PREDICTION OF TOTAL DISSOLVED GAS EXCHANGE AT HYDROPOWER DAMS

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REPORT

TABLE OF CONTENTS

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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 injuries 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. 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 versus 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 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. These data have been used to quantify the relationship between project operations, structural properties, and TDG exchange. These data have also been used to develop predictive models of TDG exchange to support real-time TDG management decisions. These empirically based predictive models have been developed for specific projects and account for both the fate of spillway and powerhouse flows in the tailrace channel and resultant exchange in route to the next downstream dam. 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. It is proposed to develop 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. TDG data from hydropower facilities located throughout the northwest region of the United States will be used to identify relationships between TDG exchange and relevant dependent variables. Data analysis and regression techniques will be used to develop predictive TDG exchange expressions for various structural categories.

2. CURRENT PRACTICES AND KNOWLEDGE

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.

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 U.S. Army Corps of Engineers (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.

There have also been numerous physical studies to ascertain the effects of TDG 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.

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. PROPOSED 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 the minimization and/or reduction of downstream TDG. 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.

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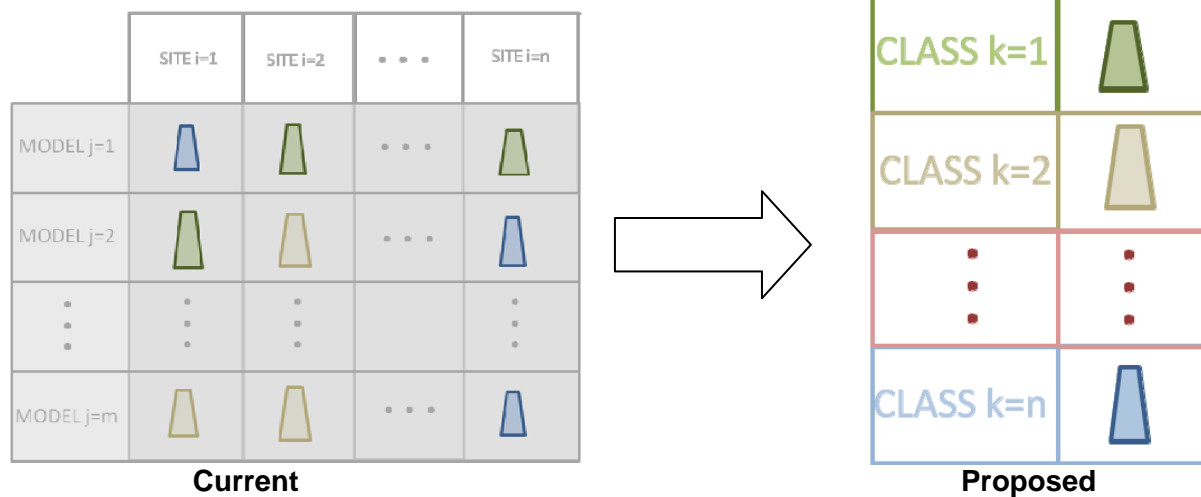
Figure 1. Schematic Diagram Illustrating a Generalized Empirical Approach to Predict TDG

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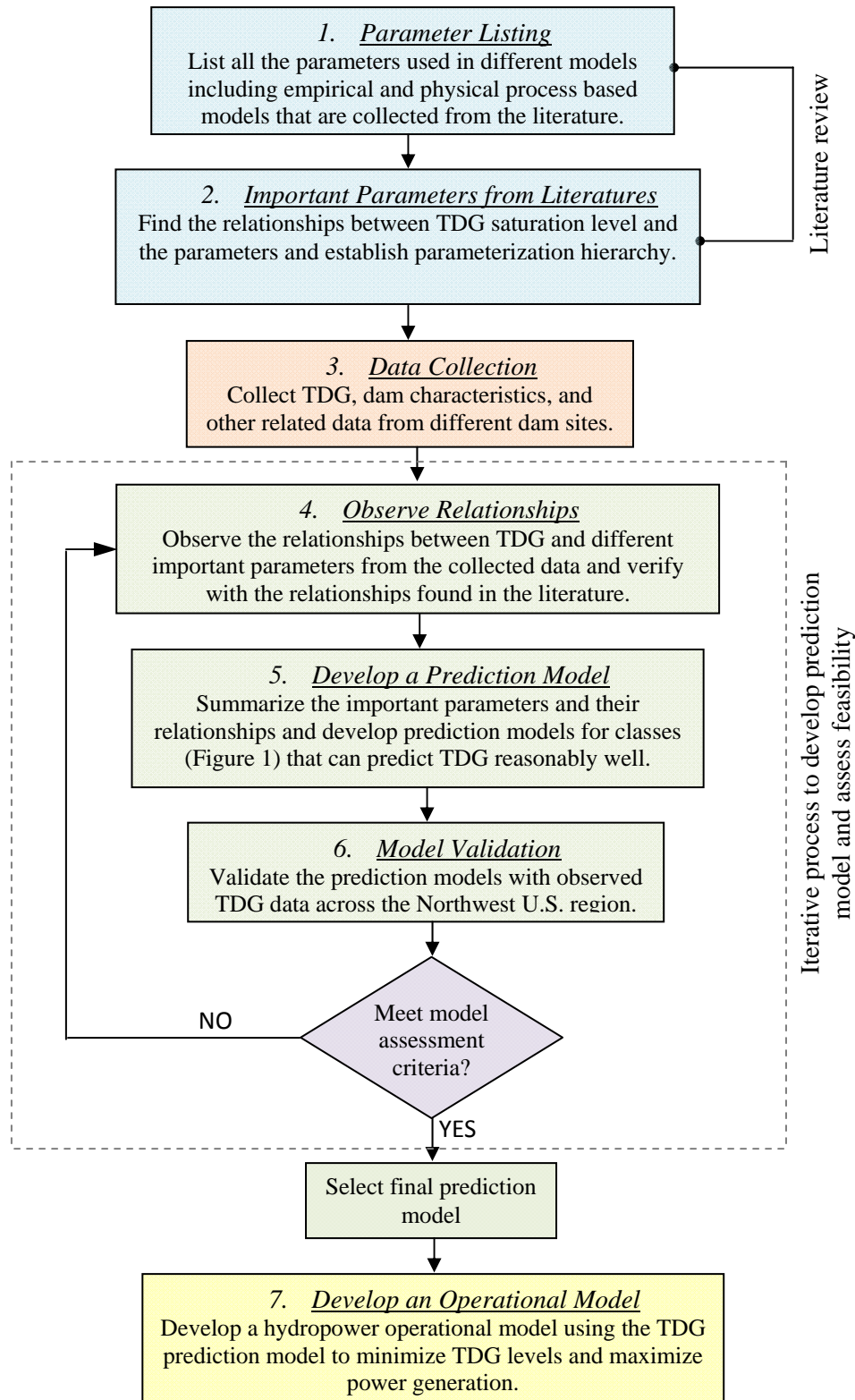
Figure 2: Flowchart to Develop an Operational Model to Predict TDG Downstream of a Dam

3.1   Team

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