Memo: Documentation of Total Dissolved Gas modeling with Special Application to COMPASS

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From: W. Nicholas Beer nickbeer@cbr.washington.edu

Summary

Forecasting TDG is important for salmon management because high levels of TDG are associated with gas bubble trauma and other sub-lethal effects that decrease salmon survival. Total Dissolved Gas (TDG) levels at the 15 Water Quality Monitoring (WQM; US Army Corps of Engineers) stations at hydropower dams on the Snake and Columbia rivers (Pacific Northwest, USA) can be forecast using environmental covariates: forebay gas levels, spill fraction and flow. All modeled, observed, and covariate data can be viewed and downloaded from https://cbr.washington.edu/shiny/DAM_CONDITIONS.

Background

Monitoring and evaluation of TDG at the Federal Columbia River Power System dams is managed by the US Army Corps of Engineers. As a part of this process, a TDG modeling framework called SYSTDG (USACE, 2009) was developed as an operational decision tool. SYSTDG has calibrated equations for TDG generation at 8 dams from Lower Granite Dam on the Snake River down to Bonneville Dam on the Columbia River. However, there are limitations to using the USACE gas models directly in a forecasting context:

- Reliance on tailwater depths. Although related to flow, there are problems with using tailwater depths as predictors. They require additional modeling to relate them to predicted elevations in pools; are very poorly modeled at some sites (especially LWG and LGS); and are poorly related to downstream elevations at dams such as PRD and BON.
- Reliance on ambient barometric pressure which is a high-variability weather phenomenon.
- Reliance on specific spill distribution patterns. Spill distribution across different gate types may not known in advance, yet SYSTDG has distinct models are specific spill patterns.
- TDG conditions at Upper Columbia River dams are not modeled.

An alternative model used primarily for predicting TDG levels when data are unavailable is embedded in NOAA's survival and traveltime model for juvenile salmon: COMPASS (Zabel et al. 2008). The model is used to hindcast and forecast survival and traveltime of migrants as well as their exposure to environmental conditions. The forecasting capacity is used with predictions of hydrosystem operations (flow, spill, etc.) which are generated by an independent process (HYDSIM model). Other environmental data (e.g. temperature and TDG) can be included or modeled internally to COMPASS so that the exposure of juvenile salmon to environmental conditions can be anticipated. The TDG modeling framework is:

- Compatible with the COMPASS modeling environment
- Requires minimal inputs
- Portable for multiple purposes
- Adaptable to any site with data on flow, spill, and TDG observations at forebay and tailrace

This memo is documentation of the development and calibration of the TDG model. The locations of the dams are shown in Figure 1.

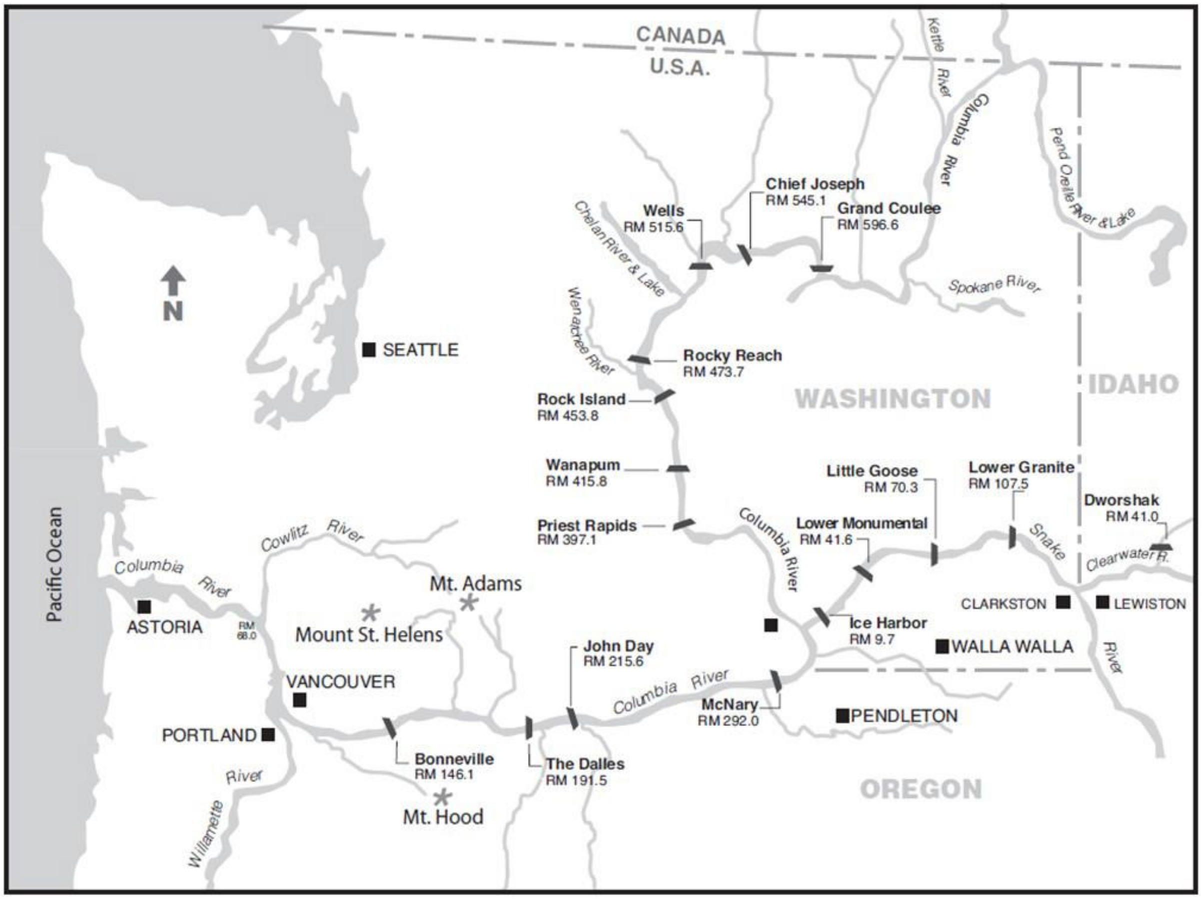

Figure 1 Location of dams. Source: 2022 Fish Passage Plan (USACE 2022). Acronyms for dam locations used in this memo and online tool are as follows: BON= Bonneville Dam, TDA=The Dalles Dam, JDA=John Day dam, MCN=McNary dam, PRD=Priest Rapids Dam, WAN=Wanapum Dam, RIS=Rock Island Dam, RRH=Rocky Reach Dam, WEL=Wells Dam, IHR=Ice Harbor Dam, LMN=Lower Monumental Dam, LGS=Little Goose Dam, LWG= Lower Granite Dam

Modeling

The system of monitoring equipment (and hence data) is slightly different than the modeling of the process. For each dam/pool system, there are multiple measures tracked by COMPASS, most notably, conditions on the left and right banks are separately modeled in the pools, passing the dams and exiting the tailrace. In contrast, there are only 2 observations: a forebay measurement and a tailrace measurement. Figure 2 illustrates the TDG process for a dam where the WQM site is on the same side as the spillway and the water moves downstream to the next dam. This is common (e.g. JDA, IHR, and LGS match this scheme), although there are various other configurations in the system. The forebay monitor side is much less important than the WQM side since waters are generally well mixed by the time they move through the reservoir from the upstream dam.

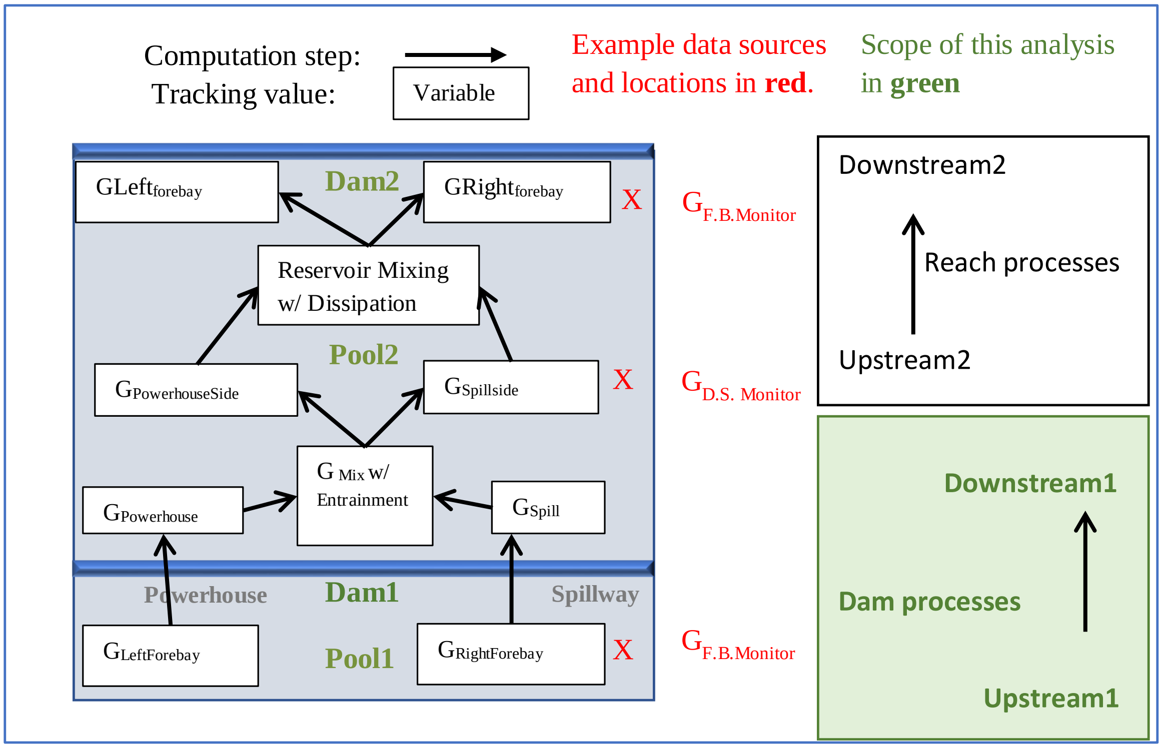

Figure 2 Schematic of one possible layout of the TDG monitoring / generation environment with computational flow and data sources identified.

A very influential process occurs when powerhouse-side water is "entrained" in the spill waters and gassed to the same level as the spill-side water so $G_{Powerhouse} > G_{Forebay}$ (USACE 2009). There is no mechanism for this at BON or TDA where the spillways are physically removed from the powerhouses, but at other locations, powerhouse water moves beneath the spillway and becomes supersaturated with the spill water. In the case of Wells dam, the spillway is over the powerhouse so entrainment is much more likely. Ignoring this phenomena results in over-generating TDG in the spill waters when in fact it is the volume of water being gassed that is important. When the spillway and powerhouse are physically isolated, the entrain_factor = 0. When entrainment occurs, the water exiting on the powerhouse side is a mixture itself and $G_{Powerhouse}$ is computed in terms of the $G_{Forebay}$ and the volume of water being entrained.

When spillway and powerhouse are adjacent, entrain_factor > 0, based on specific studies. The USACE (2009) reports that entrainment at LGS and LWG is proportional to the spill volume, and at other sites is present but poorly quantified (perhaps a volume rather than a fraction) in which case representative spills were used to compute a fraction for use in TDG model calibration. A summary of entrainment is in Table 1.

The modeling process described below uses terms defined in Table 2. The mixing process developed here enables simultaneous fitting of spill-generated gas parameters and tailrace mixing. The strength of this method is to specifically and explicitly isolate and parameterize the TDG generating processes. Modeled TDG% downstream of a dam is directly compared to WQM TDG%.

Table 1 Entrainment summary.

Site	Entrainment factor	Other entrainment	Enforced maximum k	Comment
BON	0		0	Separation of powerhouse and spill
TDA	0		0	Separation of powerhouse and spill
JDA		35 KCFS*	0.3	April – June spill is on order of 50- 100 KCFS and entrainment varies with spill (ACOE 2011a)
MCN		35 KCFS*	0.25	April – June spill is on order of 100 to 150 KCFS
IHR		30 KCFS*	0.6	April – June spill is highly variable at least 20 KCFS but often over 80 KCFS. Assuming 50 KCFS of spill
LMN		30 KCFS*	2.0	LMN spill is targeted at 30 KCFS. Adjusted at fitting.
LGS	2.0**		1	USACE 2009
LWG	1.75		1	USACE 2009 but adjusted to 1.0 during fitting
CHJ	0		1	Adjusted to 1 in refit May 2022
PRD, WAN			0	Assigned, due to separation
RRH, RIS, WEL			1	Assigned, due to proximity

* Quasi constant or variable due to operations, but poorly proportional to spill (ACOE 2009).

**Reduced to 1 during fitting process.

Table 2 Glossary of terms.

Term	Definition	Term	Definition
G_{Spill}	TDG% in the Spill flow	Q_{Spill}	Spill flow volume
$G_{Powerhouse}$	TDG% in the Powerhouse flow	$Q_{Powerhouse}$	Powerhouse flow volume
$G_{SpillSide}$	TDG% on the Spill side of the river at the WQM	$Q_{Entrain}$	Entrained Powerhouse flow volume
$G_{PowerhouseSide}$	TDG% computed for the Powerhouse side of the river	WQM	Water Quality Monitoring station
$G_{Downstream}$	TDG% measured at the WQM	f	spill fraction
$G_{Upstream}$	TDG% measured in the Forebay	k	entrainment factor: volume of powerhouse water gassed relative to the spill volume
$G_{Forebay}$	TDG% measured at the Forebay monitor	α	Mixing fraction for the difference between the left and right side TDG%
G_{Mix}	volume weighted TDG % of the mixed spill and powerhouse flow volumes	θ w	reservoir mixing parameter dissipation constant
$G_{Difference}$	TDG% difference between G_{Spill} and $G_{Powerhouse}$	$G_{DifferenceDownstream}$	TDG% Left-right Difference modeled downstream for forebay at next dam

$G_{Downstream}$ measures TDG in a mixture of water from both the powerhouse and the spillway and the method of computing it is described here. Conceptually, perfectly mixed water (in the absence of other inputs or losses) has this level of TDG:

1) $G_{Mix} = G_{Spill} f + G_{Powerhouse}(1 - f)$

where *f* is the fraction of total flow that is spilled. However, the monitoring value, $G_{Downstream}$, may be sampling incompletely mixed waters with a value somewhere between G_{Spill} and $G_{Powerhouse}$. It is mathematically convenient to represent the mixture in terms of its *separation*. Let α represent the separation and define: c. When α =0 there is complete mixing, and when α =1 , it is completely separated.

In the absence of other source of TDG, the waters on either side of the river downstream are:

2) New $G_{Spillside} = G_{Mix} + G_{Difference} f\alpha$

3) $G_{Phouseside} = G_{Mix} - G_{Difference} f\alpha$

Allowing entrainment to be proportional to spill at any site, then:

4) $Q_{Entrain} = kQ_{Spill} = kfQ$

and

5) $Q_{Powerhouse} - Q_{Entrain} = (1 - fk)Q$.

The Powerhouse side gas levels is then:

6) $G_{Powerhouse} = \left(\frac{Q_{Powerhouse} - Q_{Entrain}}{Q_{Powerhouse}} \right) G_{Forebay} + \frac{Q_{Entrain}}{Q_{Powerhouse}} G_{Spill}$

7) New $G_{Powerhouse} = \frac{(1 - fk)}{1 - f} G_{Forebay} + fkG_{Spill}$

With further substitution and algebra, we can rewrite the G_{Mix} in terms of f, k, G_{Spill} and $G_{Forebay}$:

8) $G_{Mix} = G_{Spill} f + \left((1 - fk)G_{Forebay} + fkG_{Spill}\right)(1 - f)$

9) $G_{Mix} = G_{Spill}(f + fk - f^2k) + G_{Forebay}\left(1 - f - fk + f^2k\right)$

This has an important constraint : $k \le \frac{1}{f} - 1$ because it is impossible to entrain more water than the powerhouse flow. Collecting the terms for easier notation where: $\beta = f + fk - f^2k$ and rearranging, and substituting as necessary, an expression for G_{Spill} is obtained based on observations of $G_{Downstream}$, on either the spill side or the powerhouse side depending on the location, and $G_{Forebay}$. Substituting G_{Mix} into the equations for the $G_{Spillside}$ and $G_{PowerhouseSide}$ we have expressions that model the observed $G_{Downstream}$ values. If the downstream monitor is on the spill side then:

10) $G_{SpillSide} = G_{Spill} f + G_{Powerhouse}(1 - f) + \left(G_{Spill} - G_{Powerhouse}\right)(1 - f)\alpha$

substituting $G_{Powerhouse}$ and performing some algebra yields:

11) $$G_{SpillSide} = G_{Spill}(\beta + \alpha(1-\beta)) + G_{Forebay}(1-\beta-\alpha(1-\beta))$$

Similarly:

12) $$G_{PowerhouseSide} = G_{Spill}\left(\beta - \alpha(\beta - f)\right) + G_{Forebay}\left(1 - A + \alpha(A - f)\right)$$

For sites where the downstream monitor is in the center of the river Eqn (11) is used.

The remaining unknown quantity G_{Spill} is modeled with the Q_{Spill} using one of two types of equations. The first was a bounded exponential model because of historic precedence as used in the CRiSP model (CBR, 2000), consistency with ACOE methods, and its curvi-linear properties. The second was a linear model with a simple relationship of $G_{Spill} \propto Q_{Spill}$.

13) $$G_{Spill} = P_0 + P_1 e^{P_2 Q_{Spill}}$$

14) $$G_{Spill} = P_0 + P_1 Q_{Spill}$$

Parameters for G_{Spill} were determined with a maximum likelihood method. Optimization of the maximum likelihood was done with the *optim* function in the statistical software package R, version 4.1.2 (https://cran.r-project.org/).

The final production model was selected with the G_{Spill} optimized over a set of additional parameters including: mix fractions (k), entrainment (g) and for the hourly data, the hours of delay (lag) between production and observation. When the hourly data were fit, the nominal parameters from the daily data fits were used and then a lag of 0, 1 or 2 hour was selected. The final model was selected based on the coefficient of determination (R^2), Standard Error of the residuals (SE), and Mean Absolute Deviation of the residuals (MAD) between $G_{Downstream}$ at the WQM and TDG% computed with Eqn (11) or Eqn (12) depending on the configuration of the site.

Daily and Hourly data sets

The analysis is performed with the daily-average dat set and the hourly data set. In the daily average data set, the conditions at the dam for the day are matched to the conditions at the WQM station on the same day. In principle, the lag between the dam conditions that generate TDG and the observed TDG downstream at the WQM should be considered, but the historic daily-average data are NOT sensitive to the lag.

The hourly data lag is important at the sites where the WQM monitor is signifiantly downstream from the dam. At Bonneville, the WQM is 5.8 miles downstream and at Ice Harbor is 4.1 miles downstream. Historically, conditions generally varied slowly at the dams, and the temporal-correlation of the conditions has been very high. The consequence of that for fitting the gas models to the hourly data is that calibrations for lags of 0 to 6 hours are very similar to each other within a site. In practice, lags of 0 to 1 hours are appropriate at most dams. Lags of 0 to 2 hours applies at dams such as WEL, WAN and TDA where the WQM stations are 3 to 3.3 miles downstream of the respective dams. Lags of 1 to 3 hours are appropriate for IHR and BON where the distances are 4.1 and 5.8 miles respectively.

Additional Processes

Within the COMPASS framework, modeled TDG% is propagated below the WQM. This is necessary in order to have forebay inputs for the TDG generating process at the next dam. Although beyond the scope of this analysis, it is described here. In this context, the downstream location becomes a forebay monitor and the upstream location becomes a WQM site at the previous dam.

Below the WQM site, flows carry TDG downstream through the subsequent reservoir where it continues to mix such that: $G_{DifferenceDownstream} = G_{DifferenceUpstream} e^{-\theta x}$. The USACE reports that right and left bank gas levels are ~95% mixed in 40 miles so a conservative parameter for this is to let $\theta = 0.075$ (CBR 2000) which is a fixed value in COMPASS.

In addition, TDG dissipates over time as a function of physical conditions of the river. However, since we are interested in TDG at a certain location, then this computation is made in terms of distance and velocity which are explicitly computed in COMPASS. Thus, TDG levels above equilibrium downstream from a TDG source for the reservoir will be: $G_{Downstream} = G_{Upstream} e^{-w\frac{x}{v}}$ where *x* is distance and *v* is velocity and *w* = Gas Dissipation Exponent. The nominal, historic value w = 2x10e-5 cm^2/cm is considered fixed in COMPASS and is not a part of the calibration process. Although reach-specific differences may alter the details of the process, any spatial differences would be considered secondary to proximal, temporal effects due to temperature, humidity, wind, etc. (USACE 2009) effects on the reservoir surfaces.

Results

Fitted parameters and summary diagnostics are shown in Table 3 for the daily average data. Plots of the relationship between the observed and modeled TDG at the WQM stations are shown in Figure 3.

Table 3 TDG modeling parameters and diagnostics: coefficient of determination (R^2), standard error (SE) of the residuals and mean absolute deviation (MAD). Other abbreviations: eqn = equation; lin = linear; exp = exponential; k=entrainment factor; α=mix fraction; ph = powerhouse; sp = spillway; c = center;

Dam	eqn	P0	P1	P2	mixfrac (α)	entrainment (k)	WQM side*	R^2	SE Residuals	MAD Residuals
BON	lin	14.45	0.05427	0	0	0	ph	0.97	1.4	1
TDA	lin	22.35	0.01176	0	0	0	ph	0.91	1.07	0.74
JDA	lin	22.46	0.02014	0	0	0.3	sp	0.79	2.59	1.96
MCN	lin	15.75	0.03894	0	0	0.25	sp	0.8	2.07	1.42
PRD	lin	12.84	0.06154	0	0	0	C	0.87	2.68	1.35
WAN	lin	14.88	0.1088	0	0	0	C	0.94	2	1.3
RIS	lin	18.34	0.08198	0	0	1	ph	0.83	2.5	1.36
RRH	lin	18.44	0.09034	0	0	1	C	0.87	2.49	1.94
WEL	lin	17.27	0.1116	0	0	1	sp	0.94	1.49	0.7
IHR	lin	8.547	0.1354	0	0	0.6	sp	0.86	1.66	1.25

LMN	lin	12.53	0.1432	0	0.25	2	sp	0.66	1.9	1.43
LGS	lin	9.891	0.1821	0	0	1	sp	0.83	1.74	1.28
LWG	lin	9.866	0.2127	0	0.375	1	sp	0.79	2.23	1.79
CHJ	lin	12.28	0.06078	0	0	1	sp	0.72	2.5	1.89
DWR	lin	23.94	0.5007	0	0	0	sp	0.87	1.9	1.47

*ph = powerhouse side, sp=spill side, c=center

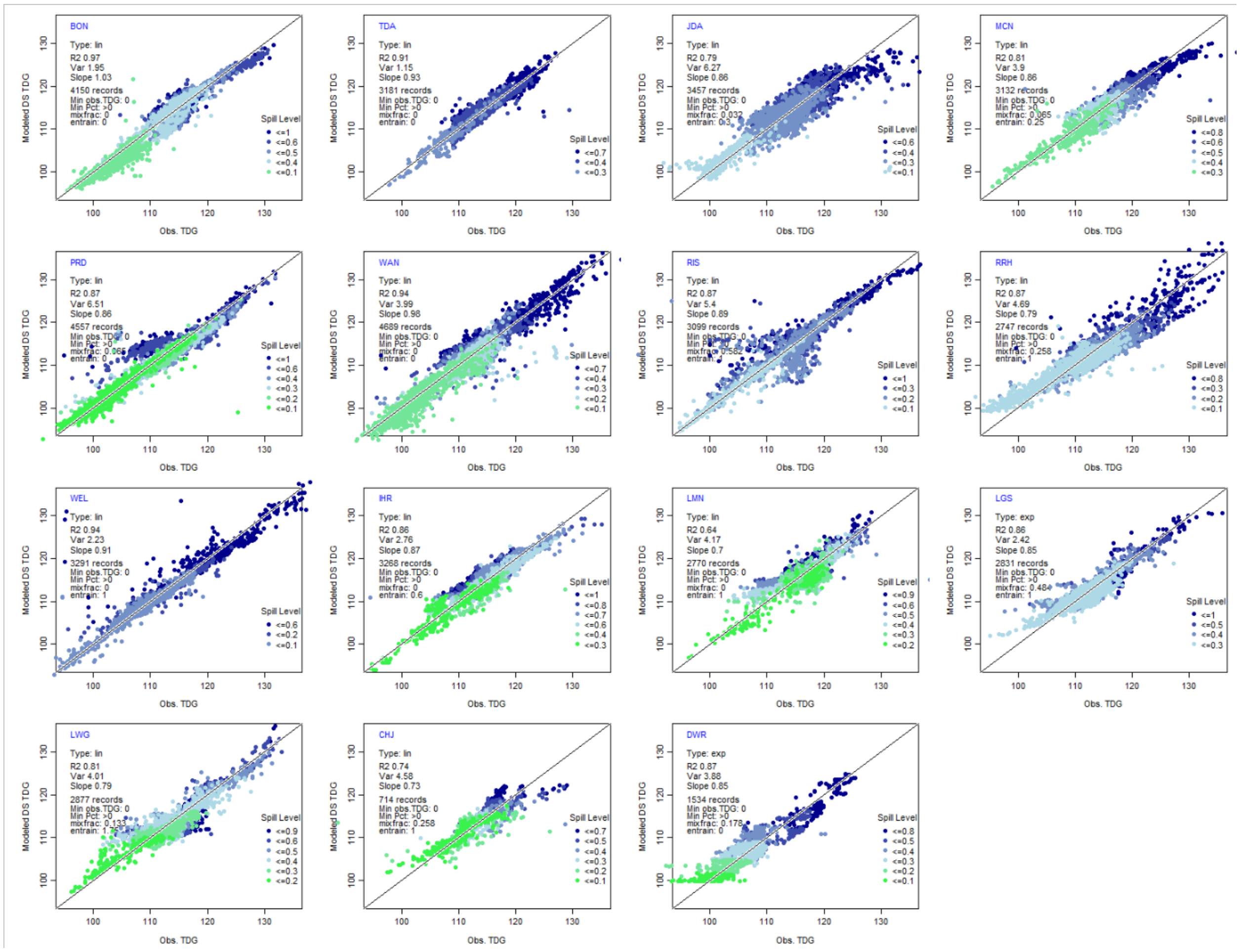

Figure 3 Relationship of modeled and observed daily average TDG% at the WQM stations for each site.

Fitted parameters for the sites using the hourly data with lags from 0 to 6 hours are not shown in this memo but can be viewed from the online tool (https://cbr.washington.edu/shiny/DAM_CONDITIONS) when the “Hourly Data” box is checked and “TDG (Model)” is selected as an axis variable or a display value.

An exploration of historic gas production from 2009 – 2021 revealed that TDG generation varies in four characteristic ways. The online tool https://cbr.washington.edu/shiny/DAM_CONDITIONS has methods for exploring and illustrating these data. Example illustrations are created with this tool.

1. Dams that generate TDG at low spills but reach peak production very quickly, e.g. BON, JDA. Here, observed TDG% reach an asymptote regardless of spill volume. There are operational requirements that have historically constrained TDG% to below a gas cap (allowable limit).
2. Dams that appear to generate a little extra TDG with spill, but mostly just pass TDG downstream from the forebay. E.g. at PRD, observed gas is ± 5% points higher than upstream for a wide range of spill level ().
3. Dams where TDG is conspicuously generated by spill. E.g. at LWG, the upstream TDG levels are usually low and spill generates the extra observed TDG measured at the tailrace monitor (Figure 6).
4. Dams that have a hybrid response, passing TDG from upstream and generating gas, e.g. WAN which has some of the highest observed TDG% concentrations in this study (Figure 7).

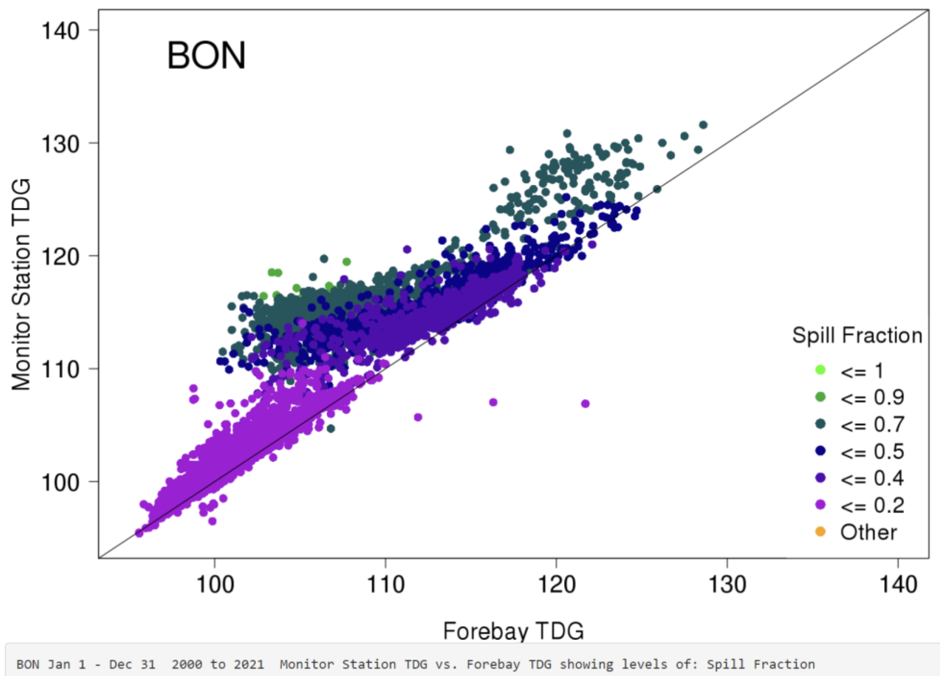

Figure 4 Bonneville Dam (BON) relationship of forebay TDG% to monitor station TDG.

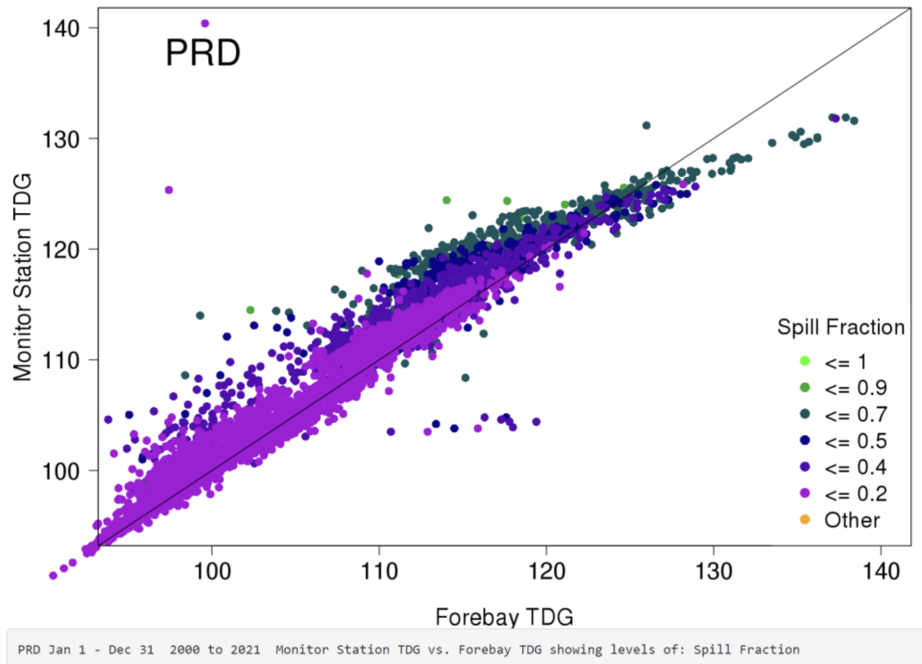

Figure 5 Priest Rapids Dam (PRD) relationship of forebay TDG% to monitor station TDG.

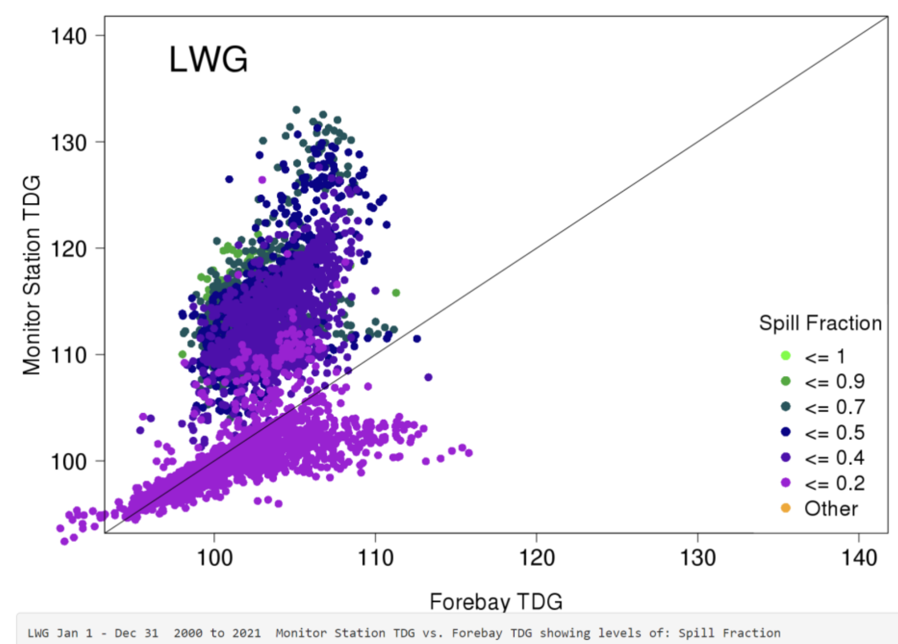

Figure 6 Lower Granite Dam (LWG) relationship of forebay TDG% to monitor station TDG%.

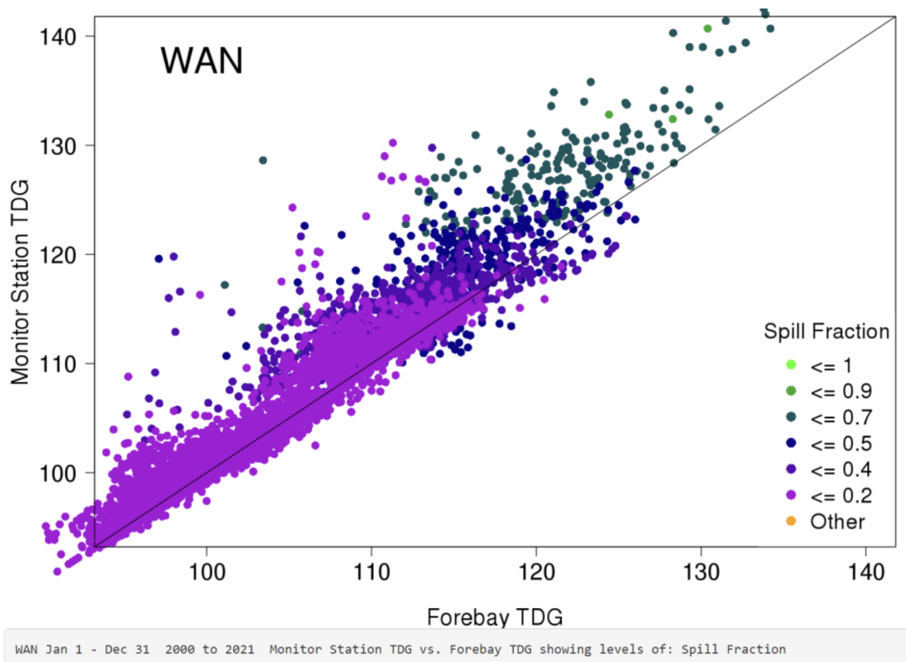

Figure 7 Wanapum Dam (WAN) relationship of forebay TDG% to monitor station TDG%.

Appendix 2. COMPASS Application

COMPASS accepts parameters: "gas_theta" $= -\log(\alpha)$ and "entrain_factor" = k. Note that "entrain_factor" is not equivalent to the legacy parameter "k_entrain" . "k_entrain" is a parameter that influences gassing of the powerhouse flow as a function of spill. Use of "entrain_factor" allows a portion of the powerhouse flow, proportional to spill, to be entrained. Either can be specified in COMPASS.

Various controls related to COMPASS and their effect are shown in Table 4. For use in COMPASS, files and tokens should be set up to include:

compute_gas On

include gas.equations.2022.dat

Other inputs in various files should be modified as:

output_gas Off # at each feature where modeling is desired output_settings should be adjusted to include “32” at each site where TDG outputs are of interest.

Table 4. Input controls related to TDG production in COMPASS.

GLOBALS	Segment modifications	Additional includes	Results to summary.dat (incl 32) and/or –o output.file
real<year>.dat			Pools: output_gas On <data> Dams: output_gas Off
		include nsat equations	Pools: output_gas On Dams: **model TDG**
ALL references to gas removed			<0 … > everywhere compute_gas On (internal switched)
compute_gas On	output_gas On <data>		<data>
	output_gas On		<0 …>
	output_gas Off	include nsat equation	**model TDG** Pools and Dams
	output_gas Off		same as upstream
compute_gas Off	output_gas On <data>		<data>
	output_gas On		<0 …>
	output_gas Off		same as upstream
	output_gas Off	include nsat equations	same as upstream
	gas_theta (dam)		Effect if: “model TDG”
	gas_theta (reach)		No effect ever
gas_dissp_exp			No effect ever

References

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