Appendix C

Technical Analysis of TDG Processes

Analysis of TDG generation processes

Introduction

The discussion in this section is taken (sometimes verbatim) from the Dissolved Gas Abatement Study (DGAS) conducted by the U.S. Army Corps of Engineers, and in particular from Appendix G: "Spillway Discharge Production of Total Dissolved Gas Pressure" (USACE, 2001a). The material in this section provides a general overview of TDG generation processes at the USACE Lower Columbia and Snake River dams, to provide background for understanding TDG generation processes in the Mid-Columbia dams.

The TDG exchange associated with spillway operation at a dam is a process that couples both the hydrodynamic and mass exchange processes. The hydrodynamics are shaped by the structural characteristics of spillway, stilling basin, and tailrace channel as well as the operating conditions that define the spill pattern, turbine usage, and tailwater stage. The hydrodynamic conditions are influenced to a much smaller extent by the presence of entrained bubbles.

The air entrainment will influence the density of the two-phase flow and impose a vertical momentum component associated with the buoyancy in the entrained air. The entrained air content can result in a bulking of the tailwater elevation and influence the local pressure field. The transfer of atmospheric gasses occurs at the air-water interface, which is composed of the surface area of entrained air at the water surface. The exchange of atmospheric gases is greatly accelerated when entrained air is exposed to elevated pressures because of the higher saturation concentrations. The pressure time history of entrained air will, therefore, be critical in determining the exchange of atmospheric gases during spill.

The volume, bubble size, and flow path of entrained air will be dependent on the hydrodynamic conditions associated with project releases. The bubble size has been found to be a function of the velocity fluctuations and turbulent eddy length. The bubble size can also be influenced by the coalescence of bubbles during high air concentration conditions. The volume of air entrained is a function of the interaction of the spillway jet with the tailwater. The entrained bubble flow path will be dependent upon the development of the spillway jet in the stilling basin and associated secondary circulation patterns. The turbulence characteristics are important to the vertical distribution of bubbles and the determination of entrainment and de-entrainment rates.

Physical Processes

The exchange of TDG is considered to be a first-order process where the rate of change of atmospheric gases is directly proportional (linear relationship) to the ambient concentration. The driving force in the transfer process is the difference between the TDG concentration in the water and the saturation concentration with the air. The saturation concentration in bubbly flow will be greater than that generated for non-bubbly flow where the saturation concentration is determined at the air-water interface. The flux of atmospheric gasses across the air-water interface is typically described by Equation 1.

$$J = K_l(C_s - C) \qquad \text{Equation 1}$$

Where:

J	=	gas flux (mass per surface area per time)
K_l	=	the composite liquid film coefficient
C_s	=	the saturation concentration (mass per volume)
C	=	the ambient concentration in water (mass per volume)

The rate of change of concentration in a well-mixed control volume, $\frac{dC}{dt}$, can be estimated by multiplying the mass flux by the surface area and dividing by the volume over which transfer occurs as shown by Equation 2:

$$\frac{dC}{dt} = K_l \frac{A}{V}(C_s - C) \qquad \text{Equation 2}$$

Where:

A	=	the surface area associated with the control volume
V	=	the volume of the waterbody over which transfer occurs

This relationship shows the general dependencies of the mass transfer process. In cases where large volumes of air are entrained, the time rate of change of TDG concentrations can be quite large, as the ratio of surface area to volume becomes large. The entrainment of air will also result in a significant increase in the saturation concentration of atmospheric gases, thereby increasing the driving potential over which mass transfer takes place. Outside of the region of aerated flow during transport through the pools, the contact area is limited to the water surface and the ratio of the surface area to the water volume becomes small, thereby limiting the change in TDG concentration. The turbulent mixing will influence the surface renewal rate and hence the magnitude of the exchange coefficient K_l.

Equation 2 can be integrated, provided the exchange coefficient, area, and volume are held constant over the time of flow. The initial TDG concentration at time=0 is defined as C_i and the final TDG concentration time=t is defined as C_f shown in Equation 3. The resultant concentration C_f exponentially approaches the saturation concentration for conditions where the term $K_l \frac{A}{V}$ is large. The final concentration becomes independent of the initial concentration under these conditions.

$$C_f = C_s(l - e^{-K_l \frac{A}{V} t}) + C_i e^{-K_l \frac{A}{V} t} \qquad \text{Equation 3}$$

Modeling TDG Transfer

The TDG exchange process involves the coupled interaction of project hydrodynamics and mass transfer between the atmosphere and the water column. Mechanistic models of TDG transfer must simulate the two-phase (liquid and gas phases) flow conditions that govern the exchange process. Several mechanistic models have been developed to simulate the TDG exchange in spillway flows.

Orlins and Gulliver (2000) solved the advection-diffusion equation for spillway flows at Wanapum Dam for different spillway deflector designs. Physical model data were used to develop the hydraulic descriptions of the flow conditions throughout the stilling basin and tailrace channel. The model results were also compared to observations of TDG pressure collected during field studies of the existing conditions.

A second model, developed by Urban et al. (2000), used the same mass transport relationships together with the hydraulic descriptions associated with plunging jets. This approach does not require the specific hydraulic information to be derived from a physical model, but it can be applied to any hydraulic structure that has plunging jet flow. This model accounted for the TDG exchange occurring across the bubble-water interface and the water surface. This model was calibrated to observations of TDG exchange at The Dalles Lock and Dam (The Dalles) and was developed as part of DGAS. This model successfully simulated the absorption and desorption exchange caused by the highly aerated flow during spillway operations.

As a part of its DGAS study, the USACE decided to use empirically derived equations of TDG exchange, based on the recognition that data were not available to support mechanistic models of the mass exchange process at all the projects in the Columbia/Snake river system. The greatest unknowns associated with the development of a mechanistic model of highly aerated flow conditions in a stilling basin revolve around the entrainment of air and subsequent transport of the bubbles. The surface area responsible for mass transfer will require estimates of the total volume and bubble size distribution of entrained air. In addition, the roughened water surface is thought to contribute to the net exchange of atmospheric gasses. The pressure time history of entrained air would also need to be accounted for to determine the driving potential for TDG mass exchange.

A description of the highly complex and turbulent three-dimensional flow patterns in the stilling basin and adjoining tailrace channel would need to be defined for a wide range of operating conditions. The influence of turbulence on both the mass exchange coefficients and redistribution of buoyant air bubbles would also need to be quantified throughout a large channel reach and for a wide range of operating conditions.

The flow conditions generated by spillway flow deflectors have been found to be sensitive to both the unit spillway discharge and submergence of the flow deflector. The presence of flow deflectors has significantly changed the rate of energy dissipation in the stilling basin and promotes the lateral entrainment of flow. These entrainment flows are often derived from powerhouse releases, which reduce the available volume of water for dilution of spillway releases.

TDG Exchange Formulation

The accumulated knowledge generated through observations of flow conditions during spill at Columbia/Snake River projects and in-scale physical models at the Waterways Experiment Station in Vicksburg, MS, along with mass exchange data collected during site-specific, near-field TDG exchange studies and from the fixed monitoring stations, has led to the development of a model for TDG exchange at dams throughout the Columbia/Snake river system for the federal hydropower projects. The general framework is based upon the observation that TDG exchange is an equilibrium process that is associated with highly aerated flow conditions that develop below the spillway. It recognizes that flow passing through the powerhouse is not generally exposed to entrained air under pressure and, therefore, does not experience a significant change in TDG pressure. It also recognizes that powerhouse releases can directly interact with the aerated flow conditions below the spillway and experience similar changes in TDG pressure that are found in spill.

The large volume of air entrained into spillway releases initiates the TDG exchange in spill. This entrained air is exposed to elevated total pressures and the resulting elevated saturation concentrations. The exposure of the bubble to elevated saturation concentrations greatly accelerates the mass exchange between the bubble and water. The amount and trajectory of entrained air is greatly influenced by the structural configuration of the spillway and the energy associated with a given spill.

The presence of spillway flow deflectors directs spill throughout the upper portion of the stilling basin, thereby preventing the plunging of flow and transport of bubbles throughout the depth of the stilling basin. Spillway flow deflectors also greatly change the rate of energy dissipation in the stilling basin, transferring greater energy and entrained air into the receiving tailrace channel.

Generally, spill water experiences a rapid absorption of TDG pressure throughout the stilling basin region where the air content, depth of flow, flow velocity, and turbulence intensity are generally high. As the spillway flows move out into the tailrace channel, the net mass transfer reverses and component gases are stripped from the water column as entrained air rises and is vented back to the atmosphere. The region of rapid mass exchange is limited to the highly aerated flow conditions within 1,000 feet of the spillway.

In general, downstream of the aerated flow conditions, the major changes to the TDG pressures occur primarily through the redistribution of TDG pressures through transport and mixing processes. The in-pool equilibrium process established at the water surface is chiefly responsible for changes to the TDG loading in the river.

One of the more important observations regarding TDG exchange in spillway flow is the high rate of mass exchange that occurs below a spillway. The resultant TDG pressure generated during a spill is almost entirely determined by physical conditions that develop below the spillway and is effectively independent from the initial TDG content of this water in the forebay.

The TDG exchange in spill is not a cumulative process where higher forebay TDG pressures will generate yet higher TDG pressures downstream in spillway flow. The TDG exchange in spill is an equilibrium process where the time history of entrained air below the spillway will determine the resultant TDG pressure exiting the vicinity of the dam.

One consequence of this observation is that spilling water can result in a net reduction in the TDG loading in a system if forebay levels are above a certain value. This was a common occurrence at The Dalles during the high-flow periods in 1997 where the forebay TDG exceeded 130% saturation. A second consequence of the rapid rate of TDG exchange in spill flow is that the influence from upstream projects on TDG loading will be passed downstream only through powerhouse releases. If project operations call for spilling a high percentage of the total river flow, the contribution of TDG loading generated from upstream projects will be greatly diminished below this project.

Given the conceptual framework for TDG exchange described above, the average TDG pressures generated from the operation of a dam can be represented by the mass conservation statement using TDG pressure shown in Equation 4:

$$P_{avg} = \frac{(Q_{sp} + Q_e)P_{sp} + (Q_{ph} - Q_e)P_{ph}}{Q_{sp} + Q_{ph}} \qquad \text{Equation 4}$$

Where:

Q_{sp}	=	Spillway discharge [thousands of cubic feet per second (kcfs)]
Q_{ph}	=	Powerhouse discharge (kcfs)
Q_e	=	Entrainment of powerhouse discharge in aerated spill (kcfs)
Q_{se}	=	$Q_{sp} + Q_e$
	=	Effective spillway discharge (kcfs)
Q_{tot}	=	$Q_{sp} + Q_{ph}$
	=	Total river flow (kcfs)
P_{ph}	=	TDG pressure releases from the powerhouse [mm Hg]
P_{sp}	=	TDG pressure associated with spillway flows (mm Hg)
P_{avg}	=	Average TDG pressure associated with all project flows (mm Hg)

This conservation statement assumes the water temperature of powerhouse and spillway flows are similar, and that the heat exchange during passage through the dam and aerated flow region is minimal. Some projects have other water passage routes besides the powerhouse and spillway, such as fish ladders, lock exchange, juvenile bypass systems, and other miscellaneous sources. These sources of water have generally been lumped into powerhouse flows and are not accounted for separately.

Equation 4 contains three unknowns: Q_e = powerhouse entrainment discharge, $P_{sp} = TDG$ pressure associated with spillway flows, and $P_{ph} = TDG$ pressure associated with powerhouse releases. The TDG pressure associated with the powerhouse release is generally assumed to be equivalent to the TDG pressure observed in the forebay. Numerous data sets support the conclusion that turbine passage does not change the TDG content in powerhouse releases. All of the near-field TDG exchange studies have deployed TDG instruments in the forebay of a project and directly below the powerhouse in the water recently discharged through the turbines. An example of this type of data is shown in Figure C-1 during the 1998 post-deflector John Day Lock and Dam (John Day) TDG exchange study (Schneider and Wilhelms, 1998).

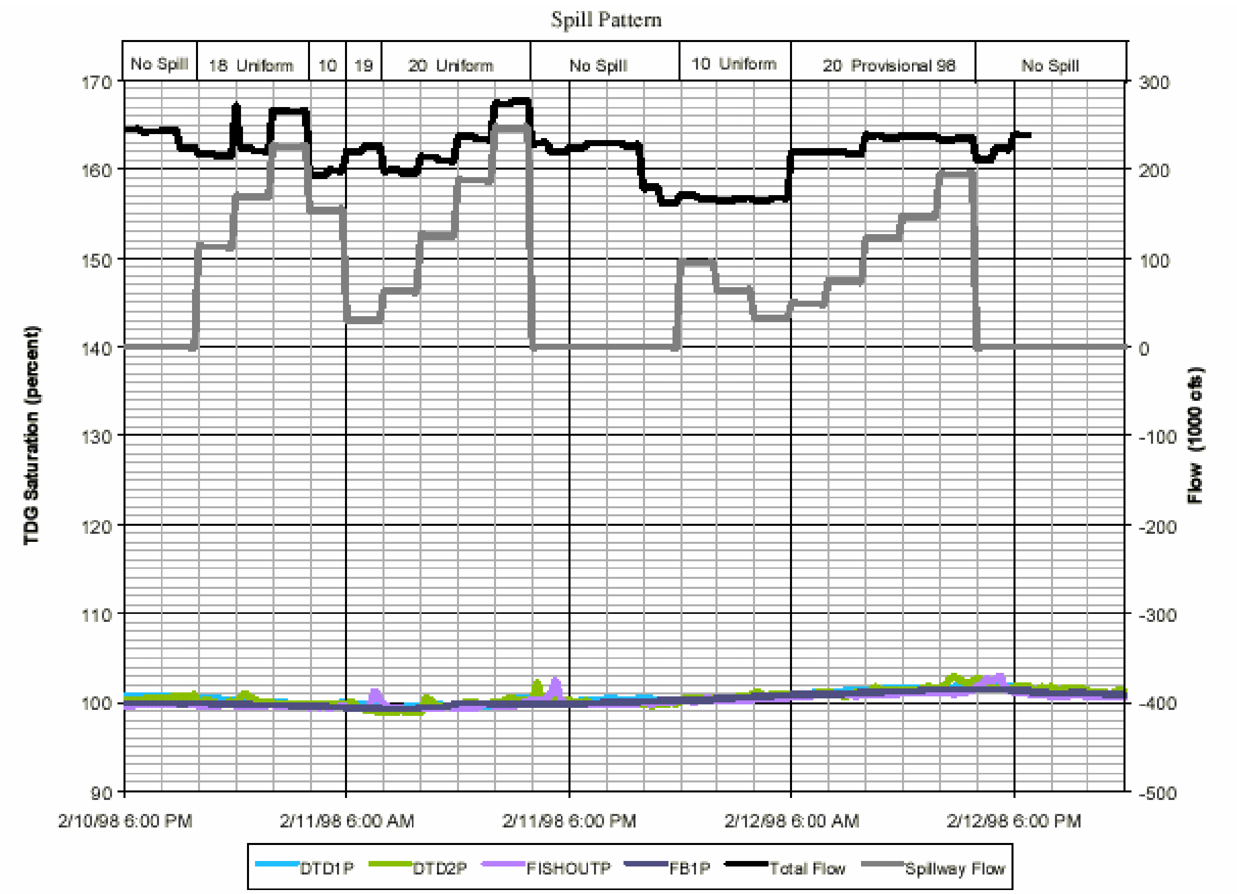

Figure C-1. TDS Saturation in the Forebay and Below the Powerhouse Draft Tube Deck of John Day Dam, February 1998.

The TDG instruments were deployed in the forebay of John Day (station FB1P) and in the tailwater below powerhouse draft tube deck (station DTD1P and DTD2P), near the fish outfall (FISHOUTP). The TDG pressure was logged on a 15-minute interval at each of these stations throughout the testing period. All four stations recorded the same TDG saturations throughout the testing period, even during operating events calling for spilling nearly the entire river on February 11 and 12. The TDG pressure from the forebay and tailwater fixed monitoring stations should also be similar during periods of no spill, provided that these stations are sampling water with similar water temperatures. In cases where a turbine aspirates air or air is injected into a turbine to smooth out operation, the above assumption will not hold.

Spillway TDG Exchange

The TDG exchange associated with spillway flows has been found to be governed by the geometry of the spillway (standard or modified with flow deflector), unit spillway discharge, and depth of the tailrace channel. The independent variable used in determining the exchange of TDG pressure in spillway releases is the delta TDG pressure (ΔP) defined by the difference between the TDG pressure (P_{tdg}) and the local barometric pressure (P_{bar}) as listed in Equation 5. The selection of TDG pressure as expressed as the excess pressure above atmospheric pressure accounts for the variation in the barometric pressure as a component of the total pressure.

$$\Delta P = P_{tdg} - P_{bar} \qquad \text{Equation 5}$$

Restating the exchange of atmospheric gases in terms of mass concentrations introduces a second variable (water temperature) into the calculation. The added errors in calculating the TDG concentration as a function of temperature and TDG pressure were the main reasons for using pressure as the independent variable. The TDG concentration would also vary seasonally with the change in water temperature.

The TDG pressure is often summarized in terms of the percent saturation or supersaturation. The TDG saturation (S_{tdg}) is determined by normalizing the TDG pressure by the local barometric pressure as expressed as a percentage. The delta pressure has always been found to be a positive value when spillway flows are sampled. The TDG saturation (S_{tdg}) is determined by Equation 6.

$$S_{tdg} = \frac{P_{tdg}}{P_{bar}} * 100 = \frac{(P_{bar} + \Delta P)}{P_{bar}} * 100 \qquad \text{Equation 6}$$

Unit Spillway Discharge

The TDG exchange associated with spillway flows has been found to be a function of unit spillway discharge (q_s) and the tailrace channel depth (D_{tw}). The unit spillway discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The higher the unit spillway discharge, the greater the TDG exchange during spillway flows. An example of the dependency between the change in TDG pressure and unit spillway discharge is shown in Figure C-2 at Ice Harbor Lock and Dam (Ice Harbor).

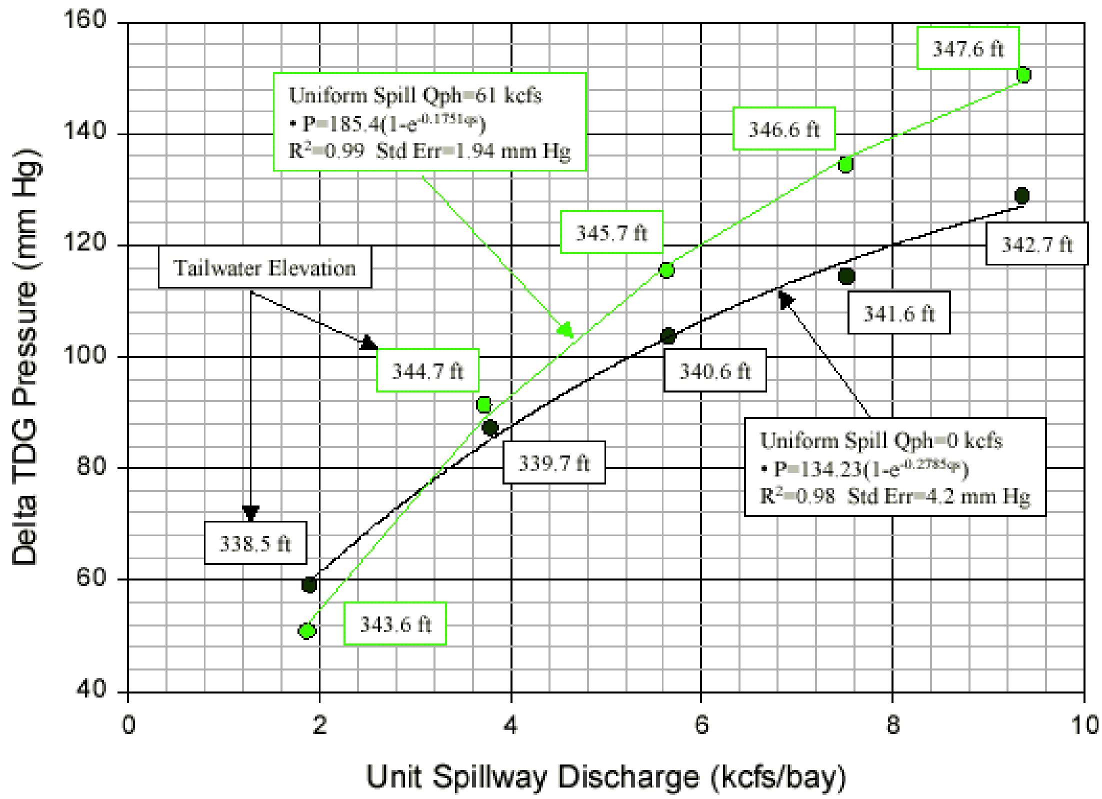

Figure C-2. TDG Pressure (Delta P) as a Function of Unit Spillway Discharge and Tailwater Elevation at Ice Harbor Dam, March 1998.

This figure shows two sets of tests involving a uniform spill pattern over eight bays with flow deflectors. The two sets of tests were distinguished only by the presence of powerhouse releases. In both cases, the resultant spill TDG pressure was found to be an exponential function of the unit spillway discharge. The determination of a single representative unit discharge becomes problematic in the face of a non-uniform spill pattern. The flow-weighted specific discharge was found to be a better determinant of spillway TDG production in cases where the spill pattern is highly non-uniform. The flow-weighted unit discharge places greater weight on bays with the higher discharges. The following Equation 7 describes the determination of the specific discharge used in the estimation of TDG exchange relationships:

$$q_s = \frac{\sum_{i=1}^{nb} Q_i^2}{\sum_{i=1}^{nb} Q_i} \qquad \text{Equation 7}$$

Where:

q_s	=	Specific discharge (flow-weighted unit discharge)
Qi	=	Flow for spill bay *i* (for *nb* number of bays)

Depth of Flow

The large amount of energy associated with spillway releases has the capacity to transport entrained air throughout the water column. In many cases, the depth of flow is the limiting property in determining the extent of TDG exchange below a spillway. An example of the influence of the depth of flow on TDG exchange is shown in Figure C-2 at Ice Harbor. The only difference between the two sets of data in this figure was the presence of powerhouse flow. The events with powerhouse flow resulted in higher TDG pressure than comparable spill events without powerhouse releases at higher spillway flows. The observed tailwater elevation is also listed in Figure C-2 for each test event. The tailwater elevation was about five feet higher during the events corresponding with powerhouse operation.

The depth of flow in the tailrace channel was hypothesized to be more relevant to the exchange of TDG pressure than the depth of flow in the stilling basin because of the influence of the flow deflectors and resultant surface jet, and the high rate of mass exchange observed below the stilling basin. The average depth of flow downstream of the stilling basin was represented as the difference between the tailwater elevation as measured at the powerhouse tailwater gauge and the average tailrace channel elevation within 300 feet of the stilling basin. The tailrace channel reach within 300 feet of the stilling basin was selected because most of the TDG exchange (degassing) occurs in this region. A summary of project features at the time of the USACE DGAS study are listed in Table C-1, including stilling basin elevation, deflector elevation, and tailrace channel elevation.

Table C-1. Columbia and Snake River Project Features (April 2001)

Project	Spillway Crest Elevation (ft)	Number Spillways: Deflectors		Deflector Elevation (ft)	Stilling Basin Elevation (ft)	Tail-water Channel Elevation (ft)	Normal Tail-water Pool (ft)	Normal Tail-water Depth (ft)
		w/	w/out					
Bonneville	24	13	5	14/7[1]	-16	-30	70	20
The Dalles	121	0	23	NA	55	58	155	80
John Day	210	18	2	148	114	125	257	162
McNary	291	18	4	256	228	235	335	267
Ice Harbor	391	10	0	338	304	327	344	17
Lower Monumental	483	6 (8)[1]	2 (0)[1]	434	392	400	441	41
Little Goose	581	6	2	532	466	500	539	39
Lower Granite	681	8	0	630	580	604	635	39

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-8 (USACE, 2001a)
[1]Additional deflectors are under construction to be completed by March 2003.

The functional form of the relationship between the change in TDG pressure change and the prominent dependent variables unit spillway discharge and tailrace channel depth of flow, takes the same form as the exponential formulation shown in Equation 3. The delta TDG pressure was found to be a function of the product of the depth of flow and the exponential function of unit spillway discharge as shown in Equation 8.

$$\Delta P = C_1 D_{tw}(1 - e^{-c_2 q_s}) + C_3 \qquad \text{Equation 8}$$

The coefficients C_1, C_2, and C_3 were determined from nonlinear regression analyses. The product of C_1 and the tailwater depth (D_{tw}) represents the effective saturation pressure in Equation 3 while the product of C_2 and the unit spillway discharge (q_s) reflects the combined contribution from the mass exchange coefficient, ratio of surface area to control volume, and time of exposure.

A second formulation used in this study relating the delta TDG pressure and independent variable involves a power series as shown in Equation 9. This equation can also result in a linear dependency between the delta TDG pressure and either tailwater depth or unit spillway discharge. A linear dependency in the tailwater depth occurs when C_2=1 and C_3=0. A linear dependency between TDG pressure and unit spillway discharge occurs when C_2=0 and C_3=1.

$$\Delta P = C_1 D_{tw}^{C_2} q_s^{C_3} + C_4 \qquad \text{Equation 9}$$

Entrainment of Powerhouse Flow

The interaction of powerhouse flows and the highly aerated spillway releases can be considerable at many of the projects. Observations of the flow conditions downstream of projects where the powerhouse is adjacent to the spillway often indicate a strong lateral current directed toward the spillway.

The clearest example of the influence of the entrainment of powerhouse flow on TDG exchange was documented during the near-field TDG exchange study at Little Goose. The study at Little Goose was conducted during February 1998 when the ambient TDG saturation in the Snake River ranged from 101 to 103%. The test plan called for adult and juvenile fish passage spill of up to 60 kcfs with the powerhouse discharging either 60 kcfs or not operating. The cross-sectional average TDG pressure in the Snake River below Little Goose was determined from seven separate sampling stations located across the river from the tailwater FMS. The project operations and resultant TDG saturation are summarized in Figure C-3 where the observations from the forebay and tailwater fixed monitoring stations are shown as LGS and LGSW respectively, the cross-sectional average TDG saturation at the tailwater FMS is labeled $T5_{avg}$, and the flow-weighted average TDG saturation assuming no entrainment of powerhouse flow is labeled FWA (flow-weighted average).

The TDG saturation estimated by assuming that powerhouse releases were available to dilute spillway flows during this test (FWA) were significantly less than estimates derived from averaging information from the seven sampling stations at the tailwater fixed monitoring station ($T5_{avg}$). This study demonstrated that nearly all of the powerhouse flows from Little Goose were entrained and acquired TDG pressures similar to those in spillway flows during this study. The circulation patterns below the dam during the test clearly supported the TDG data indicating high rates of entrainment of powerhouse flows into the stilling basin.

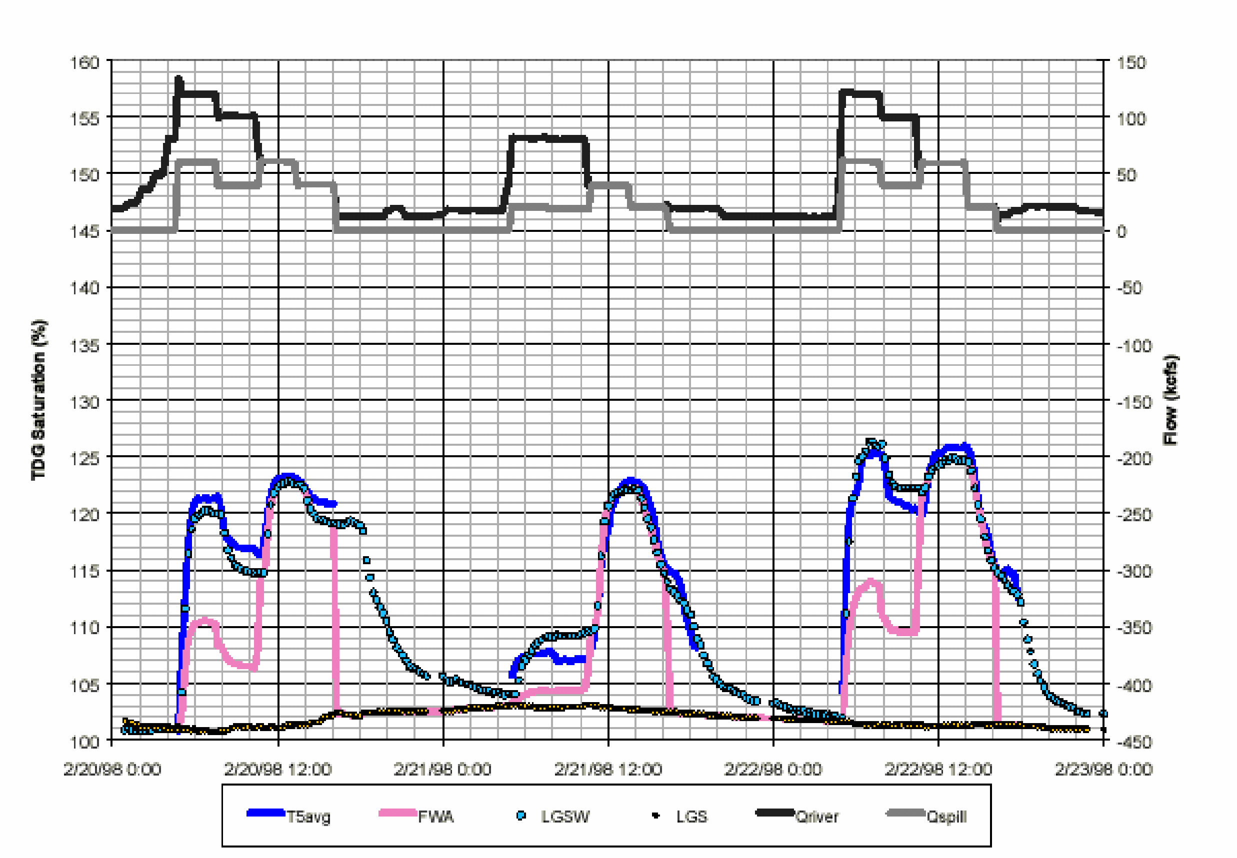

Figure C-3. Project Operation and TDG Saturation at Little Goose Dam, February 1998. ($T5_{avg}$ Average TDG Level at Tailwater FMS, LGS- Forebay FMS, LGSW- Tailwater FMS, FWA- Flow Weighted Average Assuming No Entrainment)

The entrainment of powerhouse flow was modeled as a simple linear function of spillway discharge. The relationship shown in Equation 10 was used to estimate the entrainment discharge for each project. The coefficients C_1 and C_2 are project-specific constants. The entrainment of powerhouse flow was assumed to be exposed to the same conditions that spillway releases encounter and, hence, achieve the same TDG pressures.

$$Q_e = C_1 Q_{sp} + C_2 \qquad \text{Equation 10}$$

The loading capacity of the river segments identified for this TMDL are the water quality standard, namely 110% of saturation relative to atmospheric pressure.

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