APPENDIX G

SYSTDG STATISTICAL EVALUATION

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Introduction

SYSTDG (System Total Dissolved Gas) is a decision support spreadsheet model used to estimate total dissolved gas (TDG) saturations and pressures resulting from main stem dam operations on the Columbia, Snake, and Clearwater Rivers. A statistical evaluation of the predictive errors was performed comparing observed and calculated TDG levels during the 2010 fish passage season on the Columbia and Snake Rivers in an effort to quantify the uncertainty of SYSTDG estimates and improve modeling accuracy and reliability. This evaluation was extended to include 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 2010 fish passage 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 hydro-power operated dams within the Columbia Basin. The dams of interest included Bonneville Dam, The Dalles Dam, John Day Dam, McNary Dam, Ice Harbor Dam, Lower Monumental Dam, Little Goose Dam, Lower Granite Dam, Dworshak Dam, Chief Joseph Dam, and Grand Coulee Dam.

Approach

SYSTDG simulations were run for the entire 2010 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 saturation 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 releases. In most cases, the tailwater FMS are located in either spillway flows undiluted from powerhouse flows or 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-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 TDG saturation. 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 calculated predictive errors consist of components attributed to the numerical modeling of system properties, operational settings, and the sampling errors introduced

from the FMS. One common source of error at tailwater FMS is the lagged response of TDG pressures to the change in spill operation. Depending upon the location of the tailwater FMS, it may take up to 5 hours for a TDG response, from a given operation at a dam, to show up 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. 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. In some cases, the spill patterns as established in the 2010 fish passage plan or auxiliary spill patterns were not implemented as scheduled at the dam. In some cases, alternative spill patterns were developed after the 2010 fish passage plan was completed. The model predictions are dependent upon the number of spillway bays that were active for any spill operation. The SYSTDG simulations for 2010 applied the appropriate spill patterns as defined in the fish passage plan for spring and summertime operations. 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 2-3 percent increase in the TDG saturation. 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. The challenge in reviewing the properties of the modeling errors is to determine the source of this error, and whether the error represents an estimate bias or misrepresentation of conditions from a modeling framework.

Background

The Columbia River flows in 2010 were concentrated during the month of June with when high flows occurred. The average months Columbia River flows at The Dalles Dam were the smallest on record since 1975 during the first three months of the year. The monthly flows in April and May were well below normal as shown in Figure G1 falling in the 90 plus exceedance frequency range. The box and whisker flow frequency plot shown in Figure G1 graphically identifies the monthly average flows associated with 10, 25, 50, 75, and 90 percentiles. The June runoff at The Dalles Dam averaged about 316 kcfs or well above the hydraulic capacity of the powerhouses of dams located on the lower Columbia River. These high sustained June flows resulted in periods of involuntary spill at both Columbia River and Snake River Dams with TDG saturations in excess of state water quality standards (WQS) of 120 percent in the tailwater FMSs. The monthly flows in June were above average ranking the 11th highest monthly flow since 1975. The 2010 flows during the summer months dropped quickly with near normal flows observed in July, and below average flows in August.

On the lower Columbia River, the highest percentage of total river flow spilled from April 1 through August 31 of about 47.2 percent, occurred at Bonneville Dam. The higher spill rate at Bonneville Dam resulted from the greater commitment for spill to aid fish passage during the summer months. A statistical summary of the hourly project

operations in the lower Columbia River are shown in Table G1 for the period of April 1-August 31. The average spill at Bonneville Dam was 91.7 kcfs compared to 85.5 kcfs at McNary Dam, 68.4 kcfs at The Dalles Dam, and 61.6 kcfs at John Day Dams. The highest hourly spill of 230.0 kcfs occurred at McNary Dam. The spill operations at Priest Rapids Dam during 2010 (26.2% river spilled) resulted in much lower spill volumes and TDG saturation levels entering the McNary Pool compared to the TDG levels from the Snake River. The average flows at The Dalles of 180.7 kcfs were well below the observed project flows at John Day Dam of 189.9 kcfs even with the additional flows contributed by the Deschutes River suggesting an imbalance in the water budget in these reported records.

Table G1. Statistical Summary of Hourly Project Flows from April 1-August 31, 2010 on the Lower Columbia River

Project		Bonneville		The Dalles		John Day		McNary		Priest Rapids	
		Qtotal (kcfs)*	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)
Number of Observations		3672	3672	3672	3672	3672	3672	3672	3672	3672	3672
Average		194.2	91.7	180.7	68.4	189.9	61.5	189.2	85.5	121.6	31.8
Standard Deviation		79.1	35.5	83	33.8	87.7	34.5	80.5	46.2	52.3	30.8
Maximum		401.9	200.8	415.9	147.2	425.6	147.1	395.7	230	285.7	160.6
Minimum		82.9	0	54.8	0	54.5	0	55.1	0	37.6	0
Q_{spill}/Q_{total}			47.20%		37.80%		32.40%		45.20%		26.20%
Percentile	**1%**	94.5	0	75.4	0	73.7	0	75.9	0	39.7	0
	5%	108.2	2.4	92.9	0	90.8	0	93.8	0	51.6	0
	25%	119.7	74.7	114.3	43.4	118.1	35.2	120.7	56.5	81.3	23.1
	50%	174.8	94.1	159.3	63.9	167.7	54.5	172.1	76	115.6	25.8
	75%	233.7	99.7	222.3	88.6	237.2	84.2	235.9	102.9	148.5	27.4
	95%	353.3	168.5	353.5	132	367	125	345.2	170.2	229.1	106.2
	99%	394.5	194.2	384.8	138	399.8	143.9	391.1	229.9	253.1	129.9

*Units kcfs except for Q_{spill}/Q_{total} entry.

On the Middle Columbia River, the average flows from April 1 through August 31 were slightly greater than half the Columbia River flow observed at The Dalles Dam. The spill events that occurred at Chief Joseph and Grand Coulee dams were chiefly due to involuntary spill and lack of load conditions. Although the volume of water spilled at these two projects was small relative to the amount spilled in the lower Columbia River, the level of spill was well above historic levels. A statistical summary of the hourly project operations in the middle Columbia River are shown in Table G2 for the period of April 1- August 31 for Wells, Chief Joseph, and Grand Coulee dams. The average spill at Wells Dam was nearly twice the spill rate at Chief Joseph and Grand Coulee dams due to the commitment of a sustained fish spill for much of this period. The average spill rate at Chief Joseph of 5.7 kcfs was slightly larger than the spill at Grand Coulee Dam of 4.4 kcfs. The spill at Chief Joseph and Grand Coulee Dams took place mainly during the month of June with peak hourly spill rates of 107.6 and 75.1 kcfs respectively. What this shows is that Chief Joseph spilled significantly more than Grand Coulee in 2010. The spill at Grand Coulee Dam was passed over the drum gates during the 2010 spill season.

Table G2. Statistical Summary of Hourly Project Flows from April 1-August 31, 2010 on the Middle Columbia River

Project		Wells		Chief Joseph		Grand Coulee	
		Qtotal (kcfs)*	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)	Qtotal (kcfs)	Qspill (kcfs)
N		3672	3672	3672	3672	3672	3672
Average		111.8	10.2	101.2	5.7	100.5	4.4
Standard Deviation		55.4	12.4	50.8	17.3	51.1	12.9
Maximum		268.6	113.8	266.3	107.6	260.3	75.1
Minimum		13	0	0	0	12.3	0
$\mathbf{Q_{spill}/Q_{total}}$			9.10%		5.60%		4.30%
Percentile	**1%**	18.1	0	21.6	0	23.3	0
	5%	27.2	0	30	0	31.8	0
	25%	67.6	4.8	55.4	0	56.5	0
	50%	111	7.8	97.6	0	93.4	0
	75%	148.8	10	143.5	0	139.9	0
	95%	211.9	41.1	187.7	44.9	193.3	35.1
	99%	232.5	66.7	206.5	99.7	216.7	60.3

*Units kcfs except for $\mathbf{Q_{spill}/Q_{total}}$ entry.

The Snake River contributed about 33.2 percent of the flow to the lower Columbia River during the April 1- August 31, 2010 period. Ice Harbor spilled about 56.8 percent of the Snake River flow during this period compared to 37.8, 31.0, and 37.8 percent for Lower Monumental, Little Goose, and Lower Granite Dams, respectively as listed in Table G3. The higher spill rate at Ice Harbor Dam was governed by the higher spillway capacity as limited by the TDG levels at the tailwater FMS, hydraulic capacity of the powerhouse, and the spill operation as outlined in the fish passage plan. The largest hourly spill of 152.3 kcfs occurred at Ice Harbor Dam during the 2010 spill season. The spill volume at Little Goose Dam was less than those scheduled at Lower Monumental and Ice Harbor Dams because of the fish spill operation implemented at the project. The spill at Dworshak Dam was intermittent during the study period during the 2010 and was scheduled during July and August to help manage Snake River flows and temperatures during this period. Flows in excess of powerhouse capacity at Dworshak Dam were passed exclusively through the regulating outlets. The highest spill rate at Dworshak Dam was 5.0 kcfs.

Table G3. Statistical Summary of Hourly Project Flows from April 1-August 31, 2010 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 Observations		3672	3672	3672	3672	3672	3672	3672	3672	3672	3672
Average		62.9	35.7	61.4	23.2	61.4	19.1	62.9	23.8	6.1	0.5
Standard Deviation		42	25	41.4	15.1	39.3	15	40.6	18.8	4.5	1.1
Maximum		233.7	152.3	236.6	119.8	210.3	99.8	218.2	125.9	14.5	5
Minimum		10.7	0	12.9	0	17.2	0	16.6	0	1.1	0
Q_{spill}/Q_{total}			56.80%		37.80%		31.00%		37.80%		8.60%
Percentile	**1%**	21.7	0	22	0	23.5	0	23.8	0	1.1	0
	5%	24	13.2	23.7	10.1	24.1	7.2	25.3	11.6	1.1	0
	25%	33.9	18	32.6	17.2	35.9	10.9	33.1	18.6	1.2	0
	50%	52.2	28.1	49.7	17.5	49	14.6	50.8	18.9	6.9	0
	75%	75.4	45.1	74.4	26.9	74.1	22.1	75.7	20.6	10.1	0
	95%	160.4	93.3	153.9	42.9	150.3	44	160.2	69.7	12.9	3.1
	99%	211.8	130.1	210.6	95.1	195.6	85.5	202.4	110.7	13.6	3.9

*Units kcfs except for Q_{spill}/Q_{total} entry.

The TDG saturation was monitored in the forebay and tailwater of each lower Columbia River dams throughout the spill season of 2010. The seasonal statistics of the observed TDG saturation at each FMS over the spill season provides a general perspective on the spatial properties for this type of water year, operational policy, and structural configuration. The average hourly TDG saturation in the forebay of each dam ranged from a high of 109.1 at Bonneville Dam to a low of 106.2 percent at John Day Dam (Table G4). The average TDG saturation at Camas/Washougal FMS (CWMW) located about 22 miles downstream of Bonneville Dam in mixed water and grouped with other forebay FMSs, was slightly higher at 112.8 percent as listed in Table G4. The frequency of hourly observations greater than 115 percent at forebay FMSs ranged from 24.9 percent at CWMW to a low of 0.1 percent in the forebay of John Day Dam. The TDG saturation exceeded 120 percent only at CWMW.

The average TDG saturation at the tailwater FMSs ranged from 116.3 percent at Bonneville to 113.5 percent at The Dalles and John Day dams (Table G4). The tailwater FMS at The Dalles Dam reflects the contributions from both powerhouse and spillway flows unlike the other three projects where the tailwater FMS monitors the TDG content in spillway flows undiluted from powerhouse flows. The frequency of hourly TDG observations exceeding 120 percent at the tailwater FMSs ranged from 14.0 percent below Bonneville Dam to 0.0 percent at John Day Dam. The likelihood of the TDG saturation at tailwater FMS exceeding the 120 percent level was less than the frequency of the next downstream forebay FMS exceeding 115 percent at all the Lower Columbia River projects during the 2010 fish passage season. These summary TDG statistics were based on hourly observations and not daily statistics composed of the highest 12 hourly observations or a consecutive 12 hour average as referenced by the state WQS in Oregon and Washington.

Table G4. Statistical Summary of Hourly TDG Saturation at FMS from April 1-August 31, 2010 on the Columbia River

FMS		Bonneville				The Dalles		John Day		McNary	
		CWMW	WRNO	CCIW	BON	TDDO	TDA	JHAW	JDY	MCPW	MCNA
		FB	TW	TW	FB	TW	FB	TW	FB	TW	FB
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Number of Observations		3672	3672	3672	3671	3672	3653	3672	3672	3652	3672
Average		112.8	114.9	116.3	109.1	113.5	108.1	113.5	106.2	115.3	108.6
Standard Deviation		3.1	2.4	3.2	4.1	3.4	3.1	3.8	3.6	4.2	3.7
Maximum		120.5	122.1	124.3	118.3	121.3	115.3	120	116.4	125.8	118.6
Minimum		102.8	106.1	108.4	100.5	99.9	101	99.3	98.9	99	100.7
TDG Exceedance (%)*	**100**	100	100	100	100	100	100	100	99.7	99.8	100
	105	98.1	100	100	80.4	94.4	81.5	94.2	61	94.1	79.8
	110	85.2	94.5	98.4	46	91.6	30.6	90	18.4	94	35.2
	115	24.9	54.2	63.4	7.5	35.8	0.1	29.2	0.5	59.2	6.8
	120	0.2	0.8	14.5	0	0.4	0	0	0	9	0
	125	0	0	0	0	0	0	0	0	0.1	0
	130	0	0	0	0	0	0	0	0	0	0

*Percent of hourly TDG observations exceeding the reference level saturation from April-August, 2010.

The TDG saturation was monitored in the forebay and tailwater of each lower Snake River dam throughout the spill season of 2010 and a statistical summary was conducted of these observations. The average hourly TDG saturation in the forebay of each Snake River dam increased in a downstream direction as listed in Table G5. The average forebay TDG saturation at Lower Granite, Little Goose, Lower Monumental, and Ice Harbor Dams were 102.3, 109.3, 110.0, and 112.2 percent, respectively. The frequency of exceeding 115 percent saturation in the forebay of the Snake River Dams ranged from 0 percent at Lower Granite Dam to a maximum of 19.0 percent at Ice Harbor Dam. The frequency of hourly TDG saturation exceeding 115 percent was also elevated at Lower Monumental and Little Goose Dams during the 2010 fish passage season.

Table G5. Statistical Summary of Hourly TDG Saturation at FMS from April 1-August 31, 2010 on the Columbia River

FMS		Wells		Chief Joseph		Grand Coulee		
		WELW	WEL	CHQW	CHJ	GCGW	FDRW	CIBW
		TW	FB	TW	FB	TW	FB	FB
		(%)	(%)	(%)	(%)	(%)	(%)	(%)
Number of Observations		3640	3196	3671	3672	3396	3655	3397
Average		108.8	108.3	108.5	107.7	107.6	108.5	110.5
Standard Deviation		5.8	3.3	3.8	3.4	3.6	3.8	7
Maximum		129.9	114.8	124.8	118.3	118.5	116.8	127.4
Minimum		93.1	101.6	101.6	101.1	100.5	100.8	100.8
TDG Exceedance (%) *	**100**	91.7	100	100	100	100	100	100
	105	86.6	78.4	77.3	74.1	66.3	88.1	80.9
	110	44.5	39.5	40.6	32.5	31.2	30.2	36.9
	115	9.8	0	3.2	0.8	1.1	10.6	23.7
	120	1.4	0	0.5	0	0	0	17
	125	0.2	0	0	0	0	0	3
	130	#N/A	0	0	0	0	0	0

*Percent of hourly TDG observations exceeding the reference level saturation from April-August, 2010.

The average TDG saturation at the tailwater FMSs ranged from 116.1 percent at Lower Monumental Dam to 111.4 percent at Little Goose Dam. The frequency of hourly TDG observations exceeding 120 percent at the tailwater FMSs ranged from a high of 9.0 percent below Lower Granite Dam to 4.3 percent at Little Goose Dam. The frequency of the forebay FMS exceeding the 115 percent criteria was greater than the frequency of the upstream tailwater FMS exceeding 120 percent which implies that forebay FMSs more frequently constrain spill operations on the Snake River than TDG conditions at tailwater FMSs.

Results

The following section presents a brief description of each simulation and a summary of the statistical analyses generated from each comparison. 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. Table G5 and Table G7 describe the predictive errors statistics in mm Hg of pressure while Table G6 and Table G8 describe the predictive errors in percent saturation. 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 with a duration of 4 hours and longer to exclude transient TDG observations.

Table G6. Statistical Summary of Hourly TDG Saturation at FMS from April 1-August 31, 2010 on the Snake and Clearwater River

Project		Ice Harbor		Monumental		Little Goose		Lower Granite		Dworshak	
FMS		IDSW	IHRA	LMNW	LMNA	LGSW	LGSA	LGNW	LWG	DWQI	PEKI
		TW	FB	TW	FB	TW	FB	TW	FB	TW	FB
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Number of Observations		3634	3671	3629	3671	3670	3672	3672	3671	3590	3666
Average		114.3	112.2	116.1	110	111.4	109.3	113.6	102.3	102.9	102
Standard Deviation		3.7	4.3	3.2	5.2	4	4.9	4.9	2	4.1	2.2
Maximum		130.4	125.7	128	129.7	128.3	126.2	133.8	109.7	111.1	109.8
Minimum		102.3	99.8	100.6	98.8	100.4	98.6	100.1	97.7	94.8	97.1
TDG Exceedance (%) *	100	100	99.8	100	99.3	100	97.8	100	89.2	64.1	83.7
	105	98.7	94.6	98.7	84.4	98.5	84.2	98.7	7.9	41.5	11.1
	110	92.2	72.7	98.6	53.3	66.3	40.2	85.9	0	0.7	0
	115	32	19	71.7	9.2	10	9.1	25.5	0	0	0
	120	6.1	3.3	6.4	5.2	4.3	4.7	9	0	0	0
	125	2.7	0.5	2	2.6	2.1	0.9	4.8	0	0	0
	130	0.1	0	0	0	0	0	2.4	0	0	0

*Percent of hourly TDG observations exceeding the reference level saturation from April-August, 2010.

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, 2010. A decision to change an off-gassing exchange coefficient based on observed conditions in April was made to the SYSTDG model. A reduction in the base off-gassing rate coefficient from 0.01 to 0.0025 ft/sec resulted in higher TDG pressures arriving at Camas/Washougal compared to previous year's equations. The predictive error of the hourly TDG pressure was determined throughout the interval involving 3648 observations. The calculated TDG pressures over-estimated observed conditions by an average of 7.5 mm Hg (average predictive error -7.5 mm Hg) and the standard deviation of the predictive error was 9.4 mm Hg as listed in Table G7. The size of the predictive error in 2010 at CWMW was slightly smaller than determined in 2009 due to the wider range in project operations (standard deviation of the predictive error was 10.4 mm Hg in 2009). The low flow and tailwater conditions during the month of July and August resulted in the largest errors in TDG saturation at CWMW resulting in estimated TDG levels consistently smaller than observed levels. The 50 percent confidence interval for the predictive error ranged from -14.0 to -2.1 mm Hg of pressure and the 80 percent confidence interval ranged from -17.7 to 4.7 mm Hg. The seasonal time history of observed and calculated TDG pressures at CWMW is shown in Figure G2. In retrospect, the change in the off-gassing coefficient was counterproductive in estimating the TDG pressures at CWMW in 2010. It is recommended to return the off-gassing coefficient to the previous level of 0.01 ft/sec. This alternative equation will reduce the bias in the TDG estimates at CWMW from -7.5 to -1.1 mm Hg with slightly increasing the standard error from 9.4 to 9.8 mm Hg.

For most of the study period, there were small differences in the observed and calculated TDG pressures at CWMW resulting from spillway operations as shown throughout the month of May in Figure G3. A strong daily TDG variation was evident in these records caused in part by the thermal exchange that is evident throughout this shallow open river reach even during May. The contribution of TDG loading from the Bonneville 2nd powerhouse corner collector (B2CC) outfall becomes more important during the lower total river flow conditions in April and August. In summary, predicted TDG levels during from April-June were generally closely reproduced although an over-estimation bias was present. The predictive error summary in terms of TDG saturation at CWMW is listed in Table G8. The influence of thermal cycling in the Columbia River is more prominent in the reach below Bonneville Dam than in upstream reaches and can significantly impact the daily TDG metrics used to determine compliance with state WQS.

Model update for Bonneville Dam

The TDG exchange associated with the B2CC was updated for the 2010 season based on observations of TDG pressures at the Warrendale FMS (WRNO). The WRNO was operational the entire year to support updating the sourcing relationship associated with the B2CC outfall. There were a number of events where the TDG pressure at WRNO was greater than observed at the Cascade Island FMS (CCIW). The CCIW samples spillway discharges and does not account for the additional impacts from the B2CC outfall located just downstream. The finding from previous TDG studies below Bonneville Dam has found the river conditions to be well mixed at WRNO. Therefore, for well-mixed TDG conditions at WRNO to exceed levels observed below spillway channel at CCIW implies the TDG pressures contributed by the B2CC outfall must be greater than exiting the spillway when background levels are well below conditions generated in these aerated releases. The operational conditions where TDG pressures were higher at WRNO compared to CCIW were during low river flow conditions with spillway flows of 75 kcfs or less. The observed and calculated TDG pressures at BON, WRNO and CCIW for the month of August 2010 are shown in Figure G4.

There are a number of plausible methodologies for estimating the TDG generation associated with the B2CC outfall. The approach applied for the 2010 spill season assumed both the effective TDG pressures in the outfall release and the associated entrainment of powerhouse flows into this turbulent jet. The amount of entrainment was observed to approach 4 times the discharge of the outfall during the initial sampling study of the B2CC outfall.

An alternative TDG generation equation for the B2CC outfall was evaluated for the 2010 spill season at Bonneville Dam. The added TDG mass at the outfall was assumed to equal the product of the effective B2CC outfall flow rate and the associated TDG pressure as follows:

$$TDG_{B2CC} = 1000$$
$$C_{ent} = 3.0$$
$$Q^*_{B2CC} = Q_{B2CC} + C_{ent} Q_{B2CC}$$

Where: TDG_{B2cc}= Corner Collector Outfall TDG Pressure (mm Hg)
Cent = Entrainment Coefficient for the B2CC outfall
Q_{B2CC} = Rated B2CC outfall discharge (kcfs)
Q^*_{B2CC} = Effective B2CC outfall discharge (kcfs)

The applicability of this equation was determined by comparing the observed and calculated TDG pressures at the WRNO over the entire spill season.

Table G7 Statistical summary of the predictive errors of the observed and calculated TDG pressures in mmHg at forebay FMS, April 1-August 31, 2010.

		Predictive Error at Forebay FMS* (mmHg)									
FMS		LGSA	LMNA	IHRA	MCNA	WEL	CHJ	JDY	TDA	BON	CWM
Number of Observations		3671	3670	3671	3672	3196	3672	3672	3653	3671	3672
Average		-5.4	-2.7	-6.1	0.8	-4.1	1.5	1.3	-6	1.7	-7.5
Standard Deviation		17.3	11.2	11.6	10.4	6.1	15.7	8.9	11.3	7.2	9.4
Maximum		59.7	46.3	37.6	38.4	17.6	43.4	35.2	22	32.2	28.3
Minimum		-61.2	-27	-45.7	-34.3	-27.7	-49.1	-30.3	-41.6	-29.7	-28.9
TDG Predictive Error for Percentile Occurrence (mm Hg)	5	-38.1	-17.2	-25.8	-15.5	-14.2	-25.8	-10.7	-29.5	-9.7	-20
	10	-30.1	-14.9	-21.5	-11.7	-11.8	-19.8	-8.3	-24.2	-7.7	-17.7
	25	-13.5	-9.6	-14.2	-5.6	-8.1	-8.9	-4.7	-10.7	-3.2	-14
	50	-5.6	-4.1	-5.2	0.5	-3.6	2.3	-0.2	-3.5	1.7	-9.3
	75	5.3	2.2	1.8	6.8	0	14.3	7.2	1.2	6.3	-2.1
	90	13.8	8.3	7.5	14.3	3	20.6	13.9	5.8	10.6	4.7
	95	21.3	16.7	10.8	19.1	5.5	24.4	16.7	8.3	13	10.1

*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)

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, 2010, in an effort to determine the prediction error of SYSTDG simulations in Bonneville Dam tailwater. The official tailwater compliance FMS below Bonneville Dam is located in the spillway exit channel at CCIW. However, the long term FMS at WRNO, which is located about 6 miles downstream from the dam in waters that are approaching well-mixed conditions, was active for the entire fish passage season to support updating the TDG exchange equation for Bonneville Dam. The calculated flow weighted average TDG pressures released from Bonneville Dam were lagged 4 hours and compared to the observed TDG pressures at WRNO. The calculated TDG pressures over-estimated observed conditions by an average of -5.4 mm Hg and the standard deviation of the predictive error was 9.1 mm Hg as listed in Table G9. The 50 percent confidence interval of the predictive error ranged from -11.6 to 0.5 mm Hg of pressure and the 80 percent confidence interval ranged from -16.1 to 6.2 mm Hg of pressure. The standard error of TDG pressure at the WRNO during the 2010 season was considerably

larger than determined in 2009 (9.4 to 6.5 mm Hg) however the sampling period for last year was only for the months of April and May. The seasonal time history of observed and calculated TDG pressures at WRNO is shown in Figure G5. The daily TDG values at WRNO FMS are a function of TDG levels associated with releases from the B2CC, spillway, and both powerhouses. The calculated and observed TDG pressures at WRNO are shown throughout the month of April in Figure G6. The elevation of TDG pressures in April at WRNO prior to the initiation of spill ranged from 40 to 60 mm Hg which can be attributed to the B2CC outfall. The cyclical afternoon peaks in TDG pressures at WRNO were associated with thermal cycling. It is interesting to note the uptake in TDG pressure with concurrent spill and B2CC operation in April were similar to condition without active spillway flows.

Table G8. Statistical Summary of the Predictive Errors of the Observed and Calculated TDG saturation at forebay FMS, April 1-August 31, 2010.

		Predictive Error at Forebay FMS*									
		(Saturation)									
FMS		LGSA	LMNA	IHRA	MCNA	WEL	CHJ	JDY	TDA	BON	CWMW
Number of Observations		3671	3671	3671	3672	3196	3672	3672	3653	3671	3672
Average		0.8	0.8	-0.5	0.4	-0.5	1	0.5	-0.8	0.2	-1
Standard Deviation		1.7	1.7	1.5	1.4	1.1	2.1	1.2	1.5	0.9	1.2
Maximum		5.8	5.8	5.3	5.4	2.6	6.4	5.1	3	4.2	3.7
Minimum		-3.3	-3.3	-5.7	-4.2	-6	-5.9	-3.8	-5.5	-3.9	-3.8
TDG Predictive Error for Percentile Occurrence (%)	5	-1.9	-1.9	-3.1	-1.8	-2.2	-2.7	-1.1	-3.9	-1.3	-2.6
	10	-1.4	-1.4	-2.6	-1.2	-1.7	-1.9	-0.8	-3.2	-1	-2.3
	25	-0.4	-0.4	-1.6	-0.4	-1.1	-0.4	-0.3	-1.4	-0.4	-1.8
	50	0.6	0.6	-0.4	0.4	-0.4	1	0.3	-0.5	0.2	-1.2
	75	1.9	1.9	0.5	1.2	0.1	2.7	1.2	0.2	0.8	-0.3
	90	3.1	3.1	1.3	2.2	0.7	3.6	2.1	0.8	1.4	0.6
	95	3.8	3.8	1.8	2.9	1	4.1	2.5	1.1	1.7	1.3

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

Bonneville Dam Spillway Exit Channel (CCIW)

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, 2010. The TDG estimates generated by SYSTDG reflect conditions in spillway releases undiluted from powerhouse flows and average conditions exiting the spillway channel. The TDG pressures at CCIW prior to the initiation of spill frequently exceeded 900 mm Hg in March and April as shown in Figure G6. 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 June.

The TDG production equation for the Bonneville Dam spillway flows was the most accurate of the lower Columbia River projects with the calculated mean prediction error

of TDG pressures at CCIW equaled -2.4 mm Hg and the standard deviation of the predictive error was 7.6 mm Hg as listed in Table G9. The 50 percent confidence interval for the predictive error ranged from -4.4 to 1.6 mm Hg of pressure and the 80 percent confidence interval ranged from -7.3 to 4.2 mm Hg of pressure. Elevated TDG levels registered at CCIW prior to the initiation of spill are associated with supersaturated conditions in the adult fish ladders. In March 2009 the Corps measured TDG levels in the adult fish ladder at 130% to 135%. The estimates of TDG saturation 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 discharges higher than 120 kcfs, TDG pressures observed near CCIW underestimated the cross sectional average TDG saturation in the spillway exit channel. The sample bias is considerable at CCIW for spillway flows greater than 150 kcfs and estimated average TDG saturation can fall as much as 50 mm Hg above the observed conditions. 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 2010 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.

Table G9. Statistical Summary of the Predictive Errors of the Observed and Calculated TDG Pressures at Tailwater FMS.

		Predictive Error at Tailwater FMS* (mm Hg)											
FMS		**DWQI**	**LGNW**	**LGSW**	**LMNW**	**IDSW**	**GCGW**	**CHQW**	**MCPW**	**JHAW**	**TDDO**	**CCIW**	**WRNO**
Number of Observations		764	3347	2819	2698	2643	217	296	2015	1840	1938	2814	3672
Average		5.1	-11.8	-1.8	-1.8	0.7	-31.3	-6.9	0.7	-4.2	-2.2	-2.4	-5.4
Standard Deviation		4.4	17.3	8.3	11.3	8.5	29.5	10.9	13.8	12.7	6.4	7.6	9.1
Maximum		31.3	60.5	40.4	54.3	49.5	27	50.2	48.4	23.5	13	18.4	25
Minimum		-4.9	-64.7	-33.7	-46.6	-36.2	-149	-36.7	-42	-33.3	-35.6	-50.8	-46.7
TDG Predictive Error for Percentile Occurrence (mm Hg)	**5**	-0.1	-48.2	-14.4	-20.3	-11.4	-87.8	-21.2	-20.4	-24.2	-13.2	-11.7	-18.3
	10	0	-34.2	-11.6	-15.5	-9.1	-71.6	-17.1	-16	-20.5	-10.5	-7.3	-16.1
	25	2.1	-18.7	-6.6	-9.7	-5.1	-46.3	-12.4	-9.6	-14.9	-6.2	-4.4	-11.6
	50	4.4	-9.4	-2.2	-0.9	-0.1	-22	-8.2	0.9	-4.8	-1.7	-1.8	-6
	75	7.1	-2.1	2.7	6.4	5.5	-13.8	-3.5	11.8	5.8	2.2	1.6	0.5
	90	11	4	7.4	10.9	12.3	-3.5	7	16.7	13.9	5.4	4.2	6.2
	95	13.9	9.5	10.7	13.6	15.8	3.2	12.5	19.5	15.8	7.5	5.4	10.5

*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 2010 spill season as a function of spill discharge are shown in Figure G9. These observed and calculated deviations are labeled modeling error in this Appendix G, but this characterization does not account for the sampling bias noted at CCIW in the 2002 field study. The relatively close agreement of calculated and observed TDG pressures downstream at WRNO further supports the continued use of the 2002 TDG production equation current being applied in SYSTDG. 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 relationship with spill discharge and the tailwater channel depth of flow. The tailwater spill capacity as limited by TDG saturation of 120 percent (~912 mm Hg) was found to range from 70 kcfs to as high as 160 kcfs depending upon the spill pattern, tailwater elevation, and local atmospheric pressure. The SYSTDG model has been updated to accommodate changes to spill patterns on an hourly basis through a user supplied spill pattern where the effective numbers of active spill bays are estimated as a function of the total spill discharge.

Table G10. Statistical Summary of the Predictive Errors of the Observed and Calculated TDG Saturation at Tailwater FMS.

		Predictive Error at Tailwater FMS* (Saturation)											
FMS		DWQI	LGNW	LGSW	LMNW	IDSW	GCGW	CHQW	MCPW	JHAW	TDDO	CCIW	WRNO
Number of Observations		764	3347	2819	2698	2643	217	296	2015	1840	1938	2814	3672
Average		0.7	-1.6	-0.2	-0.2	0.1	-4.3	-0.9	0.1	-0.5	-0.6	-0.5	-1
Standard Deviation		0.6	2.3	1.1	1.5	1.1	4.1	1.5	1.8	1.7	0.9	1	1.2
Maximum		4.3	8.2	5.4	7.3	6.6	3.4	6.8	6.4	3.2	2	2.4	3.6
Minimum		-0.7	-8.7	-4.5	-6.2	-4.9	-20.4	-5	-5.6	-4.4	-5	-6.8	-6.3
TDG Predictive Error for Percentile Occurrence (%)	5	0	-6.5	-1.9	-2.7	-1.5	-11.9	-2.8	-2.7	-3.2	-2.2	-1.7	-2.8
	10	0	-4.6	-1.6	-2.1	-1.2	-10	-2.3	-2.1	-2.7	-1.8	-1.1	-2.5
	25	0.3	-2.5	-0.9	-1.3	-0.7	-6.4	-1.7	-1.3	-2	-1.2	-0.7	-1.8
	50	0.6	-1.3	-0.3	-0.1	0	-3	-1.1	0.1	-0.6	-0.5	-0.4	-1.1
	75	1	-0.3	0.4	0.9	0.7	-1.9	-0.5	1.6	0.8	0	0	-0.2
	90	1.5	0.5	1	1.5	1.6	-0.5	1	2.2	1.9	0.5	0.3	0.6
	95	1.9	1.3	1.4	1.8	2.1	0.5	1.7	2.6	2.1	0.8	0.5	1.1

Bonneville Dam Forebay (BON)

The TDG pressures in the forebay of Bonneville Dam continues to be one of the most accurate estimates provided by the SYSTDG model even given the dynamic nature of this reach in terms of surface degassing 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 1.7 mm Hg and the standard deviation of the predictive error was 7.2 mm Hg as listed in Table G7. The 50 confidence interval for the predictive error ranged from -3.2 to 6.3 mm Hg of pressure and the 80 confidence interval ranged from -7.7 to 10.6 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at BON is shown in Figure G10. The TDG pressures in the forebay of Bonneville 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 calculated and observed TDG pressures at BON are shown throughout the month of May in Figure G11. The tendency for lower TDG conditions during the summer months at Bonneville Dam are related to the longer travel time from The Dalles Dam and the change in spill operation at John Day Dam during the summer. 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 speed (mps x 10) at The Dalles Airport is 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 20-50 mm Hg. Periods of calm winds are associated with the retention of the TDG levels through this river reach which can exceed the forebay TDG criterion of 115.

The Dalles Dam Tailwater (TDDO)

The 2010 TDG generation equation for The Dalles Dam remained unchanged from the equation used in 2009. The impacts of the new bay 8-9 spillway training wall in 2010 on the TDG exchange are the subject of an ongoing field study to be completed prior to the 2011 spill season. SYSTDG estimates of TDG pressure at the The Dalles tailwater FMS (TDDO) during the 2010 spill season remained accurate throughout the study period. The TDDO FMS is located about 3 miles downstream from the dam in waters that are nearly well-mixed based on observation during 2004. 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 -2.2 mm Hg. The standard deviation of the predictive error was only 6.4 mm Hg as listed in Table G9. The 50 percent confidence interval of predictive error ranged from -6.6 to 2.2 mm Hg of pressure and the 80 percent confidence interval ranged from -10.5 to 5.4 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 TDG saturation at the tailwater TDDO FMS infrequently exceeded the TDG standard of 120 percent because of the dilution with background TDG pressures contained in powerhouse releases. The amount of TDG added by The Dalles Dam spill was shaped by fish passage operation to spill 40 percent of the instantaneous total river flow. 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 contained in spillway flows undiluted from powerhouse flow (dark blue SP Cal) consistently exceeded 910 mm Hg (120 percent of saturation) as shown in Figure G15. 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 relationship was developed from a series of studies directly measuring the TDG levels in spillway releases. The tailwater elevation is directly related to both The Dalles Dam total discharge and the pool elevation established by Bonneville Dam. The completion of the spillway training wall between bays 8 and 9 has impacted the hydraulic conditions that develop throughout the tailwater channel. 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 tailwater TDG criterion of 120% was reached on several occasions for spill discharges of 125 kcfs and higher.

The Dalles Dam Forebay (TDA)

A simulation was conducted from the John Day Dam to The Dalles Dam forebay from April 1 through August 31, 2010 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 average TDG pressures were larger than the observed conditions by an average of -6.0 mm Hg. The predictive errors were large during June when spillway discharges ranged from 100 to 150 kcfs and small during the remaining four months when spill discharges were less than 100 kcfs. The standard deviation of the predictive error was 11.3 mm Hg as listed in Table G7. The 50 percent confidence interval of the predictive error ranged from -10.7 to 1.2 mm Hg of pressure and the 80 percent confidence interval ranged from -24.2 to 5.8 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 saturation in the forebay of The Dalles Dam exceeded 115 percent very briefly on June 22 during a spillway flow of 146 kcfs. The calculated and observed TDG pressures at 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 over prediction of TDG pressures in The Dalles Dam forebay during the month of June 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 addition of a new 50 ft long spillway flow deflectors in spill bay 20 and the location of the spillway weirs in spill bays 18 and 19 were the primary structural changes to the John Day spillway in 2010. The spillway weirs were located in bays 15-16 during the 2009 spill season and spill bay 20 was infrequently used. A revised spring spill pattern was implemented in 2010 at John Day Dam with heavy spill over the spillway weirs with a training spill distributed broadly over bays 2-20. The summer spill pattern does not use the spillway weirs and spill is shifted to the Washington side of the spillway creating a much greater separation between powerhouse and spillway flows. A field study composed of manual sampling of the flow and dissolved gas fields were conducted during selected spring and summer spill events to characterize the TDG exchange during these conditions. The results from these measurements should support the improvement of the TDG equation for John Day Dam.

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, 2010. The calculated average TDG pressures provided biased estimates over the study period as evidenced by an average error of -4.2 mm Hg and the standard deviation of the predictive error was 12.7 mm Hg as listed in Table G9. The 50 percent confidence interval of the predictive error ranged from -14.9 to 5.8 mm Hg of

pressure and the 80 percent confidence interval ranged from -20.5 to13.9 mm Hg of pressure.

The seasonal time history of observed and calculated TDG pressures at the JHAW FMS is shown in Figure G19. The departure of observed and calculated TDG pressures can be seen beginning during June in this figure when spillway flows ranged from 100 to 150 kcfs. The daily variation in river flows and corresponding percent river spill resulted in a broad range of spillway operations in May at John Day Dam as shown in Figure G20. The observed TDG pressures generally tended to over-estimate observed conditions during the first week of May followed by improved estimates the rest of the month.

The observed TDG pressure at the JHAW FMSwere directly related to spill discharge as shown in Figure G21. The observed TDG pressures at the tailwater FMS remained relatively weakly related to spill discharge for discharges up to about 80 kcfs. A consistent direct relationship between spillway discharge and TDG pressures at JHAW was apparent for spillway discharges greater than 80 kcfs. The large spillway allows for additional spillway bays to come on line without substantially increasing the average specific discharge of the spillway. Once all the spillbays are active, increasing the total spillway discharge will also increase the specific spillway discharge. A consistent over-estimation bias is shown in Figure G21 where TDG estimates are larger than observed conditions for higher spill discharges. A reformulation of the TDG production equation using a smaller rate coefficient for the specific spillway discharge would reduce this estimation bias.

John Day Dam Forebay (JDY)

The TDG pressures were simulated from McNary Dam to the John Day forebay from April 1 through August 31, 2010 in an effort to determine the predictive error of SYSTDG estimations in the John Day forebay during the fish passage season. The John Day pool is the longest river reach simulated and the travel time ranged from 3.2 to 13.0 days during the 2010 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 1.3 mm Hg and the standard deviation of the predictive error was 8.9 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -4.7 to 7.2 mm Hg of pressure and the 80 percent confidence interval ranged from -8.3 to 13.9 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the JDY FMS is shown in Figure G22. The lower forebay TDG levels at JDY FMS can be attributed to the long travel time and rate of off-gassing in John Day pool. The percent of river spilled at McNary Dam was among the highest in the lower Columbia River but resulted in the lowest forebay TDG levels at John Day Dam. The rapid change in TDG pressures in the forebay of John Day Dam was typically related to wind events. The predictive errors were smaller at JDY when compared to most other projects because of the dispersion of TDG events generated at McNary Dam. The observed and calculated TDG pressures at JDY are shown throughout the month of May in Figure G23. The peak observed TDG saturation at JDY on May 17 was under-estimated by the SYSTDG model by about 15 mm Hg.

McNary Dam Tailwater (MCPW)

The operation of two spillway weirs at McNary Dam and a revised spill pattern during the 2010 fish passage season resulted in changes in the TDG generation compared to previous conditions as monitored at the McNary tailwater (MCPW) FMS. The 2010 spill pattern called for continuous operation of the spillway weirs in bays 18, 19 through June 16. After this date, the spillway weirs were removed and standard spill operations in these spill bays were scheduled. The rated flow over the spillway weir was a function of the forebay elevation and was generally in the range of 9-10 kcfs. The summer time spill pattern featured a crowned spill pattern with peaked discharges 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 spill bays closed.

The SYSTDG model was used to simulate the TDG exchange associated with spillway releases from McNary Dam throughout the 2010 spill season as shown in Figure G24. The calculated TDG pressures at tailwater MCPW contained a minimal bias as evidenced by the mean error of only 0.7 mm Hg and a standard deviation of the predictive error was 13.8 mm Hg as listed in Table G9. The 50 percent confidence interval for the predictive error ranged from -9.6 to 11.8 mm Hg of pressure and the 80 percent confidence interval ranged from -16.0 to 16.7 mm Hg of pressure. The observed and calculated TDG pressures at MCPW are shown throughout the month of May in Figure G25. The small range in TDG pressures can be attributed to the small increase in the specific spillway discharge when distributed over 22 spill bays.

The spring and summer spill patterns have slightly different response curves based on TDG pressure observations at MCPW. The TDG pressures observed and calculated at MCPW are shown as a function of spillway discharge in Figure G26. The observed transitional spill pattern used between the spring and summer pattern are shown in green symbols. The observed conditions for the spring spill pattern are shown as blue symbols and the summer pattern is shown as red symbols. Although some overlap of the TDG response does exist between the summer and spring patterns, the TDG pressures for the summer pattern maintain a linear response to spill discharge with a plateau around 70 kcfs where the spill pattern shifts to the powerhouse side of the spillway. The TDG response during the spring spill pattern with active spillway weirs experienced a minimum TDG response for a spill discharge of about 80 kcfs with increasing TDG levels for spill discharges both below and above this discharge. This feature of the spring spill pattern is likely related to the greater influence from the spillway weirs for spill flow with diminishing training flow less than 80 kcfs. The transitional spill pattern generated substantially higher TDG levels due to the bulking of spill caused by the inactivity of spill bays 17-19. The addition of the summer spill pattern and any auxiliary spill pattern should be added to the SYSTDG spreadsheet to capture these influences on TDG exchange.

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 2010 called for considerable amounts of involuntary spill increasing the TDG loading from the mid-Columbia projects. 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 spill operation at Ice Harbor Dam was cycled periodically throughout most of the 2010 spill season to accommodate biological testing. This operation introduced pulses of water with high TDG levels into McNary pool. The calculated mean error of TDG pressures in the forebay of McNary Dam of 0.8 mm Hg and the standard deviation of the predictive error was 10.4 mm Hg as listed in Table G7. The standard error was slightly smaller in 2010 than determined in 2009 (10.4 versus 11.5 versus mm Hg). The 50 percent confidence interval for the predictive error ranged from -5.6 to 6.8 mm Hg of pressure, and the 80 percent confidence interval ranged from -11.7 to 14.3 mm Hg of pressure. The observed and calculated TDG pressures at MCNA are shown throughout the months of March-September in Figure G27. The calculated and observed TDG pressures at MCNA are shown in Figure G28 for the month of May. The abrupt increase in observed TDG pressures during May are associated with thermal cycling in the surface waters in the forebay of McNary Dam.

Wells Dam Forebay (WEL)

This is the first year the SYSTDG model performance has been evaluated for conditions in the Columbia River between Grand Coulee Dam and Wells Dam. This review was included for two reasons:

1. Spillway discharges occurred frequently at Chief Joseph and Grand Coulee Dams during June 2010;
2. Because of the effectiveness of the new flow deflectors at Chief Joseph Dam, there may be a change in the frequency and magnitude of spilling during high flows to better management power generation and TDG production. This is currently being evaluated but no conclusions available yet.

The observed conditions in the forebay of Wells Dam reflect the TDG generation from both upstream Federal projects. The installation of spillway flow deflectors at Chief Joseph in 2009 has significantly changed the TDG production characteristics at this project.

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 developed from the post-deflector field study in 2009 which has for following form; ($\Delta P=(TWE-746.1)^{1.2}\ q_s^{\ 0.285}$). The TDG production equation expresses the delta TDG pressure uptake in spillway flows as a function of the product of the tailwater depth (TWE-746.1) and specific spillway discharge q_s. The spill patterns used during the June spills of 2010 were collected from the project and

used to estimate the specific spillway discharge in the TDG exchange equation. The spillway operations were conducted without flow through bay 4 for spill through June 15 and bay 5 for the remainder of June. The spill patterns used even gate opening and typically alternated spill bays with higher and lower gate openings. A short spill test was scheduled during June 11 where discharges through spill bays 18 and 19 were regulated to support a spray impact analyses. The test spill patterns were initiated on June 11 at 13:15 and concluded at 16:00 hrs. The discharge through bay 19 was increase to about 39.4 kcfs during this period.

The TDG pressures from Chief Joseph Dam to Wells Dam were simulated from April 1 through the end of August for flow conditions and background TDG conditions observed during the 2010 season. The averaged predictive error of TDG pressures observed in the forebay of Wells Dam was -4.1 mm Hg and the standard deviation of the predictive errors was 6.1 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -8.1 to 0.0 mm Hg of pressure, and the 80 percent confidence interval ranged from -11.8 to 3.0 mm Hg of pressure. The predictive errors were small during the month of June when the upstream projects were actively spilling. The observed and calculated TDG pressures in the forebay of Wells Dam are shown throughout the months of March-September in Figure G29. The calculated and observed TDG pressures in the forebay of Wells Dam are shown in Figure G30 for the month of June. The passage of distinctive TDG events can be identified in the TDG patterns observed at Wells Dam. The travel time during this period was estimated to range from 0.67 to 2 days. The initiation of spill at Chief Joseph resulted in about a 45 mm Hg increase in TDG pressures at Wells Dam on June 9 and peak levels of 854 mm Hg resulting from a prolonged 100 kcfs spill at Chief Joseph Dam on June 11. These conditions approached but did not exceed the 115% TDG saturation level at the forebay of Wells Dam. The forebay TDG levels at Chief Joseph Dam were highly variable during the month of June in response to spillway operations at Grand Coulee Dam. The TDG peak on June 14 in the forebay at Wells Dam was due primarily to spill operations at Grand Coulee Dam. The small predictive errors at Wells Dam forebay during June can be attributed to the small TDG loss rate in this pool. The long periods of no spill at Chief Joseph Dam also contribute to the relatively accurate estimates of TDG pressure at Wells Dam.

Chief Joseph Dam Tailwater (CHQW)

The installation of 19 spillway flow deflectors in 2009 has significantly changed to properties of TDG exchange at Chief Joseph Dam. The spillway was exercised frequently during June of 2010 with prolonged spillway discharges ranging from 25 to 105 kcfs. The review of observed and calculated TDG properties in the tailwater of Chief Joseph Dam (CHQW) FMS will provide an opportunity to evaluate the performance of the TDG exchange equation developed from 12 independent spill events studied during the spring of 2009. This review will also allow for the revision and updating of this TDG exchange equation if warranted. This TDG exchange equation was incorporated into the 2010 SYSTDG model. The current TDG exchange equation for Chief Joseph Dam spill operations was developed from both uniform and non-uniform spill patterns. The influence of secondary factors such as tailwater elevation on TDG exchange was also studied but for a limited number for flow conditions. The spill patterns used in 2010 involved 18 of the 19 spill bays with even foot gate openings.

The SYSTDG model was used to simulate the TDG exchange associated with spillway releases from Chief Joseph Dam throughout the 2010 fish passage season as shown in Figure G31. The

spillway was not operated during most of this period, outside of June, resulting in no change in TDG pressures during passage through the dam. The month of June experienced a wide range of spill operations as shown in greater detail in Figure G32. The calculated TDG pressures at CHQW FMS for spills ranging from 10 to 105 kcfs were estimated with a mean predictive error of -6.9 mm Hg and a standard deviation of the predictive error was 10.9 mm Hg as listed in Table G9. The 50 percent confidence interval for the predictive error ranged from -12.4 to -3.5 mm Hg of pressure, and the 80 percent confidence interval ranged from -17.1 to 7.0 mm Hg of pressure. This summary indicates model predictions over estimated the observed conditions on average by 6.9 mm Hg. The performance of this TDG equation at Chief Joseph was of acceptable accuracy when compared with other projects. The equation can be updated to reduce the sampling bias that was evident in this year's simulation. However, the use of provisional spill patterns in 2010 may limit the utility of an updated model for making estimates of TDG pressures at Chief Joseph in the future.

The observed and calculated TDG pressures for steady state spillway releases with a duration of 3 hours or longer are shown in Figure G33. The TDG pressure generally increases as a function of spillway discharge but contains a wide variance of responses for repeated observations for a given discharge. This variation in TDG response can be associated with changes in tailwater elevation, spill pattern, and local atmospheric pressure. The generation of TDG levels of 120 percent and higher as observed at CHQW were attained during spill of 100 kcfs spill when accompanied by substantial powerhouse operations. The spill of 100 kcfs during no powerhouse releases was found to generate TDG level well below the 120 percent level. These observations support the conclusion that TDG exchange at Chief Joseph Dam is sensitive to tailwater stage for some flow conditions.

A detailed review of the time history of Chief Joseph Dam operations and TDG pressures during June 7-11 reveals some interesting properties of TDG exchange as shown in Figure G34. The spill of about 50 kcfs on June 9 remained nearly constant during a period when the total river flow was increased almost 100 kcfs indicating no impact of tailwater stage on TDG exchange. However, the TDG response during 100 kcfs spill on June 10-11 suggests a strong relationship between tailwater stage and changes in TDG saturation. The spillage of the entire river followed by the rapid increase in powerhouse flows on the morning of June 10 and 11 resulted in a corresponding increase in the observed TDG pressure at CHQW. In both cases the increase in TDG pressure was about 50 mm Hg and resulted in TDG saturations above 120 percent of saturation. The current equation predicted a 20 mm Hg increase in TDG pressures associated with an increase in tailwater elevation of 6.2 ft. during a 100 kcfs spill. This data suggests tailwater impacts on TDG exchange may occur unevenly across a range of flow conditions.

Chief Joseph Dam Forebay (CHJ)

The TDG pressure observed in the forebay of Chief Joseph dam (CHJ) FMS reflect the residual TDG supersaturation generated from upstream sources. A review of previous years records when high background TDG pressures passed through this pool, suggest only a small degree of degassing typically occurs between Grand Coulee and Chief Joseph dams. The spill activity at Grand Coulee Dam during June 2010 created well defined TDG events that were observed arriving and passing through Chief Joseph Dam. These events can allow the estimation of time of travel through the pool and the associated TDG loading of upstream TDG sources.

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 1.5 mm Hg and the standard deviation of the predictive error was 15.7 mm Hg as listed in Table G7. The standard error was over twice as large as found for the Wells pool simulation during this same period. Such a large predictive error for Chief Joseph forebay FMS suggests that the SYSTDG Grand Coulee TDG exchange equation did not accurately estimated the TDG flux release from Grand Coulee Dam (see Grand Coulee Dam Tailwater section for more discussion on potential causes). The 50 percent confidence interval for the predictive error ranged from -8.9 to 14.3 mm Hg of pressure, and the 80 percent confidence interval ranged from -19.8 to 20.6 mm Hg of pressure. The observed and calculated TDG pressures in the forebay of Chief Joseph Dam are shown throughout the months of March-September in Figure G35. The calculated and observed TDG pressures in the forebay of Chief Joseph Dam are shown in Figure G36 for the month of June. The shape and timing of elevated TDG events arriving to Chief Joseph Dam were accurately simulated for this case. However, the magnitude of TDG pressure is over estimated throughout the month of June.

Grand Coulee Dam Tailwater (GCGW)

A review of TDG pressure data at Grand Coulee Dam provides some insight into the TDG exchange process during project operations throughout the 2010 spill season. The Grand Coulee spill operations in June 2010 were unique in terms of both the frequency and magnitude of spill through the drum gates. The comparison of observed forebay and tailwater TDG pressures during powerhouse operations also help illuminate the TDG exchange processes at Grand Coulee Dam outside of spillway operations.

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 observed forebay TDG pressures were assumed to represent the TDG content in powerhouse releases which is the same assumption used in model simulations at all Columbia and Snake rivers projects. The TDG production equation for spill through the drum gates (Schneider, 1999) was used to estimate the TDG exchange during spill operations at Grand Coulee Dam. For comparison purposes, the river conditions at the tailwater GCGW FMS were assumed to be well mixed. The calculated mean predictive error of TDG pressures at the Grand Coulee Dam tailwater FMS of was -31.3 mm Hg and the standard deviation of the predictive error was 29.5 mm Hg as listed in Table G9. These model predictions significantly overestimated the observed conditions indicating a major departure between observed and modeled TDG pressures produced during operations at Grand Coulee Dam. The 50 percent confidence interval for the predictive error ranged from -46.3 mm Hg to -13.8 mm Hg of pressure and the 80 percent confidence interval ranged from -71.6 to -3.5 mm Hg of pressure**. The average predictive error at Grand Coulee Dam was nearly 3 times larger than the next highest average error estimate at Lower Granite Dam (LGNW) and therefore warrants further evaluation.** The observed and calculated TDG pressures in the tailwater of Grand Coulee Dam are shown throughout the months of March-September in Figure G37. The seasonal comparison of observed and calculated TDG pressures indicates the model over-estimated observed conditions during spillway operations and under-estimates conditions during powerhouse only operations in much of August. The calculated and observed TDG pressures at GCGW FMS are shown in Figure G38 for the month of June. The calculated TDG

pressures were consistently higher than the observed conditions at the GCGW FMS throughout the month of June. The correlation or general trend in hourly observed and calculated TDG pressures was also poor throughout June. It should also be noted that the modeled pressures arriving in the forebay of Chief Joseph Dam were also significantly overestimated in June by up to 50 mm Hg for selected events.

Typically, a dam's tailwater FMS data is used to quality check the SYSTDG TDG production equations. But there are several reasons for not using this approach with Grand Coulee. The SYSTDG predictive errors for Chief Joseph forebay FMS and Grand Coulee tailwater FMS were unacceptably high. At the same time, this statistical evaluation of SYSTDG shows that there is reasonable accuracy in the data from Chief Joseph and Wells forebay FMSs and there is an acceptable SYSTDG predictive error for Chief Joseph tailwater FMS. By the process of elimination, the source of high predictive error associated with GCGW FMS could be the result of one or all of the three following factors:

1. GCGW FMS SYSTDG TDG production equations are underdeveloped.
2. GCGW FMS may not be located in well mixed waters
3. GCGW FMS could be malfunctioning and the data is erroneous

The following discussion of these three factors provides insight to their potential role in causing the large predictive error.

There are two assumptions that may contribute to Grand Coulee SYSTDG TDG production equations not being representative:

1. The assumption that the forebay pressures and the tailwater temperatures are representative of powerhouse releases.
2. The assumption that the TDG production equations for drum gate operations are representative of various operations and conditions.

Because the powerhouse flows come from the penstocks which are located much deeper than the forebay FMS, there is some error entered into the TDG production equations with the assumption that pressures and the tailwater temperatures are representative of powerhouse releases. The error is even greater during the summer when GCL forebay experience thermal stratification. The SYSTDG TDG production equation for drum gate operations at Grand Coulee Dam was derived from observed data from the fixed monitoring gauges during the high flow events in 1996 and 1997 as described in (Schneider, 1999). The equation for TDG exchange during drum gate operations was subsequently updated by using the delta TDG pressure instead of the TDG saturation and takes the following form: $\Delta P=461(1-e^{-0.0298Qsp})$. This equation was based on a limited number of spill events during high discharge flood events with a sizable degree of uncertainty associated with the TDG contribution from powerhouse discharges. As a result, the estimates of TDG exchange may contain a sizeable degree of uncertainty when applied to different spill gate operations, spill magnitudes, tailwater elevations, and powerhouse operations.

Since the evaluation of SYSTDG assumes that the Grand Coulee Dam tailwater TDG gauge is in well mixed river conditions, a significant amount of predictive error could be entered into SYSTDG if the gauge is not. The interpretation of observed data at GCGW FMS as representing well mixed river conditions is based on the findings in Frizell and Vermeyen (1997). The difference between SYSTDG modeled and observed TDG pressures below Grand Coulee Dam could be related to the interpretations of data at GCGW FMS. The GCL operations in June of 2010 were considerably different than operations cited in the Frisell and Vermayen report. Therefore, the assumption of well mixed conditions at the tailwater location may be in error. The observations recorded at GCGW FMS may reflect different levels of mixing between powerhouse and spillway flows and could change with different powerhouse loading operations.

The interpretation of TDG pressures in the forebay of Chief Joseph dam at CHJ FMS as representing well mixed river conditions is accurate given the distance and time of travel of releases from Grand Coulee Dam.

Another potential source of predictive error below Grand Coulee Dam could be associated with the malfunctioning of FMS. FMS malfunctions could include limited exchange of water between the river and deployment conduit, and improper calibration/maintenance of the water quality sonde. According to the Bureau of Reclamation, the Grand Coulee Dam tailwater TDG gauge is calibrated every three weeks during spill season and during the 2010 spill season the gauge performed according to regionally accepted standards. Therefore, a clogged deployment conduit is a potential source of erroneous data from GCGW FMS which would result in a larger predictive error in SYTDG. To reduce the predictive error in SYSTDG, GCGW FMS operations should be investigated.

The TDG uptake at Grand Coulee during inefficient turbine operations such as operating outside of 1% is a complicating factor that could affect tailwater TDG levels so that the GCL tailwater gauge may appear to be malfunctioning when it is not. The variability of tailwater TDG pressures observed during periods with both low to high turbine flows is consistent with some SYSTDG TDG exchange during turbine operations. This suggests that the TDG uptake at Grand Coulee during inefficient turbine operations should be further investigated to establish if it is contributing to the inconsistencies discussed above.

Several graphs may be useful to this discussion. The observed and calculated TDG pressures below Grand Coulee Dam as a function of spillway discharge are shown in Figure G39. The Grand Coulee TDG production equations were changed so that the TDG levels in GCL tailwater resulted in close agreement with calculated and observed Chief Joseph forebay. Figure G40 shows the observed and calculated forebay conditions at Chief Joseph Dam during June using this simulation. The simulated TDG pressures in the forebay of Chief Joseph Dam compared favorably to observed conditions both in terms of magnitude and duration. The corresponding observed and calculated TDG pressures in the tailwater of Grand Coulee Dam for June are shown in Figure G41.

In order to address the large predictive error associated with GCGW FMS, it is necessary that the TDG exchange equations be updated based on data collected above and below Grand Coulee Dam under a range of operation conditions including both regulating outlet and drum gate

releases. A field study of the TDG exchange during spill operations at Grand Coulee Dam would also provide for an assessment of the monitoring stations at this location.

Use of data from the GCGW FMS and the SYSTDG model to simulate the Grand Coulee to Wells dams reach should be used with caution to manage spill and TDG levels in the Columbia River until the inconsistency of TDG data and the large predictive error for GCGW FMS are resolved.

Table G11. Statistical Summary of Hourly TDG Saturation at FMS from April 1-August 31, 2010 on the Columbia River

		Predictive Error at FMS*			
		mm Hg			
FMS		CHJ	CHJ#	GCGW	GCGW#
Number of Observations		3672	3672	217	217
Average		1.5	-1.5	-31.3	-10.8
Standard Deviation		15.7	8.6	29.5	19.2
Maximum		43.4	25.8	27	27
Minimum		-49.1	-32.3	-149	-95.6
TDG Predictive Error for Percentile Occurrence (mm Hg)	**5**	-25.8	-15.4	-87.8	-50.3
	10	-19.8	-12.5	-71.6	-37.5
	25	-8.9	-7.2	-46.3	-16.3
	50	2.3	-1.2	-22	-4
	75	14.3	3.6	-13.8	0.2
	90	20.6	8.8	-3.5	4
	95	24.4	13.4	3.2	8

Alternative TDG exchange formulation

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

Ice Harbor Dam Tailwater (IDSW)

The model of TDG production at Ice Harbor Dam resulted one of the best agreements between observed and calculated TDG pressures at a tailwater FMS for 2010. To accommodate biological testing, the spill operation at Ice Harbor Dam varied throughout the 2010 fish passage season to include spilling 30 percent of the instantaneous river flow, a fixed 45 kcfs, and spilling to the tailwater TDG capacity of 120%. Ice Harbor Dam spilled the highest voluntary spill discharge of 95 kcfs on the Snake River resulting in a TDG saturation ranging from 119.5 to 123 percent. The spill capacity as limited by the tailwater TDG constraint will be reduced below 95 kcfs at Ice Harbor Dam during periods of high river flow when tailwater levels are correspondingly high. Only five turbines were available for use at Ice Harbor Dam during the summer high flows resulting in higher involuntary spill rates. The spill pattern did not use spillbay 1 during

the 2010 fish passage season with the exception of some high involuntary spill events in June. The spillway weir remained in continuous operation with an average discharge of 7.9 kcfs. The spill patterns varied as a function of spill discharge and spill operations while generally featuring selected spill bays with high discharges (greater than 8 kcfs).

The TDG exchange at Ice Harbor Dam was simulated from April 1 through August 31, 2010 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 IDSW. The calculated mean predictive error of TDG pressure was 0.7 mm Hg and the standard deviation of the predictive error was 8.5 mm Hg as listed in Table G9. The 50 percent confidence interval of the predictive error ranged from -5.1 to 5.5 mm Hg of pressure, and the 80 percent confidence interval ranged from -9.1 to 12.3 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 daily variation in TDG pressures for observed and calculated conditions can be seen in Figure G43 for the month of June. The influence of tailwater elevation on TDG exchange can be noted in the range of TDG pressures as a function of spill discharge shown in Figure G44. The range in TDG pressures of 890 to 920 mm Hg for a spill discharge 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 discharge of any project on the Columbia or Snake Rivers. The spill capacity as limited by the 120 percent TDG saturation criterion was as high as 95 kcfs during the 2010 spill season but subject to tailwater stage conditions. The spill capacity at Ice Harbor will be significantly larger during low river flow conditions than during high river flows due to the tailwater depth of flow property. The combinations of spillway flow deflectors with a shallow tailwater channel are thought to account for this efficient TDG exchange attribute.

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, 2010 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 slightly over-estimated observed conditions by an average of -6.1 mm Hg and the standard deviation of the predictive error was 11.6 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -14.2 to 1.8 mm Hg of pressure, and an 80 percent confidence interval ranged from -21.5 to 7.5 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 observed and calculated TDG pressures in the forebay of Ice Harbor are shown in Figure G46 throughout June. The higher TDG pressures are generally associated with slack wind periods while declining pressure are usually accompanied by strong winds. The variation in TDG saturation at IHRA is related to the variation in percent of river spilled at Lower Monumental Dam and the influence of wind/wave generated degassing events.

The forebay TDG levels at Ice Harbor Dam did experience excursions above the TDG standard of 115. The frequency of hourly TDG supersaturation above 115 percent at IHRA was the highest of the four Snake River projects. The cumulative increase in TDG levels caused by spill at main-stem dams on the Snake River resulted in the hourly TDG saturation at IHRA to exceed 115 percent of saturation over 19 percent of the time.

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 releases were compared to the observed conditions at the tailwater FMS (LMNW) during spillway flows with duration of 3 hours and longer throughout the fish passage season. The calculated mean TDG pressures over-estimated observed conditions by an average of -1.8 mm Hg and the standard deviation of the predictive error was 11.3 mm Hg as listed in Table G9. The 50 percent confidence interval for the predictive error ranged from -9.7 to 6.4 mm Hg of pressure, the 80 percent confidence interval for the predictive error ranged from -15.5 to 10.9 mm Hg of pressure. The hourly variation of TDG pressures at LMNW for the entire fish passage season for observed and calculated conditions are shown in Figure G47. The hourly observed and calculated TDG pressures at LMNW or the month of June are shown in Figure G48 f. There was a tendency for calculations to under-estimate the TDG exchange associated with high spillway releases. The abrupt increase in observed TDG pressures of 20 mm Hg on June 14 during a constant spillway discharge of about 27 kcfs was caused by a spill pattern alteration where the discharge in spill bay 6 was increased from 7.8 to 9.7 kcfs and the discharge in spill bay was reduced by the same amount of flow. The over-estimation in TDG pressures in spillway flows during the first three weeks in June resulted in a consistent over-estimation in TDG pressures arriving in the forebay of Ice Harbor Dam Figure shown in Figure G46.

The observed and calculated TDG pressure in the tailwater of Lower Monumental Dam is shown in Figure G49 for spill events with duration of 3 hours or longer. The TDG production equation equates the delta TDG pressure as the product of the effective depth of flow and the square root of the unit spillway discharge ($\Delta P = [TWE\text{-}404]^{1.1} q_s^{0.5}$). This simple regression equation preformed well for most of the scheduled spill events at Lower Monumental Dam during 2010 but over estimated conditions during the higher forces spill operations in June. The response in TDG pressures and spill pattern noted previously on June 14 indicates the sensitivity of TDG generation to changes in the spill pattern that should be explored in improving the TDG equation at Lower Monumental Dam.

Lower Monumental Dam Forebay (LMNA)

The TDG pressure conditions 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, 2010 as shown in Figure G50. The calculated TDG saturation in the forebay of Lower Monumental Dam during April-June under-estimated the peak TDG pressures arriving at Lower Monumental Dam during peak spill conditions in June. The peak TDG pressures observed in the forebay of Lower Monumental Dam during June 7 of 970 mm Hg was underestimated by about 40 mm Hg. On average the calculated TDG pressures closely matched observed conditions as evidenced by the mean error of -2.7

mm Hg and standard deviation of the predictive error was 11.2 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -9.6 to 2.2 mm Hg of pressure, and the 80 confidence interval ranged from -14.9 to 8.3 mm Hg of pressure. The daily variation of TDG pressures for the month of June at LMNA are shown in Figure G51. The under-estimation of TDG pressure during the June is likely attributed to under-prediction of TDG production at Little Goose Dam. The weekly variation in TDG pressure at Lower Monumental Dam are influenced by local weather conditions where high winds increased degassing rates and slack wind decreased the off gassing of TDG pressures.

Little Goose Dam Tailwater (LGSW)

The spill operation at Little Goose Dam during the 2010 fish passage season called for spilling 30 percent of the instantaneous river flow using three different spill patterns. The spillway weir with a low crest weir configuration in bay 1 was used for most of the year with a spillway weir discharge of about 11.2 kcfs. The spillway weir with a high crest weir configuration and weir discharge of 7.2 kcfs in bay 1 was used primarily in the spring. The third pattern used a uniform spill without a using the spillway weir in bay 1. All three of these spill patterns were used with the TDG exchange equation at Little Goose Dam to estimate the resultant TDG levels in the Snake River below the dam.

A TDG simulation was conducted from Little Goose Dam to Lower Monumental Dam from April 1 through August 31, 2010 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 releases were subtracted from the observed tailwater FMS (LGSW) TDG data to estimate the predictive error by the model as shown in Figure G52. The calculated TDG pressures over-estimated observed conditions by an average of -1.8 mm Hg and the standard deviation of the predictive error was 8.3 mm Hg as listed in Table G9. The 50 percent confidence interval ranged from -6.6 to 2.7 mm Hg of pressure, and the 80 percent confidence interval ranged from -11.6 to 7.4 mm Hg of pressure. The entrainment of powerhouse flows into spillway releases at Little Goose Dam is amplified because of the large depth of the stilling basin and large spillway discharge in spill bay 1 located adjacent to the powerhouse. 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 estimated TDG pressures consistently underestimated the observed conditions by 10 to 20 mm Hg during the period of peak spillway flows on June 5-8.

The tailwater TDG pressure at Little Goose Dam is directly related to the spillway discharge. The observed and calculated TDG saturation at the tailwater FMS as a function of the spillway discharge for 2010 is shown in Figure G54. The tailwater TDG pressure does increase for increasing spillway discharge. However, the tailwater TDG pressure experiences a broad range of responses for a given spill discharge. The variance in TDG pressures is related to the influence of forebay TDG pressures, spill pattern, percent of river spilled, and local barometric pressure. The observed TDG pressures for

higher spill discharge consistently fall above the estimated values in this simulation. The equation of TDG exchange for Little Goose Dam using the alternative spill pattern should be updated to reduce the under-estimation of TDG pressures at higher spill discharge.

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, 2010. 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 -5.4 mm Hg and the standard deviation of the predictive error was 17.3 mm Hg as listed in Table G7. The 50 percent confidence interval ranged from -13.5 to 5.3 mm Hg of pressure, and the 80 percent confidence interval ranged from -30.1 to 13.8 mm Hg of pressure. The standard error of TDG pressures in the forebay of Little Goose Dam was the largest of all the forebay FMS in the lower Snake River. 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 poorly represented by model estimates with peak TDG pressures over estimating the observed conditions. The predictions of TDG pressures in the forebay of Little Goose Dam can be improved through updating the degassing coefficients used in the model. These exchange coefficients should be changed only after the TDG generation equation for Lower Granite Dam has been updated.

Lower Granite Dam Tailwater (LGNW)

The voluntary spill operations at Lower Granite Dam during the 2010 fish passage season called for a continuous spill of 20 kcfs during the spring and 18.5 kcfs during much of the summer featuring flow over the raised spillway weir. The spill patterns during the summer spill was new for the 2010 spill season featuring only 2 or 3 active spill bays. A period of involuntary spill was scheduled during June with the highest spill discharge of 125 kcfs on June 8.

The TDG levels associated with spillway releases from Lower Granite Dam were simulated from the April 1 through August 31, 2010 as shown in Figure G57. The calculated TDG pressures over-estimated observed conditions by an average of -11.8 mm Hg and the standard deviation of the predictive error was 17.3 mm Hg as listed in Table G9. The predictive errors at the Lower Granite tailwater FMS were the largest of any project with the exception of Grand Coulee Dam. The over-estimate bias occurred in the predictions of TDG exchange for spill discharges of 24 kcfs and less during the constant fish spills. The 50 percent confidence interval for the predictive error ranged from -18.7 to -2.1 mm Hg of pressure, and the 80 percent confidence interval ranged from -34.2 to 4.0 mm Hg of pressure. The TDG saturations 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 2010 spill season for spill discharges of 24 kcfs and higher. The peak spillway discharge of 125 kcfs caused a TDG saturation of about 988 mm Hg which equaled the estimated peak TDG saturation of 988 mm Hg.

The tailwater TDG pressures for spill events with a duration of 3 hours or greater are shown as a function of spill discharge at Lower Granite Dam in Figure G59. This figure indicated the spill capacity of about 30 kcfs corresponds with a TDG saturation of 120 percent. A well defined linear relationship is indicated by these data for spill discharges greater than 25 kcfs. However, for spill discharges less than 25 kcfs a broad range of TDG pressures is indicated. This wide variance of TDG pressures is likely related to the range of percent spill conditions and the varied influence of powerhouse releases on TDG pressures observed at the tailwater FMS.

The cause for the over-estimation of TDG pressures at the tailwater FMS for standard Biop or Fish Operation Plan spills of 20 kcfs and less deserves some discussion. A review of the spill patterns associated with the spillway weir training flow did reveal a change from previous years during the summer. The percent of river spilled during standard Biop or Fish Operation Plan spill did vary widely throughout the fish passage season. The TDG pressures observed at the tailwater FMS show a tendency towards lower pressures for small percent spilled events. This evidence suggests the mixing zone can encroach upon the tailwater FMS for small percent spill event. It is recommended the equation of TDG exchange be revisited at LWG by evaluating the entrainment and specific spillway discharge estimates as spill discharges become small at Lower Granite Dam.

Dworshak Dam Tailwater (DWQI)

The operations at Dworshak Dam were highly varied during the 2010 season ranging from minimum powerhouse flows to capacity powerhouse with 5 kcfs regulating outlet spill all during the month of June. The evaluation of TDG production during spillway usage at Dworshak Dam will depend upon estimates of the TDG content in powerhouse flows. The TDG content in powerhouse flows can be influenced by added TDG generation during inefficient turbine gate settings where air is aspirated into the turbine hub and draft tube. The DWQI is located in well-mixed waters influenced by both spillway and powerhouse releases. The highest spill discharge at Dworshak Dam was 5 kcfs resulting in a tailwater TDG saturation of 111 percent.

The TDG pressures in the tailwater channel below Dworshak Dam were simulated during the 2010 spill season as shown in Figure G60. The operations during March through the first week in June involved minimum powerhouse operations where the TDG pressures were supersaturated. The predictive error during regulating outlet operations of duration of 3 hours and longer were summarized at the tailwater FMS as listed in Table G9. The calculated tailwater TDG pressures under-estimated observed conditions by an average of 5.1 mm Hg and the standard deviation of the predictive error was 4.4 mm Hg. The 50 percent confidence interval for the predictive error ranged from 2.1 to 7.1 mm Hg of pressure, and the 80 confidence interval ranged from 0.0 to 11.0 mm Hg of pressure. Dworshak Dam does not have a forebay FMS and the TDG pressures observed at the tailwater FMS during powerhouse only operations were used to estimate the TDG pressures released by the powerhouse during concurrent powerhouse and spillway/regulating releases. The estimation of the forebay TDG pressure is probably a

significant component of the predictive error estimated at the tailwater FMS since powerhouse releases constitute most of the TDG loading observed at DWQI.

The observed and calculated TDG pressures in the tailwater of Dworshak Dam are shown in Figure G61 for the month of July. The estimated TDG content of spillway releases undiluted with powerhouse flows is labeled SP Cal in Figure G61. It should be noted that the TDG pressures in regulating releases are not observed directly below Dworshak. However, the DWQI has been found to reflect well mixed conditions reflecting both powerhouse and spillway flows. The estimated flow weighted tailwater TDG pressure is labeled Rel Cal that closely reproduces the observed TDG pressures at DWQI. The operation of the powerhouse at less than capacity discharges resulted in the elevation of TDG pressures on July 2, and July 6 through 9.

The observed and calculated TDG pressures at DWQI as a function of spill discharge are shown in Figure G62. Both the observed and calculated TDG pressures varied linearly with spill discharge. The events where observed TDG pressures were much greater than the forecasted values were likely caused by elevated TDG pressures in powerhouse flows.

The degree of TDG uptake during powerhouse operations was observed to be impacted by the tailwater stage at times. The minimum powerhouse operations during June 2 resulted in TDG pressures of 795 mm Hg. As flood flows on the main stem Clearwater River peaked during the first week in June, a corresponding increase in tailwater stage and reduction in TDG pressures were observed at DWQI. The elevated backpressure on the turbine units were likely responsible for the lowering of TDG pressures during minimum powerhouse operations.

Comparison of 2009 and 2010 Simulations

The performance of the SYSTDG decision support system as measured by the hourly predictive error statistics at FMS during the 2010 spill season was in some cases better and in some cases worse than the performance observed during the 2009 fish passage season. The wide range of both voluntary and involuntary spill operations in 2010 was in contrast to lower river flow rates during the 2009 spill season. The combined movement of spillway weir operation and the new spillway flow deflector at bay 20 of John Day Dam involved a structural modification to spillway releases which likely influenced both TDG exchange and entrainment of powerhouse flows this year. The new summer spill pattern at Lower Granite Dam provided for different conditions for TDG exchange. The average predictive error provides an indication of estimate bias in TDG pressures. A total of 3 out of 8 forebay FMSs in 2009 contained an average predictive error greater than ±5 mm Hg compared to 4 out of 10 in 2010. The standard error of estimate at forebay FMSs ranged from 6.1 to 17.3 mm Hg in 2010 compared to 6.5 to 13.8 in 2009. The magnitude of the standard error was lower at 4 of the 8 forebay FMSs in 2010 compared to conditions in 2009. The large size of the standard error in the forebay FMSs at Little Goose and Chief Joseph in 2010 suggest updates to the SYSTDG equations are needed at the Lower Granite and Grand Coulee Dams.

The data at the tailwater FMS were filtered by duration of spill in this year's analysis to generate a more meaningful estimate of the predictive error at tailwater FMSs. The standard deviation of the predictive errors in 2009 ranged from 6.1 to 14.3 mm Hg at tailwater FMS. In 2010, the standard deviation of the predictive errors at tailwater FMS ranged from 4.4 to 29.5 mm Hg. Improvements in predicting TDG pressures were achieved at 5 of the 10 tailwater FMSs. There were several FMSs where the predictive errors were considerably greater in 2010 compared to 2009. The standard error in the tailwater of Lower Granite Dam increased from 9.8 mm Hg in 2009 to 17.3 mm Hg in 2010. The increase in the predictive error at Lower Granite was primarily due to the TDG response for the new spill pattern employed during the summer of 2010. The standard error in the tailwater of McNary Dam increased from 8.1 mm Hg in 2009 to 13.8 mm Hg in 2010. A prominent cause of deviations between observed and estimated TDG pressures in 2010 were the influence of new spill patterns on TDG exchange in the Columbia and lower Snake rivers.

The performance of the SYSTDG model in the Columbia River from Wells to Grand Coulee Dams was new to this evaluation in 2010. The size of the predictive errors at the tailwater FMS below Grand Coulee Dam and in the forebay of Chief Joseph Dam relative to those observed at other locations suggest the need to reevaluate the monitoring and modeling of TDG pressures at Grand Coulee Dam.

Conclusions

The decision support spreadsheet SYSTDG was used to simulate the production, transport, and dissipation of TDG pressures in the Columbia River basin during the 2010 spill season. These estimates of TDG pressure were compared with observed levels from the FMS to evaluate the reliability of these calculations, and to determine the uncertainty of TDG estimates to support spill management operations. The applications of spillway operations throughout the basin in 2010 were characterized by voluntary spill conditions during most of the year with a short period of involuntary spill in June. The spill operations on the lower Snake and lower Columbia rivers during the summer months was continued in 2010 with TDG levels generally within the state WQS for TDG during the fish passage season. The spill patterns were modified at a number of projects in 2010 season to evaluate benefits to fish guidance. These unique operations resulted in conditions outside of the normal operating range under which the SYSTDG model was developed. The performance of the SYSTDG model was extended to include the Columbia River from Wells to Grand Coulee dams during 2010. A major modification to the SYSTDG model adopted during the 2010 season involved the inclusion of multiple project specific spill patterns used to estimate the effective number of active spill bays.

In general, the predictive errors at the forebay FMS in 2010 (Tables G7 and G8) were slightly larger than predictive errors estimated at tailwater FMSs (Tables G9 and G10). A review of model performance indicates that 6 out of the 10 forebay FMSs had standard errors greater than 10 mm Hg compared to only 4 out of 10 tailwater FMSs. The average predictive errors at all the forebay FMSs were less than 1 percent of saturation. The

correlation between strong winds and declining TDG pressure at forebay FMSs were again evident during the 2010 spill season.

The TDG exchange, transport, and mixing of Bonneville Dam releases during the 2010 spill season resulted in a significant improvement in the prediction of TDG pressures at the CWMW when compared to the equations used in 2009. The new equations for TDG exchange associated with the B2CC were the primary reason for the improvement in model estimates. The B2CC outfall is a critical TDG source during low river flow conditions. The low tailwater stage is likely to result in a B2CC outfall jet that entrains air at a high rate, plunges deeply into the receiving channel, and entrains significant quantities of flow next tothe plunge pool. An alternative TDG production equation was proposed for the B2CC outfall that incorporates the entrainment of powerhouse flows. The TDG production characteristics observed at CCIW during the 2010 spill season were closely simulated throughout the spill season as indicated by the standard error of estimate of 7.2 mm Hg. The spillway capacity as limited by TDG saturations of 120 percent at CCIW were observed to range from 70 to 150 kcfs during the 2010 spill season. The TDG pressures in the Columbia River at the WRNO continue to provide reliable estimates of the aggregate TDG loading of releases from Bonneville Dam for TDG management. The TDG pressures at WRNO were larger than observed at the tailwater CCIW located in the spillway exit channel during low river flows which implies the B2CC was a significant TDG source.

The prediction of TDG exchange at The Dalles Dam and throughout the Bonneville pool proved again to be one of the more reliable reaches in the study area. The standard prediction error at the Dalles tailwater FMS was estimated to be 6.4 mm Hg while the corresponding standard error in the forebay of Bonneville Dam was only 7.2 mm Hg. The impact of the bay 8-9 spillway training wall on the estimation of TDG pressures at the downstream FMS was small. The FMS TDDO resides in mixed waters influenced by both powerhouse and spillway flows. This mixed river FMS masks the higher TDG pressures generated in spillway releases that were estimated to range from 120.2 to 127.4 percent of saturation.

A spillway flow deflector was added to John Day spill bay 20 for the 2010 spill season. The spill patterns at John Day Dam were changed during the 2010 spill season to include the new locations for the spillway weirs and added spillway flow deflectors. Both summer and spring spill patterns were modified to incorporate these structural changes. The spring bulk spill pattern has altered the TDG exchange patterns at John Day Dam where the TDG contribution from the spillway weirs were masked for high flows but become more evident at lower spill discharges. The estimated TDG exchange was consistently over-estimated during spill discharges greater than 120 kcfs and under-estimated conditions for low flows less than 60 kcfs. The influence of the different spill patterns needs to be more completely integrated into the John Day TDG exchange equations to improve the forecasting accuracy. The spillway capacity as limited by the 120 percent TDG saturation criterion ranged from 130 to 145 kcfs during the 2010 spill season. The fate of powerhouse flows with the new spill patterns was investigated during

selected spill conditions during the 2010 spill season and the findings will be incorporated into the SYSTDG model.

The operations at McNary Dam involved spilling water through two spillway weirs during the spring and through conventional gates during the summer. The TDG pressures observed at MCPW were a function of the spill magnitude and pattern. The spring spillway configuration generated slightly higher TDG pressures than the summer configuration for spill discharges less than 75 kcfs. The spring spill pattern resulted in tailwater TDG pressures that were typically 0-10 mm Hg less than the summer spill pattern for spill discharge greater than 75 kcfs. The spillway capacity as limited by 120 percent TDG saturation levels were observed to range from 115 to 185 kcfs. The spring spillway configuration resulted in increasing TDG pressures at the tailwater FMS for spillway discharges falling below 85 kcfs. This property was likely related to the mixing zone from the spillway weir releases reaching the north shore during lower spillway discharges. The SYSTDG simulation of tailwater TDG pressures at MCPW were less reliable (standard error of 13.8 mm Hg, average error of 0.7 mm Hg) than conditions simulated during 2009. A closer integration of different spill patterns is a likely source for improving the TDG production equations at McNary Dam. The TDG estimates in the forebay of John Day Dam were improved over conditions in 2009. The mean and standard error in the forebay of John Day Dam were 1.3 and 8.9 mm Hg, respectively. The time of travel in John Day pool is the longest of any of the reaches modeled in this investigation. This long duration can amplify errors associated with wind driven degassing.

The TDG production from Chief Joseph Dam and fate throughout the Wells Dam pool were evaluated in SYSTDG for the first time in 2010. The spill discharges ranged from 10 to 105 kcfs during the month of June. The observed TDG saturations approached 120 percent of TDG saturation for spill discharges of 100 kcfs. The TDG response at the tailwater FMS was found to vary with tailwater stage for selected spill levels. The accuracy of estimates of TDG pressure in Chief Joseph releases were comparable to other projects evaluated in this review. The TDG pressures observed downstream at Wells Dam during June were closely reproduced in the model simulations with a standard error of estimate of 6.1 mm Hg.

The TDG production from Grand Coulee Dam and transport throughout the Chief Joseph pool were evaluated with the SYSTDG model for operations observed in 2010. The average predictive error for Grand Coulee tailwater FMS was nearly 3 times larger than the next highest average error estimate at Lower Granite Dam (LGNW) and therefore warrants further evaluation. The potential sources of high predictive error associated with GCGW FMS could be the result of one or all of the three following factors:

1. GCGW FMS SYSTDG TDG production equations are underdeveloped.
2. GCGW FMS may not be located in well mixed waters
3. GCGW FMS could be malfunctioning and the data is erroneous

In order to address the large predictive error associated with GCGW FMS, it is necessary that the TDG exchange equations be updated based on data collected above and below Grand Coulee Dam under a range of operation conditions including both regulating outlet and drum gate releases. A field study of the TDG exchange during spill operations at Grand Coulee Dam would also provide for an assessment of the monitoring stations at Grand Coulee Dam.

The TDG exchange equations for Ice Harbor Dam proved to be one of the most reliable estimates of tailwater TDG pressure on the Snake River. The consistent performance of this TDG exchange equations is related to the importance of tailwater depth of flow on TDG generation. Ice Harbor Dam continues to have the smallest TDG uptake for a comparable spill discharge of any project on the Columbia or Snake Rivers. Ice Harbor Dam spilled the highest percentage of total river flow of 56.8 percent of any project in the study area. The spill capacity as limited by the 120 percent TDG saturation criterion was as high as 90 kcfs. The combination of spillway flow deflectors with a shallow tailwater channel are thought to account for this efficient TDG exchange property.

The TDG production at Lower Monumental Dam has consistently been a poor performer in the modeling of TDG pressures in the Snake River as was the case again in 2010. The standard prediction error for the tailwater FMS below Lower Monumental Dam was the third highest behind John Day and Grand Coulee Dams. The TDG exchange characteristics at Lower Monumental Dam involve a complex spill pattern and the substantial entrainment of powerhouse flows into aerated spillway flows. A TDG production equations developed from conditions observed in 2009 was applied to the proposed spill patterns presented in the fish passage plan. The frequency of hourly TDG supersaturation above 115 percent at the Ice Harbor forebay FMS was the highest of the four Snake River projects. The spill operation at Lower Monumental Dam resulted in the TDG saturation in the Ice Harbor forebay to exceed 115 about 19 percent of the time.

The spillway operations at Little Goose Dam involved both high and low crest operation of the spillway weir and periods of no spillway weir flow. The tailwater FMS TDG pressures at Little Goose Dam have been found to be a function of both powerhouse and spillway releases because of the prominent interaction of spillway and powerhouse flow in the tailrace of the dam. The application of the existing TDG exchange equations for Little Goose Dam performed well based on the revised spill patterns. A noted short coming of model predictions during the 2010 season involved the under-estimation of TDG pressures during peak spillway discharges. The peak TDG pressures arriving at Lower Monumental Dam were higher than the corresponding peak TDG pressures observed at the tailwater FMS at Little Goose Dam generated during spillway discharges of 90 kcfs and greater.

The SYSTDG model provided reliable estimates of TDG exchange at Lower Granite Dam during the 2010 spill season with the exception when spill was 20 kcfs or less. The model over estimated the tailwater TDG pressures for small spill discharges to a degree that was uncharacteristic at Lower Granite Dam. The probable cause for these predictive errors is the development of the mixing zone at low percent river spill conditions

resulting in powerhouse releases influencing tailwater FMS observations. The TDG generation errors at Lower Granite Dam likely contributed the larger standard errors in the forebay of Little Goose Dam.

Dworshak Dam conducted a range of regulating outlet releases to manage pool filling and drafting actions during the 2010 spill season. The tailwater FMS below Dworshak Dam resides in mixed waters and is influenced by both powerhouse and spillway releases. A challenge in providing estimates of TDG exchange in releases from Dworshak include providing estimates of both the TDG content in powerhouse, spillway, and regulating outlet flows. The SYSTDG model produced accurate estimates of the TDG pressure at the tailwater FMS with a standard error of estimate of only 4.4 mm Hg. The larger prediction errors were generally associated with periods of TDG generation in powerhouse releases. The elevation of Clearwater River TDG pressures during single turbine operations were noted during the 2010 season and found to vary as a function of tailwater elevation. The turbine discharges that generate TDG supersaturation fall at the lower operating range for each turbine.

Recommendations

The following improvements and maintenance activities to the SYSTDG model are recommended for 2011.

The results from the field studies investigating of TDG exchange at The Dalles and John Day dams should be incorporated into the TDG equations at these projects. The findings regarding the adequacy of the FMS for TDG management should also be summarized.

In order to address the large predictive error associated with the Grand Coulee tailwater FMS, it is recommended that the TDG exchange equations be updated based on data collected above and below Grand Coulee Dam under a range of operation conditions including both regulating outlet and drum gate releases. A field study of the TDG exchange during spill operations at Grand Coulee Dam would also provide for an assessment of the monitoring stations at Grand Coulee Dam. Any actions required to improve SYSTDG modeling of Grand Coulee Dam should be coordinated with the Bureau of Reclamation.

Use of data from the GCGW FMS and the SYSTDG model to simulate the Grand Coulee to Wells dams reach should be used with caution to manage spill and TDG levels in the Columbia River until the inconsistency of TDG data and the large predictive error for GCGW FMS are resolved.

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.

The complete spill pattern tables for the summer, spring, and special operations should be entered into each of the project pages. The effective number of spill bays (nbays) is subsequently used to calculate the specific discharge defined as $q_s = Q_{sp}/\text{nbays}$. The

effective number of spill bays has been estimated from the proscribed spill pattern using the following equations.

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

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)

The weighting of individual spill bays is important when bulk spill patterns are used and the effects of certain bays may over ride the influence of training spill bays flows at moderate to small flows.

In several reaches, the considerations of wind direction and magnitude of wind will identify co-flowing and counter-flowing conditions that may improve the estimation of TDG off-gassing during passage through a given river reach.

The TDG exchange equations for Lower Monumental Dam should be updated to improve the accuracy at high spillway discharges 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.

The influence of the spillway weir operation at McNary Dam should be further investigated to improve TDG exchange estimates. This investigation should include the entrainment of powerhouse flows into the highly aerated stilling basin.

The description of TDG exchange during turbine operations at Dworshak Dam should be developed and included in the SYSTDG model. The production relationship for regulating and spillway operations at Dworshak Dam should be developed and incorporated into the TDG exchange equations.

The documentation of SYSTDG should be updated to reflect recent project changes.

Appendix G Figures

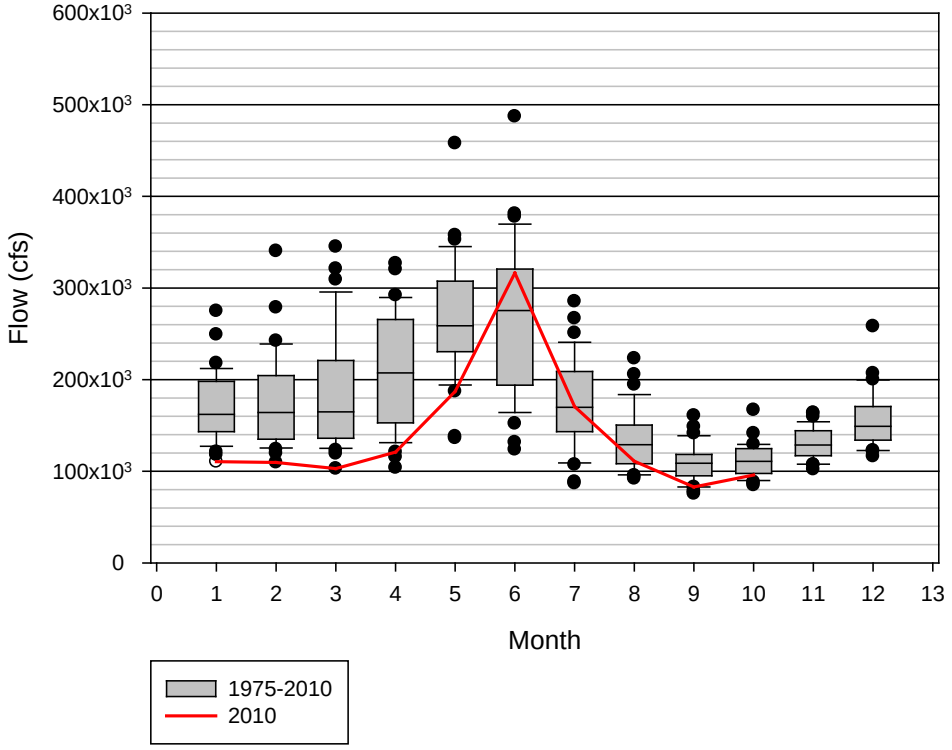

Figure G1. Statistical Summary of Columbia River Monthly Average Flows at The Dalles Dam for 1975-2010 (2010 – Red, 1975-2010 summary gray box 25, 50, 75th percentiles, whiskers 5-95th percentiles).

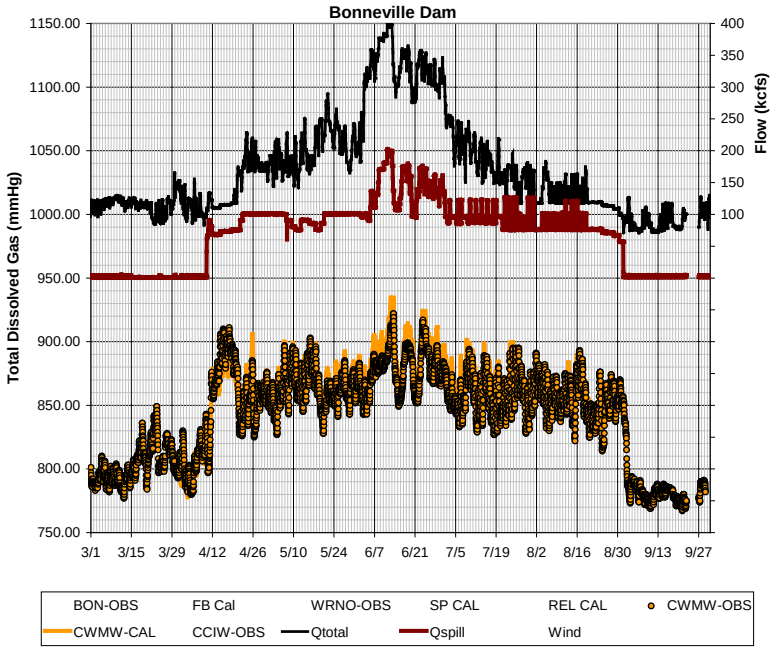

Figure G2. Observed and Calculated TDG Saturation at the Camas FMS downstream of Bonneville Dam, March-September 2010

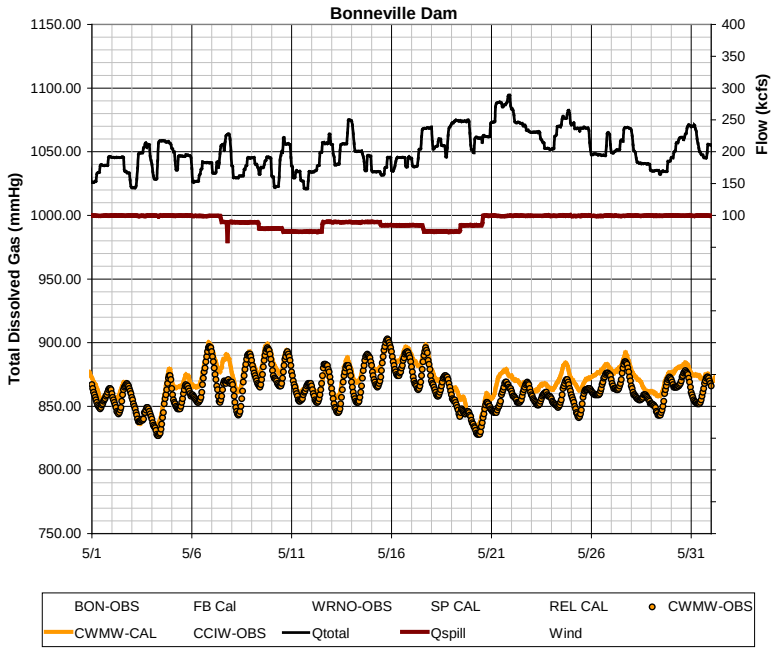

Figure G3. Observed and Calculated TDG Saturation at the Camas/Washougal FMS downstream of Bonneville Dam, May 2010

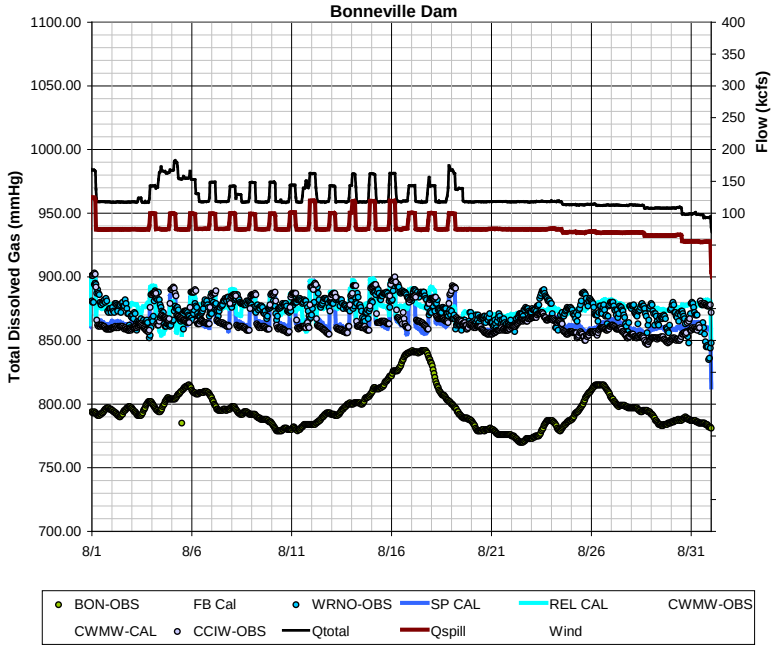

Figure G4. Observed and Calculated TDG Saturation at the Cascade Island (CCIW) and Warrendale (WRNO) FMSs downstream of Bonneville Dam, August 2010

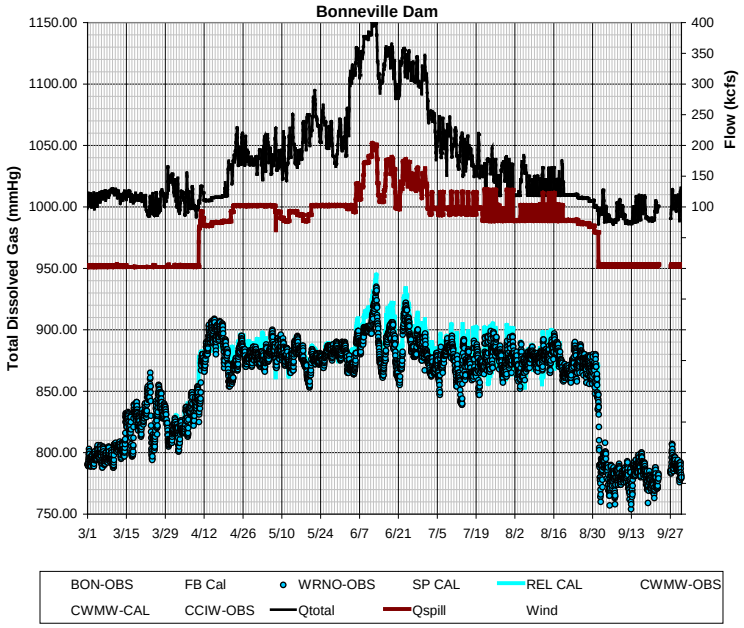

Figure G5. Observed and Calculated TDG Saturation at the Warrendale FMS downstream of Bonneville Dam, March-September 2010

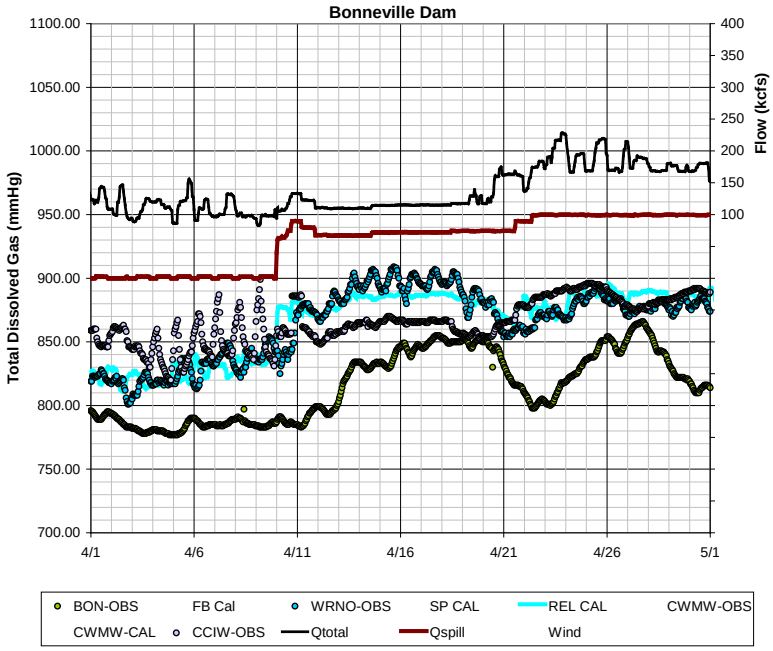

Figure G6. Observed and Calculated TDG Saturation at the Warrendale FMS downstream of Bonneville Dam, April 2010

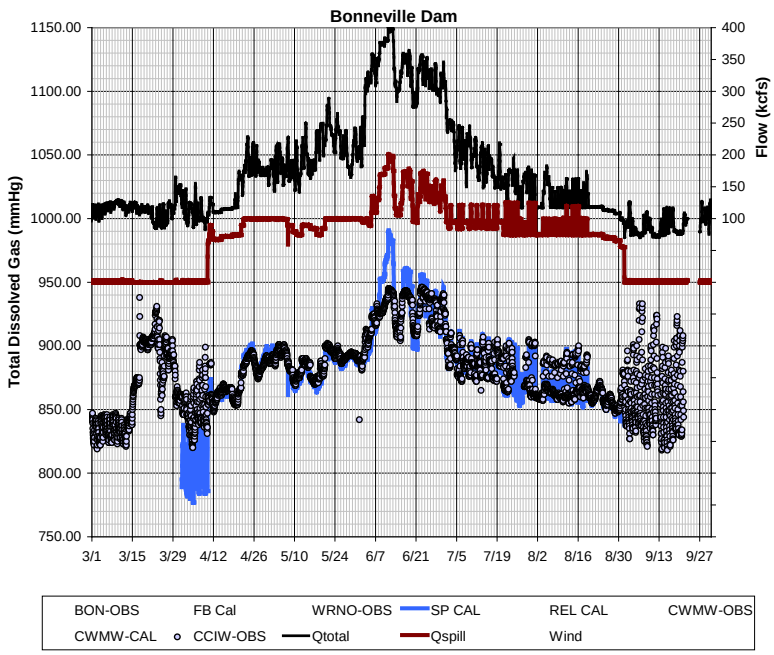

Figure G7. Observed and Calculated TDG Pressures at the Cascade Island FMS downstream of Bonneville Dam, March-September 2010

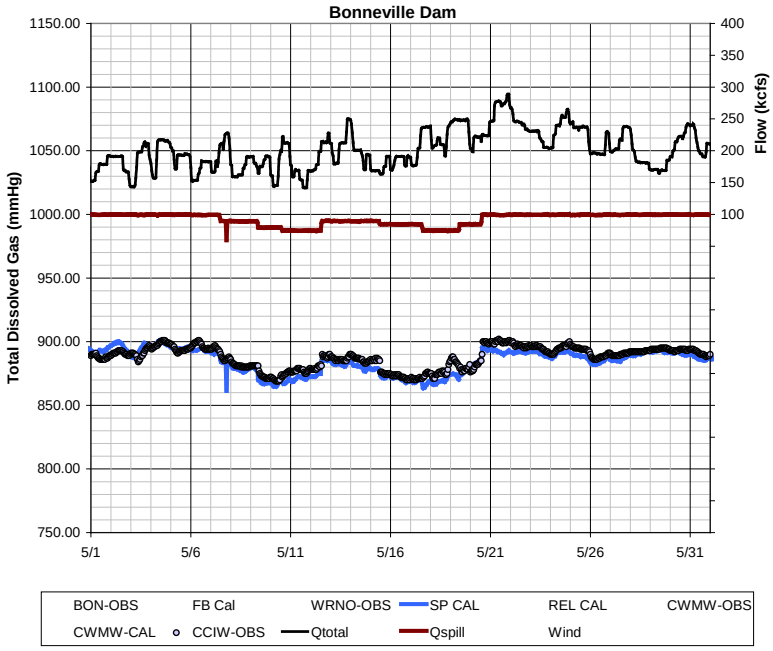

Figure G8. Observed and Calculated TDG Pressures at the Cascade Island FMS downstream of Bonneville Dam, May 2010

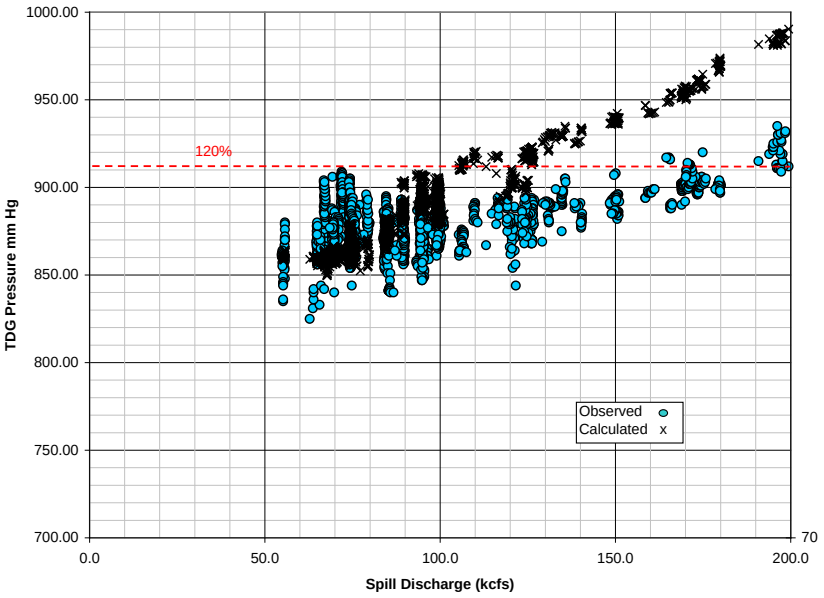

Figure G9. Observed and Calculated TDG Pressures at the Cascade Island FMS downstream of Bonneville Dam as a Function of Spill Discharge, 2010

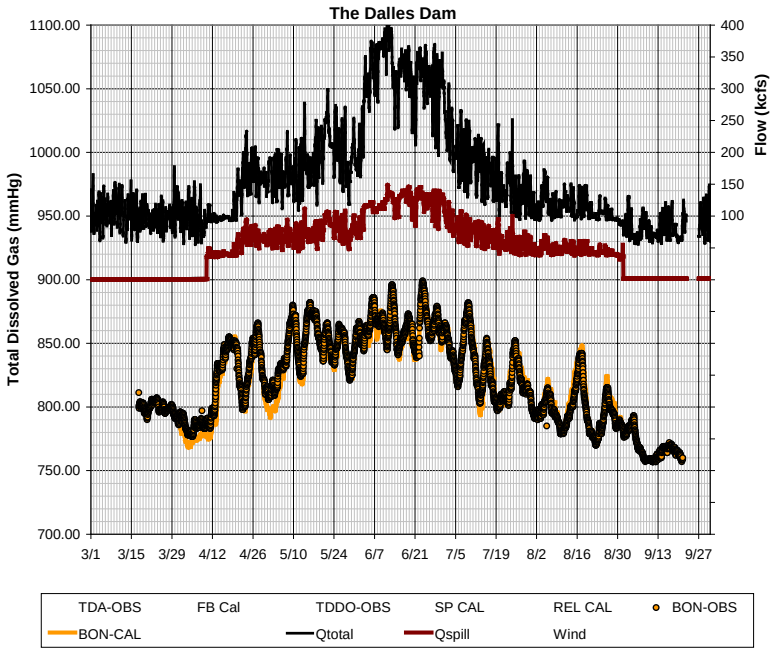

Figure G10. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the forebay of Bonneville Dam, March-September 2010

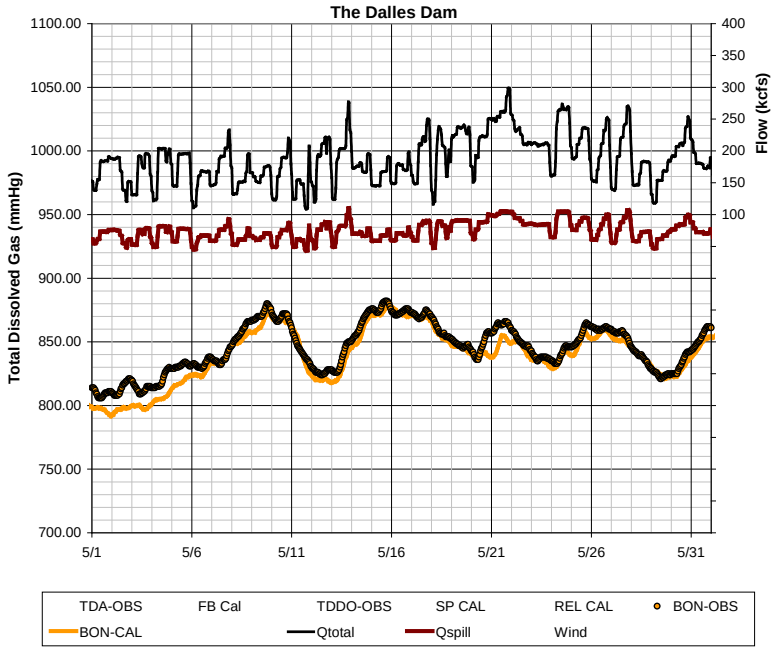

Figure G11. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the forebay of Bonneville Dam, May 2010

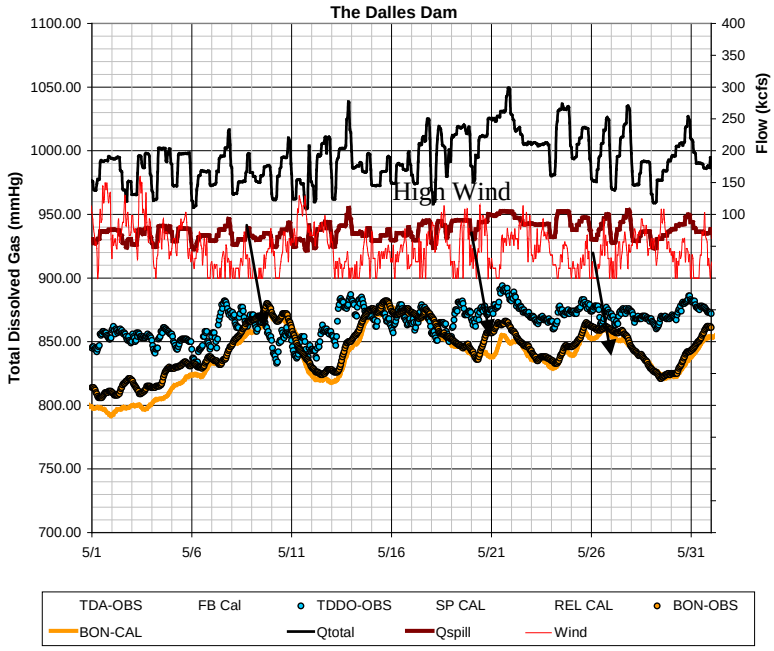

Figure G12. The Dalles Dam Operations with Observed and Calculated TDG Pressures in the forebay of Bonneville Dam and tailwater of The Dalles Dam, May 2010

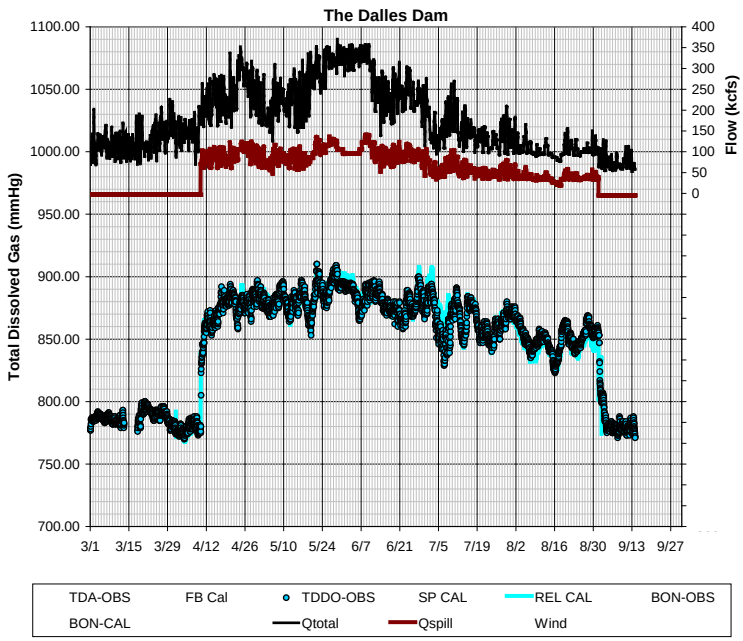

Figure G13. Observed and Calculated TDG Pressures in the tailwater channel of The Dalles Dam, March-September 2010

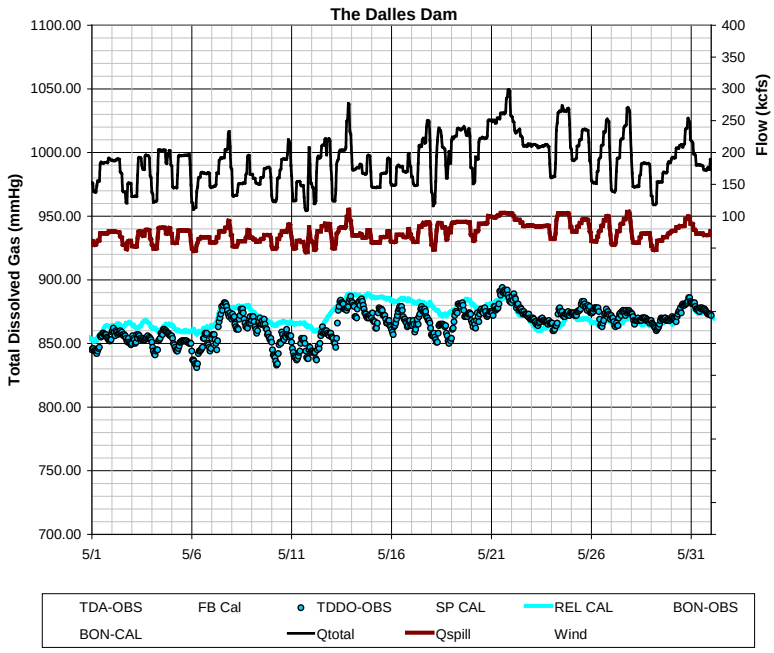

Figure G14. Observed and Calculated TDG Pressures in the tailwater channel of The Dalles Dam, May 2010

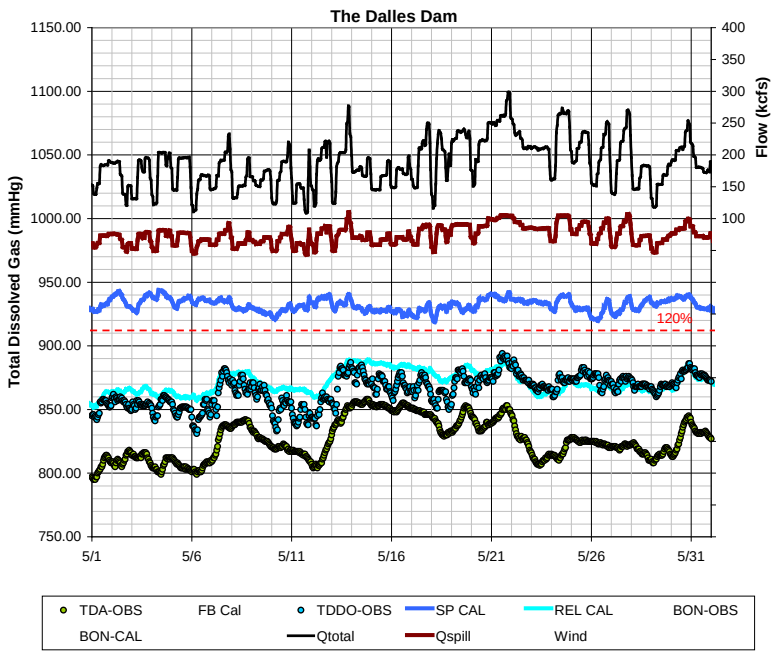

Figure G15. Observed and Calculated TDG Pressures in the tailwater channel of The Dalles Dam, May 2010

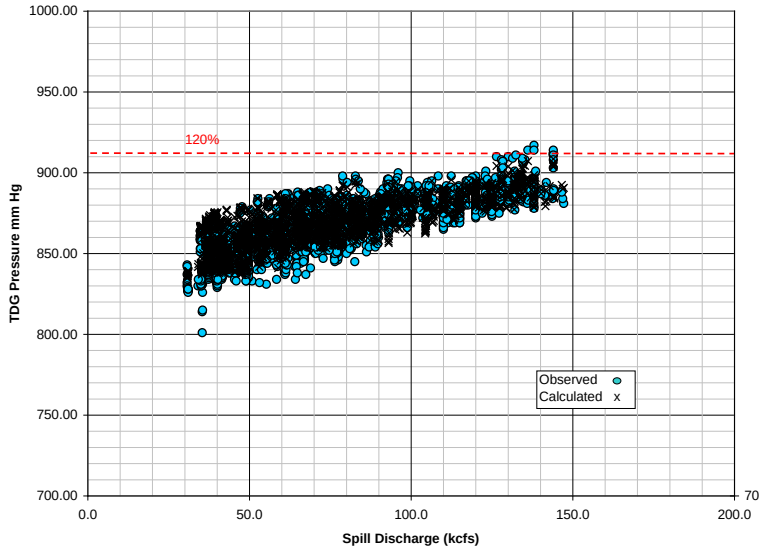

Figure G16. Observed and Calculated TDG Pressures below The Dalles Dam as a Function of Spillway Discharge, 2010

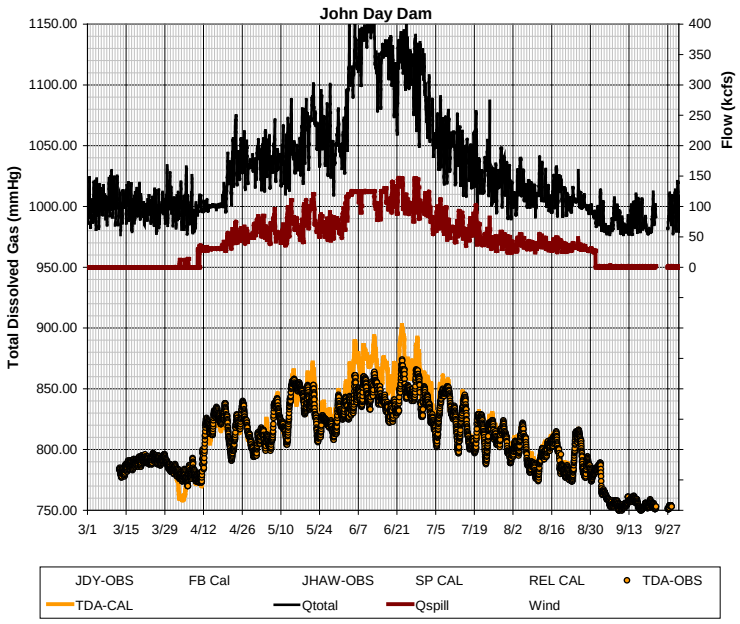

Figure G17. Observed and Calculated TDG Pressures in the forebay of The Dalles Dam, March-September 2010

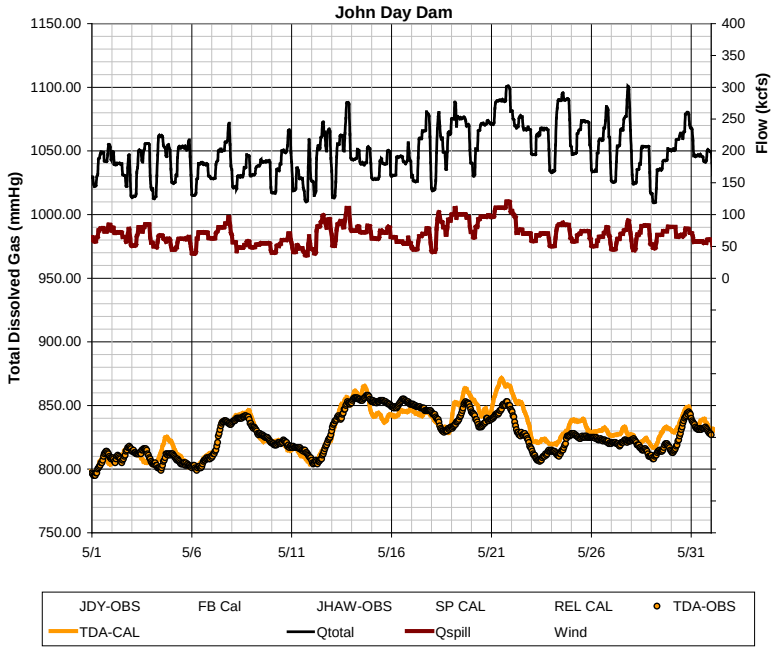

Figure G18. Observed and Calculated TDG Pressures in the forebay of The Dalles Dam, May 2010

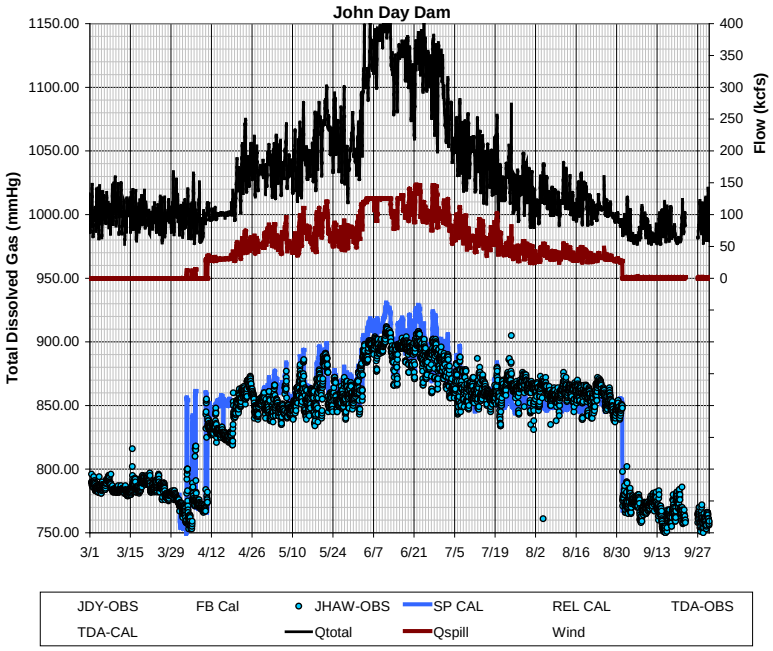

Figure G19. Observed and Calculated TDG Pressures in the tailwater channel downstream from John Day Dam, March-September 2010

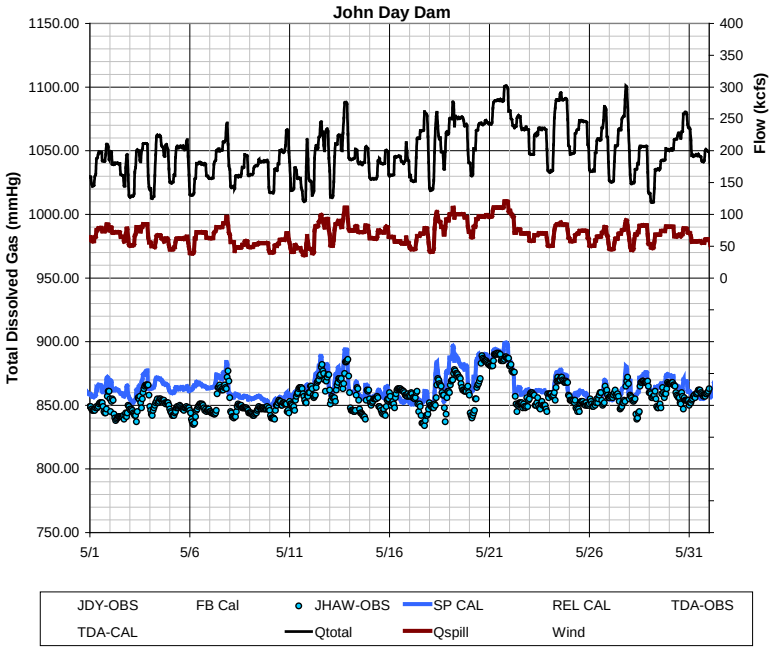

Figure G20. Observed and Calculated TDG Pressures in the tailwater channel downstream from John Day Dam, May 2010

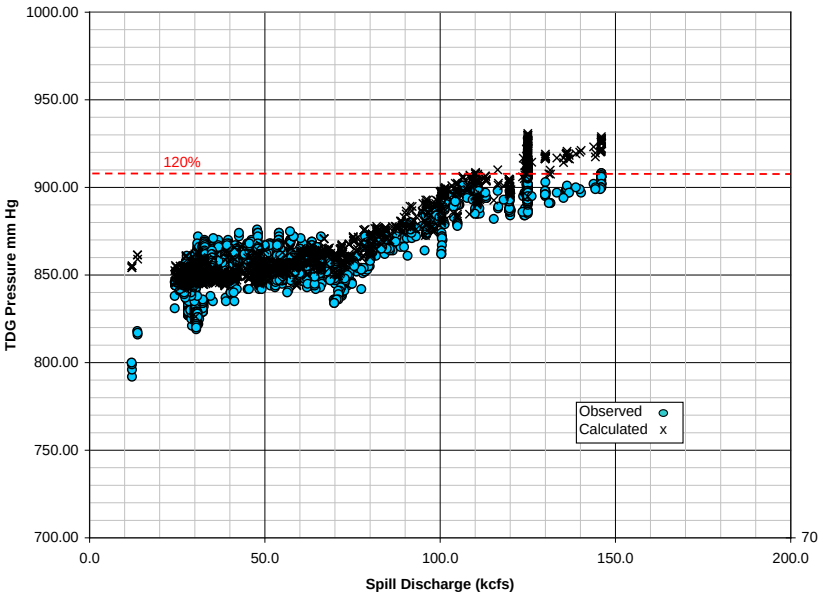

Figure G21. Observed and Calculated TDG Pressures below John Day Dam as a Function of Spillway Discharge, 2010

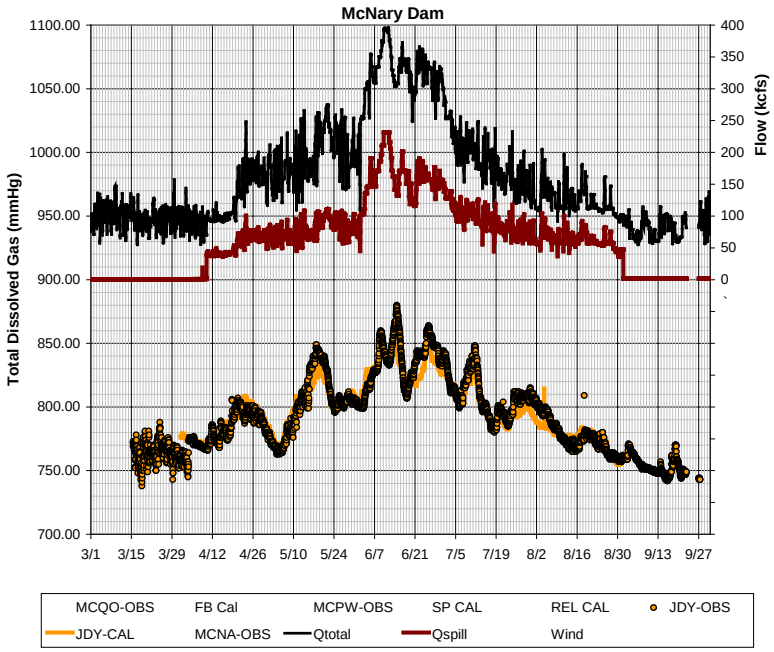

Figure G22. Observed and Calculated TDG Pressures in the forebay of John Dam, March-September 2010

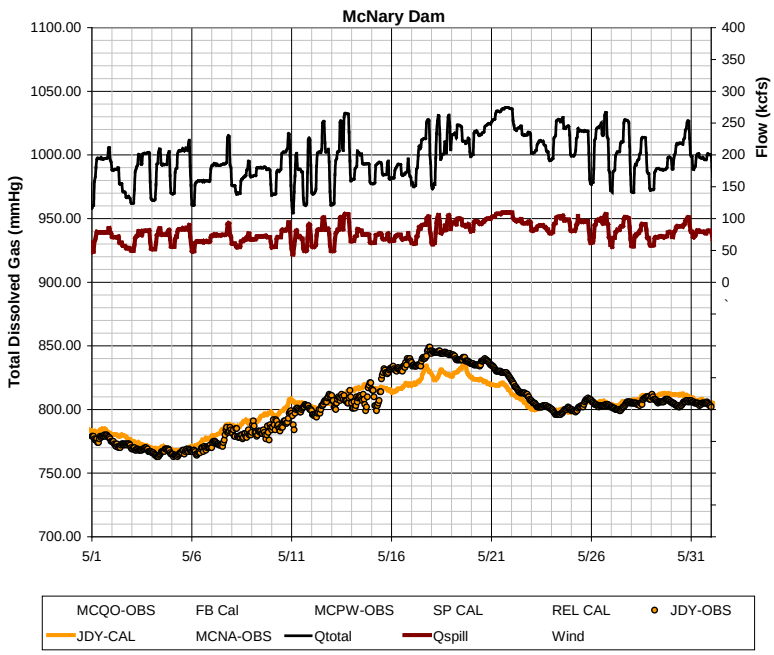

Figure G23. Observed and Calculated TDG Pressures in the forebay of John Dam, May 2010

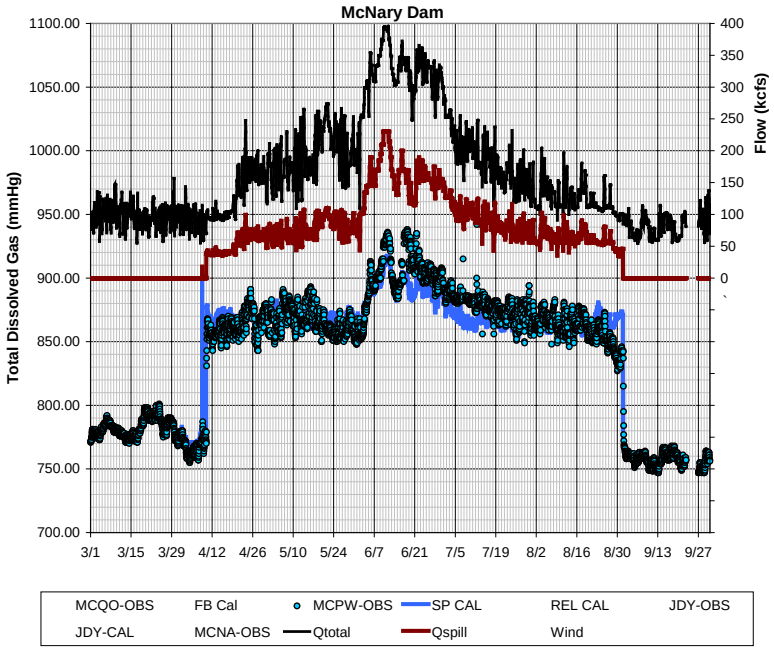

Figure G24. Observed and Calculated TDG Pressures in the tailwater of McNary Dam, March-September 2010

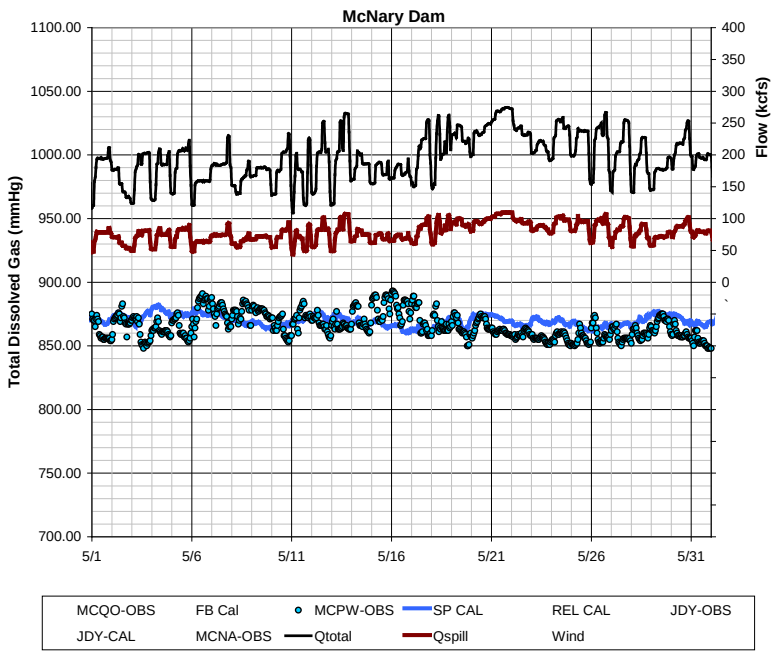

Figure G25. Observed and Calculated TDG Pressures in the tailwater of McNary Dam, May 2010

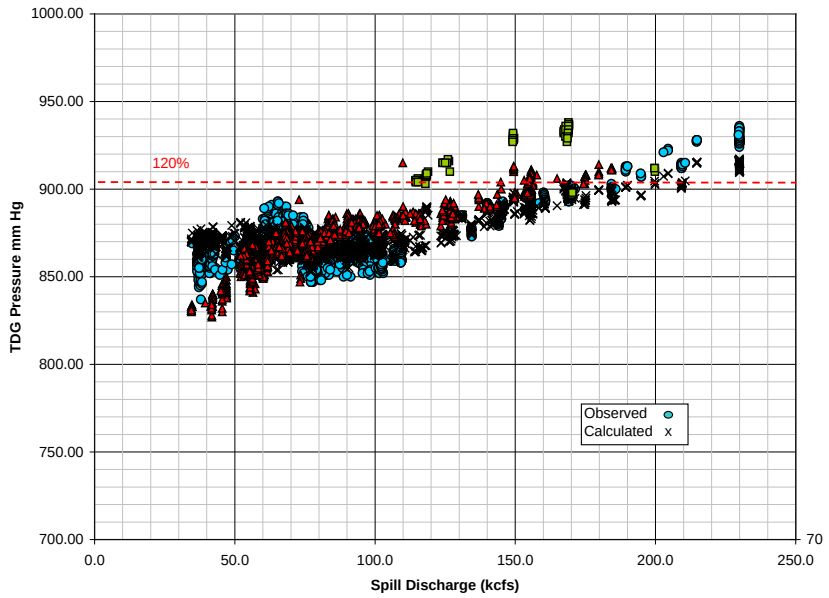

Figure G26. Observed and Calculated TDG Pressures below McNary Dam as a Function of Spillway Discharge, 2010 (Blue-Spring Spill Pattern, Red Summer Spill Pattern, Green-Transitional Spill Pattern)

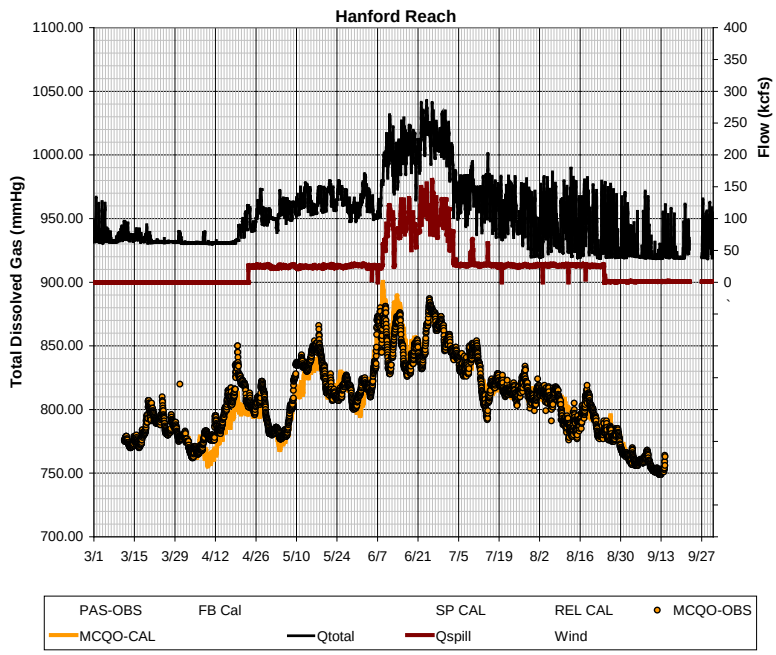

Figure G27. Observed and Calculated TDG Pressures in the forebay of McNary Dam, March-September 2010

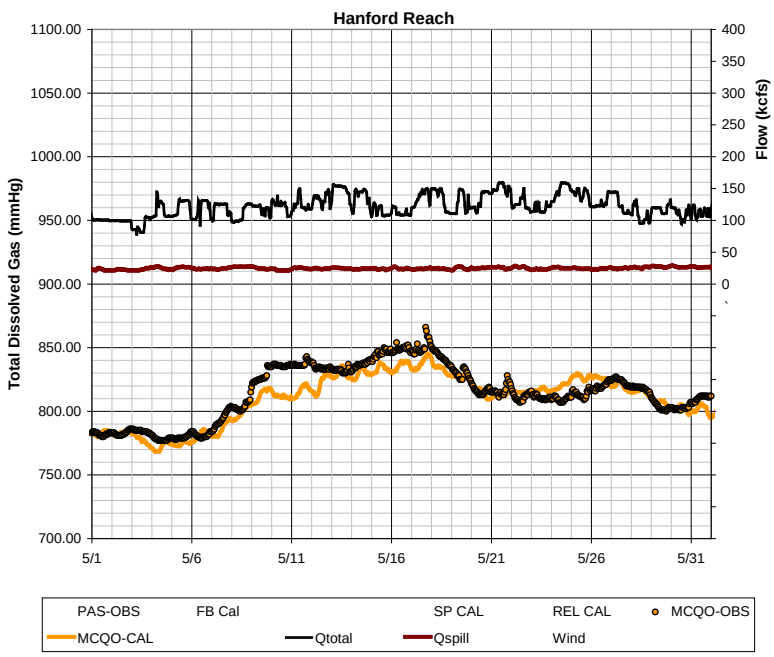

Figure G28. Observed and Calculated TDG Pressures in the forebay of McNary Dam, May 2010

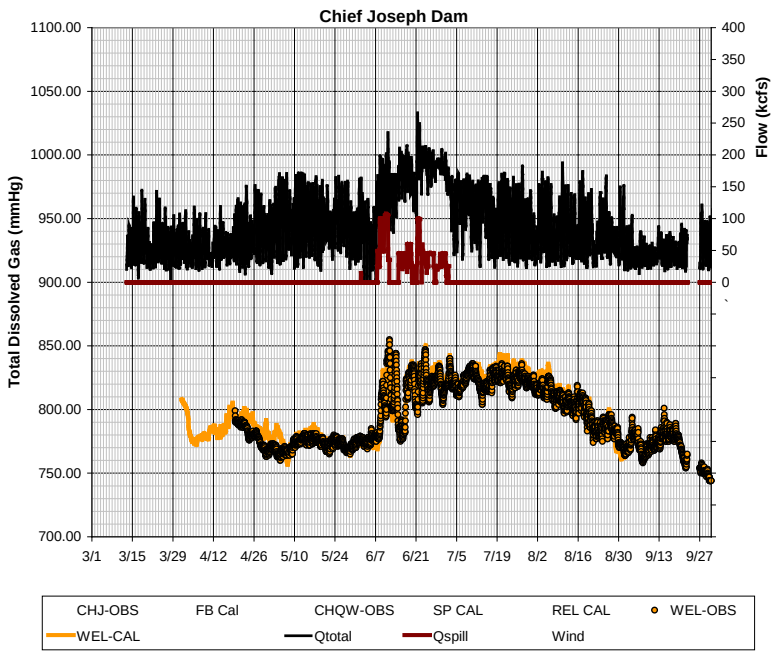

Figure G29. Observed and Calculated TDG Pressures in the forebay of Wells Dam, March-September 2010

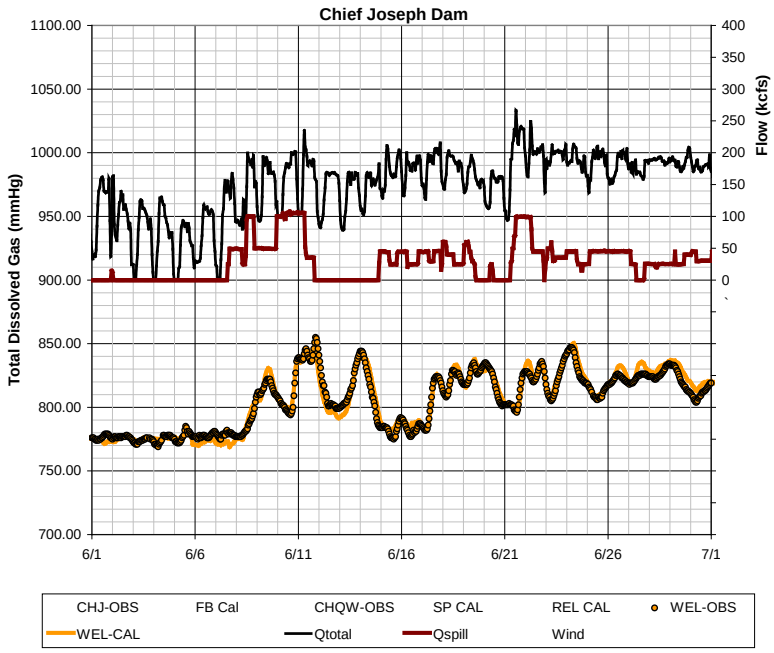

Figure G30. Observed and Calculated TDG Pressures in the forebay of Wells Dam, June 2010

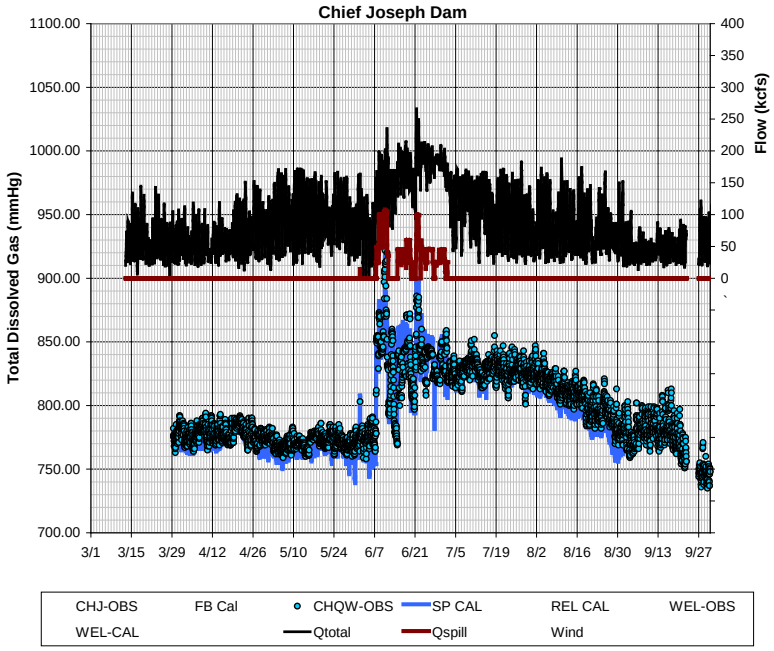

Figure G31. Observed and Calculated TDG Pressures in the tailwater of Chief Joseph Dam, March-September 2010

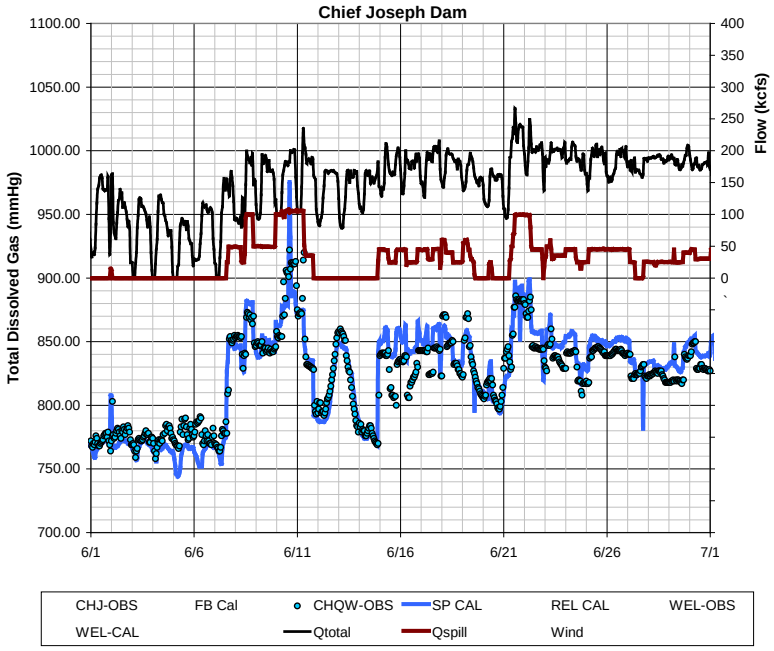

Figure G32. Observed and Calculated TDG Pressures in the tailwater of Chief Joseph Dam, June 2010

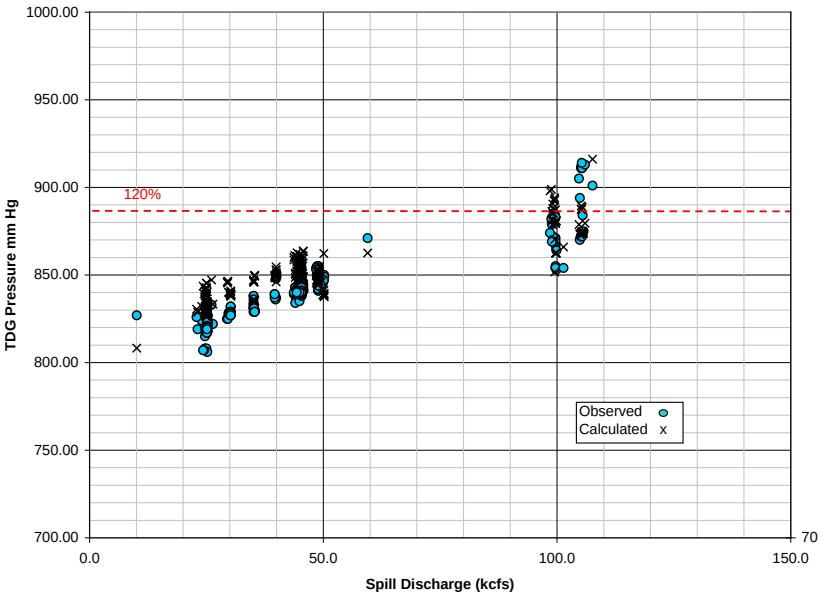

Figure G33. Observed and Calculated TDG Pressures below Chief Joseph Dam as a Function of Spillway Discharge, 2010 (Spill events with a duration of 3 hrs and longer)

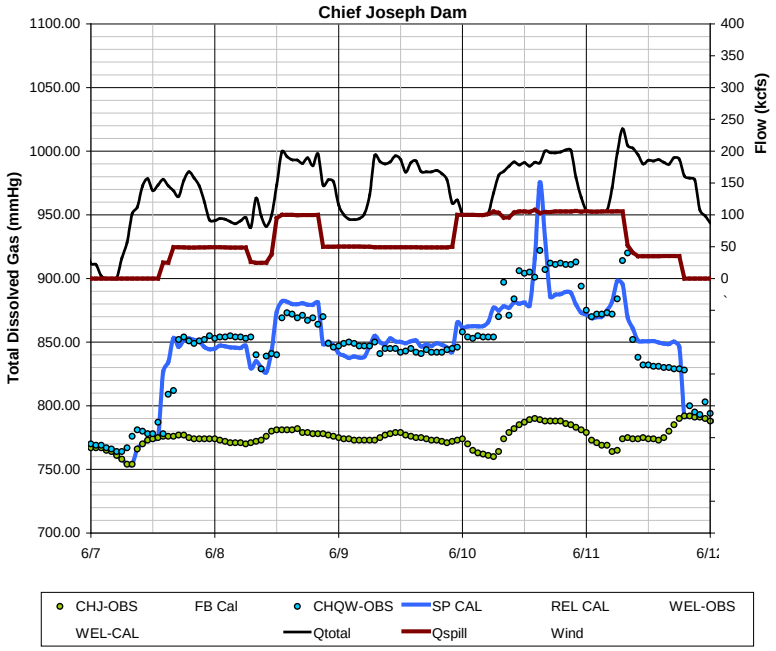

Figure G34. Observed and Calculated TDG Pressures in the tailwater of Chief Joseph Dam, June 6-11 2010

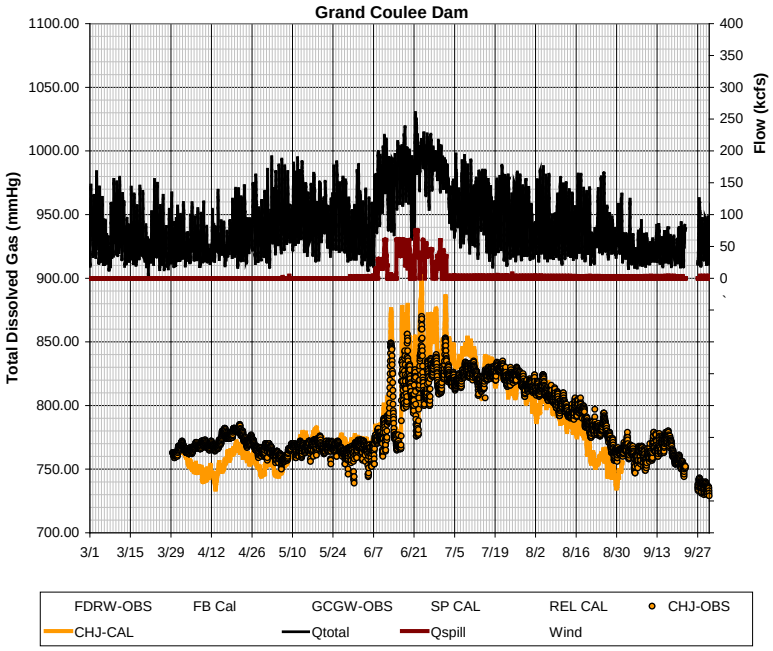

Figure G35. Observed and Calculated TDG Pressures in the forebay of Chief Joseph Dam, March-September 2010

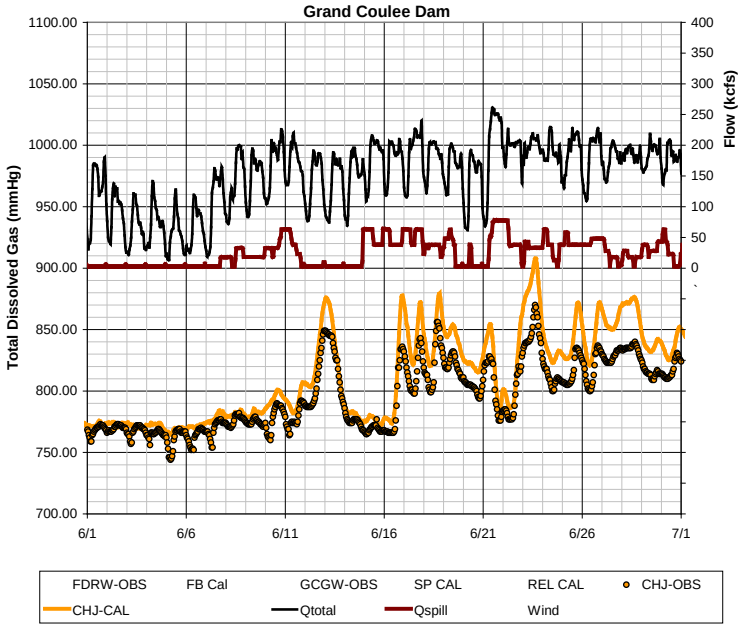

Figure G36. Observed and Calculated TDG Pressures in the forebay of Chief Joseph Dam, June2010

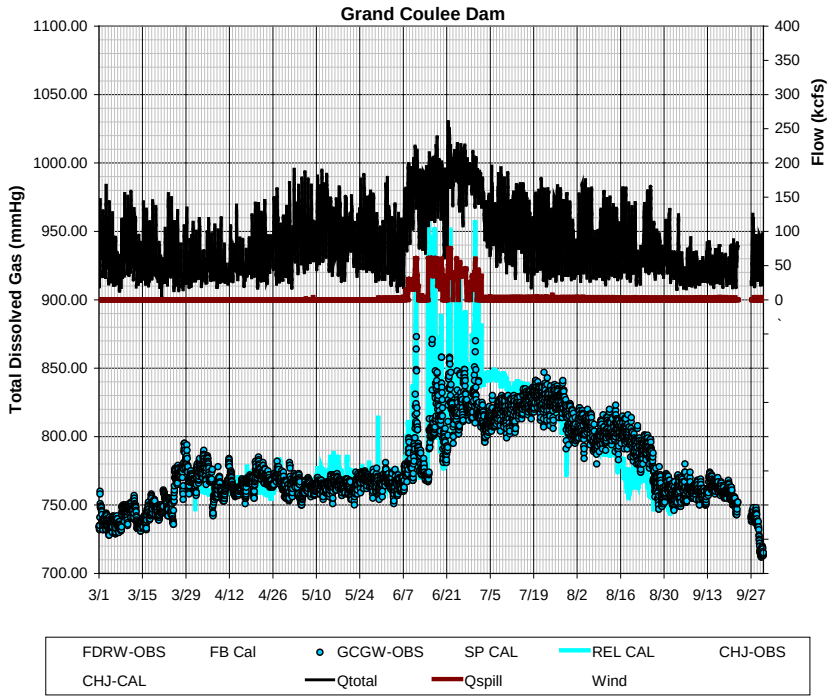

Figure G37. Observed and Calculated TDG Pressures in the tailwater of Grand Coulee Dam, March-September 2010

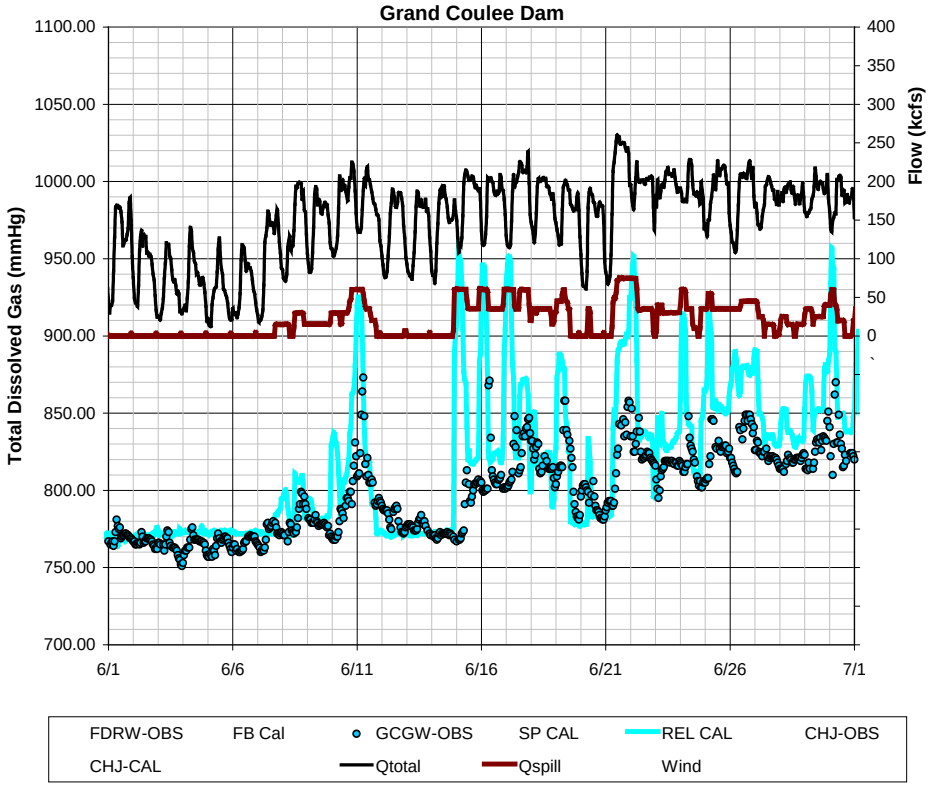

Figure G38. Observed and Calculated TDG Pressures in the tailwater of Grand Coulee Dam, June 2010

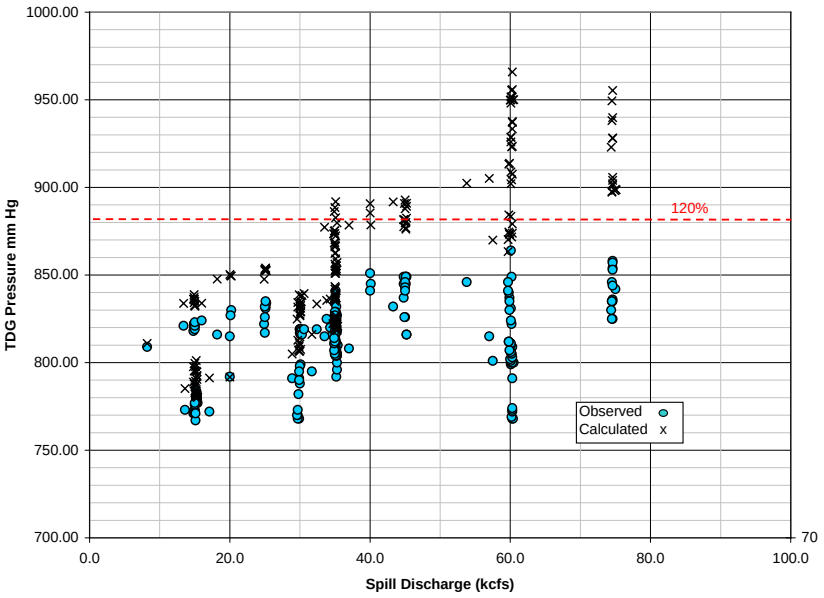

Figure G39. Observed and Calculated TDG Pressures below Grand Coulee Dam as a Function of Spillway Discharge, 2010

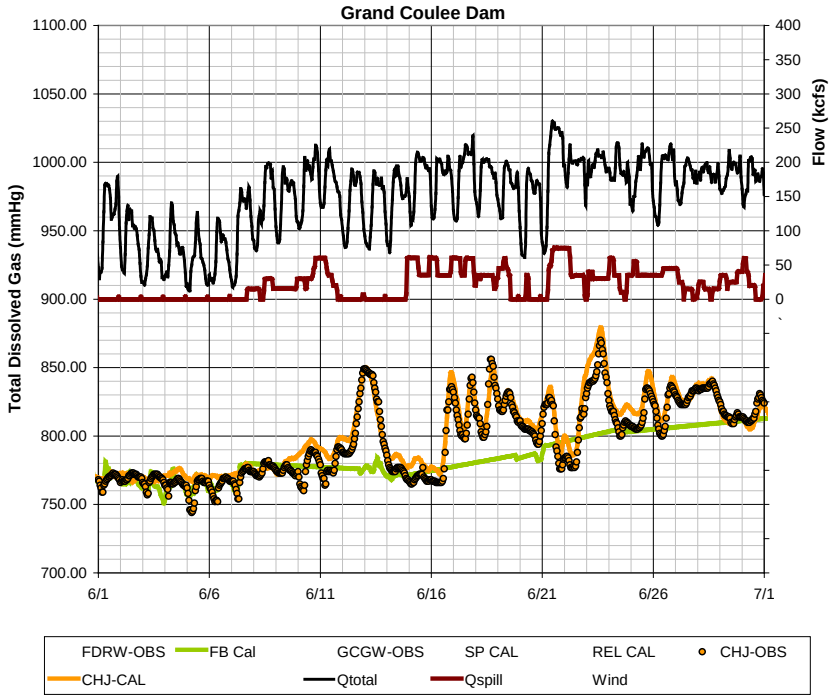

Figure G40. Observed and Calculated TDG Pressures in the Forebay of Chief Joseph Dam, June 2010 (Alternative TDG production equation for GCL)

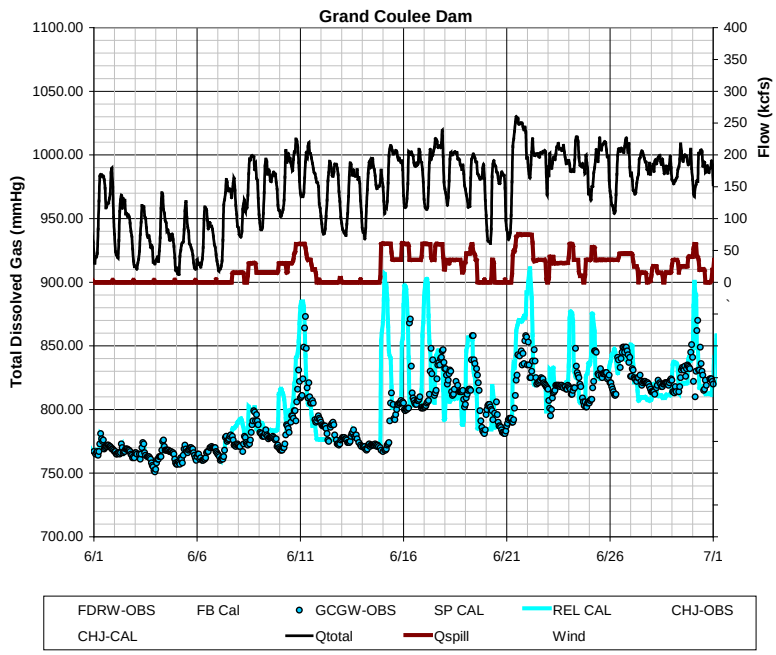

Figure G41. Observed and Calculated TDG Pressures in the Tailwater of Grand Coulee Dam, June 2010 (Alternative TDG production equation for GCL)

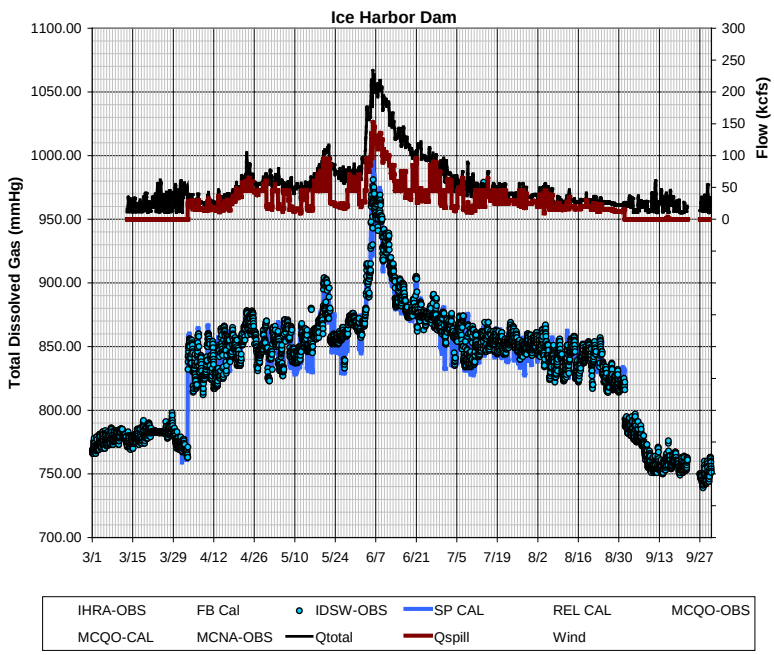

Figure G42. Observed and Calculated TDG Pressures in the Snake River in the tailwater downstream from Ice Harbor Dam, March-September 2010

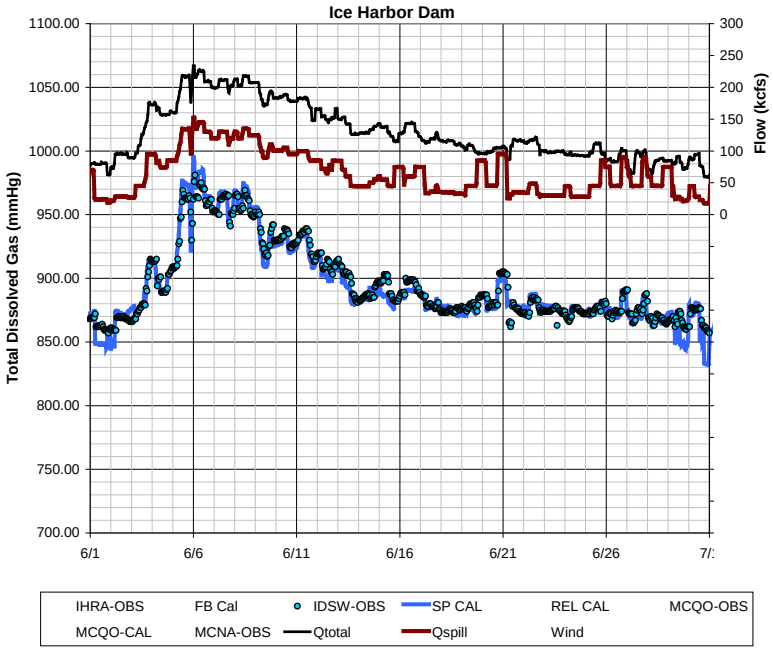

Figure G43. Observed and Calculated TDG Pressures in the tailwater downstream from Ice Harbor Dam, June 2010

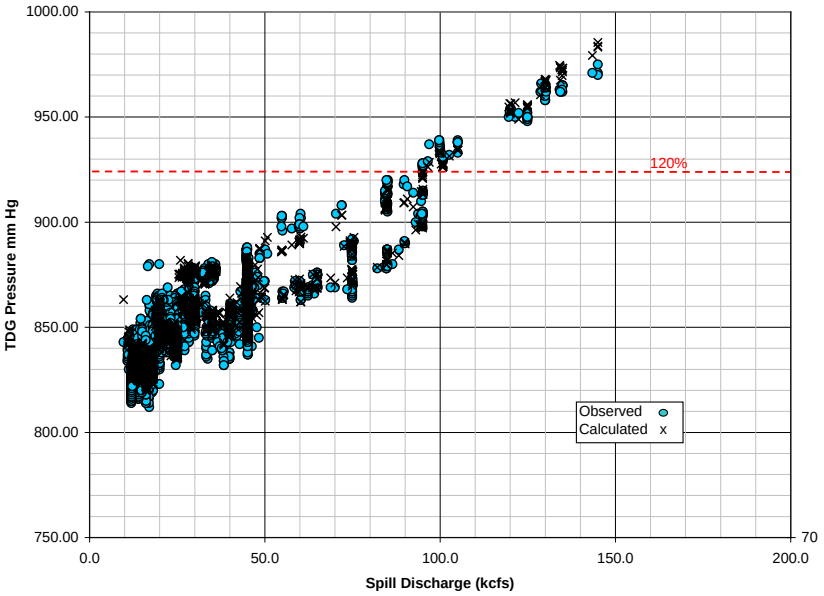

Figure G44. Observed and Calculated TDG Pressures below Ice Harbor Dam as a Function of Spillway Discharge, 2010

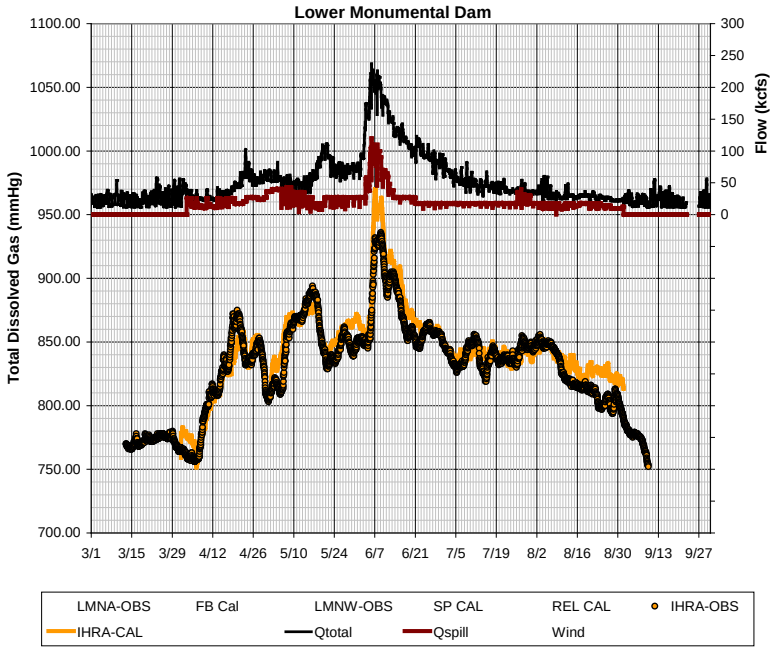

Figure G45. Observed and Calculated TDG Pressures in the forebay of Ice Harbor Dam, March-September 2010

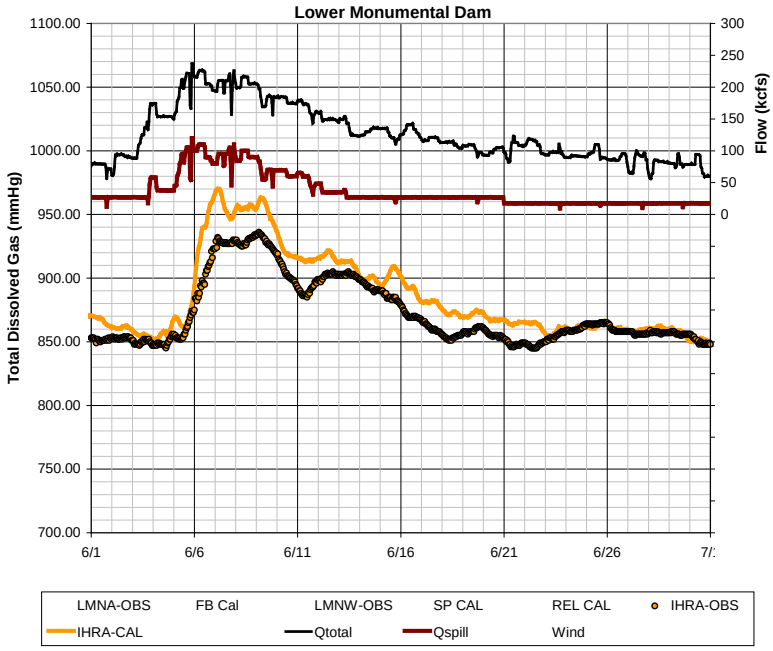

Figure G46. Observed and Calculated TDG Pressures in the forebay of Ice Harbor Dam, June 2010

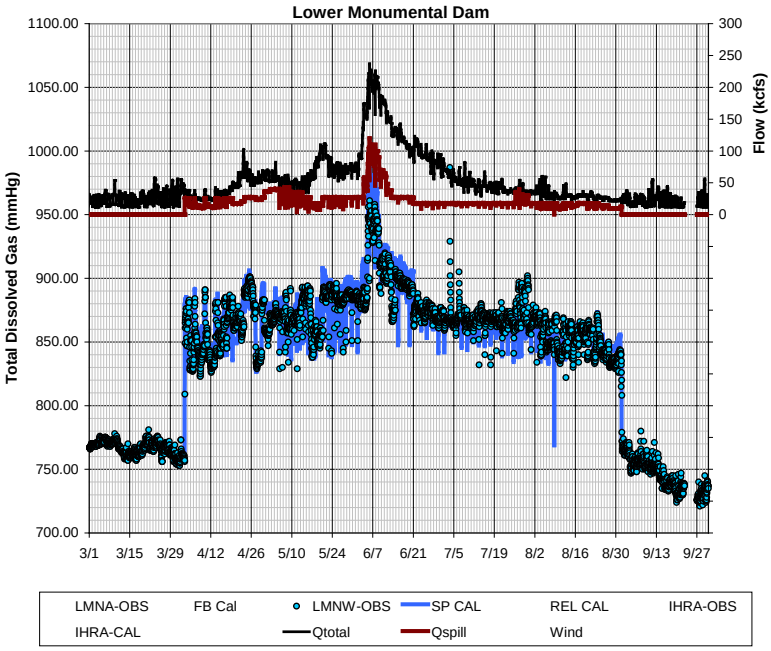

Figure G47. Observed and Calculated TDG Pressures in the tailwater channel downstream from Lower Monumental Dam, March-September 2010

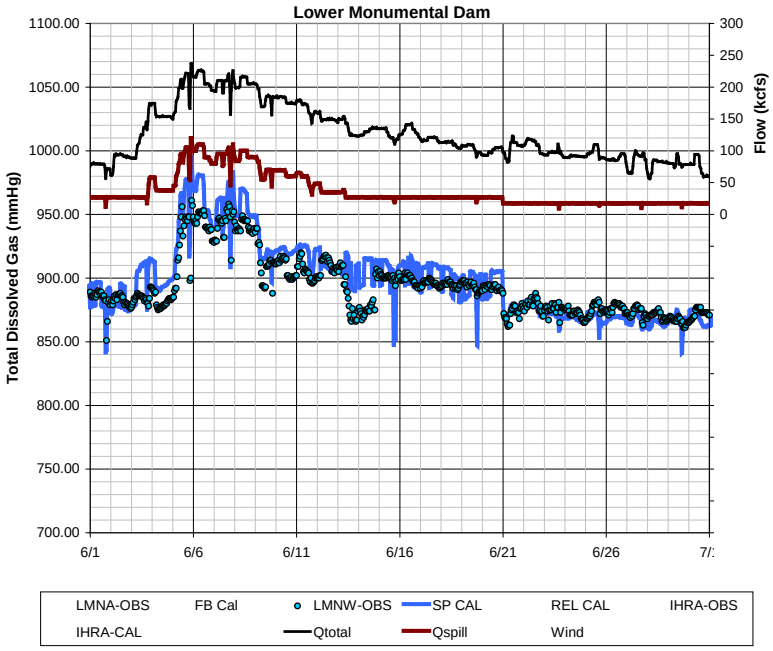

Figure G48. Observed and Calculated TDG Pressures in the tailwater channel downstream from Lower Monumental Dam, June 2010

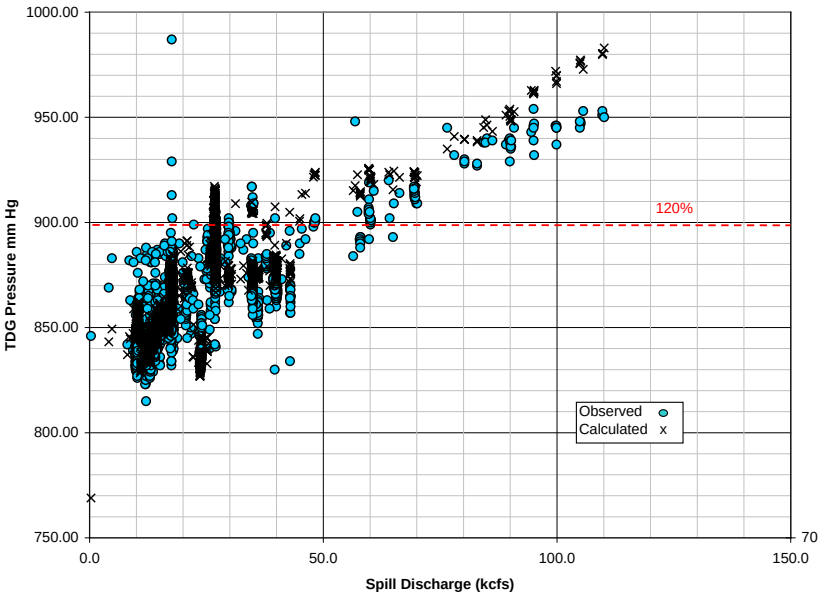

Figure G49. Observed and Calculated TDG Pressures below Lower Monumental Dam as a Function of Spillway Discharge, 2010

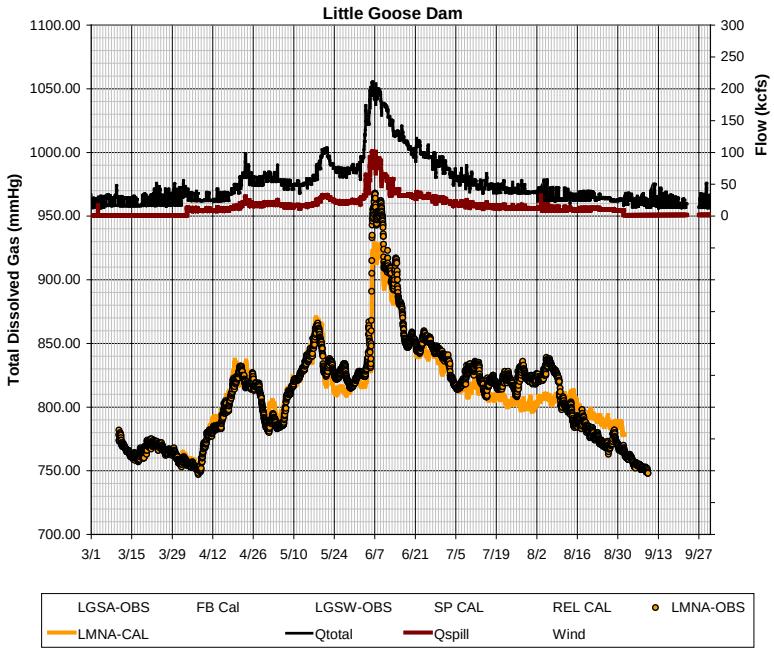

Figure G50. Observed and Calculated TDG Pressures in the forebay of Lower Monumental Dam, March-September 2010

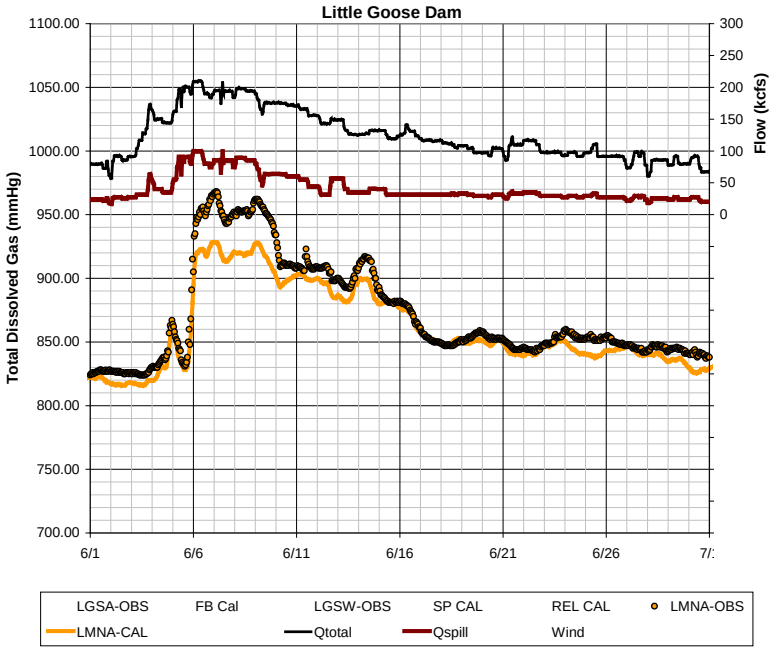

Figure G51. Observed and Calculated TDG Pressures in the forebay of Lower Monumental Dam, June 2010

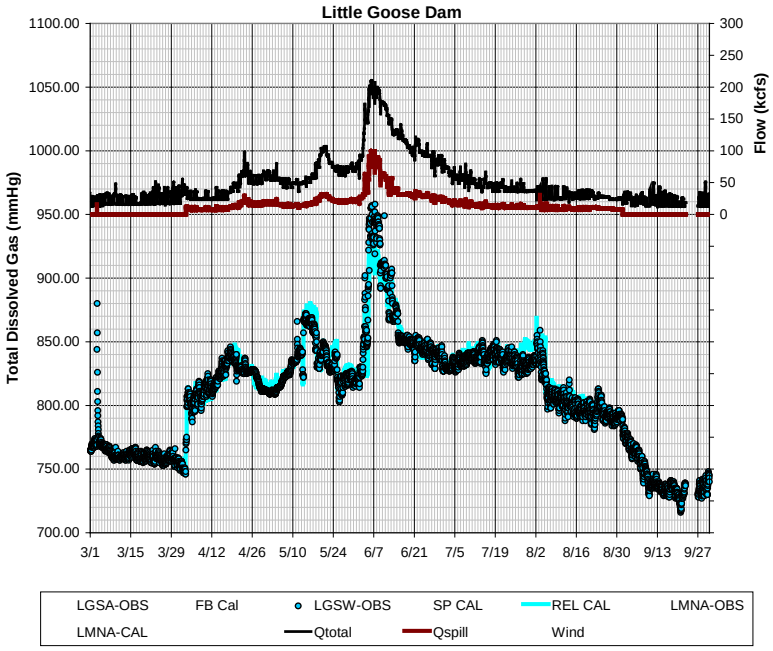

Figure G52. Observed and Calculated TDG Pressures in the tailwater channel downstream from Little Goose Dam, March-September 2010

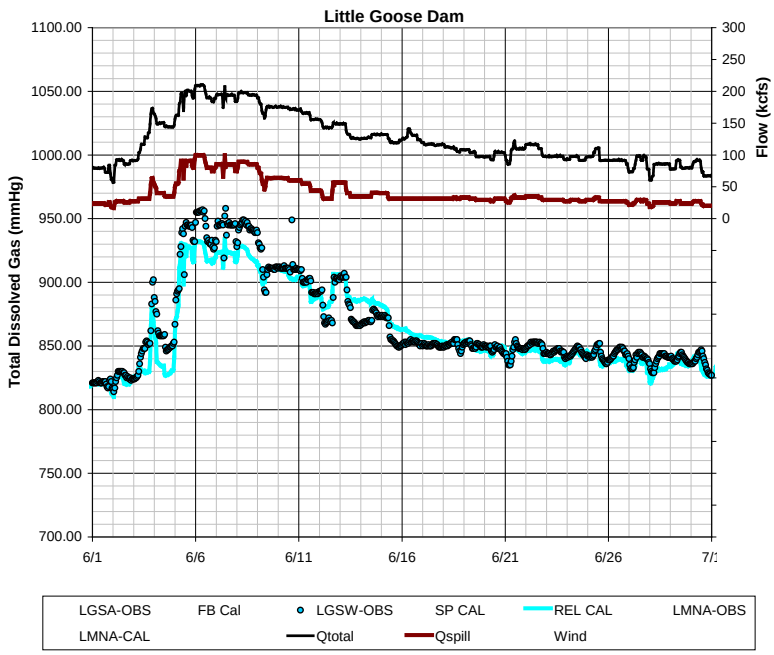

Figure G53. Observed and Calculated TDG Pressures in the tailwater channel downstream from Little Goose Dam, June 2010

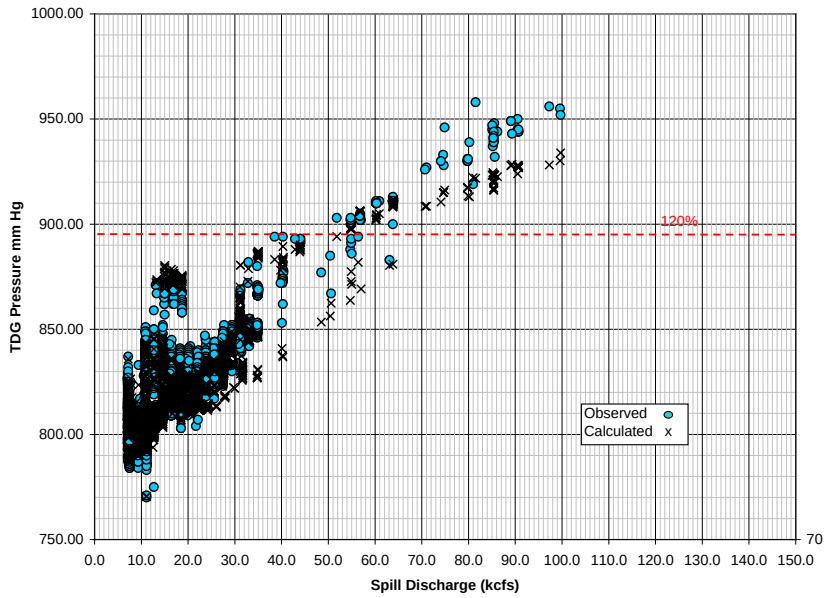

Figure G54. Observed and Calculated TDG Pressures as a Function of Spillway Discharge at the tailwater channel downstream from Little Goose Dam

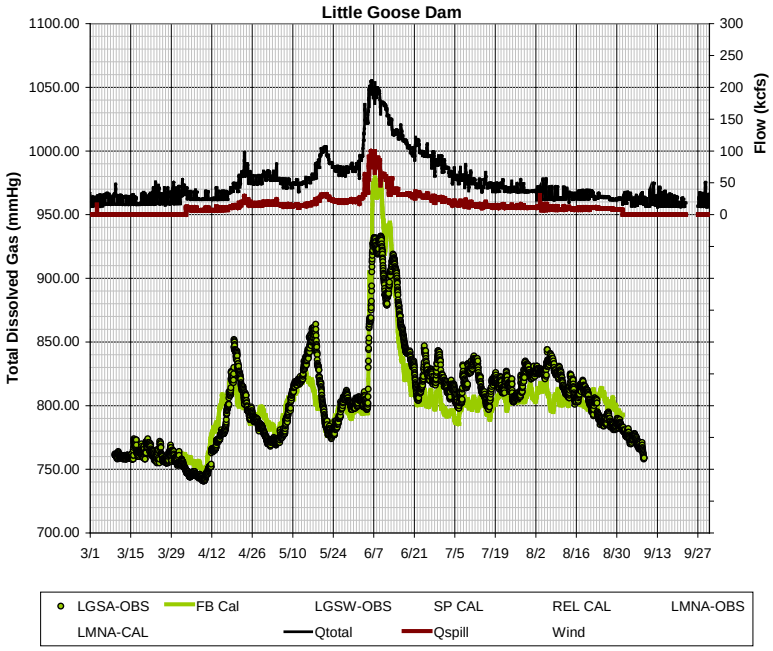

Figure G55. Observed and Calculated TDG Pressures in the forebay of Little Goose Dam, March-September 2010

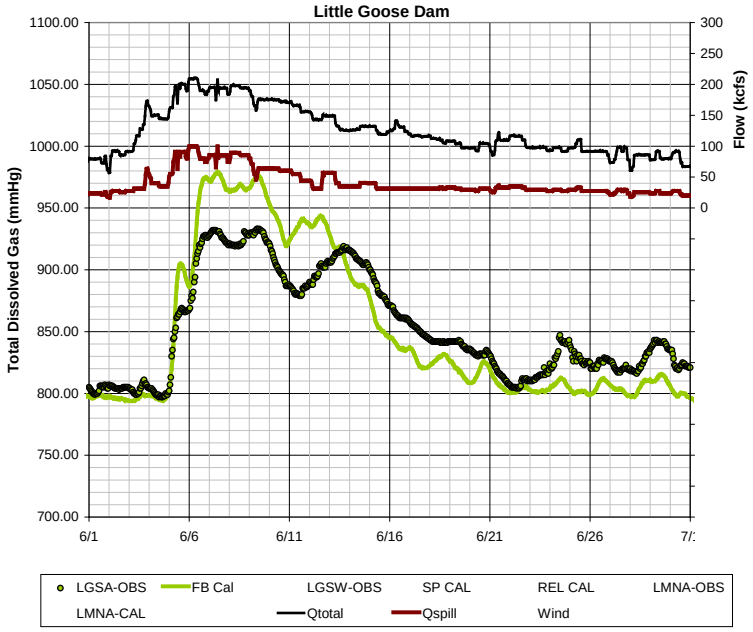

Figure G56. Observed and Calculated TDG Pressures in the forebay of Little Goose Dam, June 2010

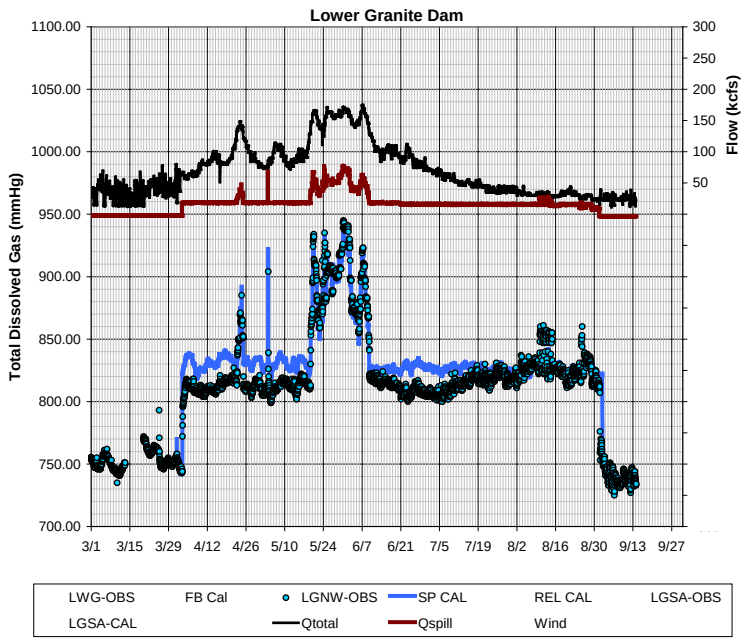

Figure G57. Observed and Calculated TDG Pressures in the tailwater channel downstream from Lower Granite Dam, March-September 2010

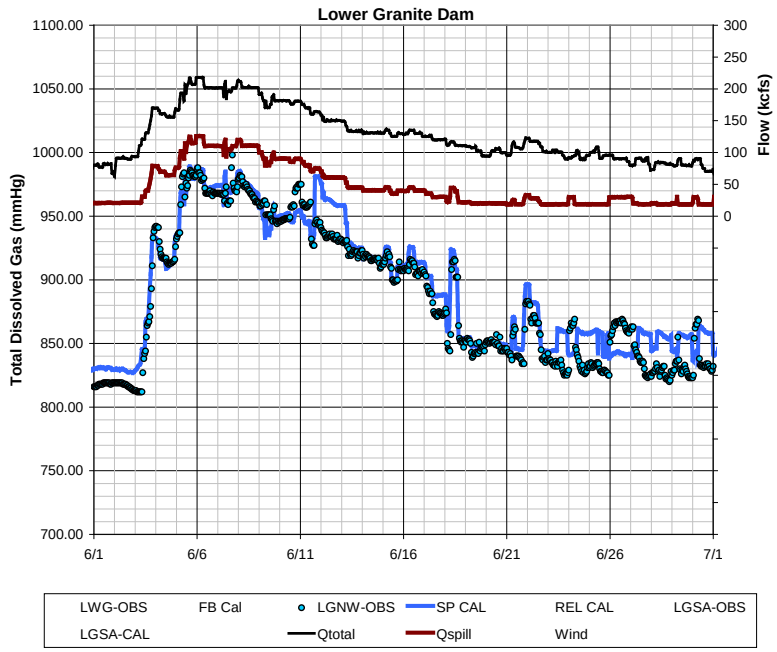

Figure G58. Observed and Calculated TDG Pressures in the tailwater channel downstream from Lower Granite Dam, June 2010

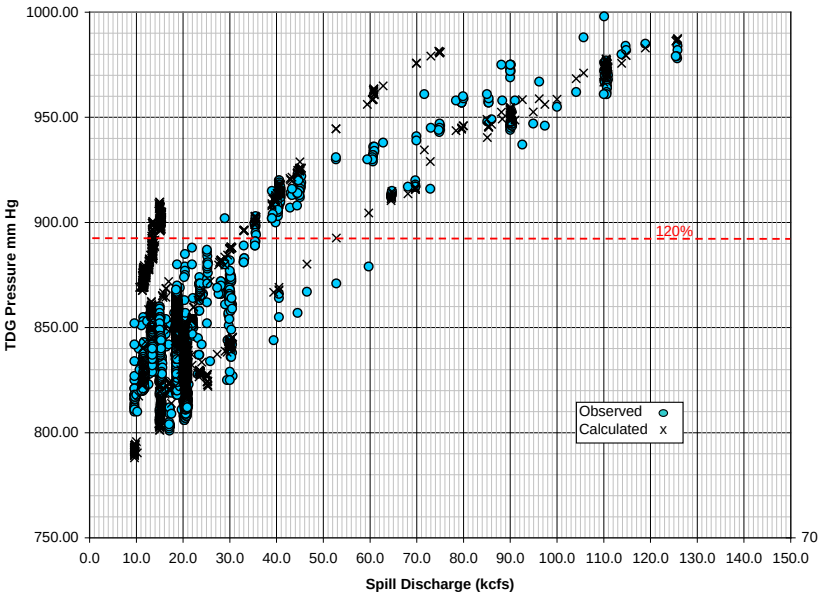

Figure G59. Observed and Calculated TDG Pressures below Lower Granite Dam as a Function of Spillway Discharge, 2010

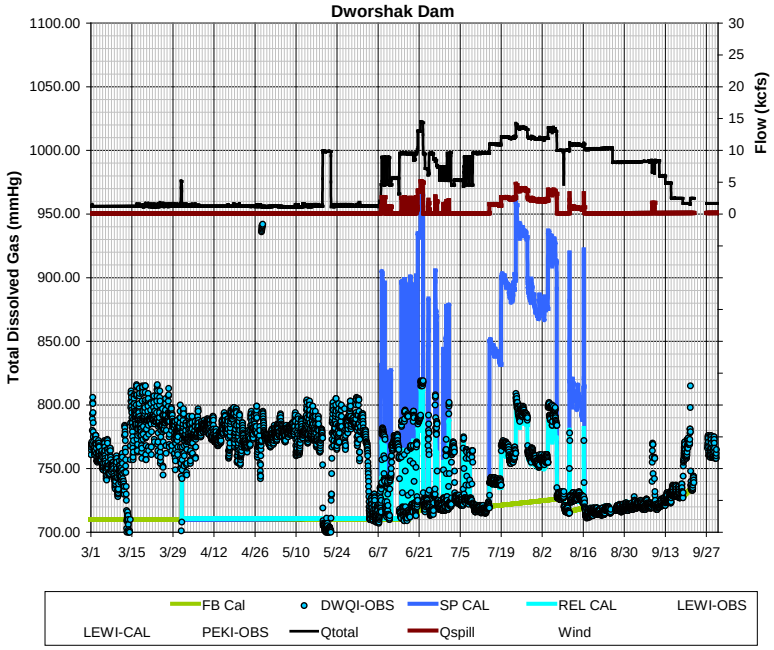

Figure G60. Observed and Calculated TDG Pressures in the tailwater channel downstream from Dworshak Dam, March-September 2010

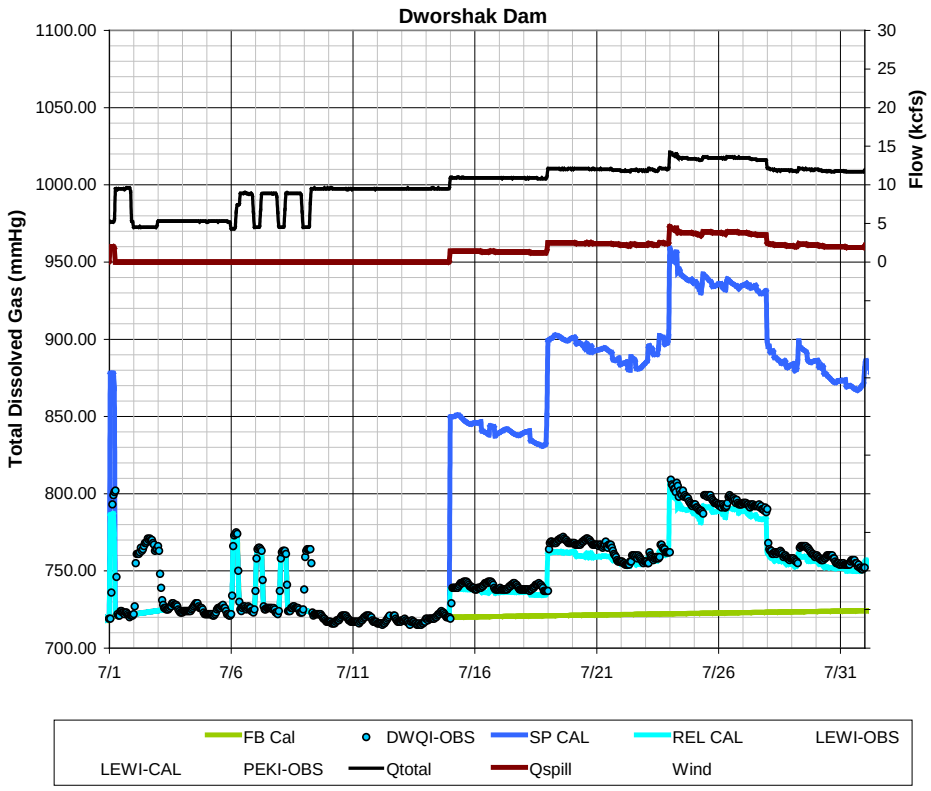

Figure G61. Observed and Calculated TDG Pressures in the tailwater channel downstream from Dworshak Dam, July 2010

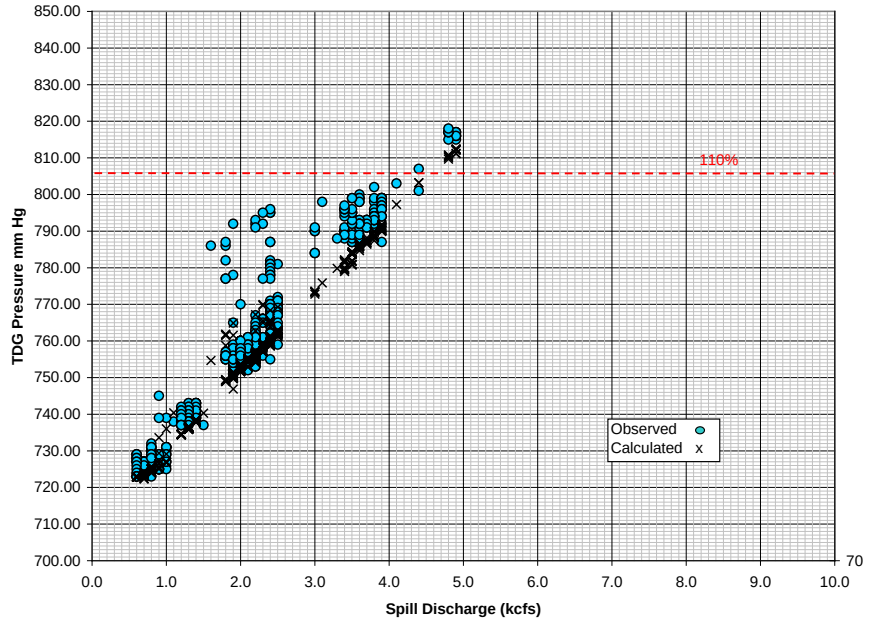

Figure G62. Observed and Calculated TDG Pressures below Dworshak Dam as a Function of Spillway Discharge, 2010