**Predicting Total Dissolved Gas (TDG) for the Mid-Columbia River System**

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## Abstract

Total dissolved gas (TDG) supersaturation in waters released at hydropower dams can cause gas bubble trauma that can lead to fish mortality. Elevated TDG related to hydropower are generally caused by air entrainment in spillway releases and the subsequent gas dissolution during passage through a stilling basin. The network of dams throughout the Columbia River Basin (CRB) are managed for irrigation, hydropower production, flood control, navigation, and fish passage that frequently result in both voluntary and involuntary spill. These dam operations are constrained by state and federal water quality standards for TDG saturation, which balance the benefits of spill with the degradation to water quality associated with TDG saturation. In the 1970s, the United States Environmental Protection Agency established a criterion not to exceed the TDG saturation level of 110%. The physical processes that affect TDG exchange at hydropower facilities have been studied throughout the CRB in site-specific studies and routine water quality monitoring programs. The resulting data have been used to quantify the relationship between project operations, structural properties, and TDG exchange and to develop TDG predictive models to support real-time management decisions. These empirically based models have been developed for specific projects and account for both the fate of spillway and powerhouse flows in the tailrace channel and the resultant exchange in route to the next downstream dam. Currently, a need exists to summarize the general findings from operational and structural TDG abatement programs conducted throughout the CRB and for the development of a generalized predictive model that pools data collected at multiple projects with similar structural attributes. A generalized TDG exchange model can be tuned to specific projects and coupled with water regulation models to allow the formulation of optimal daily water regulation schedules subject to water quality constraints for TDG. Such a model can also be applied to other hydropower dams that affect TDG in tailraces and can be used to develop alternative operational and structural measures to minimize TDG generation.

A methodology for predicting TDG levels downstream of hydropower facilities with similar structural properties as a function of a set of variables that affect TDG exchange; such as tailwater depth, spill discharge and pattern, project head, and entrainment of powerhouse releases is presented. The equations are based on fundamental mass, momentum and energy conservation principles. TDG data collected at the CRB are used to calibrate the models using multi-parameter regression analysis for various structural categories.

The uniqueness of this research is its classification of structural, operational, and environmental parameters in the development of a predictive TDG exchange formulation. A generalized empirical approach enables the development of TDG exchange formulations for application to a

whole class of projects while avoiding expensive data collection programs and complex project-specific model development formulation.

Implementation of the developed TDG predictive model for Grand Coulee and Rock Island are being integrated by CADSWES into the recently developed real-time scheduling tool RiverWare. Development and implementation of the TDG prediction model for the projects on the Mid-Columbia River system is proposed for next year.

## 1. Background and Introduction

Total dissolved gas (TDG) supersaturation in waters released at hydropower dams can cause gas bubble trauma in fisheries, resulting in physical injury and eyeball protrusion that can lead to mortality. Elevated TDG pressures in hydropower releases are generally caused by the entrainment of air in spillway releases and the subsequent exchange of atmospheric gasses into solution during passage through the stilling basin. Total dissolved gas (TDG) refers to the total amount of dissolved gases present in water. Elevated TDG supersaturation is recognized as a serious problem on the Columbia and Snake Rivers where it has caused gas bubble disease (GBD) in numerous fish. In the 1960's it became evident that TDG supersaturation affected the fish population in the Columbia River Basin (Ebel 1969). The effect of TDG supersaturation is complex and depends principally on TDG levels, exposure time, fish life stage, and swimming depth of the fish (Stroud et al. 1975, Weitkamp and Katz 1980, Bouck 1980). An early review of the gas supersaturation problem in the Columbia River basin is found at USEPA (1971). Comprehensive reviews of studies found in the literature related to biological effects of TDG on fish are documented in Weitkamp (2008a, 2008b).

The network of dams throughout the Columbia River Basin (CRB) are managed for irrigation, hydropower production, flood control, navigation, and fish passage that frequently result in both voluntary and involuntary spillway releases. These dam operations are constrained by state and federal water quality standards for TDG saturation which balance the benefits of spillway operations designed for Endangered Species Act (ESA)-listed fisheries with the degradation to water quality as defined by TDG saturation. In the 1970s, the United States Environmental Protection Agency (USEPA), under the federal Clean Water Act (Section 303(d)), established a criterion not to exceed the TDG saturation level of 110% in order to protect freshwater and marine aquatic life. The states of Washington and Oregon have adopted special water quality standards for TDG saturation in the tailrace and forebays of hydropower facilities on the Columbia and Snake Rivers where spillway operations support fish passage objectives. The U.S. Army Corp of Engineers (USACE) and the Bureau of Reclamation (Reclamation), with oversight by Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE) are developing a methodology for predicting and managing total dissolved gas (TDG) on the Columbia and Snake River dams (Pasha et al. 2012). A system-wide real-time data-driven approach is being proposed for the formulation of dam operations to maximize hydropower generation while meeting water quality standards. Currently, there exists a need to summarize the general finding from operational and structural TDG abatement programs conducted throughout the CRB and for the development of a generalized prediction model that pools data collected at multiple projects with similar structural attributes. A generalized TDG exchange model can be tuned to specific projects and coupled with water regulation models to allow the formulation of optimal daily water regulation schedules subject to water quality constraints for

TDG supersaturation. A generalized TDG exchange model can also be applied to other hydropower dams that affect TDG pressures in tailraces and can be used to develop alternative operational and structural measures to minimize TDG generation.

TDG production depends on extremely complex processes. The large energy introduced by spillway flows, mostly dissipated in the stilling basin and adjoining tailwater channel, introduces massive amounts of bubbles and creates energetic waves and sprays. When bubbles are carried down to deep, high-pressure regions in the stilling basin, the solubility increases and air is transferred from the bubbles to the water. In these deep regions, the bubble size distribution changes due to both dissolution and compression. The amount of air entrained in the spillway and during plunging of spillway flows, breakup and coalescence of entrained bubbles, and mass transfer between bubbles and water affects TDG production. As an additional complexity, the TDG distribution downstream of dams is strongly coupled with the hydrodynamics in the tailrace and river downstream. A lateral gradient of TDG is frequently observed in tailraces due to the location of the spillway or operation of the dam. Mixing with powerhouse flows can play an important role in the resulting TDG downstream of the dam. Degasification at the free surface can also be important in the routing of TDG from one project to the next project's forebay.

The most important source of elevated TDG is the gas transferred from air bubbles; therefore, a proper model for TDG prediction must account for bubble dissolution in the stilling basin. Since dissolution increases with pressure and bubble interfacial area, predicting bubble depth in the tailrace and bubble size distribution is of paramount importance.

The major issues regarding the prediction of TDG during spillway releases are air entrainment and the effect of water entrained from the powerhouse into the spillway region, two not well-understood phenomena.

Model-scale experiments scaled with the Froude number intended to reproduce hydrodynamics fail to reproduce the air entrainment observed in the prototype. As a result of scaling based on the Froude number, the Reynolds and Weber numbers are not honored, resulting in lower levels of turbulence and fewer, larger bubbles (in dimensionless terms) compared with the prototype. As a consequence, the bubble residence time is much shorter and the gas volume fractions much smaller, resulting in a rather ineffectual two-phase flow. The incorrect representation of the gas phase, along with inadequate turbulence, leads to less entrainment for the reduced-scale model.

It has been demonstrated that spillway jets may cause a significant change in the tailrace flow pattern since they attract water toward the spillway region, a phenomena called water entrainment. This entrainment increases the amount of water in the aerated zone, which can result in more supersaturated water and modified downstream mixing. In an effort to minimize the supersaturation of dissolved gases, spillway flow deflectors have been installed in several dams. Deflectors redirect spilled water horizontally, forming a surface jet that prevents the bubbles from plunging to depth in the stilling basin, thus reducing the air dissolution. It is observed that surface jets considerably increase the water entrainment. Turan et al. (2007) described the main mechanisms causing water entrainment as acceleration of the surrounding fluid as the jets decelerate, the Coanda effect of a fluid jet attracting to a surface, surface currents, and the presence of bubbles.

In this study, representative TDG equations based on mass, momentum and energy conservation principles are derived. The TDG equations are a function of tailwater depth, spill discharge, powerhouse discharge, project head, and environmental parameters such as temperature and atmospheric pressure. The air and water entrainments are modeled assuming a linear relationship with the unit spill and total spill, respectively. The bubble trajectory in the tailrace and dissolution are calculated assuming one-sized bubbles. Multi-parameter regression analysis is used to determine the experimental parameters of the model. The main advantage of this approach is that model parameters are physically meaningful and processes included such as air entrainment, water entrainment, and dissolution, are potentially observable. When available, basic experiments or models of these phenomena can be used to improve the model. This paper compares model results with available TDG data collected in Grand Coulee and Rock Island dams. The parameters were calibrated against TDG data measured in 2010, where significant spill was observed, and validated against data measured in 2008, 2009, 2011 and 2012.

## 2. METHODOLOGY

Many of the existing physically based and empirically based models require some degree of calibration with data collected at a particular hydropower site. Site-specific characteristics that may impact the TDG exchange at a hydropower facility include structural features of the spillway and stilling basin, such as spillway flow deflectors, stilling basin and tailrace channel depths, training walls, baffle blocks and endsills, and spillway gate geometry. The TDG exchange associated with spillway releases have been found to vary markedly from regulating outlet releases at Grand Coulee and Dworshak Dams. The interaction of highly aerated spillway flows with powerhouse releases may also play a prominent role in establishing the net TDG exchange in hydropower dam discharges. The entrainment of the powerhouse releases into the highly aerated flow conditions in the stilling basin has been documented for the Lower Monumental Dam on the Snake River. Though many models and approaches currently exist, the effort of this work will focus on quantifying the TDG exchange at dams in the CRB through the formulation of a generalized model. In addition, it is anticipated that more thorough and effective regression equations can be realized beyond what currently exists in other prediction models.

Currently there are no generalized predictive tools or guidelines readily available and applicable to assessing the effects of hydropower operations on of downstream TDG minimization and/or reduction. Hydropower operators and planning groups could benefit from a generalized approach to predicting TDG based on readily available parameters that are easy to measure. A generalized empirical approach could be used as a supplemental tool in daily hydropower operations or long-term planning scenarios to predict and assess TDG levels in a simplified fashion that is easily accessible and usable. The goal of this study is to ultimately couple the decisions regarding water regulation across a group of dams with water quality impacts in the form of TDG saturation.

This tool could be used in conjunction with hydropower operations and planning efforts that are already used to maximize hydropower generation while minimizing downstream TDG levels. For example, adjusted hydropower operations may involve trading power flows for spill between dams such that system hydropower generation would be maximized while TDG loading minimized. It is proposed to conduct a study to determine if such an approach to predicting TDG is feasible in the context described here and, if so, develop the corresponding methodology and protocol for implementing within a real-time water regulation model.

The uniqueness of this proposed research is its classification of the structural, operational, and environmental parameters in the development of a predictive TDG exchange formulation. The operational and environmental parameters will involve stilling basin channel depth, total head, spill volume and pattern, powerhouse flow, background TDG pressure, water temperature, and local barometric pressure. The structural properties will involve the geometry of the spillway and incorporation of spillway flow deflectors, training walls, endsill and baffle blocks, training walls, and proximity of powerhouse flows. A generalized empirical approach developed from pooling data from multiple projects with common attributes will enable the development of TDG exchange formulations being applied to a whole class of projects while avoiding expensive data collection programs and complex project-specific model development formulation. Different ranges of the main parameters associated with the highest response to TDG levels are to be established and classifications based on combinations of these main parameters are to be developed. Main-parameter-based equations developed from "curve-fitting" and similar techniques will exist for each classification. This generalized empirical approach tool, based on classifications, should be portable enough to predict absolute or relative changes to TDG levels for relatively large hydropower operations in the country based on the range and relative associations of the important parameters. Though this prediction tool may not function as accurately as specific-calibration based methodologies, it should still function as a reasonable and value-added guide to predicting TDG exchange. While tradeoffs may exist in such a simplified general prediction tool, it is important to conserve the integrity of the predictions' accuracy such that it can still be regarded as a viable alternative to predicting TDG. The schematic in Figure 1 depicts a suggestive generalized approach to establishing different classifications of guidelines, expressions, and/or methods used to predict TDG in contrast to methods requiring calibration that is specific for each case.

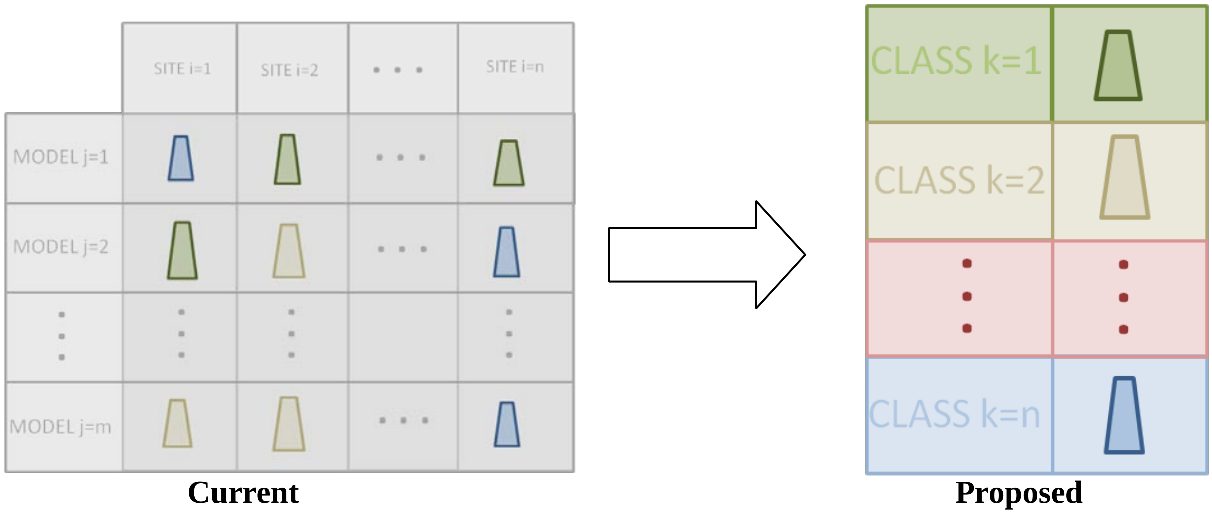


**Figure 1: Schematic Diagram Illustrating a Generalized Empirical Approach to Predict TDG**

Developing this tool will involve gathering available TDG data and selecting relative parameters from several different hydropower plants located in the northwest region of the United States. The data should be exhaustive enough to cover the range of possible flow conditions and structural configurations. Techniques used to determine levels of parameter importance and correlation will be used in conjunction with methods such as, and not limited to, optimization schemes to help determine the critical ranges of variables and division of classes based on minimization of model error with measurements. Within each classification, generalized equations, rules, and guidelines are to be transparent to extensive "site-specific" calibration, as well as sensitive and responsive to the general behavior of the parameters used to predict TDG based on categorical trends and analyses of large sets of data. An operational methodology or tool can be used in conjunction with the generalized prediction method to help assist operational decision making.

The flowchart in Figure 2 outlines the major steps in developing this model. Though this serves as a guideline for steps toward developing a new methodology, it is understood that this project ultimately functions as an assessment to determine if such a generalized approach is even viable. Assessments to determine its applicability and portability as a useful tool will be made throughout the project.

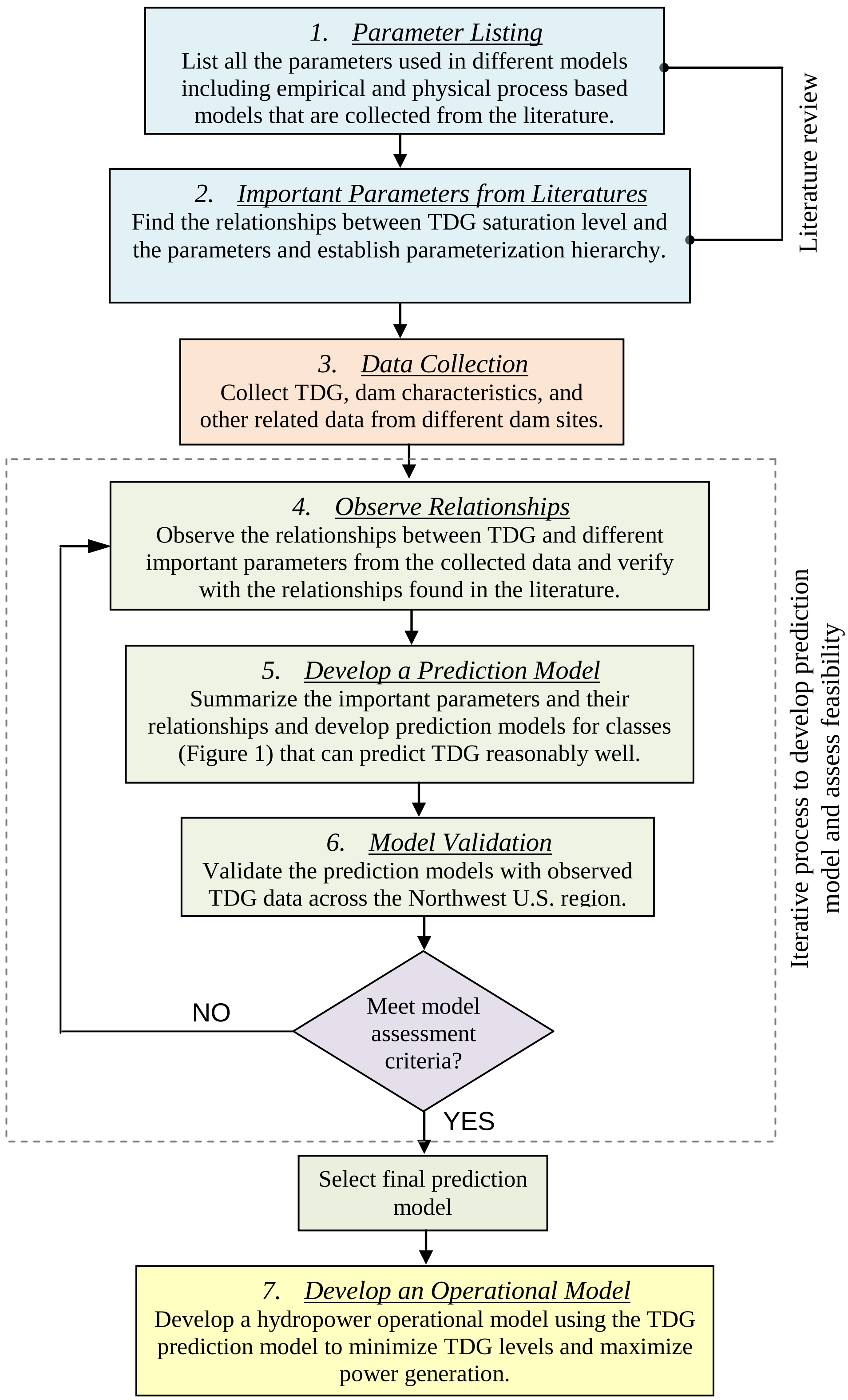


**Figure 2: Flowchart to Develop an Operational Model to Predict TDG Downstream of a Dam**

### 2.1 PROJECTS OF INTEREST

Data collection focused on eight hydroelectric projects in the CRB: Grand Coulee, Chief Joseph, Wells, Rocky Reach, Rock Island, Wanapum, Priest Rapids, and Dworshak. The first seven projects are located sequentially on the Columbia River main stem. Dworshak is positioned on the North Fork Clearwater River which eventually flows to the Columbia River via the Snake River (Figure 3).

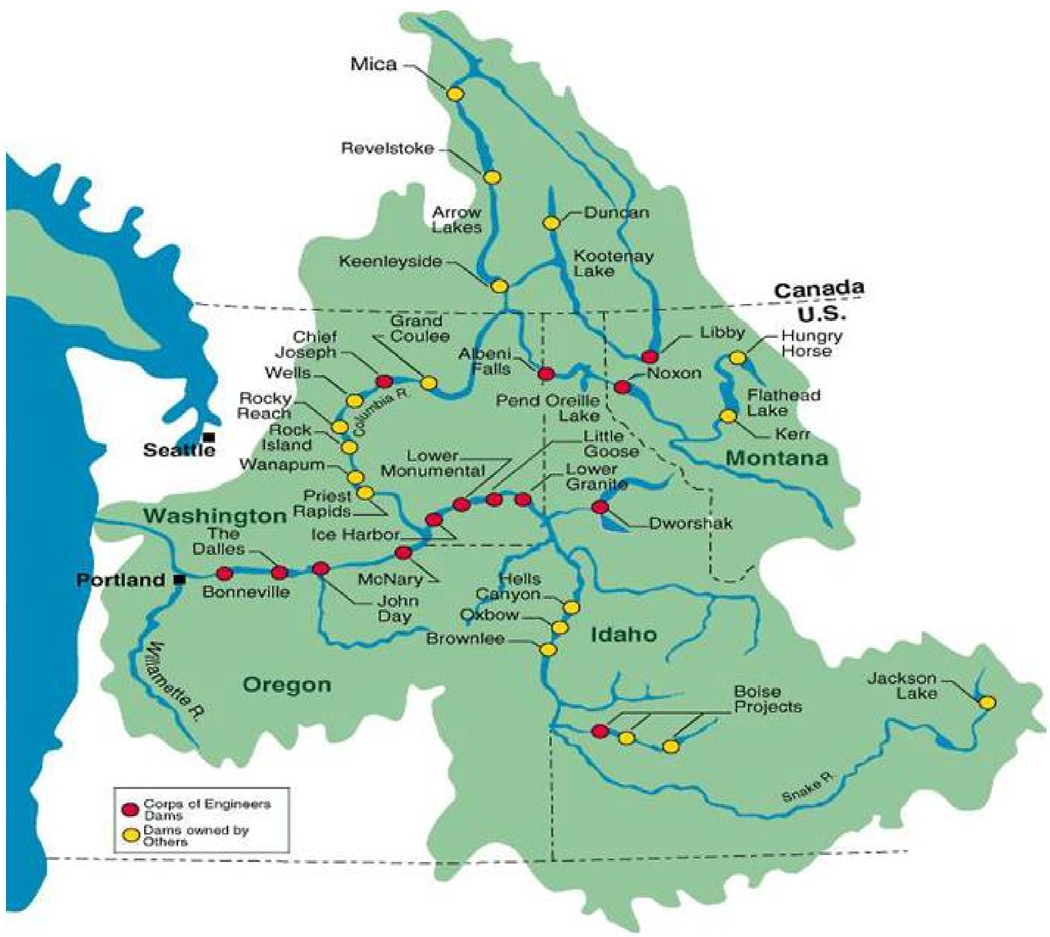


**Figure 3: Map of Major Dams along the Columbia and Snake Rivers**

Because a generalized empirical approach is desired to predict TDG generation, data is needed from a diverse set of hydroelectric projects for model calibration. Dams in the CRB employ a variety of spill bay, powerhouse, and plunge pool configurations ideal for model calibration and development. In addition, a system-wide approach is needed to examine TDG generation in the CRB because elevated TDG levels produced by projects on the upper Columbia affect TDG levels at projects down river. For these reasons, data from hydroelectric projects in the CRB was selected for use in model calibration.

A challenge associated with system-wide TDG analysis is collection of data from multiple projects operated by independent organizations. The Army Corps of Engineers (USACE), the USDOI Bureau of Reclamation (Reclamation), and multiple local utilities play a role in managing the water resources of the CRB. Some hydroelectric projects, such as Chief Joseph and Dworshak dams, are owned and operated by USACE. Other projects, such as Grand Coulee, are owned by USBR but operated by local utilities; while some CRB dams are privately owned and operated. Communication between these organizations, ORNL, and IIHR was required for data collection to occur.

Hourly data were collected from the USACE Northwestern Division's Dataquery system and Historical Water Quality Reports (HWQR) online database. The Dataquery system includes all eight CRB dams, while the HWQR database only includes Grand Coulee, Chief Joseph, and Dworshak dams. The data are derived from identical water quality gauges, and include measurements of TDG, water temperature, and elevation at both headwater and tailwater locations, as well as flow and energy measurements at the dams.

In addition to the hourly data collected from the USACE databases, hourly unit spill operational data are needed to fully model TDG exchange. Such data enables boundary condition formulation for TDG computational fluid dynamics (CFD) simulations and should include hourly records of opened spill gates and the volumetric flow rate through each gate. Unit spill operations are seldom made available to the public and must be obtained on a project-by-project basis. This information is especially important for projects which employ outlet works conduits in conjunction with traditional spill bays, such as Grand Coulee. The use of outlet works conduits can greatly influence air bubble entrainment depth, another design parameter affecting TDG generation.

Unit spill operation data were obtained using a variety of methods. For Grand Coulee, data were available for the number of drum gates and outlet work conduits open on an hourly basis. However, the data did not specify which drum gates and outlet works conduits were open or the flow rate through individual gates. Using the total spill (available from the USACE databases) in conjunction with the outlet works rating curve and headwater elevation, it is possible to calculate unit spill for the majority of spill scenarios. ORNL and IIHR communicated with Chelan County PUD and had success obtaining unit spill operation at Rock Island Dam.

## 3. MODEL DEVELOPMENT

Representative equations to predict TDG downstream of a hydropower dam were developed based on the main physical processes involved in TDG production and downstream mixing. These physical processes are: Air entrainment near the spillway face and during the plunge of spill water in the tailrace, Bubble dissolution, and Entrainment of powerhouse water into the spillway region. The independent variables of the equations are: Tailwater depth, Powerhouse flowrate, Spillway flowrate, Unit spill, Project head, and Environmental variables (atmospheric pressure and temperature).

Bubble dissolution and air and water entrainment strongly depend on the dam geometry. Though the presented methodology can be used for any hydropower project, the model parameters need to be determined for each particular dam. Any change in the dam geometry (inclusion of deflectors, training walls, etc.) requires model recalibration.

### 3.1 AIR ENTRAINMENT

A simplified model is proposed for air entrainment based on the following assumptions:

- Most of the air entrainment occurs in the tailrace at the plunging region and the entrainment along the spillway face can be considered negligible
- For a given geometry, the energy available for air entrainment is a function of the project head and unit spillway flow
- Bubbles in a spillbay n are entrained at a maximum depth $H_b^n$
- Bubbles are entrained with a monodisperse size distribution

### 3.2 MATHEMATICAL MODEL

TDG in a tailrace near the dam is modeled by applying mass and momentum balances to a control volume (CV) that extends downstream of the impingement point to the end of the aerated zone (Figure 4).

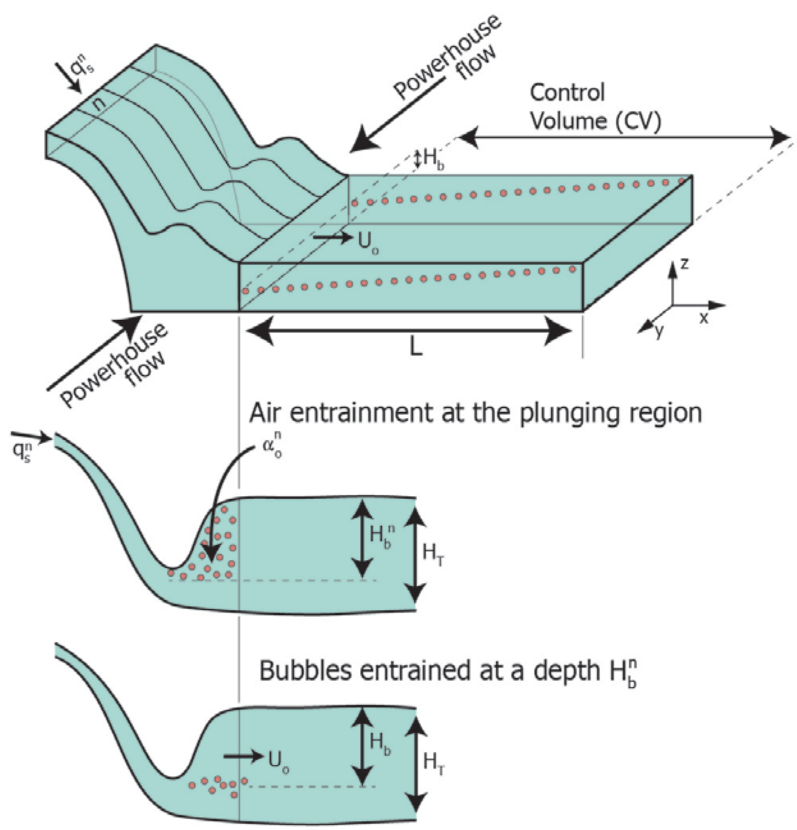


**Figure 4: Air entrainment and model parameters. Top: control volume at the aerated zone, middle: air entrainment at the plunging point in bay n and bottom: bubbles at depth $H_b$**

Total dissolved gas concentration (TDG) is defined as:

$$\text{TDG} = \frac{C}{C_{atm}}$$

where C is the concentration of dissolved gas or solubility and $C_{atm}$ is the gas concentration in equilibrium at atmospheric pressure.

The following assumptions are used to model TDG:

1. Negligible mass transfer at the free surface. The mass transfer between bubbles and liquid is a more efficient process than mass transfer at the free surface, and it can therefore be neglected in the aerated zone.
2. Vertical TDG distribution is accounted for by considering streamwise transport of TDG as shown in Figure 5.
3. A 1D model for the average TDG at a given location downstream of the spill is formally obtained by averaging the 2D TDG profile in the depth coordinate.
4. Velocity and therefore transport in the vertical direction is assumed to be negligible. Only transport downstream is considered.
5. Turbulent mixing is neglected when considering the transport of bubbles. As a consequence bubbles are confined to the aerated zone, the upper triangular in Fig. 5.
6. TDG dilution by powerhouse flows occurs downstream of the aerated zone

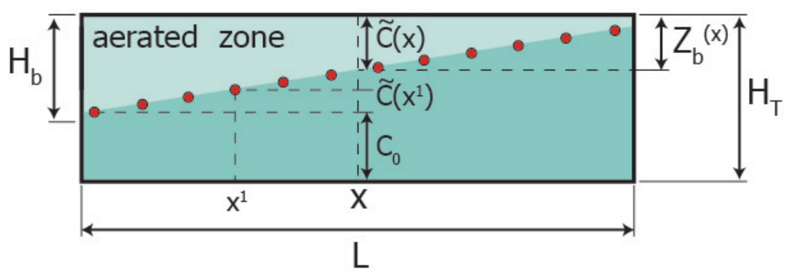


**Figure 5: Transport of TDG downstream**

Since the mean flow in the vertical direction is zero, the 2D concentration is transported according to:

$$\frac{d}{dx}[U\ C(x,z)] = S(x,z)$$

where $U$ is the streamwise velocity and $S(x,z)$ is the TDG source by bubble dissolution.

### 3.3 STREAMWISE VELOCITY

The velocity in a spillway bay n before the plunging of spillway jets in the tailrace assuming zero loss is:

$$|U_s^n| = \sqrt{2\ g\ \Delta H}$$

Part of the kinetic energy contained in the jets is lost during the plunging of the jets into the tailwater pool and at the bottom of the tailrace. Using a coefficient $C_{el}$ that takes into account the energy loss and the slope of the spillway, the velocity after the plunging can be written as:

For small gas volume fractions, the streamwise velocity can be simplified to:

$$U = U_i = \left(\frac{Q_s}{Q_s + C_{we}\, Q_p}\right) C_{el} \sqrt{2\, g\, \Delta H}$$

### 3.4 TDG CONCENTRATION DOWNSTREAM OF THE AERATED ZONE

TDG measurements are usually collected downstream of the dam where mixing with powerhouse flows has occurred. Assuming full mixing of powerhouse and spillway flows, the TDG concentration can be written as:

$$C_d^* = \frac{C^*(u = 1)\left(Q_s + Q_{pe}\right) + C_0^*\, Q_p}{\left(Q_s + Q_p\right)}$$

### 3.5 DESCRIPTION OF DAMS

Project operational data were available for three dams on the Mid-Columbia River: Grand Coulee, Rocky Reach and Rock Island. Analysis of operational and field data, as well as implementation of the proposed model, was performed using the computing environment MATLAB.

Analysis of TDG data collected at Rocky Reach Dam from 2008 to 2012 demonstrates that the mean TDG uptake in this dam was about -0.4%. Without spill, forebay TDG averaged 1.1% larger than TDG in the tailrace, indicating a clear degasification. When the dam was spilling, larger TDG values in the tailrace were correlated with larger forebay TDG, probably generated by spill in upstream dams. The average net TDG uptake when the dam was spilling is approximately 0.3%. Since TDG production in Rocky Reach is insignificant, data collected for this dam were not used for validation of the model.

#### 3.5.1 ROCK ISLAND DAM

Rock Island Dam is located on the Columbia River about 12 miles downstream of the city of Wenatchee, Washington (Figure 6). The dam comprises a spillway with 31 spillway gates, a first powerhouse with 11 generators and a second powerhouse with 8 generators. The 1,184 ft long spillway is divided into two sections by a central adult fishway. The east spillway contains 14 gates, arranged perpendicularly to the river flow, and the west spillway comprises 17 gates, at a slight angle with the river flow (Frantz 2012). A spillway deflector was installed in spillway bay 16 to reduce TDG production in the tailrace. Tailrace bathymetry is complex and ranges in elevation from approximately 580 ft. near bays 21-23 to approximately 520 ft. near bay 1 (Frantz 2012).

**Figure 6: Rock Island Dam**

Plant operations, temperature, pressure, forebay and tailwater elevations, and TDG field data from April 2008 to Sep. 2012 at 1-hour intervals during the fish spill season were provided by Chelan County PUD. Two water quality fixed monitoring stations collected TDG and temperature data at Rock Island dam from April through Autumn as part of the TDG monitoring system. TDG sensors are approximately 15 feet below the water surface. The forebay TDG monitor is located on the upstream face of powerhouse 2 near the right shoreline. The tailrace monitoring station is at about 1.5 miles downstream of the project on the left.

### 3.5.2 GRAND COULEE DAM

Grand Coulee is located on the Columbia River about 90 miles west of Spokane, Washington. The dam is comprised of a spillway, two original powerplants on the left and right sides of the spillway, and a third powerplant located almost parallel to the right abutment (Figure 7). The third powerplant is preferably used because of operational advantages. The powerplants have a total capacity of 280 kcfs and the dam has a hydraulic height of 350 feet.

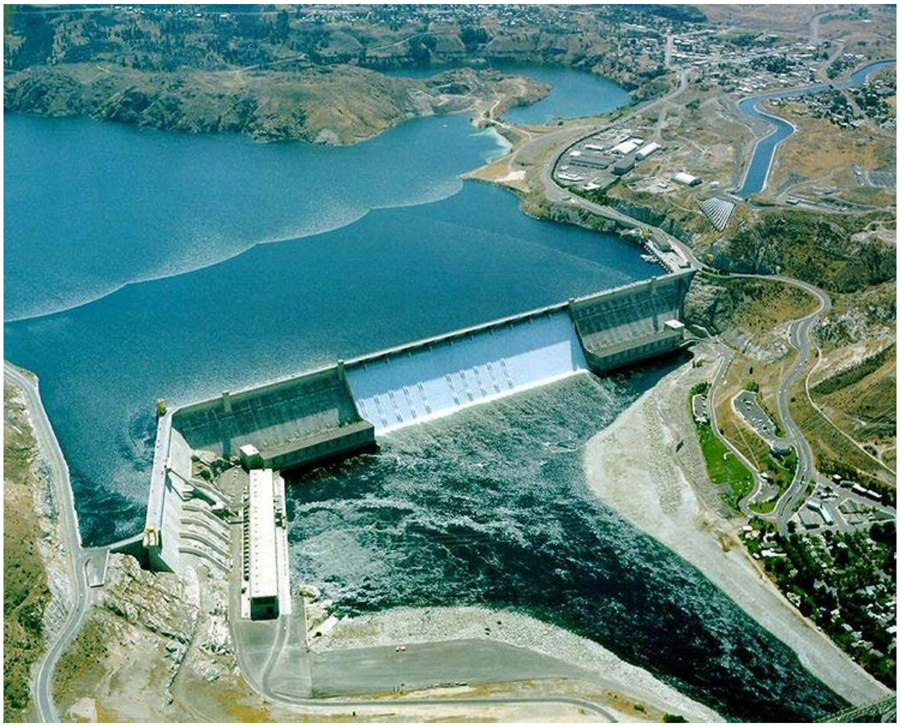

**Figure 7: Grand Coulee Dam**

The spillway includes eleven 135-foot-wide gates and 40 regulating outlets (RO) with two tiers of 20 conduits through the dam each. The RO's are generally used to lower the forebay level in the Spring when the level is below the spillway crest. The lower-level outlets have been taken out of service and are no longer operational. The spillway has a crest elevation of 1260 ft and a submerged roller bucket energy dissipater at elevations 874.4 ft. Details of Grand Coulee Dam hydraulic structures can be found at Frizell and Cohen (2000).

Two water quality monitoring stations collect TDG and temperature data at Grand Coulee Dam. Station FDRW measures TDG in the forebay and station GCGW measures TDG in the river 6 miles downstream of the dam approximately 20 feet from the left bank at a depth of about 15 feet. Hourly instantaneous TDG readings from January 2004 to July 2012, available at http://www.nwd-wc.usace.army.mil/perl/dataquery.pl, were provided by ORNL. Corresponding tailwater and forebay elevations are found at http://www.nwd-wc.usace.army.mil/tmt/wq/historical/.

Individual spillway bay and powerhouse unit operations are not available for Grand Coulee Dam (personal communication with Merlynn Bender, Reclamation). However, it is known that operators tend to use the RO below a forebay elevation of 1265.5 feet and the drum gates above 1266.5 ft. In addition, when drum gates are used, spill is uniform in all 11 gates.

## 3.6 Total Dissolved Gas (TDG)

### 3.6.1 Rock Island

Figure 8 shows TDG measured in the forebay and tailrace of Rock Island Dam. Due to its relative proximity to other upstream dams, dramatic increases in tailwater TDG compared to forebay TDG did not occur in 2011 as were seen at Grand Coulee; however, both the forebay and tailwater TDG levels were higher than in other years.

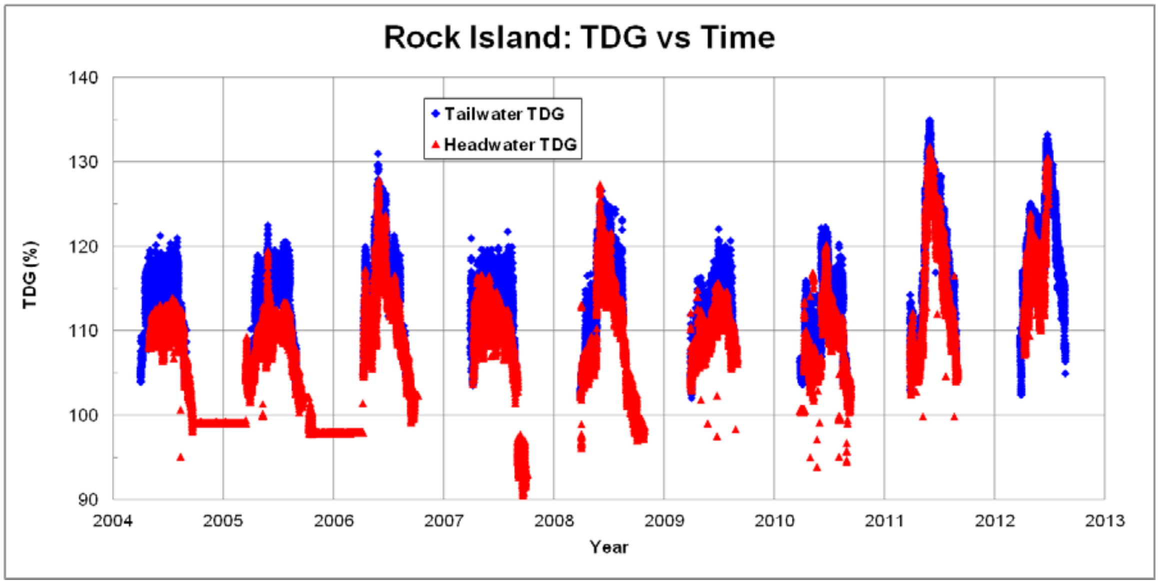


**Figure 8: Rock Island forebay and tailwater TDG from 2004 to 2012**

Figure 9 contains a plot of spill-period tailwater TDG vs spill flow at Rock Island. A strong positive correlation is noticeable, indicating a direct relationship between increased spill flow and higher tailwater TDG.

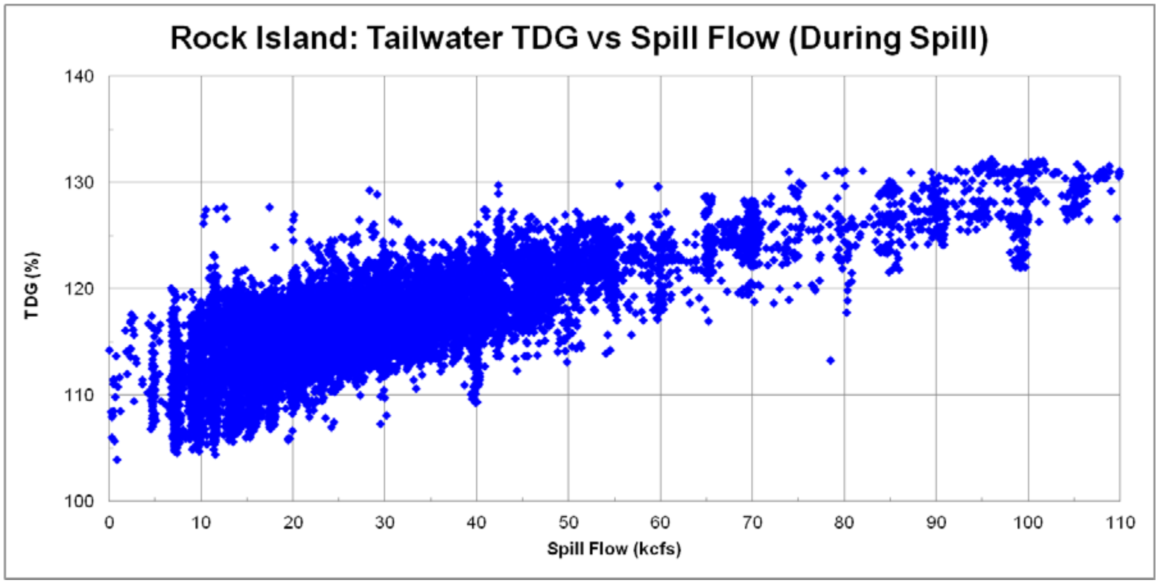


**Figure 9: Rock Island tailwater vs spill flow during periods of spill**

### 3.6.2 Grand Coulee

Figure 10 shows TDG measured in the forebay and tailrace of Grand Coulee Dam. Water released in the spillway plunges into the roller bucket energy dissipater, increasing tailwater TDG concentration. Elevated values of TDG were measured in 2011 when ratio of spill to river flow was larger than the rest of the analyzed years.

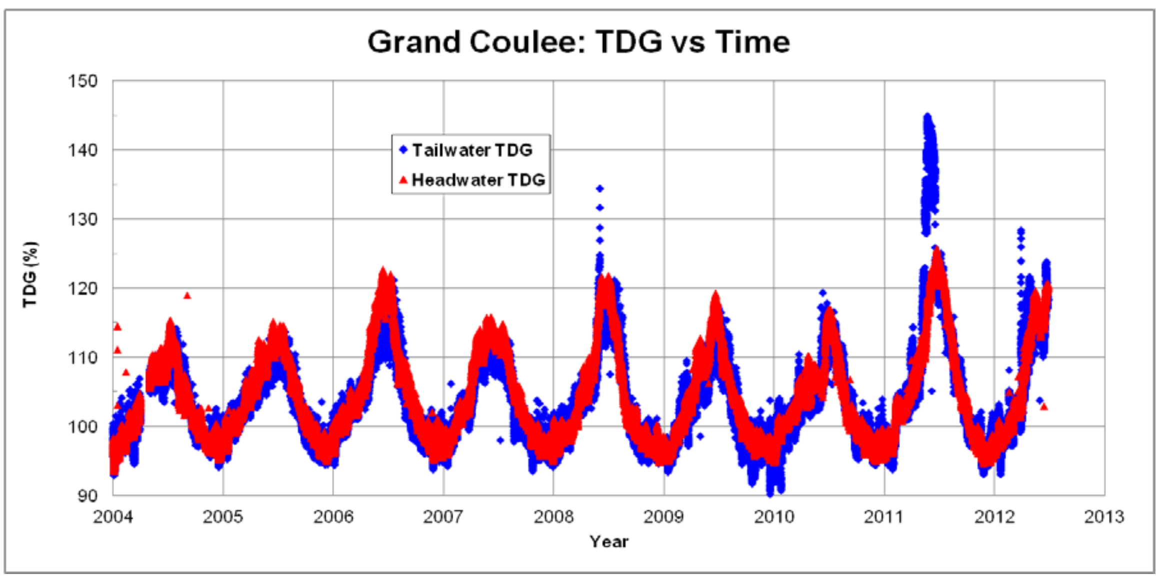


**Figure 10: Grand Coulee forebay (FDRW) and tailwater (GCGW) TDG from 2004 to 2012**

Figure 11 shows TDG measured in the forebay and tailrace of Grand Coulee Dam when the project was not spilling. TDG uptake without spill is expected to be zero since bubbles are not entrained into the tailrace and therefore gas exchange is limited to mass transfer at the free surface, which is a very inefficient process. However, some differences between measured TDG concentration in the forebay and tailwater are observed.

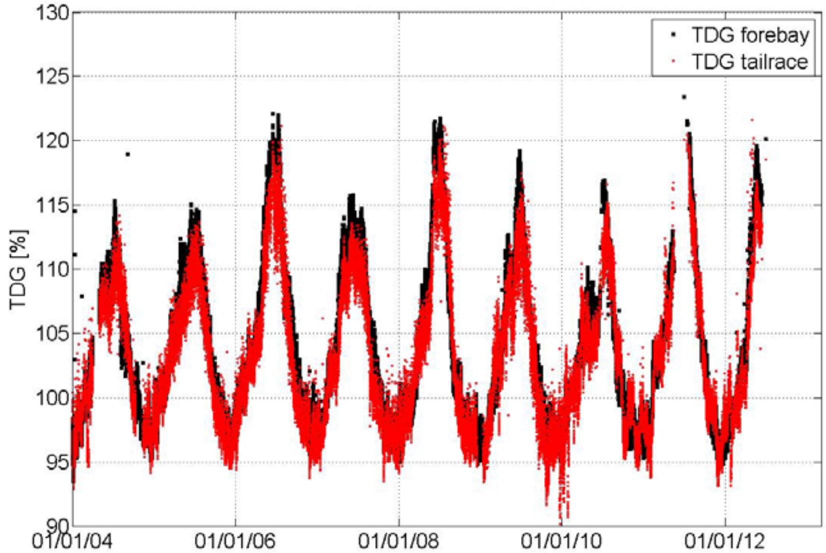


**Figure 11: TDG measured in the forebay and tailrace of Grand Coulee without spill**

Figure 12 contains a plot of spill-period tailwater TDG vs spill flow at Grand Coulee. A general positive correlation is noticeable, indicating a direct relationship between increased spill flow and higher tailwater TDG.

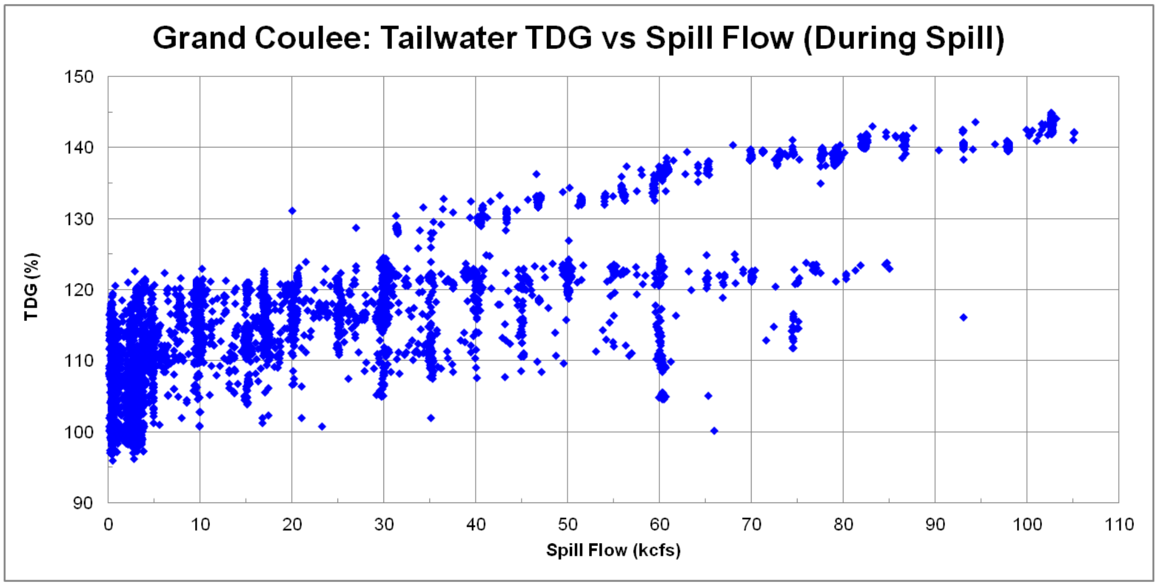


**FIGURE 12: GRAND COULEE TAILWATER VS SPILL FLOW DURING PERIODS OF SPILL**

## 4. MODEL APPLICATION

The capability of the model to represent TDG downstream of a dam was tested using the field data presented in Section 3 of this paper. Data collected at Grand Coulee and Rock Island dams were filtered to remove outliers. Scatter plots of all variables were created to visually detect outlying data. Observations that were extreme relative to others measured under similar conditions were removed. Only events with spill and TDG concentration in the tailrace larger than those measured in the forebay were considered.

### 4.1 ROCK ISLAND DAM

A nonlinear regression model was used to obtain the eight model parameters $(C_1, C_2, \alpha_0, \alpha_1 C_a, C_{el}, D_b, C_h)$ that minimize the error between predictions and field data collected at Rock Island in 2010. After calibration, the model was validated using data collected in 2008, 2009, 2011 and 2012.

Figures 13 to 17 show predicted and measured TDG in the tailrace. Symbols represent data collected in the tailrace and the red line represents model predictions. TDG predicted by the model follows the trend observed in the field.

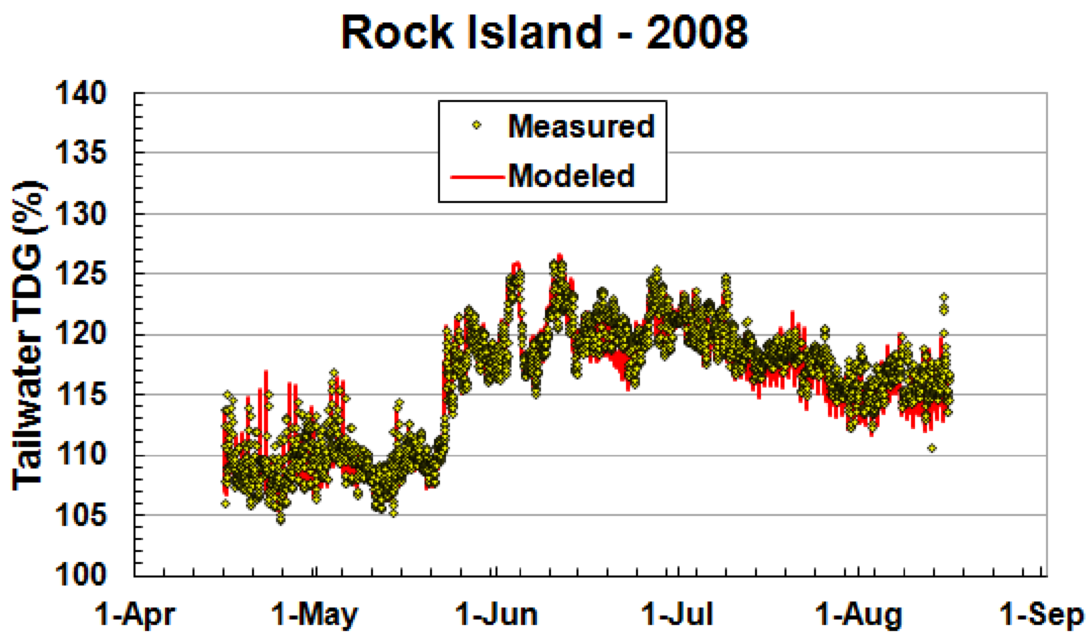


**Figure 13: Modeled and measured TDG concentration at Rock Island Dam in 2008**

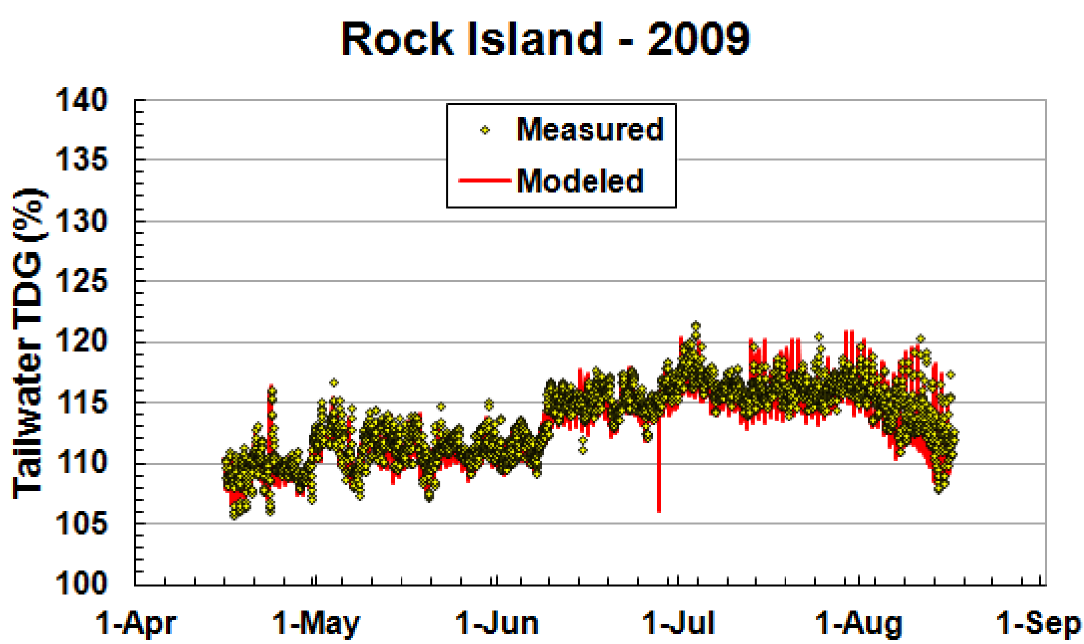


**Figure 14: Modeled and measured TDG concentration at Rock Island Dam in 2009**

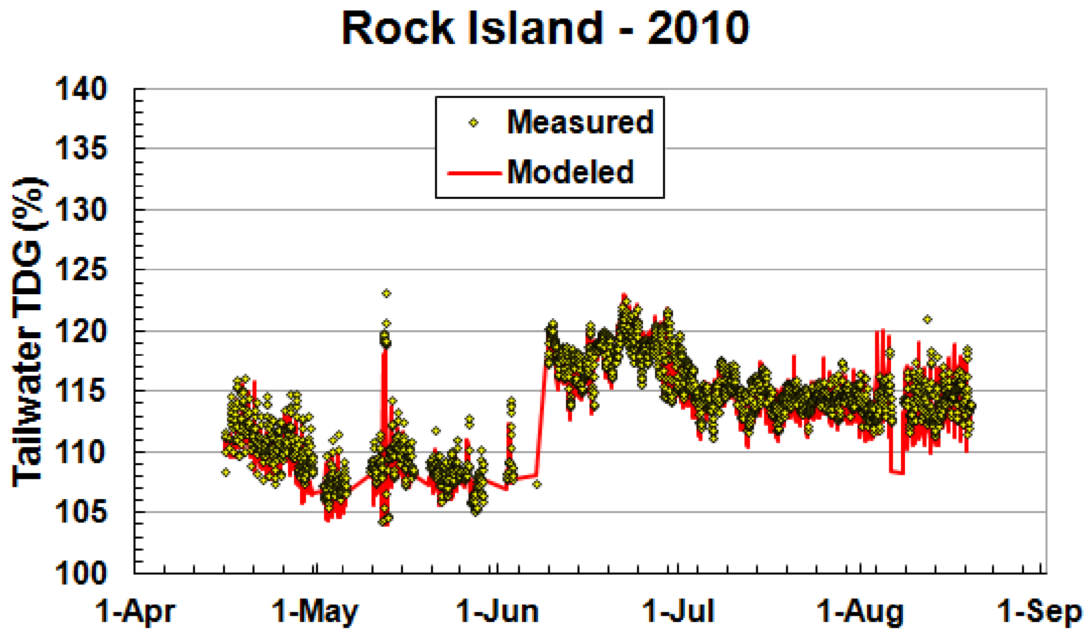


**Figure 15: Modeled and measured TDG concentration at Rock Island Dam in 2010**

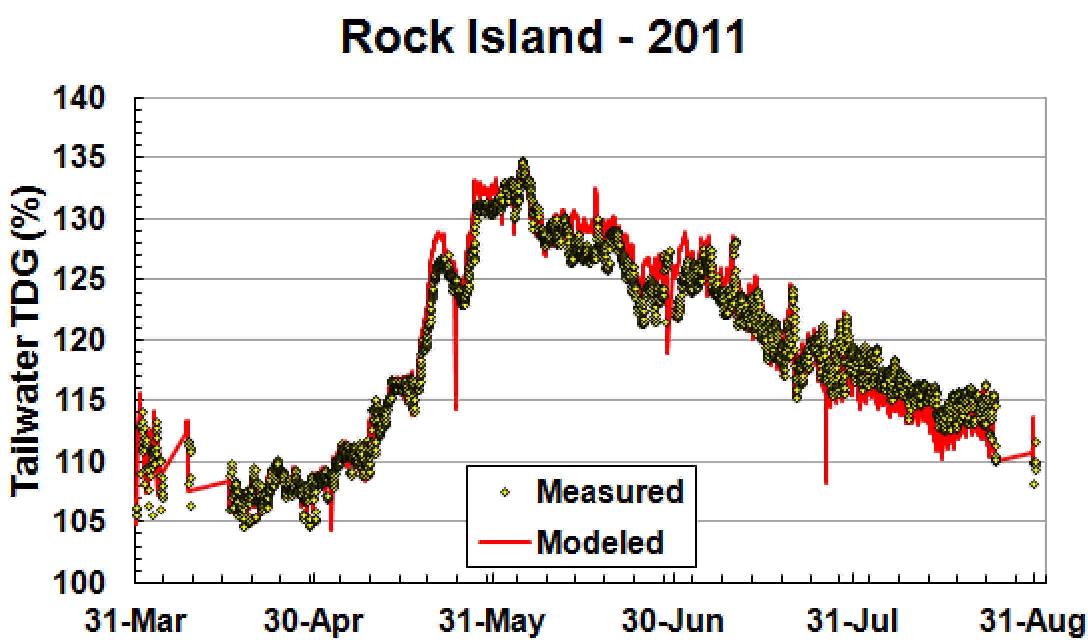


**Figure 16: Modeled and measured TDG concentration at Rock Island Dam in 2011**

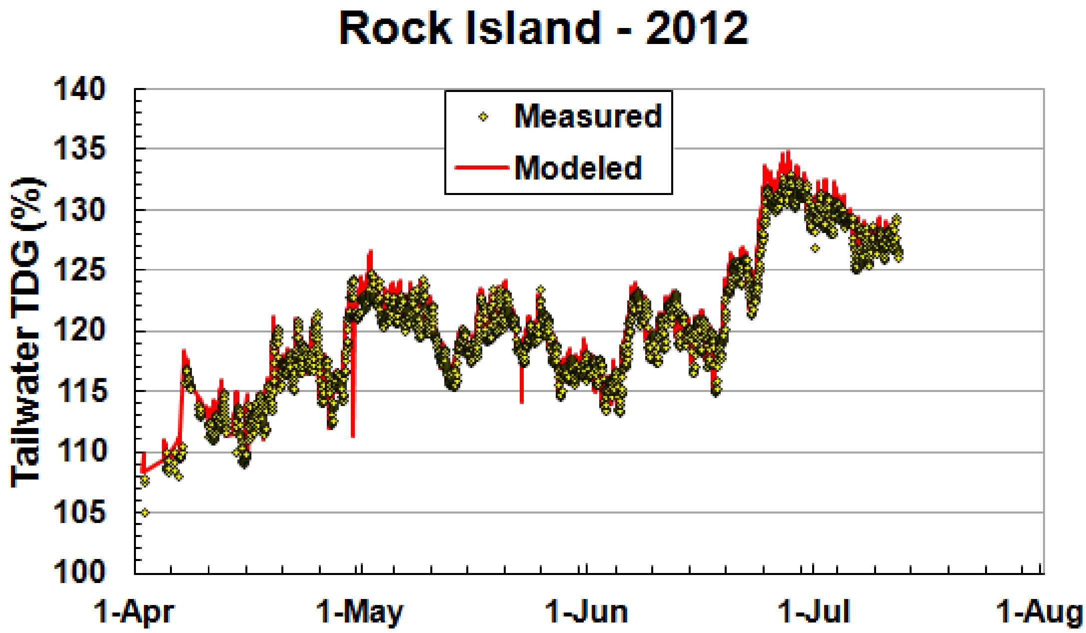


**Figure 17: Modeled and measured TDG concentration at Rock Island Dam in 2012**

The coefficient of determination $R^2$ was used to evaluate the capability of the model to reproduce the measured TDG:

$$R^2 = 1 - \frac{\sum(TDG_{measured} - TDG_{model})^2}{(TDG_{measured} - \overline{TDG}_{measured})^2}$$

The second term in the equation above represents the proportion of the variation that is unexplained by the model. The $R^2$ coefficient for all data from 2008 to 2012 was 0.9626 indicating a very good agreement between measurements and predictions. Figure 18 compares TDG predicted and measured, and Table 1 shows the $R^2$ coefficient for each year.

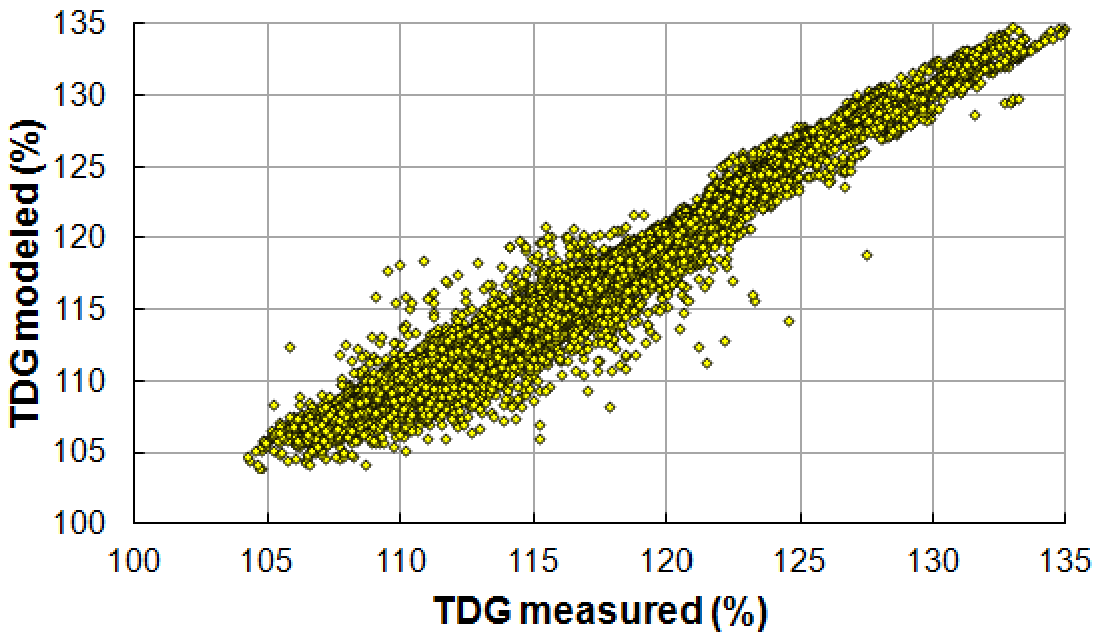


**Figure 18: Measured vs. predicted TDG in the tailrace**

**Table 1: Coefficient of determination for Rock Island Dam**

| **Year** | $R^2$ coefficient |
|---|---|
| 2008 | 0.9739 |
| 2009 | 0.8204 |
| 2010 | 0.9050 |
| 2011 | 0.9767 |
| 2012 | 0.9871 |

### 4.2 Grand Coulee Dam

Since the number and location of RO are unknown, operations with only drum gates were analyzed. Available data were filtered to consider events with spill through drum gates. Only events with TDG concentration in the tailrace larger than those in the forebay were analyzed and used to compare against model results.

Model parameters determined for Rock Island Dam were demonstrated to over-predict TDG in Grand Coulee Dam. In order to develop the most generalized model possible, only the two most important parameters, $C_a$ and $C_h$, were recalibrated for the Grand Coulee results. These parameters are related to the maximum depth bubbles can travel in the tailrace and the vertical distribution of the gas volume fraction. The model was then validated comparing model predictions against TDG and net TDG uptake collected in 2008, 2011 and 2012. Only a few days were observed with spill and positive TDG uptake during years prior to 2008 and in 2009 and therefore these years were not useful for model comparison.

Figures 19 to 22 show predicted and measured TDG in the tailrace. Symbols represent data collected in the tailrace and the red line represents model predictions. The model was able to follow the TDG reduction observed along the season during 2008, 2010 and 2011.

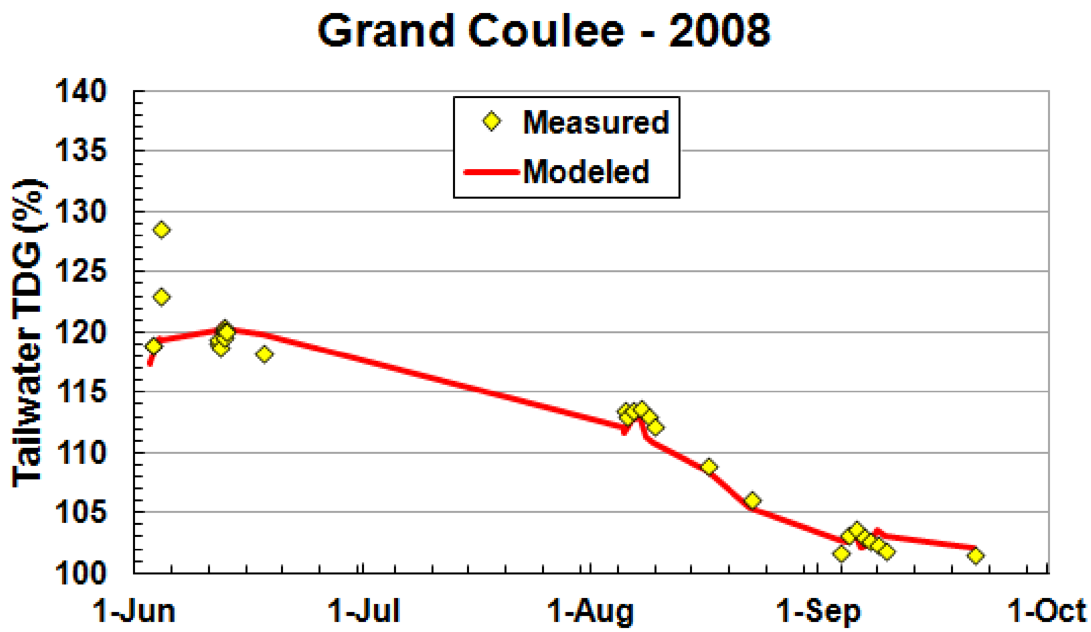


**Figure 19: Modeled and measured TDG concentration at Ground Coulee Dam in 2008**

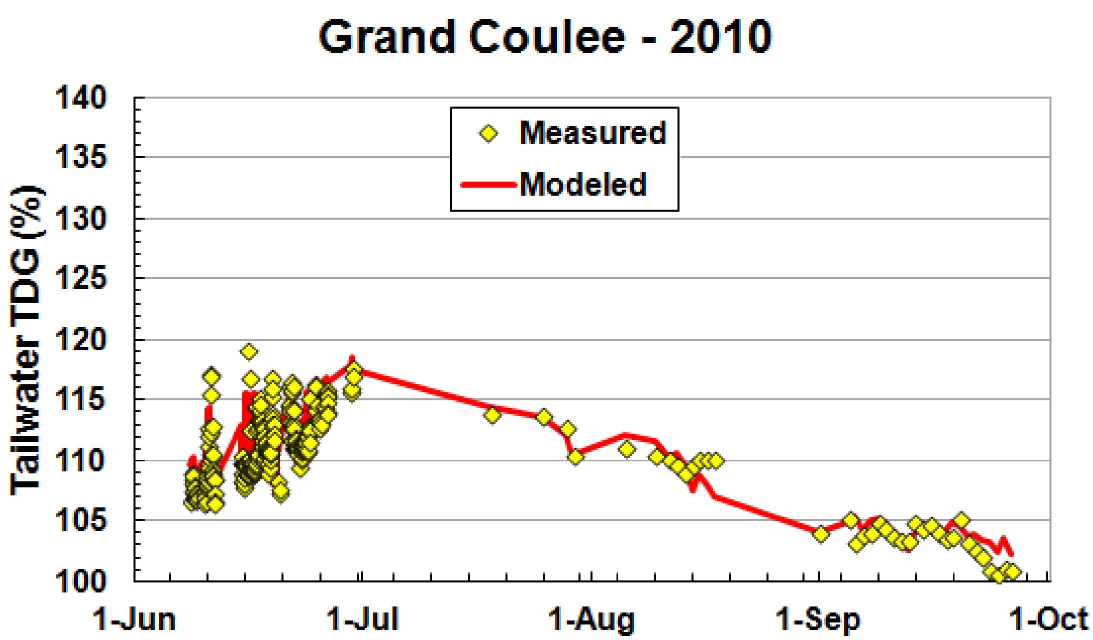


**Figure 20: Modeled and measured TDG concentration at Ground Coulee Dam in 2010**

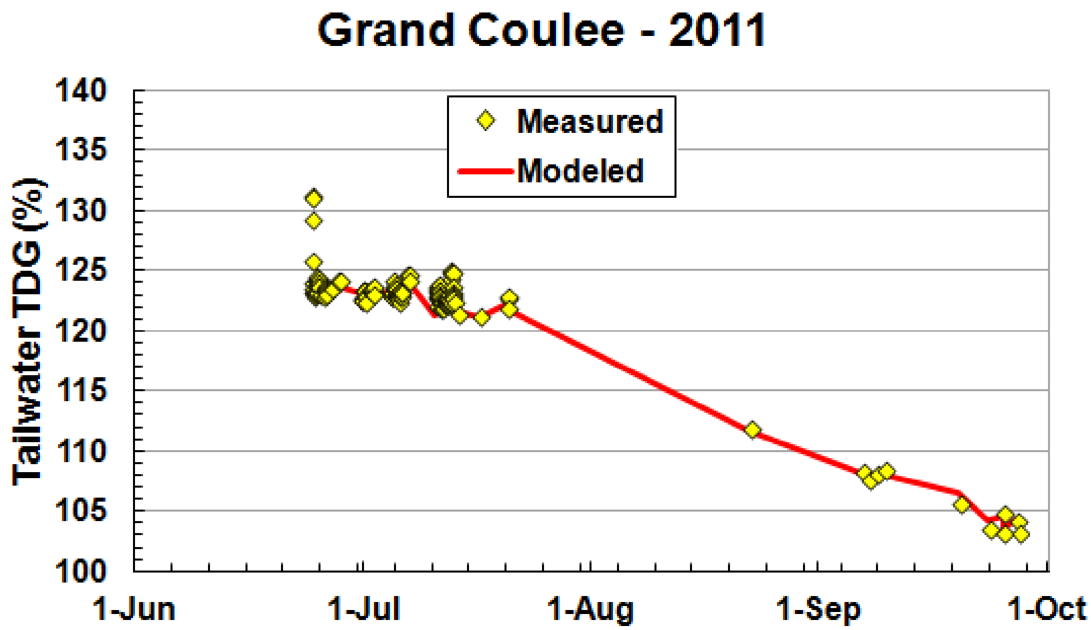


**Figure 21: Modeled and measured TDG concentration at Ground Coulee Dam in 2011**

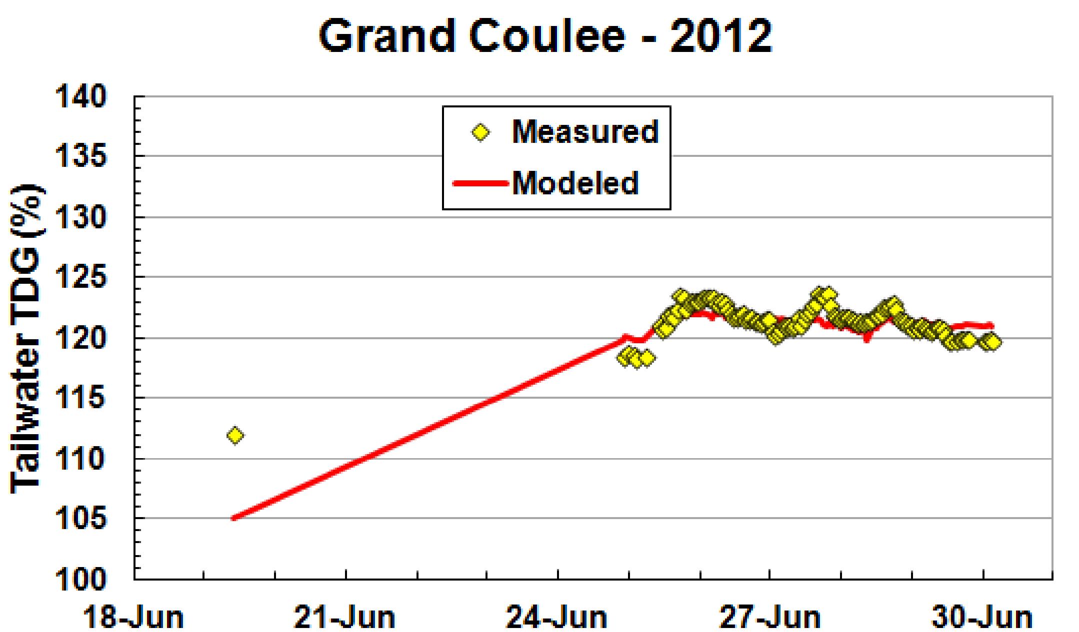


**Figure 22: Modeled and measured TDG concentration at Ground Coulee Dam in 2012**

Fit of the proposed model is shown in Figure 23. The $R^2$ coefficient for 2008 to 2012 was 0.9197 indicating a good agreement between field data and model predictions. Table 2 shows the $R^2$ coefficient for each year used for calibration and validation. The coefficient of determination of the model for 2012 is significantly lower than in the other years. With the selected model parameters, the model over-predicts the measured TDG most of the time in 2012. Data in this year are only available during the Summer for conditions with elevated powerhouse and spillway flows. These results, together with those obtained for Rock Island Dam, seem to indicate that the model should be improved for extreme powerhouse or spillway operations.

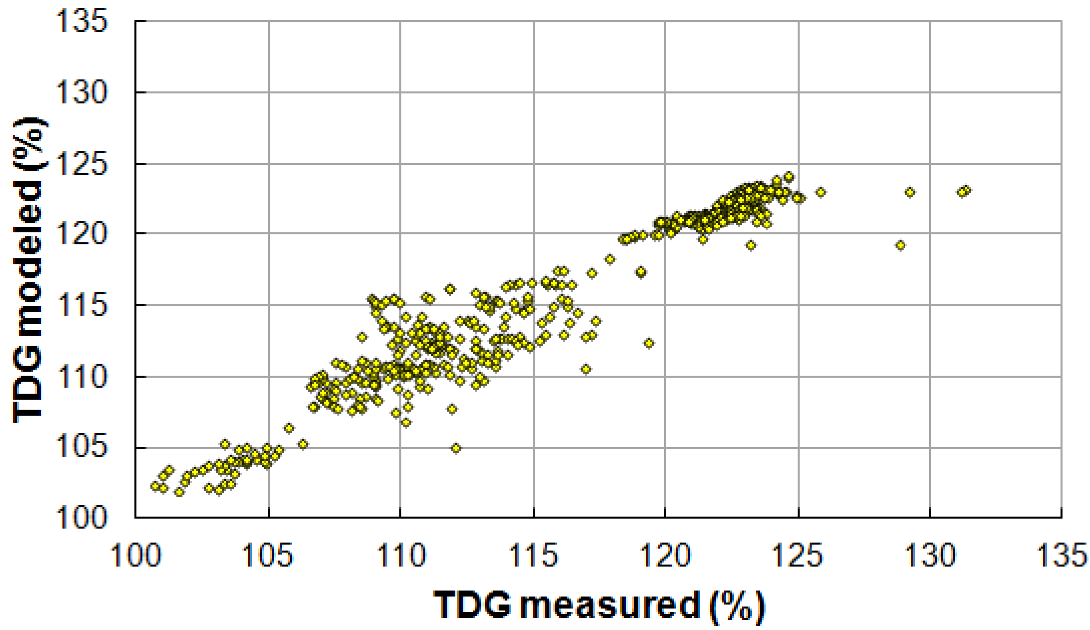


**Figure 23: Measured vs. predicted TDG in the tailrace**

**Table 2: Coefficient of determination for Grand Coulee Dam**

| **Year** | $R^2$ coefficient |
|---|---|
| 2008 | 0.9219 |
| 2010 | 0.8423 |
| 2011 | 0.9323 |
| 2012 | 0.5997 |

## 5. Conclusions and Future Directions

A one-dimensional model to predict TDG downstream of dams was developed based on mass, momentum and energy conservation principles. The independent variables of the equations are tailwater depth, powerhouse and spillway flowrates, unit spill, project head and environmental variables such as atmospheric pressure and temperature. The model comprises eight physically meaningful experimental parameters. The main advantage of this approach is that model parameters are related to processes such as air entrainment, water entrainment, and dissolution that are potentially observable. Sensitivity analysis demonstrated that the most important parameters based on the variance of TDG are related to the maximum bubble depth and how the gas is vertically distributed above this depth. The developed model was implemented in a Matlab framework to facilitate future introduction of additional processes or more comprehensive models.

The aim of this study was to demonstrate that a simplified mathematical formulation can capture the main TDG trends observed downstream of a hydropower dam. Several assumptions and simplifications were adopted to obtain a simple mathematical representation of the complex phenomena of TDG production and mixing with hydropower flows in a tailrace. Air entrainment is assumed to vary linearly with unit spill, water entrainment is assumed to vary linearly with total spill, bubble trajectory in the tailrace and dissolution are calculated assuming one-sized bubbles and neglecting vertical recirculations, dissolution is calculated assuming bubbles rise in a quiescent liquid, and turbulent dispersion and mass transfer at the free surface are neglected.

The capability of the model to predict TDG was evaluated by comparing model results against TDG data collected at Rock Island and Grand Coulee dams. Multi-parameter regression analysis was used to determine model parameters for Rock Island Dam. Data collected in 2010 were used for calibration, while data measured in 2008, 2009, 2011 and 2012 were used for validation. In order to obtain the most generalized model possible, only maximum bubble depth and gas distribution coefficients were re-calibrated for Grand Coulee Dam using field data collected in 2010. The model was then validated with TDG data from 2008, 2011, and 2012. The model reproduced the general trend of TDG and net TDG uptake measured in the tailraces and captured the observed TDG variation with spillway and powerhouse flowrates, taking into account TDG generated at the dam, TDG generated at upstream dams, and mixing of spillway and powerhouse flows. The largest differences between predictions and measurements occurred for extreme spillway or powerhouse flowrates, likely due to over-simplification of the water entrainment model. Understanding the mechanisms of water entrainment and relations with project operations is fundamental for proper modeling of this phenomenon. Numerical modeling of the hydrodynamics in the tailrace or velocity field data can guide the development of a more comprehensive water entrainment model.

In order to improve and further generalize the current model for application to other dams, it is necessary to include all important processes and geometric characteristics that affect air and water entrainment. Future model development should focus on:

1) Inclusion of mass transfer at the free surface to predict TDG routing from a dam tailrace to a downstream forebay.
2) Understanding the effect of the spillway deflectors on the maximum penetration depth of the bubbles and vertical gas distribution. TDG field data along with a deflector performance curve can be used to understand the effect of spillway jet regimes on these parameters.
3) Development of advanced mathematical models to represent air entrainment as a function of turbulence. This is expected to significantly improve model generalization.
4) Development of a simple turbulence model. This model is needed for air entrainment modeling and also to improve prediction of bubble/liquid mass transfer.

5) Improvement of water entrainment models based on numerical or velocity field data.

The proposed future work will focus first on:

1. Model development for the five remaining projects on the Mid-Columbia River
2. Implementation of the predictive developed TDG equations into a real-time scheduling tool developed by CADSWES, Colorado State University.
3. Verification, simulation and optimization of the real-time scheduling tool.
4. Added value analysis of the optimization real-time scheduling tool.
5. Final report with publications and communications.

## NOTATION

| | |
|---|---|
| $a_2 = \frac{H_b \rho\, g}{2\, C_h\, p_{\text{atm}}}$ | model constant [] |
| $a_3 = \frac{\alpha_0\, h\, L}{U_0}$ | model constant [] |
| $a_4 = 1 + a_2 + a_2/a_3$ | model constant [] |
| $C$ | air concentration in the liquid phase [kg/m$^3$] |
| $C^*$ | dimensionless air concentration in the liquid phase [] |
| $C_{atm}$ | air concentration in the liquid phase at atmospheric pressure [kg/m$^3$] |
| $C_0^*$ | dimensionless air concentration in the liquid phase in the forebay [] |
| $C_1$ | water entrainment coefficient [] |
| $C_2$ | water entrainment coefficient [] |
| $C_a$ | air entrainment coefficient [] |
| $C_D$ | drag coefficient of bubbles [] |
| $C_{el}$ | energy loss coefficient [] |
| $C_h$ | gas volume fraction distribution constant [] |
| $C_{we}$ | water entrainment coefficient [] |
| $C_n$ | contraction factor [] |
| $D_b$ | bubble diameter [m] |
| $E_b^n$ | energy of the spillway bay *n* used to entrain air per volume unit [J/m$^3$] |
| $Eo = \frac{g(\rho_l - \rho_g) D_b^2}{\sigma}$ | Eötvös number [] |
| $E_s^n$ | energy of the spillway bay *n* per volume unit [J/m$^3$] |
| $g$ | gravity [m/s$^2$ ] |
| $h = \frac{6\, k_l}{D_b}$ | model constant [1/s] |
| $H_n$ | gate opening [m] |
| $H_b$ | maximum bubble depth [m] |
| $He$ | Henry’s constant [s$^2$/m$^2$] |
| $L$ | control volume length [m] |
| $k_l$ | mass transfer coefficient [m/s] |
| $N$ | bubble number density [1/ m$^3$ ] |
| $p$ | pressure [Pa] |

| | |
|---|---|
| $p_{\text{atm}}$ | atmospheric pressure [Pa] |
| $Pe = \frac{V_b\, D_b}{\gamma}$ | bubble Peclet number [] |
| $p_i$ | partial pressure of gas [Pa] |
| $q$ | unit spill [m$^3$/ (s m)] |
| $Q_p$ | powerhouse flowrate [m$^3$/s] |
| $Q_{pe}$ | powerhouse flowrate entrained into the spillway region [m$^3$/s] |
| $Q_s$ | spillway flowrate [m$^3$/s] |
| $Re_b = \frac{D_b V_b}{\nu}$ | bubble Reynolds number [] |
| $S$ | TDG source due to bubble dissolution [kg/ (m$^3$ s) ] |
| $t_b$ | bubble residence time [s] |
| $T$ | temperature [$^o$C] |
| TDG | total dissolved gas concentration [] |
| $U$ | velocity in the streamwise direction [m/s] |
| $U_s^n$ | velocity in the spillway bay n before plunging [m/s] |
| $U_T$ | streamwise velocity in the tailrace before after plunging [m/s] |
| $V_b$ | bubble terminal velocity [m/s] |
| $z_b$ | bubble depth [m] |

**Greek Letters**

| | |
|---|---|
| $\alpha$ | gas volume fraction [] |
| $\alpha_{max}$ | model parameter for air entrainment [] |
| $\alpha_1$ | model parameter for air entrainment [] |
| $\Delta H$ | difference between forebay and tailwater elevations [m] |
| $\gamma$ | molecular diffusivity gas/liquid [m$^2$/s] |
| $\nu$ | kinematic viscosity [kg/m s] |
| $\rho$ | density [kg/m$^3$] |

**Subscripts**

| | |
|---|---|
| *0* | entrainment region |
| *b* | bubbles |
| *g* | gas |
| *i* | control volume inlet |

| | |
|---|---|
| $p$ | powerhouse |
| $n$ | spillway bay |
| $s$ | spillway |

**Superscripts**

| | |
|---|---|
| $n$ | spillway bay |

## References


Bouck G.R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 11, 505-516.

Ebel W.J. 1969. Supersaturation of nitrogen in the Columbia River and its effect on salmon and steelhead trout. United States National Marine Fisheries Service Fishery Bulletin 68:1-11.

Frantz W. 2012. 2012 Gas Abatement Annual Report. Rocky Reach and Rock Island Hydroelectric Projects FERC No. 2145 and 943.

Frizell K. and Cohen E. 2000. Structural Alternatives for TDG Abatement at Grand Coulee Dam. Feasibility Design Report, US Bureau of Reclamation, Pacific Northwest Region.

Pasha M.F.K., Hadjerioua B., Stewart K., Bender M.D. and Schneider M. 2012. Prediction of total dissolved gas (TDG) at hydropower dams throughout the Columbia River Basin (CRB) – Challenges and proposed Methodology. Hydrovision International, Louisville, KY.

Stroud, R.K., Bouck, G.R., and Nebeker, A.V. 1975. Pathology of acute and chronic exposure of salmonid fishes to supersaturated water. Pages 435-449 in W.A. Adams, editor. Chemistry and physics of aqueous gas solutions. The Electro-chemical Society, Princeton, New Jersey, USA.

Turan C., Politano M., Carrica P.M. and Weber L. 2007. Water entrainment and mixing due to surface jets. Int. J. Computational Fluid Dynamics 21(3–4), 137–153.

USEPA (United States Environmental Protection Agency). 1971. Nitrogen supersaturation in the Columbia and Snake rivers. Summary Report. Region 10, Seattle, Washington, USA.

Weitkamp D.E. and Katz M. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society 109, 659-702.

Weitkamp D.E. 2008a. Total dissolved gas supersaturation literature 1980-2007. www.ecy.wa.gov/programs/wq/tmdl/.../TDGeffectsLitRev080615.pdf.

Weitkamp D.E. 2008b. Total dissolved gas supersaturation biological effects, review of literature 1980-2007. www.ecy.wa.gov/programs/wq/tmdl/.../WeitkampTDGlitRev.pdf .

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