of 203 kcfs. All the cases are identical with an average TDG saturation of 124.2 percent.

Total River Flow

The TDG exchange at Lower Monumental Dam with a structural configuration of 8 deflectors with SW subject to the spill operation of constant spill discharge of 27 kcfs was highly variable as show in Table F7. The average TDG level declines for total river flows ranging from 50 to 150 kcfs while the TDG level in spill remains about the same. This attribute is caused by the spill pattern transitioning from a bulk to a uniform pattern where the specific discharge remains nearly constant. The TDG levels in spill only step well above the 120 level when river flows reach 200 kcfs. Average cross sectional TDG

levels rise rapidly under involuntary spill conditions as the entrainment of powerhouse flows diminish the ability of these flow to dilute spillway flows.

Forebay TDG Levels

Forebay TDG conditions are important in shaping the average conditions below the dam when spill is a small component of total river flow. Spill operations that limit the percent spill allow sufficient powerhouse flows to dilute spillway releases as listed in Table F8. The combination of high forebay TDG levels with small spillway flows can result in a net degassing of the Snake River where tailwater TDG levels are less than forebay conditions. The influence of powerhouse entrainment and not dilution is illustrated in the spill to capacity at 120 percent spill operation TDG estimates. The resultant average TDG levels below the dam range only from 118.5 to 120.5 when spilling half the river with forebay TDG levels ranging from 105 to 125 percent. The influence of upstream sources of TDG supersaturation is lost during high percent spill events because of the exposure of nearly all the river flows to highly aerated flow conditions.

Lower Monumental 2009 configuration TDG and Flow Summary

The TDG saturation in Snake River below Lower Monumental Dam was estimated for 5 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 2-4 correspond with river flows at maximum powerhouse discharge with the spillway capacity limited by TDG saturations of 110, 115, and 120 percent. The final case corresponded with the updated mean 7Q10 flow of 203 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 Lower Monumental Dam from 1974-2009 are also listed in Table F9.

The frequency for spilling water above the maximum powerhouse capacity during the fish passage season is nearly 14.6 percent of the time at Lower Monumental Dam but only about 1.3 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 16 kcfs will generate TDG levels at 110 percent of saturation or 5 percent lower than the initial conditions. Outside of the fish passage season a river flow of 132.8 kcfs occurs less than 0.50 percent of the time. This operation will result in a net decrease in the average TDG conditions of the river to 113.9 percent when forebay levels are 115 percent. The spillway discharges up to 34 kcfs will either reduce or cause no change in the TDG loading of the Snake River for total river flows up to 150.8 kcfs which occurs only about 5.9 percent of the time during the fish passage season. The spillway flows at Lower Monumental Dam up to 57 kcfs will result in TDG levels of 120 percent and less which corresponds to a total river discharge of 173.8 kcfs and a frequency of occurrence of 2.3 percent during the fish passage season. The worst case conditions will be associated with the 7Q10 flows and a

spill discharge of 86.2 kcfs resulting in TDG saturation in spillway flows of 125.4 percent.

Conclusions

Lower Monumental Dam is generally a modest producer of TDG supersaturation during current voluntary spill conditions compared other Snake River projects. The TDG levels at the tailwater fixed monitoring station generally remain within the TDG criteria during voluntary spill conditions. However, the introduction of the bulk spill pattern to support SW spill generates TDG levels that can approach and in certain cases exceed the TDG criteria at low total spillway flows. The entrainment of powerhouse flows is an important component shaping the TDG loading at Lower Monumental Dam. Spill operations that restrict the percentage of river spilled can positively limit the degree of entrainment. The inclusion of a training wall between the spillway and powerhouse is another effective method to separate project discharges. The effectiveness of partitioning flows will diminish as forebay TDG levels rise. The addition of two spillway flow deflectors significantly reduced the TDG loading in the Snake River particularly during involuntary spill events. The transition to the bulk spill pattern has had the impact of reducing the volume of water spilled at Lower Monumental Dam. The adoption of improved or alternative fish bypass systems has the potential to further reduce the reliance on spill to achieve fish management goals. Spill operations and more effective spill fish guidance structures will have little influence on TDG loading during flood flow conditions. The TDG exchange associated with flood flows causing exceedances of water quality standards in the State of Washington are infrequent and of short duration.

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Table F1

Percent of time the seven-day moving average of daily average flows exceed the reference Snake River Flow at Lower Monumental Dam, 1975-2009 water years.

Snake River Flow (kcfs)	Fish Passage Season April-Aug (%)	Non-Fish Passage Season Sept.-March (%)	Comments
25	85.60%	63.50%	
50	55.60%	14.90%	
75	38.50%	5.10%	
78.5	36.10%	4.70%	Powerhouse capacity 5 units
92.4	27.10%	3.50%	Powerhouse capacity 6 units
100	22.50%	2.70%	
125	10.90%	0.70%	
150	5.90%	0.20%	
175	2.20%	0.00%	
200	0.20%	0.00%	
203	0.00%	0.00%	Updated 7Q10 flow rate

Table F2
Configuration Matrix for
TDG Estimates in the Snake River at Lower Monumental Dam

Structural Alternative	Spill Policy	Qph-Max (kcfs)	Qtotal (kcfs)	TDGfb (%)
Base-6 Deflectors	No Voluntary Spill	116.8	25	105
8 Deflectors	Spill to Capacity @ 110% or TDG Forebay	97.6	50	110
8 Deflectors + SW	Spill 17 Kcfs		75	115
8 Deflectors + SW + PH Surfacce Bypass	Spill 27 kcfs		100	120
8 Deflectors + SW + PH Surfacce Bypass + Training Wall	Spill 30 Percent		125	125
	Spill to Capacity @ 120%		150	
			175	
			200	
			203	

Table F3

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flow of 50 kcfs, Forebay TDG level of 110% by Structural alternative and spill operation of a constant 27 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 (%)
191	Base-6 Deflectors	Spill 27 kcfs	116.8	50.0	22.3	27.0	0.7	110	117.3	110.0	117.1	7.1
461	8 Deflectors	Spill 27 kcfs	116.8	50.0	22.3	27.0	0.7	110	111.8	110.0	111.7	1.7
731	8 Deflectors + SW	Spill 27 kcfs	116.8	50.0	22.3	27.0	0.7	110	118.2	110.0	118.0	8.0
1001	8 Deflectors + SW + PH Surface Bypass	Spill 27 kcfs	116.8	50.0	18.0	27.0	5.0	110	118.2	119.8	118.1	8.1
1271	8 Deflectors + SW + PH Surface Bypass + Training Wall	Spill 27 kcfs	116.8	50.0	18.0	27.0	5.0	110	118.2	119.8	115.4	5.4

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
$\mathbf{Q_{total}}$ = Snake River Flow at Lower Monumental 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 Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F4

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flow of 125 kcfs, Forebay TDG level of 110% by Structural alternative and spill operation of a constant 27 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 (%)
194	Base-6 Deflectors	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	118.6	110.0	113.4	3.4
464	8 Deflectors	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	113.0	110.0	111.2	1.2
734	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	120.1	110.0	113.9	3.9
1004	8 Deflectors + SW + PH Surface Bypass	Spill 27 kcfs	116.8	125.0	93.0	27.0	5.0	110	120.1	119.8	114.2	4.2
1274	8 Deflectors + SW + PH Surface Bypass + Training Wall	Spill 27 kcfs	116.8	125.0	93.0	27.0	5.0	110	120.1	119.8	112.6	2.6

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$Q_{ph\text{-}max}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
Q_{total} = Snake River Flow at Lower Monumental Dam (kcfs)
Q_{gen} = Powerhouse Flow (kcfs)
Q_{spill} = Spillway Flow (kcfs)
Q_{aux} = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)
TDG_{sp} = Total Dissolved Gas Saturation in spillway flows (%)
TDG_{fb} = Total Dissolved Gas Saturation in forebay (%)
TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)
TDG_{avg} = Flow weighted Total Dissolved Gas Saturation below Dam (%)
ΔTDG = Change in average cross sectional Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F5

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flow of 203 kcfs, Forebay TDG level of 110% by Structural alternative and spill operation of a constant 27 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 (%)
152	Base-6 Deflectors	Spill 27 kcfs	116.8	203.0	116.8	85.5	0.7	110	130.2	110.0	125.3	15.3
691	8 Deflectors	Spill 27 kcfs	116.8	203.0	116.8	85.5	0.7	110	125.3	110.0	121.6	11.6
1229	8 Deflectors + SW	Spill 27 kcfs	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
1767	8 Deflectors + SW + PH Surface Bypass	Spill 27 kcfs	116.8	203.0	116.8	81.2	5.0	110	124.9	119.8	120.9	10.9
2307	8 Deflectors + SW + PH Surface Bypass + Training Wall	Spill 27 kcfs	116.8	203.0	116.8	81.2	5.0	110	124.9	119.8	116.2	6.2

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
$\mathbf{Q_{total}}$ = Snake River Flow at Lower Monumental 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 Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F6

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flow of 50, 25, and 203 kcfs, Forebay TDG level of 110% for the 8 Deflector with SW 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 (%)
821	8 Deflectors + SW	No Voluntary Spill	116.8	50.0	49.3	0.0	0.7	110	100.6	110.0	110.0	0.0
866	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	50.0	46.9	2.4	0.7	110	110.0	110.0	110.0	0.0
910	8 Deflectors + SW	Spill 17 Kcfs	116.8	50.0	32.3	17.0	0.7	110	115.7	110.0	113.5	3.5
955	8 Deflectors + SW	Spill 27 kcfs	116.8	50.0	22.3	27.0	0.7	110	118.2	110.0	118.0	8.0
1000	8 Deflectors + SW	Spill 30 Percent	116.8	50.0	34.3	15.0	0.7	110	114.7	110.0	112.5	2.5
1045	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	50.0	11.5	37.8	0.7	110	116.2	110.0	116.2	6.2
824	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	110	116.2	110.0	110.7	0.7
869	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	116.8	7.5	0.7	110	116.2	110.0	110.7	0.7
913	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	110	117.2	110.0	111.8	1.8
958	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	120.1	110.0	113.9	3.9
1003	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	110	120.0	110.0	113.9	3.9
1048	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	110	120.0	110.0	119.0	9.0
828	8 Deflectors + SW	No Voluntary Spill	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
873	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
917	8 Deflectors + SW	Spill 17 Kcfs	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
962	8 Deflectors + SW	Spill 27 kcfs	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
1007	8 Deflectors + SW	Spill 30 Percent	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8
1052	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
$\mathbf{Q_{total}}$ = Snake River Flow at Lower Monumental 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 Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F7

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flows ranging from 50 to 203 kcfs, Forebay TDG level of 110% for the 8 Deflector with SW Structural alternative and spill operation of a constant 27 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 (%)
954	8 Deflectors + SW	Spill 27 kcfs	116.8	25.0	11.5	12.8	0.7	110	114.2	110.0	114.2	4.2
955	8 Deflectors + SW	Spill 27 kcfs	116.8	50.0	22.3	27.0	0.7	110	118.2	110.0	118.0	8.0
956	8 Deflectors + SW	Spill 27 kcfs	116.8	75.0	47.3	27.0	0.7	110	118.8	110.0	115.7	5.7
957	8 Deflectors + SW	Spill 27 kcfs	116.8	100.0	73.7	25.6	0.7	110	120.0	110.0	114.6	4.6
958	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	120.1	110.0	113.9	3.9
959	8 Deflectors + SW	Spill 27 kcfs	116.8	150.0	116.8	32.5	0.7	110	119.1	110.0	113.6	3.6
960	8 Deflectors + SW	Spill 27 kcfs	116.8	175.0	116.8	57.5	0.7	110	120.3	110.0	116.1	6.1
961	8 Deflectors + SW	Spill 27 kcfs	116.8	200.0	116.8	82.5	0.7	110	125.0	110.0	121.2	11.2
962	8 Deflectors + SW	Spill 27 kcfs	116.8	203.0	116.8	85.5	0.7	110	125.6	110.0	121.8	11.8

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$\mathbf{Q_{ph\text{-}max}}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
$\mathbf{Q_{total}}$ = Snake River Flow at Lower Monumental 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 Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F8

Summary of Total Dissolved Gas Exchange at Lower Monumental Dam for Snake River flow of 125 kcfs, Forebay TDG levels ranging from 105 to 125 % for the 8 Deflector with SW 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 (%)
815	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	105	116.2	105.0	106.2	1.2
824	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	110	116.2	110.0	110.7	0.7
833	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	115	116.2	115.0	115.1	0.1
842	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	120	116.2	120.0	119.6	-0.4
851	8 Deflectors + SW	No Voluntary Spill	116.8	125.0	116.8	7.5	0.7	125	116.2	125.0	124.0	-1.0
860	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	116.8	7.5	0.7	105	116.2	105.0	106.2	1.2
869	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	116.8	7.5	0.7	110	116.2	110.0	110.7	0.7
878	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	116.8	7.5	0.7	115	116.2	115.0	115.1	0.1
887	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	61.8	62.5	0.7	120	120.0	120.0	120.0	0.0
896	8 Deflectors + SW	Spill to Capacity @ 110% or TDG Forebay	116.8	125.0	26.2	98.1	0.7	125	125.0	125.0	125.0	0.0
904	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	105	117.2	105.0	108.0	3.0
913	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	110	117.2	110.0	111.8	1.8
922	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	115	117.2	115.0	115.5	0.5
931	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	120	117.2	120.0	119.3	-0.7
940	8 Deflectors + SW	Spill 17 Kcfs	116.8	125.0	107.3	17.0	0.7	125	117.2	125.0	123.1	-1.9
949	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	105	120.1	105.0	110.9	5.9
958	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	110	120.1	110.0	113.9	3.9
967	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	115	120.1	115.0	117.0	2.0
976	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	120	120.1	120.0	120.0	0.0
985	8 Deflectors + SW	Spill 27 kcfs	116.8	125.0	97.3	27.0	0.7	125	120.1	125.0	123.1	-1.9
994	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	105	120.0	105.0	110.9	5.9
1003	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	110	120.0	110.0	113.9	3.9
1012	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	115	120.0	115.0	117.0	2.0
1021	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	120	120.0	120.0	120.0	0.0
1030	8 Deflectors + SW	Spill 30 Percent	116.8	125.0	97.1	27.2	0.7	125	120.0	125.0	123.0	-2.0

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 (%)
1039	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	105	120.0	105.0	118.5	13.5
1048	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	110	120.0	110.0	119.0	9.0
1057	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	115	120.0	115.0	119.5	4.5
1066	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	120	120.0	120.0	120.0	0.0
1075	8 Deflectors + SW	Spill to Capacity @ 120%	116.8	125.0	61.8	62.5	0.7	125	120.0	125.0	120.5	-4.5

[1] Powerhouse capacity of 116.8 kcfs based on 6 turbines at 96 ft of head, with standard length STS installed, and operated at upper generation limit defined in FPP.

Case - Case number as listed in Lower Monumental master TDG management plan.
$Q_{ph\text{-}max}$ = Maximum hydraulic capacity of the Lower Monumental powerhouse (kcfs)
Q_{total} = Snake River Flow at Lower Monumental Dam (kcfs)
Q_{gen} = Powerhouse Flow (kcfs)
Q_{spill} = Spillway Flow (kcfs)
Q_{aux} = Auxiliary Flow including Powerhouse Surface Bypass (kcfs)
TDG_{sp} = Total Dissolved Gas Saturation in spillway flows (%)
TDG_{fb} = Total Dissolved Gas Saturation in forebay (%)
TDG_{aux} = Total Dissolved Gas Saturation in auxiliary release including the surface bypass outfall (%)
TDG_{avg} = Flow weighted Total Dissolved Gas Saturation below Dam (%)
ΔTDG = Change in average cross sectional Snake River TDG saturation (average tailwater TDG saturation minus forebay TDG saturation %)

Table F8

Snake River Flow at Lower Monumental 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	116.8	116.8	0	na	115.0	14.60%	1.30%
2	Q_{sp}@110%	132.8	116.8	16	110	113.9	9.10%	0.50%
3	Q_{sp}@115%	150.8	116.8	34	115	115.0	5.90%	0.20%
4	Q_{sp}@120%	173.8	116.8	57	120	117.8	2.30%	0.00%
5	7Q10-mean	203	116.8	86.2	125.4	122.9	0.10%	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 Snake River below Ice Harbor Dam.
Case 1= Total river flow is at powerhouse hydraulic capacity with no voluntary spill operation
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 at 7Q10 flow rate.

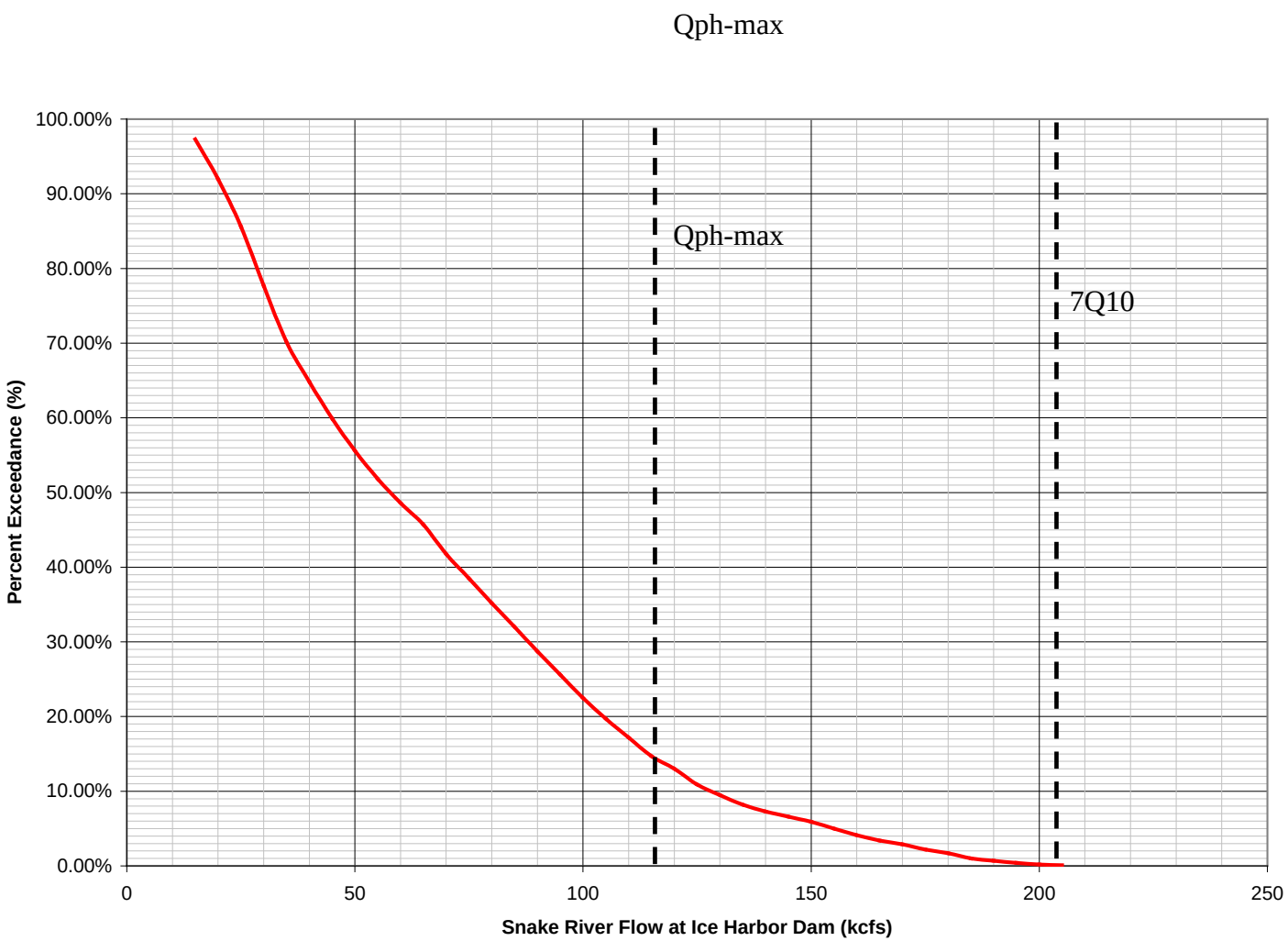

Figure F1. Percent Exceedance versus Snake River Flow at Lower Monumental Dam during April-August 1975-2009.

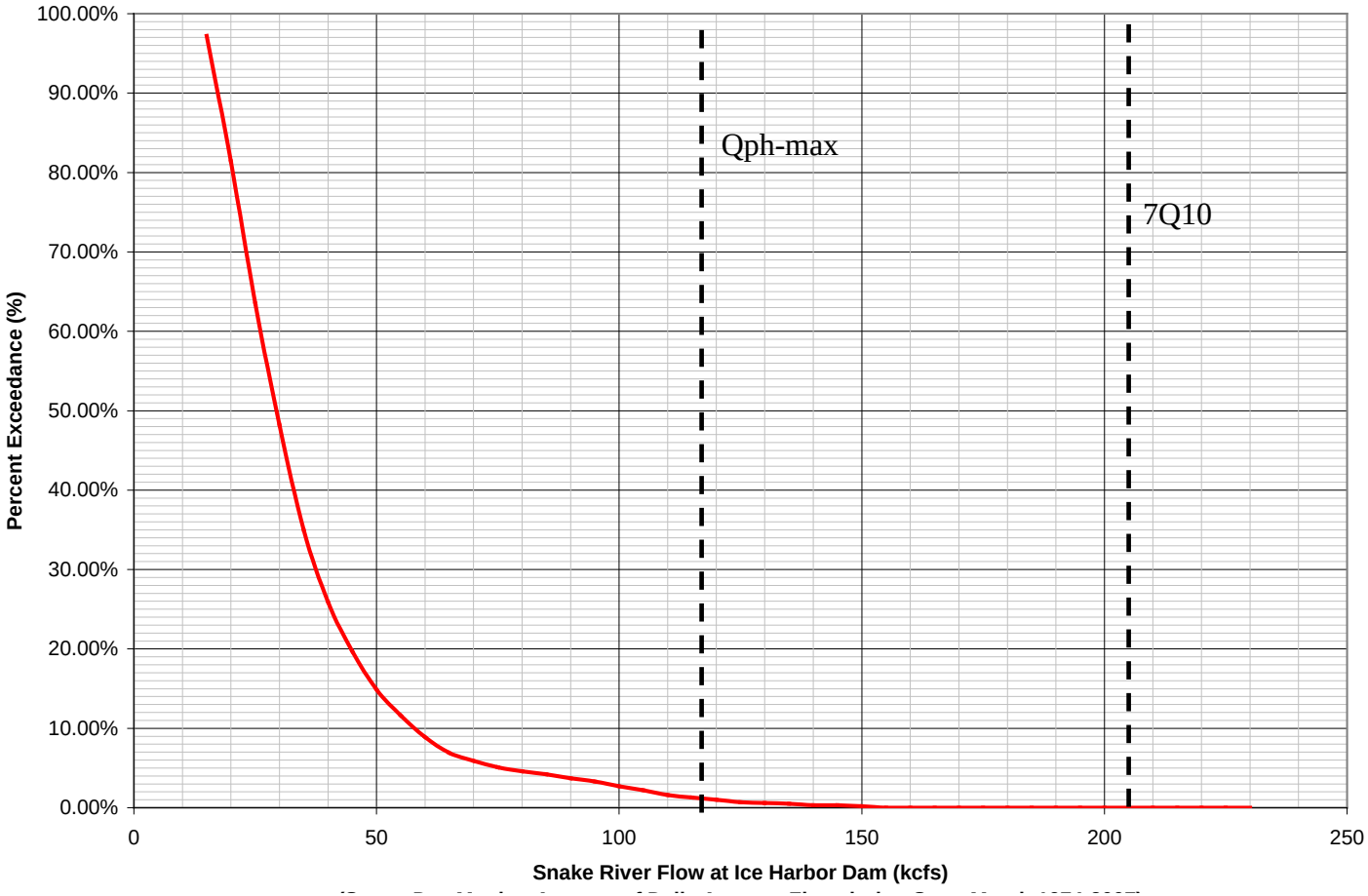

Figure F2. Percent Exceedance versus Snake River Flow at Lower Monumental Dam during Sept.-March, 1974-2009.

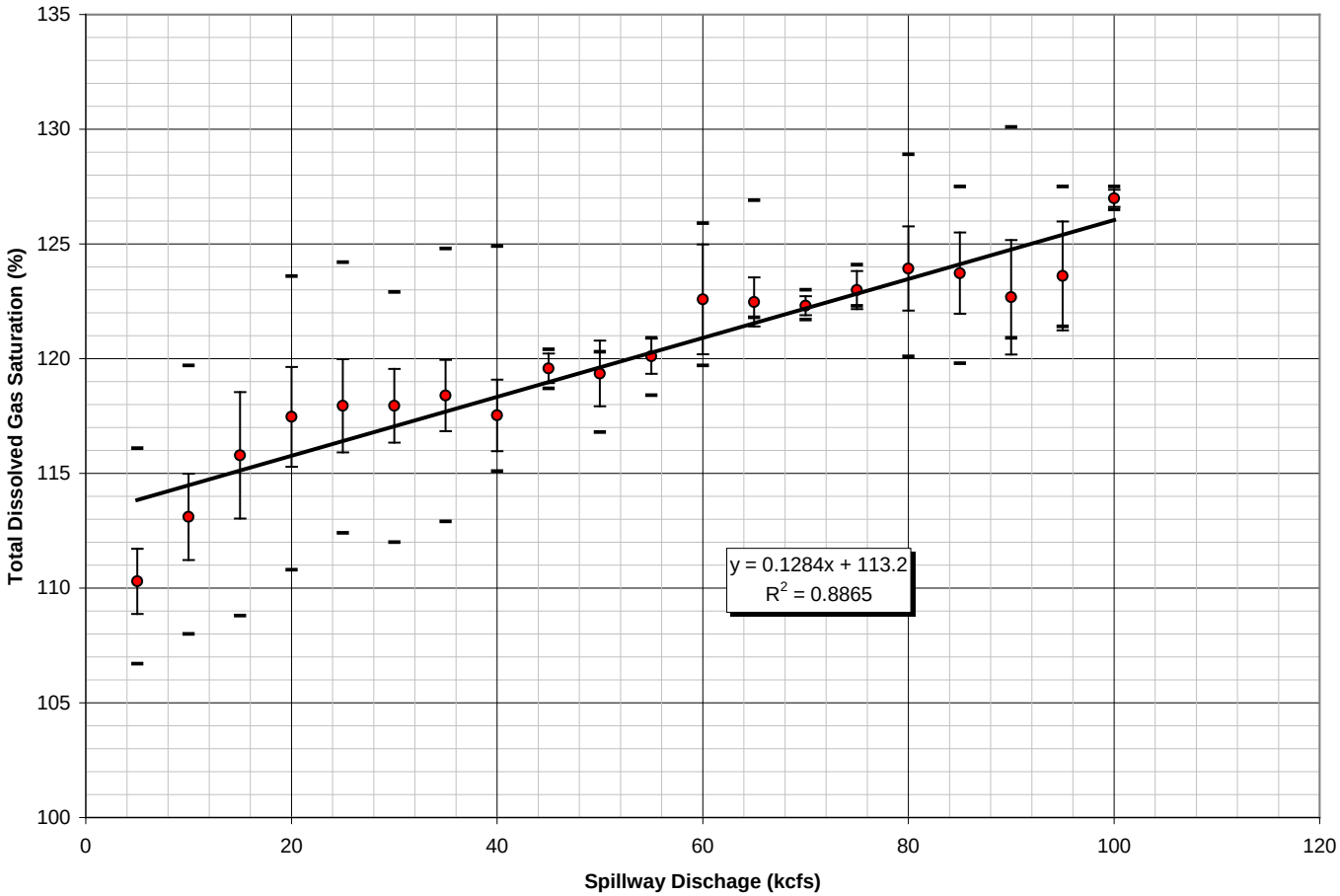

Figure F3. Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at Lower Monumental Dam as a function of Spillway Discharge, 2004-2009

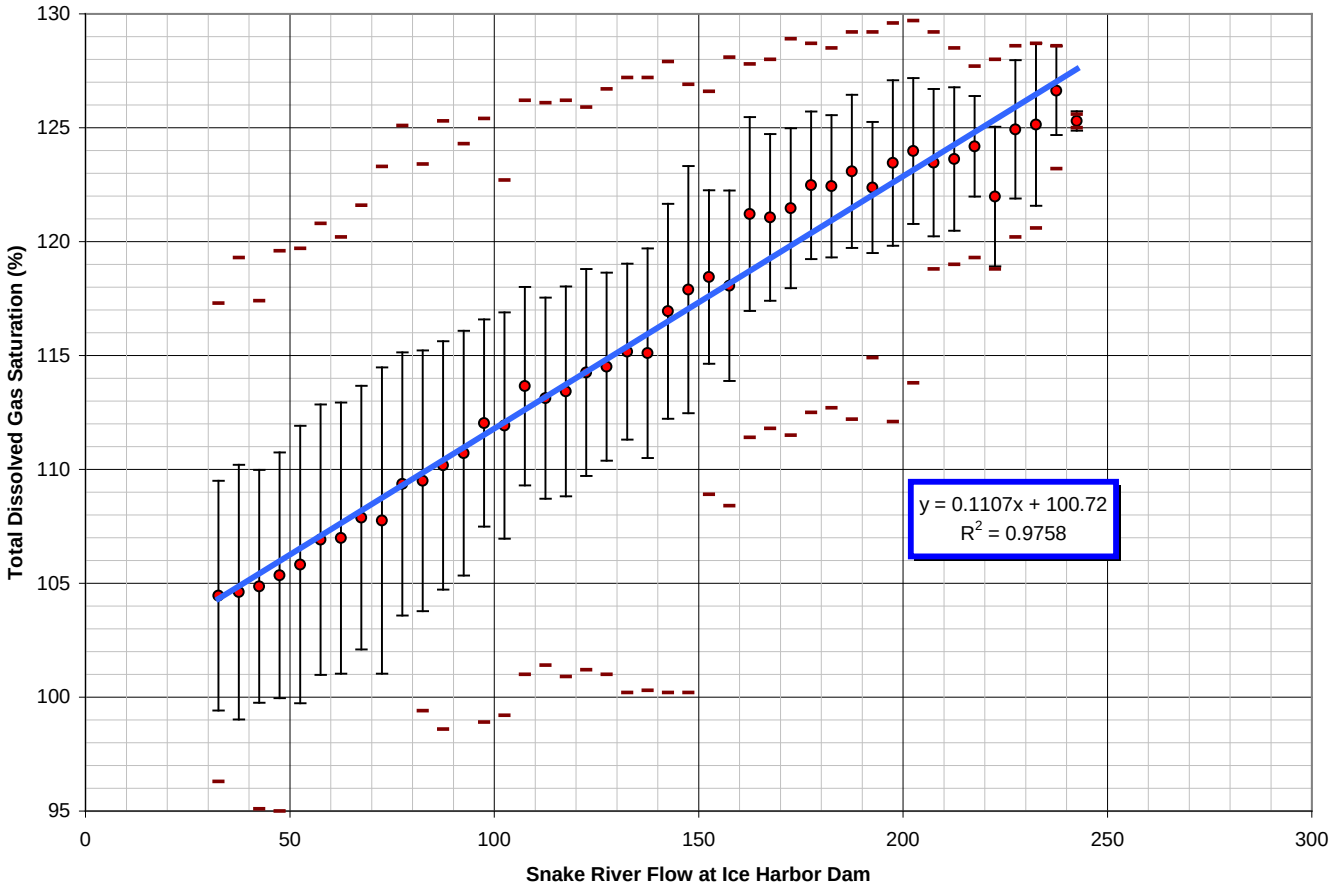

Figure F4. Total Dissolved Gas Saturation in the Forebay of Lower Monumental Dam as a function of Total Snake River Flow, 1995-2009

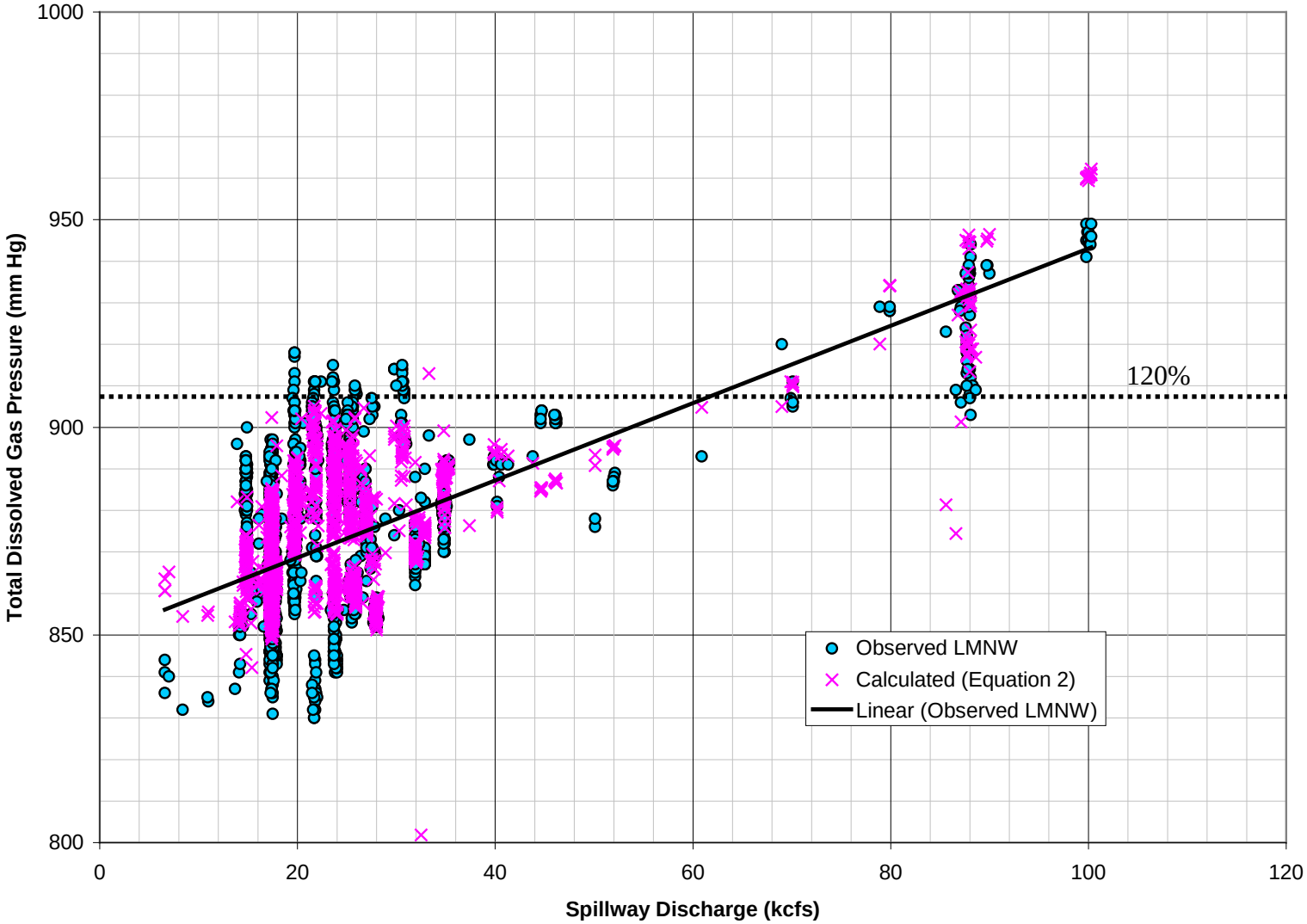

Figure F5. Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at Lower Monumental Dam as a function of Spillway Discharge, 2008 (Observed and Calculated)

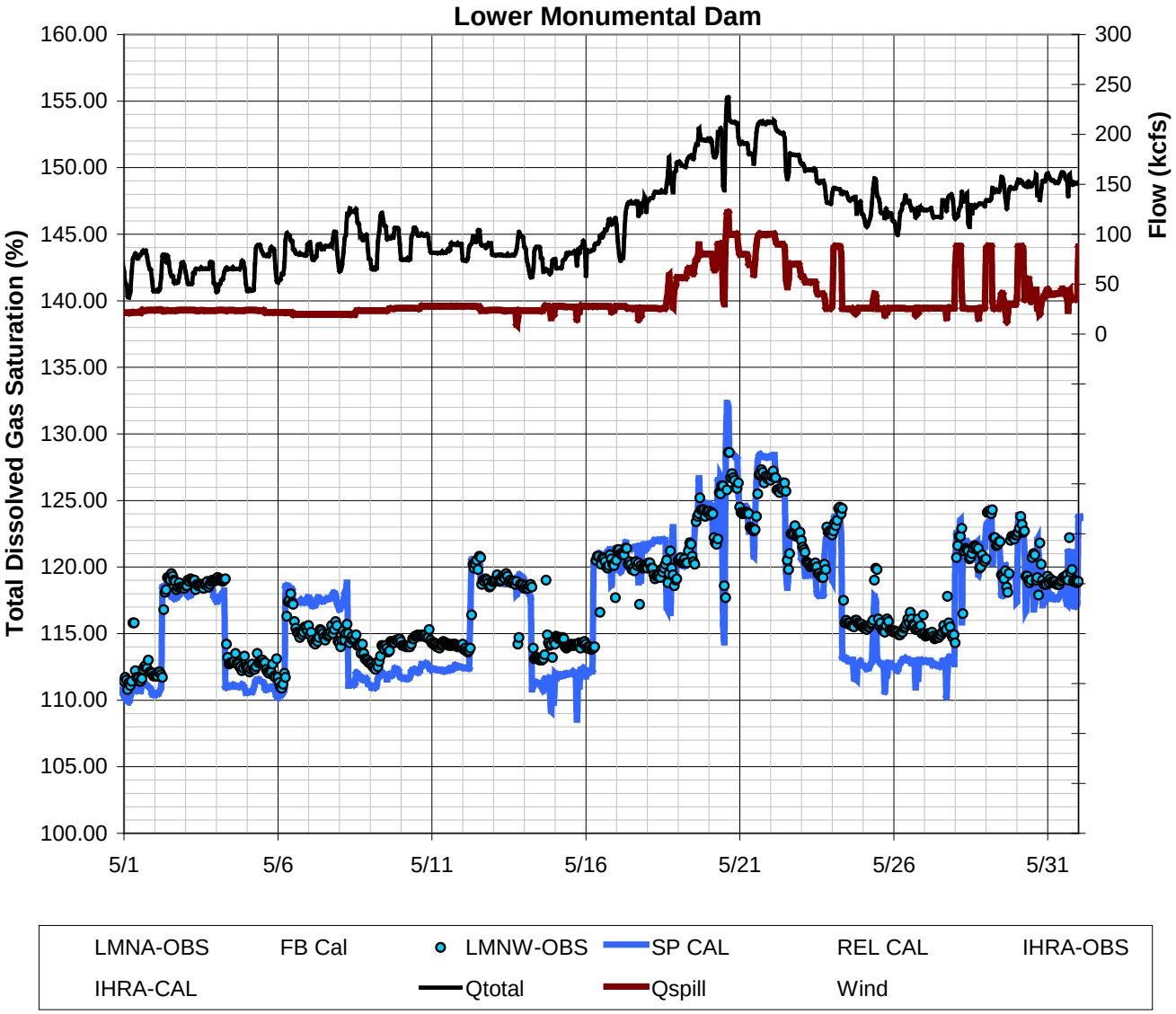

Figure F6 Lower Monumental Dam Operations and TDG Saturation Observed and Calculated at the Tailwater Fixed Monitoring Station, May 2008 (SP Cal=Calculated TDG saturation from Equation 2, LMNW=Tailwater Fixed Monitoring Station)