Preliminary Draft

Columbia River Total Maximum Daily Load (TMDL)

For
Total Dissolved Gas

State of Oregon
Department of Environmental Quality

July 2001

Prepared by the Oregon Department of Environmental Quality

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Acknowledgement

The Department wishes to acknowledge the cooperation of the following agencies in the production of this TMDL. First, the U.S. Army Corps of Engineers, Portland District, Walla Walla District and Northwest Division. Large tracts of the technical analysis for this TMDL have been lifted from the Dissolved Gas Abatement Study (DGAS). This TMDL would have been much more difficult without this work and the understanding of total dissolved gas production that we enjoy as a result of the study.

Second, the National Marine Fisheries Service. The Biological Opinion issued in December 2000 pursuant to the Endangered Species Act was invaluable in describing the studies that have been conducted to date, and in specifying the effects of total dissolved gas on fish.

Third, the U.S. Environmental Protection Agency which provided assistance, both financial and technical, in the production of this TMDL.

Finally, to Tetra Tech, acknowledgement of its technical input, and to the Western Governor's Association for its assistance in outreach.

The defects and flaws in this TMDL are entirely the responsibility of the Oregon Department of Environmental Quality. Nothing in this TMDL purports to represent the technical or policy positions of any of the above agencies or organizations.

Executive Summary

Elevated TDG levels are associated with spill events at four hydroelectric projects on the Lower Columbia River. Water spilled over the spillway of a dam entrains air bubbles. When these are carried to depth in the stilling basin of a dam, the higher hydrostatic pressure forces them into solution. The result is supersaturated water that is particularly high in dissolved nitrogen and oxygen (the major constituents of air). Fish ingesting this water will not display any signs of difficulty, unless they subsequently rise higher in the water column to a lower pressure gradient. In these circumstances, TDG may come out of solution, forming bubbles in the body tissue of fish. This gives rise to gas bubble disease (GBD) or gas bubble trauma (GBT).

This document describes the production of TDG at each of the four projects in the Lower Columbia River. General production equations are presented representing the production of TDG, and specific equations taking into account the particular physical characteristics of each of the four projects are presented.

Load allocations are presented for each of the four projects. Given the clear mathematical relationship between spill quantity and TDG, load allocations have been specified as a spill quantity per spillway unit at each of the projects.

Implementation is included and incorporates actions described and analyzed by the Corps in its Dissolves Gas Abatement Study. Both short-term and long-term measures are described along with estimates of gas abatement and implementation cost.

Introduction

Water that fails to meet water quality standards, and as a result fails to protect the beneficial uses to which water is put triggers a State action in Oregon. The Department of Environmental Quality (DEQ) is charged to assess, manage and protect Oregon's waters for beneficial uses. A number of water bodies fail to meet water quality standards. DEQ is charged with returning waterbodies to standards. The requirement under the Clean Water Act for achieving this is known as a Total Maximum Daily Load (TMDL). This document details this approach for the mainstem Columbia River from its entry into the eastern part of Oregon to its mouth at the Pacific Ocean for the pollutant, total dissolved gas. We will explain what total dissolved gas is, why it is a problem, and a strategy for managing it so water quality standards will be met.

Purpose of, and Authority for, TMDL

The Columbia River mainstem from its entry into the State of Oregon from the State of Washington to its mouth exceeds the water quality standard for total dissolved gas. It is listed on the State of Oregon's 1998 list of waterbodies failing to meet standards pursuant to Section 303(d) of the federal Clean Water Act. It is a result of the standards exceedance and subsequent listing that this Total Maximum Daily Load (TMDL) is being prepared.

TMDL's determine the quantity (load) of a pollutant that can enter a waterbody and still meet water quality standards. This pollutant load is then allocated among the various sources. An implementation component is included to identify actions that Designated

Management Agencies (DMAs) will undertake to achieve the allocated loads.

There is a great deal of overlap between this TMDL established pursuant to the Clean Water Act and anadromous fish passage for salmonids listed as threatened or endangered under the Endangered Species Act, administered by the National Marine Fisheries Service. It is therefore important that there is a clear understanding of the requirements of this TMDL relative to measures required by Biological Opinions issued in relation to the threatened and endangered species of the Snake and Columbia Rivers.

In summary, the provisions of both Acts must be met. Notwithstanding that, it is not the purpose of the Clean Water Act to usurp functions properly undertaken pursuant to the Endangered Species Act (ESA). Biological Opinions issued pursuant to the ESA require attainment of certain fish passage indices. One of the means of attaining these is through spilling water over hydroelectric dam spillways. This action, though, results in elevated total dissolved gases. Control of total dissolved gas is the purpose of this TMDL. The Clean Water Act does not envisage trade-offs of fish passage for total dissolved gas, it requires, rather, attainment of water quality standards.

This TMDL is written to reflect attainment of the total dissolved gas water quality standard. Fish passage requirements can be facilitated under an implementation plan, but the clear expectation of the Clean Water Act is that water quality standards will be attained. Doubtless, the National Marine Fisheries Service will make the same assertion relative to fish passage requirements under the Endangered Species Act. It is not, however, the purpose of this TMDL or of the Clean Water Act, to guarantee the latter requirements.

Geographic Extent

This TMDL applies to the Columbia River mainstem from its point of entry into Eastern Oregon from the State of Washington to its mouth at the Pacific Ocean. This takes in seven river segments as follows:

The mouth to Tenasillahe Island. Segment number COLUO
Tenasillahe island to Willamette River. Segment number COLUO37
Willamette River to Bonneville Dam. Segment number COLU102.
Bonneville Dam to The Dalles Dam. Segment number COLU146.
The Dalles Dam to John Day Dam. Segment number COLU191.6.
John Day Dam to McNary Dam. Segment number COLU215.6.

McNary Dam to the Washington Border. Segment Number COLU290.

These seven segments fall on the Columbia River mainstem. The hydrologic unit code for the Columbia Basin is 1707.

Total Dissolved Gas Water Quality Standard

(A) The concentration of total dissolved gas relative to atmospheric pressure at the point of sample collection shall not exceed 110 percent of saturation, except when stream flow exceeds the ten-year, seven-day average flood. However, for Hatchery receiving waters and waters of less than two feet in depth, the concentration of total dissolved gas relative to atmospheric pressure at the point of sample collection shall not exceed 105 percent of saturation;

(B) The Commission may modify the total dissolved gas criteria in the Columbia River for the purpose of allowing increased spill for salmonid migration. The Commission must find that:

(i) Failure to act would result in greater harm to salmonid stock survival through in-river migration than would occur by increased spill;

(ii) The modified total dissolved gas criteria associated with the increased spill provides a reasonable balance of the risk of impairment due to elevated total dissolved gas to both resident biological communities and other migrating fish and to migrating adult and juvenile salmonids when compared to other options for in-river migration of salmon;

(iii) Adequate data will exist to determine compliance with the standards; and

(iv) Biological monitoring is occurring to document that the migratory salmonid and resident biological communities are being protected.

(C) The Commission will give public notice and notify all known interested parties and will make provision for opportunity to be heard and comment on the evidence presented by others, except that the Director may modify the total dissolved gas criteria for emergencies for a period not exceeding 48 hours;

(D) The Commission may, at its discretion, consider alternative modes of migration.

Basin Assessment

Total dissolved gas is an artifact of spilling water over spillways of dams on the Columbia River. These are the only sources of total dissolved gas on the Columbia mainstem. Spill at dams occurs for one of two reasons:

1. voluntarily, usually for fish passage; and
2. involuntarily, usually because:
   a) hydraulic capacity is exceeded; or
   b) lack of power market.

Voluntary Spill

Voluntary spill, or spill for purposes of fish passage involves water deliberately released over dam spillways, rather than being discharged through turbines or fish bypass facilities. The intent is to reduce turbine and bypass mortalities. Schoeneman et al (1961) found that mortality in Chinook juveniles spilled over McNary Dam (Columbia River) and Big Cliff Dam (Santiam River) was less than two percent. Subsequent studies confirmed this estimate.

On this basis, the Environmental Quality Commission has granted variances to the total dissolved gas standard to enable voluntary spill for salmonid juvenile passage for species listed under the federal Endangered Species Act. This has occurred annually since 1994. Variances usually involve total dissolved gas levels of 120 percent saturation relative to atmospheric pressure in the tailrace of the spilling dam, and 115 percent total dissolved gas saturation relative to atmospheric pressure as measured in the forebay of the next dam downstream. Variance period usually extend from the middle of April through the end of August each year. Additional variances have been granted each year for spill over Bonneville Dam for up to ten days each March to assist with passage of the Spring Creek National Fish Hatchery Tule Chinook release. One variance has also been given for John Day Dam to enable testing of flow deflectors.

Involuntary Spill

Like voluntary spill, involuntary spill involves water being discharged over dam spillways. The causes and intended consequences, though, are different. As its name suggests, there is no choice involved in "involuntary" spill. At times of very high river flows, the quantity of water exceeds the capacity of a dam to constrain it. In these circumstances, water is released over the spillway. There is nowhere else for it to go. The Columbia River hydropower system is somewhat unique in that regard. It contains very little storage potential relative to the quantity of spring runoff. At times of rapid runoff, the dams cannot constrain the quantity of water, and it is spilled with attendant high total dissolved gas levels. Often dissolved gas levels from involuntary spill exceed those experienced during periods of voluntary spill for fish.

Involuntary spill as a result of lack of power market is a variant of the above. In this scenario, the power marketing authority cannot sell any more power, and even though turbines are available, water is bypassed over the spillway because there is nowhere for electricity generated to go. Running water through the turbines with no load increases wear and tear with attendant higher maintenance costs.

Deviation of Ambient Conditions from Water Quality Standards

During periods of voluntary spill, the deviation of ambient conditions from the water quality standard is usually zero. This is because spill quantities are managed to meet the variances granted by the State of Oregon for fish passage. For the past six years, the State of Oregon has granted a variance to its water quality standard for total dissolved gas to facilitate fish passage. The variances have allowed total dissolved gas levels to rise to 120 percent of saturation relative to atmospheric pressure in the tailrace of the dam that is spilling, and 115 percent in the forebay of the next dam downstream. There have been excursions beyond this level, but they are usually not more than one or two percent, and occur as a result of the imprecision in setting spillway gates. Generally, the fishery management agencies have sought spill quantities in order to remain right at the total dissolved gas variance limit. Any small change in conditions that influence total dissolved gas, such as change in barometric pressure, water temperature, incoming gas, total river flow or tailwater elevation will cause an exceedance when operated this way.

At times of involuntary spill, exceedances above the standard can rise dramatically, peaking above 130 percent of saturation, and even 140 percent. These levels of total dissolved gas saturation are lethal to fish.

Loading Capacity

Introduction

The total dissolved gas (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 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.

Equation 1

Where:

= the composite liquid film coefficient
= the saturation concentration
= the ambient concentration in water

The rate of change of concentration in a well-mixed control volume 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:

Equation 2

Where:

A = the surface area associated with the control volume
V = the volume of the water body 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 .

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=tf is defined as C_f shown in Equation 3.

The resultant concentration C_f exponentially approaches the saturation concentration for conditions where the term $K_t \frac{A}{V}$ is large. The final concentration becomes independent of the initial concentration under these conditions.

$K_l \frac{A}{V}$

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

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 the Corps' Dissolved Gas Abatement Study. 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 Corp decided to use empirically derived equations of TDG exchange based on the recognition that data was not available to support mechanistic models of the mass exchange process at all the projects in the Columbia/Snake River systems. 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 have 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.

The 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 (FMS's), has led to the development of a model for TDG exchange at dams throughout the Columbia / Snake Rivers 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 total 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 determined by physical conditions that develop below the spillway and is 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 during 1997 where the forebay TDG exceeded 130 percent 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 shown in Equation 4:

Equation 4

Where:

	=	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)

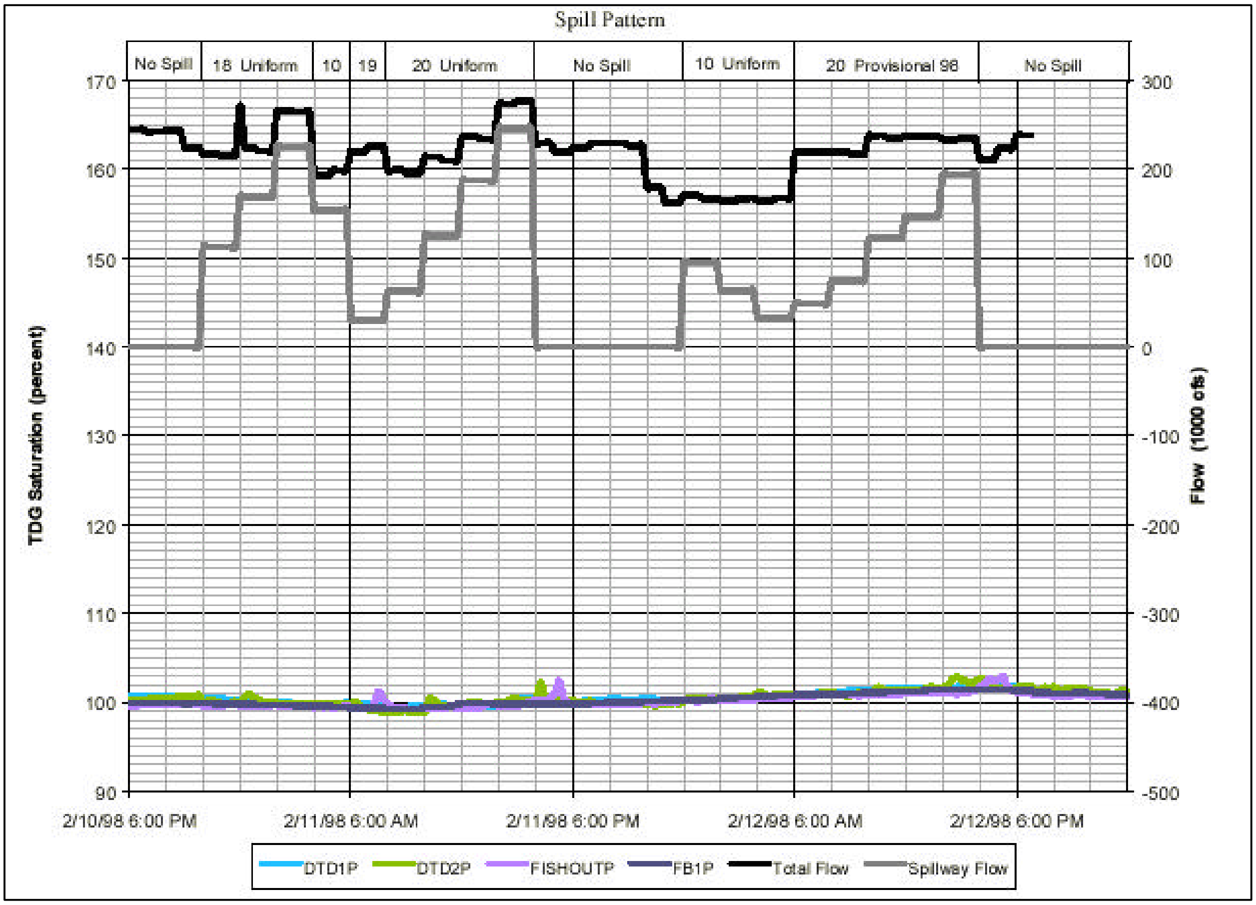
$Q_{tot} = Q_{sp} + Q_{ph}$ = Total river flow (kcfs)

P_{ph}	=	TDG Pressure releases from the powerhouse [millimeters of Mercury (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 using TDG pressure 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 1 during the 1998 post-deflector John Day Lock and Dam (John Day) TDG exchange study (Schneider and Wilhelms, 1999a).

Figure 1: Total Dissolved Gas 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 February 12. The TDG pressure from the forebay and tailwater FMS's 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_{atm}) 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.

$$\Delta P = P_{tdg} - P_{atm}$$

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.

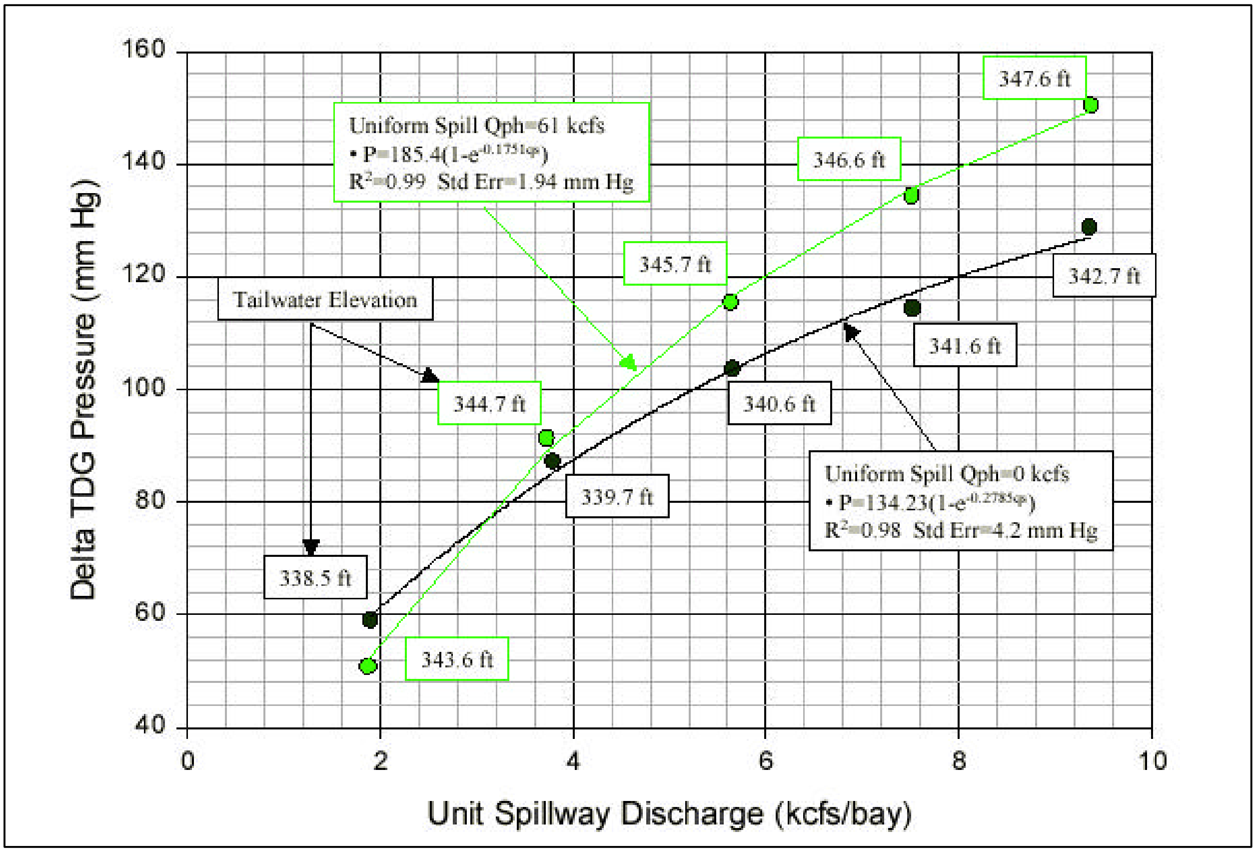
$$S_{tdg} = \frac{P_{tdg}}{P_{atm}} * 100 = \frac{(P_{atm} + \Delta P)}{P_{atm}} * 100$$

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 2 at Ice Harbor Lock and Dam (Ice Harbor).

Figure 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:

$$q_s = \frac{\sum_{i=1}^{nb} Q_i^2}{\sum_{i=1}^{nb} Q_i}$$

Equation 7

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 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 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 spilling 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 including stilling basin elevation, deflector elevation, and tailrace channel elevation are listed in Table 1.

Table 1 Columbia River and Snake River Project Features

Project	Spillway Crest Elevation (ft)	Deflector Elevation (ft)	Stilling Basin Elevation (ft)	Tailwater Channel Elevation (ft)	Minimum Operating Pool (ft)	Normal Tailwater Pool (ft)
Bonneville	24	14	-16	-30	70	20
The Dalles	121	NA	55	58	155	80
John Day	210	148	114	125	257	162
McNary	291	256	228	235	335	267

Source: U.S. Army Corps of Enginneers DGAS Study, Appendix G, p. G-8

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.

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

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

Data Sources

TDG data were available on many of the projects from several sources: the Fixed Monitoring System (FMS), near field and spillway performance tests, and in-pool transport and dispersion tests. Operational data were obtained from each project detailing the individual spillway and turbine discharge on an interval ranging from five minutes to one hour. These sources of data are discussed below. With these data sources, the most appropriate analysis was selected for each project. Individual mathematical relationships were developed on a project-by-project basis.

The FMS Data

The TDG data from the FMS's consisted of remotely monitored TDG pressure, dissolved oxygen (DO), water temperature, and atmospheric pressure from a fixed location in the forebay and tailwater of each project. Data from the FMS's provide a continuous record of TDG throughout the season, capturing detailed temporal and extreme events. However, the FMS's provide only limited spatial resolution of TDG distribution. In some cases, the TDG observed in the tailwater at the FMS location was not representative of average spillway conditions and misrepresented the TDG loading at a dam.

Spillway Performance Tests and Near-Field Studies

Spillway performance tests and near-field tailwater studies were conducted at several projects to define the relationship between spill operation and dissolved gas production more clearly. Water temperature, TDG, and DO were monitored in the immediate tailrace region, just downstream of the project stilling basin. These observations provided a means to relate the local TDG saturation to spill operations directly, and to define gas transfer in different regions of the tailrace area. Manual sampling of TDG pressures in spillway discharges from several bays was conducted downstream of the aerated flow regime at Lower Granite Lock and Dam, Little Goose Lock and Dam, Ice Harbor, and The Dalles (Wilhelms 1995); and John Day, Lower Monumental Lock and Dam, and Bonneville Lock and Dam (Wilhelms, 1996). In these studies, automated sampling of TDG pressures in spillway discharges during uniform and standard spill patterns was conducted with an array of instruments in the stilling basin and tailwater channel of all the projects in the study area with the exception of Lower Granite. Automated sampling of TDG levels provide the opportunity to assess three-dimensional characteristics of the exchange of TDG immediately downstream of the stilling basin on a sampling interval ranging from five to 15 minutes. The integration of the distribution of flow and TDG pressure can yield estimates of the total mass loading associated with a given event. These tests were of short duration, generally lasting only several days, and, therefore, pertain to the limited range of operations scheduled during testing.

In-Pool Transport and Dispersion Studies

During the 1996 spill season, in-pool transport and dispersion investigations were conducted to define the lateral mixing characteristics between hydropower and spillway releases. Water temperature, TDG levels, and DO were measured at several lateral transects located over an entire pool length. These studies focused on the lateral and longitudinal distribution of TDG throughout a pool during a period lasting from a few days to a week. In-pool transport and mixing studies were conducted below Little

Goose, Lower Monumental, Ice Harbor, John Day, The Dalles, and Bonneville during the 1996 spill season. In most cases, a lateral transect of TDG instruments was located below the dam to establish the level of TDG entering the pool, with additional transects throughout the pool. These studies provided observations of the TDG saturation in project releases as they moved throughout an impoundment. However, only a limited range of operations was possible during the relatively short duration of these tests.

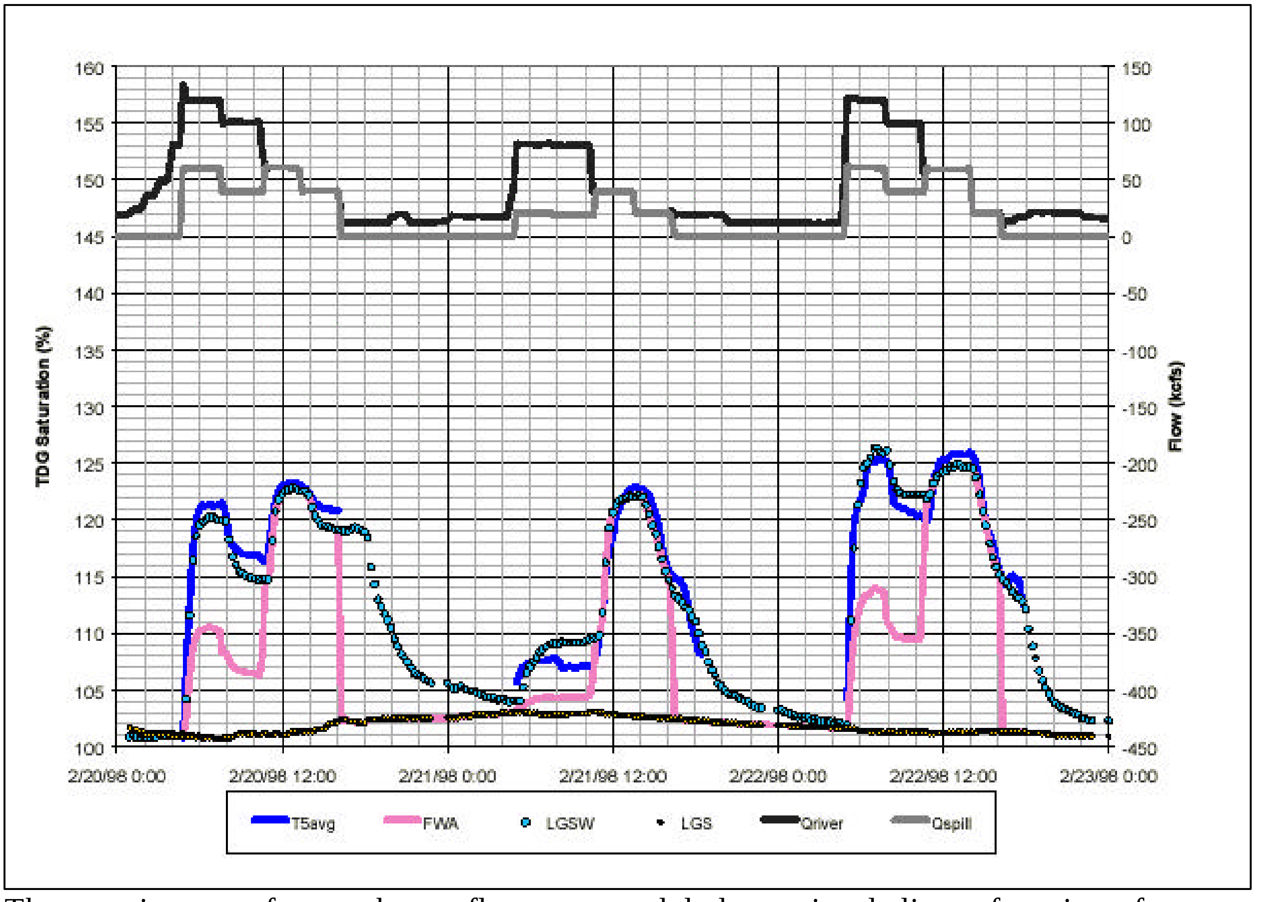
Operational Data

Operational data were obtained from each project detailing the spillway and powerhouse unit discharge on time intervals ranging from five minutes to one hour. The average hourly total spillway and generation releases, and forebay and tailwater pool elevations were summarized in the DGAS database. The tailwater pool gauge was generally located below the powerhouse of each dam. The tailwater elevation at the powerhouse was found to be within one foot of the water elevation downstream of the stilling basin in most instances.

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 presence of Bradford and Cascade Islands at Bonneville eliminates the potential entrainment of powerhouse flow into aerated spillway releases. 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 percent. 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 3 where the observations from the forebay and tailwater FMS's are shown as LGS and LGSW, 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 FMS ($T5_{avg}$). 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 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.

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

Data Interpretation

The objective of this analysis was to develop mathematical relationships between observed TDG and operational parameters such as discharge, spill pattern, and tailwater channel depth. These relationships were derived with observations from the FMS's and spillway performance tests. However, before the analysis could be conducted, the monitored data had to be evaluated to determine its reliability for this kind of analysis. For example, the monitored TDG data from the FMS's provide a basis for defining the effects of spillway operation on dissolved gas levels in the river below a dam, but the following limitations should be noted:

a. The FMS's sample water near-shore, which may not reflect average TDG levels of the spill. The monitor sites were, in general, located on the spillway side of the river to measure the effects of spillway operation. However, with a non-uniform spill distribution and geometry across the gates of the spillway, the FMS may be more representative of the spillbays closest to the shore. Outside spillbays, without flow deflectors can create elevated TDG levels downstream from these bays compared to adjacent deflectored bays. A spill pattern that dictates higher unit discharges on these outside bays can further elevate the TDG levels downstream of these bays relative to the releases originating from the deflectored interior bays.
b. Depending upon the lateral mixing characteristics, the FMS('s) downstream of a project may be measuring spillway releases that have been diluted with hydropower releases. The tailwater FMS's below The Dalles and Bonneville are located in regions where substantial mixing has occurred between generation and spillway discharges. Under most conditions, the TDG saturation of generation releases is less than the TDG level associated with spillway releases. The TDG at the tailwater FMS's will be a function of the discharge and level of TDG from both generation and spillway releases. Obviously, if there is no spill, then the monitored TDG levels will reflect the TDG saturation released by the hydropower facility.
c. Passage of generation flows through a power plant does not significantly change the TDG levels associated with this water. However, there can be a significant near-field entrainment of powerhouse flow by spillway releases at some projects, especially if flow deflectors are present. Observed data suggest that, under these conditions, some portion of the powerhouse discharges will be subjected to the

same processes that cause absorption of TDG by spillway releases. In these cases, the TDG levels measured immediately downstream of a spillway will be associated with the spillway release plus some component of the powerhouse discharge.

The observations of tailwater TDG pressure need to be paired up with project operations to conduct an evaluation of the data. A set of filters or criteria were established to select correctly-paired data for inclusion in this analysis. The travel time for project releases from the dam to the tailwater FMS was typically less than two hours and steady-state tailwater stage conditions were usually reached within this time period. Thus, the data records were filtered to include data pairs corresponding with constant operations of duration greater than two hours to exclude data corresponding with unsteady flow conditions. This filtering criterion eliminated data associated with changing operations and retained only a single observation for constant operating conditions equal to three hours in duration.

1. <u>Manual and Automated Inspections for Obviously Inaccurate Observations</u>. An automated search for values above or below expected extremes identified potential erroneous and inaccurate data in the database. These data were inspected and, if appropriate, excised from the database.

2. <u>Comparison of Measurements from Forebay and Tailwater Instruments During Non-Spill Periods</u>. During the non-spill periods, downstream measurements should approach the forebay concentration when only the hydropower project is releasing water. Inspection of the data was conducted to identify errors when this condition was not met.

3. <u>Comparison of Measurements from Redundant Tailwater TDG Monitors, if Available</u>. TDG tailwater data was rejected when measurements of two instruments at the same site varied by more than three percent saturation.

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

Identification of Sources

There are four sources of total dissolved gas within the geographic scope of this TMDL. They are:

1. McNary Dam;
2. John Day Dam;
3. The Dalles Dam; and
4. Bonneville Dam

Water entering the State of Oregon from the State of Washington at times exceed the TDG standard. The State of Washington numeric criteria for total dissolved gas is identical to that of the State of Oregon. Sources of total dissolved gas entering the State of Oregon are the hydroelectric projects on the mid-Columbia and Snake Rivers in the State of Washington. These will be subject to separate TMDLs to be developed by the State of Washington. This TMDL addresses those loads of total dissolved gas introduced by dams on the lower Columbia River that fall within the State of Oregon.

McNary Dam

The TDG Exchange

A TDG exchange field investigation was conducted at McNary during February 11-13, 1996, with the study summarized in Wilhelms and Schneider (1997a). The study consisted of sampling TDG pressures below the spillway during spillway discharges ranging from 50 to 285 kcfs. Two different spill patterns were investigated during this study - standard and uniform. The study findings indicated that the TDG production was directly related to the unit spillway discharge. The TDG saturation ranged from 108 to 135 percent during the study for unit spillway discharges ranging from two to 17 kcfs/bay. The influence of the operation of spillway bays without flow deflectors was found to increase the TDG exchange for comparable unit spill discharges. The relatively small total river flows and associated range in tailwater elevations resulted in test spill conditions corresponding with tailwater elevations ranging from 265.5 to 269.0 feet above mean sea level (fmsl).

Regression

The TDG production during spillway releases from McNary, as defined by . $P = P_{tw} - P_{bar}$, was found to be a power function of tailwater depth and the specific discharge as shown in Equation 11. The regression equation was based on data collected during the 1997 spill season. The data filtering resulted in 172 observations. The delta TDG pressure ranged from 81.9 mm Hg to a maximum value of 307.6 mm Hg as listed in table 2. The range in unit spillway discharge ranged from 2.0 kcfs/bay to 21.9 kcfs/bay and the tailwater depth ranged from 30.8 to 40.5 feet.

$$\Delta P = D_{tw}^{0.647} q_s^{0.969} + 82.14$$ Equation 11

Where:

ΔP = P_{tw} - P_{bar}

P_{tw} = TDG pressure at the tailwater FMS (mm Hg)

q_s = Flow-weighted unit spillway bay discharge (kcfs/bay)

D_{tw} = Tailrace channel depth (feet) (E_{tw} - E_{ch})

E_{tw} = Elevation of the tailwater (ft)

E_{ch} = Average elevation of the tailrace channel (320 fmsl)

P_{bar} = Barometric pressure at the tailwater FMS (mm Hg)

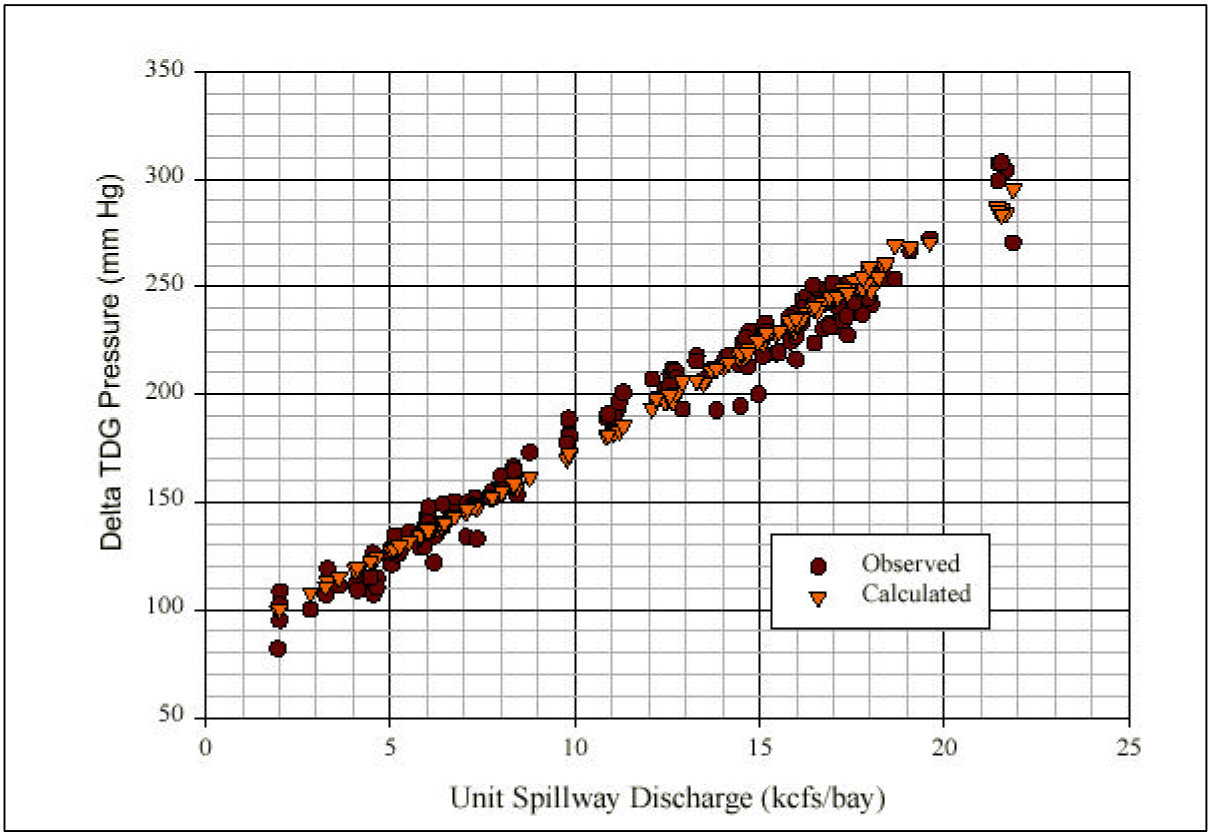
Table 2**: Statistical Summary of Regression Variables for McNary Dam**

Delta Pressure (P (mm/Hg)	Unit Spillway Discharge EMBED Equation.3 (kcfs/bay)	Tailwater Depth (ft) EMBED Equation.3	
Number	173	173	173
Minimum	81.9	2.0	30.8
Maximum	307.6	21.9	40.5
Average	191.6	11.7	35.0
Standard Deviation	53.0	5.4	2.2

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-29

The unit spillway discharge was plotted against the observed and calculated tailwater TDG pressure difference in figure 4.

Figure SEQ Figure * ARABIC 4 : Unit Spillway Discharge versus Total Dissolved Gas Pressure Above Barometric Pressure at McNary Dam, 1997



The near linear relationship between the TDG pressure and unit discharge is evident in this figure as the TDG pressure continues to increase as the specific unit discharge becomes large. Much of the variability in the TDG pressure for a constant unit discharge can be accounted for by the variation in the tailrace channel depth. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in table 3. This formulation explained much of the variability in the data with an EMBED Equation.3 of 0.97 and a standard error of 9.25 mm Hg.

Table SEQ Table * ARABIC 3 . Statistical Summary of Nonlinear Regression at McNary 1997 Spill Season

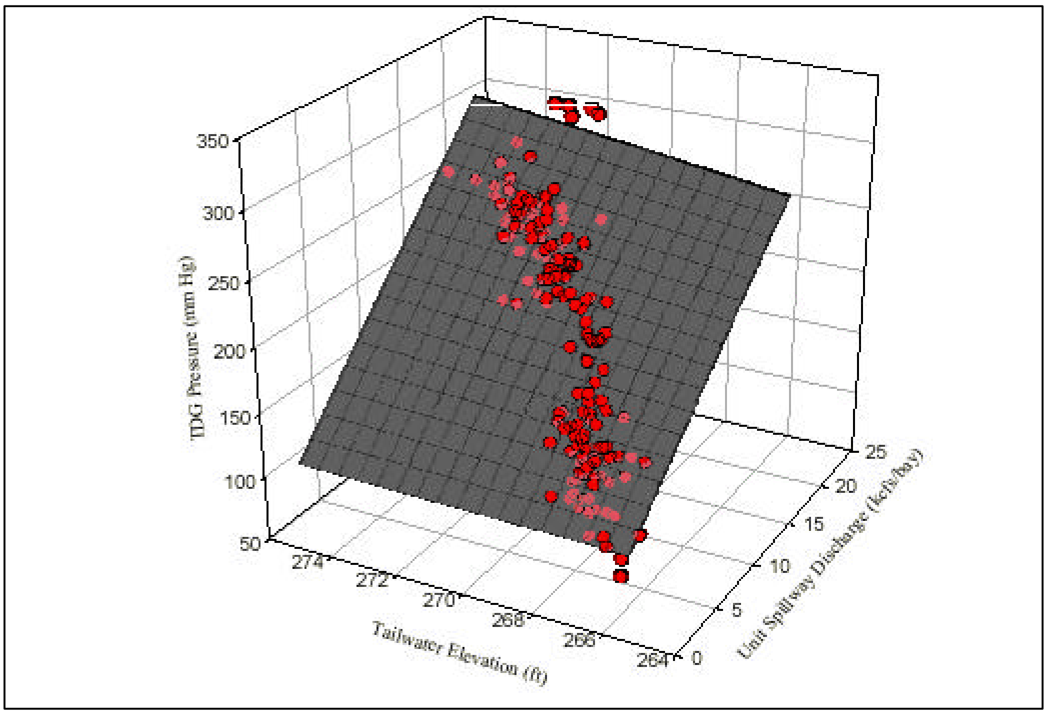
EMBED Equation.3 Number of Observations n=173 EMBED Equation.3 Std Error = 9.26 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
EMBED Equation.3	0.647	0.0693	12.71	<0.0001

EMBED Equation.3	0.969	0.0762	9.35	<0.0001
EMBED Equation.3	82.14	5.89	14.08	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-29

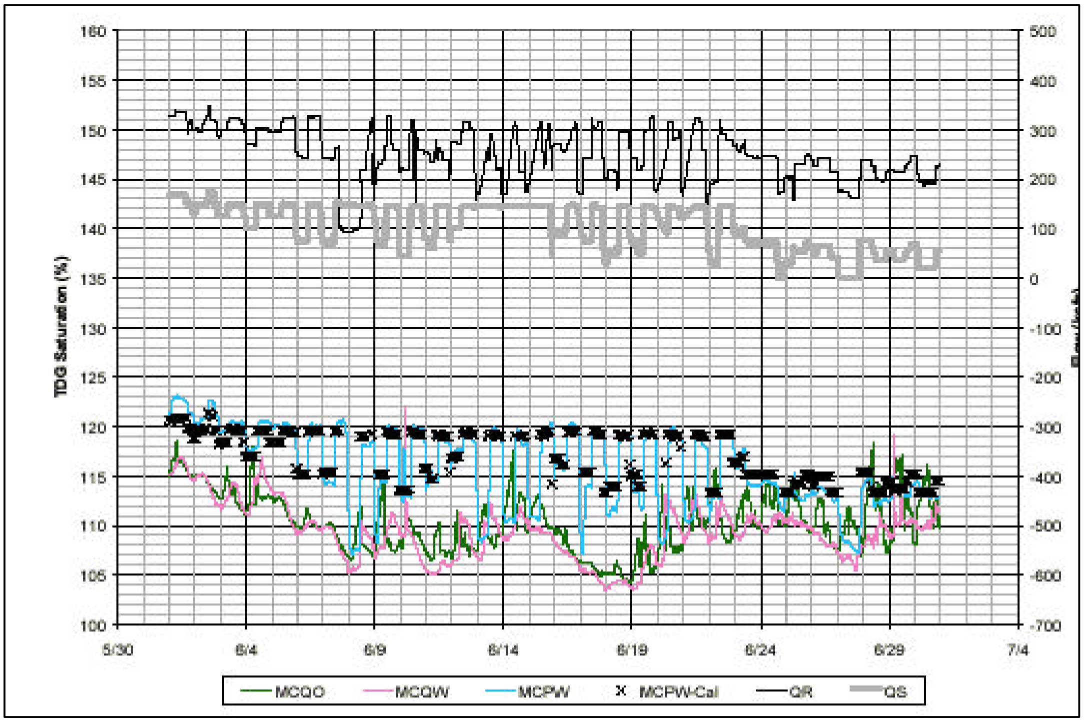
A review of the regression coefficients in Equation 11 reveals that the TDG exchange is relatively insensitive to the variation in the depth of flow below McNary. The response surface for TDG pressure above atmospheric pressure as a function of both unit spillway discharge and tailwater stage is shown in figure 5

Figure SEQ Figure * ARABIC 5 : Unit Spillway Discharge, Tailwater Elevation, and Total Dissolved Gas Pressure Above Barometric Pressure at McNary Dam, 1997



The response function as defined in Equation 11 was used to create a hindcast of the TDG production observed during the 1997 spill season. The hourly project operation and TDG saturation at the McNary FMS's for the month of June 1998 are shown in figure 6 along with the estimates of TDG saturation based on Equation 3.

Figure SEQ Figure * ARABIC 6 : Observed and Estimated Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at McNary Dam, May 1997. (MCQO / MCQW= Observed Forebay TDG, MCPW= Observed Tailwater TDG, MCPW- cal =Calculated Tailwater TDG, QR= Hourly Total River Flow, QS= Hourly Spillway Flow)



In general, the estimated TDG saturation was generally within one percentage point of the observed tailwater TDG saturation. The maximum daily spillway discharge remained constant during much of the month of June with little variation in the production of TDG saturation. The forebay TDG level however, varied. The TDG performance of the spillway bays without flow deflectors was needed to derive the TDG exchange from the exiting spillway. Spillway bays 1, 2, 21, and 22 do not have flow deflectors and are typically operated by raising only the upper leaf of the split leaf vertical gates. This operation results in a jet that plunges into the stilling basin as a fully aerated nap. It should be noted that bay 22 is not typically operated due to absence of a dedicated gate hoist.

The results from the near-field TDG exchange test were used to estimate the TDG exchange characteristics of standard spillway bays. The TDG production resulting from uniform spill flows from bays 3 through 20 (bays with flow deflectors) was subtracted from the TDG response for the standard spill pattern. The difference in the delta TDG pressure generated between these curves was divided by the discharge from the spillway bays 1, 2, and 21 to arrive at the response relation listed in Equation 12. A linear relationship between the unit spillway discharge and delta TDG pressure was estimated for these end bays at McNary. The non-deflectored bays generated TDG saturation about ten percent greater on average than deflectored bays.

EMBED Equation.3
Equation SEQ Equation * ARABIC 12

Powerhouse Entrainment

Estimates of the entrainment of powerhouse flows into spillway discharge were not available from this study because of the limited amount of powerhouse discharge and the absence of flow distribution information. Since direct determination of the entrainment of powerhouse flows into the highly aerated conditions below McNary were not practical, it was assumed for this study that the entrainment characteristics of McNary were similar to John Day. The estimates of the entrainment of powerhouse flows was estimated to average 35 kcfs at McNary and to be independent of the total spillway discharge.

John Day Dam

The TDG Exchange

The installation of spillway flow deflectors at John Day was completed during the winter of 1997-98. Deflectors were installed in spillway bays two through 19 at elevation 148 fmsl. The flow deflectors significantly changed the TDG exchange properties of releases from John Day. A detailed near-field study of TDG exchange below John Day was conducted during February 10-12, 1998, as described by Schneider and Wilhelms (1999a). The study consisted of sampling TDG pressures below the stilling basin during spillway discharges ranging from 36 to 246 kcfs. Several different spill patterns were investigated during this study - uniform bays two through 19, uniform bays one through 20, provisional standard spill pattern, and uniform bays ten through 19. The study findings indicated that the TDG production was directly related to the unit spillway discharge. The TDG saturation was found to be an exponential function of unit spillway discharge with 115 percent saturation associated with a unit spillway discharge of four kcfs/bay and 120 percent saturation generated for a unit spillway discharge of nine kcfs/bay for the uniform spill pattern. The main limitation of this

TDG exchange study was the small range in tailwater elevations (158.4 to 161.3 fmsl).

The influence of standard operating conditions on TDG exchange was further investigated through analyzing the TDG exchange indicated by the FMS during the 1998-spill season. These conditions involved the newly adopted spill pattern, a wider range in tailwater elevation, and forced and voluntary spill discharges. The observed TDG data at the John Day tailwater FMS were used to generate a description of TDG exchange. The filtering of this data resulted in a total of 51 observations as summarized in table 4. The observed delta pressure ranged from 108 mm Hg to 184.0 mm Hg for these 51 events. The unit spillway discharge was found to range from 4.3 to 9.4 kcfs/bay and the tailwater depth was found to range from 33.6 to 42.4 feet.

Table SEQ Table * ARABIC 4 : Statistical Summary of Regression Variables

Delta Pressure EMBED Equation.3 (mm/Hg)	Unit Spillway Discharge EMBED Equation.3 (kcfs/bay)	Tailwater Depth EMBED Equation.3 (ft)	
Number	52.0	52.0	52.0
Minimum	108.0	4.3	33.8
Maximum	184.0	9.4	42.4
Average	152.7	7.1	38.7
Standard Deviation	16.7	1.2	1.9

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-31

The functional relationship between TDG production and project operation at John Day was similar to those relationships derived for upper Snake River projects. The delta TDG pressure, as defined by EMBED Equation.3 , was found to be proportional to the product of tailwater depth and an exponential function of the specific discharge as shown in Equation 13. Both of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in table 5. This formulation explained much of the variability in the data with an EMBED Equation.3 of 0.84 and a standard error of 6.8 mm Hg.

EMBED Equation.3 Equation SEQ Equation * ARABIC 13

Where:

EMBED Equation.3 = EMBED Equation.3
EMBED Equation.3 = TDG pressure at the tailwater FMS (mm Hg)
EMBED Equation.3 = Unit spillway bay discharge (kcfs / bay)
EMBED Equation.3 = Tailrace channel depth (feet) (Etw-Ech)
EMBED Equation.3 = Elevation of the tailwater (fmsl)
EMBED Equation.3 = Average elevation of the tailrace channel (125 fmsl)
EMBED Equation.3 = Barometric pressure at the tailwater FMS (mm Hg)

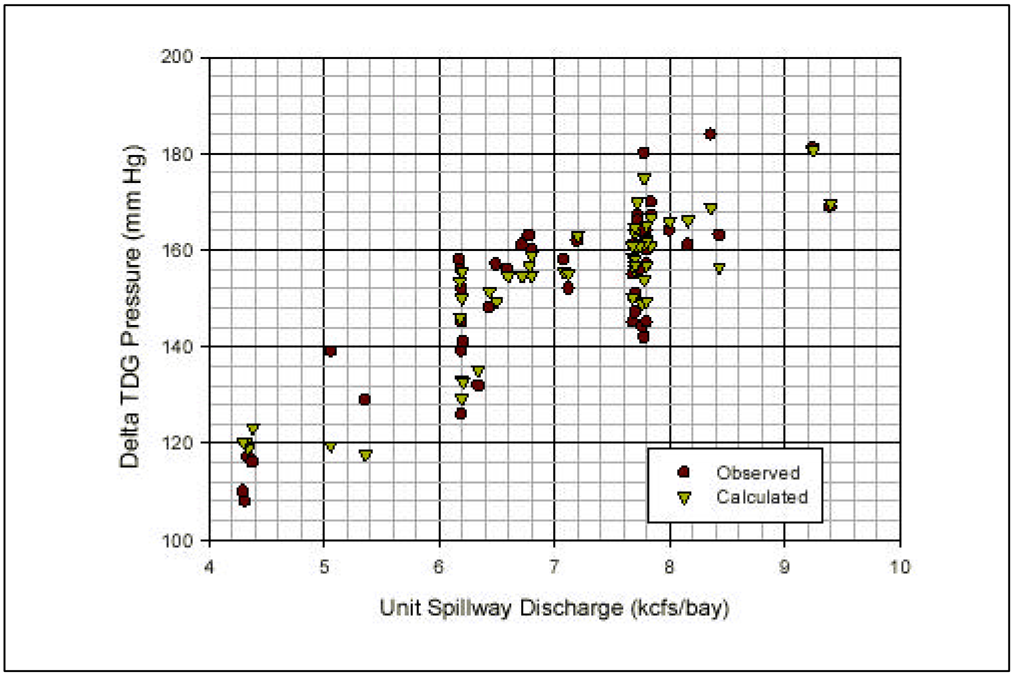
Table SEQ Table * ARABIC 5 : Statistical Summary of Nonlinear Regression at John Day 1998 Spill Season (Bays 2 Through 19 With Flow Deflectors)

EMBED Equation.3 Number of observations n=51 EMBED Equation.3 Std. Error=6.78 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
EMBED Equation.3	4.969	0.192	25.908	<0.0001
EMBED Equation.3	-0.2278	0.0221	10.3069	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-32

The unit spillway discharge was plotted against the observed and calculated tailwater TDG pressure above the local barometric pressure as shown in figure 7.

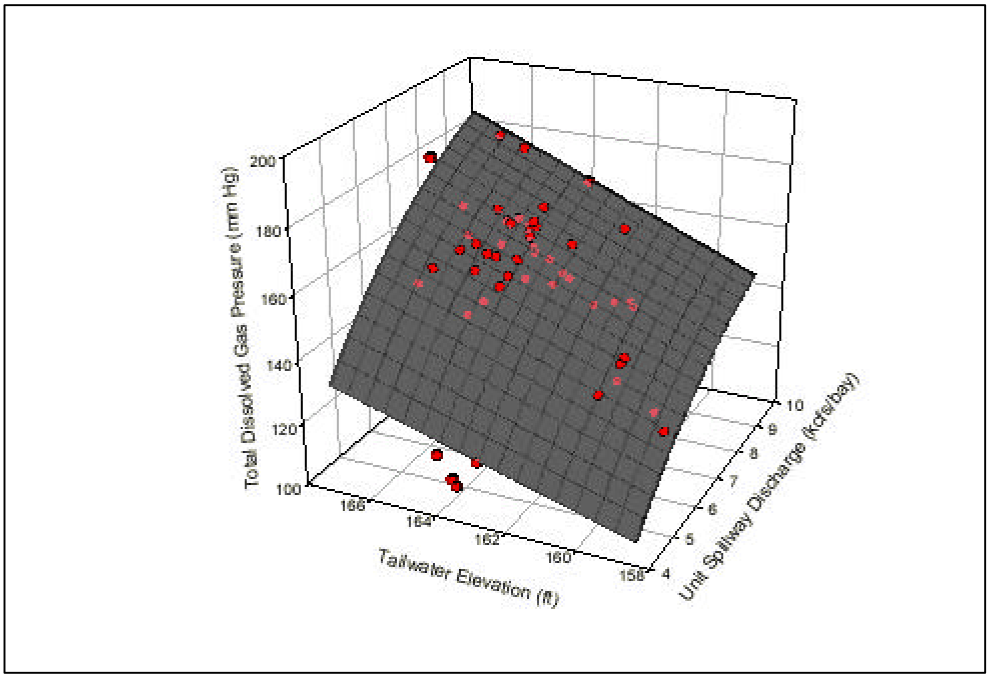
Figure SEQ Figure * ARABIC 7 : Unit Spillway Discharge versus Total Dissolved Gas Pressure Above Barometric Pressure John Day Dam, 1998.



The exponential relationship between the TDG pressure and specific discharge is not as clearly defined at John Day as at other projects with this functional form. Much of the variability in the TDG pressure for a constant unit discharge can be accounted for by the variation in the tailrace channel depth. Equation 13 can be solved directly for the unit specific discharge assuming a delta pressure of 150 mm Hg (120 percent saturation) and a tailwater depth of 35 feet. The resultant unit spillway discharge of about nine kcfs/bay is the solution to this equation. This unit spillway discharge was similar to the spillway capacity determined during the near-field TDG exchange study.

The three-dimensional response surface for Equation 13 is shown in figure 8 along with the observed data.

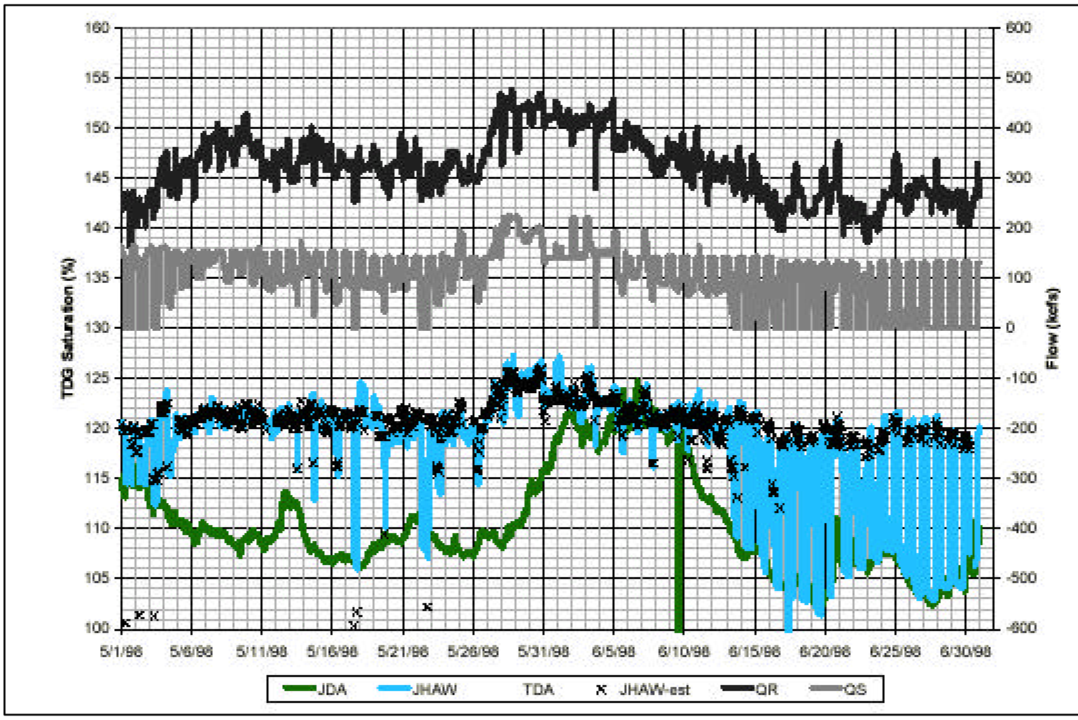
Figure SEQ Figure * ARABIC 8 : Unit Spillway Discharge, Tailwater Elevation, and Total Dissolved Gas Pressure Above Barometric Pressure at John Day Dam, 1998



The TDG pressure increases for a constant unit spillway discharge as the tailrace channel depth increases. The influence of the tailwater depth is significant as evidenced by the slope in the response surface for a constant unit discharge. The upper limit in delta TDG pressure will continue to increase with increasing tailwater elevation. The TDG response during voluntary spill conditions will be different than a comparable spill discharge at a much higher total river flow.

The tailwater TDG saturation as approximated by Equation 13 was used to create a hindcast of the TDG production observed during the 1998 spill season below John Day. The hourly project operation and TDG saturation at the John Day tailwater FMS's (JHAW) for the months of May and June 1998 are shown in figure 9 along with estimates of the tailwater TDG saturation (JHAW-est).

Figure SEQ Figure * ARABIC 9 : Observed and Estimated Total Dissolved Gas Saturation at the Tailwater Fixed Monitoring Station at John Day Dam, May- June 1998. (JDA= Observed Forebay TDG, JHAW= Observed Tailwater TDG, JHAW- est =Calculated Tailwater TDG, QR= Hourly Total River Flow, QS= Hourly Spillway Flow)



In general, the estimated average TDG saturation was generally within seven mm Hg of the observed tailwater TDG pressure. The operating conditions during May 1998 depict both forced and voluntary spill conditions. The spill discharges were as high as 230 kcfs for total river flows over 400 kcfs, resulting in tailwater TDG saturation of about 126 percent. The nighttime-only spill operations during the last two weeks of June imply voluntary spill conditions. Note the range in TDG response for the constant nighttime spill operations during this period. The nighttime spill on June 21 corresponded with elevated total river flows and high tailwater conditions resulted in TDG saturation exceeding 121 percent. A comparable spill two days later during much lower total river flow and tailwater stage conditions resulted in TDG saturations of only 119 percent.

Regression

John Day has two spillway bays without flow deflectors. The TDG response of these two bays were estimated using tailwater TDG pressures observed prior to the installation of the 18 flow deflectors during the 1996 and 1997 spill seasons. A total of 1,137 hourly observations were pooled from the 1996 and 1997 spill seasons. The presence of two flow deflectors located in bays 18 and 19 during the 1997 spill season were not thought to influence the TDG response at the tailwater FMS below John Day . The delta pressure for these events ranged from 84 to 324 mm Hg as shown in table 6. The unit spillway discharge ranged from 1.8 to 15.3 kcfs/bay and the tailwater depth ranged from 35.6 to 46.7 feet during this sample period.

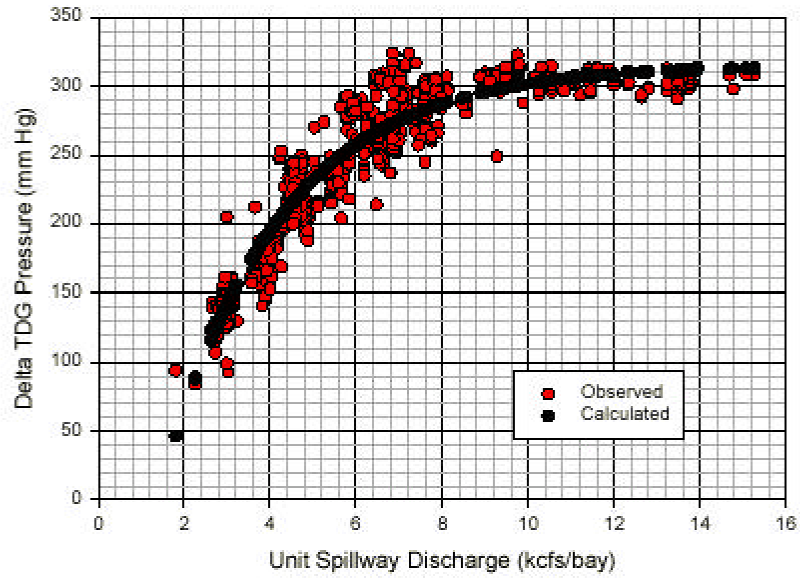
Table SEQ Table * ARABIC 6 : Statistical Summary of Regression Variables

Delta Pressure EMBED Equation.3 (mm Hg)	Unit Spillway Discharge EMBED Equation.3 (kcfs/bay)	Tailwater Depth EMBED Equation.3 (ft)	
Number	1137.0	1137.0	1137.0
Minimum	84.0	1.8	35.6
Maximum	324.0	15.3	48.7
Average	223.0	5.8	41.1
Standard Deviation	64.6	3.0	2.3

Source: U.S. Army Corps of Engineers DGASD Study, Appendix G, p. G-33

The delta pressure of a standard spillway bay at John Day was determined to be a function of the unit spillway discharge. The functional form of this relationship is shown in Equation 14 where a threshold delta pressure of 315.3 mm Hg is approached for large unit spillway discharges as shown in figure 10.

Figure SEQ Figure * ARABIC 10 : Observed and Calculated Delta TDG pressure at John Day Dam(Standard Spillway – no Deflector)



The maximum TDG saturation generated by this relationship approaches 141 percent for a barometric pressure of 760 mm Hg. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in table 7. This formulation explained much of the variability in the data with an EMBED Equation.3 of 0.94 and a standard error of 15.9 mm Hg. The TDG exchange for a known spill pattern using bays with and without flow deflectors can be estimated by using both Equations 13 and 14. The average TDG pressure associated with a spill discharge would be determined by calculating a flow-weighted average of the individual spillway bay responses.

EMBED Equation.3 Equation SEQ Equation * ARABIC 14

Table SEQ Table * ARABIC 7 : Statistical Summary of Nonlinear Regression at John Day 1996-1997 Spill Season

EMBED Equation.3 Number of observations = 1137 EMBED Equation.3 Std. Error = 15.95 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability

EMBED Equation.3	315.29	1.647	191.48	<0.0001
EMBED Equation.3	-519.09	10.3867	-49.975	<0.0001
EMBED Equation.3	-0.3649	0.0084	-43.38	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-34
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Powerhouse Entrainment

The entrainment of powerhouse flows into the highly aerated flow conditions below John Day was estimated from data collected during the 1998 spillway TDG exchange study (Schneider and Wilhelms, 1999a). The average TDG pressure of project and spillway releases was used with a simple mass balance statement of project flows to provide estimates of the effective spillway discharge and entrainment of powerhouse flows. The estimates of the entrainment of powerhouse flows were found to range from five to 60 kcfs average and average about 35 kcfs. The powerhouse entrainment discharge was not found to vary as a function of the total spillway discharge.

The Dalles Dam

The TDG Exchange

A TDG exchange field investigation was conducted below The Dalles during August 28-29, 1996, with the study summarized in Schneider and Wilhelms (1996a). The study consisted of sampling TDG pressures below the spillway during spillway discharges ranging from 50 to 200 kcfs. Three different spill patterns were investigated during this study--adult, juvenile, and uniform spill patterns. The study findings indicated that the TDG production was weakly related to the unit spillway discharge. The TDG saturation ranged from 119 to 124 percent during the study for unit spillway discharges ranging from two to 14 kcfs/bay. The influence of the spill pattern was found to be accounted for by representing the total spillway discharge as defined by unit spillway bay discharge. The main limitation of this TDG exchange study was the small range in tailwater elevation (75.7 to 78.3 fmsl).

Regression

The high river flows and spillway discharges during 1997 generally fell outside of the range of conditions scheduled during the 1996 spillway performance test. The application of the TDG production relationship determined during the 1996 near-field study did not replicate TDG conditions observed below The Dalles during the 1997 spill season. The observed TDG data at The Dalles from the forebay and tailwater FMS were used to generate an alternative description of TDG exchange. The TDG pressures observed at the forebay FMS were assumed to represent the conditions discharged from the powerhouse. The TDG pressures observed at the tailwater FMS were assumed to reflect the average TDG pressures in the Columbia River. The TDG properties of spillway discharge were estimated by performing a simple mass balance of project releases. The hourly data were filtered to retain only those data having constant project operations for a six hour duration. This criterion was selected to allow steady-state conditions to develop at the tailwater FMS located three miles downstream of the project. This criterion also allowed the inclusion of a single datum for each extended event. This data filtering resulted in a total of 87 observations as summarized in table 8. The estimated delta pressure ranged from 143.3 mm Hg to 203.6 mm Hg for these 87 events. The unit spillway discharge was found to range from 4.3 to 19.0 kcfs/bay and the tailwater depth was found to range from 8.3 to 23.3 feet.

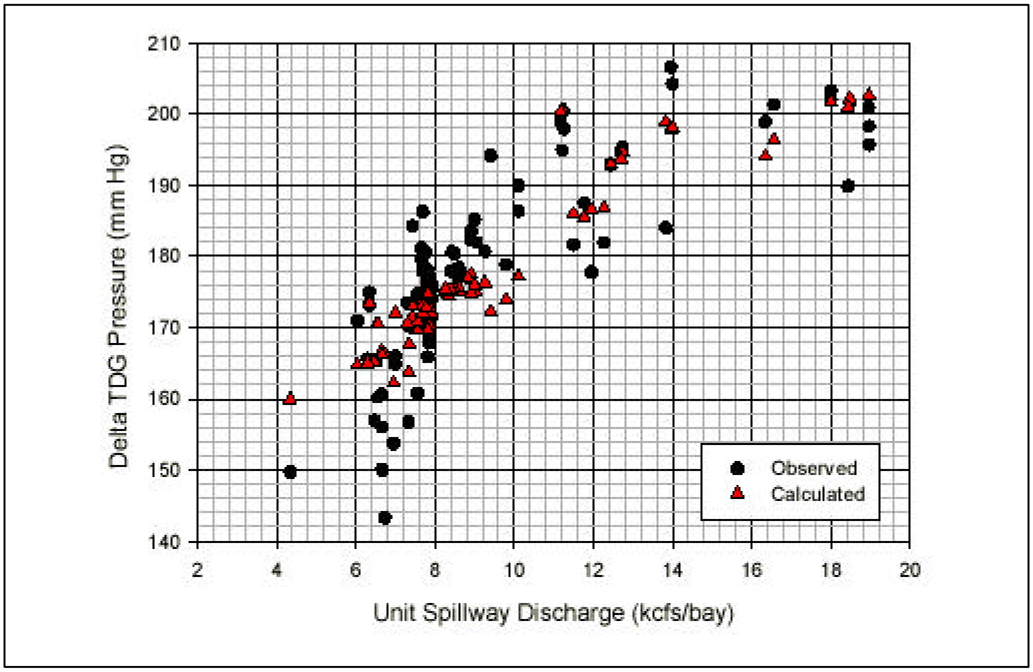
Table SEQ Table * ARABIC 8 Statistical Summary of Regression Variables

Delta Pressure EMBED Equation.3 (mm Hg)	Unit Spillway Discharge EMBED Equation.3 (kcfs/bay)	Tailwater Depth EMBED Equation.3 (ft)	
Number	87.0	87.0	87.0
Minimum	143.3	4.3	8.3
Maximum	206.6	19.0	23.3
Average	178.4	9.6	14.5
Standard Deviation	14.1	3.6	3.6

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-35

The spillway releases from The Dalles, as defined by EMBED Equation.3 , was found to be proportional to the product of tailwater depth and the specific discharge as shown in Equation 15. The regression equation was based on data collected during the 1997 spill season. The data filtering resulted in a total of 87 independent observations. The unit spillway discharge was plotted against the estimated and calculated tailwater delta TDG pressure in figure 11.

Figure SEQ Figure * ARABIC 11 Unit Spillway Discharge versus Total Dissolved Gas Pressure Above Barometric Pressure at The Dalles Dam, 1997



The form of the relationship shown in Equation 15 implies the TDG exchange for small spillway discharge will exceed 120 percent as was observed during the 1996 near-field investigation. All of the coefficients determined by the nonlinear regression analysis were significant to the 99 percent confidence interval as shown in table 9. This formulation explained much of the variability in the estimated dependent variable with an EMBED Equation.3 of 0.735 and a standard error of 7.3 mm Hg.

EMBED Equation.3 Equation SEQ Equation * ARABIC 15

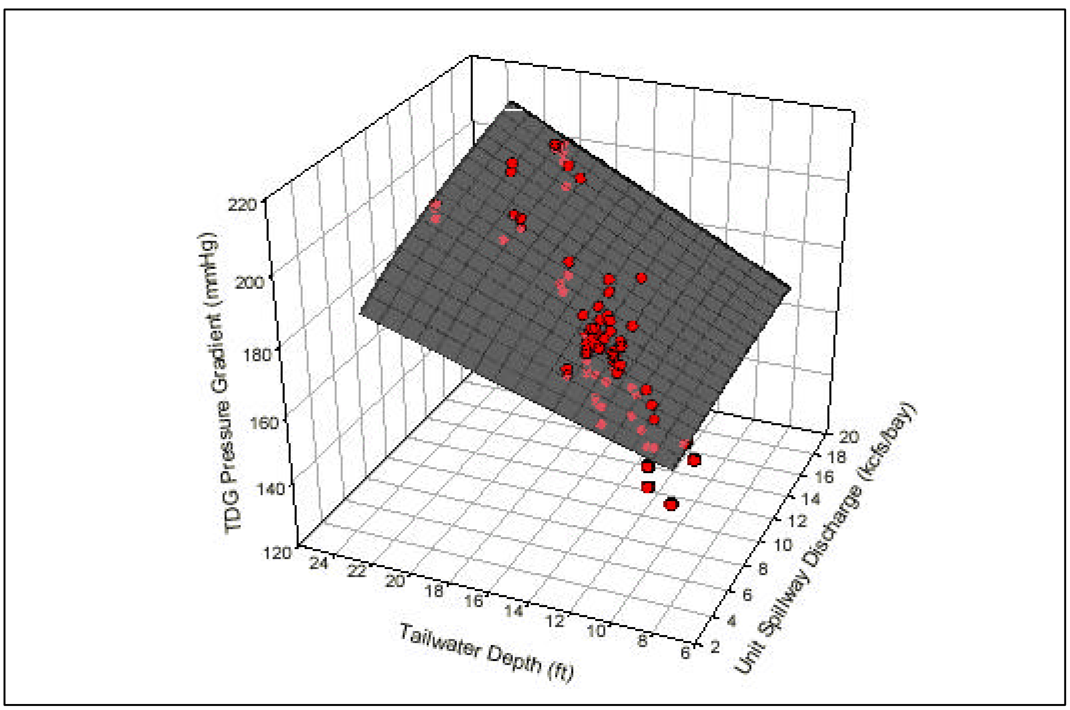
Table SEQ Table * ARABIC 9 Statistical Summary of Nonlinear Regression at The Dalles 1997 Spill Season

EMBED Equation.3 Number of observations = 87 EMBED Equation.3 Std. Error = 7.34 mm Hg				
Coefficient	Estimate from Regression	Standard Error	t-statistic	Probability
EMBED Equation.3	1.02	0.12	2.69	<0.0086
EMBED Equation.3	0.33	0.12	8.72	<0.0001
EMBED Equation.3	145.9	2.21	66.11	<0.0001

Source: U.S. Army Corps of Engineers DGAS Study, Appendix G, p. G-36

The dual dependency of the delta pressure change on tailwater depth and unit spillway bay discharge is shown in figure 12.

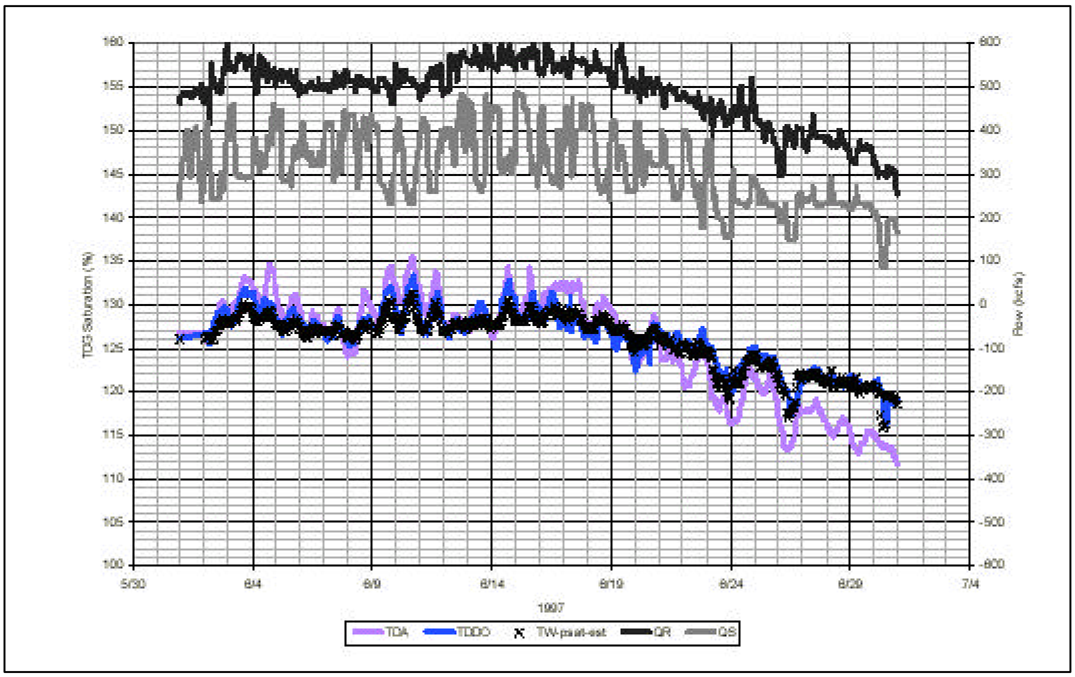
Figure SEQ Figure * ARABIC 12 : Unit Spillway Discharge, Tailwater Elevation, and Total Dissolved Gas Pressure Above Barometric Pressure at The Dalles Dam, 1997.



This equation also indicates that the depth of flow accounts for most of the variability in the increase in TDG pressure associated with spillway discharges. The increase in TDG pressure was found to be a linear function of the depth of flow for a constant unit spillway discharge. The tailrace channel depth is a function of the total river flow and the pool elevation of the lower reservoir. This relationship couples the operation of the powerhouse at The Dalles and the storage management in Bonneville pool to the TDG production in spillway releases from The Dalles spillway.

The response function as defined in Equation 15 was used to create a hindcast of the TDG production observed during the 1997 spill season. The hourly project operation and TDG saturation at The Dalles tailwater FMS (TDDO) for the month of June 1997 are shown in figure 13 along with the estimates of the flow-weighted TDG saturation (TW-psat-est) released from The Dalles based on Equation 15 and observations of TDG pressures in the forebay. In general, the estimated average TDG saturation was generally within seven mm Hg of the observed tailwater TDG pressure.

Figure SEQ Figure * ARABIC 13 : Observed and Estimated Total Dissolved Gas Saturation at the Tailwater
Fixed Monitoring Station at The Dalles Dam, June 1997.
(TDA= Observed Forebay TDG, TDDO= Observed Tailwater TDG, TW- psat- est =Calculated Tailwater TDG, QR= Hourly Total River Flow, QS= Hourly Spillway Flow)



The maximum daily spillway discharge and percent of river spilled varied greatly during June 1997, with spill discharges as high as 480 kcfs. The forebay TDG pressures often were higher than the tailwater TDG pressures, implying a net reduction in TDG conditions in the Columbia River as a result of the operation of The Dalles. The second half of June found the TDG pressures below The Dalles larger than observed at the forebay station, implying a net increase in TDG conditions in the Columbia River as a result of the operation of The Dalles. The conditions during the latter half of June in

1997 reflect conditions more typical of voluntary spill conditions where spill at The Dalles contributes to higher TDG loading in the Columbia River.

Powerhouse Entrainment

The entrainment of powerhouse water into the aerated spilling basin was assumed to be zero at The Dalles. The powerhouse is located a considerable distance from the spillway. The standard spillway design efficiently dissipates energy in the stilling basin, which minimizes the potential to entrain flow laterally. The extent of aerated flow generally does not extend downstream of the shallow shelf below the stilling basin. The TDG exchange was not found to be large near the downstream limits of the shallow tailwater shelf below the spillway (Schneider and Wilhelms, 1996a).

Bonneville Dam

The TDG Exchange

A description of TDG exchange at Bonneville is needed to evaluate dissolved gas abatement alternatives and develop a system model of TDG properties. The following summarizes the findings of two TDG exchange studies conducted below Bonneville and the TDG production relationships that were derived from this body of work. The first study was conducted during February 1-4, 2000, and involved measuring TDG pressures and velocities below the Bonneville spillway. The objective of this investigation was to describe the TDG exchange processes associated with non-deflectored bays, deflectored bays, and a combination of deflectored and non-deflectored bays as dictated by the standard spill patterns. The second test was conducted during May 7-June 7 and involved measuring TDG pressures near the exit of the Bonneville spillway channel. The objective of this test was to investigate the role of tailwater elevation changes on the exchange of TDG associated with spillway releases during standard operating conditions.

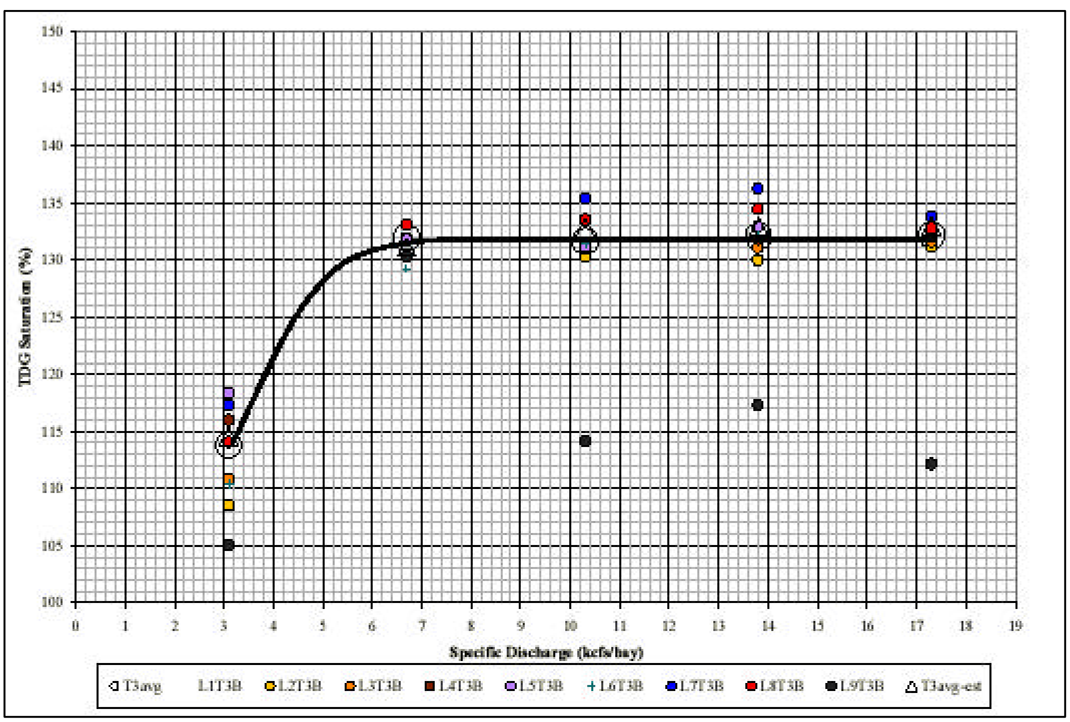
The TDG pressures and flow distributions were measured near the exit of the Bonneville spillway channel during the first week in February (Schneider, 1999). A total of 11 TDG instruments were deployed across the channel at fixed locations and logged TDG pressure, water temperature, DO, and instrument depth on a 15-minute interval.

The velocity field was also measured near this array of instruments using an Acoustic Doppler Current Profiler. The TDG pressures were then integrated with the velocity field to estimate the TDG loading produced during spillway operations.

The test conditions involved spillway flows over non-deflectored bays, deflectored bays, and a combination of both deflectored and non-deflectored bays. A total of five spill levels corresponding with gates setting of one, two, three, four, and five dogs were investigated for four different spill patterns. The first day of testing utilized only non-deflectored bays two, three, 16, and 17 (day one). The spill pattern for the second day of testing involved only deflectored bays eight through 15 with spill flow uniformly distributed (day two). The third day of testing involved a uniform pattern over deflectored bays nine through 15, and non-deflectored bays 16 and 17 (day three). The spill pattern tested on the fourth day involved the standard 1997 spill pattern (day four).

The non-deflectored bays generated the highest TDG saturation for gate setting(s) up through three dogs as shown in figure 14.

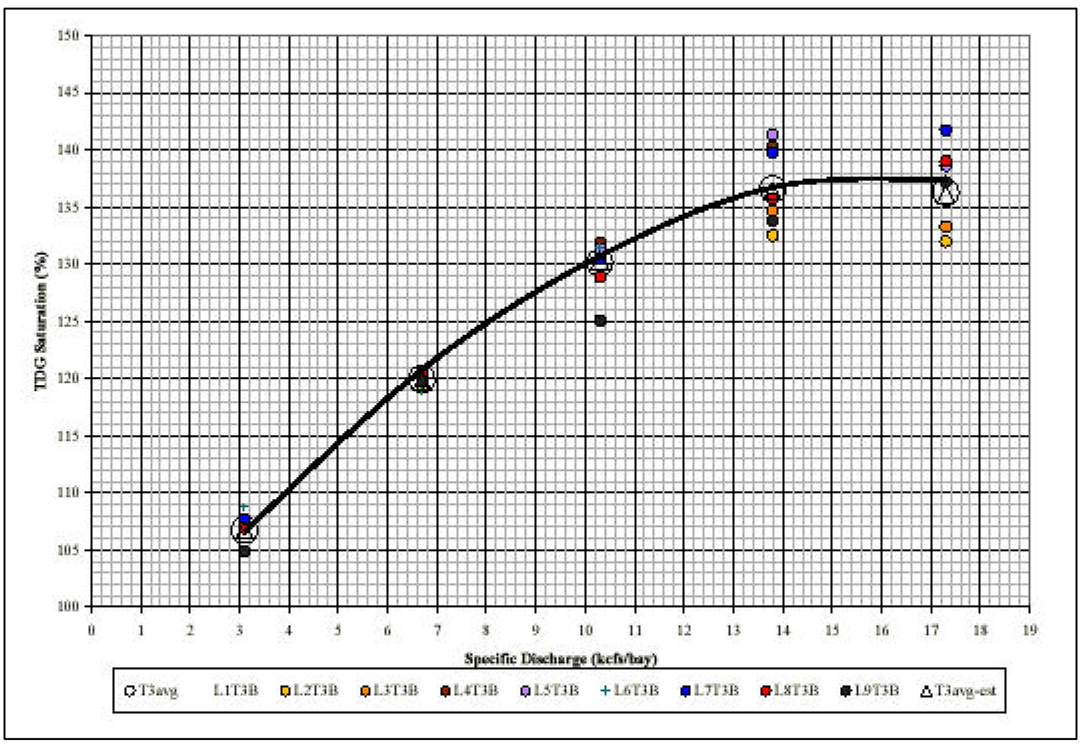
Figure SEQ Figure * ARABIC 14 : TDG Saturation from Non- deflectored Bays at Exit of the Bonneville Spillway Channel, February 1, 1999



The steady-state TDG saturation at nine sampling stations on transect T3 located at the mouth of the spillway channel are shown in this figure. The stations were labeled L1 through L9 from south to north along this transect. The flow-weighted TDG saturation on this transect is labeled T3avg. During the two-dog setting, the non-deflectored bays generated an average TDG saturation of 132 percent or about 12 percent greater than the comparable flows during day two. The TDG saturation associated with non deflectored bays remained constant for gate settings of two dogs and higher.

The TDG saturation response to the unit spillway discharge over only deflectored bays was nearly linear for gate settings of one through four dogs. This relationship was nearly identical to similar conditions measured during the initial Bonneville spillway performance test (Wilhelms and Schneider, 1997b). The TDG saturation at two dogs was observed to be about 120 percent on all 11 instruments located across the spillway exit channel. Larger lateral gradients in TDG pressure were observed for higher discharges over the deflectored bays as shown in figure 15

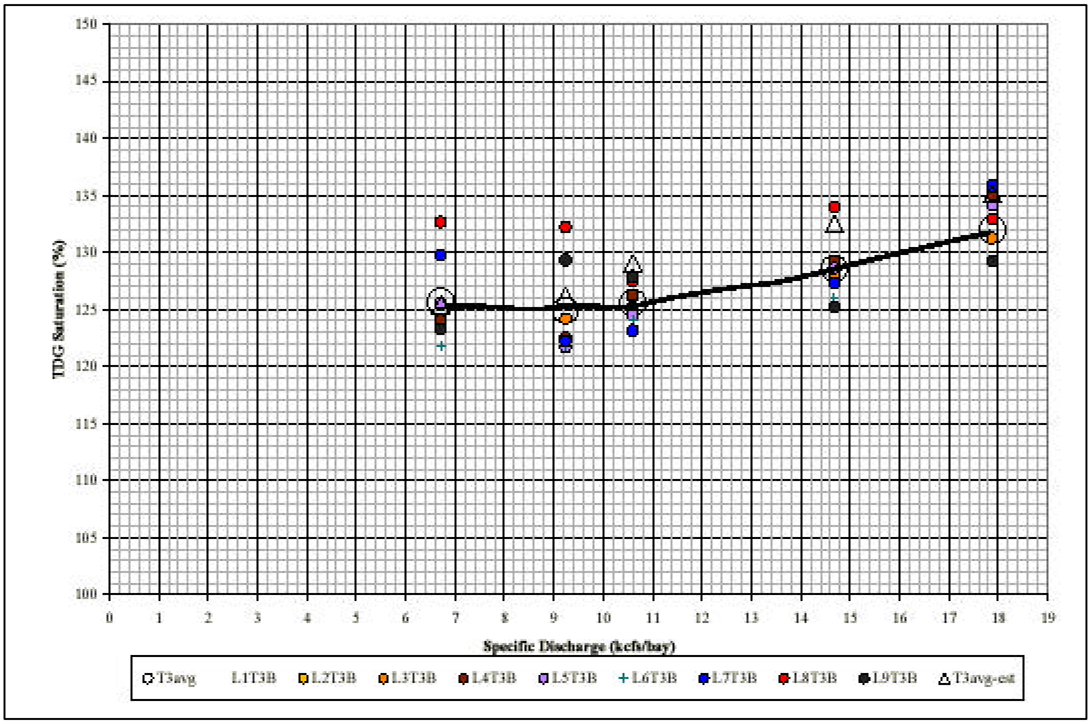
Figure SEQ Figure * ARABIC 15 : Observed Total Dissolved Gas Saturation below Bonneville Spillway during Uniform Flow over Deflected Bays 8- 15, February 1- 4, 1999



The TDG pressures generated with deflectored spillway releases were observed to be greater than conditions for non-deflectored bays for spillway flows of four dogs and higher.

A flow-weighted specific spillway discharge was determined for the standard spill pattern because of the non-uniform distribution of flow. This representation of unit spillway discharge places more importance on flows from bays with larger discharges. The spill patterns during the five test conditions on day four are shown in figure 16.

Figure SEQ Figure * ARABIC 16 : Observed Total Dissolved Gas Saturation below Bonneville Spillway During Standard Spill Patterns Over Deflected Bays 4- 15 and Non-Deflected Bays 2- 3, 16- 17, February 1- 4, 1999



The initial discharge of 50 kcfs on day four had a flow-weighted discharge of over 6 kcfs/bay due to the gap-toothed pattern where a highly non-uniform flow distribution was used. The high percentage of flow over the non-deflectored bays resulted in nearly a constant TDG saturation for the first three test conditions. The slope of the TDG saturation and unit discharge curve approached conditions observed during the uniform patterns on day 3 during spill over both deflectored and non-deflectored bays. The TDG saturation associated with the standard spill pattern was 125 percent and higher for all the test conditions.

Empirical relationships were derived for non-deflectored and deflectored bay spill conditions. These regression equations were then applied to the individual bays used in the mixed bay spill patterns on the third and fourth day of the test to determine if these properties were additive. An exponential equation was fitted to the five flow conditions observed on the first day (non-deflectored bays only). The following equation expresses the increase in TDG pressure over barometric pressure as a function of the unit discharge. Equation 16 is applicable only to non-deflectored bays 1, 2, 3, 16, and 17 at the Bonneville spillway.

EMBED Equation.3 Equation SEQ Equation * ARABIC 16

Where:

. EMBED Equation.3 = EMBED Equation.3 (mmHg)
EMBED Equation.3 = Unit spillway discharge (kcfs / bay)
EMBED Equation.3 > 3.0 kcfs / bay

A third order polynomial was fit to the five test conditions associated with the uniform spill over deflectored bays. A third order polynomial was chosen because of the rapid change in slope of the curve at the higher discharges. Equation 17 expresses the increase in TDG pressure over barometric pressure as a function of the unit discharge. This equation only applies to the deflectored bays four through 14 at the Bonneville spillway. This equation is not appropriate for unit discharges less than three kcfs / bay.

EMBED Equation.3 Equation SEQ Equation * ARABIC 17

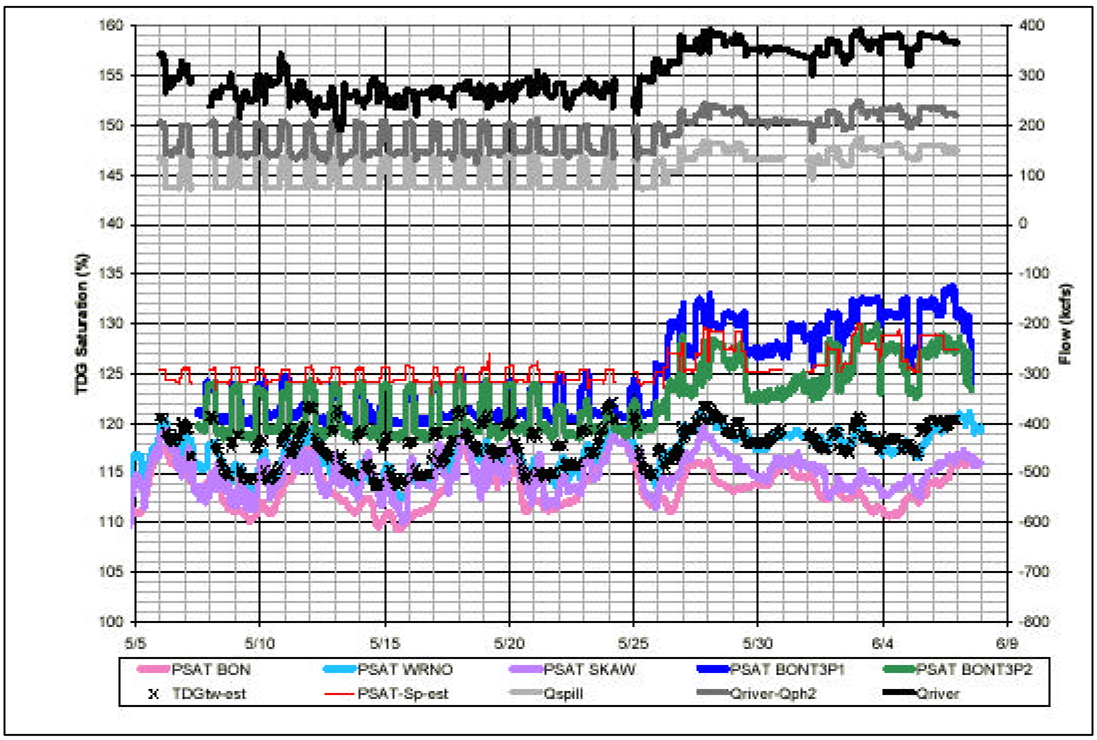
Where:

. EMBED Equation.3 = EMBED Equation.3 (mmHg)
EMBED Equation.3 = Unit spillway discharge (kcfs / bay)
EMBED Equation.3 > 3.0 kcfs / bay

Equations 1 and 2 were applied to the individual spillway bay discharges observed during the third and fourth day of testing during the first week in February. The resulting pressures were then multiplied by the ratio of spillway bay discharge to total spillway discharge and summed to determine the flow-weighted pressure change. The barometric pressure was then applied to calculate the TDG saturation. The individual station saturations (L1T3B-L9T3B), cross-sectional average saturation (T3avg), and forecasted aggregate saturation (T3avg-est) are shown in figure 14 for the standard spill pattern. The forecast of the TDG saturation associated with the standard pattern followed the general trend in the data. The forecasted TDG saturation overestimated the observed average conditions for the higher gate settings. The forecasted value falls within the range of observed values of TDG saturation downstream of the highly aerated flow regime.

The two-equation flow-weighted average formulation was also applied to the operations data gathered during the supplemental TDG test conducted below Bonneville from May 7-June 7. Equations 1 and 2 were applied to the observed spillway bay discharge and average TDG saturation for spillway releases was determined using a flow-weighted approach. The average spillway TDG saturation was plotted with project operations, forebay FMS TDG saturation, tailwater FMS TDG saturation, and auxiliary station TDG saturation as shown in figure 17.

Figure SEQ Figure * ARABIC 17 : Observed and Estimated Total Dissolved Gas Saturation Below Bonneville Spillway During Spill Season, May 5 – June 8, 1999



The average TDG saturation released from Bonneville was estimated using the formulation presented above for the spillway contribution. The TDG loadings associated with powerhouse releases were estimated by the product of powerhouse discharge and forebay FMS TDG saturation. The estimated loading from the spillway was determined by the product of the spillway discharge and estimated spillway TDG saturation. The flow-weighted average TDG saturation released from Bonneville is shown in figure 17 under the heading of TDG-tw-est. The estimated average TDG saturation closely followed the observed data at the tailwater FMS's during most of the study period. The TDG distribution at the tailwater FMS is often not uniform and, therefore, cannot be used as a rigorous validation of this formulation. However, this comparison does lend additional credence to the formulation cited above.

Powerhouse Entrainment

The entrainment of powerhouse flow was assumed to be zero at Bonneville because of the physical barriers created by Bradford and Cascade Islands. The TDG exchange was not found to extend below the spillway channel during near-field investigations.

Load Allocations

Based on the foregoing discussion, load allocations for each project can be established. Load allocations are based on a spill quantity. While allocations could have been based on a volume of air, for management purposes it is more practical to base them on a quantity of water spilled. There is a clear mathematical relationship between these two variables. Load allocations are contained in table 10.

Table SEQ Table * ARABIC 10 : Proposed Load Allocations for Lower Columbia River Hydroelectric Projects at or Below 7Q10 Flows

Project	10-Year 7-Day Discharge (cfs (1)1	Powerhouse Hydraulic Capacity (cfs) (2)2	Spill Capacity to 110 percent (cfs) (3)3	Additional Required Capacity (cfs) (4)4
McNary	480,000	146,000	56,000	278,000
John Day	498,000	310,000	60,000	128,000
The Dalles	498,000	290,000	23,000	185,000
Bonneville	498,000	216,0005	44,000	172,000

Source: U.S. Army Corps of Engineers DGAS Study, p. 5-3.

Notes to Table:

1 Column (1). Statistical analysis of historical discharge data

2 Column (2). Powerhouse hydraulic capacity assumes that units are operating at highest hydraulic capacity within one percent of peak efficiency for fish passage and that one unit is out of service on Snake River projects and two units out of service on Columbia River projects.
3 Column (3). Identifies the volume of water that can be passed over the existing spillways without exceeding 110 percent TDG at the tailrace fixed monitoring station. This spill volume assumes incoming forebay TDG is 110 percent or less and is based on current existing conditions which are about 3,000 cfs per deflected spillbay and 1,000 cfs per non-deflected bay. This number will change as additional deflectors are added to existing spillways.
4 Column (4). The additional required capacity or discharge that must be passed by the project in some manner so as to not exceed the 110 percent TDG value as recorded at the tailrace fixed monitoring station. Column (4) is calculated as (4)=(1)-(2)-(3). The design discharges from column (4) are conservative values that were used as target flow for design of new structures.
5 Assumes Minimum Gap Runner (MGR) installation on Bonneville First Powerhouse (B1).

Margin of Safety

A margin of safety is usually identified in a TMDL to recognize uncertainty in the data used to produce the TMDL. Due to the monitoring requirements imposed by the Environmental Quality Commission as a part of its annual variances to the standard for fish passage over the past seven years, there is a great deal of hourly data of total dissolved gas levels, barometric pressure, water temperature, tailwater elevation, forebay elevation, total river flow and spill quantity. This data is publicly available on the Technical Management Team homepage, hosted by the Northwest Division of the U.S. Army Corps of Engineers at:

HYPERLINK http://www.nwd-wc.usace.army.mil/TMT/welcome.html
http://www.nwd-wc.usace.army.mil/TMT/welcome.html

As a result of this monitoring there is ample data for constructing this TMDL. Further, the U.S. Army Corps of Engineers has undertaken an extensive gas abatement (DGAS) study over the past five years. The study included development of a mathematical model to describe the production, dissipation and behavior of TDG in the Columbia system for the federal projects. The production of TDG at the four hydroelectric projects that are the identified sources in this TMDL are, therefore, well understood.

As a result, the margin of safety developed for this TMDL is zero. This means that the full loading capacity is allocated to each of these four projects.

Seasonal Variations

Exceedances of the TDG standard occur either during the fish migration season (mid-April to the end of August), or during the high flow season in conjunction with spring runoff. One of the determinants of TDG levels is total river flow. When flows in the river are particularly high TDG levels rise if there is any water spilled over the spillway. During low flow periods, other than voluntary spill for fish passage, there is generally not a TDG problem.

Occasionally turbine units will be out service for maintenance, either scheduled, or on an emergency basis. This may require water to be spilled because there are insufficient turbines available to handle the water in the river. Clearly, there is little control over emergency outages. Maintenance is generally scheduled to coincide with low electricity demand periods, and when river flows are such that they will not cause total dissolved gas exceedances.

Implementation Plan

The following are the alternatives evaluated by the U.S. Army Corps of Engineers as reducing TDG.

Operational Alternatives

The following operational measures will reduce TDG production:

Maximize powerhouse releases;
Reduce (restrict) spill through non-deflectored spillway bays;
Concentrate spill to shallow tailrace regions; and
Prioritize spill at projects with lower TDG production.

Structural Alternatives

The following structural alternatives will reduce TDG production:

Additional/modified deflectors;
Raised tailrace channel;
Raised spilling basin;
Submerged conduits;
Baffled chute spillway;
Side channel spillway;
Pool and weir channels;
Additional spillway bays;
Powerhouse/spillway wall;
New spillway gates (Bonneville only);
Conversion of turbines to sluices;
Hydro-Combine powerhouse;
V-Shaped spillway;
Additional powerhouse.

A number of these alternatives have been evaluated as being deleterious to fish passage.

The following are the alternatives that have been evaluated both on a short-term and long-term timetable:

Table SEQ Table * ARABIC 11 : Short Term Gas Abatement Actions

Project	Alternative 1	Alternative 2	Alternative 3	Alternative 4
McNary	Uniform Spill (18/22)	Uniform Spill Four new deflectors	Uniform Spill Powerhouse/ Spillway Wall	Uniform Spill Powerhouse/ Spillway Wall
John Day	Uniform Spill (18/20)	Standard Spill Two new deflectors	Uniform Spill (20/20)	Uniform Spill (20/20)
The Dalles	Uniform Spill (0/23)	Existing Condition	Uniform Spill 23 new deflectors	Uniform Spill (23/23)
Bonneville	Uniform Spill (13/18)	Uniform Spill Five new deflectors	Uniform Spill (18/18)	Uniform Spill (18/18) Raised Tailrace

Table SEQ Table * ARABIC 12 : Long Term Gas Abatement Actions

Project	Alternative 1	Alternative 2	Alternative 3
McNary	Uniform Spill (20/20) powerhouse/ spillway wall	Uniform Spill Powerhouse/ spillway wall Nine new spill bays	Uniform Spill Powerhouse/ spillway wall Nine new spill bays
John Day	Uniform Spill (20/20) Six new spill bays	Uniform Spill (20/20) Six new spill bays	Uniform Spill (20/20) Six new spill bays
The Dalles	Uniform Spill (23/23)	Uniform Spill (23/23)	Uniform Spill (23/23)
Bonneville	Uniform Spill (18/18) Raised tailrace	Uniform Spill (18/18) Raised tailrace	Uniform Spill (18/18) 18 Sub gates

The following provide estimated improvements in TDG production and estimated costs of implementation for the various alternatives.

Table SEQ Table * ARABIC 13 : McNary Dam Estimated TDG Reduction and Cost

McNary Lock and Dam	TDG Reduction from Base Condition			Total Cost Estimate ($Million)
	Case 1	Case 2	Case 3	
Total River Flow (kcfs)	300	400	500	
Base Condition TDG (%)	116.8	122	127.9	
Spillway Flow (kcfs)	154	254	354	
Four additional deflectors	-2.5	-2.2	-2.2	3
Raised tailrace channel	-2.5	-3.7	-3.7	200-300
Nine additional spillway bays	-4.2	-5.5	-7.0	458-732
Powerhouse/spillway wall	-3.3	-3.4	-3.7	
Side channel spillway	-6.8	-12.0	-17.9	477-763
Submerged conduits	-6.8	-12.0	-17.9	236-378

Table SEQ Table * ARABIC 14 : John Day Dam Estimated TDG Reduction and Cost

John Day Lock and Dam	TDG Reduction from Base Condition			Total Cost Estimate ($Million)
	Case 1	Case 2	Case 3	
Total River Flow (kcfs)	300	400	500	
Spillway Flow (kcfs)	0	90	190	
Base Condition TDG (%)	110	113	117.6	
Two additional deflectors	0.0	-0.2	-0.6	
Raised tailrace channel	0.0	-0.6	-1.1	67
Nine additional spillway bays	0.0	-1.8	-2.1	382-611
Powerhouse/spillway wall	0.0	-0.8	-1.2	
Side channel spillway	0.0	-3.0	-7.6	425-629
Submerged conduits	0.0	-3.0	-7.6	261-418

Table SEQ Table * ARABIC 15 : The Dalles Dam Estimated TDG Reduction and Cost

The Dalles Lock and Dam	TDG Reduction from Base Condition			Total Cost Estimate ($Million)
	Case 1	Case 2	Case 3	
Total River Flow (kcfs)	300	400	500	
Spillway Flow (kcfs)	10	110	210	
Base Condition TDG (%)	110.4	113.7	116.4	
23 new deflectors	-0.3	-1.7	-1.5	16-36
Nine additional spillway bays	-0.3	-1.3	-0.7	247-395
Side Channel Spillway	-0.4	-3.7	-6.9	946-1,513
Submerged Conduits	-0.4	-3.7	-6.9	326-522

Table SEQ Table * ARABIC 16 : Bonneville Dam Estimated TDG Reduction and Cost

Bonneville Lock and Dam	TDG Reduction from Base Condition			Total Cost Estimate ($Million)
	Case 1	Case 2	Case 3	
Total River Flow (kcfs)	300	400	500	
Spillway Flow (kcfs)	84	184	284	
Base Condition TDG (%)	114.3	119.5	123.7	
Six additional deflectors	-3.1	-0.2	1.4	4
Raised tailrace channel	-1.0	-1.0	-0.3	109-174

Nine additional spillway bays	-4.3	-2.4	-1.4	519-830
Submerged Conduits	-4.3	-9.5	-13.7	351-561
Submerged Spillway gates	-4.3	-9.5	-13.7	180-288

The Dissolved Gas Abatement Study undertaken by the Corps made some general observations concerning TDG abatement. These included:

1. High ratios of spill to total project flow tend to eliminate or override upstream project contributions of TDG to a river reach;
2. In-pool events, such as wind in long reservoirs often resulted in more significant decreases in TDG than any gas abatement structures;
3. McNary and Bonneville Dams have added significance due to the extremely large volumes and reaches of the receiving waters. Abatement at these projects will impact larger volumes of aquatic habitat and proportions of the river system;
4. Maximizing powerhouse flow reduces TDG;
5. With current operations, the Snake and Columbia Rivers are not strongly coupled.

From a systemwide viewpoint, maximum TDG reductions are achieved by alternative 3 in Table 11 in the short-term, and alternative 3 in Table 12 for the long-term. On a project-by-project basis, the following seem to offer the greatest benefits:

1. Bonneville Dam - all gas abatement measures significantly improve TDG loading conditions. Of all the projects, Bonneville has the greatest range in change of TDG saturation loading downstream. The installation of deflectors at Bonneville and The Dalles result in significant improvements in TDG;
2. The Dalles Dam - The addition of deflectors at The Dalles resulted in significant improvements in TDG;
3. John Day Dam - The most significant change in TDG occurs with the addition of spillway bays;
4. McNary Dam - The greatest improvements in TDG are associated with a uniform spill pattern, added deflectors, and additional spillway bays. John Day pool into which McNary Dam discharges is very large, which results in the project potentially impacting a great volume of aquatic habitat.

Immediate Actions

For the short term, measures should include those specified in Table 11 above for

McNary, The Dalles and Bonneville. Following implementation of these measures a reassessment of TDG abatement should be undertaken. Implementation of measures designed to meet the load allocations for this TMDL will need to be undertaken on an iterative, and adaptive basis, with a careful evaluation and assessment following each meaasure.

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