PREDICTION OF TOTAL DISSOLVED GAS EXCHANGE AT HYDROPOWER DAMS: MID-COLUMBIA RIVER SYSTEM

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Environmental Sciences Division

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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 levels 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.

The developed TDG predictive models for the network of dams throughout the CRB are being integrated by the University of Colorado’s Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) into RiverWare (Zagona et. al, (2001, 2005)), a recently developed real-time scheduling tool. 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.
Model calibration and validation are performed for projects of interests along the Columbia River. The results are examined for anomalies and appropriateness. The prediction methodology and derived equations will be adjusted as necessary to satisfy requirements for use as a predictive model in the context of reservoir system analysis and scheduling.

2. CURRENT PRACTICES AND KNOWLEDGE

2.1 TDG Effects on Fish

The effects that elevated levels of TDG have on fish and invertebrates are well documented in a host of scientific reports and academic papers. Many studies reveal strong cases of gas bubble disease (GBD) in fish at TDG levels of 120% (Dawley, 1986; Cochnauer, 2000; Backman and Evans, 2002; Marotz et al., 2007; Ryan et al., 2000). Johnson et al. (2005) found that fishes that remain deeper than two (2) meters are unlikely to encounter exposures to TDG levels 120% or above and thus have less chance of developing GBD. However, at extremely high TDG levels, fish can die without even showing visible GBD signs. When compensating water depth is available, TDG levels up to 120% for short-term periods do not produce significant effects on juvenile or adult salmonids (McGrath et al., 2006). Other researchers investigated GBD issues at TDG levels of up to 130%. In a laboratory test, Mesa et al. (2000) found strong correlation between GBD signs and mortality in Chinook salmon and steelhead when the TDG level is about 130%. At or above 130%, numerous signs of GBD were observed in resident fish just downstream of Ice Harbor Dam (Schrank et al., 1997). An entire wealth of information on the effects of TDG on fish can be found in papers by Weitkamp and Katz (1980) and Weitkamp (2008). The first cited paper covers the literatures until 1979 and the later cited paper reviewed the literatures from 1980 to 2007.

The gas mixture also has a significant impact on the effect that elevated levels of TDG have on fish. Dissolved oxygen is the key component in fish production, while excess dissolved nitrogen can cause mortality. Speece (1981) reviewed the conventional aeration techniques used to enhance dissolved oxygen and strip dissolved nitrogen. He concluded that the use of commercial oxygen in hatchery water quality management could result in net savings for trout production. Speece (1983) also mentioned that symptoms and mortality related to gas bubble disease increase as oxygen/nitrogen ratio decreases. He suggests that turbine venting can be used as a means of supplemental oxygenation of hydropower discharge; but, due to the scarcity of correlation data, it is difficult to determine the effects of turbine discharge. Therefore, he recommends caution when attributing levels of dissolved nitrogen and TDG to this process. Colt et al. (1991) suggested considering the effects of oxygen supplementation on other quality variables such as gas pressure and carbon dioxide since less information is available on the maximum allowable dissolved oxygen level. If un-ionized ammonia and carbon dioxide concentrations approach their maximum limits, they recommended increasing the minimum dissolved oxygen criteria by 3 to 4 mg/L. However, it is suggested to avoid the rapid changes in oxygen pressure.
2.2 TDG Predictive Methods

There are several quantitative assessments/methodologies for predicting TDG based on physical (mechanistic) and empirical methodologies. The various physically based models are based on a wide array of parameters ranging from small-scale bubble mass transfer quantities involving bubble diameters, gas void ratios, kinetic energies and viscosities, diffusion coefficients, surface tension to larger-scale parameters like stilling basin depths, spillway widths, water depths, spillway and total flows, and hydraulic head. Some models are based on mass transfer of air bubbles into the water and through direct air-water surface gas transfer. Urban et al. (2008) presented a model to predict TDG saturation just downstream of a spillway based on physical processes of mass transfer. The effects of bubble size distribution (Politano et al., 2007, 2005, 2003) and bubble volume and normal velocity fluctuation attenuation (Turan et al., 2007) have been studied to better understand and model air entrainment. Physically-based models have incorporated geometrical aspects of the dams such as stilling basin and river depths (Geldert et al., 1998), spillway configurations and flow parameters (Hibbs and Gulliver, 1997), upstream TDG concentration (Roesner and Norton, 1971), and flood discharge characteristics, such as water depths and pressures (Ran et al., 2009), to predict gas transfer and downstream TDG levels. Columbia Basin Research (2000) uses two physically based equations in their USACE CRiSP Model 1.6, which are based on the physical processes of producing spill and dissolving excess TDG. This procedure is based on the model developed by Roesner and Norton (1971) and includes geometric information about the spill bay and gas entrainment physics. Computational fluid dynamics (CFD) models have been used to model the TDG exchange, mixing, and transport to predict TDG levels (Xiao-li et al., 2010 and Weber et al., 2004). In general, most of the methodologies used in the physically based TDG prediction models require calibration of some equation coefficients which are specific for each case.

Whereas physically based methodologies rely on the mass transfer occurring in two-phase flow regimes, as defined by conservation equations of momentum and mass, empirical approaches are based upon analyzing the behaviors and correlative trends of the physical parameters using various data-mining and curve-fitting techniques to predict TDG. Columbia Basin Research (2000) uses four empirical equations in their CRiSP Model 1.6. The four empirical equations are in the forms of linear, exponential and hyperbolic developed by the USACE Waterways Experiment Station (WES) as a part of the Dissolved Gas Abatement Study (USACE, 1997). Parkinson and Minns (online) presented a tool to develop relationships between TDG saturation level and measurable data. Artificial neural network (ANN) and genetic programming (GP) approaches are used to predict the TDG. Observed TDG data from a specific dam site (Little Goose Dam in the U.S.) has been used to train the ANN and subsequently used to predict TDG. ANN performs better than the USACE CRiSP model. The ANN resulted in lower root-mean-square (RMS) errors and resolved TDG levels associated with lower spill flow when compared with standard multivariate regression models. Expressions are derived for TDG levels based on parameters like spill and upstream temperature and actual TDG levels, but are specific for each case and not very portable or applicable to other dams. Abdul-Aziz et al. (2007a and 2007b) proposed an empirical model based on an extended stochastic harmonic analysis algorithm to predict the dissolved oxygen, which is one of the main constituents of TDG. Fourier transform analysis was used to determine certain model coefficients.
2.3 Controlling and Monitoring TDG

One of the most responsive parameters in controlling TDG is flow over spillways and energy dissipation structures (Lu et al., 2011). The turbulent nature of spillway operations acts to entrain air into the spilled water thereby increasing tailwater TDG levels. Spillway operations play a crucial role in controlling the amount of TDG in a tailrace and are often highly correlated with project operations (Schneider and Barko 2006). Sullivan et al. (online) performed an operational study to control TDG at Noxon Rapids and Cabinet Gorge Dams on the Lower Clark Fork dams. Their study suggested that spill gate configuration can substantially reduce the downstream TDG supersaturation. They also investigated spillway operation procedures and found that the spill patterns concentrating flow through the central portion of the spillway can reduce the TDG level up to 12%. A study on Rocky Reach Dam conducted by Schneider and Wilhelms (2005) assessed potential operational and structural alternatives to manage TDG supersaturation. Nine operational and structural alternatives were tested and it was found that TDG pressures generated in a spill are related to spill magnitude and distribution where a uniform spill pattern using the entire spillway produced lower levels of TDG pressure. Gulliver et al. (2009) presented a simplified physically based operational model to control TDG just downstream of the Cabinet Gorge Spillway. For example, it was shown that using tunnels to bypass flow downstream, in lieu of spillway bays, can reduce TDG saturation downstream to some degree. Lu et al. (2011) did a field study at Zipingpu, Three Gorges, Ertan, Manwan, Dachaoshan, and Gongzui Dams in China to observe the factors that affect TDG exchange and dissipation. They found that energy dissipation structures, spillway flow, and operational patterns are the main factors governing TDG exchange. They also observed that TDG supersaturation is not uniformly distributed in vertical and transverse directions.

Most of the analyses and research work on TDG exchange and its effect are associated with hydroelectric dams located throughout the Pacific Northwest of the United States. TDG monitoring stations are located in the forebay and tailrace of each dam on the lower Columbia River in Oregon and Washington (Tanner et al., 2011) and monitor water temperatures and TDG pressure on an hourly frequency during the fish passage season (USACE, 2010). The large range in seasonal flows in the Columbia River basin results in frequent spillway operations on a series of dams throughout the basin. The location of eleven dams on the Columbia River and four dams on the Lower Snake River result in cumulative impacts of TDG loading during forced spillway operations. The use of spillway flows for fish guidance past dam powerhouses extends the duration of spillway operations throughout this region from April through August. Spill-water is a major contributor to increased levels of TDG in the river. The headwaters of these rivers also contribute significantly since they already contain high TDG levels from upstream dams located in Canada. The water depth downstream of the dams on these rivers is typically shallow and compensation depths are not achieved; thereby increasing the potential for higher TDG levels. This study focuses on the TDG prediction downstream of the dams located in the Pacific Northwest mainly because the TDG issues are predominately higher in this region, the data are readily available, and effective scheduling of hydropower operations requires daily management of TDG levels.
3. 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 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 incorporate water quality impacts, such as TDG, with water regulation decisions for a reservoir system.

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, endsills 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.

![Schematic Diagram Illustrating a Generalized Empirical Approach to Predict TDG](image)

**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.
1. **Parameter Listing**
   List all the parameters used in different models including empirical and physical process based models that are collected from the literature.

2. **Important Parameters from Literatures**
   Find the relationships between TDG saturation level and the parameters and establish parameterization hierarchy.

3. **Data Collection**
   Collect TDG, dam characteristics, and other related data from different dam sites.

4. **Observe Relationships**
   Observe the relationships between TDG and different important parameters from the collected data and verify with the relationships found in the literature.

5. **Develop a Prediction Model**
   Summarize the important parameters and their relationships and develop prediction models for classes (Figure 1) that can predict TDG reasonably well.

6. **Model Validation**
   Validate the prediction models with observed TDG data across the Northwest U.S. region.

   - **Meet model assessment criteria?**
     - **YES**
     - **NO**

   Select final prediction model

7. **Develop an Operational Model**
   Develop a hydropower operational model using the TDG prediction model to minimize TDG levels and maximize power generation.

---

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

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 USACE, US Bureau of Reclamation (USBR), 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.

3.2 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 via the Snake River. Detailed descriptions of the projects, spillway configurations, and selected plots of collected data are provided in Appendices A through H.
3.3 Data Collection Procedure

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.

For the three projects included in the HWQR database, TDG and water temperature data from both Dataquery and HWQR were consolidated, with preference given to Dataquery when data were available from both sources. Hourly data were available from 2004 to 2012 to ensure an adequate supply of data for model development and calibration. The following table identifies hourly records collected from the Dataquery and HWQR databases:
Table 1: Hourly data collected from USACE databases for eight Columbia River Basin projects.

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Grand Coulee</th>
<th>Chief Joseph</th>
<th>Wells</th>
<th>Rocky Reach</th>
<th>Rock Island</th>
<th>Wanapum</th>
<th>Priest Rapids</th>
<th>Dworshak</th>
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<tr>
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<td></td>
<td></td>
<td></td>
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</tr>
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<td>-</td>
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</tr>
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<td>-</td>
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<td>Type 2</td>
<td>Type 2</td>
<td>Type 1</td>
</tr>
</tbody>
</table>

*For Type 1 sources, TDG and water temp data came from the Dataquery system; elevation and flow came from the Historical Water Quality Database. For Type 2, all data was obtained from the Dataquery system.

Hourly records including energy and miscellaneous flow were not available for some projects in the databases; however, these hourly records were not essential to proceed with model development. In contrast, Dataquery contained corrupt tailwater TDG data for Rocky Reach and Rock Island, which are essential to modeling TDG formation at dams. Chelean County PUD, owner and operator of the Rocky Reach and Rock Island projects, was contacted and agreed to provide the missing hourly TDG data for the dams. Headwater TDG data at Dworshak Dam is unavailable due to the lack of a forebay water quality monitoring station.

Excel spreadsheets were created for each of the hydroelectric projects, with hourly records from the USACE databases included. Initial data screening included processing missing information and removing outlying water temperature and TDG data. Water temperature values below 32°F and above 80°F were removed. Additionally, TDG values below 50 and above 300 were removed. Further screening was also completed when the presence of invalid data was clear. For example, during a period in October 2004, the USACE Dataquery system provided TDG saturation numbers for Grand Coulee forebay exceeding 10,000%. Plots of the data and preliminary, single-variable regression analysis were also provided in the spreadsheets, before being sent to IIHR.

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.

4. 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.

4.1 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 are entrained at a maximum depth $H_b$
- Bubbles are entrained with a monodisperse size distribution

4.2 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).
Total dissolved gas concentration (TDG) is defined as:

\[ \text{TDG} = \frac{C}{C_{\text{atm}}} \]

where \( C \) is the concentration of dissolved gas or solubility and \( C_{\text{atm}} \) 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 Figure 5.

6. TDG dilution by powerhouse flows occurs downstream of the aerated zone

![Figure 5: Transport of TDG downstream](image)

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.

### 4.3 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:

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

### 4.4 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:

\[
C_d = \frac{C^* (u = 1) \left( Q_s + Q_{pe} \right) + C_0 Q_p}{Q_s + Q_p}
\]
5. MODEL APPLICATION

Two empirical models were developed by IIHR to predict TDG downstream of dams – a comprehensive model and a simplified model. The comprehensive model (described in Section 4) is based on mass, momentum, and energy conservation principles. As a consequence, boundary conditions must be fully defined with respect to the number of spill bays open and the unit flow through the bays. Unit spill operation data were available for the Rock Island and Grand Coulee projects. The simplified model is based on the assumption that TDG downstream of a spillway can be represented by assuming saturation at local depth and a dissolution efficiency.

For the simplified model, hourly unit spill operations, such as number of open spill bays and flow through each bay, are not required to compute a TDG estimate. Because hourly unit spill operations were not available for many projects, the simplified model is applied in cases where the unit spill operations were unavailable. Projects where the simplified model was applied include, Chief Joseph, Wells, Wanapum, and Priest Rapids.

Comprehensive model results for Rock Island and Grand Coulee are presented in Section 5.1 while simplified model results for Chief Joseph, Wells, Wanapum, and Priest Rapids are presented in Section 5.2. Due to data limitations, models for Rocky Reach and Dworshak Dams are not yet developed. The proceeding simplified model results presented in this report are preliminary and represent the first tier of calibration and validation efforts that serve as a baseline for assessing the feasibility of the defined approach and parameter estimation and performance.

Subsequent calibration and validation work will focus on systematically identifying the best predictive performance of the model. This will entail investigating the utilization of seasonable-partitioned sets of historical data and representative periods of flow condition similarities for calibration used to increase the model’s predictive ability. Final results will be verified by IIHR.

5.1 Comprehensive Model

The capability of the comprehensive model to represent TDG downstream of a dam was tested using the field data presented graphically in the project appendices. 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. The comprehensive model approach is shown graphically in Figure 6.
Figure 6: Comprehensive TDG Model Approach
5.1.1 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 7 to 11 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 7: Modeled and measured TDG concentration at Rock Island Dam in 2008
Figure 8: Modeled and measured TDG concentration at Rock Island Dam in 2009

Figure 9: Modeled and measured TDG concentration at Rock Island Dam in 2010
Figure 10: Modeled and measured TDG concentration at Rock Island Dam in 2011

Figure 11: 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:

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

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 12 compares TDG predicted and measured, and Table 2 shows the $R^2$ coefficient for each year.

![Figure 12: Measured vs. predicted TDG in the tailrace](image)

**Table 2: Coefficient of determination for Rock Island Dam**

<table>
<thead>
<tr>
<th>Year</th>
<th>$R^2$ coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.9739</td>
</tr>
<tr>
<td>2009</td>
<td>0.8204</td>
</tr>
<tr>
<td>2010</td>
<td>0.9050</td>
</tr>
<tr>
<td>2011</td>
<td>0.9767</td>
</tr>
<tr>
<td>2012</td>
<td>0.9871</td>
</tr>
</tbody>
</table>
5.1.2 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 13 to 16 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.

![Grand Coulee - 2008](image)

Figure 13: Modeled and measured TDG concentration at Grand Coulee Dam in 2008
Figure 14: Modeled and measured TDG concentration at Ground Coulee Dam in 2010

Figure 15: Modeled and measured TDG concentration at Ground Coulee Dam in 2011
Fit of the proposed model is shown in Figure 17. The $R^2$ coefficient for 2008 to 2012 was 0.9197 indicating a good agreement between field data and model predictions. Table 3 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 17: Measured vs. predicted TDG in the tailrace

Table 3: Coefficient of determination for Grand Coulee Dam

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<th>Year</th>
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5.2 Simplified Model

The capability of the simplified model to represent TDG downstream of a dam was tested using the field data presented in the project appendices. Data collected at Chief Joseph, Wells, Wanapum, and Priest Rapids 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. Preliminary results for the simplified model follow and represent the first tier of calibration and validation efforts that serve as a baseline for assessing the feasibility of the defined approach and parameter estimation and performance. The simplified model approach is shown graphically in Figure 18.
The following sections include preliminary simplified model results for Chief Joseph, Wells, Wanapum, and Priest Rapids.

### 5.2.1 Chief Joseph

Spillway flow deflectors were installed at Chief Joseph beginning in 2006 with construction finished in 2009. The spillway modifications changed the flow regime in Chief Joseph’s stilling basin during spill and reduced TDG uptake at the project by preventing bubbles from reaching entrainment depths. As a consequence, frequency and magnitude of spill at Chief Joseph has significantly increased after the installation of the flow deflectors. Two sets of simplified model coefficients are used to model pre-and-post 2009 spill at Chief Joseph due to this significant change in spillway geometry and the subsequent change in project management.
Figure 19: Modeled and measured TDG concentration at Chief Joseph Dam in 2008

Figure 20: Modeled and measured TDG concentration at Chief Joseph Dam in 2009
Figure 21: Modeled and measured TDG concentration at Chief Joseph Dam in 2010

Figure 22: Modeled and measured TDG concentration at Chief Joseph Dam in 2011
5.2.2 Wells

Figure 23: Modeled and measured TDG concentration at Chief Joseph Dam in 2012

Figure 24: Modeled and measured TDG concentration at Wells Dam in 2008
Figure 25: Modeled and measured TDG concentration at Wells Dam in 2009

Figure 26: Modeled and measured TDG concentration at Wells Dam in 2010
Figure 27: Modeled and measured TDG concentration at Wells Dam in 2011
5.2.3 Wanapum

Figure 28: Modeled and measured TDG concentration at Wanapum Dam in 2008

Figure 29: Modeled and measured TDG concentration at Wanapum Dam in 2009
5.2.4 Priest Rapids

Figure 30: Modeled and measured TDG concentration at Wanapum Dam in 2010

Figure 31: Modeled and measured TDG concentration at Priest Rapids Dam in 2008
Figure 32: Modeled and measured TDG concentration at Priest Rapids Dam in 2009

Figure 33: Modeled and measured TDG concentration at Priest Rapids Dam in 2010
These results indicate the preliminary assessment of the simplified model calibration and validation. In general, the agreement is acceptable with coefficients of determination near 0.9 for most datasets. However in some cases, the results indicate some level of discrepancy in predicting TDG under extreme powerhouse and spill conditions when observed spikes occur, leading to higher levels of. Future improvements may be made to account for such conditions.

The aforementioned results rely on calibration performed on a yearly basis. Calibration and validation based on yearly TDG levels potentially limits the credibility of the model to estimate TDG levels in certain scheduling scenarios since seasonal and interannual variation is not taken into account. In some cases, predictive abilities may require a more aggressive and temporally-specific identification of an historical calibration dataset.

Whereas, the performance indicator, $R^2$, identifies a “general” TDG agreement condition on a yearly basis – it may not account for its short term prediction performance necessary in a hydro scheduling scenario for which a specified “window” of immediately subsequent conditions may be most appropriate for calibration consideration. Subsequent calibration and validation work will focus on systematically identifying the best predictive performance of the model for this situation. This will entail investigating the utilization of seasonable-partitioned sets of historical data and representative periods of flow condition similarities for calibration used to increase the model’s predictive ability.

Preliminary efforts have centered on identifying performance results for various “lead-time” calibration datasets (i.e., prediction of the current year based on systematic varying quantities of preceding years). These efforts also entail identification of seasonal effects on a monthly basis as well. Results from preliminary analyses on a monthly basis suggest the possible influence of another unidentified variable on the TDG concentrations at each dam. Additional plans will attempt to address performance improvement associated with “parameter-based” inclusion of historically congruent datasets with similar conditions.

6. CONCLUSIONS

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.

Two empirical models were developed for estimating TDG production downstream of dams. A one-dimensional comprehensive model, based on mass, momentum, and energy conservation principles, was developed to better capture the dynamic processes involved in TDG formation. To date, this comprehensive model approach has been developed for Grand Coulee and Rock Island Dams. An alternative, simplified model was developed by assuming saturation and dissolution can be approximated
with less complexity. To date, this simplified model approach has been developed for Chief Joseph, Wells, Wanapum, and Priest Rapids Dams. Although data have been collected for Rocky Reach and Dworshak Dam, data limitations have prevented model development at those sites.

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 would likely improve the development of a more comprehensive water entrainment model in the future.

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.

7. FUTURE WORK

ORNL will work with two Universities, through sub-contracts, University of Boulder Colorado, through CADWES, and the University of Iowa, through IIHR. The work will consist of two complimentary research efforts for modeling TDG levels. The first is the development of an operational scheduling model (simulation and optimization) for the Mid-Columbia River (Mid-C) by CADWES. This modeling solution is unique because a system-wide approach will be developed for modeling TDG levels while optimizing the river operations. For the second research project, ORNL will fund the University of Iowa to work with ORNL to help with the development and implementation of new simplified and comprehensive TDG equations for the Mid-C projects.

It is proposed that the results of these two research efforts be combined by integrating the TDG equations developed by IIHR and ORNL into the RiverWare model (Zagona et. al, (2001, 2005)), developed in 2011 by CADSWES for the Mid-C.
Since its initial development, data infrastructure automation of the model, which runs twice an hour has been added. The RiverWare optimization model includes all operational constraints and objectives needed to schedule the Mid-C. To calculate TDG, the optimization uses linear approximations of the TDG equations based on the first two terms of the Taylor series with a preemptive goal program. Approximation error is reduced through an optimization process in which new approximations are generated. This optimization routine runs through up to 10 iterations. Since the TDG equations are nonlinear and non-convex, the procedure converges on a solution that is heuristic and not guaranteed to be a global optima. However, in practice, there has been no noticeable distinction.

Integration of the IIHR TDG equations into the RiverWare model will occur through the creation of two RiverWare Policy groups for the simplified and comprehensive TDG models. It is desired to include both TDG models because the simplified model is expected to provide faster convergence while the comprehensive model can provide a more accurate solution. Several changes to the RiverWare model, including modification of spill concentration equations and the associated partial derivatives will also be required. Since the new TDG equations also depend on the tailwater and forebay elevations, the modified model will also have to incorporate these parameters into the Taylor series expansions.

The current version of RiverWare exports the results to Microsoft Excel after each iteration and reimports the values to continue calculation. In order to improve efficiency and reduce computation time, it is desired to remove the Excel dependency and have RiverWare store the intermediate results internally. It is proposed that this modification be made in conjunction with the integration of the IIHR TDG equations. Currently, ORNL is working on a contract with CADSWES for integrating the TDG model results into RiverWare, and it is expected that operational scheduling implementation will occur in early 2015.

Since the equations developed by IIHR are general in nature, it is expected that the equations could be applied to other parts of the Columbia River Basin that plan to use the RiverWare model or in other river basins across the U.S. In the long run, it is also possible that the generalized methodology used for developing and integrating the TDG equations into RiverWare could be used to solve other water quality problems.
APPENDIX A: GRAND COULEE

Hourly data were available year-round for Grand Coulee from 2004 to 2012 in the USACE Dataquery System. Generated and used energy for the project were not available in the database. Several cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Grand Coulee hourly data are provided on the following pages. Raw data is publicly available through the Dataquery System.

Grand Coulee (Figure 34) is the largest hydro electric project with regard to size and capacity in the United States; its three powerhouses and pump generating plant have a combined capacity of 6.8 GW. The dam has a hydraulic head of 350 feet. For spill, eleven 28 by 135-ft drum gates are positioned in the center of the dam at an elevation of 1260 ft. The spillway was designed to accommodate a flow of 1,000,000 cfs. Grand Coulee is also equipped with sixty 8.5-ft-diameter regulating outlets for spilling at elevations below 1260 ft. The regulating outlets are positioned in three groups of 20 at elevations of 936, 1036, and 1136 ft. The lowest row of regulating outlets has been taken out of service leaving 40 operational units. Both the drum gates and regulating outlets spill onto a submerged roller bucket energy dissipater at the base of the dam. Spill using the regulating outlets is avoided when possible because the concentrated spill pattern produced by the outlets forces air to greater entrainment depths and increases tailwater TDG. The regulating outlets are usually used in the spring to lower the lake level in anticipation of higher summer flows.

Grand Coulee presents a TDG modeling challenge because of the complexity of the spill regime and the geometry of the hydraulic structures. The original two powerhouses are positioned on the left and right sides of the spillway; they are capable of discharging about 50,000 cfs each. Looking downriver, flow from the right powerhouse is aligned with the river channel. Flow from the left powerhouse is somewhat isolated from the main plunge pool and river channel, especially during spill events. The third powerhouse is positioned on the right side of the dam almost normal to the right spillway and powerhouse; it is capable of discharging about 180,000 cfs. Flow from the third powerhouse crosses the river channel and travels along the left bank. The third powerhouse flow has a significant influence on tailrace flow characteristics because of the large volume of water that can be discharged through the facility and the position of the facility relative to the other hydraulic features. Flow from the third powerhouse generally does not readily mix with the other flows until several miles downstream of the project.
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. Figure 35 shows a typical cross-section of the dam.
Figure 35: Grand Coulee Dam cross-sectional schematic

Figure 36 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 36: Grand Coulee forebay and tailwater TDG from 2004 to 2012

Figure 37 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 37: TDG measured in the forebay and tailrace of Grand Coulee without spill

Figure 38 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 38: Grand Coulee tailwater vs spill flow (during periods of spill)
Figure 39: Grand Coulee TW-HW TDG vs spill flow (during periods of spill)
Figure 40: Grand Coulee tailwater TDG vs plunge pool depth (during periods of spill)

Figure 41: Grand Coulee TW-HW TDG from 2008 to 2012
Figure 42: Grand Coulee spill flow from 2008 to 2012
APPENDIX B: CHIEF JOSEPH

Hourly data were available during the summer and parts of spring and fall for Chief Joseph from years 2004 to 2012 in the USACE Dataquery System. Several cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Chief Joseph hourly data are provided on the following pages. Raw data is publicly available through the Dataquery System.

Chief Joseph dam is located 51 miles downriver of Grand Coulee. It is a large run-of-river hydroelectric project with a capacity of 2.6 GW. Spill occurs via 19 bays equipped with 35 by 58-ft tainter gates; the spillway can accommodate flows up to 1,200,000 cfs. The powerhouse is positioned parallel to the left bank (looking downriver) almost perpendicular to the spillway. A non overflow dam on the downstream side of the powerhouse connects the facility to the left river bank. The powerhouse is capable of discharging 219,000 cfs.

Chief Joseph has little storage capacity, and Rufus Woods Lake extends to the Grand Coulee tailrace with little free-flowing river. As a result, little degasification occurs as water from Grand Coulee and Canadian hydro projects flows to Chief Joseph. TDG levels at Chief Joseph are already elevated in the forebay during spill events at Grand Coulee. The lack of degassing can be seen in the data by comparing the Chief Joseph headwater TDG to the Grand Coulee tailwater TDG in the TDG vs. Time plots.

Between 2005 and 2009, flow deflectors were added to the Chief Joseph spillway. The spillway deflectors adjust spill flows to skim over the plunge pool surface and prevent gas bubbles from reaching entrainment depths. The deflectors significantly reduced TDG generation at Chief Joseph. Because of the TDG improvements, Chef Joseph operates jointly with Grand Coulee by shifting generation to Grand Coulee and spill to Chief Joseph. The benefit of the Chief Joseph spill deflectors is demonstrated in the data by the plot of Chief Joseph TW-HW TDG vs Spill Flow (Figure 46). Unlike other projects considered in the study, there appears to be little to no positive correlation between high spill flows and elevated TDG generation. Figure x demonstrates that elevated spill flows can sometimes result in a net decrease in TDG at Chief Joseph if TDG levels in Rufus Woods Lake are already elevated from spill events at Grand Coulee. When TDG levels are elevated near maximum, degassing can occur at Chief Joseph resulting in a net decrease in TDG.
Figure 43: Chief Joseph Dam cross-sectional schematic

Figure 44: Chief Joseph forebay and tailwater TDG from 2004 to 2012
Figure 45: Chief Joseph tailwater vs spill flow (during periods of spill)

Figure 46: Chief Joseph TW-HW TDG vs spill flow (during periods of spill)
Figure 47: Chief Joseph tailwater TDG vs plunge pool depth (during periods of spill)

Figure 48: Chief Joseph TW-HW TDG vs Time from 2008 to 2012
Figure 49: Chief Joseph spill flow from 2008 to 2012
APPENDIX C: WELLS

Hourly data were available during the summer and parts of spring and fall for Wells from years 2004 to 2012 in the USACE Dataquery System. Elevation and flow data were collected from the Historical Water Quality Database. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Wells hourly data are provided on the following pages. Raw data is publicly available through the Dataquery and Historical Water Quality systems.

Wells dam is a run-of-river project located approximately 30 miles downriver of Chief Joseph. It is owned and operated by Douglas County PUD and has an installed capacity of 840 MW. The project is a unique hydrocombine design that integrates the spillway, powerhouse, fish passage facilities, and switchyard into a single structure. The design was partially chosen to aid fish passage; the main spillway is used to attract fish away from the turbines towards two fish ladders located on the left and right sides of the hydrocombine. The spillway consists of 12 bays installed with 50 by 58-ft tainter gates. The Wells powerhouse is capable of discharging 195,000 cfs, and 10,000 cfs are used to operate the fish bypass system.

Wells’ reservoir, Lake Pateros, can encroach on the Chief Joseph powerhouse—reducing the amount of generation that occurs at Chief Joseph. Douglas County PUD reimburses the USACE and Bonneville Power Administration (BPA) when encroachment occurs by crediting some energy generation to BPA. Little degasification occurs in Lake Pateros between Chief Joseph and Wells dam because of limited storage capacity and lack of free flowing river. The lack of degassing can be seen in the data by comparing the Chief Joseph tailwater TDG to the Wells headwater TDG in the TDG vs. Time plots.

The hydrocombine presents a unique TDG modeling scenario not seen at other dams on the Columbia River. Because spill flows discharge above powerhouse flows, dissolved gas in the spill flows can become entrained in powerhouse flows. Unlike other projects on the Columbia, a concentrated spill pattern using a single gate is desirable to minimize gas entrainment in the powerhouse flows.
Figure 50: Wells forebay and tailwater TDG from 2004 to 2012

Figure 51: Wells tailwater vs spill flow (during periods of spill)
Figure 52: Wells TW-HW TDG vs spill flow (during periods of spill)

Figure 53: Wells tailwater TDG vs plunge pool depth (during periods of spill)
Figure 54: Wells TW-HW TDG from 2008 to 2012

Figure 55: Wells spill flow from 2008 to 2012
APPENDIX D: ROCKY REACH

Hourly data for Rocky Reach with the exception of tail water TDG were available during the summer and parts of spring and fall from 2004 to 2012 in the USACE Dataquery System. Tail water TDG data were obtained directly from Chelan PUD. Elevation and flow data were collected from the Historical Water Quality Database. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Rocky Reach hourly data are provided on the following pages. Raw data, with the exception of tail water TDG, is publicly available through the Dataquery and Historical Water Quality systems.

Rocky Reach is owned and operated by Chelan County PUD. It is a run-of-river project with a capacity of 1.3 GW located about 42 miles downstream of Wells Dam. The spillway consists of 12 bays with 50 by 58-ft tainter gates. The powerhouse is positioned parallel to the right bank (looking downriver) and nearly perpendicular to the spillway; the dam is L-shaped similar to Chief Joseph. The powerhouse is capable of discharging 220,000 cfs. A non-overflow dam connects the powerhouse to the right bank.

The Rocky Reach stilling basin was designed to dissipate spill energy over a short distance (Schneider). Eleven of the 12 spill bays feature two notched nappe deflectors in the stilling basin. Spill bay 1, the bay closest to the powerhouse, lacks this feature and is seldom used. The nappe deflectors are designed for energy dissipation, not TDG abatement like the spillway deflectors at Chief Joseph. An impact sill is present in the stilling basin 70 feet downstream of the nappe deflectors in bays 2 through 12. A fish ladder is present between spill bays 8 and 9, and a training wall is positioned between bays 1 and 2. Finally, a notched, sloping end sill is located 150 feet downstream of the nappe deflector at the end of the stilling basin. Many of these hydraulic features are designed for energy dissipation and prevention of cavitation damage by aerating spill flow; they do not mitigate the generation of TDG in the stilling basin. These hydraulic features complicate analysis of TDG generation because of the turbulent and energetic flow pattern they produce in the silling basin.

Powerhouse flows are directed into the stilling basin almost normal to spillway flows. The high energy environment in the stilling can cause powerhouse releases to become entrained, reducing ability of powerhouse flows to dilute spill flows with high TDG concentrations downstream of the project.
Figure 56: Rocky Reach Dam cross-sectional schematic

Figure 57: Rocky Reach forebay and tailwater TDG from 2004 to 2012
Figure 58: Rocky Reach tailwater vs spill flow (during periods of spill)

Figure 59: Rocky Reach TW-HW TDG vs spill flow (during periods of spill)
Figure 60: Rocky Reach tailwater TDG vs plunge pool depth (during periods of spill)

Figure 61: Rocky Reach TW-HW TDG vs Time

Figure 61: Rocky Reach TW-HW TDG from 2008 to 2012
Figure 62: Rocky Reach spill flow from 2008 to 2012
APPENDIX E: ROCK ISLAND

Hourly data for Rock Island with the exception of tail water TDG were available during the summer and parts of spring and fall from 2004 to 2012 in the USACE Dataquery System. Tail water TDG data were obtained directly from Chelan PUD. Elevation and flow data were collected from the Historical Water Quality Database. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Rock Island hourly data are provided on the following pages. Raw data, with the exception of tail water TDG, is publicly available through the Dataquery and Historical Water Quality systems.

Rock Island (Figure 63) was the first hydroelectric dam to be built on the Columbia River; initial construction was completed in 1932. It is a run-of-river project that has been modified several times over its history and presently has a capacity of 624 MW. Two powerhouses are present on the left and right sides of the dam, and two spillways with a total of 31 bays are separated by a fishway in the middle of the facility. The left spillway (looking downriver) contains 14 bays and is aligned with the river flow; the right spillway contains 17 bays and is at a slight angle relative to the east spillway and river flow (Frantz 2012). The right spillway is also arced towards the headwater whereas the left spillway is linear. The powerhouses have a combined hydraulic capacity of 220,000 cfs, and the project head is 41 feet. 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).

Rock Island does not use tainter gates as is common on most run-of-river projects; instead, crest gates are used. Some of the crest gates at the projects are modified to aid in fish passage or reduce TDG generation. Notched gates are used in 6 bays to reduce the volume of water necessary for fish passage. The use of notched gates reduces TDG during spill for fish passage since less water is passed through the spillway. Over/under gates are used at 3 bays to provide surface flow attraction for fish bypass yet spill in a manner that minimizes gas uptake. One of the spill bays also employs a spill deflector. Preference is given to the use of the notched and over/under gates to minimize TDG generation during spill operations. The Rock Island stilling basin is unique in that the bathymetry varies in elevation by approximately 80 feet between spill bay 1 and bays 21-23.

Figure 63: 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.

Figure 64 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 64: Rock Island forebay and tailwater TDG from 2004 to 2012

Figure 65 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 65: Rock Island tailwater TDG vs spill flow (during periods of spill)

Figure 66: Rock Island TW-HW TDG vs spill flow (during periods of spill)
Figure 67: Rock Island tailwater TDG vs plunge pool depth (during periods of spill)

Figure 68: Rock Island TW-HW TDG from 2008 to 2012
Figure 69: Rock Island spill flow from 2008 to 2012
APPENDIX F: WANAPUM

Hourly data were available during the summer and parts of spring and fall from 2004 to 2012 in the USACE Dataquery System for the Wanapum project. Elevation and flow data were collected from the Historical Water Quality Database. TDG data were not available in the database during a period from late 2010 to early 2012. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Wanapum hourly data are provided on the following pages. Raw data is publicly available through the Dataquery and Historical Water Quality systems.

Wanapum Dam is a run-of-river project 37.6 miles downstream of Rock Island owned and operated by Grant County PUD; the project has a capacity of 1.038 GW. The spillway consists of 12 bays with 50 by 67-ft tainter gates; they were the largest tainter gates ever installed at the time of construction. A 20 foot wide top spilling sluice gate is positioned on the left side of the spillway (looking downstream) for fish passage. The spillway is positioned on the right side of the project at a slight angle to the river channel. The powerhouse is attached to the left side of the spillway and positioned parallel to the river bank. A non overflow dam connects the upstream side of the powerhouse to the left bank. The configuration of the hydraulic structures is similar to Chief Joseph and Rocky Reach dams, except the position of the spillway and non overflow dam is inverted.

Grant County PUD has taken several measures to reduce TDG generation at the project. In 2000, spillway deflectors were installed to reduce TDG generation by preventing aerated spill flows from reaching entrainment depths. New turbines were installed to increase the flow rate through the powerhouse from 178,000 cfs to 188,000 cfs. Increased flow through the powerhouse reduces the amount of time the project must operate the spillway. The sluice gate was modified in 2004 to reduce TDG generation and improve fish survival, and a fish bypass system was installed in 2008 to reduce water use for fish spills.
Figure 70: Wanapum Dam cross-sectional schematic

Figure 71: Wanapum forebay and tailwater TDG from 2004 to 2012
Figure 72: Wanapum tailwater vs spill flow (during periods of spill)

Figure 73: Wanapum TW-HW TDG vs spill flow (during periods of spill)
Figure 74: Wanapum tailwater TDG vs plunge pool depth (during periods of spill)

Figure 75: Wanapum TW-HW TDG from 2008 to 2012
Figure 76: Wanapum spill flow from 2008 to 2012
APPENDIX G: PRIEST RAPIDS

Hourly data were available for Priest Rapids during the summer and parts of spring and fall from 2004 to 2012 in the USACE Dataquery System. TDG data were not available in the database during a period from late 2010 to early 2012. Elevation and flow data were collected from the Historical Water Quality Database. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Priest Rapids hourly data are provided on the following pages. Raw data is publicly available through the Dataquery and Historical Water Quality systems.

Priest Rapids is a run-of-river project approximately 18 miles downriver of Wanapum owned and operated by Grand County PUD. The project has a capacity of 956 MW and a head of approximately 80 feet. The spillway consists of 22 bays with 40 by 50-ft tainter gates. The spillway is aligned with the river flow and positioned on the right side of the dam (looking downriver). A sloped end sill is present at the end of the stilling basin, and a training wall separates the powerhouse from the spillway. The powerhouse is positioned on the left side of the dam and has a hydraulic capacity of 187,000 cfs. Fish ladders are positioned on both sides of the dam next to the river bank.

The Priest Rapids spillway is currently being modified to improve fish bypass. The project involves modification of three spill bays that significantly reduces the volume of water Priest Rapids is required to spill for fish bypass. Since TDG is a function of spill flow and much of the spill at Columbia run-of-river projects is for fish bypass, the bypass system should reduce TDG levels at the dam. The fish bypass system is expected to be completed in 2014. Grant County PUD is also researching the benefits of upgrading the turbines at the Priest Rapids project to increase fish passage survival, increase hydraulic capacity, and reduce TDG. Flow deflectors were also considered at the project, but it is believed the fish bypass modifications should be adequate to mitigate TDG challenges at the site (EIS).
Figure 77: Priest Rapids Dam cross-sectional schematic

Figure 78: Priest Rapids forebay and tailwater TDG from 2004 to 2012
Figure 79: Priest Rapids tailwater vs spill flow (during periods of spill)

Figure 80: Priest Rapids TW-HW TDG vs spill flow (during periods of spill)
Figure 81: Priest Rapids tailwater TDG vs plunge pool depth (during periods of spill)

Figure 82: Priest Rapids TW-HW TDG vs Time from 2008 to 2012
Figure 83: Priest Rapids spill flow from 2008 to 2012
APPENDIX H: DWORSHAK

Hourly data were available year-round for Dworshak from 2004 to 2012 in the USACE Dataquery System. Forebay TDG data were not available since Dworshack is the first dam on the North Fork Clearwater River. A few cases of invalid data were present in the dataset. Notes were made of the time the invalid data occurred, and the data were removed from the dataset. Selected plots of the Dworshak hourly data are provided on the following pages. Raw data is publicly available through the Dataquery system.

Dworshak is a gravity dam located on the North Fork Clearwater River and the third tallest dam in the United States. The facility is a storage project with a maximum capacity of 460 MW from three generating units; the net head is 560 ft. The powerhouse was initially designed to accommodate six units for peaking power production, but it was later determined that operation of six units would cause too large of fluctuations in tail water elevation. Initially, it was planned that a run-of-river project would be built below Dworshak to smooth flows, but the project faced local opposition. Plans for installation of more units at Dworshak were abandoned.

Dworshak is equipped with two spillways and three regulating outlets. The spillway crest elevation is 1545 ft, and spill is controlled by 50 by 56.4-ft tainter gates. The regulating outlets are positioned at elevation 1362 ft and are also controlled by tainter gates. Looking downriver, the powerhouse is positioned on the right side of the dam, and the spillway is positioned on the left. Dworshak was included in the study because TDG spikes can occur during large spill events, and the TDG spikes can elevate TDG at projects downriver of Dworshak. Dworshak will help provide model validation by providing another project for modal calibration and testing.
Figure 84: Dworshak Dam cross-sectional schematic

Figure 85: Dworshak tailwater vs spill flow during periods of spill
Figure 86: Dworshak tailwater TDG vs plunge pool depth (during periods of spill)

Figure 87: Dworshak tailwater TDG from 2004 to 2012
Figure 88: Dworshak spill flow from 2008 to 2012
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