APPENDIX G

SYSTDG STATISTICAL EVALUATION

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Section 1 Introduction

SYSTDG (System Total Dissolved Gas) is a decision support spreadsheet model used to estimate total dissolved gas (TDG) percent and pressures resulting from mainstem dam operations on the Columbia, Snake, and Clearwater rivers. A review of project operations and resultant TDG exchange observed across the fixed monitoring network of water quality monitoring stations was conducted during the 2011 fish passage season. As a subset of these efforts, a statistical evaluation of the predictive errors was performed comparing observed and calculated TDG levels from the SYSTDG model in an effort to quantify the uncertainty of SYSTDG estimates and improve modeling accuracy and reliability. This evaluation included the mid-Columbia River from river mile 515.1 at Wells Dam to river mile 596.6 at Grand Coulee Dam, due to the increased scheduling of spill at Chief Joseph and Grand Coulee dams during the 2011 season. This evaluation was conducted by comparing calculated hourly TDG pressures generated by the SYSTDG model to observed hourly TDG pressures measured on the fixed monitoring stations (FMS), located in the forebays and tailwaters of Corps hydropower operated dams within the Columbia Basin. The dams of interest included Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, Lower Granite, Dworshak, Chief Joseph, and Grand Coulee.

The purposes of this statistical evaluation of SYSTDG include:

1. Evaluate the effectiveness of the SYSTDG model and identify ways to improve it.
2. Addressing the 2010 Supplemental Biological Opinion, RPA 15 which states "Continued development and use of SYSTDG model for estimating TDG production to assist in real-time decision making".
3. Provide the SYSTDG modelers with an understanding of the predictive error for each gauge for more effective use of the model when setting daily spill caps.

Section 2 Description of the 2011 Water Year

2011 Water Year from an Hourly Flows Perspective

The Columbia River flows in 2011 were the highest since 1997 during the months of May and June with near record high flows based on a period of record from 1975through 2011. It should be noted that the flows experienced on the Columbia and Snake rivers during the 2011 season represent unique events not previously experienced for the current spillway structures and spill patterns at projects in the region. This year's high flows provided an opportunity to evaluate the performance of SYSTDG's TDG exchange equations for conditions that were not included into their original design. The unique operations and flow conditions experienced during the 2011 season resulted in the application of the SYSTDG model outside of conditions for which it was developed.

The highest daily average flow on the Columbia River at The Dalles Dam was 498 kcfs on June 4, 2011 with daily average flows exceeding 400 from May 16 through July 4. The monthly flows leading up to the freshet in April and May were above normal as shown in Figure G1 falling near the 75th percentile. The box and whisker flow frequency plot shown in Figure G1 graphically identifies the monthly average flows associated with

5, 25, 50, 75, and 95 percentiles. The symbols (black and grey circles) in Figure G1 show the monthly average flows during 1997 and 1996, respectively. The June runoff at The Dalles Dam averaged about 462 kcfs or well above the hydraulic capacity of the dam powerhouses located on the lower Columbia River. These high sustained summer flows resulted in prolonged periods of involuntary spill at both Columbia River and Snake River dams with percent TDG in excess of state water quality standards (WQS). The reliance on spillway flows during high base flow conditions in 2011 were further amplified due to turbine maintenance activities at certain projects and idling turbines due to lack of load events. The monthly flows in June were above average ranking the second highest monthly flows since 1975 while the average July flows were the highest on record.

A statistical summary of the hourly project operations in the lower Columbia River are shown in Table G1 for the period of April 1through August 31. On the lower Columbia River, the highest percentage of total river flows spilled from April 1 through August 31 of about 58 percent, occurred at McNary Dam. The higher spill rate at McNary Dam resulted from small powerhouse hydraulic capacity and the extent and duration of high river flows present in the lower Columbia River. The average spill was 160.0 kcfs at Bonneville Dam, 192.0 kcfs at McNary Dam, 134.1 kcfs at The Dalles Dam, and 122.5 kcfs at John Day Dam.

Table G1. Statistical Summary of Hourly Project Flows from April 1through August 31, 2011 on the Lower Columbia River

		Bonneville		The Dalles		John Day		McNary		Priest Rapids	
Project		Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)
Number of Obs		3672	3672	3672	3672	3672	3672	3672	3672	3672	3672
Average		335.2	160.0	319.7	134.1	331.7	122.5	327.1	192.0	210.7	88.8
Standard Deviation		110.8	80.0	115.2	61.7	117.0	63.7	105.1	89.6	67.0	69.7
Maximum		511.2	317.8	509.5	273.7	539.1	270.6	535.0	375.5	378.0	242.6
Minimum		142.2	25.3	89.1	0.0	104.8	30.1	129.2	54.7	51.6	0.0
Qspill/Qtotal			0.5		0.4		0.4		0.6		0.4
Percentile	1%	158.2	74.4	115.4	40.0	112.7	33.4	164.8	82.5	106.0	0.0
	5%	177.3	74.9	144.8	53.8	151.6	45.3	181.7	90.5	127.3	0.0
	25%	246.4	99.4	226.2	88.3	236.7	71.3	247.7	109.7	154.4	27.7
	50%	309.7	129.8	297.3	117.0	310.5	100.3	294.3	159.6	193.4	70.4
	75%	444.8	247.6	432.4	190.0	446.1	175.5	430.6	279.6	267.8	144.7
	95%	501.8	293.6	494.9	242.7	508.5	235.2	495.0	340.4	331.3	213.7
	99%	505.4	303.6	501.1	254.2	520.7	250.4	502.8	354.1	351.2	221.7
Units kcfs except for Qspill/Qtotal summary (%)											

A statistical summary of the hourly project operations in the mid Columbia River are shown in Table G2 for the period of April 1through August 31 for Wells, Chief Joseph, and Grand Coulee dams. The average spill at both Wells and Grand Coulee dams were impacted by powerhouse turbine outages during a portion of this time period. The spill rate at Wells and Chief Joseph dams were nearly twice the average spill discharge at Grand Coulee Dam. The scheduling of power reserves was directed away from Grand Coulee Dam during the high flow periods to minimize the volume of water passed through the regulating outlets or over the spillway. The average spill rate at Chief Joseph

Dam of 48.8 kcfs was the largest since the completion of the spillway flow deflector in 2009, and represented about 27.7 percent of the total flow in the Columbia River. The highest spillway discharge of 196.5 kcfs at Chief Joseph Dam was scheduled to evaluate potential dam safety concerns during high spillway flows.

Table G2. Statistical Summary of Hourly Project Flows from April 1through August 31, 2011 on the Middle Columbia River

Project		Wells Dam		Chief Joseph		Grand Coulee	
		Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)
Number of Obs		3668	3668	3663	3663	3672	3672
Average		191.3	46.8	176.3	48.8	174.6	23.9
Standard Deviation		57.1	47.9	49.7	54.5	47.0	32.3
Maximum		327.8	185.5	326.1	196.5	269.3	105.1
Minimum		49.6	0.0	38.5	0.0	40.0	0.0
Qspill/Qtotal			24.4%		27.7%		13.7%
Percentile	1%	79.6	0.0	69.2	0.0	68.2	0.0
	5%	108.9	0.0	99.1	0.0	100.2	0.0
	25%	146.6	10.0	142.4	0.0	142.6	0.0
	50%	175.8	14.3	169.2	24.7	168.6	2.9
	75%	244.5	81.2	214.8	98.2	209.6	45.0
	95%	285.2	136.4	265.4	145.6	262.4	98.0
	99%	300.8	160.3	285.4	160.4	267.9	102.7
Units kcfs except for Qspill/Qtotal Summary (%)							

A statistical summary of the hourly project operations in the lower Snake River are shown in Table G3 for the period of April 1 through August 31 for Lower Granite, Little Goose, Lower Monumental, and Ice Harbor dams. The small variation in the average flow conditions through the lower four Snake River projects indicates the very small contribution from tributary flows. Ice Harbor spilled about 58.0 percent of the Snake River flow during this period compared to 32.4, 42.4, and 36.8 percent for Lower Monumental, Little Goose, and Lower Granite dams, respectively as listed in Table G3.

Table G3. Statistical Summary of Hourly Project Flows from April 1through August 31, 2011 on the Snake River

Project		Ice Harbor		Lower Monumental		Little Goose		Lower Granite		Dworshak	
		Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)
Number of Obs		3672	3672	3672	3672	3672	3672	3672	3672	3672	3672
Average		113.9	66.0	110.4	35.7	106.3	45.1	111.0	40.9	10.8	2.6
Standard Deviation		54.5	30.7	53.2	22.5	48.7	38.8	52.9	23.8	5.4	3.2
Maximum		256.5	175.1	245.7	157.4	215.0	199.6	223.9	120.9	25.2	14.6
Minimum		24.8	15.3	24.4	0.0	23.8	0.0	30.9	18.0	1.4	0.0
Qspill/Qtotal			58.0%		32.3%		42.4%		36.8%		24.1%
Percentile	1%	31.7	20.9	30.8	13.9	35.8	10.8	32.2	18.3	1.5	0.0
	5%	36.2	25.0	35.7	16.8	36.2	10.9	35.6	18.4	1.6	0.0
	25%	67.4	44.7	65.9	17.1	67.3	20.4	68.2	19.1	9.5	0.0
	50%	104.6	65.0	101.8	28.9	99.4	29.8	102.0	35.0	11.9	1.7
	75%	163.2	90.1	157.4	48.6	150.8	59.8	160.6	54.9	13.9	4.2
	95%	201.6	119.7	195.5	80.2	183.5	138.2	192.2	89.9	20.8	10.2
	99%	220.2	137.2	218.1	104.2	200.4	179.1	211.4	105.3	24.3	13.8

Units kcfs except for Qspill/Qtotal summary (%)

2011 Water Year from a High 12-Hour Average TDG Perspective

Reviewing the high 12-hour average TDG at the Columbia and lower Snake River dams' forebay and tailwater gauges gives a big picture perspective of an unusually high 2011 water year. The high TDG levels seen on the Columbia and Snake Rivers during the 2011 spill season represent unique events not previously experienced for the current spillway structures and spill patterns at projects in the region. This year's high TDG levels provided an opportunity to evaluate the performance of SYSTDG's TDG exchange equation for conditions that were not incorporated into the original design.

There were 23 fixed monitoring stations that the Corps uses for real time spill operations in 2011. The eight year (2003-2010) average of the 12-hour average TDG for all gauges from April through August was 111percent. By contrast, the 2011 average of the 12-hour average TDG for all gauges from April through August was 116 percent. This represents a 5 percent TDG increase systemwide on the Columbia and Lower Snake rivers. The gauges with the largest increases were Grand Coulee tailwater with a 10 percent increase; Chief Joseph forebay with an 8 percent increase; and a 7 percent increase at Wells forebays, Lower Monumental forebay; Lower Granite, Little Goose, and McNary tailwaters.

Section 3 Approach

SYSTDG simulations were run for the entire 2011 spill season for one project and river reach at a time, so that predictive errors could be calculated independently for each dam and river reach. The difference between the hourly observed and calculated TDG pressure or percent TDG was the definition used for the predictive error where negative errors reflect over-estimation of observed conditions and positive errors reflect an under-estimation of observed conditions. The tailwater FMS comparison was dependent upon the location of the FMS relative to the mixing zone of project flows. In most cases, the tailwater FMS are located in spillway flows undiluted from powerhouse flows but some are in mixed river waters. The summary of predictive error was limited to a period of active spillway operations at each project at the tailwater FMS for constant spill operations of 3 hours duration.

The TDG pressures transported to the forebay of the next downstream dam were used to determine the predictive error during the period from April 1 through August 31 for the lower Snake River and Columbia River projects. The TDG exchange during transit at the water surface was estimated in each river reach as a function of wind activity. The change in water temperatures during passage through each river reach was also included in estimates of the percent TDG. In each reach simulation the observed temperatures and total pressures in the forebays were used as boundary conditions for the simulation. Adjustments were made to boundary conditions where forebay and tailwater temperatures were different by over 0.3^{o}C. A detailed description of model input parameters and coefficients can be found in the SYSTDG user's manual (USACE, 2004).

The five possible causes for higher than normal predictive errors include:

1. The operational records used in these simulations were averaged on an hourly basis. Any operational change occurring within the hour was prorated by the cumulative discharge to determine the average hourly value. This hourly average operation falls between actual operating conditions introducing an erroneous result.
2. Depending upon the location of the tailwater FMS the lagged response of TDG pressures at tailwater FMS to the change in spill operation may take up to 5 hours for a TDG response, from a given operation at a dam, to reach equilibrium at the FMS. An error in pairing a spill operation with the corresponding TDG response at a tailwater FMS can result in a large predictive error.
3. The presence of local TDG gradients near a FMS introduced by thermal patterns or project operations can bias the observed TDG pressure and introduce a prominent source of error when comparing to model estimates. Thermally induced errors may occur at forebay FMS where a 1°C increase in temperature above bulk river conditions can result in a 2 to 3 increase in the percent TDG.
4. Sampling errors at tailwater FMSs have been identified at a number of the projects in the study area and will be noted in greater detail in the following discussion of study findings.
5. TDG gauge monitoring observations can suffer from either sampling biases or instrument malfunction.

Large predictive error documented in this statistical evaluation may represent influences of any of the above five causes and may not reflect negatively on the SYSTDG model accuracy. One of the challenges in reviewing the differences between observed and calculated TDG levels involve identifying what caused the predictive error.

Section 4 Statistical Analysis Results

The following section presents a brief description of a reach specific simulation using the SYSTDG model and a summary of the comparison of calculated and observed TDG pressures. The statistical analyses of the predictive error for the FMS includes the descriptive statistics of average, minimum, maximum, standard deviation, and the predictive error associated with the following percentiles: 5, 10, 25, 50, 75, 90, and 95 percent. Tables G4 and G6 describe the predictive error statistics in mm Hg of pressure while Tables G5 and G7 describe the predictive errors in percent TDG. The prediction error was calculated by subtracting the observed TDG level from the calculated value ($TDG_{error} = TDG_{obs} - TDG_{cal}$). A prediction error with a negative sign indicates the calculated value was larger than the observed value. For tailwater FMSs, the predictive errors were analyzed only for spill operations of 4 hours and longer in order to exclude transient TDG observations.

Camas/Washougal (CWMW)
A hind cast of Bonneville Dam operations were simulated using the SYSTDG model for the river reach from Bonneville Dam to the FMS located at Camas/Washougal (CWMW) from April 1 through August 31, 2011. The total river flows were maintained near 500 kcfs for nearly one month at Bonneville causing spillway flows to remain at 300 kcfs for extended time periods. The TDG production equation for the Bonneville Spillway was based on a transect data set from the 2002 spill season where the highest spill discharge was 248 kcfs. The simulations of TDG conditions at Camas/Washougal involve an extrapolation of the relationships identified during this field study. The predictive error of the hourly TDG pressure was determined throughout the 3670 observations. The calculated TDG pressures over-estimated observed conditions by an average of 8.2 mm Hg (average predictive error -8.2 mm Hg) and the standard deviation of the predictive error was 5.8 mm Hg as listed in Table G4. The size of the predictive error in 2011 at CWMW was slightly larger than determined in 2010 due to the wider range in project operations. The tendency to over-predict the TDG pressures at CWMW was observed throughout the entire season. The highly dynamic daily patterns of the observed TDG pressure were well represented by model estimates as dynamic wind and temperature related processes influence the transport and exchange of TDG conditions in the river.

The highest TDG pressures observed at CWMW of 996 mm Hg (131 percent TDG) was associated with the highest spillway discharge of the season of 318 kcfs. The seasonal time history of observed and calculated TDG pressures at CWMW is shown in Figure G2. The TDG pressures at CWMW continued to vary by as much as 60 mm Hg during the relatively constant spill of 300 kcfs during the late spring and early summer time frame. The range in TDG pressures was generally associated with the synoptic wind events causing rapid degassing to the atmosphere. For most of the study period, there were small consistent differences in the observed and calculated TDG pressures at CWMW resulting from spillway operations as shown throughout the month of May in Figure G3. As the spillway discharge increased above 100 kcfs the TDG levels at CWMW exceeded 115 percent TDG and remained above this level until mid-July. A strong daily TDG variation was evident in these records during August caused in part by the thermal exchange that is evident throughout this shallow open river reach and the night-time peaking operations.

In an effort to reduce the bias in the predicted TDG pressures at CWMW, the wind exchange coefficients were reinstated to levels used during the 2009 season. The impact of increasing the background reaeration coefficient to 0.01 ft/sec dropped the average predictive error to -2.0 mm Hg and the standard error of estimate to 4.8 mm Hg as shown in Figure G4. Updating these reaeration coefficients resulted in the most accurate prediction of TDG pressures at CWMW ever documented by the SYSTDG model and should be retained in future applications of this model. These results were obtained for flow years well outside the conditions experienced since the spillway flow deflector construction prior to the 2002 fish passage season. The predictive error summary in terms of percent TDG at CWMW is listed in Table G5 using the current reaeration coefficients.

Table G4 Statistical summary of the predictive errors of the observed and calculated TDG pressures in mmHg at forebay FMS, April 1 through August 31, 2011.

Fixed Monitoring Stations		Predictive Error* at Forebay FMS in mm Hg									
		LGSA	LMNA	IHRA	WEL	CHJ	MCNA	JDY	TDA	BON	CWMW
Number of Obs		3671	3670	3672	3429	3581	3672	3670	3640	3668	3670
Average		7.7	6.0	-2.3	-6.1	-3.2	-6.7	0.6	-4.2	0.7	-8.2
Standard Deviation		12.6	12.6	12.8	6.1	7.4	13.2	12.4	9.1	7.1	5.8
Maximum		48.1	35.1	30.0	24.0	52.9	27.4	65.2	19.8	19.8	14.5
Minimum		-44.6	-41.6	-51.4	-31.3	-29.4	-43.1	-34.7	-36.1	-30.2	-22.7
TDG Predictive Error in mm Hg	Percentile										
	5%	-11.6	-17.0	-25.4	-16.4	-15.5	-30.3	-18.3	-19.1	-10.5	-16.5
	10%	-7.1	-11.9	-18.3	-13.0	-12.6	-25.6	-13.6	-15.6	-7.9	-15.1
	25%	0.5	-1.0	-9.6	-9.5	-7.3	-15.5	-6.6	-10.3	-4.2	-12.4
	50%	6.7	9.0	-1.5	-5.9	-2.7	-5.5	0.2	-4.7	0.3	-8.8
	75%	14.8	14.6	6.7	-2.8	0.8	3.0	6.8	1.8	5.7	-4.8
	90%	25.4	19.8	13.0	-0.2	4.3	9.2	13.8	8.4	10.2	-0.7
	95%	30.2	22.5	16.9	2.9	8.2	12.8	18.4	11.8	13.1	2.4

*Predictive error is the observed minus calculated TDG pressure where negative values reflect an over-estimation and positive values reflect an under-estimation

Bonneville Dam Tailwater (WRNO)

The importance of the tailwater fixed monitoring station at Warrendale (WRNO) was highlighted this year by the failure of the monitoring gauge in the spillway exit channel (CCIW) for much of the spill season. After the Cascade Island gauge discontinued transmitting data May 18, the WRNO gauge was used to manage spill at Bonneville Dam until the CCIW gauge was transmitting data again in mid-August. The WRNO gauge is located near the Oregon shore about 6 miles below Bonneville Dam in waters that generally are well mixed. A hind cast of Bonneville operations was conducted using the SYSTDG model of the river reach from the Bonneville Dam to the FMS located at WRNO from April 1 through August 31, 2011, in an effort to determine the prediction error of SYSTDG simulations in Bonneville Dam tailwater. The calculated flow weighted average TDG pressures released from Bonneville Dam were compared to the observed TDG pressures at WRNO for spill events of three hours or longer. The calculated TDG pressures over-estimated observed conditions by an average of -4.7 mm Hg and the standard deviation of the predictive error was 6.9 mm Hg as listed in Table G6. The 50 percent confidence interval of the predictive error ranged from -8.9 to -1.7 mm Hg of pressure and the 80 percent confidence interval ranged from -11.7 to 4.4 mm Hg of pressure. The standard error of TDG pressure at the WRNO during the 2011 season was considerably smaller than determined in 2010 (6.9 to 9.4 mm Hg) even with the much larger range of operating conditions. The seasonal time history of observed and calculated TDG pressures at WRNO is shown in Figure G5 from March through September. The daily TDG values at WRNO FMS are a function of both the TDG levels associated with flows from the B2CC, spillway, and both powerhouses. The percent TDG exceeded 120 in mid-May and remained at or above this criterion until mid-July. The peak TDG pressure observed at the WRNO gauge of 1013 mm Hg (132.5 percent TDG) was a result of the highest spillway discharge scheduled at Bonneville Dam on June 25. The calculated and observed TDG pressures at WRNO are shown throughout the month of April in Figure G6. The TDG pressures at WRNO consistently were less than observed in the spillway exit channel at CCIW but greater than the forebay TDG pressures. The estimated TDG pressures at WRNO were highly correlated with the observed conditions but remain slightly larger than observed levels. The small added TDG source of the B2CC outfall was assumed to remain constant throughout the spill season. Removing the B2CC TDG source when the tailwater remains above a given elevation and thereby, preventing a plunging flow will improve the predictions of TDG conditions at the WRNO gauge and should be investigated in model development programs. This recommendation is included in the 2012 improvements list shown in Section 9. The hindcasting of TDG pressures at the Warrendale gauge proved to be remarkably accurate throughout the entire range of spillway flows supporting the extrapolation of equations currently being used in the TDG production equation.

Table G5. Statistical summary of the observed and calculated Percent TDG at forebay FMS, April 1 through August 31, 2011

Fixed Monitoring Stations		Predictive Error at Foreaby FMS in % TDG									
		LGSA	**LMNA**	**IHRA**	**WEL**	**CHJ**	**MCNA**	**JDY**	**TDA**	**BON**	**CWMW**
Number of Obs		3671	3671	3672	3429	3581	3672	3670	3640	3668	3670
Average		1.4	1.2	0.0	-0.8	0.5	-0.6	0.5	-0.6	0.1	-1.1
Standard Deviation		1.7	1.7	1.7	0.8	1.2	1.7	1.7	1.2	0.9	0.8
Maximum		6.9	5.1	4.3	3.3	8.3	3.9	9.2	2.6	2.6	1.9
Minimum		-5.6	-5.1	-6.5	-4.2	-3.8	-5.5	-4.2	-4.8	-4.0	-3.0
TDG Predictive Error in % TDG	Percentile										
	5%	-1.1	-1.9	-3.0	-2.2	-1.1	-3.7	-1.9	-2.5	-1.4	-2.2
	10%	-0.5	-1.2	-2.1	-1.8	-0.9	-3.1	-1.3	-2.1	-1.0	-2.0
	25%	0.5	0.2	-0.9	-1.3	-0.2	-1.7	-0.4	-1.4	-0.5	-1.6
	50%	1.3	1.6	0.1	-0.8	0.5	-0.4	0.5	-0.6	0.0	-1.2
	75%	2.4	2.3	1.2	-0.4	1.0	0.7	1.4	0.2	0.7	-0.6
	90%	3.8	3.0	2.1	0.0	1.6	1.5	2.3	1.1	1.3	-0.1
	95%	4.4	3.4	2.6	0.4	2.4	2.0	2.9	1.6	1.7	0.3
*Predictive error is the observed minus calculated TDG pressure where negative values reflect an over-estimation and positive values reflect an under-estimation											

Bonneville Dam Spillway Exit Channel (CCIW)

The failure of the fixed monitoring station at the CCIW gauge located on Cascade Island made SYSTDG model a valuable tool for estimating TDG levels in spillway flows at Bonneville Dam during much of the 2011 spill season. The TDG gauge stopped transmitting data on May 18 when spillway flows reached 242 kcfs, tailwater elevations exceeded 31 feet and the gauge was inundated. The real-time operation of this gauge was restored in mid-August. A hind cast of Bonneville operations was simulated using the SYSTDG model of the river reach from the Bonneville Dam to the FMS located at

Camas/Washougal in an effort to determine the predictive error of SYSTDG simulations in the Bonneville Dam spillway exit channel on the bank of CCIW from April 1 through August 31, 2011. The TDG estimates generated by SYSTDG reflect conditions in spillway flows undiluted from powerhouse flows and average conditions exiting the spillway channel. The TDG pressures at CCIW prior to the initiation of spill exceeded 850 mm Hg in March and April. The seasonal time history of observed and calculated TDG pressures at the CCIW FMS is shown in Figure G7. The observed and calculated TDG pressures were similar with the notable exception during the high spill flows greater than 150 kcfs during May.

The TDG production equation for the Bonneville Dam spillway flows closely reproduced observed conditions at CCIW for spill up to 120 kcfs. The calculated mean prediction error of TDG pressures at CCIW was equal to -0.6 mm Hg and the standard deviation of the predictive error was 11.1 mm Hg as listed in Table G6. The 50 percent confidence interval for the predictive error ranged from -1.6 to 3.1 mm Hg of pressure and the 80 percent confidence interval ranged from -12.6 to 9.8 mm Hg of pressure. The elevated TDG levels registered at CCIW prior to the initiation of spill are associated with supersaturated conditions in the adult fish ladders. The estimates of percent TDG in the Bonneville Dam exit channel were based on the cross sectional average TDG pressures as determined during the 2002 TDG exchange study conducted at Bonneville Dam (Schneider, 2003). This study determined that for spill flow rates higher than 120 kcfs, TDG pressures observed near CCIW underestimated the cross sectional average percent TDG in the spillway exit channel. The sample bias is considerable at CCIW for spillway flows greater than 150 kcfs and estimated average TDG pressures can be as much as 50 mm Hg above the observed conditions of previous years. The estimation of TDG levels exiting the spillway channel therefore, reflect average conditions that typically exceeded the near shore TDG levels sampled at CCIW during elevated spillway flows. A detailed summary of calculated and observed TDG pressures in spill at CCIW during May 2011 is shown in Figure G8. The variation in TDG pressures observed during this period reflects variations in tailwater stage, local atmospheric pressures, and spill pattern variants. The overestimation of the SYSTDG model of conditions observed at CCIW was consistent with previous study findings. The estimated TDG pressures in the spillway exit channel were larger than 1000 mm Hg (131 percent TDG) during the lengthy period of peak spill flow rates near 300 kcfs. The highest TDG pressures of about 1050 mm Hg or 137.5 percent TDG was projected for a spillway release of 310 kcfs.

Table G6. Statistical Summary of the Predictive Errors of the Observed and Calculated TDG Pressures at Tailwater FMS.

Fixed Monitoring Stations		Predictive Error* at Tailwater FMS in mmHg											
		DWQI	**LGNW**	**LGSW**	**LMNW**	**IDSW**	**GCGW**	**CHQW**	**MCPW**	**JHAW**	**TDDO**	**CCIW**	**WRNO**
Number of Obs		2431.0	2488.0	2488.0	2305.0	1941.0	1177.0	1027.0	2272.0	1348.0	1433.0	1153.0	2779.0
Average		-2.1	1.4	1.4	4.8	1.3	-3.9	2.2	12.4	-0.6	-3.2	-0.6	-4.7
Standard Deviation		7.4	15.5	15.5	12.6	7.0	12.1	10.4	13.6	14.1	7.6	11.1	6.9
Maximum		21.4	89.4	89.4	37.8	34.0	67.9	39.0	271.6	34.2	25.9	30.1	24.8
Minimum		-36.0	-87.0	-87.0	-76.8	-18.7	-34.7	-22.5	-12.6	-25.1	-27.6	-49.8	-29.3
TDG Predictive Error in mmHg	Percentile												
	5%	-14.3	-18.1	-18.1	-16.3	-10.9	-21.8	-14.0	-3.8	-21.0	-14.8	-21.5	-13.4
	10%	-12.2	-13.5	-13.5	-9.1	-8.7	-18.9	-11.2	-1.6	-19.8	-12.7	-12.6	-11.7
	25%	-6.9	-6.4	-6.4	-1.4	-2.9	-11.9	-5.8	5.0	-11.8	-8.8	-1.6	-8.9
	50%	-2.2	3.3	3.3	8.2	1.8	-3.8	2.0	11.2	-2.8	-3.4	0.9	-6.1
	75%	3.7	11.1	11.1	13.2	5.6	3.0	9.6	19.0	11.8	2.3	3.1	-1.7
	90%	7.2	17.4	17.4	16.2	9.0	10.2	16.7	25.0	18.1	7.1	9.8	4.4
	95%	9.1	20.9	20.9	18.3	13.4	15.0	19.4	30.5	21.1	9.5	12.9	9.5

*Predictive error is the observed minus calculated TDG pressure where negative values reflect an over-estimation and positive values reflect an under-estimation

The systematic divergence of the observed and calculated TDG pressures in the spillway exit channel during the 2011 spill season as a function of spill discharge are shown in Figure G9. These observed and calculated deviations are labeled modeling error in Appendix G, but this characterization does not account for the sampling bias noted at CCIW in the 2002 field study. The calculated pressures begin to over-estimate the observed conditions around spill levels of 120 kcfs. The difference between the observed values and calculated continue to increase as a function of spill discharge. The calculated TDG response in the exit channel is a bi-linear equation with spill discharge and the tailwater channel depth of flow as shown by the linear response of estimated TDG pressures in Figure G9. Although it would have been valuable to have had some direct measurement of TDG levels in the spillway exit channel for these high spill flow rates, the reliability of estimating TDG levels downstream of Bonneville Dam at the WRNO and CWMW stations provides sufficient validation of the TDG production equation at Bonneville Dam.

Table G7. Statistical Summary of the Predictive Errors of the Observed and Calculated Percent TDG at Tailwater FMS

Fixed Monitoring Stations		Predictive Error at Tailwater FMS in % TDG											
		DWQI	LGNW	LGSW	LMNW	IDSW	GCGW	CHQW	MCPW	JHAW	TDDO	CCIW	WRNO
Number of Obs		2504	2488	2488	2305	1941	1177	1027	2272	1348	1433	860	2779
Average		-0.4	0.2	0.2	0.6	0.2	-0.5	0.3	1.6	-0.1	-0.7	-0.2	-0.9
Standard Deviation		1.3	2.1	2.1	1.7	0.9	1.7	1.4	1.8	1.9	1.1	1.5	1.0
Maximum		3.3	12.0	12.0	5.0	4.5	9.5	5.3	36.1	4.5	3.0	3.0	3.1
Minimum		-5.7	-11.7	-11.7	-10.3	-2.4	-4.7	-3.0	-1.6	-3.3	-4.3	-6.9	-4.4
TDG Predictive Error in % TDG	Percentile												
	5%	-2.5	-2.4	-2.4	-2.2	-1.5	-3.0	-1.9	-0.5	-2.8	-2.4	-4.8	-2.2
	10%	-1.9	-1.8	-1.8	-1.2	-1.2	-2.6	-1.5	-0.2	-2.6	-2.1	-0.6	-1.9
	25%	-1.1	-0.9	-0.9	-0.2	-0.4	-1.6	-0.8	0.7	-1.6	-1.5	-0.4	-1.6
	50%	-0.3	0.4	0.4	1.1	0.2	-0.5	0.3	1.5	-0.4	-0.7	-0.1	-1.1
	75%	0.4	1.5	1.5	1.8	0.8	0.4	1.3	2.5	1.6	0.1	0.2	-0.5
	90%	1.1	2.3	2.3	2.2	1.2	1.4	2.3	3.3	2.4	0.7	1.1	0.3
	95%	1.4	2.8	2.8	2.4	1.8	2.0	2.6	4.1	2.8	1.0	1.4	0.9

*Predictive error is the observed minus calculated TDG pressure where negative values reflect an over-estimation and positive values reflect an under-estimation

Bonneville Dam Forebay (BON)

The estimation of TDG pressures in the forebay of Bonneville Dam with the SYSTDG model continues to be one of the most reliable river reach simulations even given the dynamic nature of this reach in terms of surface reaeration processes. The strong winds that frequent this river reach have been associated with synoptic degassing events that reduce the TDG levels arriving at Bonneville Dam. The calculated average estimation error of TDG pressures was only 0.7 mm Hg and the standard deviation of the predictive error was 7.1 mm Hg as listed in Table G4. The 50 confidence interval for the predictive error ranged from -4.2 to 5.7 mm Hg of pressure and the 80 confidence interval ranged from -7.9 to 10.2 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at BON is shown in Figure G10. The maximum TDG pressures observed in the forebay of Bonneville Dam was 125 percent TDG. TDG levels exceeded 115 percent from mid-May through mid-July at this forebay station. The TDG pressures in the forebay of Bonneville Dam are a complex interaction of the TDG loading released from The Dalles Dam, thermal cycling, and wind induced degassing. Currently, the wind field observed from The Dalles municipal airport is applied uniformly throughout this river reach to estimate the rate of degassing.

The cyclical variation of TDG pressures observed in the forebay of Bonneville Dam are more closely related to reaeration events associated with high winds than the variation in operations at The Dalles Dam. The calculated and observed TDG pressures at BON are shown throughout the month of May in Figure G11. The TDG pressure rises gradually as river flows and elevated TDG levels are introduced by The Dalles Dam. The shorter periods of abruptly rising and falling pressures are typical of conditions in the lower Columbia River. The degree of wind induced off-gassing is illustrated in Figure G12 where the average cross section TDG pressures leaving The Dalles Dam is labeled as “TDDO-obs” and BON reflects the residual TDG pressure remaining in the Columbia River. The hourly wind speeds (mps x 10) at The Dalles municipal airport are shown in Figure G12. The appearance of strong winds with a duration of several days trigger declining TDG pressures at Bonneville Dam on the order of 20-60 mm Hg. Periods of calm winds are associated with the retention of the TDG levels through this river reach. Any additional improvement to the simulations of TDG pressures in the Bonneville pool will need to involve the improvements in the applied wind field or the reaeration equation. This recommendation is included in the 2012 improvements list shown in Section 9.

The Dalles Dam Tailwater (TDDO)

The 2011 TDG generation equation for The Dalles Dam remains a function of the tailwater depth of flow. The shallow flow conditions below The Dalles Dam spillway is an important feature in determining TDG exchange since spillway flow deflectors were not deemed suitable for this project. The impacts of the spillway training wall between bays 8 and 9 on TDG exchange were determined to be small for flow conditions observed prior to 2011. SYSTDG estimates of TDG pressures at The Dalles Dam tailwater FMS (TDDO) during the 2011 spill season remained accurate throughout the study period and for spillway flows not experienced since 1997. The TDDO FMS is located about 3 miles downstream from the dam in waters that approach well-mixed conditions based on observations during 2009. The flow-weighted average TDG conditions were simulated for The Dalles Dam during the spill season and compared to the observed conditions at the TDDO FMS. The calculated TDG pressures were lagged 4 hours, due to the travel time, in making this comparison. The calculated TDG pressures contained a small over-estimation bias as quantified by the average predictive error of -3.2 mm Hg. The standard deviation of the predictive error was only 7.6 mm Hg as listed in Table G6. The 50 percent confidence interval of predictive error ranged from -8.8 to 2.3 mm Hg of pressure and the 80 percent confidence interval ranged from -12.7 to 7.1 mm Hg of pressure. One aspect of the relatively small predictive error for the TDDO FMS is the inclusion of the observed background TDG pressures in the computation of this estimate. The seasonal time history of both the observed and calculated TDG pressures at the TDDO FMS is shown in Figure G13. The maximum TDG level observed below The Dalles Dam was 127 percent. The TDG levels at the tailwater TDDO FMS frequently exceeded the TDG standard of 120 percent during high flows. The calculated and observed TDG pressures at TDDO are shown throughout the month of May in Figure G14. The TDDO FMS is influenced by both powerhouse and spillway flows. The estimated TDG pressures were found to slightly overestimate the observed conditions during the last two weeks in May when peak river flow approached 500 kcfs.

The estimated TDG pressures contained in spillway flows undiluted from powerhouse flow (dark blue SP Cal) consistently exceeded 910 mm Hg (120 percent TDG) as shown in Figure G15. The TDG levels in spillway flows were estimated to range from 121 to 129 percent during these flow conditions. Although background TDG pressures were elevated in the forebay of The Dalles Dam during the high summer flows, spillway operations always contributed to raising the TDG loading in the Columbia River.

The TDG generation in spillway flows at The Dalles Dam has been found to be a simple linear function of the effective tailwater depth of flow. This spillway production equation was developed from a series of studies directly measuring the TDG levels in spillway flows. The tailwater elevation is directly related to both The Dalles Dam total discharge and the pool elevation established by Bonneville Dam. The calculated and observed TDG pressure at the

TDDO FMS as a function of spillway discharge is shown in Figure G16. The wide range of TDG values for a given spill discharge reflects the wide range of forebay TDG levels contributed by the powerhouse for a given spill discharge.

The Dalles Dam Forebay (TDA)

The TDG levels in the forebay of The Dalles Dam remained above 120 percent during the high flows in late May through mid-June. A simulation was conducted from the John Day Dam to The Dalles Dam forebay from April 1 through August 31, 2011 to determine the predictive error of SYSTDG simulations in The Dalles Dam forebay during spill events at John Day Dam. The estimated TDG generation equation at John Day Dam was based upon applying both the spring and summer spill patterns to estimate the TDG exchange associated with spillway operations. The calculated TDG pressures were larger than the observed conditions by an average of 4.2 mm Hg. The estimations of TDG pressures in The Dalles Dam forebay were generally very reliable throughout the spill season subject to spillway flows up to 271 kcfs. The highest TDG pressures in the forebay of The Dalles Dam were not caused by the high flows at John Day Dam. The peak TDG levels at The Dalles Dam can be traced back to spill operations at McNary Dam on June 8 where a partial spill pattern was employed resulting in high TDG conditions in project flows. This high TDG event arrived at John Day Dam on the morning of June 11 reaching The Dalles Dam on the afternoon of June 11. The standard deviation of the predictive error was 9.1 mm Hg as listed in Table G4. The 50 percent confidence interval of the predictive error ranged from -10.3 to 1.8 mm Hg of pressure and the 80 percent confidence interval ranged from -15.6 to 8.4 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the TDA FMS is shown in Figure G17.

The TDG levels in the forebay of The Dalles Dam increased gradually during the month of May from 106 percent on May 1 to 125 percent on May 31. The calculated and observed TDG pressures at the forebay gauge TDA are shown throughout the month of May in Figure G18. The SYSTDG model estimates were highly correlated with observed conditions throughout the month with periods of rapidly declining TDG pressures associated with strong and extended wind events. The tendency for estimates to over predict TDG pressures in The Dalles Dam forebay during the month of May were likely caused by the over prediction of TDG exchange associated with spillway flows greater than 100 kcfs at John Day Dam.

John Day Dam Tailwater (JHAW)

The spillway weirs (SW) were located in spillbays 18 and 19 during the 2011 season and were accompanied by a training spill from bay 20 with the 50-foot-long spillway flow deflector. The spill pattern applied at John Day Dam involved spill flows of about 10 kcfs over the SW's with a training spill distributed broadly over bays 2-20. The spillway weirs were used throughout the fish passage season. The SYSTDG model was used to simulate the TDG production associated with spillway operations at John Day Dam as measured at the tailwater FMS (JHAW) from April 1 through August 31, 2011. The calculated average TDG pressures provided biased estimates over the study period as evidenced by an average error of -0.6 mm Hg and the standard deviation of the predictive error was 14.1 mm Hg as listed in Table G6. The 50 percent confidence interval of the predictive error ranged from -11.8 to 11.8 mm Hg of pressure and the 80 percent confidence interval ranged from -19.8 to18.1 mm Hg of pressure.

The seasonal time history of observed and calculated TDG pressures at the JHAW FMS is shown in Figure G19. A period of consistent departure of observed and calculated TDG pressures can be seen beginning during July in this figure when spillway flows ranged from 140 to 170 kcfs. The high river flows during 2011 resulted in a broad range of spillway operations in May at John Day Dam as shown in Figure G20. The calculated TDG pressures generally tended to replicate observed conditions for spillway flows less than 100 kcfs. As spillway flows increased the reliability of TDG estimates dropped. The TDG production equation over-estimated some flow conditions while under-estimating others.

The observed TDG pressures at the JHAW FMS were directly related to spill discharge as shown in Figure G21. The observed TDG pressures at the tailwater FMS increased as a linear function of spill discharge. The TDG production equation used by SYSTDG is based on an exponential function of the specific spillway discharge and depth of flow. This non-linear function can be updated to reflect a more linear response to project operations. A consistent over-estimation bias is shown in Figure G21 for intermediate spillway flows and under-estimation for the highest spillway flows. A redesign of the TDG production equation using a smaller rate coefficient for the specific spillway discharge would reduce this estimation bias and should be explored in the next version of the SYSTDG model. This recommendation is included in the 2012 improvements list shown in Section 9.

John Day Dam Forebay (JDY)

The TDG dynamics in the John Day Pool are of particular importance because of the magnitude and frequency of spill at McNary Dam. The TDG pressures arriving at John Day Dam during the spring and summer of 2011 were characterized by cyclical passage of high and low TDG fronts with a period of about 5 days. These TDG patterns are thought to be caused by wind events that generate periods of high and low off-gassing. The TDG pressures were simulated from McNary Dam to the John Day Dam forebay from April 1 through August 31, 2011 in an effort to determine the predictive error of model estimates. The John Day pool is the longest river reach (76 miles) simulated and the travel time ranged from 2.5 to 7.0 days during the 2011 fish passage season. Calculated forebay TDG pressures were subtracted from the observed John Day forebay (JDY) FMS data to produce an hourly predictive error. The calculated TDG pressures on average under-estimated observed conditions by an average of 0.6 mm Hg and the standard deviation of the predictive error was 12.4 mm Hg as listed in Table G4. The 50 percent confidence interval for the predictive error ranged from -6.6 to 6.8 mm Hg of pressure and the 80 percent confidence interval ranged from -13.6 to 13.8 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the JDY FMS is shown in Figure G22. The wide variance in TDG pressures observed in the forebay of John Day Dam was generally reproduced in model simulations. The largest prediction errors in the John Day forebay were associated with under-predicting the TDG generated during the removal of the spillway weirs at McNary Dam June 8 and 9. As shown on Table G5, the predictive errors at JDY were similar to other forebay TDG gauges based on the standard deviation of predictive error. The observed and calculated TDG pressures at JDY are shown throughout the month of May in Figure G23. The model TDG pressure estimate are both greater than and less than observed conditions. The length of travel time through this reach and variations in wind conditions makes this a difficult river reach for closely reproducing observed conditions.

McNary Dam Tailwater (MCPW)

The highest spillway flows on the Columbia River occurred at McNary Dam with spill flows being initiated on January 19 nearly running continuously through the end of August. TDG levels generated at McNary Dam were some of the highest seen in the basin with maximum levels in excess of 140 percent. The percent of river spilled was also the highest on the mainstem Columbia River, where during the month of June nearly 70 percent of the river was spilled at McNary Dam. The combination of high TDG levels resulting from spill and low dilution rates by powerhouse flow has the potential to significantly elevate TDG levels downstream. A critical spill operation was scheduled on June 7 when 5 spillbays were shut-down to allow removal of the spillway weirs on bays 19 and 20. The TDG levels observed at the tailwater fixed monitoring station increased by 8 percent in conjunction with this spill pattern change while holding total spill constant.

The operation of two SW's at McNary Dam in bays 19 and 20 from April 9 through June 7 determined the type of spill pattern applied at McNary Dam. A summer spill pattern, not involving spillway weirs, was used for the remainder of the summer. The rated flow over the SW was a function of the forebay elevation and was generally in the range of 9-10 kcfs. The limited flow over the spillway weirs caused the unit spillway discharge to increase over the active spillbays. Spillbay 1 was not put in use during the high flow period in May through July due to mechanical failure. The summer time spill pattern featured a crowned spill pattern with peaked flows through bays 4 and 5 for spill flows greater than 70 kcfs. The summer spill pattern shifts abruptly towards the powerhouse for spill flows of 70 kcfs and less leaving the northern spillbays closed.

The SYSTDG model was used to simulate the TDG pressures associated with spillway flows from McNary Dam throughout the 2011 spill season as shown in Figure G24. The calculated TDG pressures at the tailwater MCPW contained a noticeable bias as evidenced by the mean error of 12.4 mm Hg and a standard deviation of the predictive error of 13.6 mm Hg as listed in Table G6. A great portion of the estimation bias occurred during the late summer months where observed TDG levels were larger than estimates. The 50 percent confidence interval for the predictive error ranged from 5.0 to 19.0 mm Hg of pressure and the 80 percent confidence interval ranged from -1.6 to 25.0 mm Hg of pressure. The observed and calculated TDG pressures at MCPW are shown throughout the month of May in Figure G25. The model performed well in estimating the TDG levels in spill during the month of May with larger errors occurring for spill flow rates of 300 kcfs and higher. The model did not adequately capture the increase in TDG pressure during the 5 bay closure spill event in June.

An alternative equation for TDG production at McNary Dam was formulated in response to the large predictive errors encountered in 2011 and poor TDG response to spill pattern changes. The following equation was developed from a non-linear regression analysis using selected hourly data at McNary Dam during 2011.

$$TDG_{sp}=BP+(TWE\text{-}228)^{0.91}(Q_{sp}/nbay)^{0.71}$$

$$nbays = \frac{\sum_{i=1}^{i=NB} q_i \sum_{i=1}^{i=NB} q_i^{N-2}}{\sum_{i=1}^{i=NB} q_i^{N-1}}$$

Where:

q_i = spillway flow in bay i (kcfs)
NB = Total number of spill bays.
N = weighting coefficient (N=1 arithmetic average, N=2 flow weighted)

This equation closely captured the response of higher TDG pressures generated during the 5 bay closure event in June and closely tracked the TDG levels associated with the summer spill pattern at McNary Dam.

McNary Dam Forebay (MCNA)
The TDG response at the McNary forebay (MCNA) FMS was estimated by simulating the contributions from Priest Rapids Dam on the Columbia River at Pasco and Ice Harbor Dam on the Snake River. The spill activity at Priest Rapids Dam during 2011 called for considerable amounts of involuntary spill. However, the impacts of involuntary spill at Priest Rapids Dam did not cause much of a change to the TDG loadings on the Columbia River because of the shallow conditions below the spillway. In addition, the TDG loading introduced into McNary pool was further moderated by the degassing throughout the open river reach in the Hanford area. The reduction in TDG levels typically ranged from 4 to 6 percent during passage through the open river reach. Ice Harbor Dam spilled consistently about 100 kcfs for much of May and June with TDG levels ranging from 120 to 130 percent. The levels of TDG exiting the Snake River were about 5 percent higher on average than TDG levels measured at the Pasco gauge on the Columbia River. The Snake River contributed about one-third of the flow to the Columbia River at the confluence.

The calculated mean prediction error of TDG pressures in the forebay of McNary Dam was -2.9 mm Hg and the standard deviation of the predictive error was 10.4 mm Hg as listed in Table G4. The standard error of estimate in the McNary forebay in 2011 was identical to conditions determined in 2010. The 50 percent confidence interval for the predictive error ranged from -9.4 to 4.1 mm Hg of pressure, and the 80 percent confidence interval ranged from -17.4 to 9.7 mm Hg of pressure. The observed and calculated TDG pressures at MCNA are shown from March through September in Figure

G27. Typical TDG levels in the forebay ranged from 115 to 120 percent with the highest observation of 122 percent. The calculated and observed TDG pressures at MCNA are shown in Figure G28 for the month of June. The model estimates generally over-estimated the observed values in June. The source of the higher estimated TDG pressures is due to over-estimation of conditions entering the McNary Pool.

Wells Dam Forebay (WEL)

The observed conditions in the forebay of Wells Dam reflect the TDG generation from both upstream Federal projects that reached record levels not seen in over 30 years. The installation of spillway flow deflectors at Chief Joseph in 2009 has significantly changed the TDG production characteristics at this project and participation in system spill management operations.

The TDG conditions in the Columbia River from Chief Joseph Dam to Wells Dam were simulated with the SYSTDG model for the time period from April 1 through the end of August. The tributary flows and temperatures from the Okanogan and Methow rivers were included in these model runs. The water temperatures in the Okanogan River were assumed to be representative for both rivers. The TDG exchange equation for Chief Joseph Dam used the observed forebay TDG pressure to approximate the TDG levels in powerhouse flows. The TDG pressure generated in spillway flows were estimated by applying the TDG equation listed in the next section. The averaged predictive error of TDG pressures observed in the forebay of Wells Dam was -6.1 mm Hg and the standard deviation of the predictive errors was 6.1 mm Hg as listed in Table G4. The 50 percent confidence interval for the predictive error ranged from -9.5 to -2.8 mm Hg of pressure, and the 80 percent confidence interval ranged from -13.0 to -0.2 mm Hg of pressure. The predictive errors of the TDG pressures at the forebay of Wells Dam were small during the months of April and May as shown in Figure G29. The model tended to generate TDG pressure slightly higher than observed conditions during selected periods in June and July. The influence of the tributary flows was noteworthy during June when these rivers contributed as much as 17 percent of the river flow at Wells Dam. The calculated and observed TDG pressures in the forebay of Wells Dam are shown in Figure G30 for the month of June. The highest TDG pressure observed in the forebay at Wells Dam of 960 mm Hg on June 4 corresponded with the experimental spill pattern test at Chief Joseph Dam. The estimated travel time from Chief Joseph to Wells dams during this period was less than 12 hours. The short durations of high spillway flows were generally followed by declining TDG pressures in the Wells Dam forebay 12 hours later as these TDG events moved into this region of the Columbia River. There was little opportunity to manage TDG levels at the forebay of Wells Dam to the 115 percent level during this period because of the very high TDG levels present in the forebay of Chief Joseph Dam. The relatively small predictive errors observed in the forebay of Wells Dam support estimates of average TDG pressures leaving Chief Joseph Dam.

The underestimation of the influence of wind generated degassing through the Brewster Flats region could be a source for the overestimation of TDG pressures in the forebay of Wells Dam. Because there is no weather station with real time wind reading at Brewster Flats, the Chief Joseph Dam weather station wind readings are used. It is thought that using this weather station wind readings to estimate the degassing rate in this reach may be resulting in higher predictive error. A nearby weather station wind readings indicated high sustained winds on June 15 and 16 while the actual wind readings at Chief Joseph forebay were moderate. As a result, the higher predictive error may be due to the wind station used in the model. It is recommended that an investigation be performed to see if there is a better weather station that can be used to reflect more accurate degassing rates.

Chief Joseph Dam Tailwater (CHQW)

The SYSTDG model was used to simulate the TDG exchange associated with spillway flows from Chief Joseph Dam throughout the 2011 fish passage season as shown in Figure G31. The spillway was operated for short periods at the beginning of April with sustained spill operations beginning on May 13. The highest TDG levels were observed during the end of May and beginning of June during elevated flows using partial spill patterns. The peak TDG levels dropped after June 4 when the full 19 bay spill pattern was implemented. The observed forebay TDG pressures at Chief Joseph Dam, shown by the green circles in Figure G31, provide a clear illustration of the magnitude and duration of reduction in TDG pressures in spillway flows. The month of June experienced a wide range of spill operations with short periods of high spillway flows scheduled to facilitate system hydropower demand requirements as shown in Figure G32. The calculated TDG pressures at CHQW FMS for spills ranging from 0 to 196 kcfs were estimated with a mean predictive error of 2.2 mm Hg and a standard deviation of the predictive error was 10.4 mm Hg, as listed in Table G6. The 50 percent confidence interval for the predictive error ranged from -5.8 to 9.6 mm Hg of pressure, and the 80 percent confidence interval ranged from -11.2 to 16.7 mm Hg of pressure. The performance of this TDG equation at Chief Joseph Dam was of similar accuracy when compared with other projects. The following TDG production equation at Chief Joseph Dam, generated from the 2009 spill test, was updated with the 2011 data:

$$TDG_{avg}=(TDG_{sp}(Q_{sp}+Q_{ent})+TDG_{ph}(Q_{ph}-Q_{ent}))/(Q_{ph}+Q_{sp})$$

$$TDG_{ph}=TDG_{fb}$$
$$Q_{ent} = 0$$

$$TDG_{sp}=BP+(TWE-743)^{1.16}(Q_{sp}/nbay)^{0.26}$$

Where:

Q_{ph}= Powerhouse flow rate (kcfs)
Q_{sp}= Spillway flow rate (kcfs)
Q_{ent}= Entrainment of powerhouse flow into spillway flow (kcfs)
TWE=Tailwater elevation (ft)
Nbay = Active number of spillbays (19 max)
TDG_{ph} = TDG pressure of powerhouse flows (mm Hg)
TDG_{sp} = TDG pressure of spillway flows (mm Hg)
TDG_{fb}= TDG pressure in the forebay of the dam (mm Hg)
BP= Local barometric pressure (mm Hg)
TDG_{avg} = Flow weighted average TDG pressure in river below dam (mm Hg)

The observed and calculated TDG pressures for steady state spillway flows with a duration of 3 hours or longer are shown in Figure G33. Typically, TDG levels generally increases as a function of spillway flow but contains a wide variance of responses for repeated observations for a given flow. This variation in TDG response can be associated with changes in tailwater elevation, spill pattern, and local atmospheric pressure. During the 2011 spill season at Chief Joseph Dam, a wide range of spill discharges resulted in approximately 118 percent TDG as measured at CHQW. This TDG exchange characteristic where the resultant TDG levels were generally insensitive to increased spillway flows is not commonly seen at lower head projects on the lower Columbia and Snake rivers. The relatively weak response in TDG levels to changes in spillway flow at Chief Joseph Dam, observed during the 2011 season, was consistent with data collected during the previous two years. The causes for these unique TDG exchange properties at Chief Joseph Dam are not completely understood, but could be due to the variation in spill patterns, total project head, spillway deflector design, tailwater elevation influences, length of the spillway, and tailwater channel bathymetry.

The evidence of a net reduction in the average TDG levels in the Columbia River during spillway flows is supported by the observations of TDG levels at the tailwater FMS and at the forebay at Wells Dam. The flow weighted average TDG pressure was computed by applying the tailwater TDG pressure with spillway flows and the forebay TDG levels to powerhouse flows. The flow weighed average TDG pressure for the month of June is shown in Figure G34 (labeled REL-CAL). The reduction in the average TDG pressure in the Columbia River typically ranged from 50 to 60 mm Hg (7.4 percent TDG) during the month of June.

Chief Joseph Dam Forebay (CHJ)

The TDG levels observed in the forebay of Chief Joseph Dam (CHJ) FMS reflect the residual high TDG levels generated from upstream sources. The very high TDG levels produced at Grand Coulee Dam during regulating outlet (RO) operations were generally transported through this 51.5 mile long pool with only a small reduction in magnitude of about 2 to 4 percent. The spill activity at Grand Coulee Dam during RO flows created well defined TDG events that were observed arriving and passing through Chief Joseph Dam. These events can allow the estimation for time of travel through the pool and the associated TDG loading of upstream TDG sources. The time of travel for TDG events through Lake Rufus Woods was a little more than one day during the high flows in June (velocity of 2 mph).

The TDG simulation was performed from Grand Coulee Dam to Chief Joseph Dam for the period of April 1 through August 31. The calculated mean error of TDG pressures at CHJ was -3.2 mm Hg and the standard deviation of the predictive error was 7.4 mm Hg as listed in Table G4. The standard error for the Rufus Woods TDG simulation was smaller than many modeled reaches suggesting the model was successful in simulating both the upstream TDG exchange process, and the subsequent transport and dissipation of these TDG exchange events. The 50 percent confidence interval for the predictive error ranged from -7.3 to 0.8 mm Hg of pressure, and the 80 percent confidence interval ranged from -12.6 to 4.3 mm Hg of pressure. The observed and calculated TDG pressures in the forebay of Chief Joseph Dam are shown throughout the months of March through September in Figure G35. It is clear from these figures that the single RO outlet release of 4.9 kcfs at Grand Coulee Dam on April 6, resulted in a significant increase of 40 mm Hg (5 percent TDG) in the TDG levels arriving at Chief Joseph

Dam two days later. The calculated and observed TDG pressures in the forebay of Chief Joseph Dam are shown in greater detail in Figure G36 for the month of June. The estimated TDG pressures in the forebay of Chief Joseph Dam closely tracked the observed conditions over a wide range of RO flows and also during the transition to drum gate operations at Grand Coulee Dam. The daily cycling of TDG levels in the forebay of Chief Joseph Dam are caused by the thermal cycles which develop in this river reach. The degassing rates are determined by what the TDG levels are in the forebay. As forebay TDG levels increase, degassing will increase and as forebay TDG levels decrease, degassing will decrease.

Grand Coulee Dam Tailwater (GCGW)
The amount of spill through both the regulating outlets (RO's) and drum gates (DG's) at Grand Coulee Dam during the fish passage season of 2011 resulted in the highest spill since 1981 and resulted in the generation of TDG levels as high as 144.9 percent.

The TDG simulation was performed from Grand Coulee Dam to Chief Joseph Dam for the period of April 1 through August 31 using the SYSTDG model. The fate of powerhouse flows in determining the resultant TDG loading in the Columbia River below Grand Coulee Dam remains one of the critical elements in formulating an accurate TDG exchange equation. A visit to Grand Coulee Dam on June 3 during a RO spill of 98 kcfs revealed circulation patterns resulting in the transport of powerhouse flow directed into the aerated flow conditions in the stilling basin. A review of the surface flow conditions contained in the following video http://www.youtube.com/watch?v=ukTyfPrgGls illustrates the entrainment of flows from all three powerhouses into the aerated flow conditions below the spillway. The observed forebay TDG levels were assumed to represent the TDG levels in powerhouse flows. However, a significant amount of powerhouse flows that are entrained into the highly aerated spillway will become spillway like, when exposed to entrained air at a deep enough depth. As the flow through the RO's decreases the extent of the entrainment of powerhouse flows into the spillway will diminish proportionately.

The Grand Coulee Dam TDG exchange equation developed in 1999 was updated for regulating outlet operation as recommended in the 2010 statistical evaluation. The updated equation is based on the 2011 observed data and spill operations and is a function of the spill, powerhouse flow, and TDG content of powerhouse releases. The following TDG exchange equation was used for estimating the TDG exchange at GCL during the 2011 season:

$$TDG_{avg}=(TDG_{sp}(Q_{sp}+Q_{ent})+TDG_{ph}(Q_{ph}-Q_{ent}))/(Q_{ph}+Q_{sp})$$

$$TDG_{ph}=TDG_{fb}$$

Regulating Outlet

$$Q_{ent} = 1.36\ Q_{sp}+22.6$$
$$Q_{ent}\leq Q_{ph}$$
$$TDG_{sp}=BP+312$$

Drum Gates

$$Q_{ent}=0$$

$$TDG_{sp}=400(1-\exp(-0.02Q_{sp}))+BP$$

Where:

Q_{ph}= Powerhouse flow rate (kcfs)
Q_{sp}= Regulating Outlet or Drum Gate flow rate (kcfs)
Q_{ent}= Entrainment of powerhouse flow into spillway flow (kcfs)
TDG_{ph} = TDG pressure of powerhouse flows (mm Hg)
TDG_{sp} = TDG pressure of spillway flows (mm Hg)
TDG_{fb}= TDG pressure in the forebay of the dam (mm Hg)
BP= Local barometric pressure (mm Hg)
TDG_{avg} = Flow weighted average TDG pressure in river below Grand Coulee Dam (mm Hg)

This equation is similar to the 1999 equation where the entrainment discharge was estimated as a function of spillway discharge and spillway flows TDG levels that are independent of spill through the ROs. This equation was developed to replicate the TDG levels observed at the tailwater fixed monitoring station located about 6 miles downstream of the dam. The interpretation of observed data at GCGW FMS as representing well mixed river conditions is based on the findings in Frizell and Vermeyen (1997) for a limited number of flow conditions. This exchange equation approaches the TDG levels in powerhouse flows as the RO's discharge approaches zero. For high spill flow rates the influence of powerhouse flows goes zero and the average TDG pressure reaches an upper threshold at a delta pressure of 312 mm Hg or about 142 percent TDG. The flow from a single RO will range from 4-5 kcfs, depending upon the forebay stage, and the estimated entrainment flow will be over six times the spill flow.

The TDG exchange equation for drum gate operation was determined from the spill events observed during the 2010 season. The Grand Coulee Dam tailwater gauge during 2010 was experiencing both delayed and attenuated TDG responses during the drum gate operations. This equation was based on fitting the TDG exchange equation to the TDG pressures arriving at Chief Joseph Dam.

A statistical and graphic summary of TDG estimates were prepared for the SYSTDG simulation of TDG pressures at Grand Coulee Dam. The calculated mean predictive error of TDG pressures at the Grand Coulee Dam tailwater FMS was -3.9 mm Hg and the standard deviation of the predictive error was 12.1 mm Hg as listed in Table G6. These equations slightly over-estimated the observed conditions with higher predictive errors associated with drum gate operations after June 24. The 50 percent confidence interval for the predictive error ranged from 3.0 mm Hg to -11.9 mm Hg of pressure and the 80 percent confidence interval ranged from 10.2 to -18.9 mm Hg of pressure**.** The average predictive error of tailwater TDG levels below Grand Coulee Dam were similar to those determined at other projects and significantly improved over model estimates during the 2010 spill season. The observed and calculated TDG pressures in the tailwater of Grand Coulee Dam are shown throughout the months of March through September in Figure G37. The significant increase in the TDG pressures over background levels in the forebay are clearly illustrated in this figure. The transition to drum gate operations on June 24 is also a significant event with marked reduction in TDG generation. The calculated and observed TDG pressures at GCGW FMS are shown in Figure G38 for the month of June. The observed and calculated TDG pressures during RO operations are similar with distinct changes in tailwater TDG pressures associated with changing spillway flows. After changing to drum gate spill, the TDG pressures experienced a significant decrease to the point where tailwater TDG levels were even less than forebay pressures. The abrupt decrease in TDG pressure at GCGW on June 28 during constant operations and increase on July 11 of about 15 mm Hg as shown in Figure G39, may indicate a TDG gauge measurement error. Figures G40 – 41 show TDG pressures during RO and drumgate spill.

Ice Harbor Dam Tailwater (IDSW)

The equation of TDG production at Ice Harbor Dam resulted in one of the best agreements between observed and calculated TDG pressures at a tailwater FMS for 2011. The spill operations at Ice Harbor Dam was varied to accommodate biological testing involving spilling 30 percent of the instantaneous river flow, a fixed 45 kcfs, or spilling to the tailwater TDG capacity of 120 percent. During most of the late spring and early summer, the Ice Harbor powerhouse was fully loaded with spill flow rates as high as 175 kcfs resulting in TDG levels of 135 percent. The spill pattern did not use spillbay 1 during the 2011 fish passage season and spillbay 10 was limited to a 2 stop opening. The SW remained in continuous operation with an average flow of 7.9 kcfs.

The TDG exchange at Ice Harbor Dam was simulated from April 1 through August 31, 2011 in an effort to determine the predictive error of SYSTDG estimations in the tailwater of Ice Harbor Dam during spill events. The calculated TDG produced in undiluted spill waters was compared with observed hourly conditions at the tailwater FMS gauge IDSW. The calculated mean predictive error of TDG pressure was 1.3 mm Hg and the standard deviation of the predictive error was 7.6 mm Hg as listed in Table G6. The 50 percent confidence interval of the predictive error ranged from -2.9 to 5.6 mm Hg of pressure, and the 80 percent confidence interval ranged from -8.7 to 9.0 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the IDSW is shown in Figure G42. The calculated values tend to compare favorably to observed conditions throughout most of the year. The one event when the TDG equation significantly under-estimated observed condition was on April 1 when spill was 115 kcfs, which was the entire river. The simulations conducted before April 1 involved much smaller percent spill events. In these cases, the observed tailwater TDG pressure was closely approximated by the calculated flow weighted average TDG pressure. The daily variation in TDG pressures for observed and calculated conditions can be seen in Figure G43 for the month of June. The TDG equation closely estimates the rapid variation in TDG pressures with changing spillway flow. Ice Harbor Dam spill operations resulted in reductions in the TDG loading of the Snake River during high forebay pressures in late May and early June.

The general linear variation in TDG exchange as a function of spillway flow is shown in Figure G44. The range in TDG pressures of 880 to 925 mm Hg for a spill flow rate of 90 kcfs was chiefly attributed to the variation in tailwater elevation. Ice Harbor Dam continues to have the smallest TDG uptake for a comparable spill flow rate of any project on the Columbia or Snake rivers for lower river flows.

Ice Harbor Dam Forebay (IHRA)

A simulation was run from Lower Monumental Dam to the forebay of Ice Harbor Dam from April 1 through August 31, 2011 to determine the predictive error of SYSTDG estimations in the forebay of Ice Harbor Dam. Calculated forebay TDG pressures were subtracted from the observed TDG pressures at the forebay FMS at Ice Harbor Dam (IHRA) to determine the hourly predictive error. The calculated TDG pressures consistently over-estimated observed conditions by an average of -9.0 mm Hg and the standard deviation of the predictive error was 9.6 mm Hg as listed in Table G4. The 50 percent confidence interval for the predictive error ranged from -14.7 to -2.3 mm Hg of pressure, and an 80 percent confidence interval ranged from -20.6 to 2.3 mm Hg of pressure. The estimates of forebay conditions at Ice Harbor Dam tended to reproduce the general trends observed during the spring and summer conditions as shown in Figure G45. The consistent over-estimation during the months of May and June also correspond with periods of very high TDG pressure in the forebay of Lower Monumental Dam. The observed and calculated TDG pressures in the forebay of Ice Harbor Dam are shown in Figure G46 throughout June. The consistent over-estimation of forebay TDG pressures at Ice Harbor Dam in June were likely caused by the transport of higher TDG pressures in powerhouse flows and the over-estimation of TDG pressure during high spillway flows. The spill at Lower Monumental Dam was responsible for degassing the conditions in the Snake River, and under-estimating the entrainment demand would lead to higher TDG pressures at Ice Harbor Dam.

Lower Monumental Dam Tailwater (LMNW)

The SYSTDG model estimated TDG pressures for Lower Monumental Dam tailwater that over-estimated conditions during the high spillway flows, while providing reasonably good estimates for intermediate and lower flows. The estimated TDG properties in undiluted spillway flows were compared to the observed conditions at the tailwater FMS (LMNW) during spillway flows with 3 hours duration and longer throughout the fish passage season. The calculated mean TDG pressures under-estimated observed conditions by an average of 4.8 mm Hg and the standard deviation of the predictive error was 12.5 mm Hg, as listed in Table G6. The 50 percent confidence interval for the predictive error ranged from -1.4 to 13.2 mm Hg of pressure, the 80 percent confidence interval for the predictive error ranged from -9.1 to 16.2 mm Hg of pressure. The hourly variation of TDG pressures at LMNW are shown in Figure G47 for the entire fish passage season for observed and calculated conditions. The largest contribution to the average error at this tailwater station occurred during the prolonged spill of 17 kcfs during the months of July and August. A review of the computation of the number of spillbays for this pattern should be updated to reflect the prominent spill from bays 6 and 8. The hourly observed and calculated TDG pressures at LMNW are shown in Figure G48 for the month of June. There was a tendency for calculations to over-estimate the TDG exchange associated with high spillway flows of 100 kcfs and higher. The over-estimation of TDG pressures for spill flow rates of 100 kcfs and higher is shown in Figure G49 where the blue symbols represent observed conditions and the black symbols represent the calculated pressures. The updated TDG production equation based on the higher flows observed in 2011 equates the delta TDG pressure as the product of the effective depth of flow and the square root of the unit spillway flow should be established. This recommendation is included in the 2012 improvements list shown in Section 9.

Lower Monumental Dam Forebay (LMNA)

The TDG pressures generated at Little Goose Dam and transported to Lower Monumental Dam were the results of extensive spillway operations caused by closing the powerhouse from May 24 to June 1. The highest spillway flow of 199 kcfs occurred on May 24 during the powerhouse outage. The interpretation of the TDG loading in Lower Monumental pool was complicated by observing higher TDG levels arriving at Lower Monumental Dam than those leaving Little Goose Dam tailwater monitoring station. The TDG levels were simulated from the tailwater of Little Goose Dam to the forebay of Lower Monumental Dam during spill events for the period of April 1 through August 31, 2011 as shown in Figure G50. The calculated percent TDG in the forebay of Lower Monumental Dam were generally less than observed except during periods of peak spillway flows at Little Goose Dam. The peak TDG pressure observed in the forebay of Lower Monumental Dam during May 27 of 1045 mm Hg was closely reproduced in SYSTDG simulations. On average the calculated TDG pressures generally under - estimated observed conditions as evidenced by the mean error of 6.0 mm Hg and standard deviation of the predictive error was 12.6 mm Hg as listed in Table G4. The 50 percent confidence interval for the predictive error ranged from -1.0 to 14.6 mm Hg of pressure, and the 80 confidence interval ranged from -11.9 to 19.8 mm Hg of pressure. The daily variation of TDG pressures for the month of June at LMNA are shown in Figure G51 for observed and predicted conditions. The two series of pressures are highly correlated but the predicted values fell below observed conditions.

Little Goose Dam Tailwater (LGSW)

The calculated TDG pressures in the tailrace of Little Goose Dam departed significantly from observed conditions for spillway flows above 100 kcfs. However, the fact that higher TDG levels were seen in the forebay of Lower Monumental Dam than exiting Little Goose Dam, casts a shadow in the representativeness of observations at the Little Goose Tailwater station. A TDG simulation was conducted from Little Goose Dam to Lower Monumental Dam from April 1 through August 31, 2011 in order to determine the predictive error of SYSTDG estimations in the tailwater of Little Goose Dam during spill events. The TDG levels calculated from flow weighted project flows were subtracted from the observed tailwater FMS gauge (LGSW) TDG data to estimate the predictive error by the model as shown in Figure G52. The calculated TDG pressures under-estimated observed conditions by an average of 1.4 mm Hg and the standard deviation of the predictive error was 15.5 mm Hg, as listed in Table G6. The 50 percent confidence interval ranged from -6.4 to 11.1 mm Hg of pressure, and the 80 percent confidence interval ranged from -13.5 to 17.4 mm Hg of pressure. The interpretation of the observed TDG response at the tailwater FMS is closely related to the near field circulation patterns and prominent interaction of powerhouse and spillway flows. The calculated and observed tailwater TDG pressures below Little Goose Dam during the month of June are shown in Figure G53. The large calculated TDG pressures on June 1 were generally supported by the arrival of high TDG pressures in the Lower Monumental forebay.

The tailwater TDG pressure at Little Goose Dam is directly related to the spillway flow. The observed and calculated TDG pressures at the tailwater FMS as a function of the spillway flow for 2011 is shown in Figure G54. The tailwater TDG pressures increase as the spillway flows increase until flow reaches about 100 kcfs. The observed TDG pressure remained at the same level for spillway flows ranging from 100 to 160 kcfs. The observed TDG levels sharply increased for spills above 160 kcfs. The estimated TDG pressures followed a continuously increasing pattern as a function of spill flow rate. Although the forebay TDG pressures at Lower Monumental Dam were not replicated with great accuracy, the calculated TDG pressures at Little Goose Dam for flow above 100 kcfs appear to be more reliable than the observed conditions.

Little Goose Dam Forebay (LGSA)

SYSTDG was used to hind cast the TDG pressures in Little Goose pool in response to operations at Lower Granite Dam from April 1 through August 31, 2011. The elevated TDG levels in the forebay of Little Goose Dam, as shown in Figure G55, are a consequence of the TDG uptake associated with spill at Lower Granite Dam, the thermal exchange during transport through the pool, and the surface exchange of dissolved gasses with the atmosphere. The average calculated TDG pressure was generally an unbiased estimate of observed conditions with an average predictive error of 7.7 mm Hg and the standard deviation of the predictive error was 12.6 mm Hg as listed in Table G4. The 50 percent confidence interval ranged from 0.5 to 14.8 mm Hg of pressure, and the 80 percent confidence interval ranged from -7.1 to 25.4 mm Hg of pressure. The under-estimation of observed conditions by SYSTDG in July is noteworthy given the close agreement for much of the year. The calculated and observed tailwater TDG pressures in the forebay of Little Goose Dam during the month of June are shown in Figure G56. The peak TDG events were accurately represented by model estimates.

Lower Granite Dam Tailwater (LGNW)

The SYSTDG model provided accurate estimates of TDG levels in the Lower Granite tailwater during the intermediate to high spill events. The TDG levels associated with spillway flows from Lower Granite Dam were simulated from the April 1 through August 31, 2011 as shown in Figure G57. The calculated TDG pressures generally agreed with observed conditions as indicated by an average error of 1.4 mm Hg and the standard deviation of the predictive error of 15.5 mm Hg as listed in Table G6. The under-estimate of tailwater conditions during July and August departs prominently from the small predictive errors for April through June. The 50 percent confidence interval for the predictive error ranged from -6.4 to 11.1 mm Hg of pressure, and the 80 percent confidence interval ranged from -13.5 to 17.4 mm Hg of pressure. The TDG pressures during the month of June are shown in Figure G58 at LGNW. The predicted TDG pressure closely tracked the observed TDG pressure below Lower Granite Dam during the 2011 spill season except for July and August. The peak spillway flow of 120 kcfs caused an observed TDG pressure of about 980 mm Hg and the estimated peak TDG pressure was 980 mm Hg.

The tailwater TDG pressures for spill events with a 3 hour duration or greater are shown as a function of spill flow rates at Lower Granite Dam in Figure G59. This figure indicated the spill capacity of about 25 kcfs corresponds with a TDG level of 120 percent. A well defined linear relationship is indicated by the observed data for spill flow rates greater than 40 kcfs. However, a broad range of TDG pressures are observed for spill flow rates less than 40 kcfs. This wide variance of TDG pressures is likely related to the range of percent spill conditions and the varied influence of powerhouse flows on TDG pressures observed at the tailwater FMS.

Dworshak Dam Tailwater (DWQI)

The operations at Dworshak Dam were highly varied during the 2011 season ranging from minimum powerhouse flows of 1.4 kcfs to full capacity powerhouse flows with regulating outlet flows, and total project flows of 14.6 kcfs. The spillway was used for several weeks in July with flows as high as 5.2 kcfs. The TDG pressures associated with full capacity powerhouse flows will be dependent upon the TDG properties withdrawn from the forebay. Powerhouse flows can contain TDG pressures elevated above forebay conditions when air is aspirated into the turbine hub and draft tube during low turbine flows. Dworshak Dam operations resulting in elevated TDG levels are shown in Figure G60. The highest spill flow rate at Dworshak Dam was 14.5 kcfs resulting in a tailwater TDG pressure of 902 mm Hg (122.5 percent TDG).

The tailwater fixed monitoring station DWQI is located approximately 1.5 miles below the dam in well mixed waters influenced by both powerhouse and spillway flows. The simulation of TDG levels in the North Fork of the Clearwater River requires the estimation of TDG levels in powerhouse flows. The background TDG levels associated with powerhouse flows during spillway/RO flows were interpolated from TDG observations during capacity powerhouse flows with no spill.

The following TDG exchange equation for Dworshak Dam was updated in SYSTDG based on the analyses of flow and TDG pressure data from 2009-2011:

$$TDG_{avg}=(TDG_{sp}(Q_{sp}+Q_{ent})+TDG_{ph}(Q_{ph}-Q_{ent}))/(Q_{ph}+Q_{sp})$$

Regulating Outlet

$$Q_{ent} = 0$$

$$TDG_{sp}=BP+288.2(1-Exp(-0.51Q_{ro}))$$

Spillway

$$Q_{ent}=0$$

$$TDG_{sp}=BP+468.6(1-exp(-0.21Q_{sp/}nbays))$$

Dworshak Dam is the beginning of the extent of the model, so it is necessary to have the incoming TDG levels entered as boundary conditions. At other projects, there is a forebay gauge that provides the incoming TDG levels and an estimated powerhouse TDG levels, but this doesn't exist at Dworshak Dam. As a result, the SYSTDG modeler must estimate what the incoming TDG levels are since SYSTDG does not contain an expression for estimating the forebay or powerhouse TDG levels. The simulation of TDG levels in the Dworshak Dam tailwater requires having powerhouse TDG levels.

Because there are no upstream sources of TDG, the Dworshak Dam forebay TDG levels have been observed to vary approximately 3 percent during April through August.

The TDG pressures in the tailwater channel below Dworshak Dam were simulated during the 2011 spill season as shown in Figure G60. The operations during March contained a steady ramping up of regulating outlet flow and TDG pressures. This period of operations was followed by limited powerhouse flow and the production of high TDG levels. The spillway was utilized throughout most of July as shown in Figure G61. The regulating outlet flows were switched to the spillway at mid-day on July 7. The dark blue line in Figure G61 reflects the estimated TDG pressures contained in either spillway or regulating outlet flows as defined by the equations listed above. Spillway flows generate lower TDG pressures than regulating outlets for comparable flow conditions. In this simulation for a flow of approximately 5 kcfs, the regulating outlets generate TDG pressures of 995 mm Hg (135 percent TDG) compared to TDG pressures of 925 mm Hg (125.6 percent TDG) for spillway flows. These TDG response equations were derived from TDG levels observed in mixed waters at DWQI and do not involve direct observations of the TDG levels spillway flows.

The TDG exchange equation estimates (light blue line labeled REL CAL in Figure G61) closely approximated observed conditions (blue circles) during both RO and spillway flows for a wide range of operations at Dworshak Dam. The predictive error during both regulating outlet and spillway operations of 3 hours and longer were summarized at the tailwater FMS as listed in Table G6. The calculated tailwater TDG pressures contained only a small bias as determined from the average predictive error of -2.1 mm Hg. The standard error of estimate was determined to be 7.4 mm Hg which was better than determined at most other projects. The 50 percent confidence interval for the predictive error ranged from -6.9 to 3.7 mm Hg of pressure, and the 80 confidence interval ranged from -12.2 to 7.2 mm Hg of pressure. Dworshak Dam does not have a forebay FMS and the TDG levels observed at the tailwater FMS during powerhouse operations were used to estimate the TDG levels released by the powerhouse during concurrent powerhouse and spillway/regulating flows. The estimation of the powerhouse TDG levels was probably a significant component of the predictive error estimated at the tailwater FMS since powerhouse flows constitute most of the TDG loading observed at DWQI.

The observed and calculated TDG pressures at DWQI as a function of spill flow rates are shown in Figure G62 along with the estimated TDG pressures in undiluted regulating and spillway flows. The spillway flow generates significantly lower TDG pressures when compared to regulating outlet flows. Both the observed (blue circles) and calculated (black x) cross sectional average TDG pressures in the Clearwater River varied linearly with spill flow rate.

Section 5 Comparison of 2010 and 2011 Simulations

The extremely high river flows and corresponding spillway flows experienced during the 2011 fish passage season created additional challenges to modeling the TDG conditions throughout the system. These high river flows resulted in spill conditions which had not been encountered with the current structural configurations of many of the dams. The wide range of both voluntary and involuntary spill operations in 2011 resulted in the highest spill flow rates in over 30 years at many projects. The added focus on Grand Coulee Dam regulating outlet flows and the generation of TDG levels as high as 145 percent, created new challenges in managing TDG levels throughout the mid-Columbia River.

The performance of the SYSTDG as measured by the hourly predictive error statistics at FMS during the 2011 spill season was of comparable accuracy to conditions observed during the 2010 spill season with superior performance noted in certain reaches and poorer performance in others. The combined implementation of new spill patterns at John Day Dam involving the spillway weir operation or the shutdown of the powerhouse at Little Goose Dam provided unique spill events that had not occurred since spillway structures incorporated additional flow deflectors. A general comparison of model performance evaluates the bias in the estimate as reflected by the average predictive error and the variance of the predictive error or standard error of estimate. A total of 4 out of 10 forebay FMSs in 2010 contained an average predictive error greater than ±5 mm Hg compared to 4 out of 10 in 2011. The standard error of estimate at forebay FMSs ranged from 6.1 to 12.8 mm Hg in 2011 compared to 6.1 to 17.3 in 2010. In 2011, the magnitude of the standard error was less than or equal to calculated forebay conditions in 2010 in 7 of the 10. The reaeration coefficients used prior to 2010 at Bonneville Dam to CWMW resulted in a significant improvement in TDG predictions at CWMW. The bias in TDG pressures was changed from -8.2 (over-estimation) to 3.6 (under-estimation) when using the older reaeration coefficients.

The data at the tailwater FMSs were filtered by duration of spill to generate a more meaningful estimate of the predictive error. The standard deviation of the predictive errors in 2010 ranged from 4.4 to 29.5 mm Hg at tailwater FMS. In 2011, the standard deviation of the predictive errors at tailwater FMSs ranged from 6.9 to 13.6 mm Hg. Improvements in predicting TDG pressures were achieved at 6 of the 12 tailwater FMSs based on the size of the standard error of estimate. The cause of the large predictive error at Little Goose tailwater was likely due to sample error. The cause for TDG levels to be higher at Lower Monumental forebay than those coming from Little Goose tailwater is sampling bias, and in this case the SYSTDG model results are probably more accurate than the observed data.

The prediction of TDG pressures below McNary Dam proved to be troublesome during much of 2011. The model performed well for a range of spill flow rates but performed poorly during the summer and during high spill flow rates. The frequent use of the bulk spill pattern during high summer flows through spillbays 2 and 3 likely caused observed conditions to be higher than estimated. The extent that the spillway flow pressures reflect these higher TDG pressures is not known. A new McNary Dam spillway TDG production equation based on the effective number of spillbays, and functional relationship between TDG pressures, specific flows and tailwater elevations is proposed for 2012. This equation should be evaluated with data from other years before being used in subsequent models. This recommendation is included in the 2012 improvements list shown in Section 9.

The performance of the SYSTDG model in the Columbia River from Wells to Grand Coulee dam provided reliable estimates of TDG levels. The 2010 Grand Coulee Dam TDG exchange equation was updated early in the 2011 season to more closely predict the very large TDG levels generated during regulating outlet operation. The consistency and accuracy of prediction in the Wells pool supports the observations that spill at Chief Joseph Dam significantly reduced the TDG loading in the Columbia River.

Section 6 Highlights of the Statistical Evaluation

SYSTDG was used to simulate the production, transport, and dissipation of TDG levels in the Columbia River basin during the 2011 spill season. These estimates of TDG levels were compared with observed TDG levels from the FMS to evaluate the reliability of these calculations, and to determine the uncertainty of TDG estimates to support spill management decisions. The magnitude and duration of spillway operations during 2011 with spillway flow deflectors and spillway weirs have not been experienced previously. The McNary, Chief Joseph, and John Day dams spill patterns were modified in the 2011 season due to structural and dam safety concerns. The unique operations and flow conditions experienced during the 2011 season resulted in the application of the SYSTDG model outside of condition for which it was developed.

The predictive errors computed for SYSTDG in 2011 compared favorably with estimates from previous years despite the extremely high water year modeled. In most cases, the TDG exchange equations established for a much lower range of flow conditions accurately predicted the TDG conditions during the peak flow events. The Lower Monumental and McNary dams TDG exchange equations under-estimated the TDG levels for the high 2011 flows. In these cases, updated TDG exchange equations should be developed.

The performance of SYSTDG in the mid-Columbia River from Wells to Grand Coulee dams deserved considerable attention during 2011 due to the generation of extremely high TDG pressures in regulating outlet flows from Grand Coulee Dam. The high background TDG levels at Chief Joseph Dam created opportunities to reduce the TDG loading in the Columbia River through spillway operations.

An updated TDG exchange equation for Grand Coulee Dam during regulating outlet operation was developed from the 2011 observed data and is a function of the spill flow rate, powerhouse flow, and TDG levels in powerhouse flows. A more detailed evaluation of regulating outlets using data from other years could help validate this equation. The effectiveness of outlet tube patterns (pair tube flows) may provide some additional insight into the TDG levels observed below Grand Coulee Dam. The TDG exchange from Grand Coulee Dam and transport throughout the Chief Joseph pool were evaluated with SYSTDG for operations observed in 2011. The model performed well during a wide range of flow conditions at Grand Coulee Dam and shows a degassing rate of 2 to 4 percent for the reach between Grand Coulee and Chief Joseph dams during the 2011 spill season.

The spillway flows from Bonneville Dam were maintained close to 300 kcfs for over a month since six spillway flow deflectors were added to the spillway. The TDG exchange, transport, and mixing of Bonneville Dam flows during the 2011 spill season resulted in SYSTDG estimates of TDG levels that closely corresponded with observed conditions. The predictions of TDG levels at the Camas/Washougal gauge were generally slightly higher than the observed conditions. Returning the reaeration coefficients to levels used prior to the 2010 season resulted in predictions with little bias and a smaller standard error. The standard error of estimate for the Warrendale tailwater station was 7.7 mm Hg and of comparable accuracy with previous performance statistics. The estimated TDG levels associated with spillway flows were consistent with the TDG levels observed downstream at both CWMW and WRNO.

The TDG levels in spillway flows at The Dalles Dam were estimated to be above 122 percent, but not to exceed 130 percent. This narrow range of percent TDG is caused by the shallow flow conditions downstream of the spillway. The model proved to be very accurate in predicting the TDG levels both below The Dalles Dam and in the forebay of Bonneville Dam.

The TDG exchange study determined that the impacts of The Dalles Dam spillway training wall between bays 8 and 9 on TDG exchange equation were small. As a result, the installation of the new spillway training wall did not produce a need to update The Dalles Dam TDG exchange equation.

The large John Day Dam powerhouse capacity and spillway helped moderate the spillway flow and peak TDG levels observed at the tailwater fixed monitoring stations. The operation of spillway weirs on bays 18 and 19 continued to influence the spill patterns and resultant TDG levels at John Day Dam. The spillway TDG exchange equation performed well except at flows over 200 kcfs where TDG levels approach 130 percent.

A TDG exchange equation was developed for Dworshak Dam spillway and regulating outlet flows. The equation estimations closely tracked the observed TDG pressures measured at the tailwater fixed monitoring station. Accurate estimates of the TDG levels in the Clearwater River will require estimating the TDG levels in powerhouse flows during concurrent spill operations.

Section 7 Recommended TDG Monitoring Studies

TDG monitoring studies are included as actions associated with the TDG TMDL and are needed to update the SYSTDG model. The information needed to update the SYSTDG TDG exchange equations could be provided by conducting TDG monitoring studies at Grand Coulee Dam, McNary Dam with the spillway weirs in place, and Dworshak Dam.

During the 2010 spill season a TDG monitoring study was conducted at John Day Dam. The study was to evaluate the impacts of the installation of spillbay 20 spillway flow deflector on the interaction of the powerhouse and spillway flows, the TDG generation impact of the John Day Dam spillway weir, and whether the tailwater FSM was representative of river conditions. The evaluation of the mobile velocity and dissolved oxygen data collected at John Day Dam in 2010 has not been completed due to resource availability. It is recommended that the data be evaluated. This recommendation is included in the 2012 improvements list shown in Section 9.

The influence of bulk spill through the spillway weirs at bays 18 and 19 at John Day Dam, and the performance of the 50 foot flow deflector in bay 20 remain difficult to assess from the single measurement station below the dam. The impact of this spill pattern on the entrainment of powerhouse flows into the stilling basin may contribute to modeling errors at downstream stations. These issues warrants additional field measurements involving transect sampling for dissolved gasses.

Section 8 Improvements Made to SYSTDG in 2011

The 2011 high flows and spill provided the opportunity to collect the information needed to update the TDG exchange equations in SYSTDG for several projects. The high water year played an important role in achieving the following five improvements to SYSTDG this year:

1. Grand Coulee Dam: The Grand Coulee Dam TDG exchange equation was updated for regulating outlet operation as recommended in the 2010 statistical evaluation. The updated equation is based on the 2011 observed data and spill operations and is a function of the spill, powerhouse flow, and TDG content of powerhouse releases.

2. Chief Joseph Dam: The Chief Joseph Dam TDG exchange equation was updated based on observed data and spill operations.

3. Dworshak Dam: The Dworshak Dam TDG exchange equation was updated as recommended in the 2010 statistical evaluation. The updated equation addressed spill from the regulating outlet and spillway, and was based on observed data and spill operations.

4. McNary Dam: The McNary Dam TDG exchange equation was updated as recommended in the 2010 statistical evaluation. The updated equation that addressed the spillway weir operation was based on observed data and spill operations.

5. Camas Washougal: SYSTDG for the Camas Washougal gauge was improved for accuracy as recommended in the 2010 statistical evaluation. The wind degassing coefficients were reinstated to levels used during the 2009 season to reduce the bias in the predicted TDG pressures at this gauge. The impact of increasing the background degassing coefficient resulted in the most accurate prediction of TDG pressures at CWMW ever documented by the SYSTDG model.

Section 9 SYSTDG Improvements Recommended for 2012

The following improvements and maintenance activities to the SYSTDG model are recommended for 2012.

1. Dwworshak Dam: The TDG levels in RO and spillway flows at Dworshak Dam were estimated from conditions in well mixed waters at the tailwater fixed monitoring stations DWQI. Direct measurements of the TDG levels in spill flows should be conducted to confirm the TDG exchange equation.

2. Grand Coulee Dam: The Grand Coulee Dam spill pattern should be added to SYSTDG.

3. Grand Coulee Dam: Estimation of TDG exchange at Grand Coulee Dam remains at an elemental level of understanding. One key component for improving estimates of TDG exchange at Grand Coulee Dam will involve developing a better understanding of the TDG levels in powerhouse flows and the contribution of these flows to the cross sectional average TDG levels introduced into Rufus Woods pool.

4. Chief Joseph Dam: The functional dependency of TDG exchange at Chief Joseph Dam should continue to be investigated.

5. Chief Joseph Dam: The wind conditions in the Wells pool and influence on reaeration/degassing of flows from Chief Joseph Dam should be pursued to improve model estimates of TDG pressures arriving at Wells Dam.

6. McNary Dam: The McNary Dam's TDG exchange equations under-estimated the TDG levels for the high flows. An updated TDG exchange equations should be developed.

7. McNary Dam: A new McNary Dam TDG exchange equation was proposed for McNary spillway based on an updated equation for the effective number of spillbays and functional relationship between TDG pressures, specific flows, and tailwater elevations. This equation should be evaluated with data from other years before being used in subsequent models.

8. John Day Dam: The influence of bulk spill through the spillway weirs at bays 18 and 19 at John Day Dam, and the performance of the 50 foot flow deflector in bay 20 remain difficult to assess from the single measurement station below the dam. The impact of this spill pattern on the entrainment of powerhouse flows into the stilling basin may contribute to modeling errors at downstream stations. These issues warrant additional field measurements involving transect sampling for dissolved gasses.

9. John Day Dam: Perform the evaluation of the mobile velocity and dissolved oxygen data collected at John Day Dam in 2010.

10. John Day Dam: A redesign of the John Day Dam tailwater TDG production equation using a smaller rate coefficient for the specific spillway discharge would reduce this estimation bias and should be explored in the next version of the SYSTDG model.

11. Bonneville Dam: The TDG pressures observed at the CCIW station in the spillway exit channel of Bonneville Dam have consistently underestimated the average TDG pressures in spillway flows when spillway flows exceed approximately 150 kcfs. The SYSTDG model provides reliable estimates of the TDG levels in high spillway flows at Bonneville Dam based upon the wide range of flow conditions experienced in 2011.

12. Bonneville Dam: The B2CC outfall can contribute significantly to the TDG loading below Bonneville Dam during low flow and low tailwater conditions. The TDG exchange at this outlet during higher flows and tailwater conditions remains difficult to model and is an area for further model development.

13. Bonneville Dam: Removing the B2CC TDG source when the Bonneville Dam tailwater remains above a given elevation and thereby, preventing a plunging flow will improve the predictions of TDG conditions at the WRNO gauge and should be investigated in model development programs.

14. Lower Granite Dam: The TDG exchange description for Lower Granite Dam should be updated to more accurately estimate conditions developing for lower spillway flows and summertime spill patterns.

15. Lower Monumental Dam: The TDG exchange equations for Lower Monumental Dam should be updated to improve the accuracy at high spillway flows and include data from multiple years. The identification of the influence of forebay TDG pressures on data observed at the tailwater FMS should be quantified.

16. Lower Monumental Dam: A review of the Lower Monumental Dam tailwater computation of the number of spillbays for this pattern should be updated to reflect the prominent spill from bays 6 and 8.

17. Lower Monumental Dam: The updated Lower Monumental Dam tailwater TDG production equation based on the higher flows observed in 2011 equates the delta TDG pressure as the product of the effective depth of flow, and the square root of the unit spillway flow should be established.

18. Lower Monumental Dam: The Lower Monumental Dam TDG exchange equations under- estimated the TDG levels for the high 2011 flows. In these cases, updated TDG exchange equations should be developed.

Figures for Appendix G

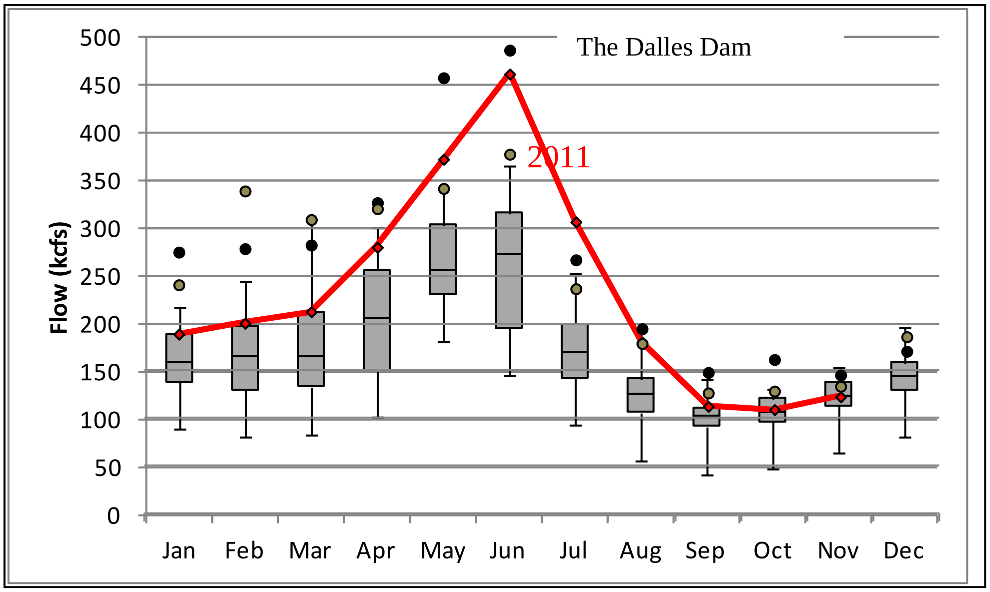

Figure G1. Statistical Summary of Columbia River Monthly Average Flows at The Dalles Dam for 1975-2011
(2011 – Red, 1975-2011 summary gray box 25, 50, 75th percentiles, whiskers 5-95th percentiles).

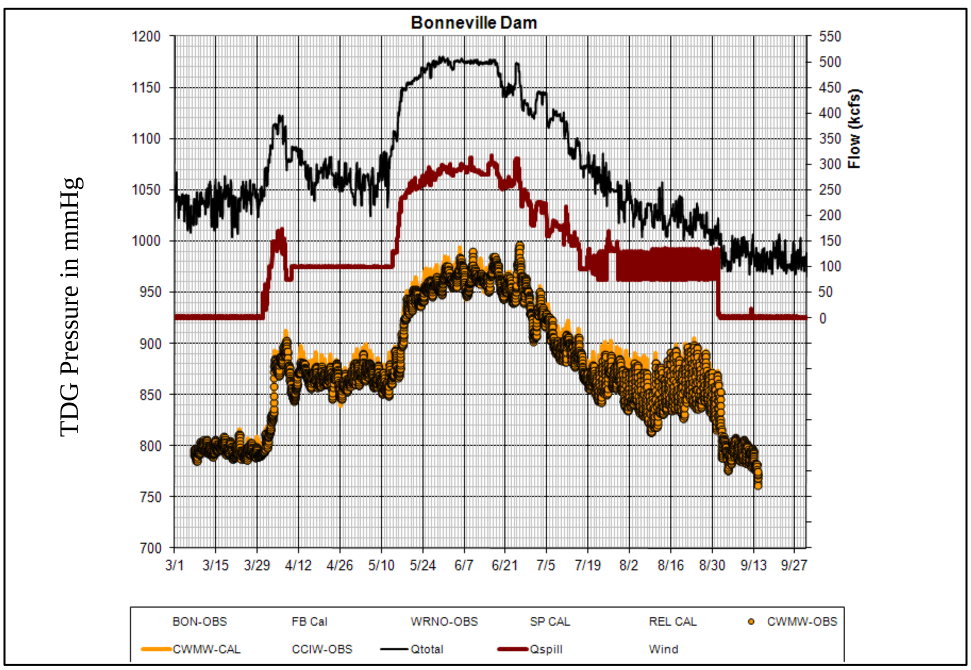

Figure G2. Observed and Calculated TDG Pressures in the Columbia River at the Camas/Washougal FMS downstream of Bonneville Dam, March-September 2011

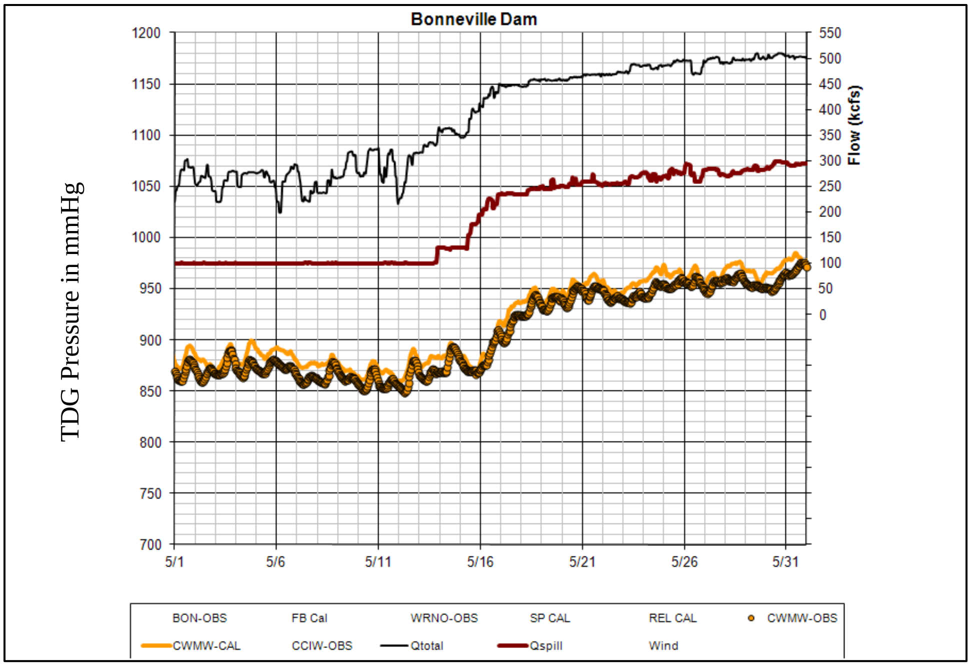

Figure G3. Observed and Calculated TDG Pressures in the Columbia River at the Camas/Washougal FMS downstream of Bonneville Dam, May 2011

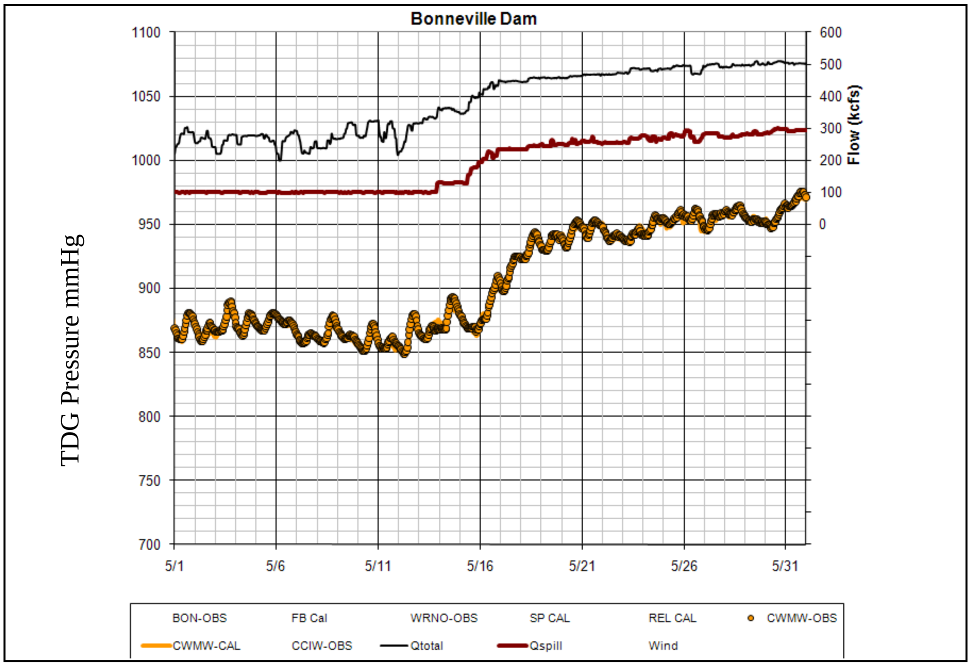

Figure G4. Observed and Calculated TDG Pressures in the Columbia River at the Camas/Washougal FMS downstream of Bonneville Dam, May 2011 with reinstated reaeration coefficients.

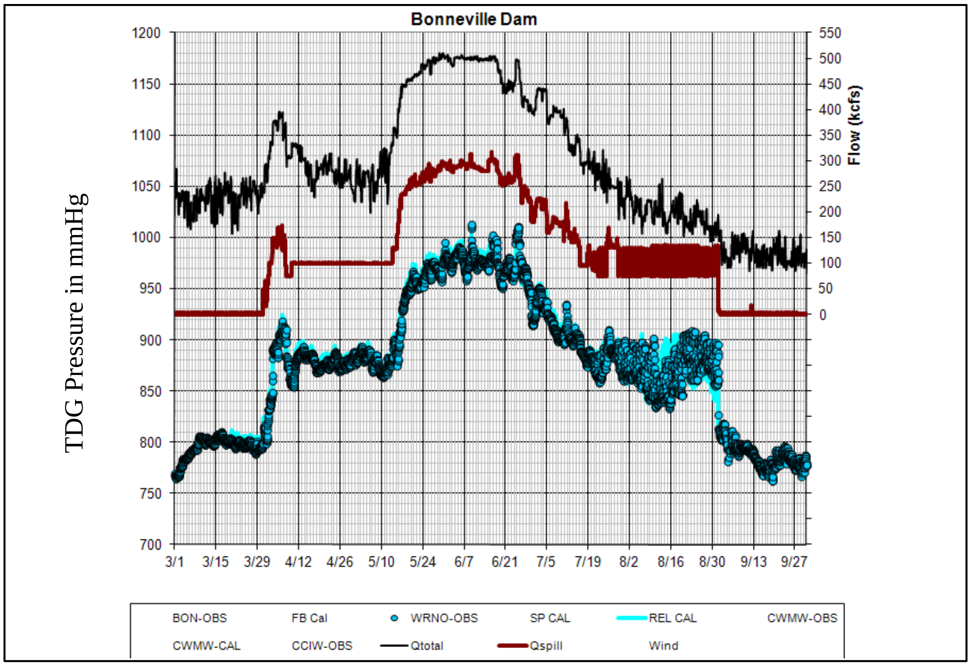

Figure G5. Observed and Calculated TDG Pressures in the Columbia River at the Warrendale FMS downstream of Bonneville Dam, March-September 2011

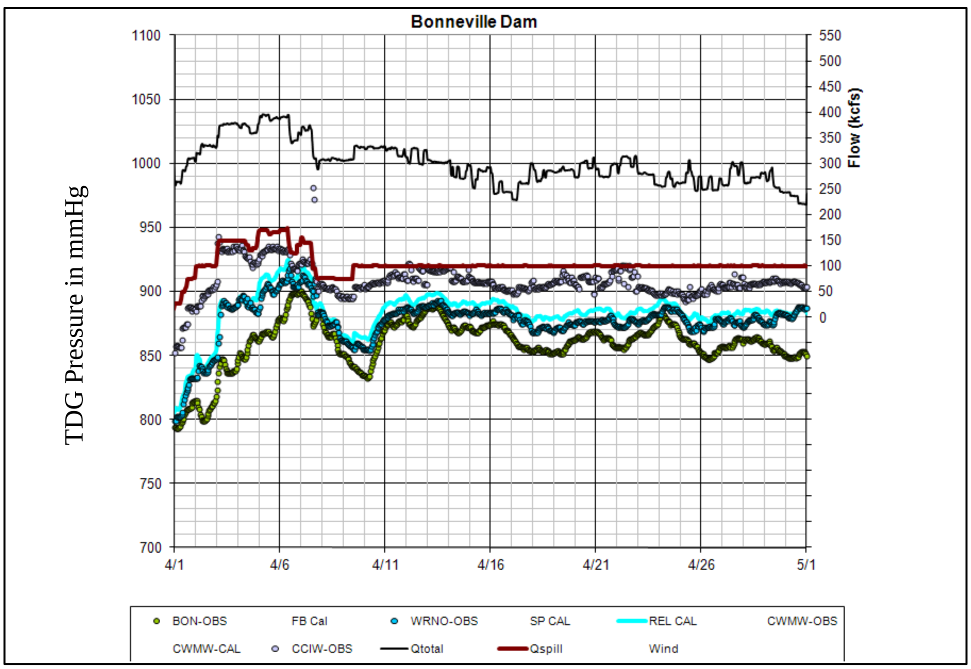

Figure G6. Observed and Calculated TDG Pressures in the Columbia River at the Warrendale FMS downstream of Bonneville Dam, April 2011

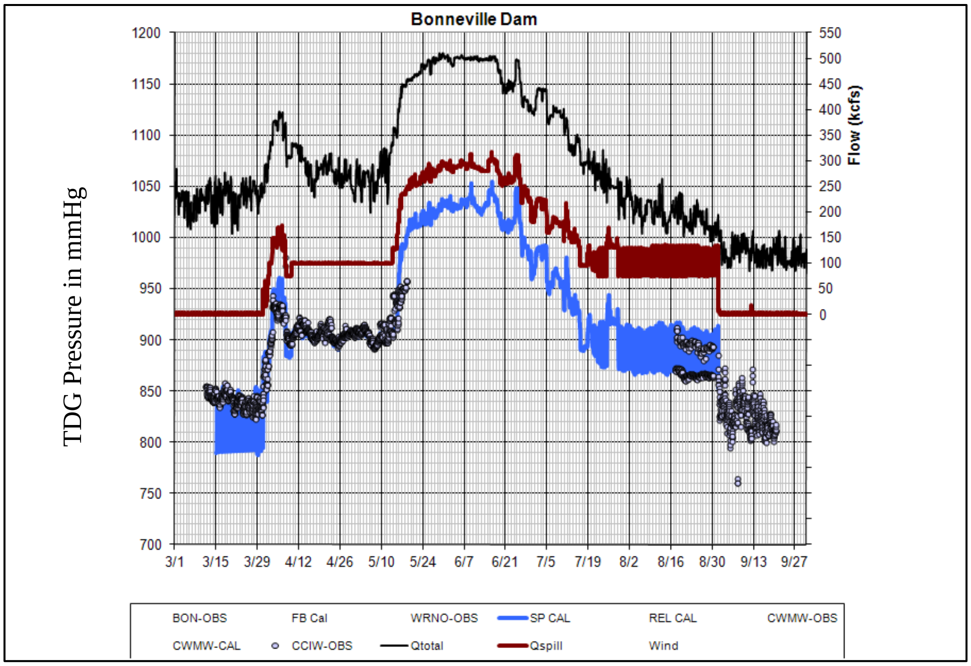

Figure G7. Observed and Calculated TDG Pressures in the Columbia River at the Cascade Island FMS downstream of Bonneville Dam, March-September 2011

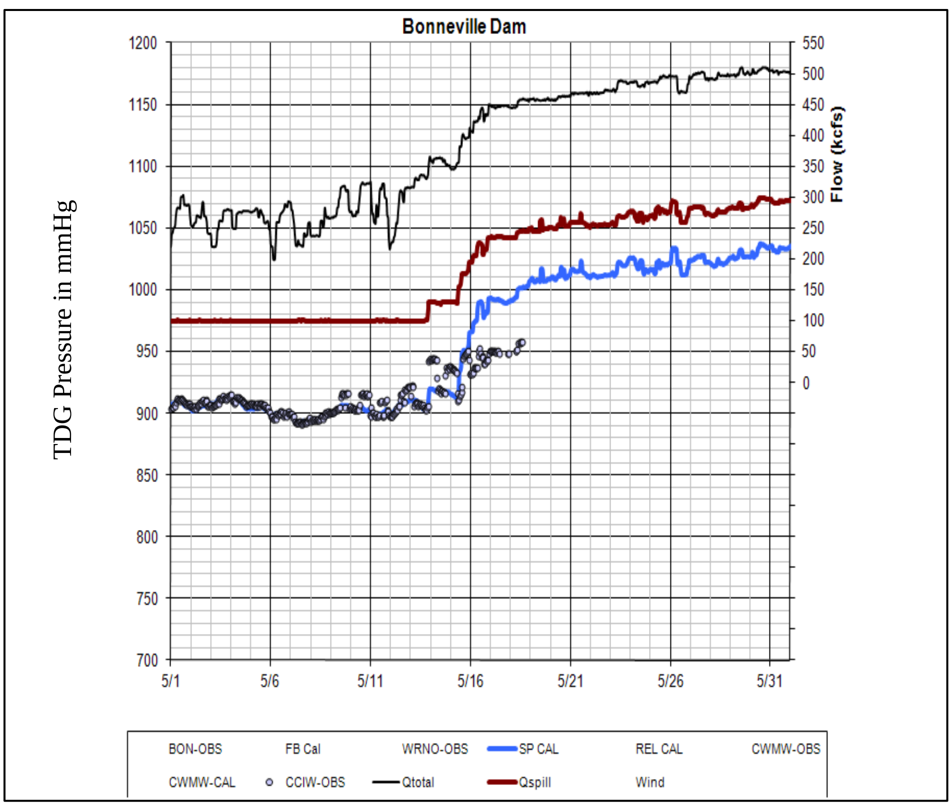

Figure G8. Observed and Calculated TDG Pressures in the Columbia River at the Cascade Island FMS downstream of Bonneville Dam, May 2011

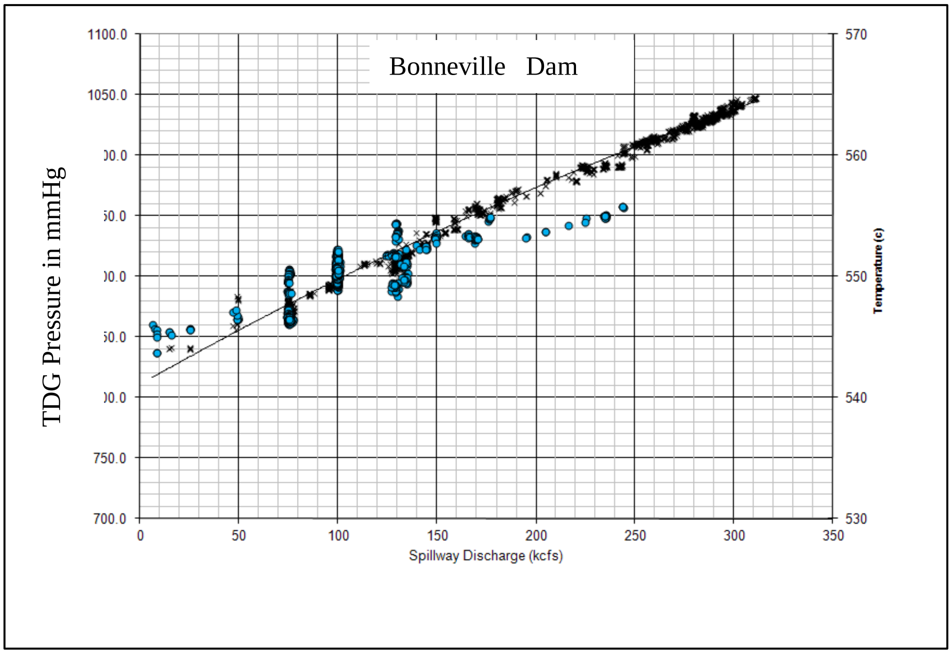

Figure G9. Observed and Calculated TDG Pressures in the Columbia River at the Cascade Island FMS downstream of Bonneville Dam as a Function of Spill Flow Rate, 2011

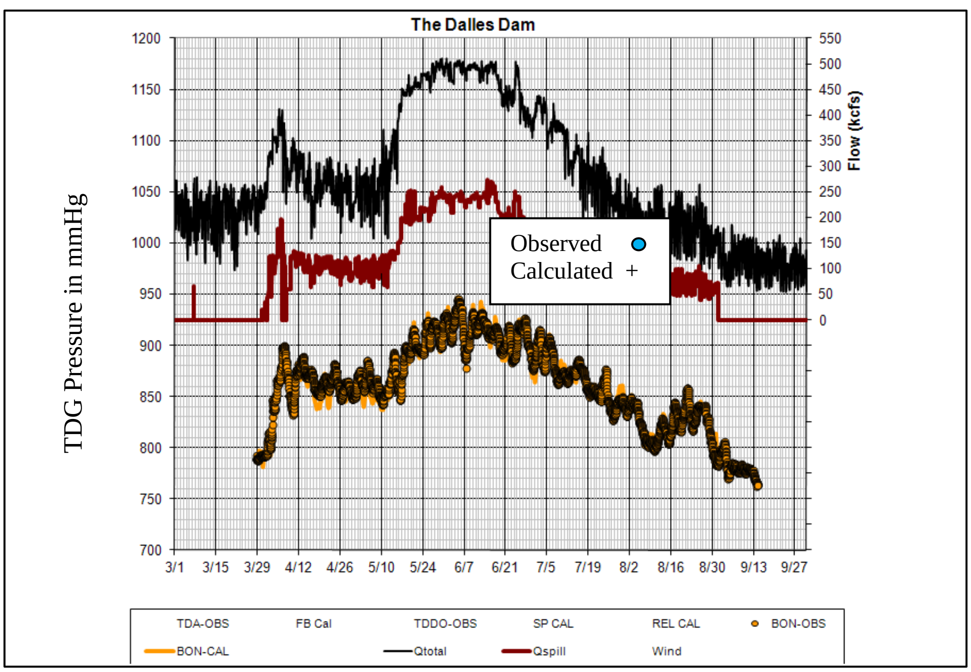

Figure G10. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the Columbia River in the forebay of Bonneville Dam, March-September 2011

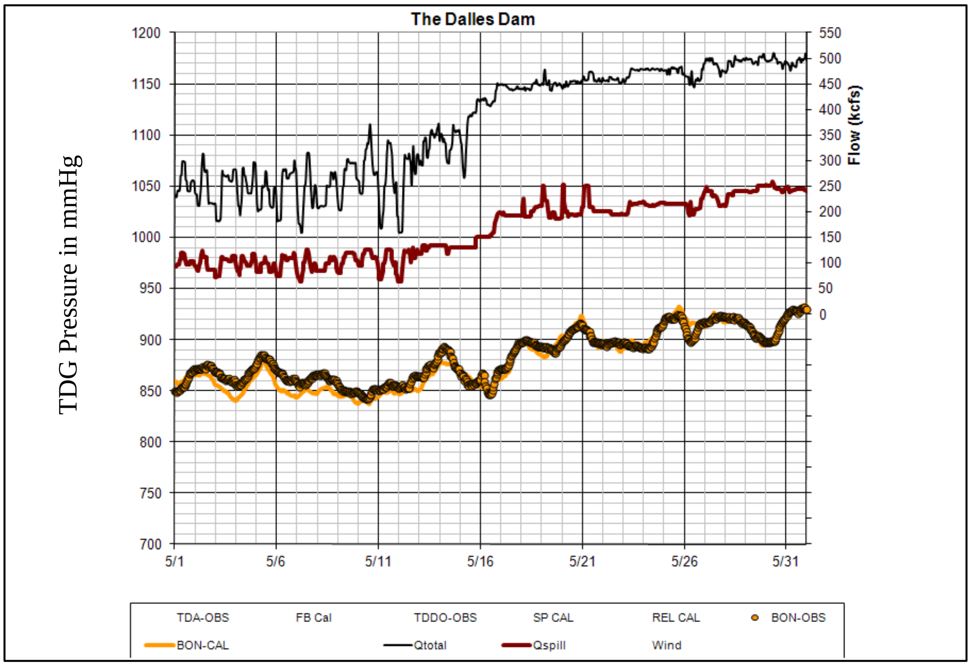

Figure G11. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the Columbia River in the forebay of Bonneville Dam, May 2011

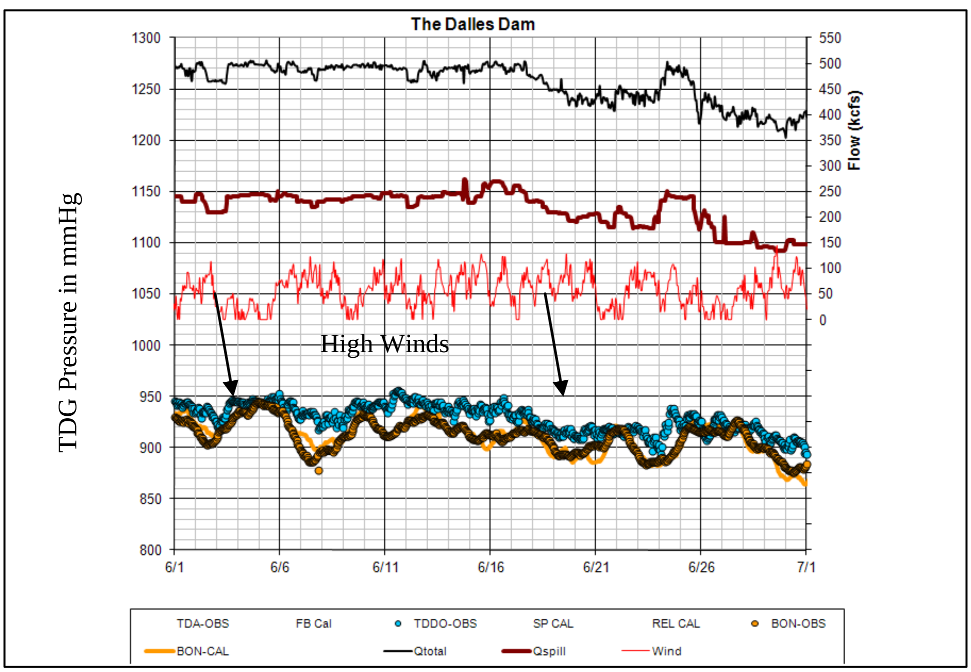

Figure G12. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the Columbia River in the forebay of Bonneville Dam and tailwater of The Dalles Dam, June 2011

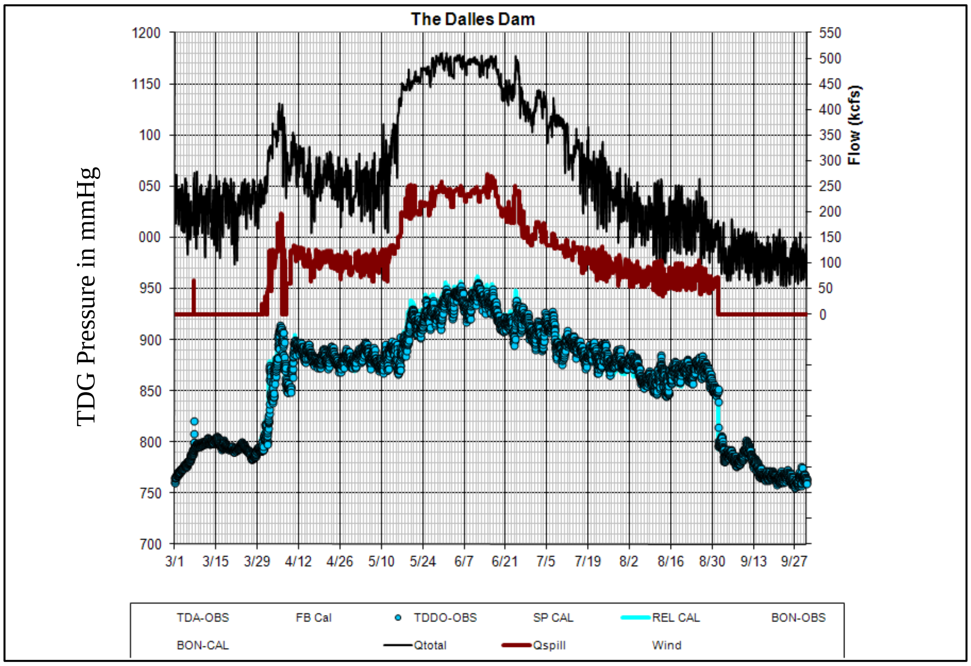

Figure G13. Observed and Calculated TDG Pressures in the Columbia River in the tailwater channel of The Dalles Dam, March-September 2011

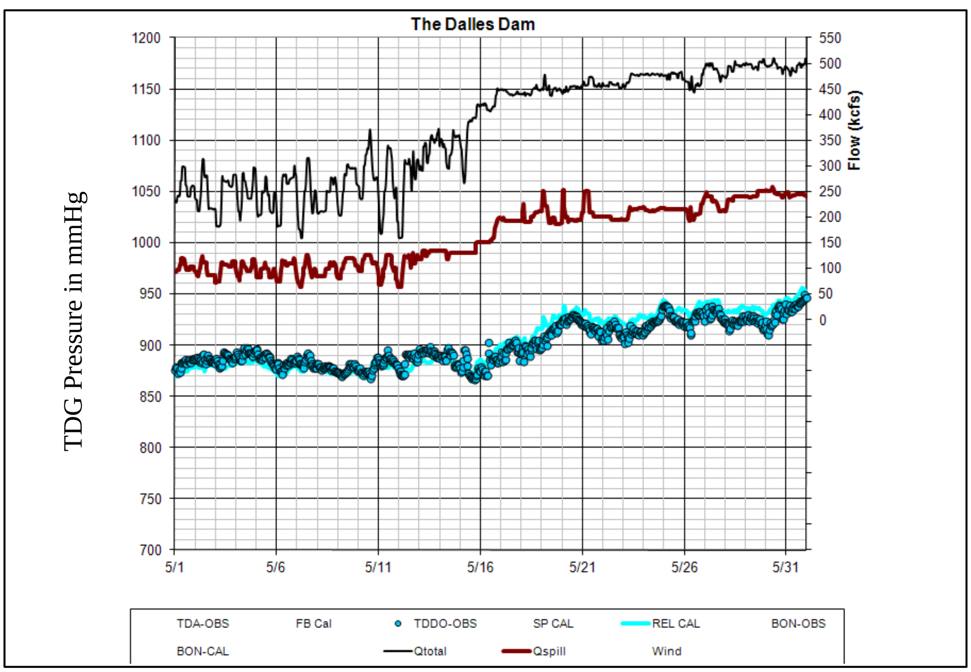

Figure G14. Observed and Calculated TDG Pressures in the Columbia River in the tailwater channel of The Dalles Dam, May 2011

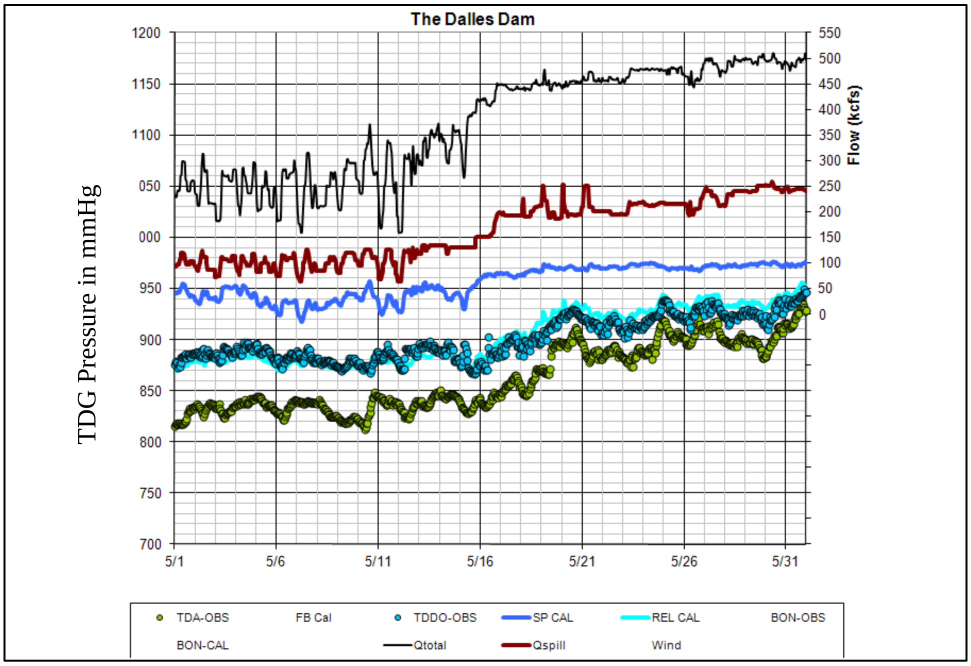

Figure G15. Observed and Calculated TDG Pressures in the Columbia River in the tailwater channel of The Dalles Dam, May 2011

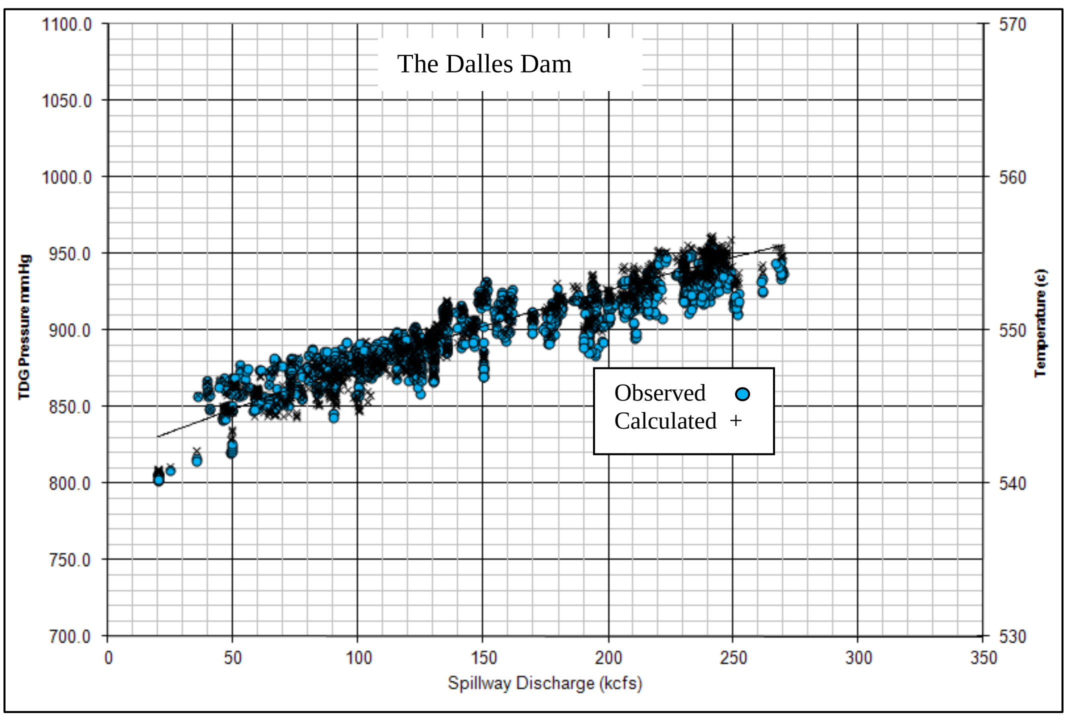

Figure G16. Observed and Calculated TDG Pressure in the Columbia River below The Dalles Dam as a Function of Spillway Flow, 2011

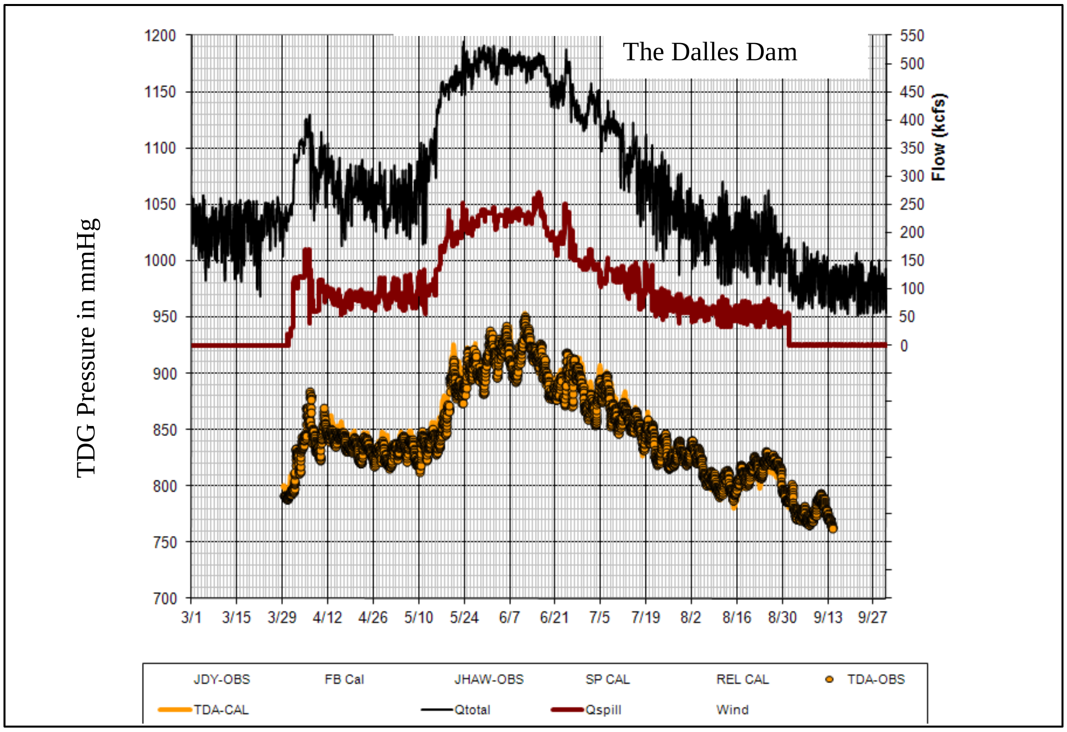

Figure G17. Observed and Calculated TDG Pressures in the Columbia River in the forebay of The Dalles Dam, March-September 2011

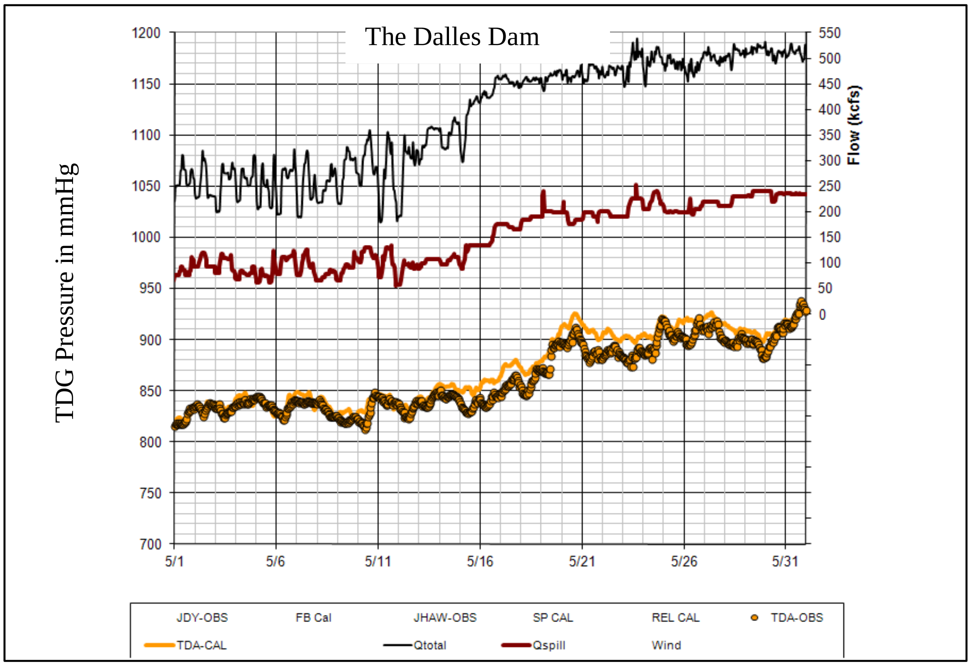

Figure G18. Observed and Calculated TDG Pressures in the Columbia River in the forebay of The Dalles Dam, May 2011

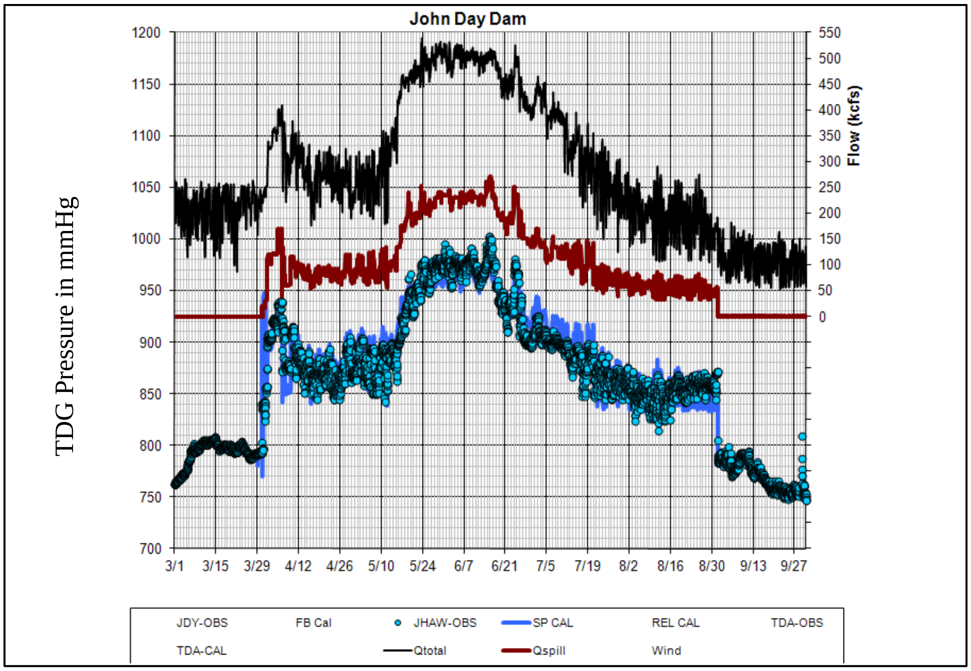

Figure G19. Observed and Calculated TDG Pressures in the Columbia River in the tailwater channel downstream from John Day Dam, March-September 2011

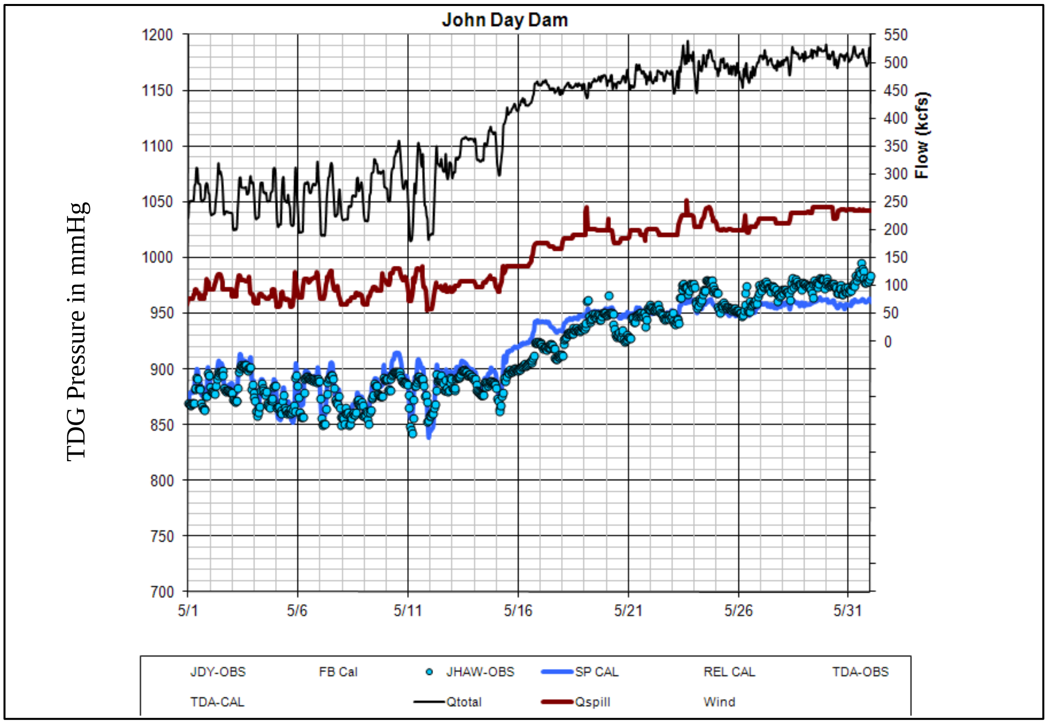

Figure G20. Observed and Calculated TDG Pressures in the Columbia River in the tailwater channel downstream from John Day Dam, May 2011

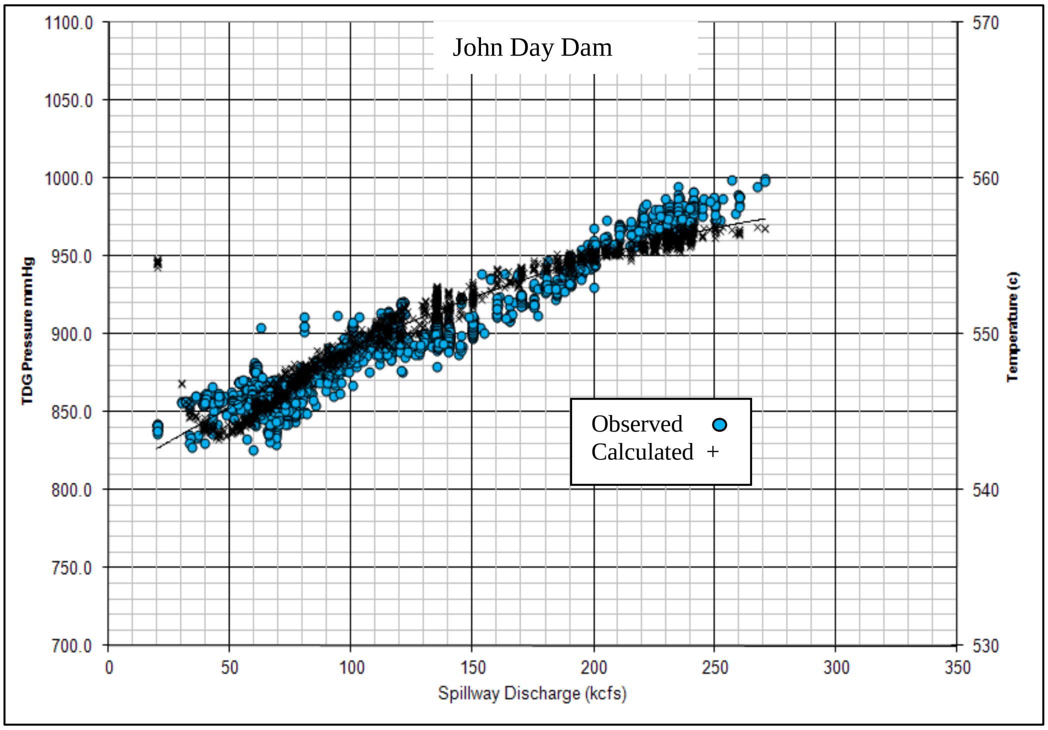

Figure G21. Observed and Calculated TDG Pressure in the Columbia River below John Day Dam as a Function of Spillway Flow, 201

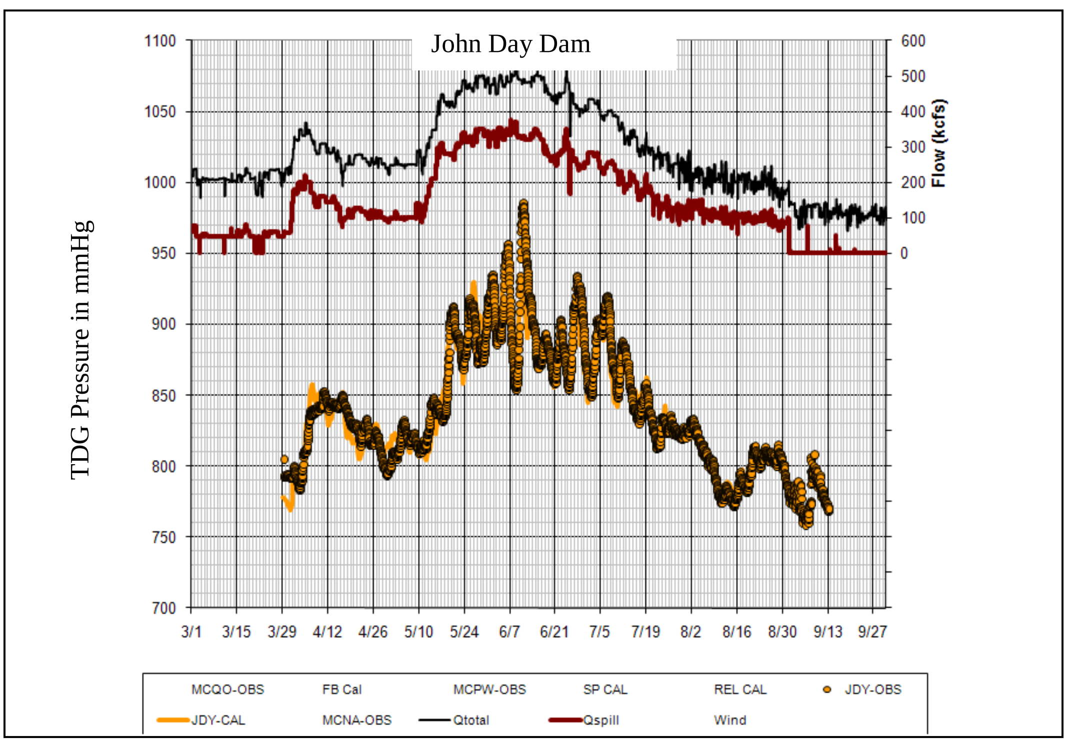

Figure G22. Observed and Calculated TDG Pressures in the Columbia River in the forebay of John Dam, March-September 2011

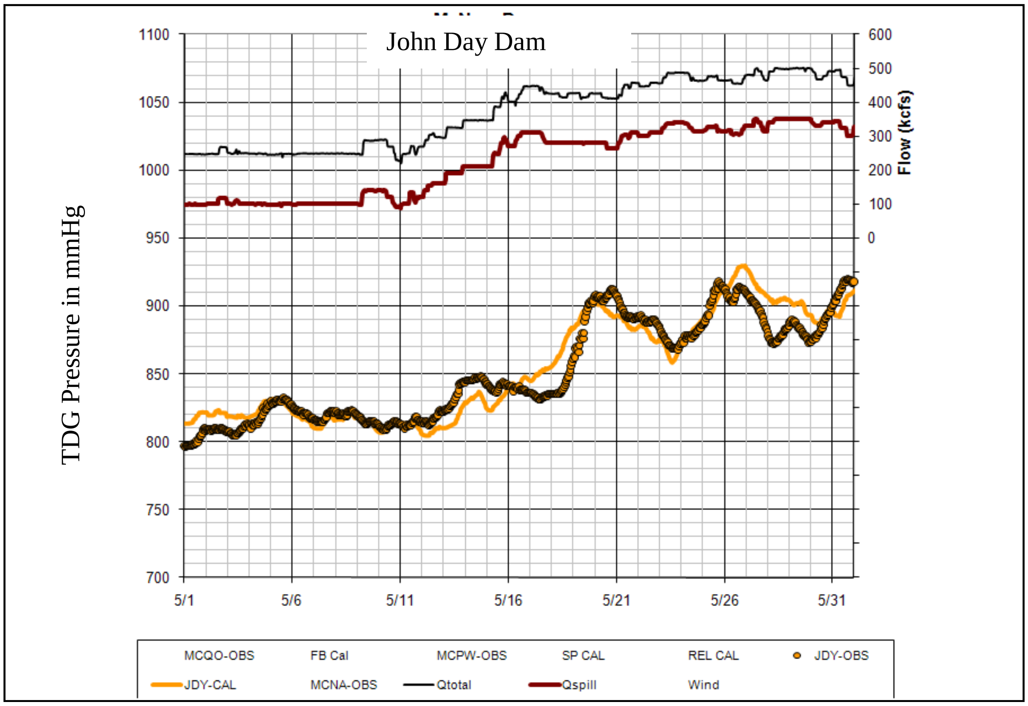

Figure G23. Observed and Calculated TDG Pressures in the Columbia River in the forebay of John Dam, May 2011

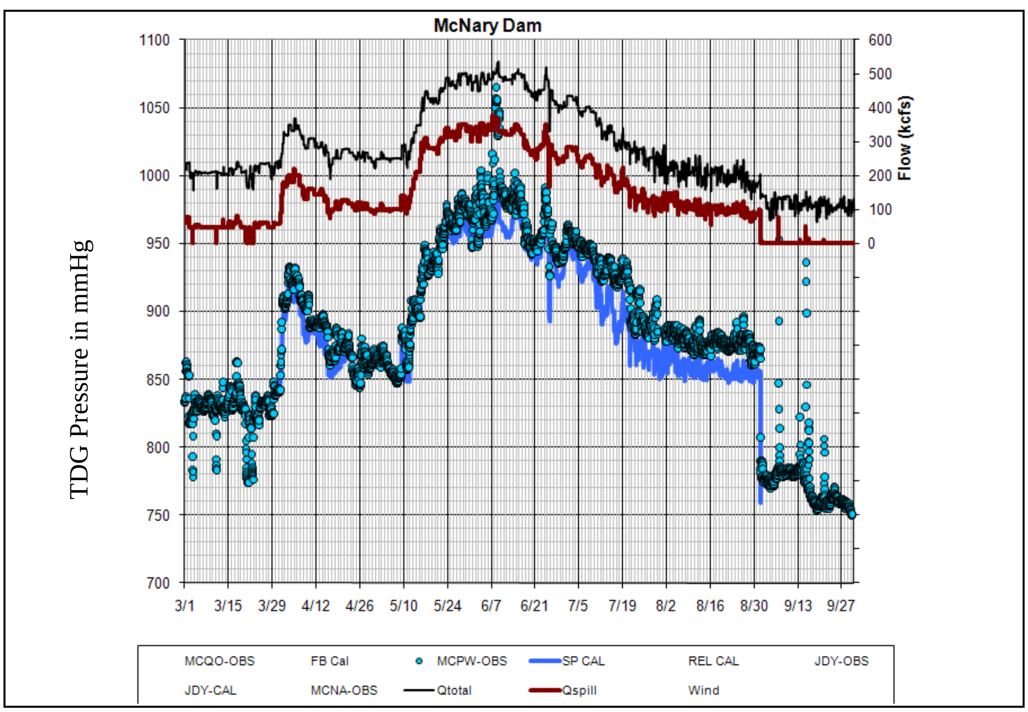

Figure G24. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of McNary Dam, March-September 2011

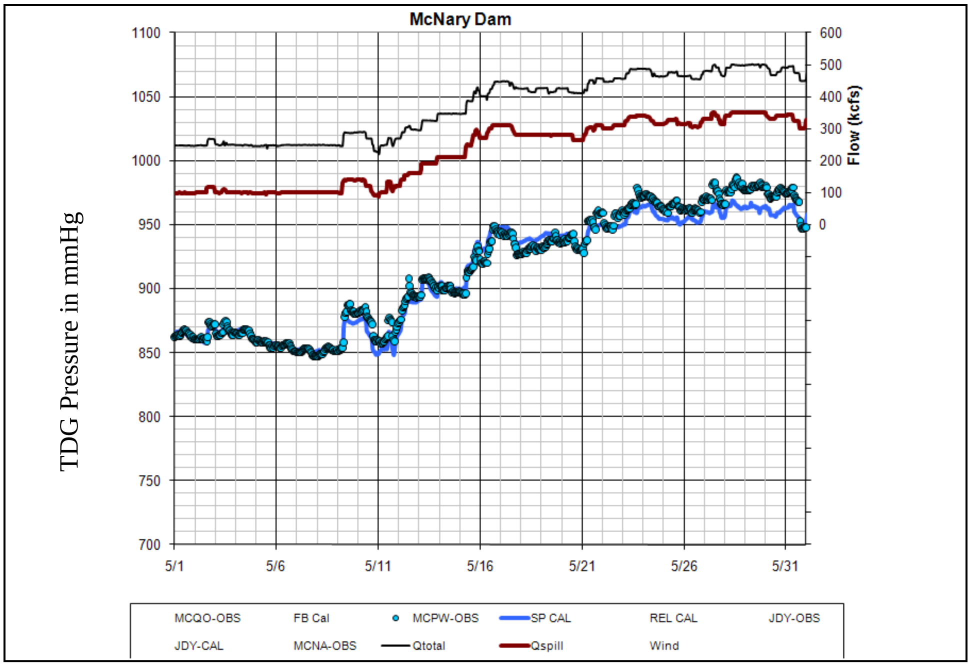

Figure G25. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of McNary Dam, May 2011

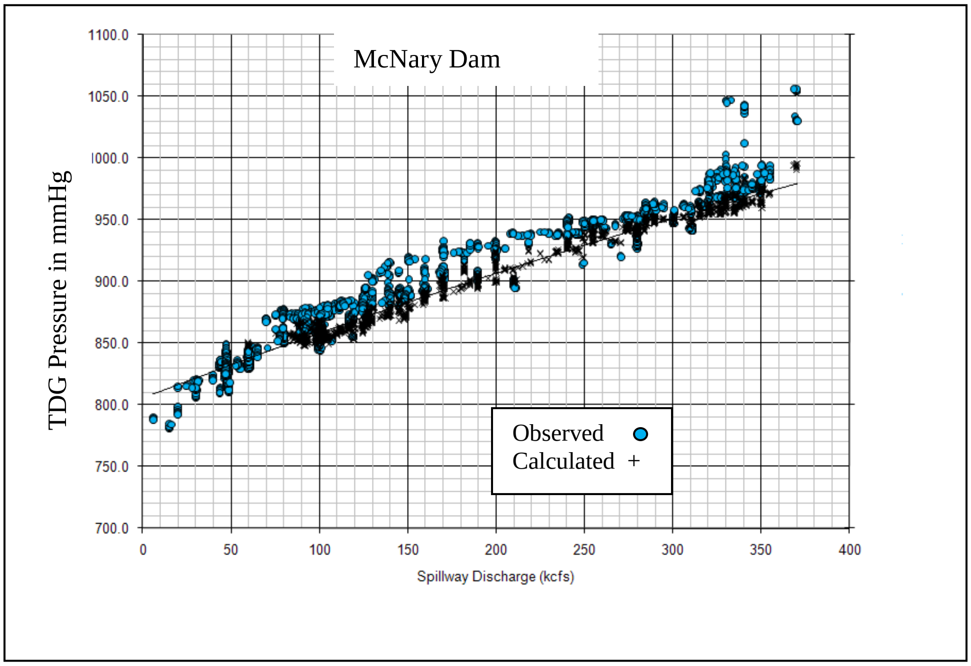

Figure G26. Observed and Calculated TDG Pressure in the Columbia River below McNary Dam as a Function of Spillway Flow, 2011

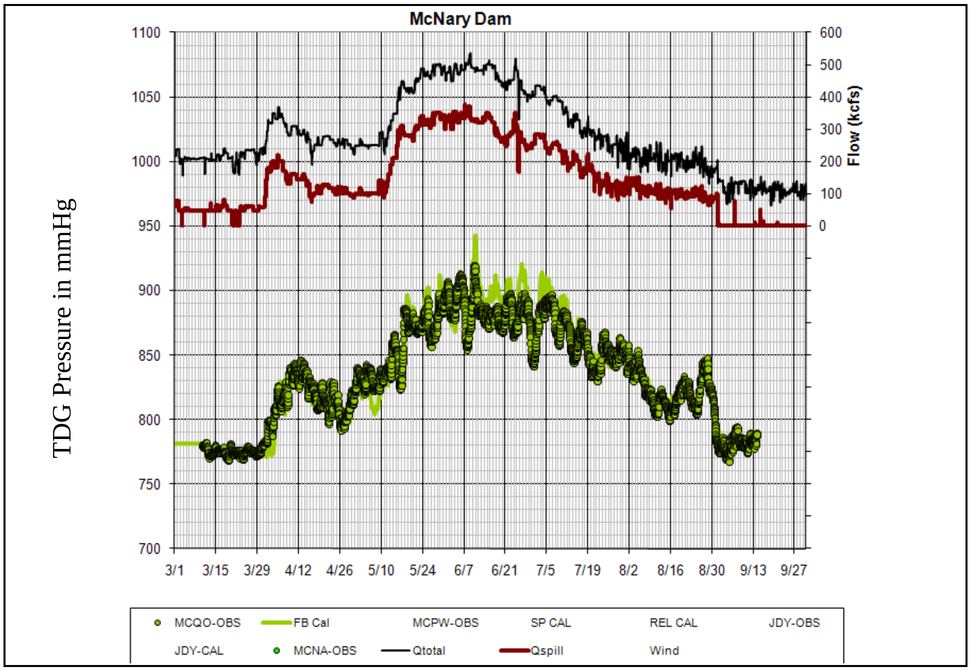

Figure G27. Observed and Calculated TDG Pressures in the Columbia River in the forebay of McNary Dam, March-September 2011

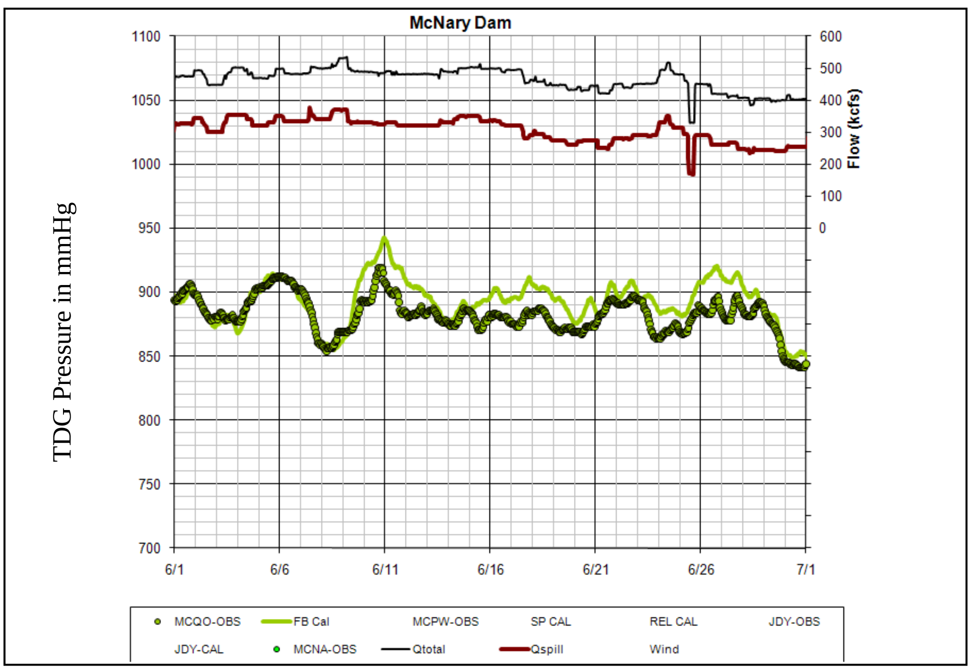

Figure G28. Observed and Calculated TDG Pressures in the Columbia River in the forebay of McNary Dam, June 2011

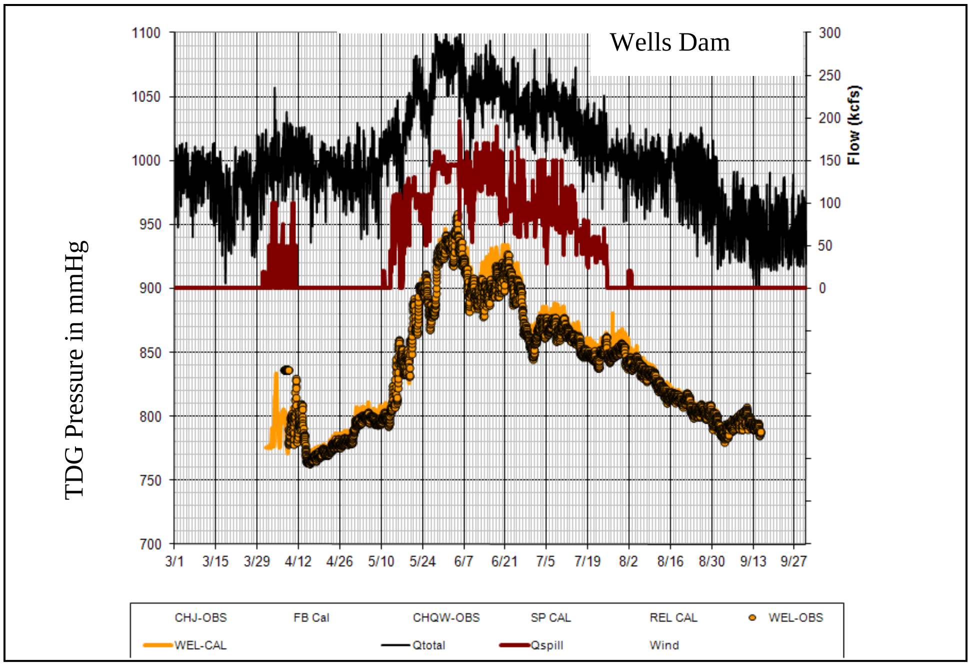

Figure G29. Observed and Calculated TDG Pressures in the Columbia River in the forebay of Wells Dam, March-September 2011

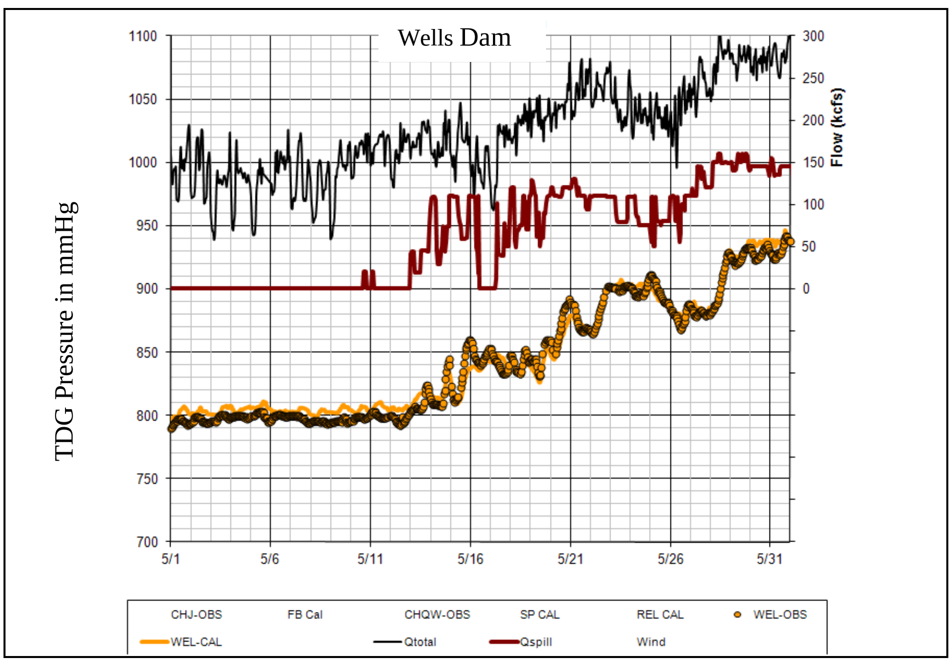

Figure G30. Observed and Calculated TDG Pressures in the Columbia River in the forebay of Wells Dam, May 2011

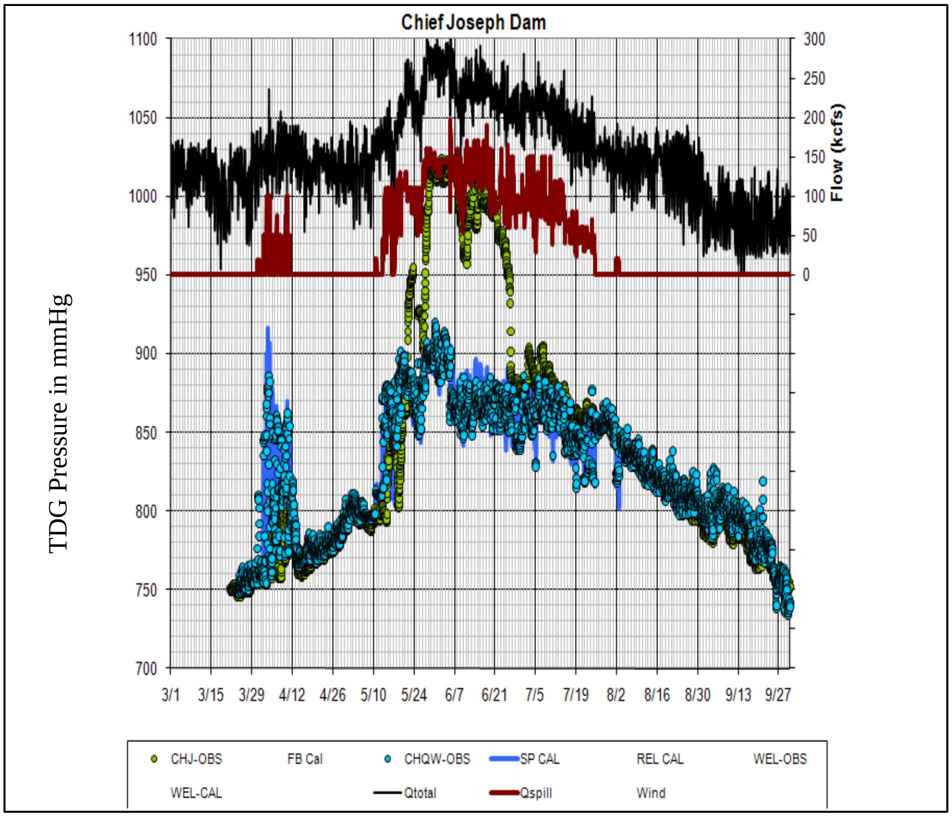

Figure G31. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of Chief Joseph Dam, March-September 2011

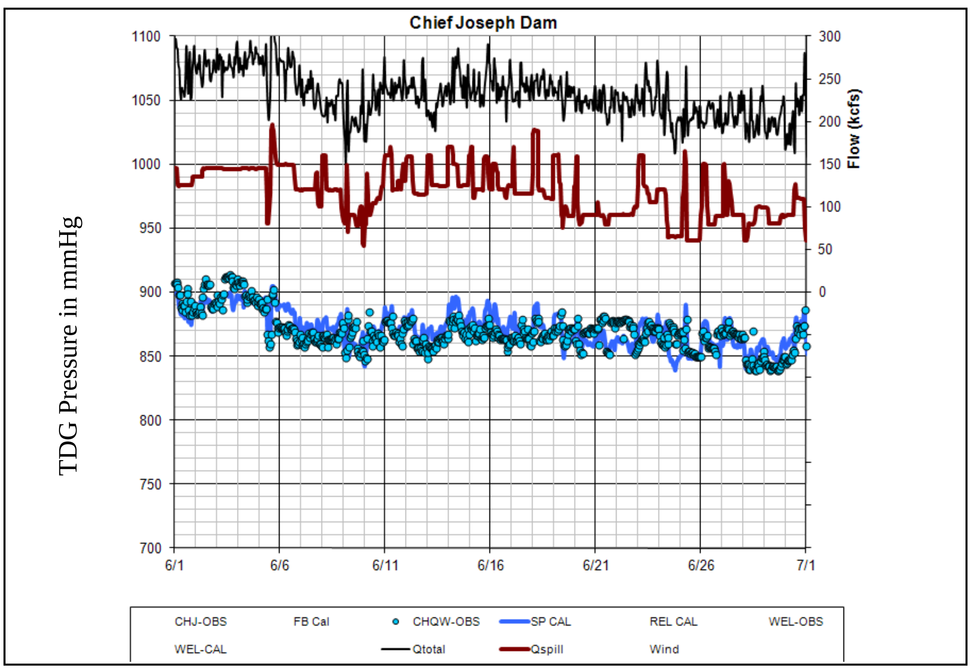

Figure G32. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of Chief Joseph Dam, June 2011

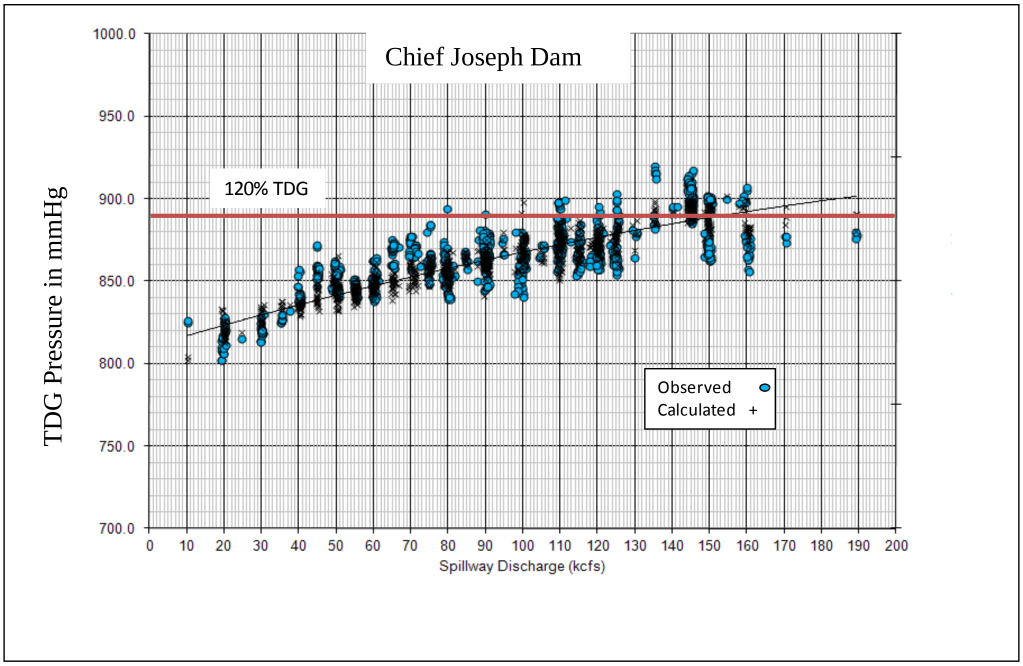

Figure G33. Observed and Calculated TDG Pressure in the Columbia River below Chief Joseph Dam as a Function of Spillway Flow, 2011 (Spill events with a duration of 3 hrs and longer)

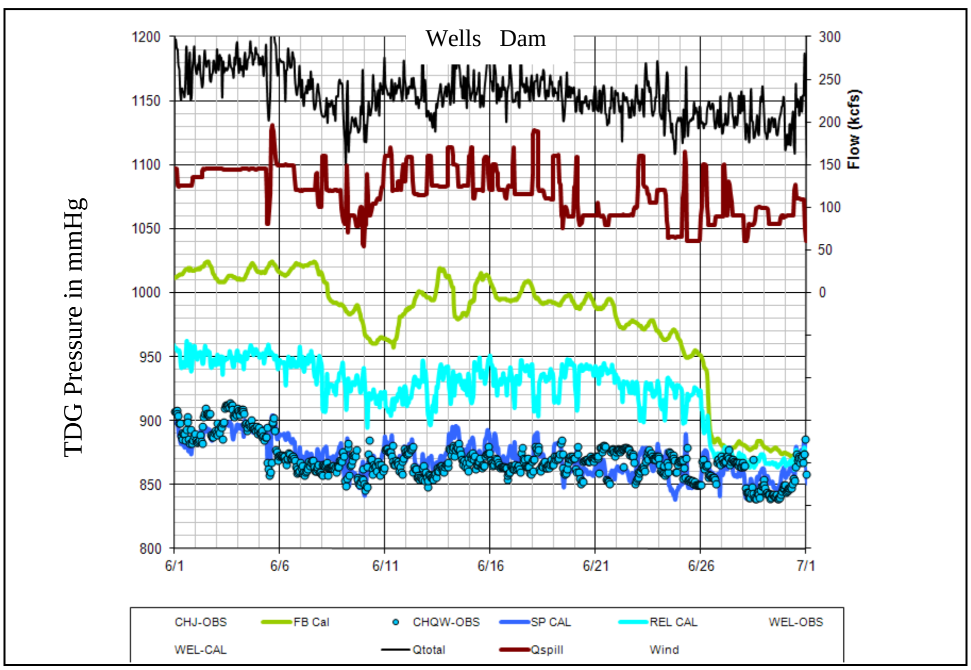

Figure G34. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of Chief Joseph Dam, June 2011 (Green line observed forebay TDG pressures, REL-CAL flow weighted average TDG pressure downstream of CHJ)

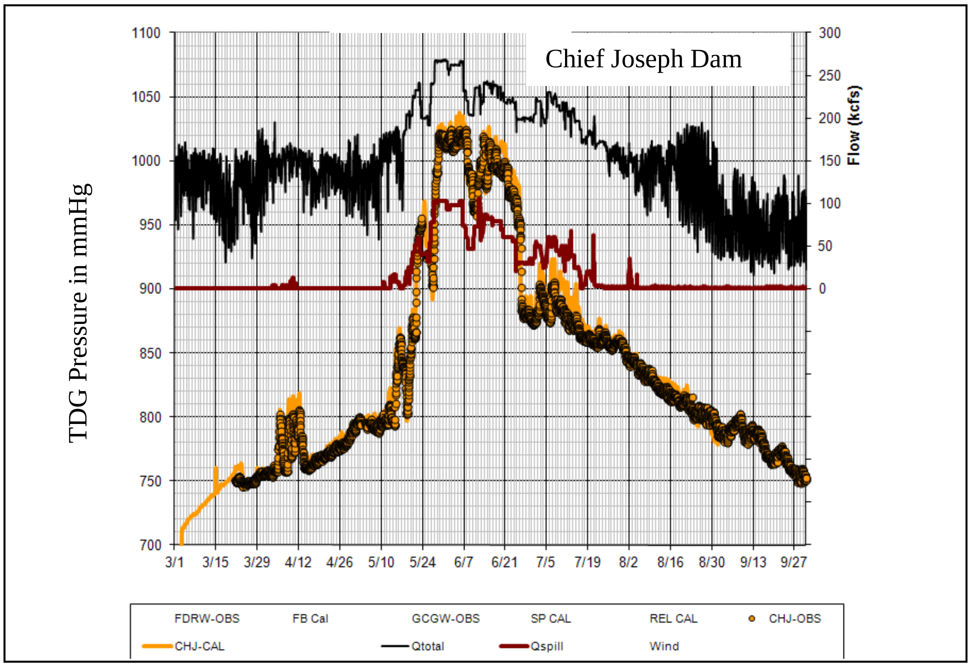

Figure G35. Observed and Calculated TDG Pressures in the Columbia River in the forebay of Chief Joseph Dam, March-September 2011

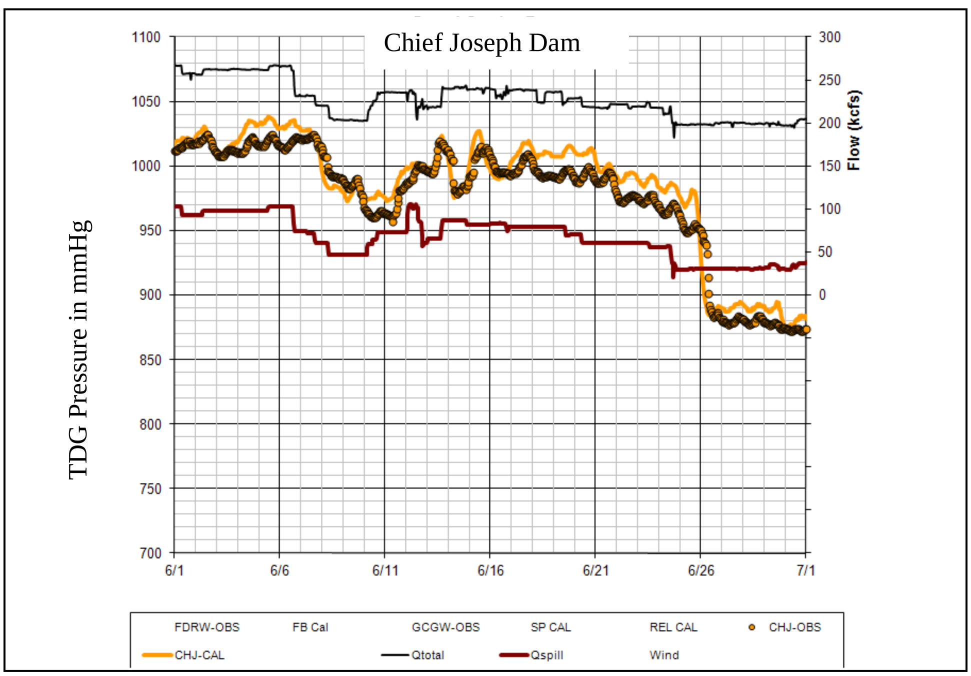

Figure G36. Observed and Calculated TDG Pressures in the Columbia River in the forebay of Chief Joseph Dam, June 2011

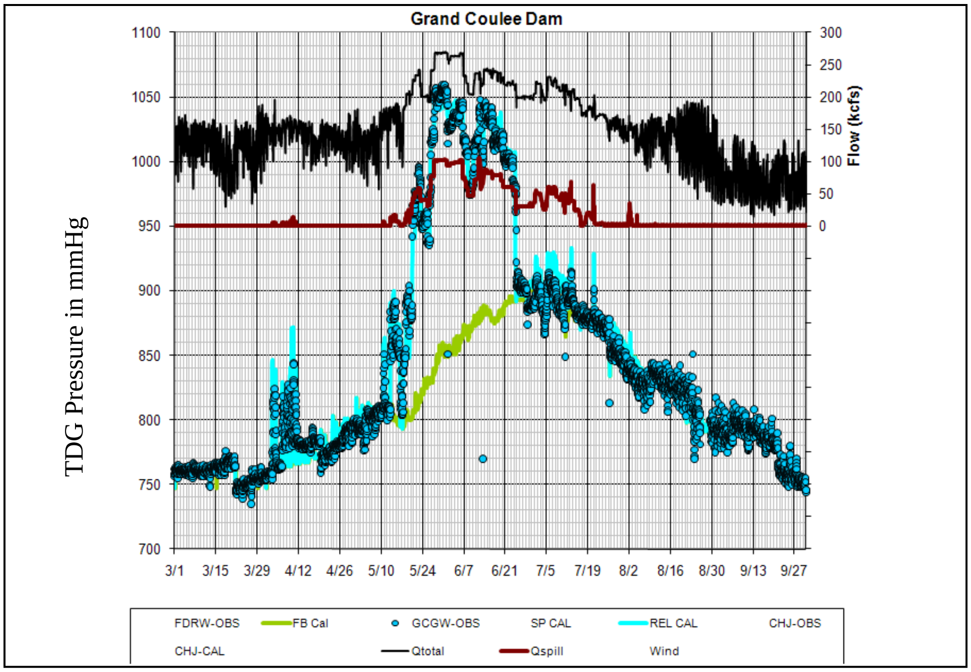

Figure G37. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of Grand Coulee Dam, March-September 2011

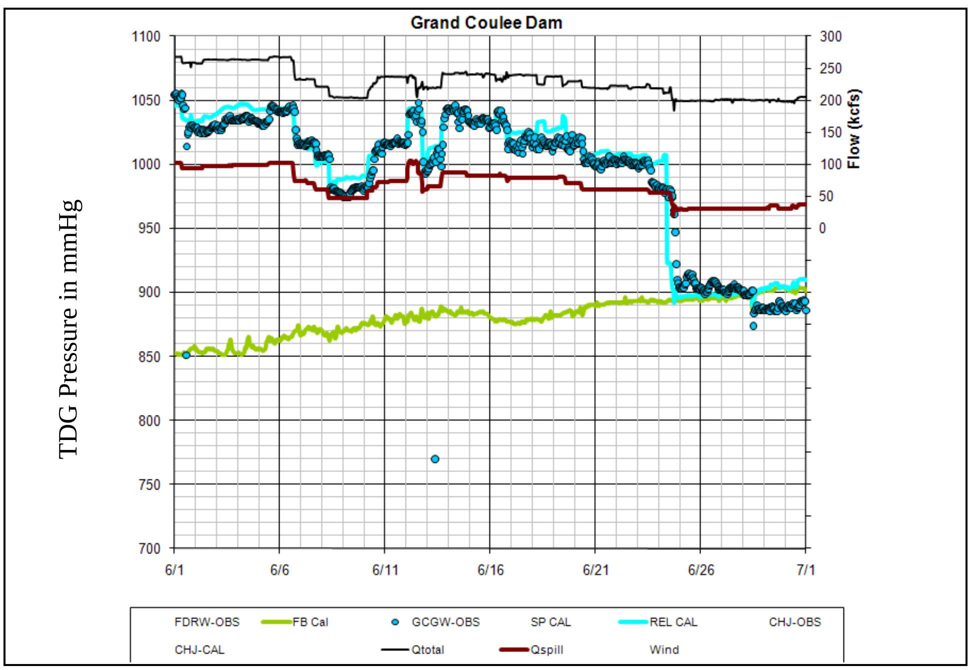

Figure G38. Observed and Calculated TDG Pressures in the Columbia River in the tailwater of Grand Coulee Dam, June 2011 (June 24 change over from regulating outlet to drum gate spill)

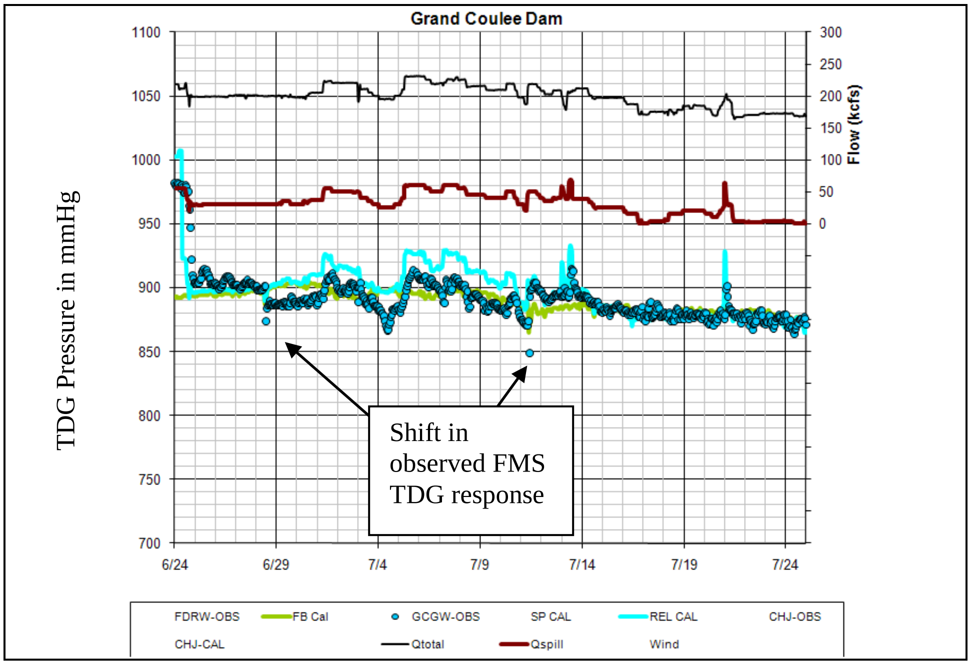

Figure G39. Observed and Calculated TDG Pressures in the Columbia River in the Tailwater of Grand Coulee Dam, June 24-July 24, 2011 (Drum gate spill began at Grand Coulee Dam on June 24)

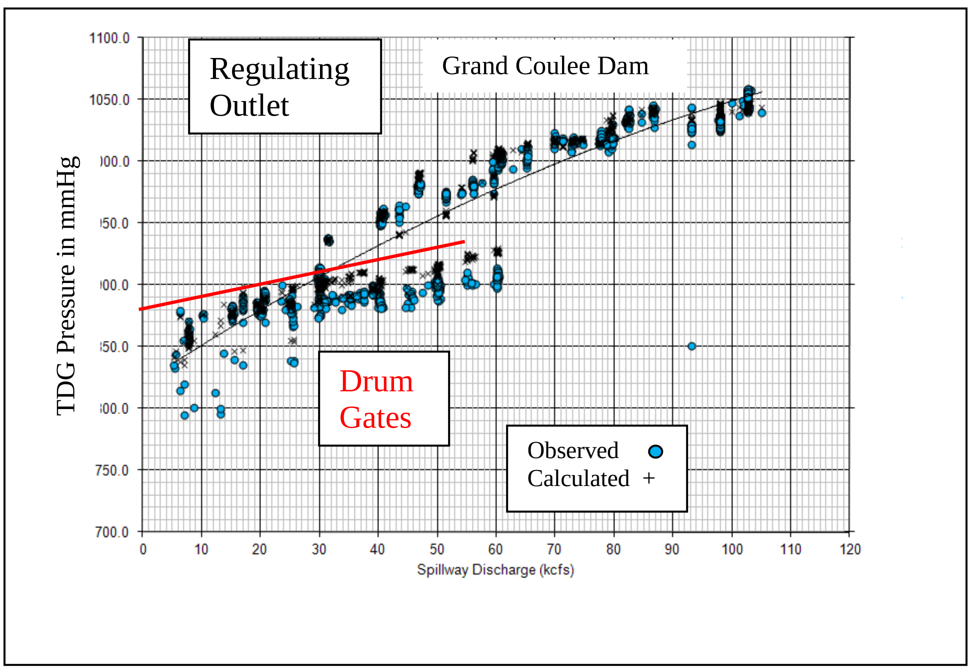

Figure G40. Observed and Calculated TDG Pressure in the Columbia River below Grand Coulee Dam as a Function of Spillway Flow, 2011

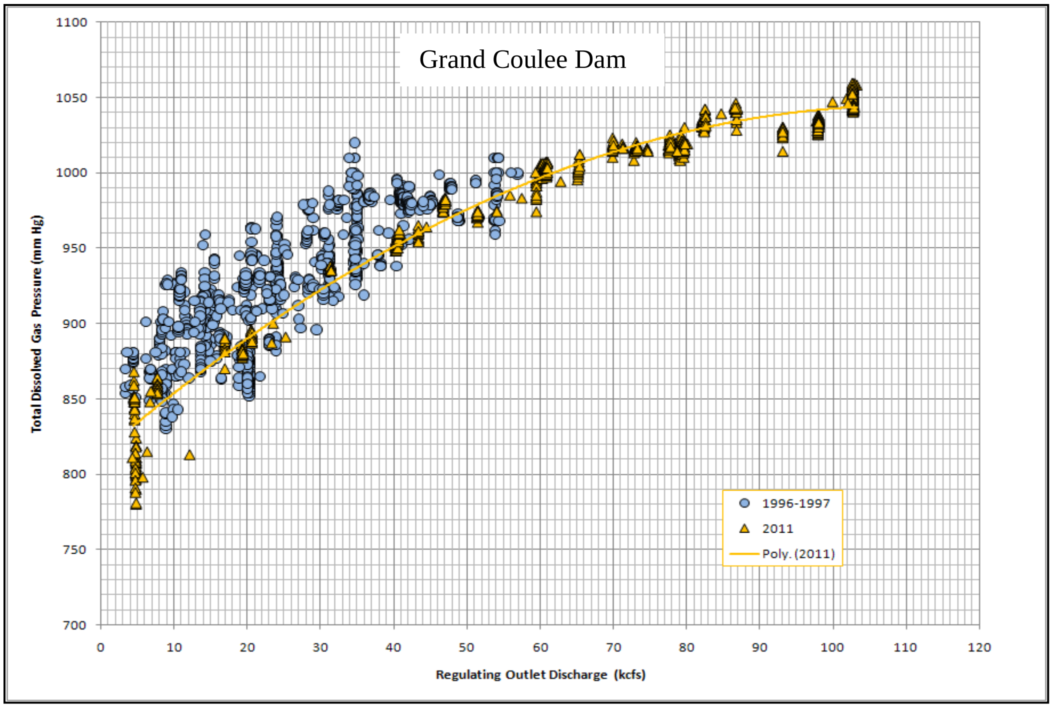

Figure G41. Observed and Calculated TDG Pressure in the Columbia River below Grand Coulee Dam as a Function of Spillway Flow, 1996, 1997, and 2011

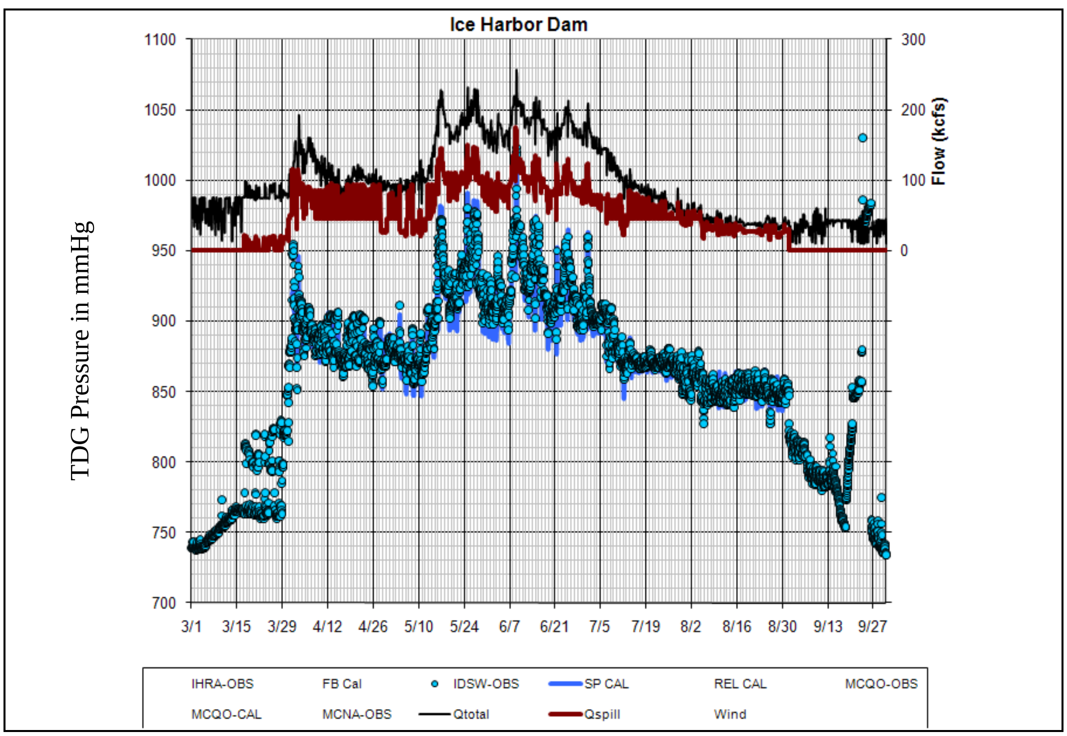

Figure G42. Observed and Calculated TDG Pressures in the Snake River in the tailwater downstream from Ice Harbor Dam, March-September 2011

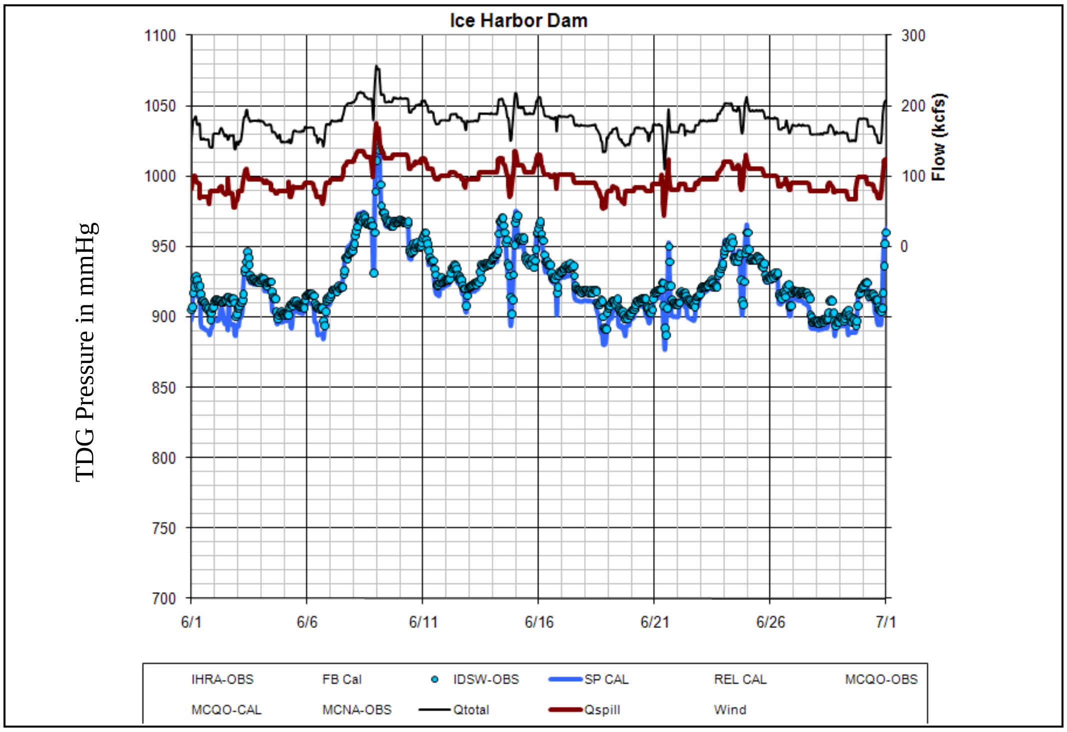

Figure G43. Observed and Calculated TDG Pressures in the Snake River in the tailwater downstream from Ice Harbor Dam, June 2011

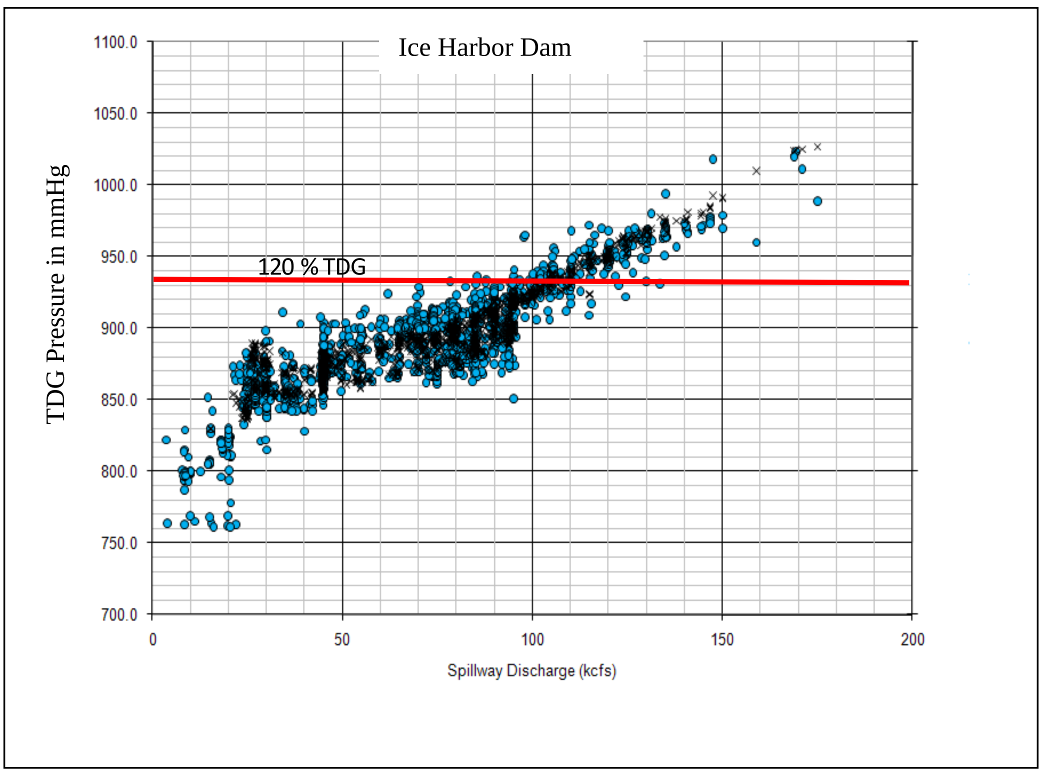

Figure G44. Observed and Calculated TDG Pressure in the Snake River below Ice Harbor Dam as a Function of Spillway Flow, 2011

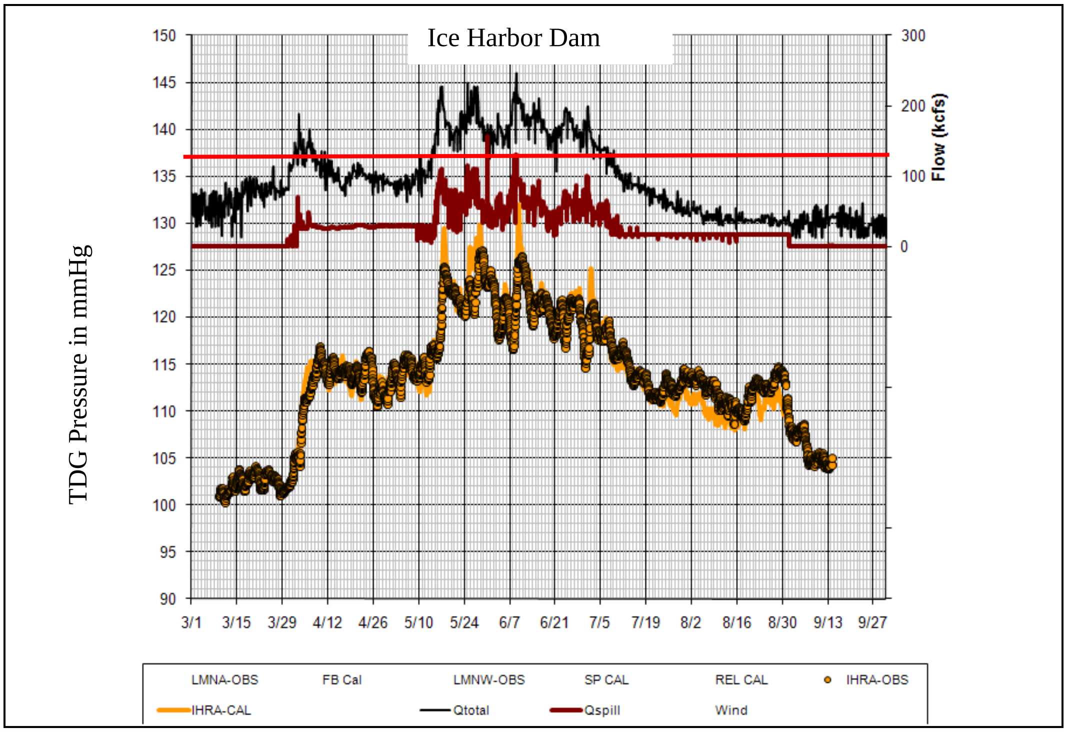

Figure G45. Observed and Calculated TDG Pressures in the Snake River in the forebay of Ice Harbor Dam, March-September 2011

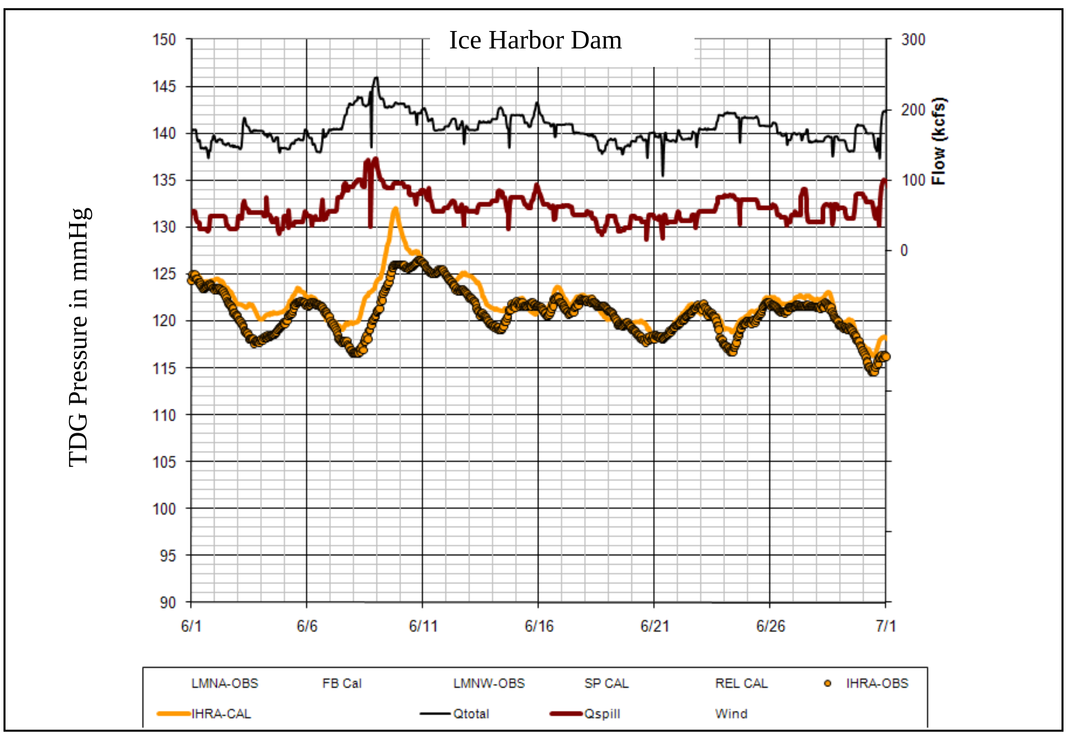

Figure G46. Observed and Calculated TDG Pressures in the Snake River in the forebay of Ice Harbor Dam, June 2011

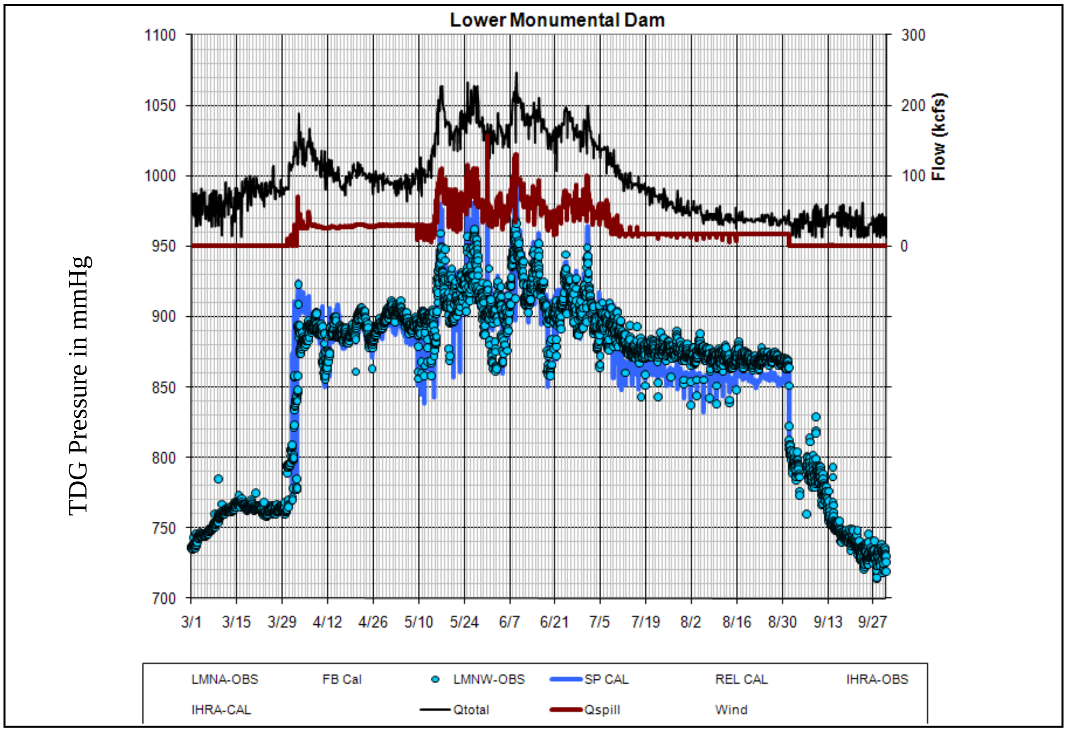

Figure G47. Observed and Calculated TDG Pressures in the Snake River in the tailwater channel downstream from Lower Monumental Dam, March-September 2011

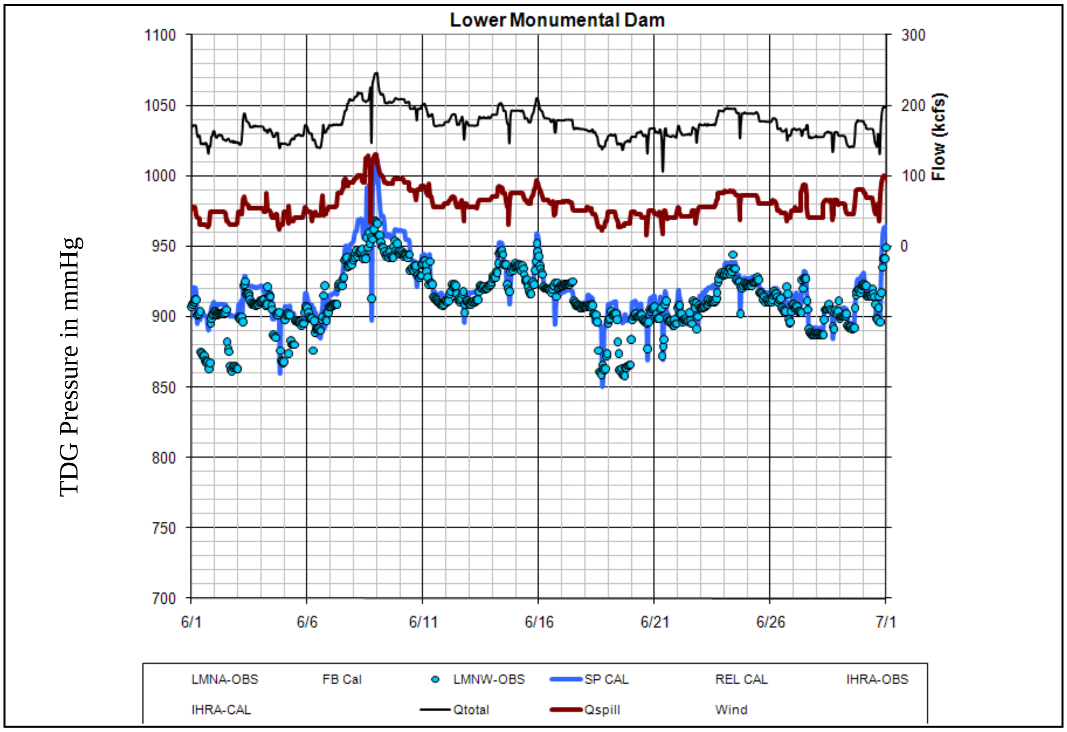

Figure G48. Observed and Calculated TDG Pressures in the Snake River in the tailwater channel downstream from Lower Monumental Dam, June 2011

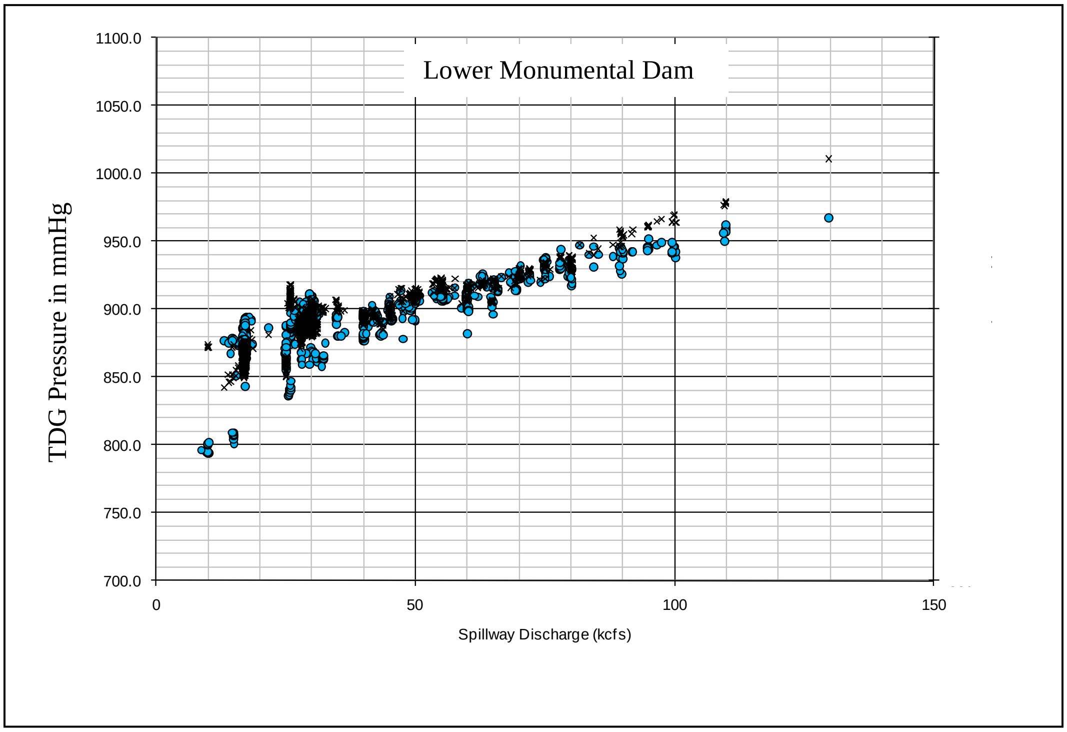

Figure G49. Observed and Calculated TDG Pressure in the Snake River below Lower Monumental Dam as a Function of Spillway Flow, 2011

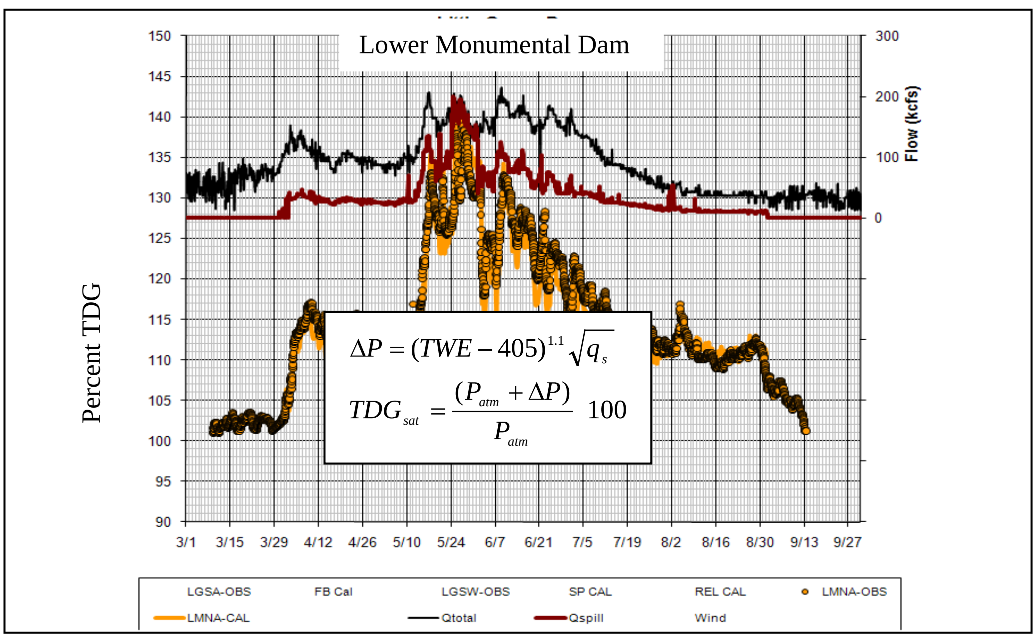

Figure G50. Observed and Calculated Percent TDG in the Snake River in the forebay of Lower Monumental Dam, March-September 2011

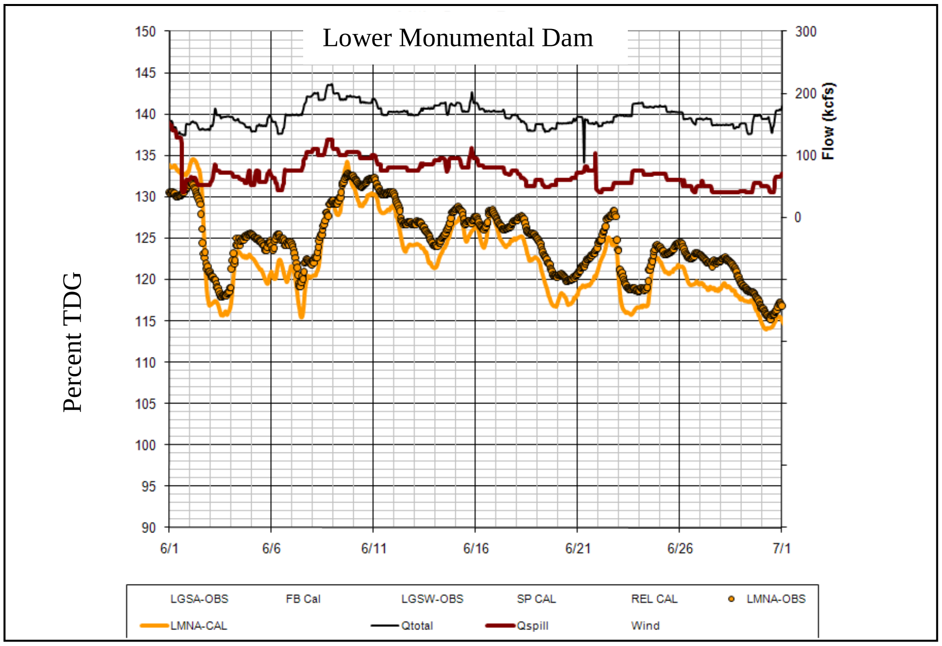

Figure G51. Observed and Calculated Percent TDG in the Snake River in the forebay of Lower Monumental Dam, June 2011

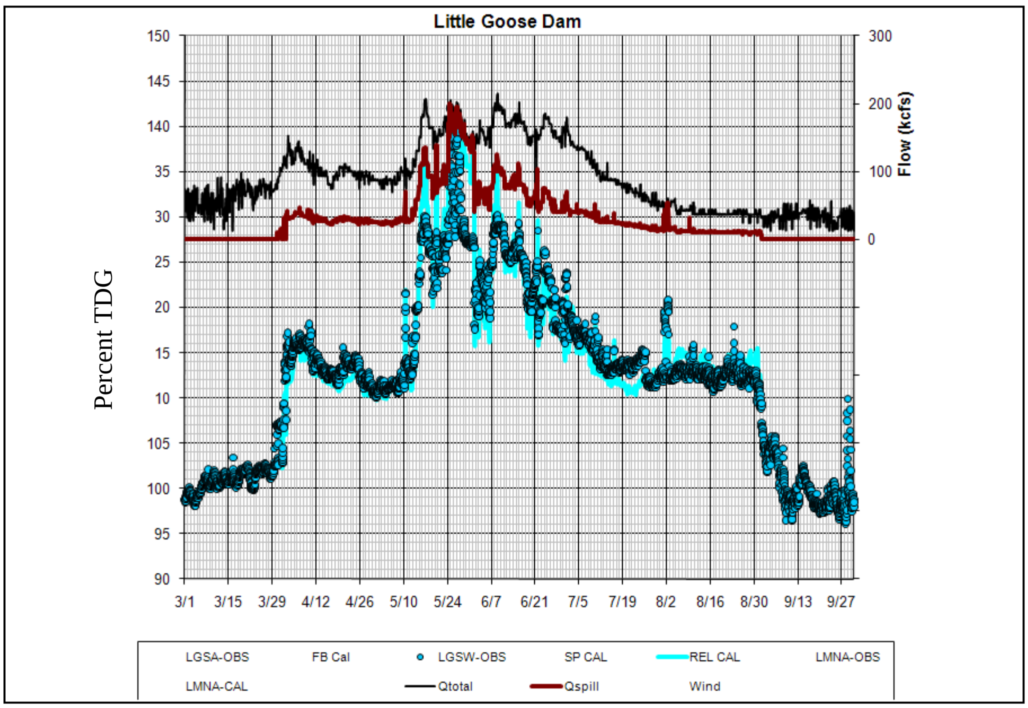

Figure G52. Observed and Calculated Percent TDG in the Snake River in the tailwater channel downstream from Little Goose Dam, March-September 2011

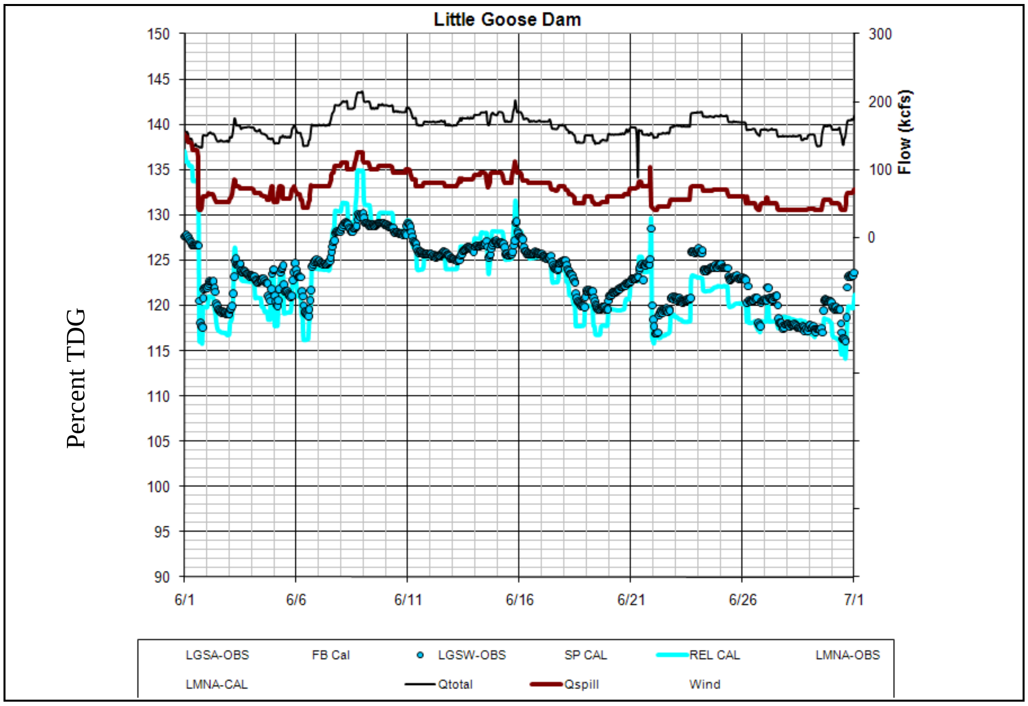

Figure G53. Observed and Calculated Percent TDG in the Snake River in the tailwater channel downstream from Little Goose Dam, June 2011

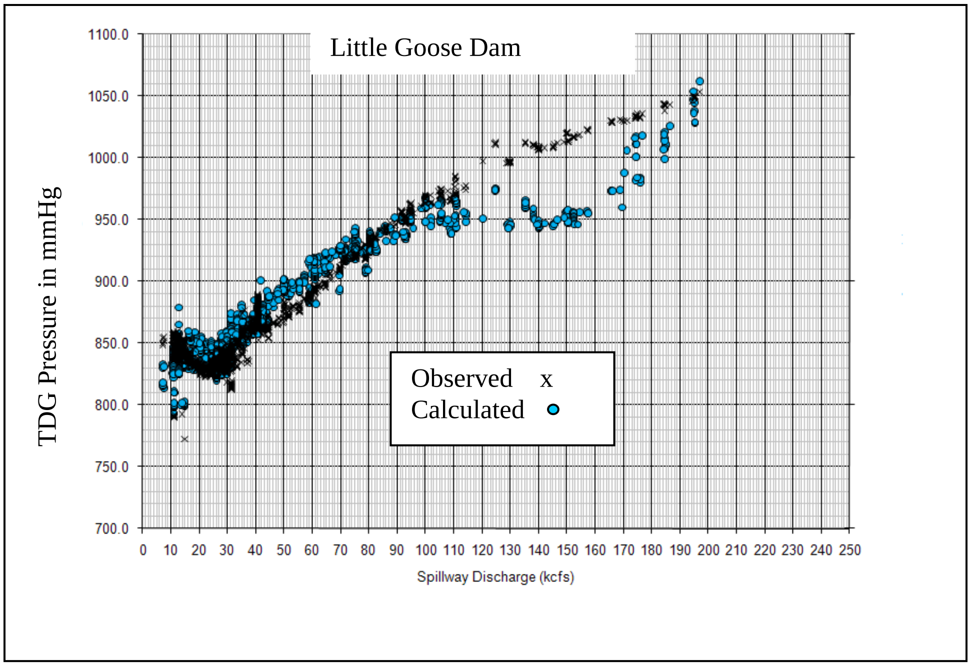

Figure G54. Observed and Calculated TDG Pressures as a Function of Spillway Flow in the Snake River at the tailwater channel downstream from Little Goose Dam, 2011

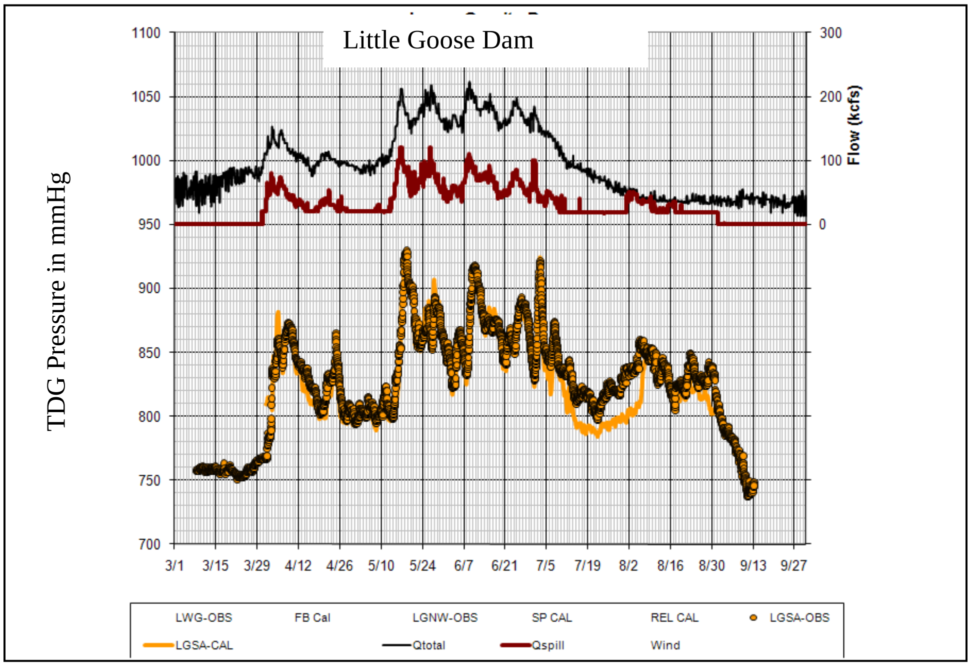

Figure G55. Observed and Calculated TDG Pressures in the Snake River in the forebay of Little Goose Dam, March-September 2011

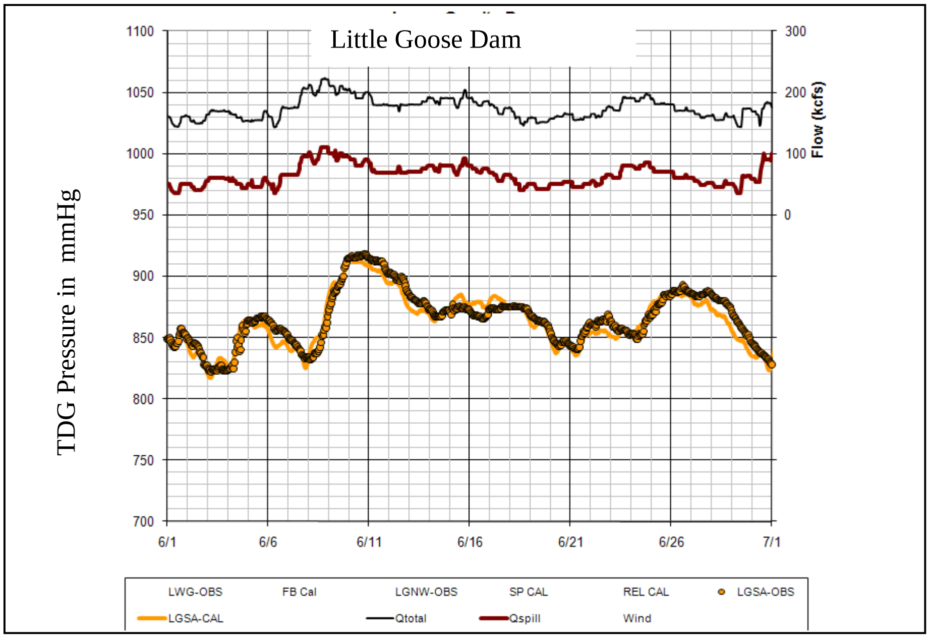

Figure G56. Observed and Calculated TDG Pressures in the Snake River in the forebay of Little Goose Dam, June 2011

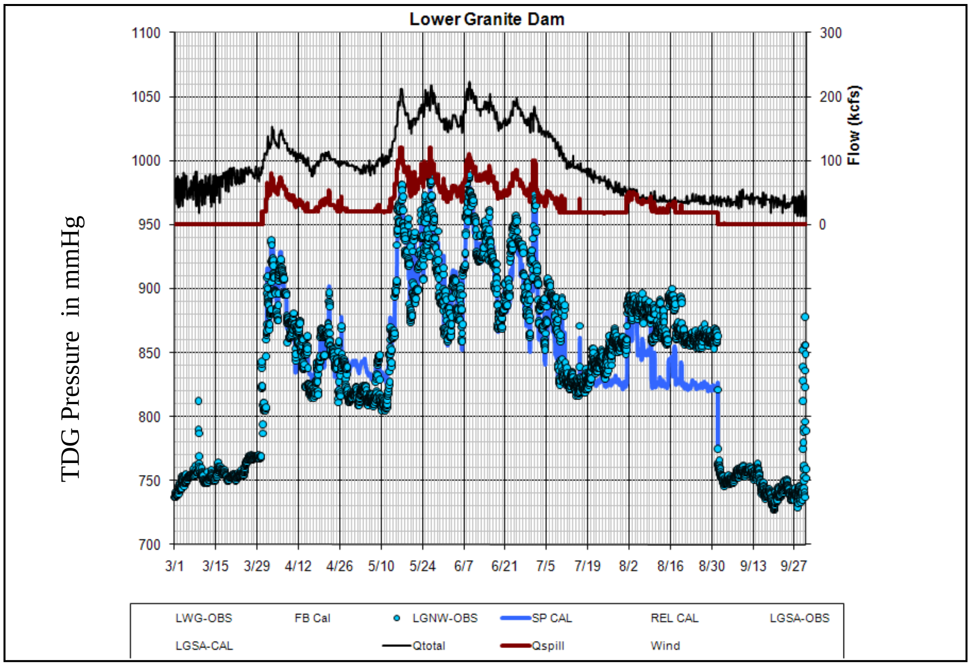

Figure G57. Observed and Calculated TDG Pressures in the Snake River in the tailwater channel downstream from Lower Granite Dam, March-September 2011

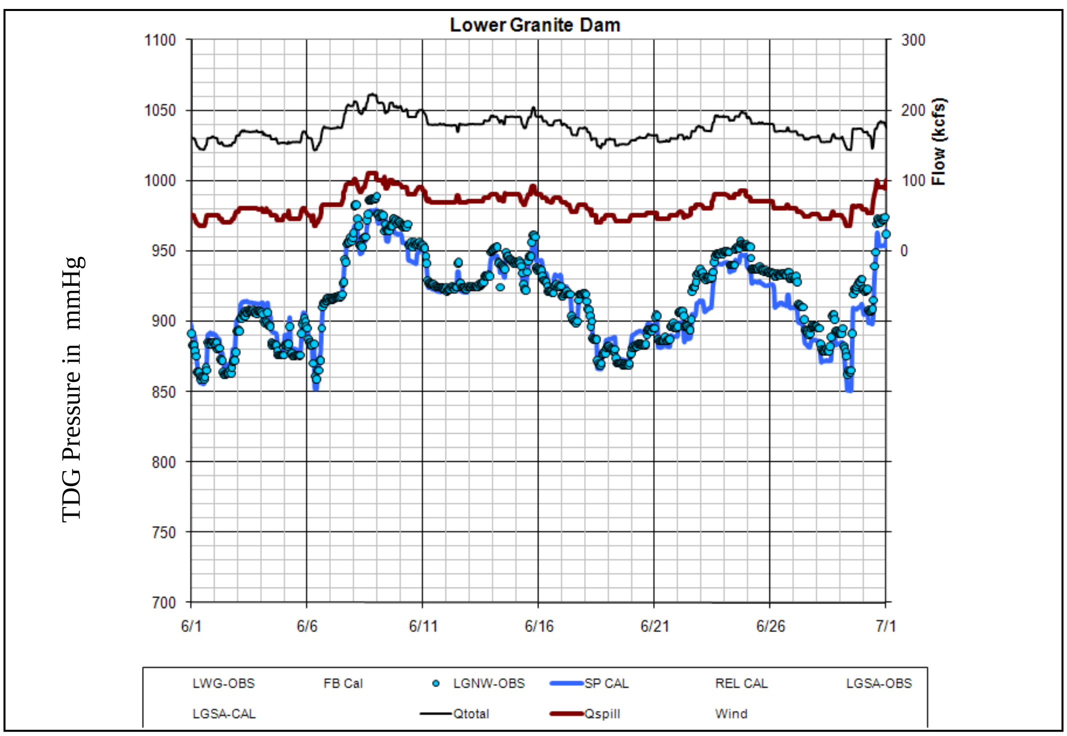

Figure G58. Observed and Calculated TDG Pressures in the Snake River in the tailwater channel downstream from Lower Granite Dam, June 2011

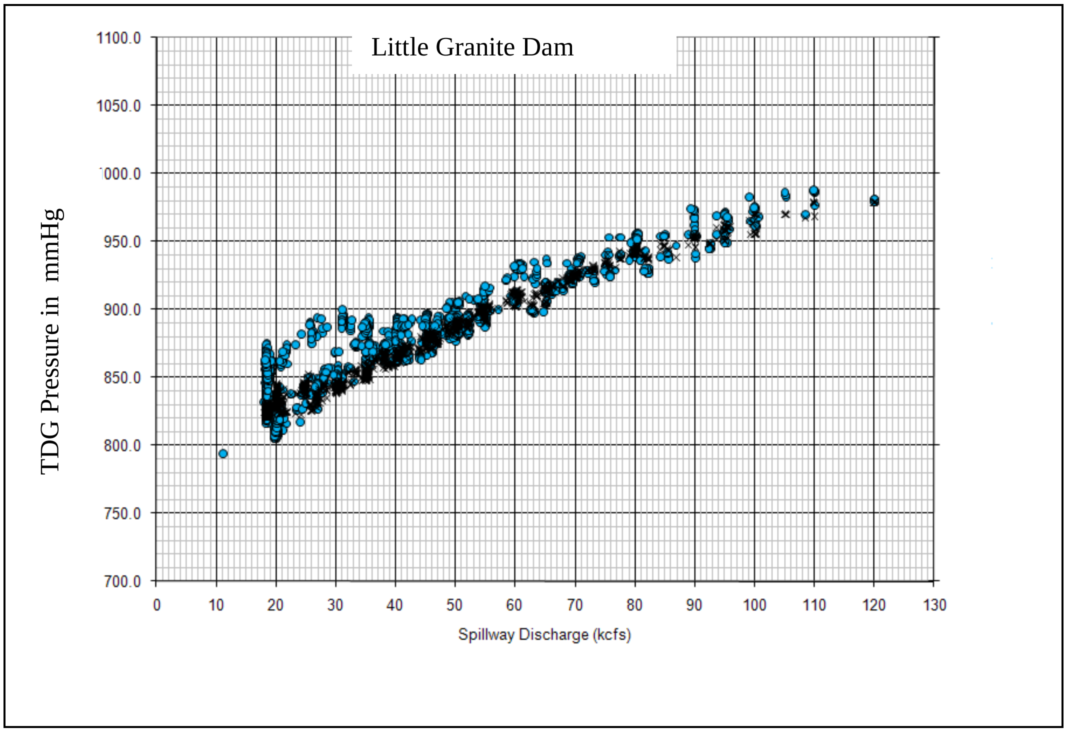

Figure G59. Observed and Calculated TDG Pressures in the Snake River below Lower Granite Dam as a Function of Spillway Flow, 2011

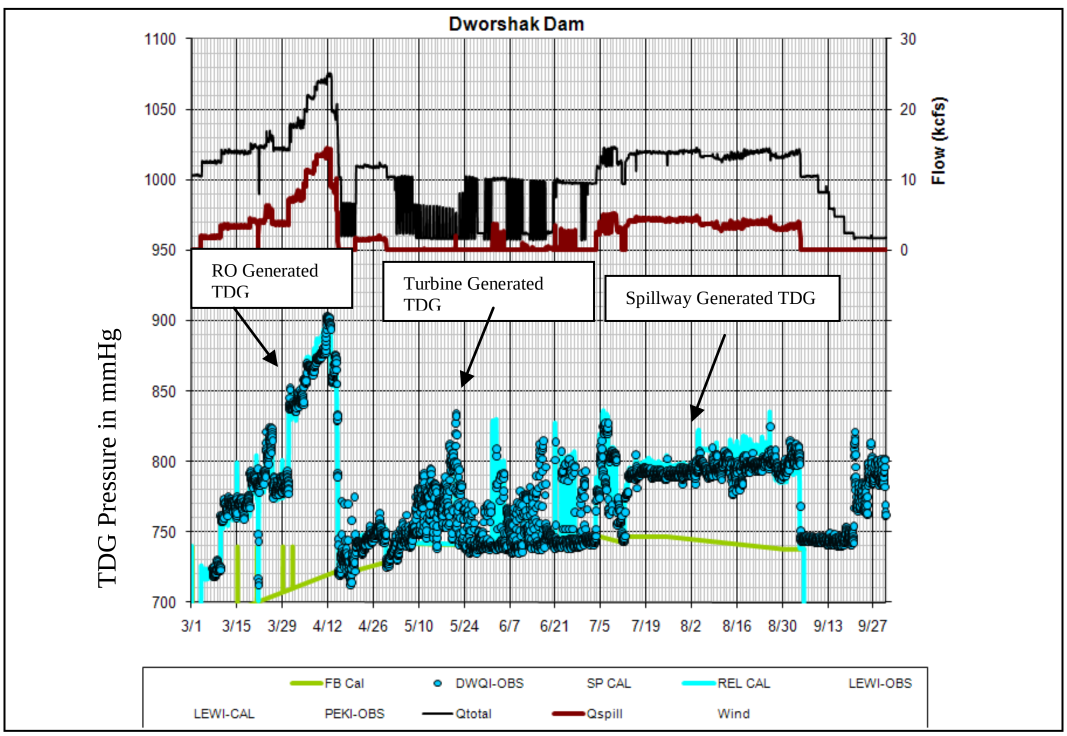

Figure G60. Observed and Calculated TDG Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, March-September 2011

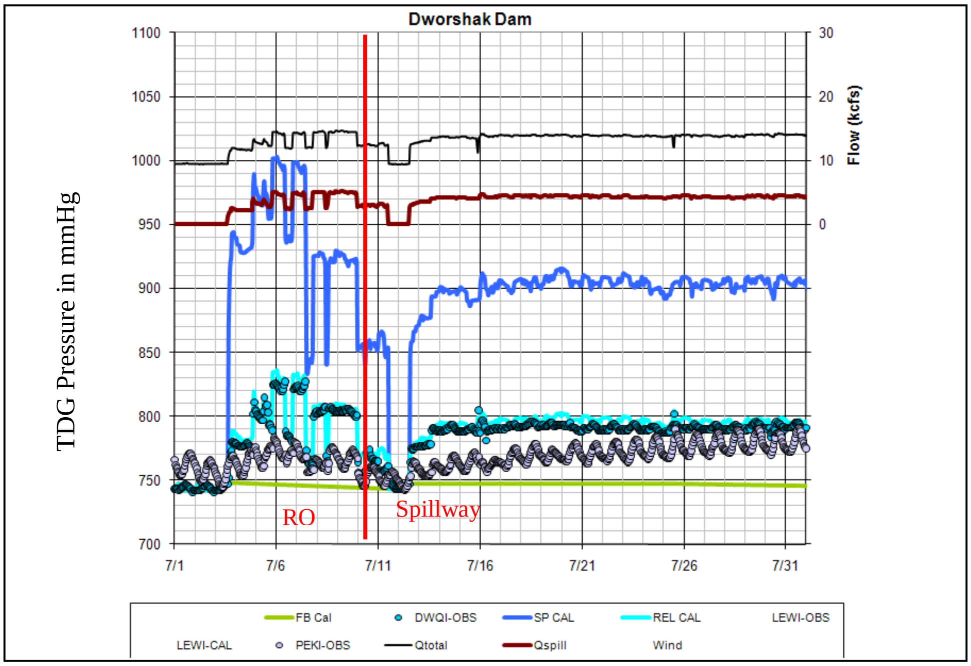

Figure G61. Observed and Calculated TDG Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, July 2011

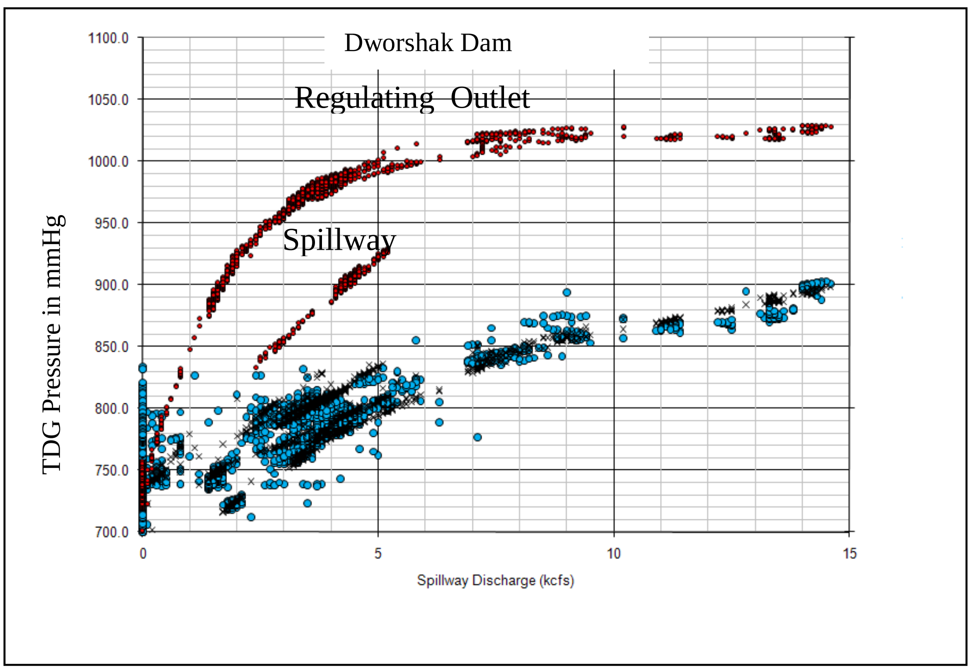

Figure G62. Observed and Calculated TDG Pressure in the Clearwater River below Dworshak Dam as a Function of Spillway Flow, 2011 (Red-TDGsp-cal, Blue-TDGavg-obs, Black=TDGavg-cal)