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 2009 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 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 and Dworshak Dam.

Approach

SYSTDG simulations were run for the entire 2009 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 sampling station 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 4 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 Lower 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 changes in water temperatures during passage through each river reach were 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 monitoring station. 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 2009 fish passage plan or auxiliary spill patterns were not implemented as scheduled at the dam. The model predictions are dependent upon the number of spillway bays that were active for any spill operation. 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 are common 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 stations 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 2009 were below normal in March, July, and August and near normal during the months of April, May, and June resulting in infrequent periods of forced spill causing the TDG saturation to exceed of the state water quality standards. The monthly average flow in the Columbia River at The Dalles Dam during the 2009 season was compared to flow conditions from 1975-2009 in Figure G1. The average Columbia River flow in March of 2009 was well below normal falling in the lower quartile of flows since 1975. The Columbia River flows rapidly increased in April with near normal flow conditions maintained through June. The monthly flows in July were below normal ranking the 13th smallest monthly flow since 1975. The flows in August of 2009 were also below normal causing longer travel times in pool reaches and lower tailwater conditions in the open river reach below Bonneville Dam.

On the Lower Columbia River, the highest percentage of total river flow spilled from April 1 through August 31 of about 43.8 percent, occurred at McNary Dam. The higher spill rate at McNary Dam resulted from the limited hydraulic capacity of the powerhouse and commitment to spill 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 McNary was 91.8 kcfs compared to 92.1 kcfs at Bonneville Dam, 73.5 kcfs at The Dalles Dam, and 61.6 kcfs at John Day Dams. The highest hourly spill of 204.5 kcfs occurred at McNary Dam. The spill policy at Priest Rapids Dam during 2009 (16% 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.

Table G1. Statistical Summary of Hourly Project Flows from April 1-August 31, 2009 on the 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)
N		3672	3672	3670	3670	3672	3672	3672	3672	3672	3672
Avg		214.2	92.1	199.9	73.5	205.5	61.6	209.4	91.8	116.1	18.6
Stdev		77	33.4	78.9	33.4	81.7	29.4	76.6	42	40.7	13.1
Max		369.1	171.7	371.5	145.1	405.8	130	362.5	204.5	238.3	81.2
Min		92.5	0	70.5	0	68.1	0	71.8	0	37.9	0
Q_{spill}/Q_{total}			43		36.8		30		43.8		16
Percentile	1%	93.5	0	84.2	0	81.8	0	85.9	0	41.2	0
	5%	108.3	2.4	95.4	0	94.8	0	109.3	0	48.4	0
	25%	143.3	75.2	127.9	46.2	130.9	37	141.6	66.3	82.1	17.1
	50%	217.6	94.5	190	76.1	199.3	64	206.1	90.3	120.4	21.7
	75%	270	101.1	264	100	269.7	84.9	267.9	112.6	145.7	23.4
	95%	344.6	149.4	336.2	124.4	349	108	342	170	179.2	39.7
	99%	351	159.6	355.5	137.9	372.9	120	356.2	181	202.4	61
*Units kcfs except for Q_{spill}/Q_{total} entry.											

The Snake River contributed about 38 percent of the flow to the Lower Columbia River during the period from April 1- August 31, 2009. Ice Harbor spilled about 55.2 percent of the Snake River flow during this period compared to 30.3, 28.8, and 30.0 percent for Lower Monumental, Little Goose, and Lower Granite Dams, respectively as listed in Table G2. 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 and the biological testing of the removable spillway weir (RSW). The largest hourly spill of 102.0 kcfs occurred at Ice Harbor Dam during the 2009 spill season. The spill volume at Lower Granite Dam was similar to those scheduled at Little Goose and Lower Monumental Dams. The spill at Dworshak Dam was intermittent during the 2009 study period and was scheduled during July and August to help manage Snake River temperatures. Flows in excess of powerhouse capacity at Dworshak Dam were passed either by the regulating outlets or over the spillway. The highest spill rate at Dworshak Dam was 6.5 kcfs.

Table G2. Statistical Summary of Hourly Project Flows from April 1-August 31, 2009 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)
N		3672	3672	3672	3672	3672	3672	3672	3672	3672	3672
Avg		80.4	44.4	78.4	23.7	76.7	22.1	80.3	24.1	8.9	1.3
Stdev		41.9	23.7	41.2	9.8	38.3	10.8	41.1	13.1	4.1	1.7
Max		181.3	102	176.9	75.1	165.4	57.7	175.9	79.7	17.1	6.5
Min		21.4	0	19.2	0	17.2	0	18.7	0	1.6	0
Q_{spill}/Q_{total}			55.2		30.3		28.8		30		14.4
Percentile	1%	24.5	0	23.9	0	24.5	0	25.9	0	1.6	0
	5%	29.9	15.6	29.3	12.5	26.3	8.1	29.9	16.8	1.7	0
	25%	40.2	25	37.8	17.5	39.9	11.8	43.7	18.7	6.4	0
	50%	78.6	40.1	75.8	19.9	74.3	22.1	78.7	20.3	9.6	0
	75%	103.1	64.8	101.2	28.9	98.2	29.4	103.6	20.6	12.1	2.7
	95%	160.9	89.7	158.6	42.1	151.3	44.1	162.1	56.5	14.9	4.3
	99%	173.9	94.8	171.9	55	158.6	49.6	169.2	75.4	15.1	4.5
*Units kcfs except for Q_{spill}/Q_{total} entry.											

The total dissolved gas saturation was monitored in the forebay and tailwater of each Lower Columbia River Dam throughout the spill season of 2009. The average hourly TDG saturation in the forebay of each dam ranged from a high of 110.0 at Bonneville Dam to a low of 107.4 percent at John Day Dam (Table G3). The average TDG saturation at Camas/Washougal station (CWMW) located about 22 miles downstream of Bonneville Dam in mixed water and grouped with other forebay stations, was slightly higher at 113.2 percent as listed in Table G3. The frequency of hourly observations greater than 115 percent at forebay stations ranged from 29.3 percent at CWMW to a low of 1.8 percent in the forebay of McNary Dam. The TDG saturation exceeded 120 percent only at CWMW fixed monitoring station.

The average TDG saturation at the tailwater stations ranged from 116.9 percent at Bonneville to 114.0 percent at The Dalles Dam (Table G3). The tailwater station at The Dalles Dam reflects the contributions from both powerhouse and spillway flows unlike the other three projects where the tailwater station monitors the TDG content in spillway flows undiluted from powerhouse flows. The frequency of hourly TDG observations exceeding 120 percent at the tailwater monitoring stations ranged from 15.0 percent below Bonneville Dam to only 0.0 percent at The Dalles Dam. The likelihood of the TDG saturation at tailwater station exceeding the 120 percent level was less than the frequency of the next forebay station exceeding 115 percent at all the Lower Columbia River projects during the 2009 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 moving 12 hour average as referenced by the state water quality standards in Oregon and Washington.

Table G3. Statistical Summary of Hourly Total Dissolved Gas Saturation at Fixed Monitoring Stations from April 1-August 31, 2009 on the Columbia River

Station		Bonneville				The Dalles		John Day		McNary
		CWMW	WRNO	CCIW	BON	TDDO	TDA	JHAW	JDY	MCPW
		FB	TW	TW	FB	TW	FB	TW	FB	TW
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
N		3672	376	3672	3618	3671	3671	3657	3671	3610
Avg		113.2	108.7	116.9	110	114	109.3	114.8	107.4	115.3
Stdev		3.4	4.1	3.6	4.5	3.6	3.8	3.9	4.5	3.3
Max		121.3	115.2	125.6	119.6	119.9	119.7	121.1	118.6	122.4
Min		101.7	102.7	108.2	100.7	100.7	100.5	100.9	98.8	100.5
TDG Exceedance (%)	100	100	100	100	100	100	100	100	95.4	100
	105	96.6	78.2	100	81.4	94.1	82.9	94.1	66.2	96.3
	110	89.7	41.5	99.5	56.5	92.2	49.8	94	31	94.1
	115	29.3	0.3	59.4	15.3	46.3	6	52.4	5.3	65.7
	120	1.2	0	15	0	0	0	4.2	0	0.9
	125	0	0	0.1	0	0	0	0	0	0
	130	0	0	0	0	0	0	0	0	0

The total dissolved gas saturation was monitored in the forebay and tailwater of each Lower Snake River dam throughout the spill season of 2009. The average hourly TDG saturation in the forebay of each Snake River dam increased in a downstream direction as listed in Table G4. The average forebay TDG saturation at Lower Granite, Little Goose, Lower Monumental, and Ice Harbor Dams wer3.2, 108.6, 111.4, and 112.8 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 24.9 percent at Ice Harbor Dam. The frequency of hourly TDG saturation exceeding 115 percent was also high at Lower Monumental Dam at 15.6 percent during the 2009 fish passage season.

The average TDG saturation at the tailwater stations ranged from 116.5 percent at Lower Monumental Dam to 111.2 percent at Lower Granite Dam. The frequency of hourly TDG observations exceeding 120 percent at the tailwater monitoring stations ranged from a high of 11.9 percent below Ice Harbor Dam to 0.2 percent at Little Goose Dam. The frequency of the forebay station exceeding the 115 percent criteria was greater than the frequency of the upstream tailwater station exceeding 120 percent which implies that forebay stations more frequently constrain spill operations on the Snake River than TDG conditions at tailwater stations.

Table G4. Statistical Summary of Hourly Total Dissolved Gas Saturation at Fixed Monitoring Stations from April 1-August 31, 2009 on the Snake and Clearwater River

Project		Ice Harbor		Lower Monumental		Little Goose		Lower Granite	
		IDSW	IHRA	LMNW	LMNA	LGSW	LGSA	LGNW	LWG
		TW	FB	TW	FB	TW	FB	TW	FB
Station		(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
N		3672	3672	3671	3672	3672	3596	3672	3672
Avg		115.6	112.8	116.5	111.4	112.9	108.6	111.2	103.1
Stdev		3.2	3.3	2.7	3.9	2.5	3.9	4.4	2
Max		123.2	119.5	123.1	121.6	122	122	127.4	108.2
Min		102.5	100.7	101.1	99.1	99.8	99.3	100.7	99
TDG Exceedance (%)	**100**	100	100	100	99.2	99.8	98.4	100	96.9
	105	98.7	97.1	98.7	95.4	98.7	93	98.7	16.8
	110	98.1	85.5	98.7	69.5	96	22.8	48.7	0
	115	59	24.9	80.2	15.6	15	9.5	14.8	0
	120	11.9	0	8.4	0.6	0.2	1.8	8.2	0
	125	0	0	0	0	0	0	1.5	0
	130	0	0	0	0	0	0	0	0

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 stations 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 G7 describe the predictive errors statistics in mm Hg of pressure while Table G6 and 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 stations, the predictive errors were analyzed only for spill operations with a duration of 4 hours and longer to exclude transient TDG observations.

Camas/Washougal (CWMW)

A hind cast of Bonneville operations were simulated using the SYSTDG model for the river reach from Bonneville Dam to the fixed monitoring station located at

Camas/Washougal (CWMW) from 1 April through 31 August 2009. The predictive error of the hourly total dissolved gas pressure was determined throughout the interval involving 3648 observations. The calculated TDG pressures under-estimated observed conditions by an average of 10.2 mm Hg (average predictive error +10.2mm Hg) and the standard deviation of the predictive error was 13.8 mm Hg as listed in Table G5. The size of the predictive error in 2009 at CWMW was slightly greater than determined in 2008 due to the wider range in project operations (standard deviation of the predictive error was 10.4 mm Hg in 2008). The low flow and tailwater conditions during the month of July and August resulted in the largest errors in TDG saturation at the CWMW gauge resulting in estimated TDG levels consistently smaller than observed levels. The influence of the Bonneville 2nd powerhouse corner collector outfall was likely the source for the under prediction of the TDG loading at Bonneville Dam. The 50 percent confidence interval for the predictive error ranged from +18.1 to +0.2 mm Hg of pressure and the 80 confidence interval ranged from +32.0 to -2.7 mm Hg. The seasonal time history of observed and calculated TDG pressures at the CWMW gage is shown in Figure G2. There were instances where the TDG saturation at the CWMW exceeded the TDG criteria of 115% of saturation in each of the months of spill. The excursions during the first two months of the year were often related with elevated background TDG levels. The excursions during the summer months were associated mainly with spill to capacity directives during the nighttime hours.

For most of the study period, there were small differences in the observed and calculated TDG pressures at the CWMW gage 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 July and August. The estimated TDG saturation generally underestimated the observed conditions during the late summer month even with the more prominent TDG contributions from the B2CC. In summary, predicted TDG levels during from April-June were closely reproduced. However, the TDG levels during July and August months under-estimated the observed conditions. The predictive error summaries in terms of TDG saturation at the CWMW stations are listed in Table G6. 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 water quality standards.

Model update for Bonneville Dam There are a number of plausible explanations for the biased estimates of TDG pressure during the months of July and August at CWMW. The most likely source for these errors is the TDG loading associated with the B2CC outfall. The under estimation of TDG pressures at CWMW generally corresponded with low powerhouse flow and tailwater conditions. It is reasonable to believe that the amount of entrained air and trajectory of the outfall jet will be a function of tailwater elevation, particularly when the tailwater elevation falls below the outlet channel invert of 16 ft. The available depth of plunge (-70 ft elevation in plunge pool) and entrainment of bounding spillway and powerhouse 2 discharge will directly contribute to the TDG

exchange. The contribution of TDG generation associated with the B2CC outfall is contained in columns labeled Qtr, Tmptr, and TDGtr on the BON workbook. The discharge of the B2CC outfall was determined from a rating curve developed in the 1 to 50 scale general model of the Bonneville 2nd powerhouse and is a function of the forebay elevation. The temperature of the B2CC outfall was set equal to the forebay conditions. The TDG response in the 2009 version of SYSTDG assumed a constant level of 1250 mm Hg. The TDG contribution was based on observations of TDG exchange during a detailed near field study of TDG exchange at the outfall. The estimated TDG level is considered the effective TDG pressure and includes the mass uptake associated in entrained waters. The amount of entrainment was observed to approach 4 times the discharge of the outfall.

An alternative TDG generation formulation for the B2CC outfall was evaluated for the 2009 spill season at Bonneville Dam. The added TDG mass at the outfall was assumed to be piecewise linear as described by the following relationship:

$$TDG_{B2cc} = 1250 \qquad TWE>16 \text{ ft}$$
$$TDG_{B2cc} = 1250(16-TWE)/8+1250 \qquad TWE<16 \text{ ft}$$

Where TDG_{B2cc}=Corner Collector Outfall TDG Pressure (mm Hg)
TWE = Tailwater Elevation (ft)

The relationship will retain the constant TDG pressures applied during high tailwater conditions where the outfall retains a horizontal orientation while attaining increasingly higher levels as the tailwater drops and the outfall transitions to a plunging flow. The modified corner collector TDG relationship was incorporated in the SYSTDG model significantly reducing the predictive error of estimate. The average predictive error was 2.0 mm Hg compared to 10.2 mm Hg for the 2009 SYSTDG formulation and the standard error was 7.7 mm Hg down from 13.8 mm Hg. The original (CWMW-cal) and updated (CWMW-cal2) SYSTDG estimates of TDG pressure at the CWMW gage are shown in Figure G4 for the month of August. The proposed TDG exchange formulation for the outfall provides for an additional 20 to 50 mm Hg at the CWMW station compared to the 2009 TDG exchange model. The proposed formulation was not based upon direct observations of TDG pressures near the B2CC outfall but the residual TDG pressures observed over 20 miles downstream. Other processes that could also account for the under-estimation of TDG pressures at the CWMW gage include under-estimation of TDG generated in spillway flows (plunging jet originating from bays with elevation 14 ft deflectors), temperature induced pressure changes in route, biological productivity, and off gassing exchange rates.

Table G5. Statistical summary of the predictive errors of the observed and calculated total dissolved gas pressures at forebay fixed monitoring station, April 1-August 31, 2009.									
		Predictive Error at Forebay FMS* (mmHg)							
Parameter/Station		LGSA	LMNA	IHRA	MCNA	JDY	TDA	BON	CWMW
Number of		3543	3649	3673	3673	3647	3645	3592	3648
Average		1.8	-5.4	-2.7	-0.3	3.8	0	0.2	10.2
Standard Deviation		13.4	12	9	11.5	10.2	8.9	6.5	13.8
Maximum		41.1	20.6	24.8	37.9	34.4	34.8	38.6	58.8
Minimum		-38.6	-41.6	-32.7	-34.5	-36.4	-27	-23.2	-20.3
TDG Predictive Error for Percentile Occurrence (mm Hg)	5%	-24.5	-31	-21	-18.1	-8.8	-14.4	-10.6	-4.1
	10%	-17.5	-25.2	-16.9	-14	-7	-10.8	-9	-2.7
	25%	-5.9	-11.4	-6.9	-8.5	-3.9	-5.5	-4.4	0.2
	50%	4.2	-2.2	-1.2	-1.4	1.4	0	0.7	5
	75%	10.5	3.3	3.3	7.6	9.4	4.6	4.6	18.1
	90%	16	7	6.9	14.8	19.4	9.9	7.5	32
	95%	20.8	9.3	9.4	19	24.4	15.8	9.4	39.3

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

Bonneville Dam Tailwater (WRNO)

A hind cast of Bonneville operations was conducted using the SYSTDG model of the river reach from the Bonneville Dam to the fixed monitoring station located at Camas/Washougal from 1 April through 31 August 2009, in an effort to determine the prediction error of SYSTDG simulations in Bonneville Dam tailwater. The official tailwater compliance station below Bonneville Dam is located in the spillway exit channel at station 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 from January 1 to April 16 during part of the 2009 fish passage season. One short-coming of the Warrendale gage is its location in an eddy or recirculation cell located near the Oregon shore which tends to dampen its response to bulk TDG properties in deeper portions of the river away from the channel bank. The calculated flow weighted average TDG pressures released from Bonneville Dam were lagged 4 hours and compared to the observed TDG pressures at the WRNO gage. The calculated TDG pressures under-estimated observed conditions by an average of 2.3 mm Hg (average predictive error +2.3 mm Hg) and the standard deviation of the predictive error was 6.5 mm Hg as listed in Table G7. The 50 confidence interval of the predictive error ranged from -2.7 to 7.0 mm Hg of pressure and the 80 confidence interval ranged from -5.7 to 10.8 mm Hg of pressure. The standard error of TDG pressure at the WRNO station during the 2009 season was considerably smaller than determined in 2008 (6.5 to 10.2 mm Hg). The seasonal time history of observed and calculated TDG pressures at the WRNO gage is shown in Figure G5. The daily TDG values at Warrendale are a function of both the TDG levels associated with spillway operations at Bonneville Dam and the TDG levels produced at upstream dams and discharged through both powerhouses at Bonneville Dam. The calculated and observed TDG pressures at WRNO are shown throughout the month of April in Figure G6. The B2CC was activated on April 3 and accounts for an increase in TDG pressures of about 10-20 mm Hg. The

spillway discharge of 100 kcfs was begun on April 10 resulting in a 50 mm Hg increase over previous operating conditions at the WRNO gage.

Table G6. Statistical summary of the predictive errors of the observed and calculated total dissolved gas saturation at forebay fixed monitoring station, April 1-August 31, 2009.

		Predictive Error at Forebay FMS* (Saturation %)							
Station		LGSA	LMNA	IHRA	MCNA	JDY	TDA	BON	CWMW
Number of		3543	3649	3673	3673	3647	3645	3592	3648
Average		0.6	-0.4	0	0.3	0.9	0	0	1.3
Standard Deviation		1.8	1.6	1.2	1.5	1.3	1.2	0.9	1.8
Maximum		5.9	3.1	3.7	5.2	5	4.6	5.1	7.7
Minimum		-4.9	-5.2	-4	-4.3	-4.6	-3.6	-3.1	-2.7
TDG Predictive Error for Percentile Occurrence (mm Hg)	5%	-3	-3.8	-2.4	-2.1	-0.9	-1.9	-1.4	-0.5
	10%	-2	-3.1	-1.9	-1.6	-0.6	-1.4	-1.2	-0.4
	25%	-0.5	-1.2	-0.5	-0.8	-0.2	-0.7	-0.6	0
	50%	0.9	0.1	0.2	0.1	0.5	0	0.1	0.7
	75%	1.8	0.8	0.8	1.3	1.6	0.6	0.6	2.4
	90%	2.5	1.3	1.3	2.3	2.9	1.3	1	4.2
	95%	3.1	1.6	1.6	2.8	3.6	2.1	1.2	5.1

*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 fixed monitoring station 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 Cascade Island (CCIW) from 1 April through 31 August 2009. 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 spill exceeded 900 mm Hg in March in several cases. The seasonal time history of observed and calculated TDG pressures at the CCIW gage are shown in Figure G7.

The calculated mean prediction error of TDG pressures at the CCIW gage was equal to 4.7 mm Hg and the standard deviation of the predictive error was 6.1 mm Hg as listed in Table G7 under the label of CCIW. The 50 confidence interval for the predictive error ranged from -2.9 to 7.0 mm Hg of pressure and the 90 confidence interval ranged from 12.3 to -7.2 mm Hg of pressure. It should be noted that the calculated TDG pressures under-estimated the observed values during periods with little of no spill in April. The elevated TDG levels registered at the CCIW gage during the first week in April are associated with supersaturated conditions in the Adult fish ladders. The estimates of TDG saturation in the Bonneville exit channel were based on the cross sectional average TDG pressures as determined during the 2002 TDG exchange study conducted at Bonneville (Schneider, 2003). This study determined that for spill discharges higher than 120 kcfs, TDG pressures observed near the CCIW station underestimated the cross sectional average TDG saturation in the spillway exit channel. The sample bias is considerable at CCIW 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 station CCIW during nighttime spill in the summer. A detailed summary of calculated and observed TDG pressures in spill at the CCIW gage during May 2009 is shown in Figure G8. The uniform spill of 100 kcfs during much of the month of May resulted in a broad range of TDG pressures due to subtle changes in the spill pattern and fluctuations in the tailwater elevation. The exact form of the spill pattern is subject to the discretion of the plant operator. Two alternative spill patterns used at Bonneville for a 100 kcfs spill are shown in Figure G9. In Case A, the gate opening for bay 2 was set at 3.5 stops as compared to 3.0 stops for Case B. This subtle variation in the spill pattern had a significant effect on the TDG pressures measured downstream at the CCIW gage with Case A (higher Bay 2 opening) resulting in a TDG pressure of 923 mm Hg compared to 903 mm Hg for the Case B pattern.

Table G7. Statistical summary of the predictive errors of the observed and calculated total dissolved gas pressures at tailwater fixed monitoring stations.

		Predictive Error at Tailwater EMS* (mm Hg)									
Paramaters/Stations		DWQI	LGNW	LGSW	LMNW	IDSW	MCPW	JHAW	TDDO	CCIW	WRNO
Number of Observations		1353	3322	3243	2893	2158	1551	1517	3431	2799	371
Average		-3.2	-11	0.3	1.1	-2.8	2.7	10.7	-3.9	4.7	2.3
Standard Deviation		12.2	9.8	8.4	13	7.5	8.1	14.3	7.2	6.1	6.5
Maximum		26.6	45.9	39.8	49.1	17.7	35.4	40.8	15.1	57.7	21
Minimum		-45.2	-30.8	-36.7	-35.6	-27.6	-30.8	-19.7	-48.3	-11.7	-19.5
TDG Predictive Error for Percentile Occurrence (mm Hg)	5%	-26.7	-23.5	-13.9	-27.6	-16.8	-10.1	-10	-5	-7.2	-14.5
	10%	-23.3	-22	-10	-17.1	-14	-6.7	-7.5	-2.7	-5.7	-10.2
	25%	-5.9	-19.4	-4.2	-3.6	-6.3	-2.4	-0.9	0.5	-2.9	-5.8
	50%	-0.5	-12.1	0.4	2.3	-2.3	1.7	9.7	4.8	2.4	-1.5
	75%	5	-3.9	5	8	2.1	7.7	22	8.1	7	5.6
	90%	10.3	3.1	10	14.8	6.1	14	32.9	12.4	10.8	10.3
	95%	11.9	5.5	13.5	17.8	8.4	18	35.6	15.6	12.3	13.1

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

The observed and calculated TDG pressure in the spillway exit channel during the 2009 spill season as a function of spill discharge are shown in Figure G10. The observed TDG pressure reached a maximum level for a spill of 150 kcfs and did not increase during the higher spillway flows. The calculated TDG response in the exit channel is a linear relationship with spill discharge and is also influenced by 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 95 kcfs to as high as 140 kcfs depending upon the spill pattern, tailwater elevation, and local atmospheric pressure. The under-estimation of TDG pressures near 100 kcfs spill is associated with subtle variations in spill pattern as noted above. The SYSTDG model has been updated to accommodate changes to spill patterns on an hourly basis through a user supplied input of the effective number of spill bays.

Statistical summary of the predictive errors of the observed and calculated total dissolved gas saturation at tailwater fixed monitoring stations.											
		Predictive Error at Tailwater FMS* (Saturation %)									
Parameters/Stations		DWQI	LGNW	LGSW	LMNW	IDSW	MCPW	JHAW	TDDO	CCIW	WRNO
Number of Observations		1353	3322	3243	2893	2158	1551	1517	3431	2799	371
Average		-0.4	-1.5	0	0.1	-0.4	0.4	1.4	-0.8	0.4	-0.1
Standard Deviation		1.7	1.3	1.1	1.7	1	1.1	1.9	1	0.8	0.9
Maximum		3.6	6.2	5.3	6.6	2.3	4.7	5.4	1.8	7.3	2.2
Minimum		-6.2	-4.2	-4.9	-4.8	-3.7	-4	-2.6	-6.7	-1.7	-3
TDG Predictive Error for Percentile Occurrence (mm Hg)	5%	-3.6	-3.1	-1.9	-3.7	-2.2	-1.3	-2.6	-0.9	-1.5	-2.2
	10%	-3.2	-3	-1.3	-2.3	-1.8	-0.9	-1.5	-0.6	-1.2	-1.7
	25%	-0.8	-2.6	-0.6	-0.5	-0.8	-0.3	-0.3	-0.1	-0.8	-1.1
	50%	-0.1	-1.6	0.1	0.3	-0.3	0.2	1.1	0.4	-0.1	-0.5
	75%	0.7	-0.5	0.7	1.1	0.3	1	2.7	0.8	0.6	0.3
	90%	1.4	0.4	1.3	2	0.8	1.9	4.3	1.4	1.2	1.1
	95%	1.6	0.8	1.8	2.3	1.1	2.4	4.7	1.8	1.4	1.4
*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 Forebay (BON)

The TDG pressures in the forebay of Bonneville Dam have been one of the most accurate estimates provided by the SYSTDG model despite the time of travel from TDA to BON, distance, and variability 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 TDG pressures was only 0.2 mm Hg and the standard deviation of the predictive error was 6.5 mm Hg as listed in Table G5. The 50 confidence interval for the predictive error ranged from -4.4 to 4.6 mm Hg of pressure and the 80 confidence interval ranged from -9.0 to 7.5 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the BON gage are shown in Figure G11. 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 G12. 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 policy at John Day Dam during the summer. The degree of wind induced off-gassing is illustrated in Figure G13 where the average cross section TDG pressures leaving The Dalles Dam is labeled as “TDDO-obs” and the Bonneville forebay station reflects the residual TDG pressure remaining in the Columbia River. The hourly wind speed (mps x 10) at The Dallesport Airport is shown in Figure G13. 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 SYSTDG estimates of TDG pressure at the The Dalles tailwater FMS (TDDO) during the 2009 spill season were remained accurate throughout the study period. The Dalles tailwater gage

is located about 3 miles downstream from the dam in waters that are well-mixed. The flow-weighted average TDG conditions were simulated for The Dalles Dam during the spill season and compared to the observed conditions at the tailwater TDG gage TDDO. The calculated TDG pressures were lagged 4 hours, due to the travel time, in making this comparison. The calculated TDG pressures contained a small under-estimation bias as quantified by the average predictive error of 4.7 mm Hg. The standard deviation of the predictive error was only 6.1 mm Hg as listed in Table G7. The 50 percent confidence interval of predictive error ranged from -2.9 to 7.0 mm Hg of pressure and the 80 percent confidence interval ranged from -7.2 to 12.3 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the TDDO gage are shown in Figure G14. The TDG saturation at the tailwater station TDDO infrequently exceeded the TDG standard of 120 percent because of the dilution influence of the TDG content in powerhouse releases. The amount of TDG added by The Dalles Dam spill was moderated by the policy 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 tailwater station at The Dalles Dam 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 120 percent of saturation as shown in Figure G16. 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 partial construction (200 ft length) of the spillway training wall between bays 8 and 9 did not influence TDG generation during the 2009 spill season. A new spill pattern and completed spill wall is slated for completion for the 2010 spill season. The calculated and observed TDG pressure at the The Dalles tailwater FMS as a function of spillway discharge is shown in Figure G17. The wide range of TDG values for a given spill discharge reflects the wide range of forebay TDG levels contributed by the powerhouse for a given spill discharge.

The Dalles Dam Forebay (TDA)

A simulation was conducted from the John Day Dam to The Dalles Dam forebay from 1 April through 31 August to determine the predictive error of SYSTDG simulations in The Dalles Dam forebay during spill events at John Day Dam. The estimated TDG generation model was based upon spill patterns prior to the addition of the temporary spillway weirs (TSW) on spill bays 15 and 16. The calculated average TDG pressures were generally unbiased when compared to observed conditions as evidenced by an average prediction error of 0.0 mm Hg. The standard deviation of the predictive error was 8.9 mm Hg as listed in Table G5. The 50 percent confidence interval of the predictive error ranged from -5.5 to 4.6 mm Hg of pressure and the 80 percent confidence interval ranged from 9.9 to -10.8 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the TDA gage are shown in Figure G18. The TDG saturation exceeded 115 percent about 6 percent of the time during the fish passage season. The calculated and observed TDG pressures at TDA are shown throughout the month of May in Figure G19. The SYSTDG model tended to over-predict the TDG pressures arriving at The Dalles Dam during April and May and under-predicted TDG pressures during June-August. The TDG levels arriving at The Dalles Dam in the summer were influenced by application of a single spill pattern at John Day Dam throughout the

entire spill season. The peak TDG pressures observed in the forebay of The Dalles Dam were under-estimated by 30-40 mm Hg during the summer months primarily because of the application of the wrong spill pattern at John Day Dam.

John Day Dam Tailwater (JHAW)

SYSTDG was used to simulate the TDG production associated with spillway operations at John Day Dam as measured at the tailwater fixed monitoring station JHAW from 1 April through 31 August 2009. The spill patterns at John Day Dam were changed during the 2009 spill season incorporating two spill bays with temporary spillway weirs (TSW) in April and May (Case A) and a uniform spill pattern (Case B) over bays 2-14 during the summer months as shown in Figure G20. The spring spill (Case A) pattern called for higher spill discharges through the TSW's in bays 15 and 16. The change from the spring to the summer spill pattern was not implemented in the SYSTDG model resulting in the predicted TDG pressures under-estimating the observed conditions for much of the year. The calculated average TDG pressures provided biased estimates over the study period as evidenced by an average error of 10.7 mm Hg and the standard deviation of the predictive error was 14.3 mm Hg as listed in Table G7. The 50 percent confidence interval of the predictive error ranged from -0.9 to 22.0 mm Hg of pressure and the 80 percent confidence interval ranged from -7.5 to 32.9 mm Hg of pressure.

The seasonal time history of observed and calculated TDG pressures at the JHAW gage are shown in Figure G21. The departure of observed and calculated TDG pressures can be seen beginning during the first week of June in this figure when the summer spill pattern was applied. The daily variation in river flows and corresponding percent river spill policy resulted in a broad range of spillway operations in May at John Day Dam as shown in Figure G22. The observed TDG pressures began to fall above predicted levels during the middle of the month and continued to slowly decline despite the spill levels remaining above 100 kcfs. On May 27 the observed TDG pressures abruptly increased and closely matched the estimated TDG levels as was the case during the first half of the month. A reasonable interpretation of these observations is a slow incremental failure of the TDG instrument at station JHAW followed by a maintenance visit on May 27.

The observed TDG pressure at the tailwater FMS below John Day Dam were directly related to spill discharge as shown in Figure G23. The groupings of observed TDG data appear in this figure correspond with the spring spill pattern, summer spill pattern, and erroneous data logged during mid-May. The upper grouping of data corresponds to the summer spill pattern using only 13 of the 20 spill bays. The spring pattern generally used 17 or 18 bays but not bays 1 or 20 without spillway flow deflectors. The calculated TDG pressures are consistent with the observed data associated with the spring spill pattern since only one pattern was applied by the model. The erroneous data falls below these two groups of data as increasingly lower TDG pressures were recorded.

Model update for John Day- The hind cast of TDG pressures associated with spillway flows at John Day Dam were repeated using both the spring and summer spill patterns. The improvement in the prediction of TDG pressures at the tailwater station was significant. The bias in tailwater TDG pressures was dropped from 10.7 mm Hg to -1.8

mm Hg. The standard error of estimate was also reduced from 14.3 mm Hg for the original SYSTDG simulation to 9.2 mm Hg for the updated formulation. The capability to flexibly enter different spill patterns in the SYSTDG model for each project was demonstrated by the operations at John Day Dam during the 2009 spill season. The SYSTDG model has been updated for the user to enter the hourly effect number of active spill bays for each spill event.

John Day Dam Forebay (JDY)

The TDG pressures were simulated from McNary Dam to the John Day forebay from 1 April through 31 August 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 3.6 to 12.0 days during the 2009 fish passage season. Calculated forebay TDG pressures were subtracted from the observed John Day forebay fixed monitoring station data to produce an hourly predictive error. The calculated TDG pressures on average under-estimated observed conditions by an average of 3.8 mm Hg and the standard deviation of the predictive error was 10.2 mm Hg as listed in Table G5. The 50 percent confidence interval for the predictive error ranged from -3.9 to 9.4 mm Hg of pressure and the 80 percent confidence interval ranged from -7.0 to 19.4 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the JDY gage are shown in Figure G24. The lower forebay TDG levels at John Day Dam 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 larger in the John Day forebay when compared to most other projects because of the uncertainty in estimating the in-pool TDG exchange during the long time of travel between dams. The observed and calculated TDG pressures in the forebay of John Day Dam are shown throughout the month of May in Figure G25. The peak observed TDG saturation at JDY on May 31 was under-estimated by the SYSTDG model by about 10 mm Hg.

McNary Dam Tailwater (MCPW)

The operation of two TSW's at McNary Dam and a revised spill pattern during the 2009 fish passage season resulted in a small change in TDG generation from previous conditions as monitored at the tailwater fixed monitoring station. The SYSTDG model was used to simulate the TDG exchange associated with spillway releases from McNary Dam throughout the 2009 spill season as shown in Figure G26. The 2009 spill pattern called for bulked releases at spillbays with the TSW's in several locations (bays 6, 19 before June 16, bays 18, 19 after June 16). The rated flow over the TSW was a function of the forebay elevation and was generally in the range of 9-10 kcfs. The calculated TDG pressures at tailwater station MCPW contained a minimal bias as evidenced by the mean error of only 2.7 mm Hg and a standard deviation of the predictive error was 8.1 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -2.4 to 7.7 mm Hg of pressure and the 80 percent confidence interval ranged from -6.7 to 14.0 mm Hg of pressure. The observed and calculated TDG pressures in the tailwater of McNary Dam are shown throughout the month of May in Figure G27. 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 TDG estimates tended to slightly under-estimate the TDG exchange when spill discharges dropped below 85 kcfs as shown in Figure G28. The TDG pressure typically increased at the Tailwater FMS when the spill discharge was changed from just above 85 kcfs to below 85 kcfs. This response is likely the result of training spills over bays at smaller specific discharges no longer masking the impacts of the much higher discharges and TDG pressures generated from the bays with the TSW's.

Several observations regarding the new spill pattern at McNary Dam are worth noting. The location of the TSW in bay 6 appeared to have a noticeable influence on TDG exchange as measured at the tailwater fixed monitoring station when compared to the TSW orientation during the summer months. The TDG pressures observed at the tailwater FMS before and after June 16 are shown as a function of spillway discharge in Figure G29. Although some overlap of the TDG response does exist between the two cases, the general tendency was for the TSW in bay 6 to generate higher TDG pressure as observed at the tailwater fixed monitoring station. The TDG pressures before June 16 continue to decline for spillway flows less than 85 kcfs despite the increasing contribution from the TSW in bay 6. This is contrasted with the post June 16 location of the TSW's where spillway flows less than 85 kcfs resulted in an increase in TDG pressures at the tailwater FMS.

The large variance in tailwater TDG pressures during July and August were partially attributed to periods of spillway closure and variations in the spill pattern. Hourly records of spill bay flow conditions reveals frequent closure of the spillway triggering declining TDG pressures at the tailwater fixed monitoring station. Short term alterations in the spill pattern transitioning to a more uniform spill distribution was also a frequent occurrence during this same period and typically resulted in declining TDG pressures at the tailwater fixed monitoring station.

An important component in the TDG exchange at McNary Dam involves the entrainment of powerhouse flows into aerated conditions. The proximity of the TSW to the powerhouse may have a significant influence on this exchange. The entrainment coefficient of 0.35 was not altered for the 2009 spill patterns simulated in the SYSTDG model.

McNary Dam Forebay (MCNA)

The TDG response at the McNary forebay 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 policy at Priest Rapids Dam during 2009 called for considerably lower spill rates during voluntary spill flows than in previous years. 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 policy at Ice Harbor Dam was cycled periodically throughout most of the 2009 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 -0.3 mm Hg

and the standard deviation of the predictive error was 11.5 mm Hg as listed in Table G5. The standard error was slightly larger in 2009 than determined in 2008 (11.5 versus 11.0 versus mm Hg). The 50 percent confidence interval for the predictive error ranged from -8.5 to 7.6 mm Hg of pressure and the 80 percent confidence interval ranged from -14.0 to 14.8 mm Hg of pressure. The observed and calculated TDG pressures in the forebay of McNary Dam are shown throughout the months of March-September in Figure G30. The calculated and observed TDG pressures in the forebay of McNary Dam are shown in Figure G31 for the month of May.

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 station for 2009. The spill policy at Ice Harbor Dam was varied throughout the 2009 fish passage season to accommodate biological testing of the removable spillway weir (RSW) located in bay 2. Ice Harbor Dam spilled the highest voluntary spill discharge of 100 kcfs on the Snake River resulting in a TDG saturation of 122.5 percent in May 7. The spill pattern did not use spill bay 1 during the 2009 fish passage season. The RSW remained in continuous operation with an average discharge of 7.9 kcfs. The spill patterns varied the number of active spill bays providing training flow for the RSW release. The typical spill pattern called for a crowned pattern skewed toward bay 2. The adjacent spill bay 3 was commonly inactive for moderate to low spill discharges.

The TDG exchange at Ice Harbor Dam was simulated from 1 April through 31 August 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 station IDSW. The calculated mean predictive error of TDG pressure was -2.8 mm Hg and the standard deviation of the predictive error was 7.5 mm Hg as listed in Table G7. The 50 percent confidence interval of the predictive error ranged from -6.3 to 2.1 mm Hg of pressure and the 80 percent confidence interval ranged from -14.0 to 6.1 mm Hg of pressure. The seasonal time history of observed and calculated TDG pressures at the IDSW gage are shown in Figure G32. The calculated values tend to compare favorably to observed conditions throughout most of the year when spill rates are above 30 kcfs. The predictive error tended to be larger during the spill activities during late July and August. The daily variation in TDG pressures for observed and calculated conditions can be seen in Figure G33 for the month of May. 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 G34. The range in TDG pressures of 870 to 920 mm Hg for a spill discharge of 90 kcfs is 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 90 kcfs. 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 1 April through 31 August 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 fixed monitoring station at Ice Harbor Dam (IHRA) to determine the hourly predictive error. The calculated TDG pressures slightly over-estimated observed conditions by an average of -2.7 mm Hg and the standard deviation of the predictive error was 9.0 mm Hg as listed in Table G5. The 50 percent confidence interval for the predictive error ranged from -6.9 to 3.3 mm Hg of pressure and an 80 percent confidence interval ranged from -16.9 to 6.9 mm Hg of pressure. The estimates of forebay conditions at Ice Harbor Dam tended to closely approximate observed conditions during the spring and early summer and began to diverge during the late summer as shown in Figure G35. The local minimum TDG events were captured during the summer but the synoptic maximums were under estimated by a significant amount. This under-estimation was related to production of TDG pressures in spill at Lower Monumental Dam. The observed and calculated TDG pressures in the forebay of Ice Harbor are shown in Figure G36 throughout May. 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 in the forebay of Ice Harbor Dam 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 the Ice Harbor forebay station was the highest of the four Snake River projects. The spill policy at Lower Monumental Dam (bulk spill pattern) resulted in the hourly TDG saturation in the Ice Harbor forebay to exceed 115% over 24.9 percent of the time.

Lower Monumental Dam Tailwater (LMNW)

The SYSTDG model for Lower Monumental Dam tailwater produced one of the highest standard error of projects modeled in the system. The estimates typically under-estimate the TDG saturation observed at the tailwater FMS. The complexities in the TDG exchange characteristics include the application of multiple spill patterns and the entrainment of powerhouse flows into spillway flows. The scheduling of a bulk spill pattern resulted in higher TDG pressures when compared with the standard spill pattern. The SYSTDG model was applied to simulate the TDG levels produced from spill operations at Lower Monumental Dam from 1 April though 31 August. The TDG properties in undiluted spill waters were compared to the observed conditions at the tailwater fixed monitoring station LMNW. The calculated mean TDG pressures under-estimated observed conditions by an average of 16.3 mm Hg and the standard deviation of the predictive error was 20.1 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from 0.4 to 33.7 mm Hg of pressure. The 80 percent confidence interval for the predictive error ranged from -13.1 to 37.7 mm Hg of pressure. The daily variation of TDG pressures at the tailwater FMS below Lower Monumental Dam are shown in Figure G37 for the entire fish passage season. There was a tendency for calculations to under-estimate the TDG exchange associated with high spillway releases. The hourly observed and calculated TDG pressures at the tailwater FMS (LMNW) are shown in Figure G38 for the

month of May. This figure shows the poor correlation between the observed and calculated TDG response at LMNW for voluntary spillway flows.

During much of this study period, the applied spill pattern differed in some fashion from the official spill pattern. The consistency of setting the spill pattern at Lower Monumental Dam was uneven during the 2009 spill season and can be a difficult pattern to follow because of large changes in spill bay flows for small incremental changes in total spill. In many cases, the application of the spill pattern differed substantially from the official pattern causing significant differences in TDG generation for the same spill discharge. The bulking of the spill pattern in the range of flows from 23 to 32 kcfs is shown in Figure G39. The intermediate spill pattern for 27 kcfs generates the highest TDG pressures because of the high discharge in bay 6 when observed at the tailwater fixed monitoring station. The observed and calculated TDG pressure in the tailwater of Lower Monumental Dam is shown in Figure G40 for spill events with a duration of 3 hours or longer. The TDG production model consists of the product of the effective depth of flow and the exponential function of unit spillway discharge.

Model Update for Lower Monumental Dam An alternative TDG production formulation consisting of the power function of tailwater depth of flow and the specific spillway discharge was applied to the observed spill pattern as determined from hourly project records of individual spill bay operations for 2009. Although there were still events that were not simulated with a high level of accuracy, the agreement of most of the events in May were greatly improved over the existing production model in SYSTDG. The observed and calculated TDG pressures using the updated formulation and observed spill pattern are shown in Figure G41. This formulation show promise in capturing the intricate spill pattern changes applied at Lower Monumental Dam. The calculated abrupt increases in TDG pressure in this simulation are the result of mismatched total spill and spill pattern data and can be disregarded. This figure illustrates the importance of using an accurate spill pattern to estimate the specific spillway discharge which is a critical input to estimating TDG exchange.

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 1 April through 31 August as shown in Figure G42. The calculated TDG saturation in the forebay of Lower Monumental Dam during April-June closely approximated the observed conditions although there was a tendency to under estimate observed conditions. The peak TDG pressures observed in the forebay of Lower Monumental Dam during June 1 of 903 mm Hg was slightly underestimated by about 7 mm Hg. The larger predictive errors were observed during the summer months with calculated TDG levels generally over-predicting the observed conditions. On average the calculated TDG pressures closely matched observed conditions as evidenced by the mean error of -5.4 mm Hg and standard deviation of the predictive error was 12.0 mm Hg as listed in Table G5. The 50 percent confidence interval for the predictive error ranged from -11.4 to 3.3 mm Hg of pressure and the 80 confidence interval ranged from -25.2 to 7.0 mm Hg of pressure. The over-estimation of TDG pressure during the summer is likely attributed to over-prediction of TDG generation at Little Goose Dam. The daily variation of TDG pressures for the month of May at the forebay FMS above Lower Monumental Dam are

shown in Figure G43. The higher TDG level during the second half of the month is caused by the elevated spillway discharges 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 construction of end bay flow deflectors in spill bays 1 and 8 at Little Goose Dam and the focus on elevated surface bypass flow through spill bay 1 presented the potential for significant changes to the TDG exchange properties in the Little Goose Dam tailwater during the 2009 fish passage season. The end bay spillway flow deflectors are 12.5 ft long and at the same elevation 532 ft as the interior bays. However, the end bays flow deflectors have a toe curve with a radius of 25 ft compared to no transition radius on the interior bay flow deflectors. The 2009 spill patterns at Little Goose Dam involved continuous spill through bay 1 at a discharge of about 10.9 kcfs during April-June and 8.0 kcfs during July and August. The spill pattern called for training spill from adjacent spill bays to bay 1 first followed by activation of all 8 spill bays for spillway discharges of 25 kcfs and higher. The TDG saturation at Little Goose Dam tailwater fixed monitoring station has been found to be a function of the forebay TDG levels passing the powerhouse turbines and TDG levels developed in spillway flows. At higher spill discharges the TDG saturation in the tailwater approaches the TDG saturation generated in aerated spill as most of the powerhouse flows become entrained into the stilling basin.

A TDG simulation was conducted from Little Goose Dam to Lower Monumental Dam from 1 April through 31 August 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 fixed monitoring station (LGSW) TDG data to estimate the predictive error by the model as shown in Figure G44. The calculated TDG pressures under-estimated observed conditions by an average of 0.3 mm Hg and the standard deviation of the predictive error was 8.4 mm Hg as listed in Table G7. The 50 percent confidence interval ranged from -4.2 to 5.0 mm Hg of pressure and the 80 percent confidence interval ranged from -10.0 to 10.0 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 May are shown in Figure G45. The spillway discharge ranged from 19 to 55 kcfs during the month of May with the TDG pressures of ranging from 825 to 911 mm Hg.

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 2009 is shown in Figure G46. 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 river spilled, and local barometric pressure.

RSW versus non-RSW TDG Exchange

The influence of the surface spill through the RSW on bay 1 at Little Goose Dam on the tailwater TDG pressures exhibited a range of responses when compared to spill without RSW spill. Spill was initiated on April 3 at 0000 hrs with bays 2-7 spilling 18.6 kcfs with background TDG pressures of 750 mm Hg resulting in a tailwater TDG pressure of 800 mm Hg after 9 hours of operation. The spill pattern was changed on April 3 at 900 hrs to a bulk spill pattern with RSW spill and training spill for a net spill of 18.5 kcfs resulting in a resultant tailwater TDG pressure of 840 mm Hg or nearly twice the increase from background levels compared to the uniform pattern. In this case, the higher specific discharge associated with the RSW spill resulted in a much larger generation of TDG pressures. The total river flow throughout these spill events remained steady at 62 kcfs or about 30 percent of the river was spilled.

The second sequence non-RSW spill occurred on June 3 at 1100 hrs with a duration of about 24 hours to June 4, 1000 hrs. The bays 2-7 were operated initially to spill about 29.5 kcfs followed by a reduction in spill to 25.8 kcfs. The total river flow was held relatively constant ranging in flow from 130-140 kcfs. The background TDG pressures were 900 mm Hg on June 3 and declined to 875 mm Hg by 1000 hrs on June 4. The observed TDG pressures at the tailwater FMS remained nearly constant during this period ranging from 860-870 mm Hg. These conditions suggest that a net reduction in TDG saturation resulted from spillway operations. Observations of lateral gradients in TDG pressure at the tailwater FMS suggest small differences between average cross sectional TDG pressures and the monitored TDG pressure at the tailwater monitoring station. On June 4 at 1000 hrs, the spill pattern was returned to the bulk pattern featuring the RSW spill and training spill for a net discharge of 25.7 kcfs. This operation was maintained for nearly 24 hours while the total river flow remained nearly steady ranging in discharge from 130-135 kcfs. The forebay TDG pressures continue to drop steadily falling from 880 to 850 mm Hg. The observed tailwater TDG pressures were observed to continue to fall from 860 to 850 mm Hg during this spill event. In both cases, less than 19% of the total river flow was spilled during these events. The difference in TDG exchange resulting from these two spill pattern is difficult to determine in this case because of the elevated background TDG conditions, small percentage of river spilled, and smaller difference in specific spillway discharge.

The third sequence of spill patterns involving RSW and non-RSW spill was scheduled on July 7-9, 2009. The total spill of 18.5 kcfs with a bay 1 spill of 10.6 kcfs was set during hrs 800-1100 hrs on June 7. The TDG levels in the forebay were steady at 817 mm Hg and the observed tailwater TDG pressures were 856 mm Hg during a total river discharge of 61 kcfs (30 percent river spilled). The closure of the RSW on July 7, at 1100 hrs and establishment of a total spill of 18.5 over 7 spill bays (2-8) resulted in a corresponding drop in TDG pressure at the tailwater FMS to 830 mm Hg. This reduction in TDG

pressure of 26 mm Hg can be compared to the 40 mm Hg difference observed in the April case study. On July 8 at 1200 hrs the bulk spill in bay was initiated but at a smaller discharge of 8.0 kcfs with additional training spill of 11.2 kcfs for a total spill discharge of 19.2 kcfs. The change in the tailwater TDG pressure associated with the return to a bulk RSW spill was negligible as the tailwater TDG pressures ranged from 818-828 mm Hg while forebay TDG pressures of about 800 mm Hg. The TDG difference between the high RSW spill and non-RSW spill was significant and clearly identifiable. The TDG difference between the low RSW spill and non-RSW spill was small.

The TDG model for Little Goose Dam based on observations prior to the structural and operational changes in 2009 performed well in predicting the TDG exchange during the fish passage season. The production formulation adequately estimated the uniform and bulk spill events described above when the observed spill patterns were used on model inputs. The short coming of this TDG exchange formulation involved the prediction of peak TDG levels for spill discharges of 40 kcfs and greater.

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 1 April 31 August. The elevated TDG levels in the forebay of Little Goose Dam as shown in Figure G47 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 1.8 mm Hg and the standard deviation of the predictive error was 13.4 mm Hg as listed in Table G5. The 50 percent confidence interval ranged from -5.9 to 10.5 mm Hg of pressure and the 80 percent confidence interval ranged from -17.5 to 16.0 mm Hg of pressure. The standard error of TDG pressures in the forebay of Little Goose Dam was the largest of all the forebay stations in the Snake River. The calculated and observed tailwater TDG pressures in the forebay of Little Goose Dam during the month of May are shown in Figure G48. The peak TDG events were well represented by model estimates upon arriving at the forebay of Little Goose Dam having undergone a significant reduction in TDG pressure in route. The predictions of TDG were less accurate during the months of July and August where the travel time was the longest, thermal effects greatest, and estimates of TDG levels in the tailwater of Lower Granite Dam the poorest.

Lower Granite Dam Tailwater (LGNW)

The voluntary spill policy at Lower Granite Dam during the 2009 fish passage season called for a continuous spill of 20 kcfs during the spring and 18.5 kcfs during the summer. These spill discharges provided the most frequent spill events over a wide range of powerhouse flows. The TDG levels associated with spillway releases from Lower Granite Dam were simulated from the 1 April through 31 August as shown in Figure G49. The calculated TDG pressures over-estimated observed conditions by an average of -11.0 mm Hg and the standard deviation of the predictive error was 9.8 mm

Hg as listed in Table G7. The over-estimate bias occurred in the predictions of TDG exchange for spill discharges of 24 kcfs and less. The 50 percent confidence interval for the predictive error ranged from -19.4 to -3.9 mm Hg of pressure and the 80 percent confidence interval ranged from -22.0 to 3.1 mm Hg of pressure. The TDG saturation during the month of May is shown in Figure G50 at the Lower Granite Dam tailwater FMS LGNW. The predicted TDG pressure closely tracked the observed TDG pressure below Lower Granite Dam during the 2009 spill season for spill discharges of 24 kcfs and higher. The peak spillway discharge of 79.7 kcfs caused a TDG saturation of about 125.8 percent and the estimated peak TDG saturation was 125.9 percent.

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 G51. This figure indicated the spill capacity of about 50 kcfs corresponds with a TDG saturation of 120 percent (892 mm Hg). A well defined linear relationship is indicated by this relationship 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 fixed monitoring station.

The cause for the over-estimation of TDG pressures at the tailwater FMS for standard Biop spills of 20 kcfs and less deserves some discussion. A review of the spill patterns associated with RSW spill with training flow did not reveal a change from previous years. The percent of river spilled during standard Biop spill did vary widely throughout the fish passage season. The TDG pressures observed at the tailwater fixed monitoring station show a tendency towards lower pressures for small percent spilled events. This evidence suggests the mixing zone can encroach upon the tailwater station for small percent spill event. It is recommended to revisit the formulation used to calculate entrainment as spill discharges become small at Lower Granite Dam. Improvements in forecasts of tailwater TDG conditions maybe derived through using a flow weighted integration of average TDG pressures for low percent spill events and use of the modeled TDG content in spill for higher percent spill events.

Dworshak Dam Tailwater (DWQI)

Both the spillway and regulating releases were scheduled at Dworshak Dam during the 2009 season to manage both the refill and drafting of the pool. The tailwater fixed monitoring station below Dworshak Dam is in mixed waters influenced by both spillway and powerhouse releases. The highest spill discharge at Dworshak Dam was 6 kcfs resulting in a tailwater TDG saturation of 111%.

The TDG pressures in the tailwater channel below Dworshak Dam were simulated during the 2009 spill season as shown in Figure G52. The calculated tailwater TDG pressures under-estimated observed conditions by an average of -3.2 mm Hg (average predictive error -3.2 mm Hg) and the standard deviation of the predictive error was 12.2 mm Hg as listed in Table G7. The 50 percent confidence interval for the predictive error ranged from -5.9 to 5.0 mm Hg of pressure and the 80 confidence interval ranged from -23.3 to

10.3 mm Hg of pressure. Dworshak Dam does not have a forebay TDG station and the TDG pressures observed at the tailwater station 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 error since powerhouse releases constitute most of the TDG loading observed at the tailwater station. The observed and calculated TDG pressures in the tailwater of Dworshak Dam are shown in Figure G53 for the month of April. The estimated TDG content of spillway releases undiluted with powerhouse flows is labeled SP Cal in this figure. The estimated flow weighted tailwater TDG pressure is labeled 'Rel Cal' that closely reproduces the observed TDG pressures at the tailwater FMS DWQI. The highest TDG pressure observed at the Dworshak tailwater FMS was 116% during a spill of 3.7 kcfs and a partial reduction in generation releases on April 8 (Figure G53). The high percent river spill during this event limited dilution from powerhouse releases generating the TDG pressures that were observed at the tailwater fixed monitoring stations.

There was also a tendency for regulating releases to generate slightly higher TDG pressures than comparable spillway flow. On June 2, a 2.1 kcfs release through the regulating outlets was conducted with a resultant TDG pressure of 805 mm Hg as shown in Figure G54. The regulating outlets were closed and a spillway discharge of 2.6 kcfs was initiated on the afternoon of June 2 resulting in a TDG pressure of 790 mm Hg. The average water temperatures also increased by 3 ^{o}C with this operational change. The warmer temperatures of the spillway release when mixed with the much colder temperature from powerhouse discharge may account for the reduction in TDG pressures associated with spillway flows.

The TDG exchange formulation for Dworshak Dam currently does not account for the TDG production associated with turbine releases. Turbine releases at inefficient gate setting can aspirate air to smooth operations resulting in an elevation of TDG pressures below the dam. The joint and individual turbine operations without spillway or regulating releases and the associated tailwater TDG pressures are shown in Figure G55 for May 4-28, 2009. The solid blue line represents an estimate of background TDG pressures withdrawn from the forebay. The small discharge from Unit 1 of 1454 cfs caused a marked increase in the TDG pressures below Dworshak Dam. These pressures increased when the discharge from Unit 1 was increased to 1600 cfs. Unit 2 was placed into action at a discharge of 2035 cfs resulting in rising TDG pressures exceeding 110% of saturation. The tailwater pressures returned to background levels when all three units where operating near powerhouse capacity of 10 kcfs. Unit 3 was operated individually at flows of 5582 cfs and 4530 generating supersaturated conditions. This interpretation of TDG uptake caused by turbine operation depends upon best estimates of background TDG levels. It should also be noted the diurnal variation in tailwater TDG pressures is influenced by thermal exchange in the Clearwater River.

The observed and calculated TDG pressures in the tailwater of Dworshak Dam are shown in Figure G56 as a function of spillway discharge. The lack of a consistent trend between spillway discharge and tailwater TDG pressure is caused by the influence of the TDG content in powerhouse flows in shaping the aggregate tailwater conditions in the Clearwater River. Both higher spill discharge and percent composition of spill can increase the tailwater TDG pressures.

Comparison of 2008 and 2009 Simulations

The performance of the SYSTDG decision support system as measured by the hourly predictive error statistics at fixed monitoring stations during the 2009 spill season was in some cases better and worse than the performance observed during the 2008 fish passage season. The wide range of both voluntary and forced spill operations in 2008 was in contrast to lower river flow rates during the 2009 spill season. The movement of TSW operation at McNary Dam in 2009 involved a structural modification to spillway releases which likely influenced both TDG exchange and entrainment of powerhouse flows. The new spill pattern and added spillway flow deflectors at Little Goose Dam provided for a different conditions for TDG exchange. The average predictive error provides an indication of estimate bias in TDG pressures. A total of 4 out of 8 forebay stations in 2008 contained an average predictive error greater than +/-5 mm Hg compared to 3 out of 8 in 2009. The standard error of estimate at forebay stations ranged from 7.4 to 16.2 mm Hg in 2008 compared to 6.5 to 13.8 in 2009. The TDG estimates at Camas/Washougal contained larger error in 2009 than determined in 2008. The data at the tailwater station were filtered by duration of spill in this year's analysis to generate a more meaningful estimate of the predictive error at tailwater stations. The standard deviation of the predictive errors in 2008 ranged from 6.8 to 18.0 mm Hg at tailwater fixed monitoring stations. In 2009, the standard deviation of the predictive errors at tailwater fixed monitoring stations ranged from 6.5 to 20.1 mm Hg. Significant improvements in predicting TDG pressures the tailwater station were achieved at Bonneville Dam. There were several stations where the predictive errors were considerably greater in 2009 compared to 2008. The average error in the tailwater of Lower Monumental Dam increased from 4.2 mm Hg in 2008 to 16.3 mm Hg in 2009. The average error in the tailwater of John Day Dam increased from 0.6 mm Hg in 2008 to 10.7 mm Hg in 2009. A prominent source of predictive errors in TDG estimates in 2009 was the influence of new spill patterns on TDG exchange in the Columbia and Snake Rivers.

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 2009 spill season. These estimates of TDG pressure were compared with observed levels from the fixed monitoring stations to evaluate the reliability of these calculations, and to determine the uncertainty of TDG estimates to support spill management policy. The applications of spillway operations throughout the basin in 2009 were characterized by voluntary spill conditions during most of the year with a short period of forced spill in May and June. The operational policy involving spilling water on the Snake and Lower

Columbia Rivers during the summer months was continued in 2009 with TDG levels generally within the state water quality standards for TDG during the fish passage season. The spill patterns were modified at a number of projects in 2009 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 predictive error was computed by subtracting the hourly estimates of TDG pressure from observed conditions. The error statistics at tailwater stations were limited to constant spill operations with a duration of 3 hours or longer. All observed TDG data at forebay stations were included in the summary of the predictive error.

In general, the predictive errors at the forebay station in 2009 (Tables G5 and G6) were slightly larger than predictive errors estimated at tailwater stations (Tables G7 and G8). A review of model performance indicates that 6 out of the 8 forebay station has standard error greater than 10 mm Hg compared to only 3 out of 9 tailwater stations. The average predictive errors at forebay stations were less than 1 percent of saturation with the exception of Ice Harbor Dam and the Camas/Washougal mixed river station. The overestimation of forebay TDG pressures at the Camas/Washougal station was attributed to misrepresenting the production of TDG associated with the B2CC outfall. The correlation between strong winds and declining TDG pressure at forebay stations was again evident during the 2009 spill season. 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, transport, and mixing of Bonneville Dam releases during the 2009 spill season proved to be reliably modeled during higher flow conditions from April through June. The low flow conditions at Bonneville proved to be much more problematic for estimating the hourly TDG properties at the Camas/Washougal FMS during periods in July and August. The under estimation of TDG levels in the Columbia River at the Camas/Washougal mixed river station have proven to be problematic during low flow conditions in other years. The likely source of the error in estimate at CWMW is the contribution of TDG pressure associated with the Bonneville 2nd powerhouse corner collector. The low flow condition places much greater importance on secondary sources of TDG pressure. 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 bounding the plunge pool. An alternative TDG production model was proposed for the B2CC outfall that is a function of tailwater elevation. This formulation provided more reliable estimates of TDG pressure at the Camas/Washougal monitoring station during low flow conditions when the B2CC was operational. The TDG production characteristics observed at Bonneville Dam tailwater station (CCIW) during the 2009 spill season were closely simulated throughout the spill season as indicated by the standard error of estimate of 6.1 mm Hg. The spillway capacity as limited by TDG saturations of 120 percent were observed to range from 95 to 140 kcfs during the 2009 spill season. The TDG pressures in the Columbia River at the Warrendale fixed monitoring station continue to provide reliable estimates of the

aggregate TDG loading of releases from Bonneville Dam for TDG management during the winter and spring time.

The modeling 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 error observed at the Dalles tailwater station was estimated to be 7.2 mm Hg while the corresponding standard error in the forebay of Bonneville Dam was only 6.5 mm Hg. The reason for the more reliable estimates of TDG pressure in the forebay of Bonneville Dam when compared to the tailwater station below The Dalles Dam is likely attributed to the greater variability in hourly operations at the dam. The tailwater monitoring station at The Dalles Dam resides in mixed waters influenced by both powerhouse and spillway flows. This mixed river sampling station masks the higher TDG pressures generated in spillway releases that were estimated to range from 122 to 127 percent of saturation. There was no indication that the TDG generation properties at The Dalles Dam has changed noticeably during the construction of the spillway training wall between spill bays 8 and 9.

The spill patterns at John Day Dam were changed during the 2009 spill season involving a spring pattern featuring the operation of two temporary spillway weirs in spill bays 14 and 15 and a summer spill pattern employing a uniform spill pattern over bays 2-13. The spring bulk spill pattern has altered the TDG exchange patterns at John Day Dam where the TDG contributions from the TWS's are masked for high flows but become more evident at lower spill discharges. The spring spill pattern called for higher surface discharges through the two TSW's to support fish guidance past John Day Dam. The summer spill pattern resulted in higher TDG pressures when compared to the spring pattern at the same total spillway flow. The simulations for TDG exchange and transport from John Day Dam did not anticipate the implementation of the summer spill pattern at John Day Dam resulting in a sizable under-estimation bias in the TDG generation as monitored at the tailwater fixed monitoring station. However, when model inputs were updated to reflect the applied spill patterns, both the model bias and standard error were significantly reduced to levels comparable to other projects. The SYSTDG model estimates can be used to screen TDG data collected from the fixed monitoring network as evidenced by the declining drift in TDG pressure recorded at the tailwater fixed monitoring station at John Day Dam in May. The spillway capacity as limited by the 120 percent TDG saturation criterion is considerably less using the summer spill pattern (as low as 80 kcfs) compared to the spring spill pattern (120 kcfs lower bound). The fate of powerhouse flows with the alternative spill patterns continues to be an uncertain component in estimating the TDG loading associated with John Day Dam releases.

The operations at McNary Dam involved spilling water through a couple of TSW's throughout the entire fish passage season. The location of these spill bay control structures changed in 2009 being located in spill bays 6 and 19 during the spring and bays 18 and 19 during the summer. The TDG pressures observed at the tailwater fixed monitoring station were a function of the spill pattern and usage of the TSW's. The spring spillway configuration generated consistently higher TDG pressures than the summer configuration for spill discharges of 75 and greater. The spring spill pattern

resulted in tailwater TDG pressures that were typically 10-20 mm Hg higher than the summer spill pattern. The difference in tailwater stage and effective depth could account for some of the differences between the two patterns. There was insufficient data collected at McNary Dam to evaluate the change in spillway capacity as limited by the TDG criterion of 120 percent. The summer 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 TSW releases reaching the north shore during lower spillway discharges. The continuously declining TDG pressures at lower spill discharges for the spring spillway configuration maybe related to the shallow tailwater conditions downstream from the northern end of the stilling basin. The SYSTDG simulation of tailwater TDG pressures at McNary Dam were reliable (standard error of 8.1 mm Hg, average error of 2.7 mm Hg) during the fish passage season even with the variable location of the TSW's. The TDG estimates in the forebay of John Day Dam were improved over conditions in 2008. The mean and standard error in the forebay of John Day Dam were 3.8 and 10.2 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 exchange formulation for Ice Harbor Dam provides one of the most reliable estimates of tailwater TDG pressure for the Snake River with a mean error estimate of -2.8 mm Hg and a standard error estimate of 7.5 mm Hg. The consistent performance of this TDG exchange model 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 55.2 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 2009. The tailwater TDG pressures were systematically under estimated with a mean error of estimate of 16.3 mm Hg throughout the spill season. The complexity in the TDG exchange characteristics at Lower Monumental Dam involves a complex spill pattern and the substantial entrainment of powerhouse flows into aerated spillway flows. An alternative TDG production formulation was developed consisting of the simple product of the tailwater depth of flow and square root of the specific spillway discharge that demonstrated a significant improvement in the estimation of TDG exchange. The determination of the effective number of spill bays is a critical component in determining the specific spill discharge in the TDG exchange formulation. The observed TDG saturation at the tailwater FMS was found to be function of the forebay TDG saturation for small total river flows requiring reformulation of powerhouse entrainment. The frequency of hourly TDG supersaturation above 115 percent at the Ice Harbor forebay station was the highest of the four Snake River projects. The spill policy at Lower Monumental Dam resulted in the TDG saturation in the Ice Harbor forebay to exceed 115% over 24.9 percent of the time.

The structural configuration of the spillway at Little Goose Dam were altered significantly prior to the 2009 spill season with the construction of spillway flow deflectors on bays 1 and 8 along with the installation of a removable spillway weir in spill bay 1. The concentration of spill in bay 1 was observed to have a significant influence over the tailwater TDG pressures during moderate total river flows and low background TDG levels when compared to uniform spill over bays 2-8. The influence of RSW spill at higher river flow conditions is likely to diminish because of more comparable specific discharges from other bays. 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 formulation for Little Goose Dam preformed well based on the new structure and spill pattern was a mean and standard error of estimate of 0.3 and 8.4 mm Hg respectively. A noted short coming of model predictions during the 2009 season involved the estimation of TDG pressures during peak spillway discharges. The initial review of tailwater TDG data suggest the new spillway flow deflectors perform similarly to the original deflectors in terms of TDG exchange.

The SYSTDG model provided reliable estimates of TDG exchange at Lower Granite Dam during the 2009 spill season with the exception of estimates of the standard fish spills of 20 kcfs and 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 both spillway and regulating releases to manage pool filling and drafting actions during the 2009 spill season. The highest TDG levels observed at the tailwater FMS were generated during a modest spill of 3.7 kcfs during limited powerhouse flows. The tailwater station below Dworshak Dam resides in mixed waters and is influenced by both powerhouse and spillway/RO releases. A challenge in providing estimates of TDG exchange in releases from Dworshak includes providing estimates of the TDG content in powerhouse flows. The scheduling of sequential regulating outlet and spillway discharge events in 2009 with the same powerhouse flows suggests the spillway produces lower TDG pressures than a comparable regulating outlet release. The elevation of Clearwater River TDG pressures during single turbine operations were noted during the 2009 season. The turbine discharges that generate TDG supersaturation fall at the lower operating range for each turbine but specific operating zones of high rates of air entrainment are apparent.

Recommendations

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

The hourly description of the applied spill pattern should be optional input on each project page. This feature has been implemented on a trial basis and includes the designation of the number of effective spill bays in operation at any given hour. The effective number of spill bays is subsequently used to calculate the specific discharge. The effective number of spill bays has been estimated from the proscribed spill pattern using the following formulation.

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

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.

The evaluation of the TDG exchange properties at Little Goose Dam with the modified structure and spill pattern is loosely defined using a single monitoring station below the dam. A much more rigorous evaluation of spillway flow deflectors, RSW, and alternative spill patterns at Little Goose Dam should involve additional field sampling.

The alternative TDG exchange formulation for Lower Monumental Dam should be investigated with additional data from other years. The identification of the influence of forebay TDG pressures on data observed at the tailwater FMS should be quantified.

The influence of TSW on TDG production should be quantified at John Day and McNary Dams. The potential for TSW's to influence entrainment of powerhouse flows and create local regions of elevated TDG pressure undetected by the tailwater FMS will require additional field sampling.

The proposed TDG exchange formulation for the Bonneville 2nd powerhouse corner collector should be evaluated with data form previous years. The potential for other secondary sources of TDG supersaturation should be explored such as the 1st Powerhouse ice and trash outfall or the Bonneville 2nd powerhouse juvenile bypass outfall.

The impacts of wind speed and direction should be examined as an improved description of TDG exchange with the atmosphere. The generation of breaking wave by co-flowing and counter-flowing wind and water currents may result in a better description of degassing. The use of multiple weather stations for long pools may also improve model estimates.

The identification of consistent sampling bias at tailwater fixed monitoring stations should be documented and incorporated into management activities.

The uncertainty of TDG predictions should be factored into a risk based management policy for spill.

The potential use of Chief Joseph Dam to spill during lack of market events should be initiated into spill management activities. The growing availability of wind power may generate more frequent lack of market spill events. The model can be used to evaluate load allocations and TDG impacts throughout the mid-Columbia River. The evaluation of spillway flow deflectors at Chief Joseph Dam has greatly increased the spill capacity of CE projects limited by state water quality criteria.

The statistical computation of the new daily Washington compliance metric for TDG saturation should be implemented in SYSTDG.

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

Figures Appendix G

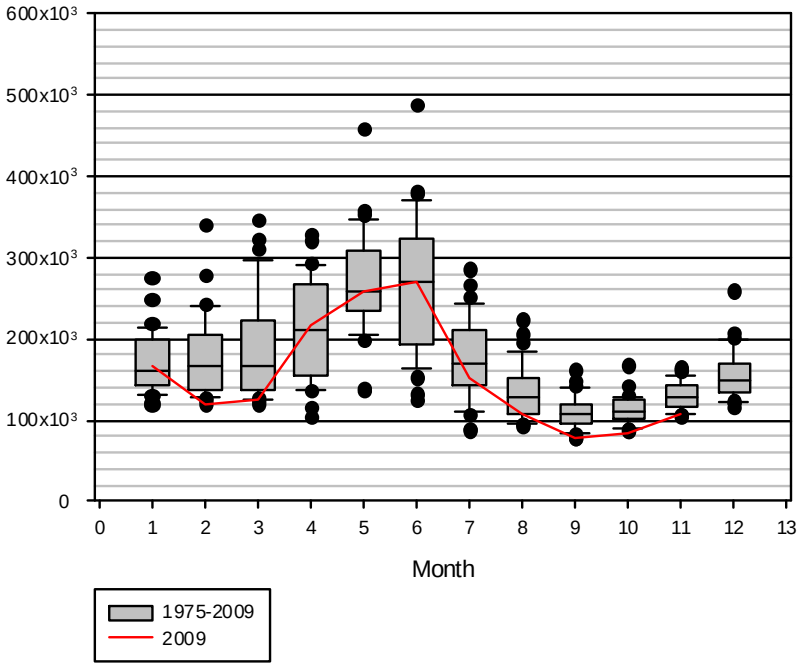

Figure G1. Statistical Summary of Columbia River Monthly Average Flows at The Dalles Dam for 1975-2009 (2009 – Red, 1975-2009 summary gray box 25, 50, 75th percentiles, whiskers 5-95th percentiles).

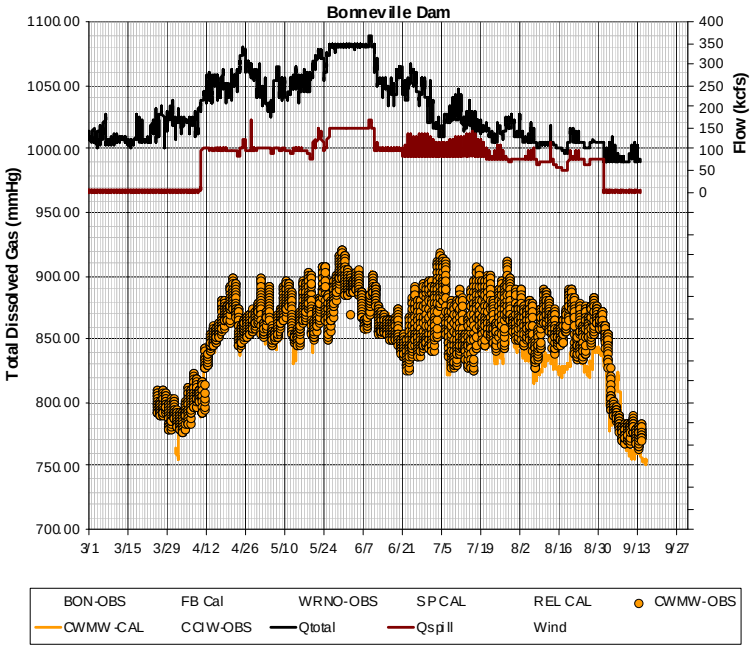

Figure G2. Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Camas/Washougal fixed monitoring station downstream of Bonneville Dam, March-September 2009

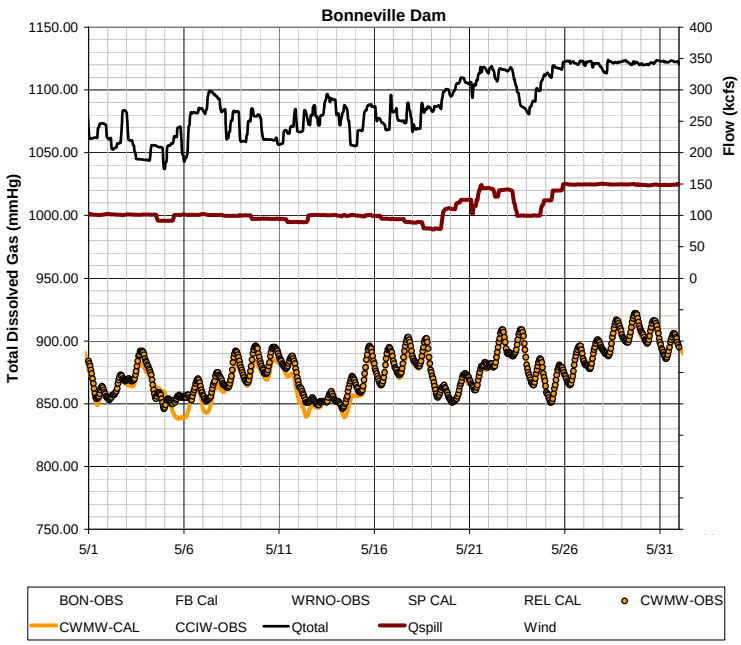

Figure G3. Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Camas/Washougal fixed monitoring station downstream of Bonneville Dam, May 2009

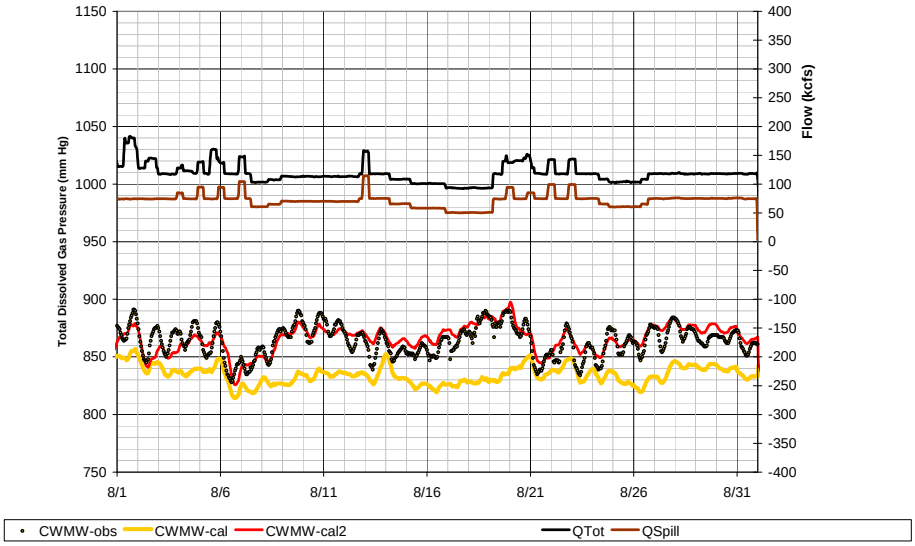

Figure G4. Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Camas/Washougal fixed monitoring station downstream of Bonneville Dam, August 2009 (CWMW-cal=2009 SYSTDG formulation, CWMW-cal2=Updated formulation)

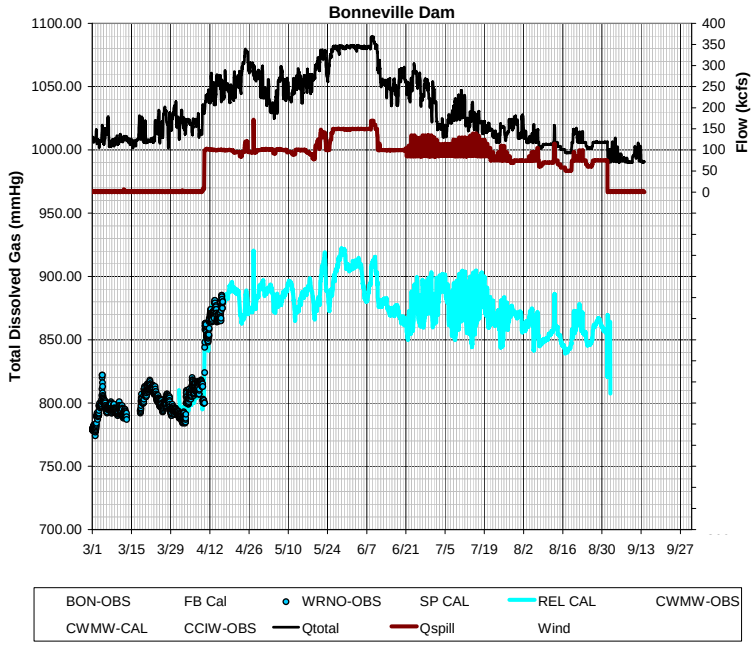

Figure G5. Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Warrendale fixed monitoring station downstream of Bonneville Dam, March-September 2009

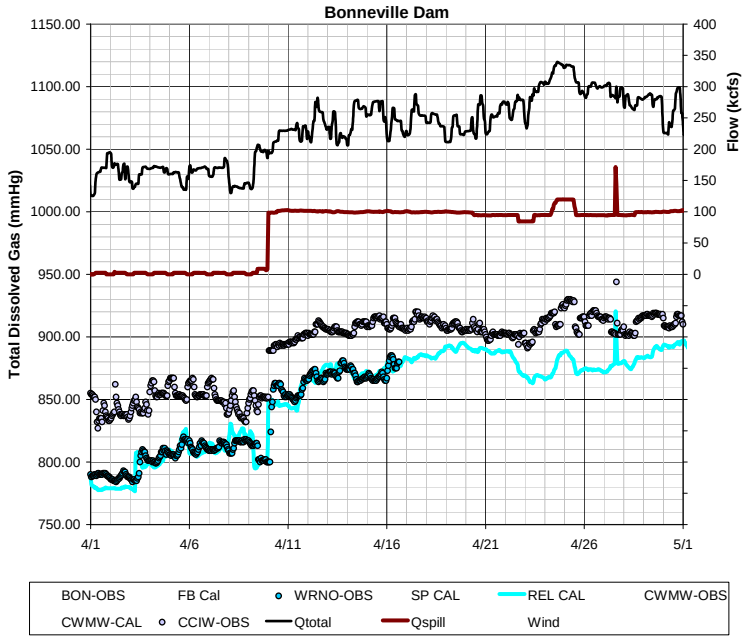

Figure G6. Observed and Calculated Total Dissolved Gas Saturation in the Columbia River at the Warrendale fixed monitoring station downstream of Bonneville Dam, April 2009

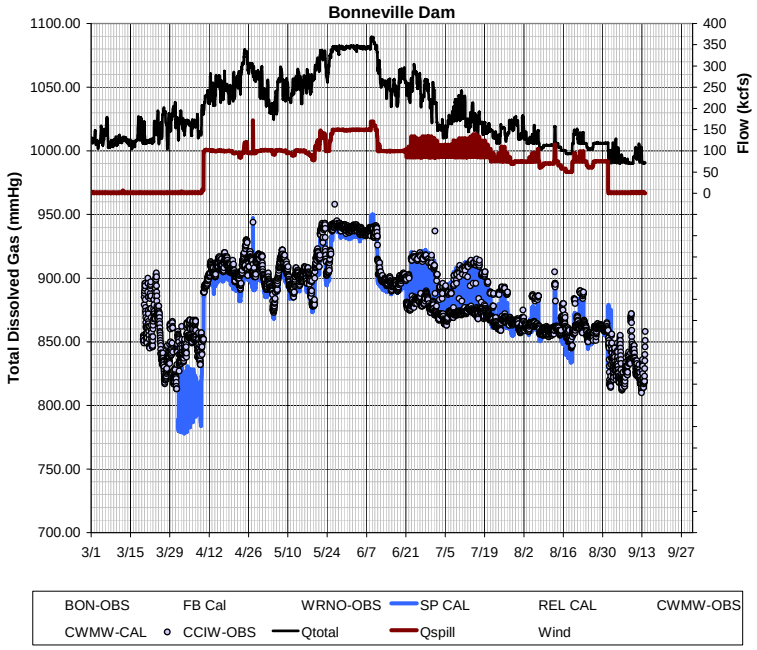

Figure G7. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River at the Cascade Island fixed monitoring station downstream of Bonneville Dam, March-September 2009

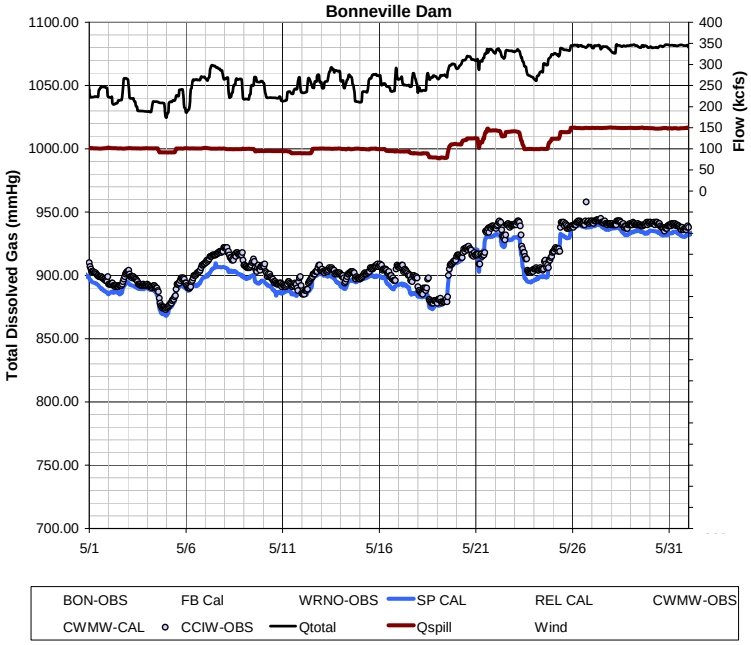

Figure G8. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River at the Cascade Island fixed monitoring station downstream of Bonneville Dam, May 2009

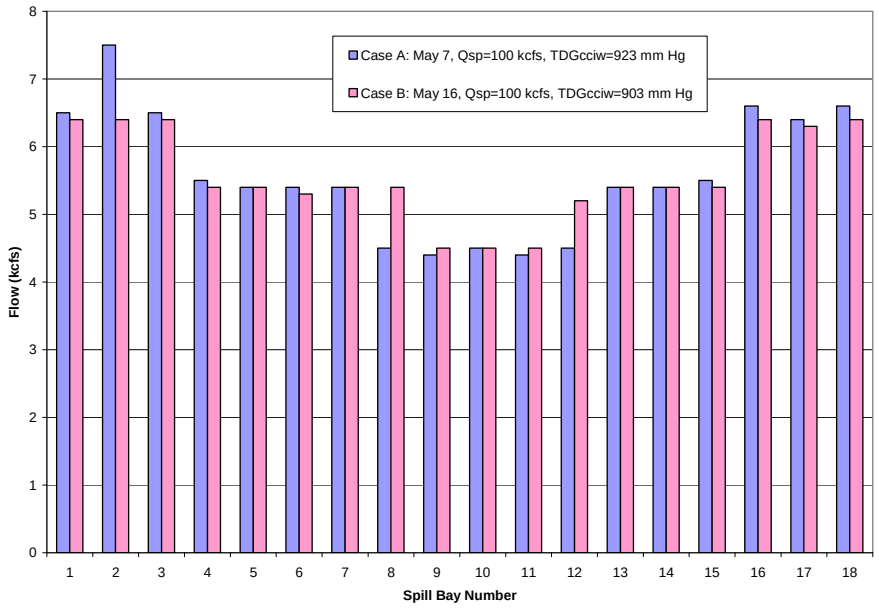

Figure G9. Spill Pattern at Bonneville Spillway for a total spill discharge of 100 kcfs: Case A May 7, 2009 and Case B May 16, 2009

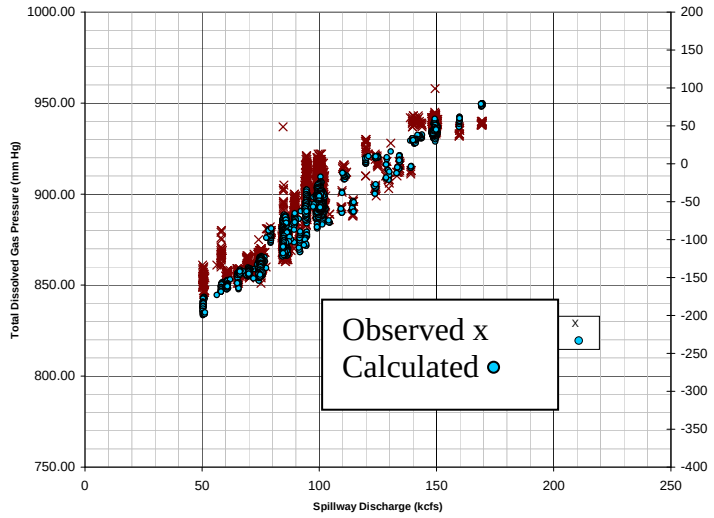

Figure G10. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River at the Cascade Island fixed monitoring station downstream of Bonneville Dam as a Function of Spill Discharge, 2009

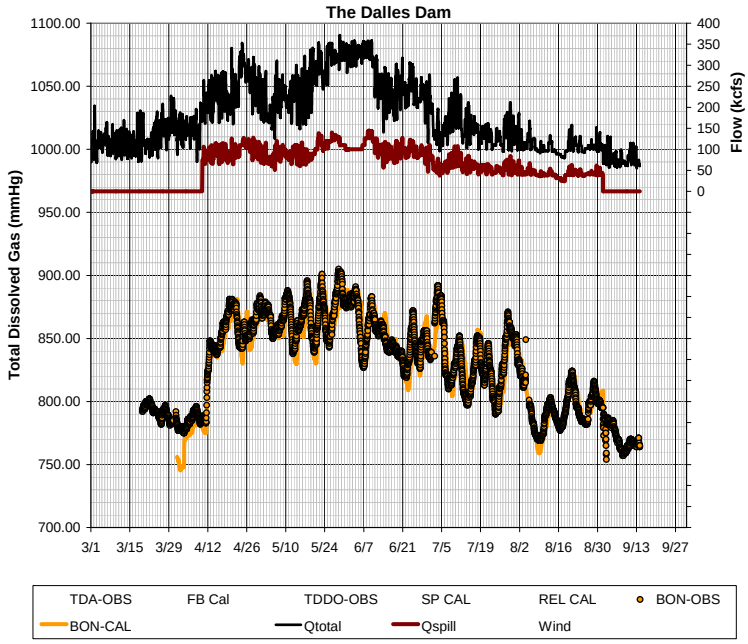

Figure G11. The Dalles Dam Operations with Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of Bonneville Dam, March-September 2009

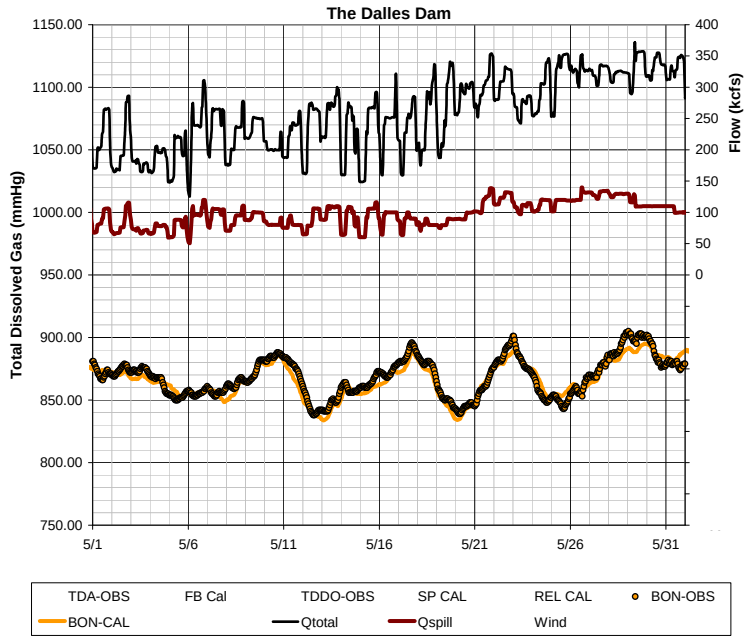

Figure G12. The Dalles Dam Operations with Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of BonnevilleDam, May 2009

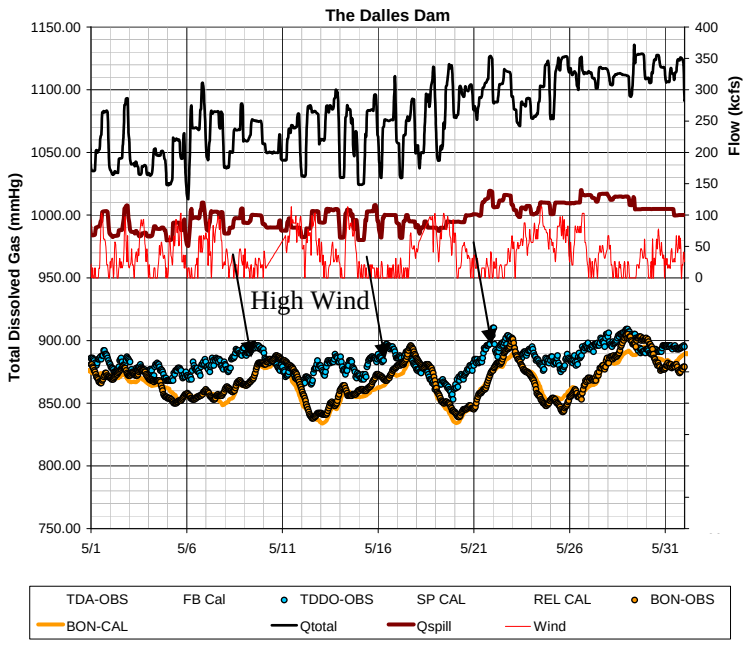

Figure G13. The Dalles Dam Operations with Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of Bonneville Dam and tailwater of The Dalles Dam, May 2009

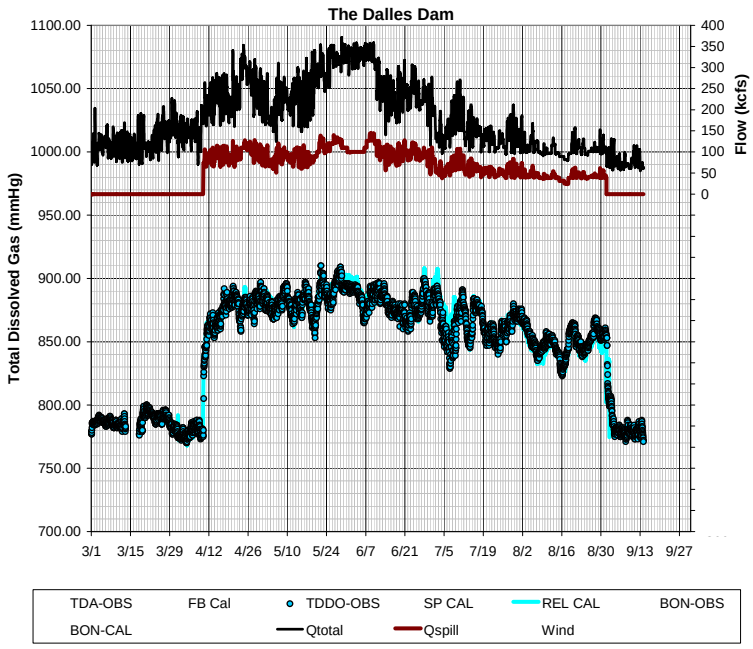

Figure G14. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater channel of The Dalles Dam, March-September 2009

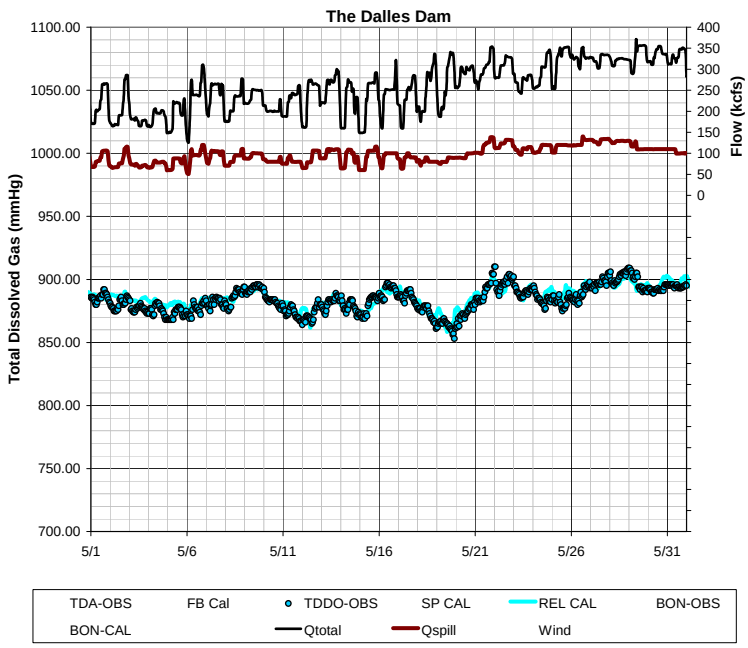

Figure G15. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater channel of The Dalles Dam, May 2009

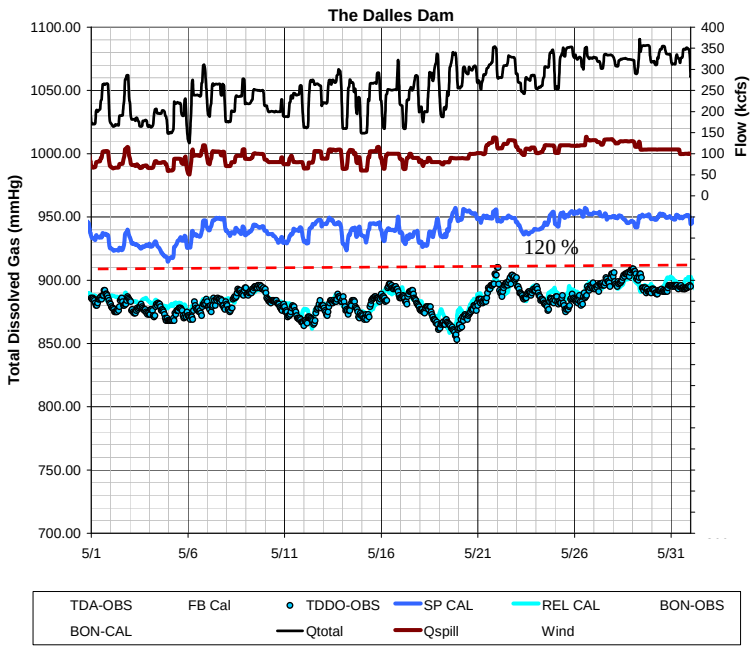

Figure G16. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater channel of The Dalles Dam, May 2009

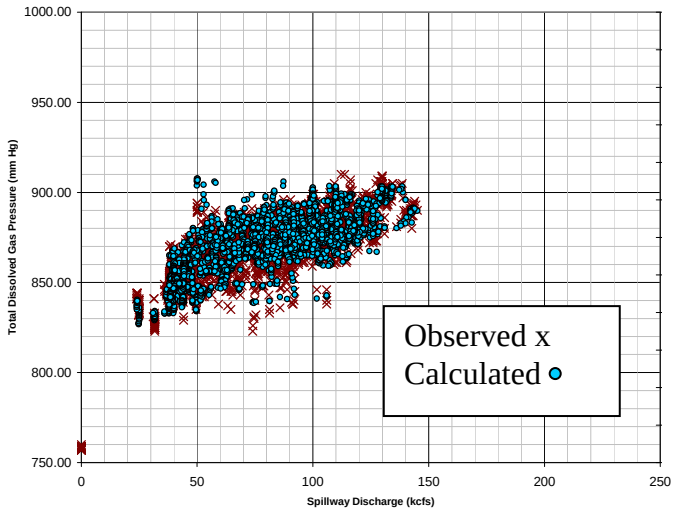

Figure G17. Observed and Calculated Total Dissolved Gas Pressure in the Columbia River below The Dalles Dam as a Function of Spillway Discharge, 2009

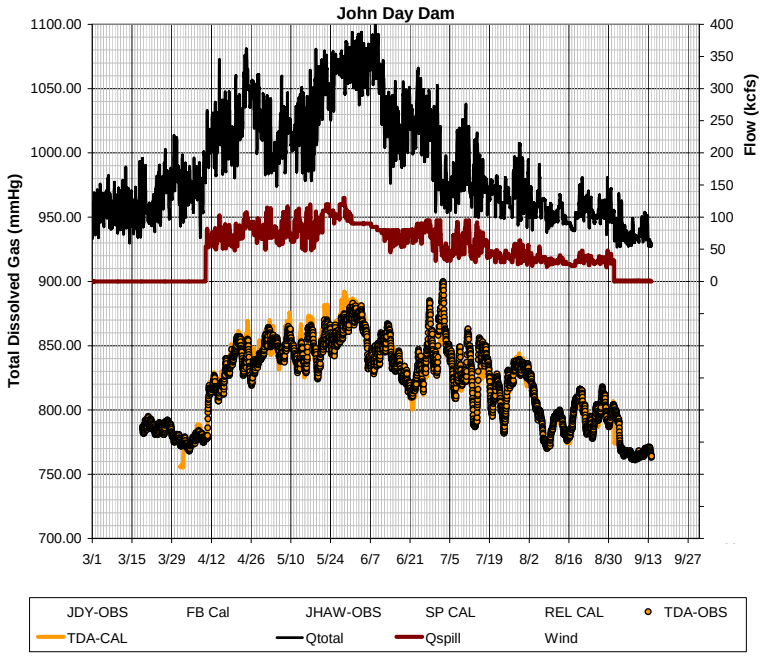

Figure G18. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of The Dalles Dam, March-September 2009

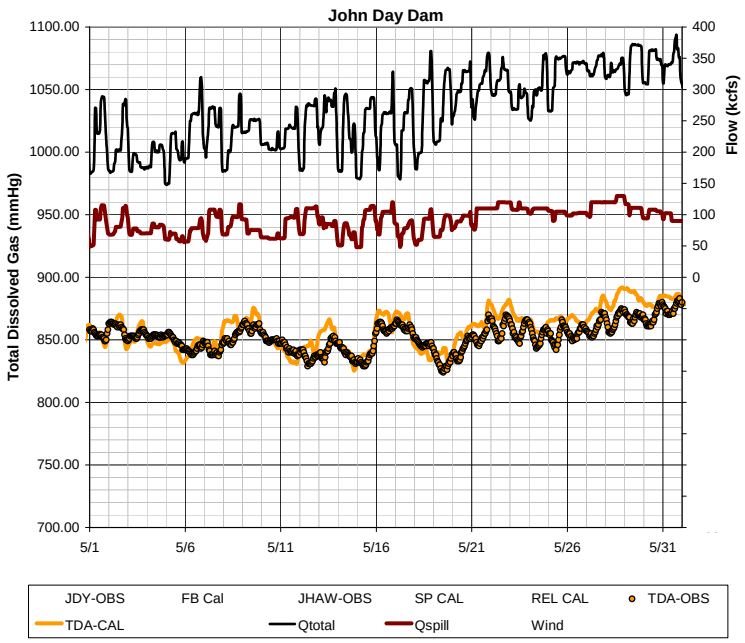

Figure G19. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of The Dalles Dam, May 2009

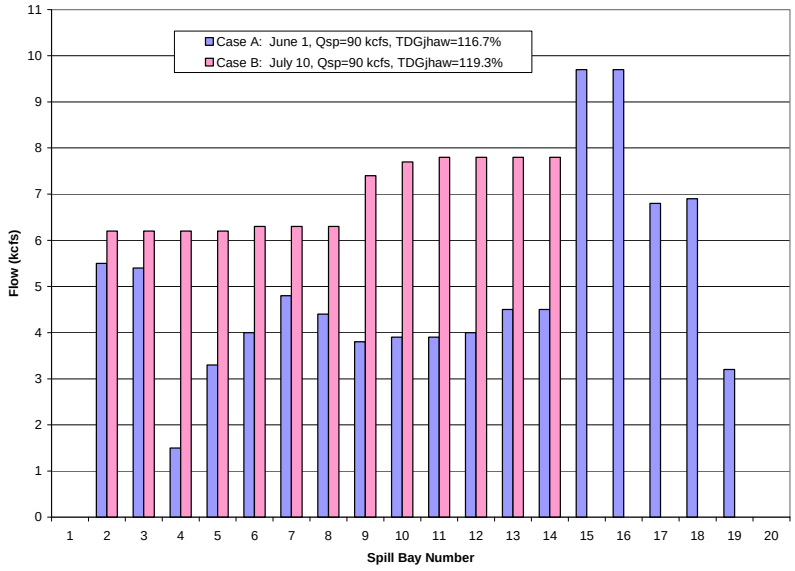

Figure G20. Alternative spill patterns at John Day Dam with (Case A) and without (Case B) temporary spillway weirs located in bays 15 and 16.

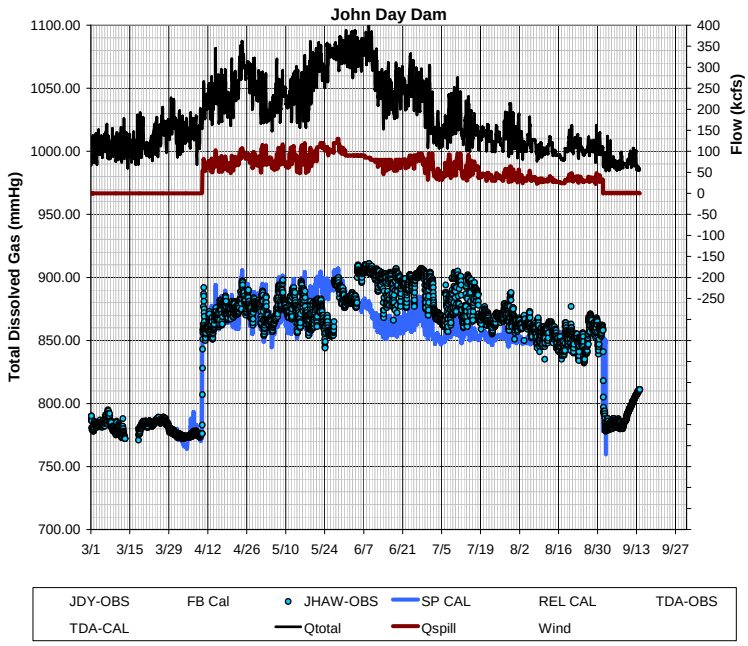

Figure G21. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater channel downstream from John Day Dam, March-September 2009

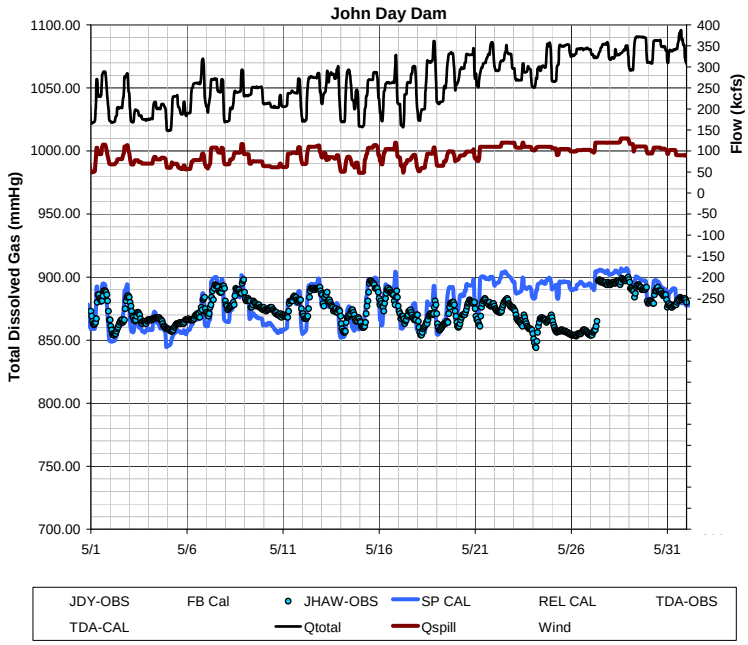

Figure G22. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater channel downstream from John Day Dam, May 2009

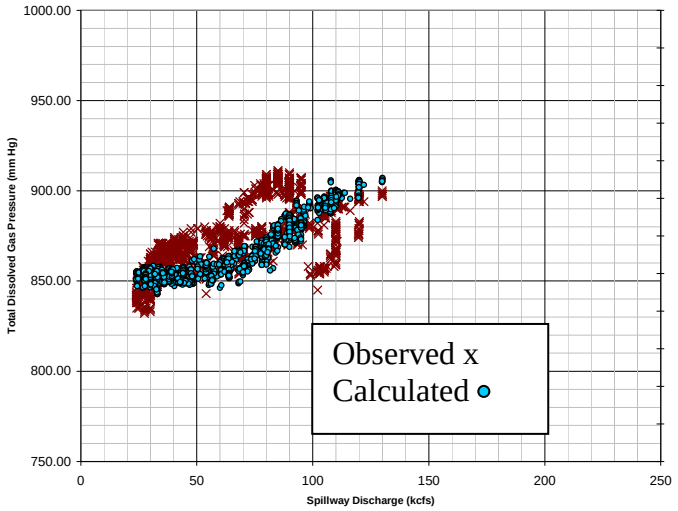

Figure G23. Observed and Calculated Total Dissolved Gas Pressure in the Columbia River below John Day Dam as a Function of Spillway Discharge, 2009

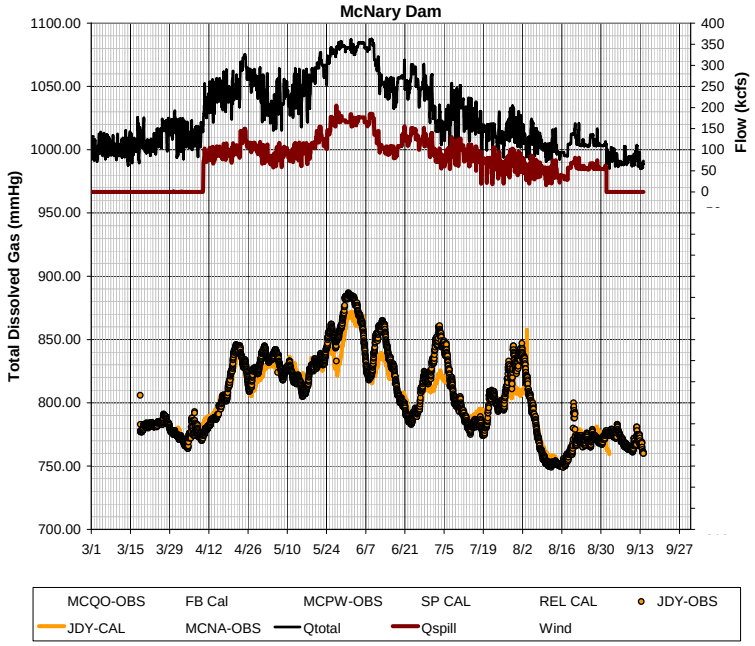

Figure G24. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of John Dam, March-September 2009

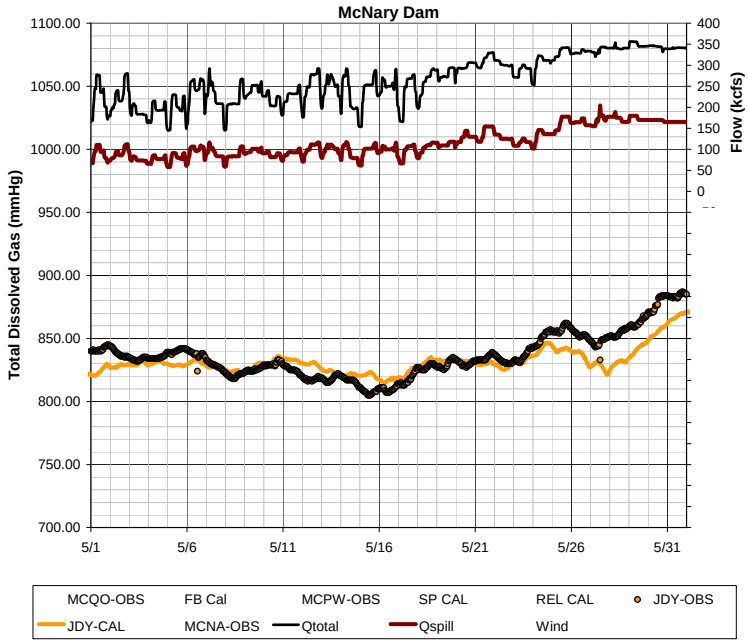

Figure G25. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of John Dam, May 2009

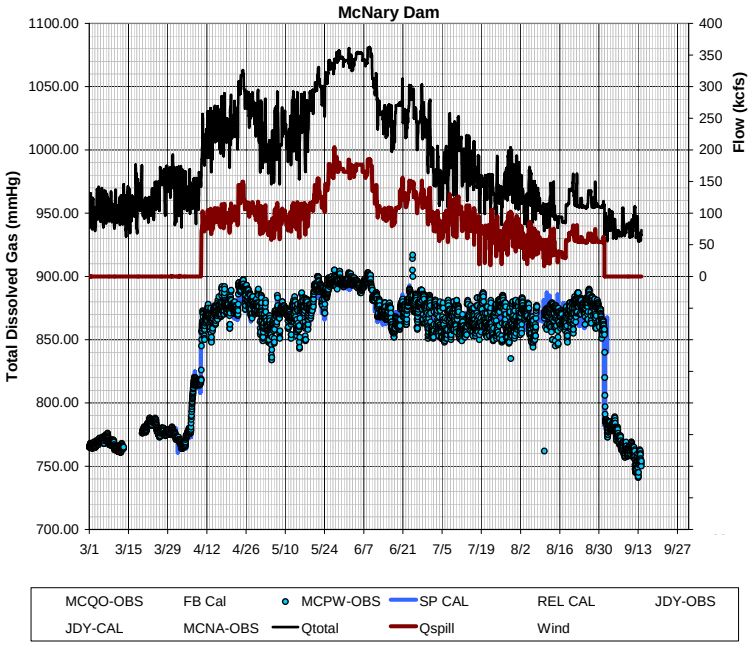

Figure G26. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater of McNary Dam, March-September 2009

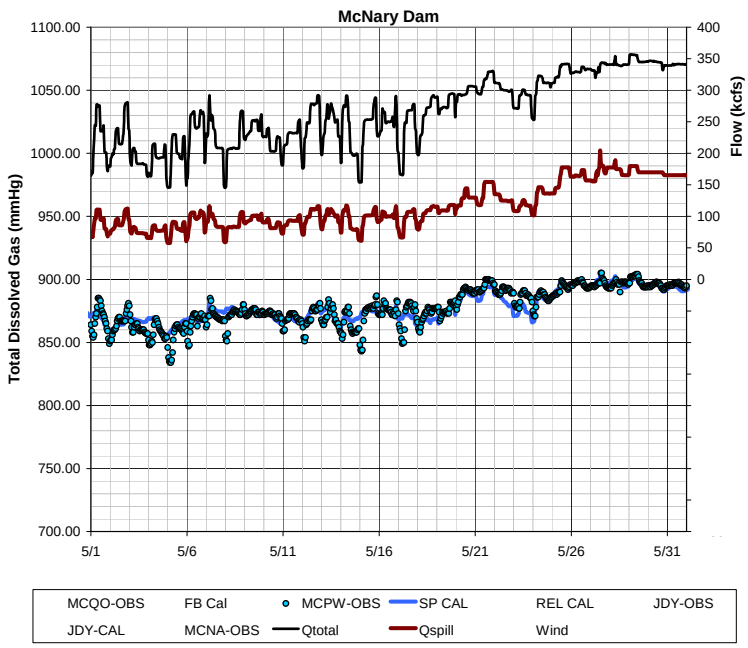

Figure G27. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the tailwater of McNary Dam, May 2009

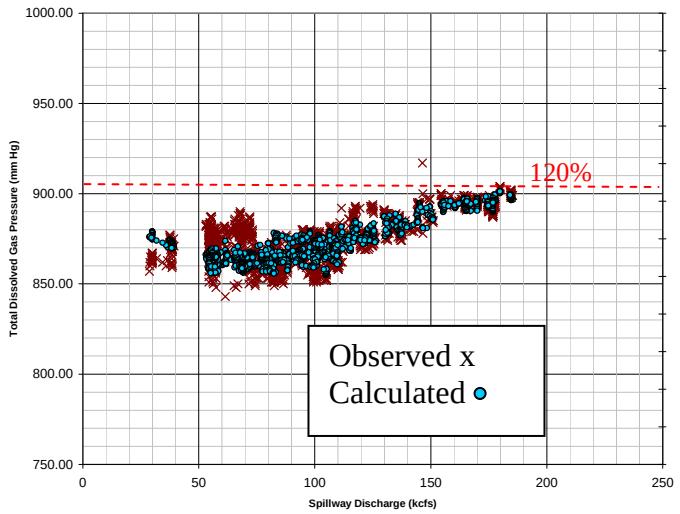

Figure G28. Observed and Calculated Total Dissolved Gas Pressure in the Columbia River below McNary Dam as a Function of Spillway Discharge, 2009

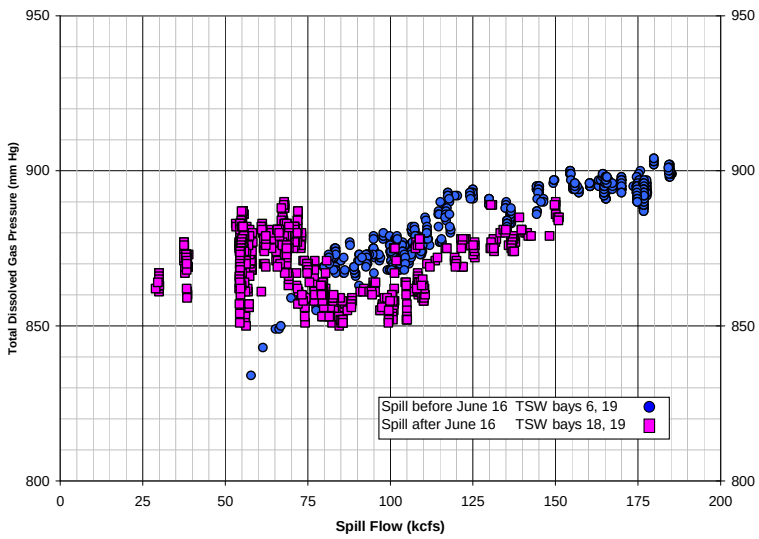

Figure G29. Observed Total Dissolved Gas Pressure in the Columbia River below McNary Dam before and after June 16, 2009 as a Function of Spillway Discharge

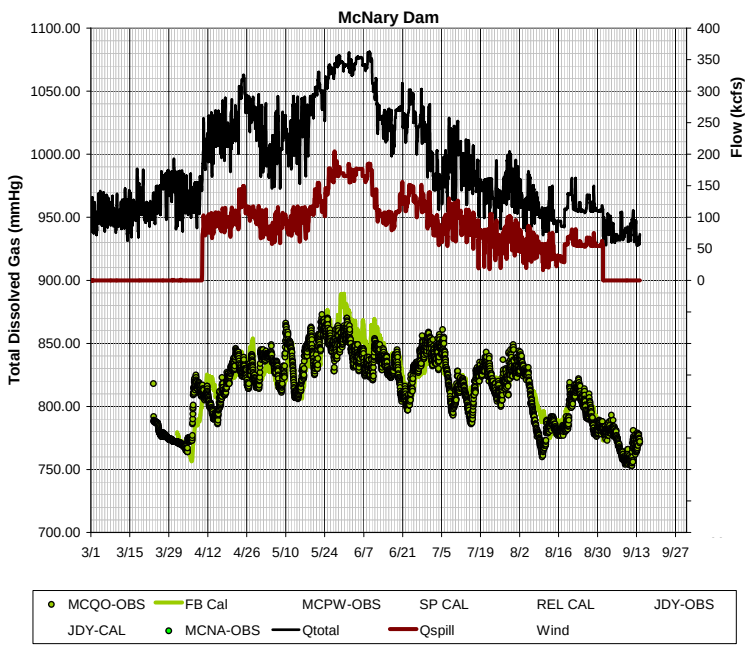

Figure G30. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of McNary Dam, March-September 2009

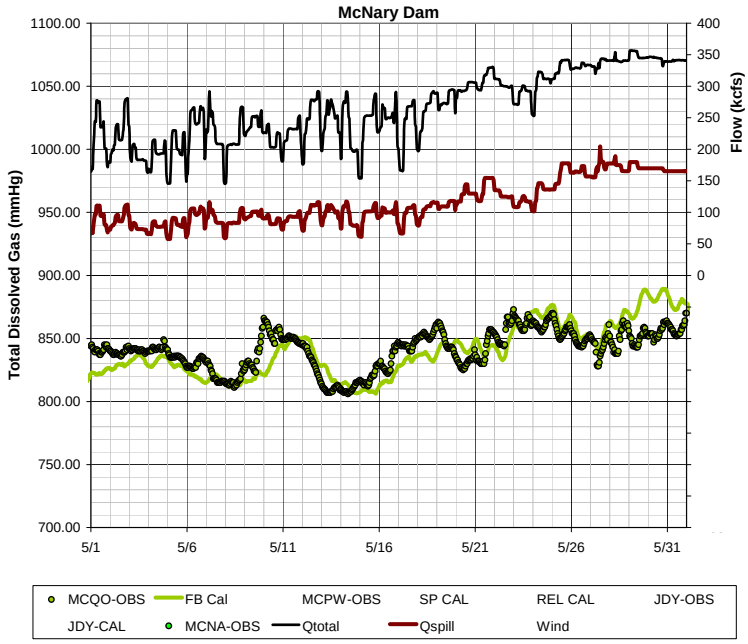

Figure G31. Observed and Calculated Total Dissolved Gas Pressures in the Columbia River in the forebay of McNary Dam, May 2009

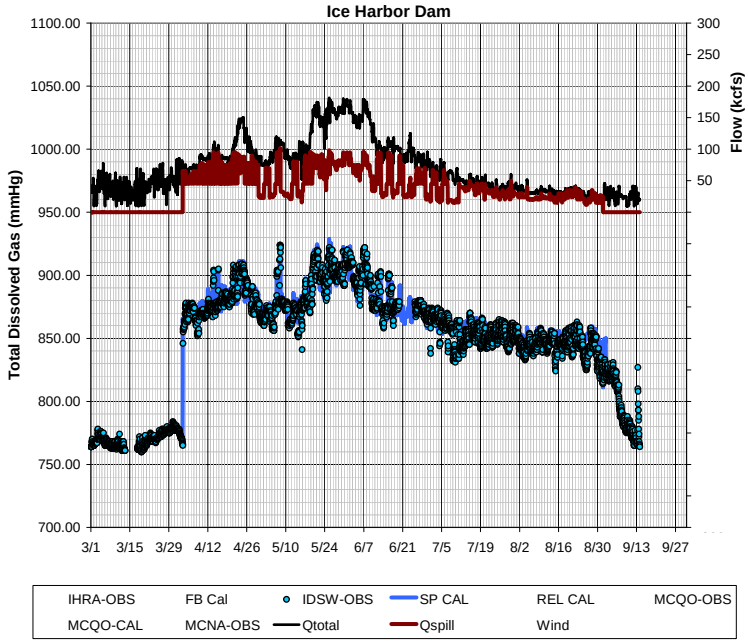

Figure G32. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater downstream from Ice Harbor Dam, March-September 2009

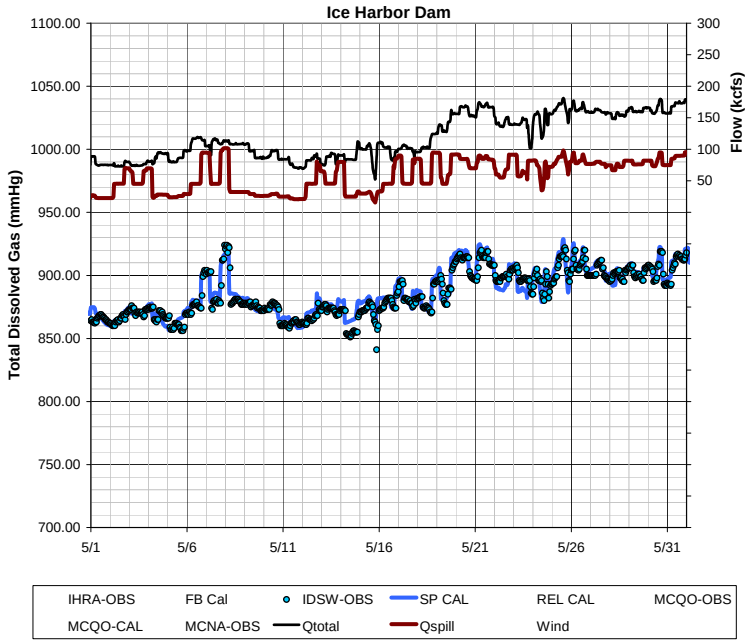

Figure G33. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater downstream from Ice Harbor Dam May 2009

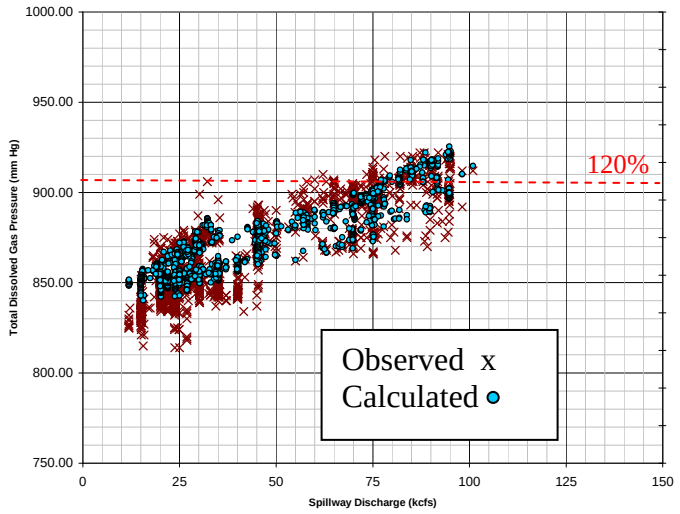

Figure G34. Observed and Calculated Total Dissolved Gas Pressure in the Snake River below Ice Harbor Dam as a Function of Spillway Discharge, 2009

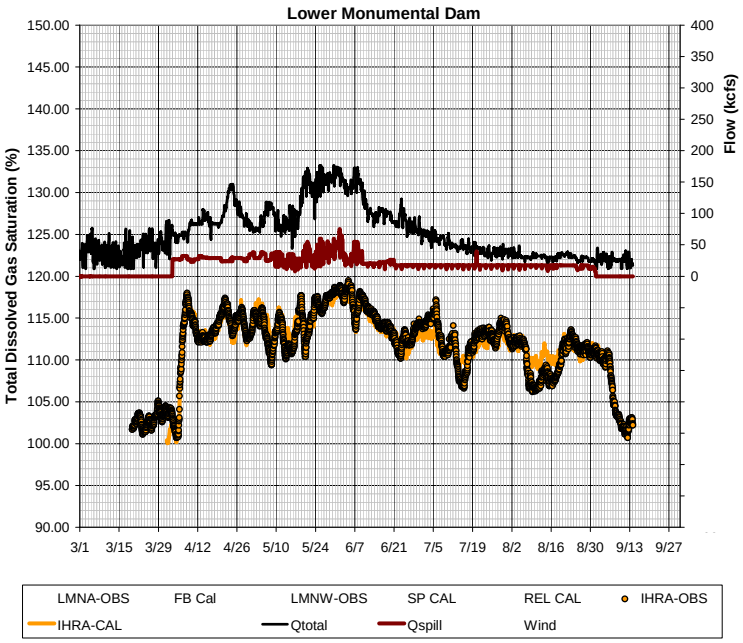

Figure G35. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Ice Harbor Dam, March-September 2009

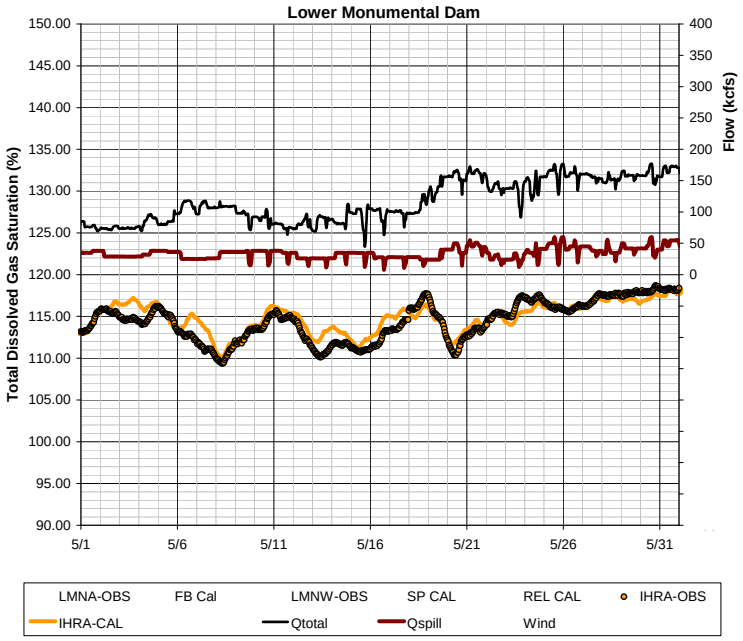

Figure G36. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Ice Harbor Dam, May 2009

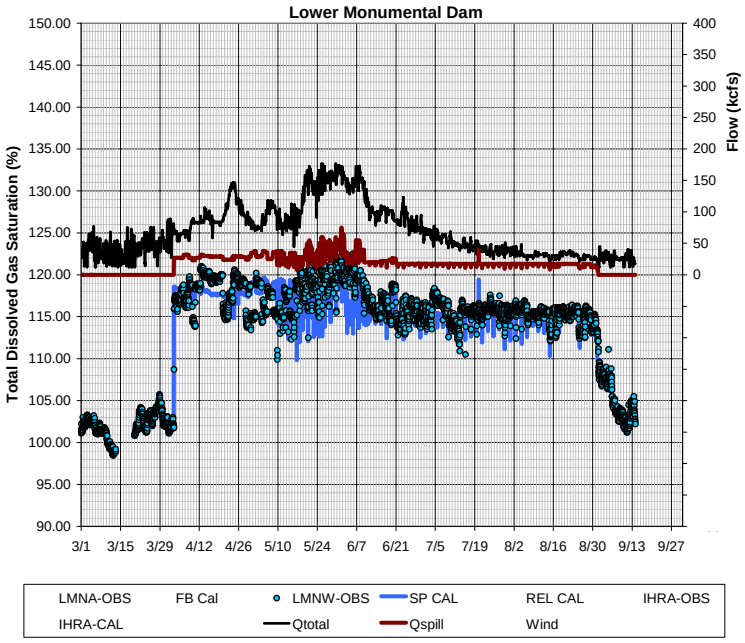

Figure G37. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Lower Monumental Dam, March-September 2009

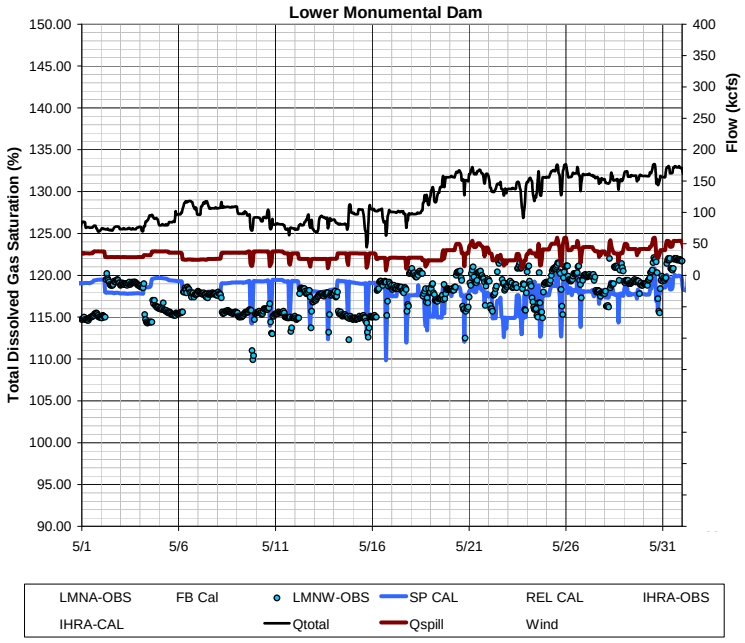

Figure G38. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Lower Monumental Dam, May 2009

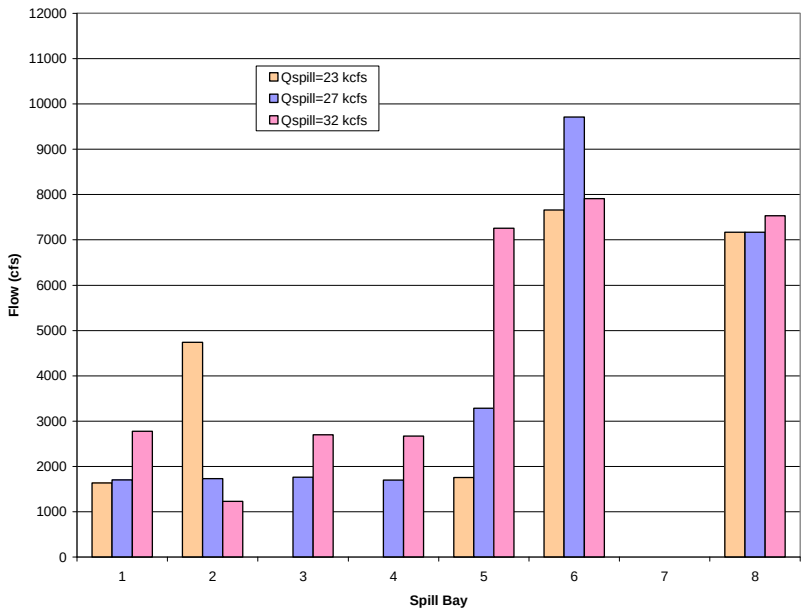

Figure G39. Spill Pattern at Lower Monumental Dam for 23, 27, and 32 Kcfs.

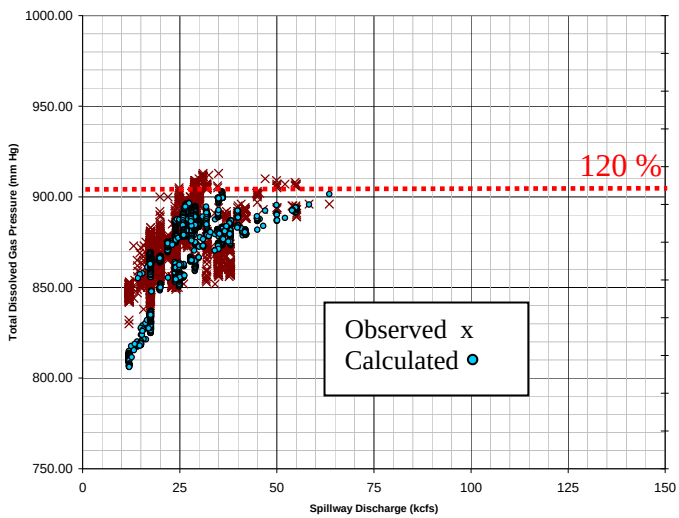

Figure G40. Observed and Calculated Total Dissolved Gas Pressure in the Snake River below Lower Monumental Dam as a Function of Spillway Discharge, 2009

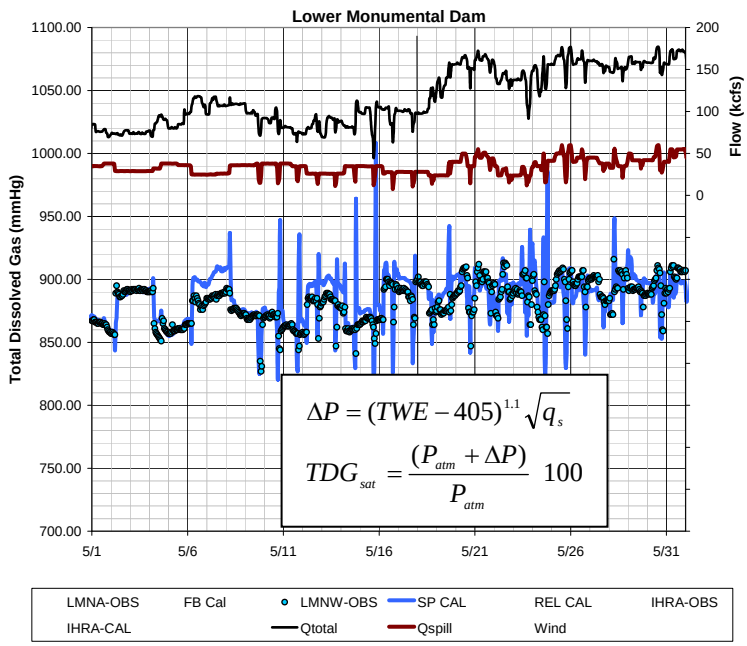

Figure G41. Observed and Calculated Total Dissolved Gas Pressure in the Snake River below Lower Monumental Dam using an alternative TDG generation model and the observed spill patterns, May 2009

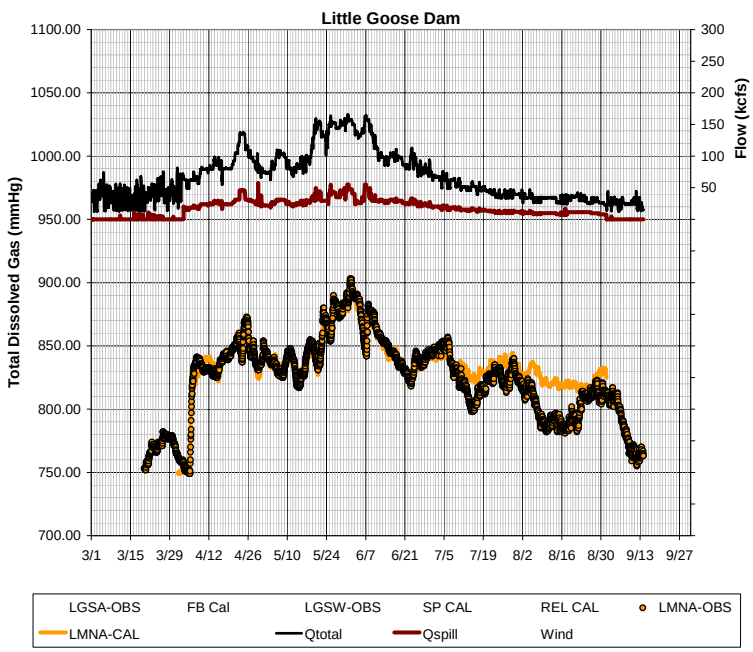

Figure G42. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Lower Monumental Dam, March-September 2009

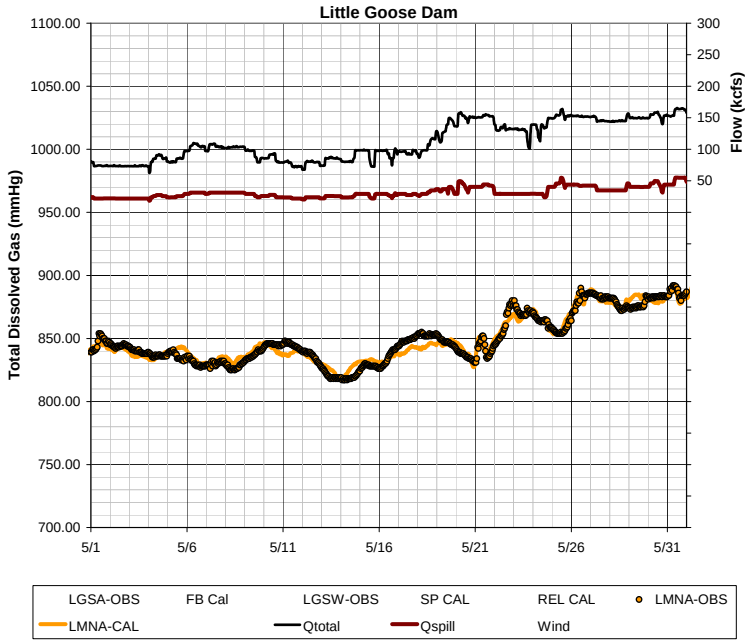

Figure G43. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Lower Monumental Dam, May 2009

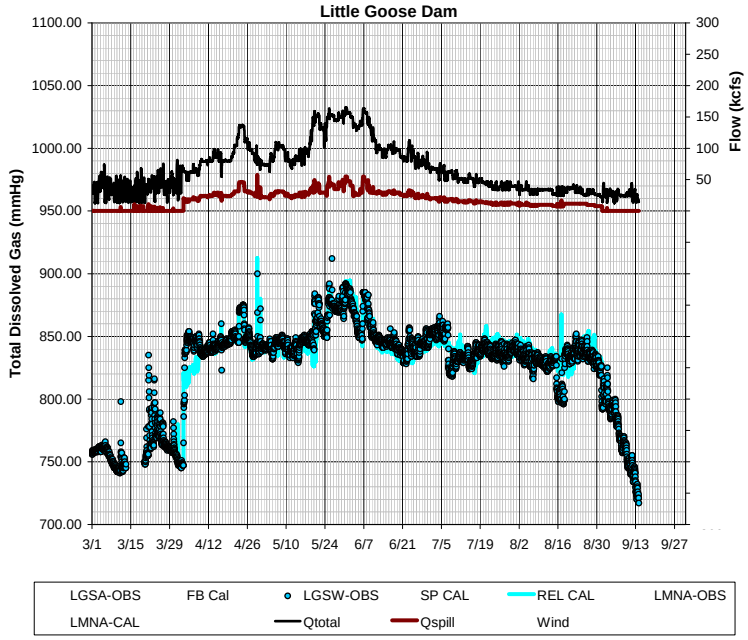

Figure G44. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Little Goose Dam, March-September 2009

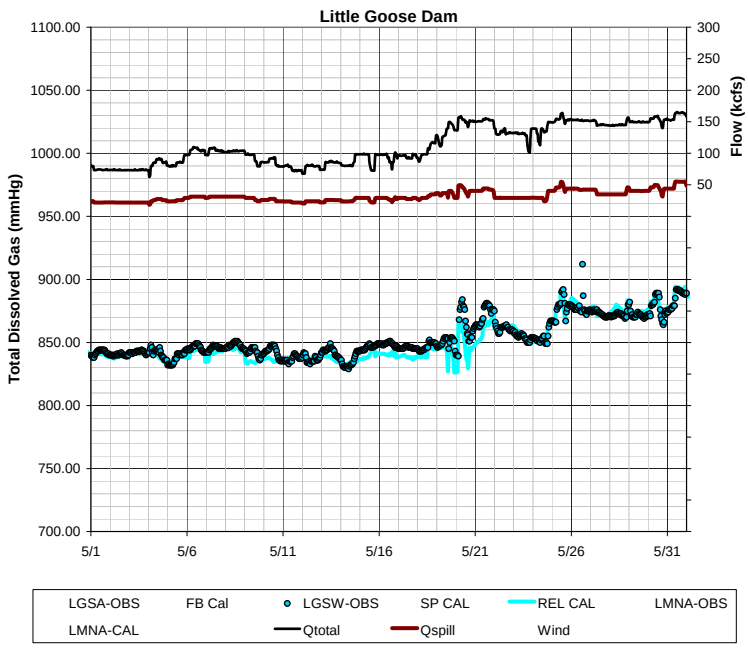

Figure G45. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Little Goose Dam, May 2009

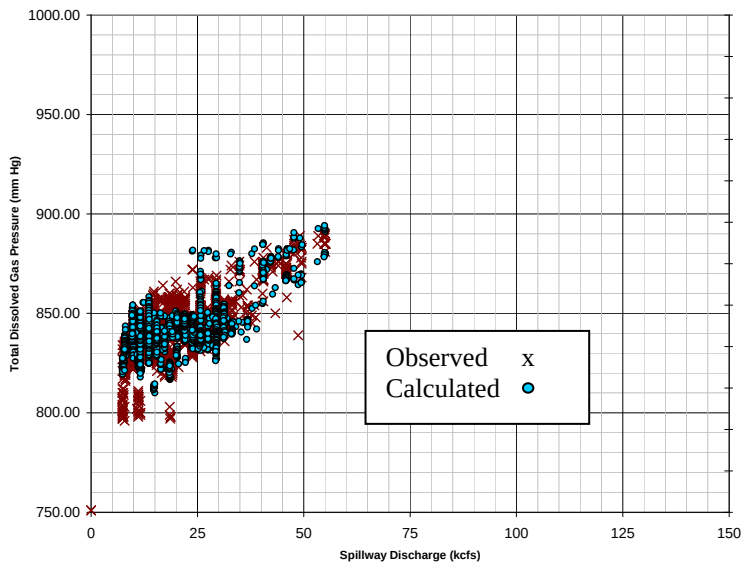

Figure G46. Observed and Calculated Total Dissolved Gas Pressures as a Function of Spillway Discharge in the Snake River at the tailwater channel downstream from Little Goose Dam, 2009

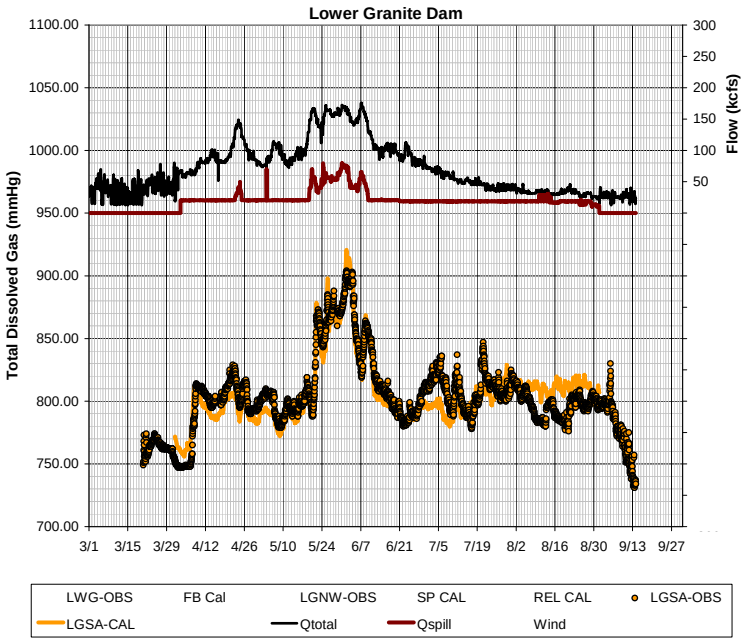

Figure G47. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Little Goose Dam, March-September 2009

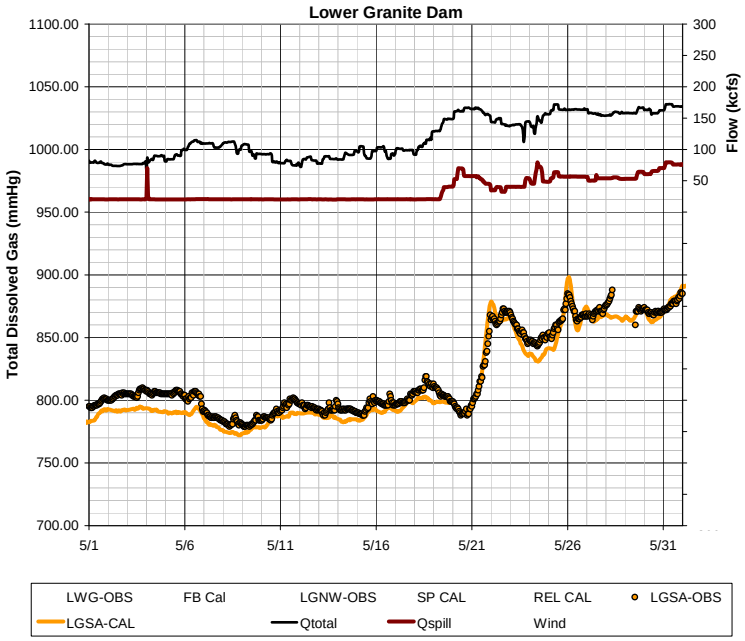

Figure G48. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the forebay of Little Goose Dam, May 2009

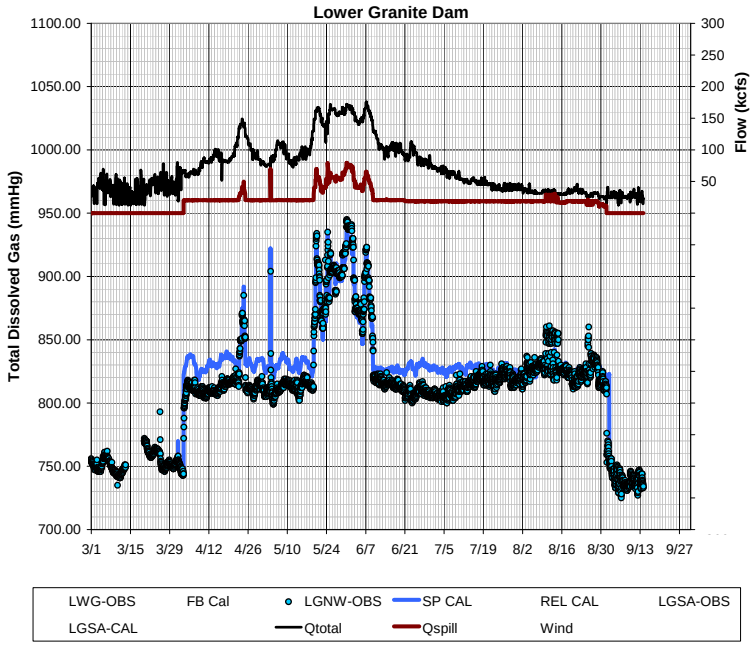

Figure G49. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Lower Granite Dam, March-September 2009

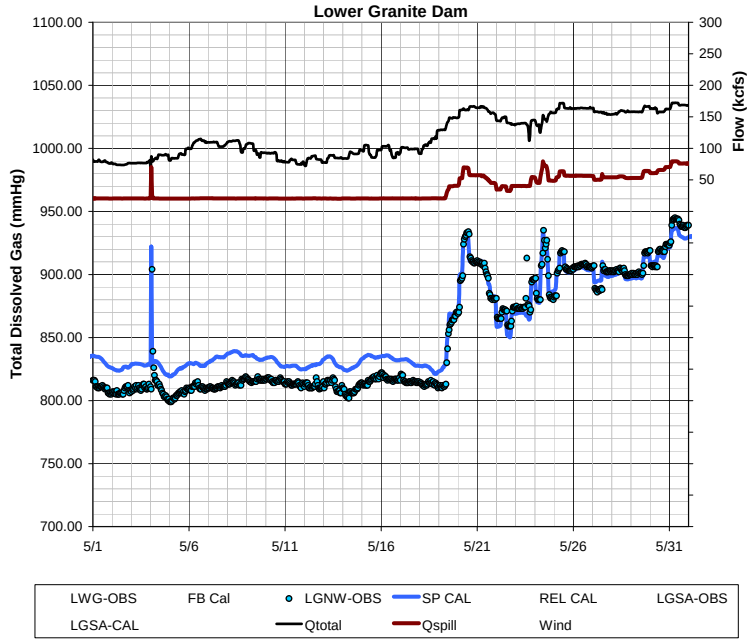

Figure G50. Observed and Calculated Total Dissolved Gas Pressures in the Snake River in the tailwater channel downstream from Lower Granite Dam, May 2009

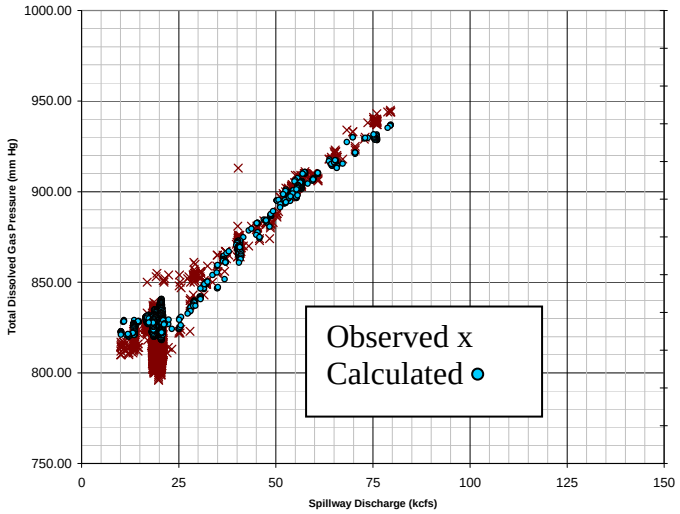

Figure G51. Observed and Calculated Total Dissolved Gas Pressure in the Snake River below Lower Granite Dam as a Function of Spillway Discharge, 2009

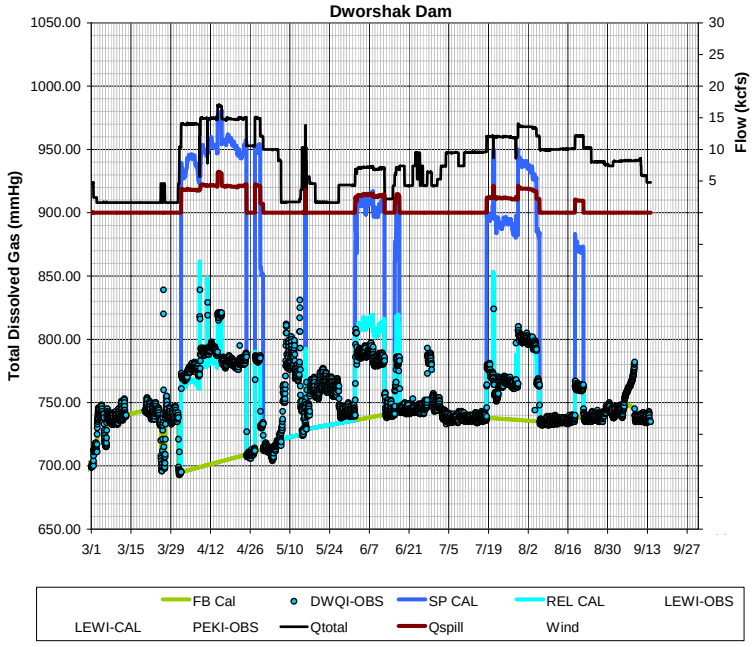

Figure G52. Observed and Calculated Total Dissolved Gas Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, March-September 2009

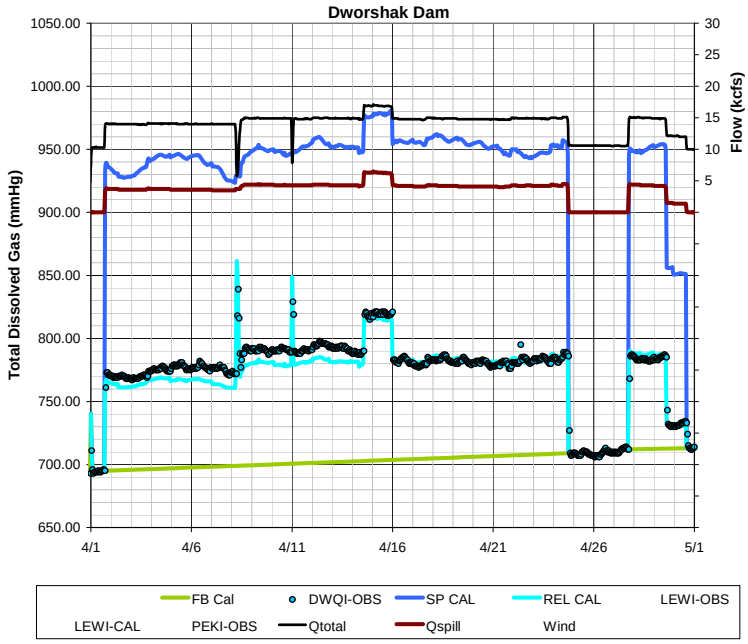

Figure G53. Observed and Calculated Total Dissolved Gas Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, April 2009

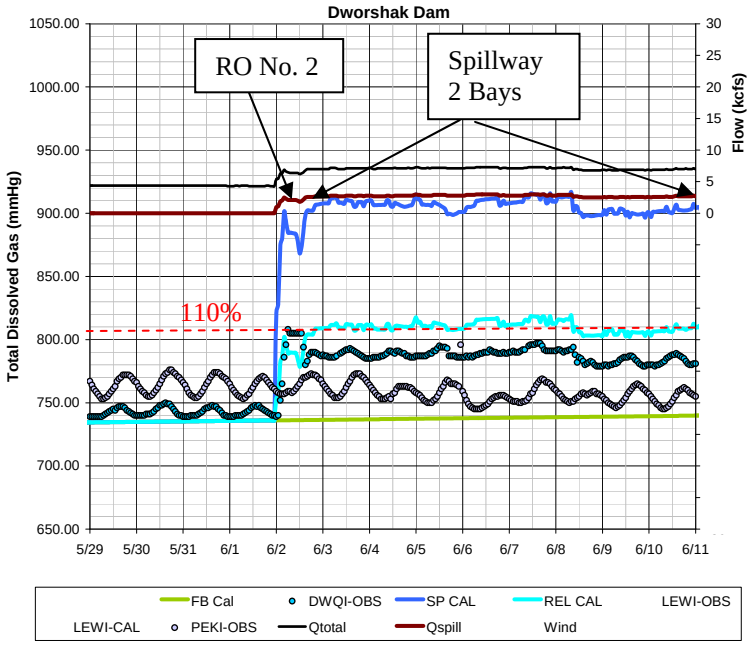

Figure G54. Observed and Calculated Total Dissolved Gas Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, May 29-June 10, 2009

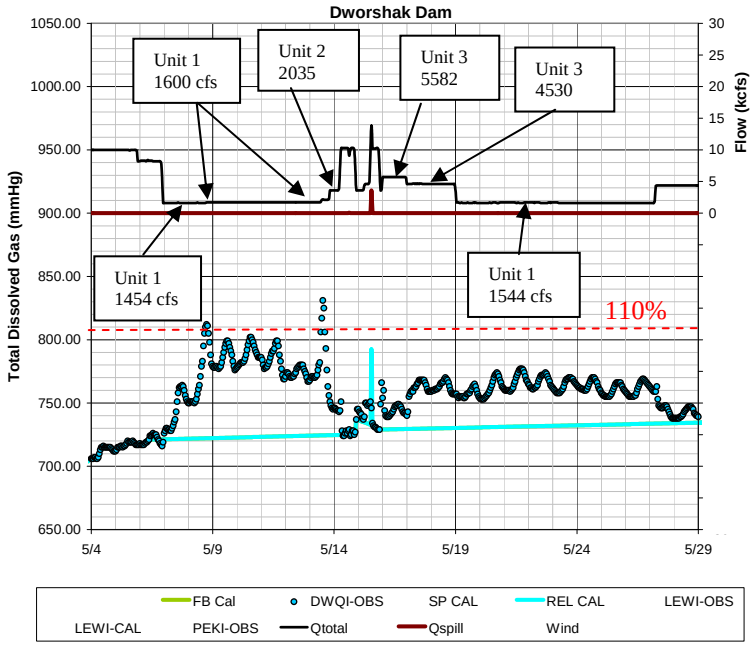

Figure G55. Observed and Calculated Total Dissolved Gas Pressures in the Clearwater River in the tailwater channel downstream from Dworshak Dam, May 4-28, 2009

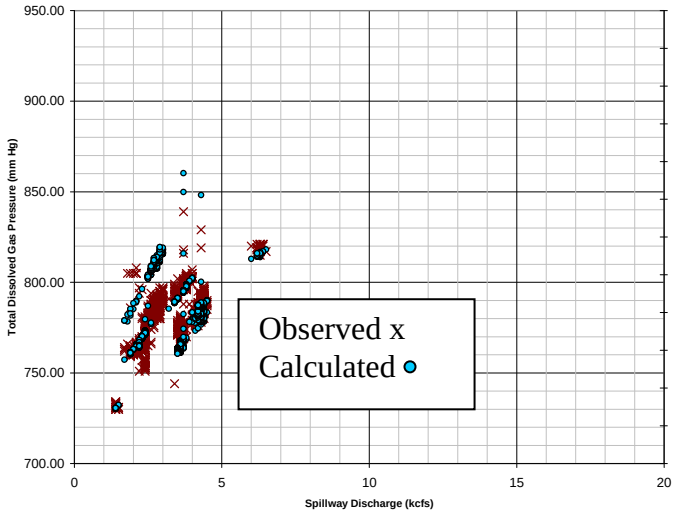

Figure G56. Observed and Calculated Total Dissolved Gas Pressure in the Clearwater River below Dworshak Dam as a Function of Spillway Discharge, 2009