Prediction of Total Dissolved Gas (TDG) at Columbia River Basin dams

Merlynn D. Bender[1] and Boualem Hadjerioua[2]

[1] *U.S. Department of Interior, Bureau of Reclamation, Technical Service Center, USA*
[2] *Environmental Sciences Division, Oak Ridge National Laboratory, USA*

Abstract

The network of dams in the Columbia River Basin (CRB) is managed for irrigation, power production, flood control, and navigation. Spilling water mostly occurs during high river flows for flood control and for fish passage. During release events, air is entrained in the spilled water which could elevate the levels of total dissolved gas (TDG) saturation at the dam tailwater and for several miles downstream. More pumping for irrigation and more generation from pumped storage/wind integration may provide balancing reserves and may reduce spill and TDG.

There is a need for a generalized TDG exchange model that can be implemented to site-specific dam operation for use in water regulation models to better address TDG super saturation concerns. Physical data have been collected and analyzed to develop site-specific predictive models of TDG exchange. And a generalized TDG model that pools collected data at multiple projects with similar structural attributes is being developed. Additional pumped storage for wind integration and more irrigation add complexity. Grand Coulee Dam, the John W. Keys III (JWK) pump generating plant, and the Columbia Basin Project irrigation system have many parameters affecting TDG.

Information for Grand Coulee Dam and JWK pump generating plant were selected to demonstrate prediction of tailrace TDG levels as a function of a set of variables that affect TDG exchange. These facilities are unique due to pumped storage for wind integration and irrigation requirements for balancing reserves. A generalized model predicting TDG is being investigated to reduce spill and TDG, to potentially increase hydropower generation, and to minimize impact on fish habitat.

Keywords: Total Dissolved gas, hydropower, fish habitat, mid-Columbia River, Grand Coulee Dam, Dworshak Dam

Background

Columbia River high-water operations during June 2010 (Bonneville Power Administration (BPA), September 2010) demonstrated a continuing need for tools to address oversupply of water (BPA fact sheet, May 2012). Oversupply management protocols were implemented during 2011 and 2012 (BPA, January 2013). Figure 1 shows Grand Coulee Dam spill during June 2010. In the Pacific Northwest, during high river flow conditions, decreasing hydropower generation for balancing the system for wind integration results in additional and more frequent spills. Spill could result in more total dissolved gas (TDG) super saturation which in turn might result in gas bubble disease (GBD) and harm to fisheries. Water management techniques to reduce TDG are being tested. System-wide approaches using generalized predictive tools (Hadjerioua, 2012) are needed.

Figure 1. Grand Coulee Dam spill during June 2010.

Operational modeling is primarily balancing water, energy, and environmental compliance. Tools to accommodate TDG need to be incorporated into various operational models. A mid-Columbia (mid-C) RiverWare model has been developed from Grand Coulee Dam to Vernita Bar (Clement, et al, February 1, 2012). Because the Grand Coulee project is substantially larger than downstream projects, the amount and timing of its releases directly affect operations at downstream projects (FERC, April 17, 2008). Flow constraints for the Hanford Reach of the Columbia River at Vernita Bar during salmon spawning season results in higher flows at night and lower flows during daylight hours from Priest Rapids Dam just upstream of Vernita Bar. TDG and wind integration was demonstrated in the mid-Columbia RiverWare model using data and equations from the CRiSP model (University of Washington) and the SYSTDG TDG model (Schneider, USACE, 2011). The focus area of this study is from Grand Coulee Dam forebay (FDR Lake) to the tailwater of Priest Rapids at Vernita Bar above the confluence of the warm Snake River inflows. The focus period is spring flood or high-water events under the 7-day average flow that occurs once every ten years (the 7Q10 flow) of 6,824 cubic meters per second (241 thousand cubic feet per second (kcfs)) at Grand Coulee Dam corresponding with deep plunge pools below mid-Columbia River dams. The Columbia River flows in 2011 were the highest since 1997. SYSTDG simulations were run for the entire 2011 spill season for one project and river reach at a time, so that predictive errors could be calculated independently for each dam and river reach. The gauge with the largest TDG increase was Grand Coulee Dam tailwater with a 10 percent increase. The scheduling of power reserves was directed away from Grand Coulee Dam during the high flow periods to minimize the volume of water passed through the regulating outlets or over the spillway (Schneider, USACE, 2011). However, TDG values below Grand Coulee Dam were relatively high and there is a system-wide need to further direct flood control to other dams. A system-wide water, energy, and TDG model is needed to optimize the system.

Spill operations at Grand Coulee Dam are delegated to Chief Joseph Dam which has spillway flow deflectors (flip-lips) to reduce TDG. With the installation of flow deflectors at Chief Joseph, spill operations can increase flow from 566.3 cubic meters per second (cms) to 2,831.7 cms (20,000 cubic feet per second (cfs) to 100,000 cfs) (BPA, September 2010). Less may be spilled if additional water can be pumped or diverted from Franklin Delano Roosevelt (FDR) Lake, which is upstream of Grand Coulee Dam. The John W. Keys (JWK) pump generation plant pumps water "over the hill" to irrigation projects. About an additional 200 thousand hectares (a half million acres) could be irrigated if developed. Additional irrigation may allow more water to be pumped thereby factoring into balancing reserves for wind power integration. Balancing reserves correct for deviations between scheduled and actual wind output within each hour. Unfortunately during wet years when spill becomes a concern, FDR Lake is drawn down for flood control, and the pumps may not pump enough water "over the hill" due to the large head differential between FDR Lake and Banks Lake, the equalizing reservoir at the top of the hill (Bender, 2012).

Operational solutions for TDG reduction at Grand Coulee Dam were studied during the gas abatement study at Chief Joseph Dam (USACE, May 2000). Spillway flow deflectors (alternative 1) have been installed at Chief Joseph Dam and other dams. However, modifying operations at Grand Coulee Dam in combination with other dams was discussed, investigated (USACE, June 2002), and implemented at Chief Joseph Dam which is the next dam downstream. When FDR water surface elevation is below 384 meters (m) (1260 feet (ft)) elevation above project datum, spilling from the sluice regulating outlets would allow more TDG; Frizell (1998) recommended using turbines including operating at speed-no-load or inefficiently at low flows to minimize TDG concerns. Alternatively, when FDR Lake water surface elevation is between 384.0 m and 393.2 m (1260 ft and 1290 ft), spilling from the drum gates would reduce TDG. This alternative also has the benefit of removing warm surface water while preserving cold bottom water for use during autumn.

A secondary benefit of operational changes at Grand Coulee Dam is temperature management of the Columbia River. The more modern third powerhouse turbines are about 27.1 m (89 ft) higher than the left and right powerhouse turbines. Using third powerhouse turbines more often after winter saves cold water in storage for use during autumn. Cursory best-case scenario modeling of FDR Lake indicated that modeling only third powerhouse releases during July and August (not operationally realistic because the smaller left and right powerhouse turbines are also used for load following to save water) could save a maximum about two to three weeks of cold water for release during early September. Cold Canadian water could potentially link up with the larger cold water pool by late September (Figure 2, Bureau of Reclamation, September 26, 2005).

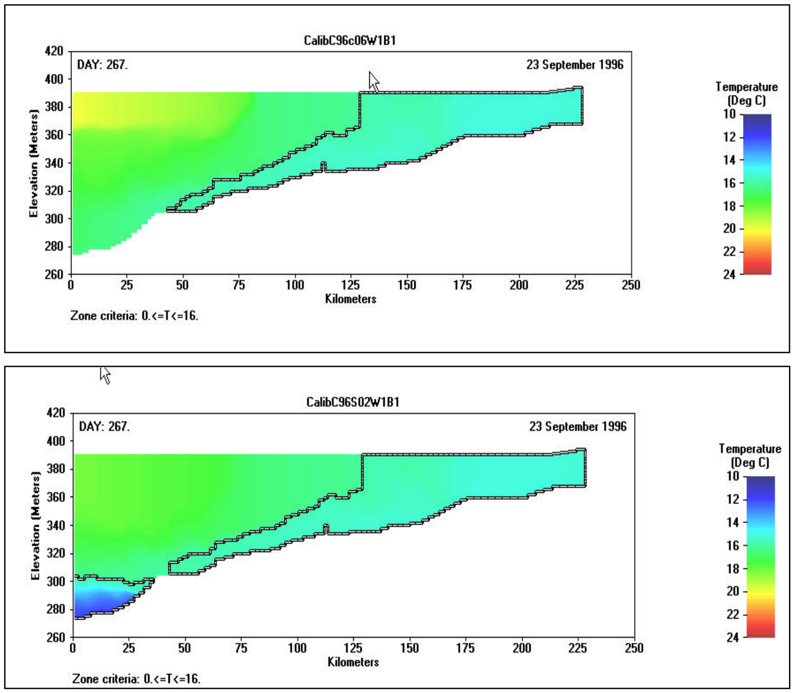

Figure 2. Modeled normal operations (top) versus saving cold water via third powerhouse turbines (bottom).

Accommodating Wind Integration

Decrementing hydropower for wind integration is predicted to nearly triple by 2018 (Figure 3). If hydropower is reduced, spill increases; increased spill results in more TDG. Therefore as wind energy is added, more TDG concerns are expected due to grid transmission constraints, more spill, and insufficient balancing reserve flexibility to accommodate additional wind energy penetration into the electrical grid.

BPA runs hydro generation roughly 1000 megawatts (MW) higher than minimum generation to stand ready at all times to reduce hydro generation (decrementing or dec) if the wind picks up and wind power suddenly increases above its schedule. BPA also runs hydro generation roughly 850 MW below maximum generation at all times to stand ready to increase hydro output (incrementing or inc) instantly if the wind dies off and wind generation falls below the schedule within one hour (BPA, 2010).

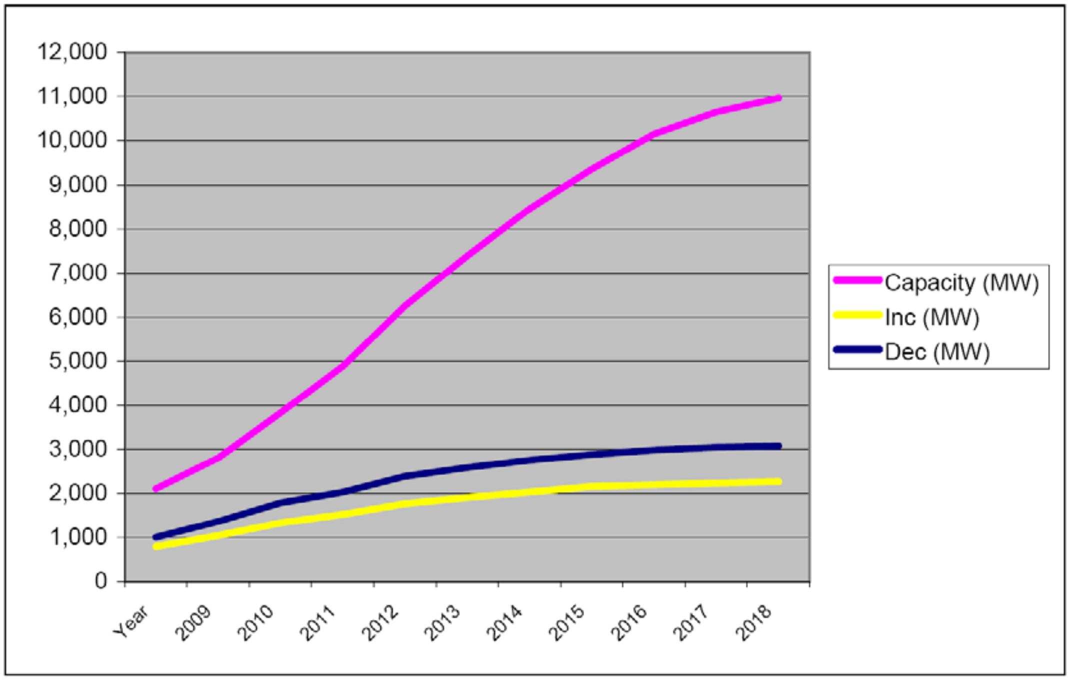

Figure 3. BPA incrementing (Inc is the bottom line) and decrementing (Dec) supplemental reserves (MW) compared to capacity (top line) (Bender, 2012).

Oversupply Management Actions

Operators are using capacity recallable energy (C-RE), the mid-Columbia Spill Exchange Agreement, rescheduling of non-essential outages, nuclear power reduction at the Columbia Generating Station, reduction of balancing reserves for wind, maximizing pumping for irrigation, purchased intertie transmission for increased power exportation, and coordinated spill at downstream Columbia River dams and the Willamette Basin dams as tools to manage oversupply of electricity from renewable energy generation such as wind energy (BPA, May 2012 and BPA, January 2013) and to minimize environmental redispatch (ER). When system conditions trigger Environmental Redispatch, BPA will replace scheduled generation in BPA's Balancing Authority Area with Federal hydropower at no cost. However, BPA will not pay negative energy prices under these conditions (BPA 2011) because doing so would undesirably encourage less energy production overall. Capacity recallable energy, a recent innovation, holds reserves in a separate transmission system and generates little revenue; however, it helps control TDG without asking a thermal or renewable energy source to reduce or cut its output. As with irrigation pumping, C-RE allows holding less spinning reserves and generating more hydropower in heavy load hours, which has the effect of lessening spill during light load hours and therefore lessening TDG (BPA, January 2013). When oversupply management actions are insufficient, excess generation is turned off and replaced with free federal hydropower or compensation is provided to affected energy producers. During a mild flood, thermal operators are asked to produce less so that hydro generation for balancing reserves can help accommodate wind energy management.

During the relatively mild high flows during June 2010, many oversupply management actions were used. In any year, there is a thirty percent chance that such a mild flood can occur on the Columbia River due to the limited capacity of the reservoir system for this wet area of the country. Agencies canceled or delayed unit outages, moved spill to downstream dams while moving generation to fish-passage projects, reduced flows of upstream dams, arranged for more flood control space in John Day Reservoir, shaped Hungry Horse Dam and Dworshak Dam generation into hours of heavy electrical use, asked a nuclear plant to derate, asked the Canadians to reduce flows of Hugh Keenleyside (Arrow) Dam, reduced balancing reserves to minimize spill caused by unscheduled wind energy production (sometimes resulting in feathering the blades), worked with neighboring utilities to defer their transmission maintenance, and moved generation around the system to minimize transmission constraints.

There are tools and flexibility to manage oversupply of power under current conditions. However, during an extended spring flooding period, the system will be taxed and additional excess spill is expected in the future. This will result in giving power away to energy producers for free or less than the cost of associated transmission. If generators are turned off, producers may desire compensation for lost revenues, including renewable energy credits and production tax credits. By lowering decrementing reserves, there is less chance that changes in wind generation would cause reductions in hydro generation that potentially could result in additional spill and TDG.

A more effective way to manage system TDG levels may be achieved by reducing the amount of incrementing reserves; that may allow for the potential increase of on-peak hydro generation thereby minimizing spill. Also more pumping for irrigation, such as Managed Aquifer Recharge (MAR), increased pumping for irrigation during lower energy use periods, or additional pumping at JWK pump generation plant might be considered by advantageously positioning the head differential between Franklin D. Roosevelt (FDR) Lake and Banks Lake. That could require shifting some flood control operations back to Dworshak Dam by reducing Dworshak Dam tailwater TDG, potentially with a degassing hydraulic structure.

Irrigation and drought

The High Plains Aquifer (the Ogallala Aquifer is part of it) lies within seven Midwestern states and can already be drawn down several hundred feet by submersible pumps. Agricultural water from groundwater pumping will be a greatly reduced option from what it was during the "dirty thirties" during a future extended Midwest drought that lasts for several years. With three times the United States population today than during the 1930s, dry land farming could be greatly reduced and insufficient during a potential future Midwestern drought. More irrigated agricultural acreage in the Pacific Northwest will likely need to make up for the Midwestern agricultural shortfall. The July 16, 2013 drought monitor (Figure 4) shows conditions that may have been worse than the drought of 1933 and better than the drought of 1934.

Additional Columbia River Project water could be used to reduce reliance on groundwater pumping. Additional diversions could affect the variability of Banks Lake water surface elevation thereby requiring more study.

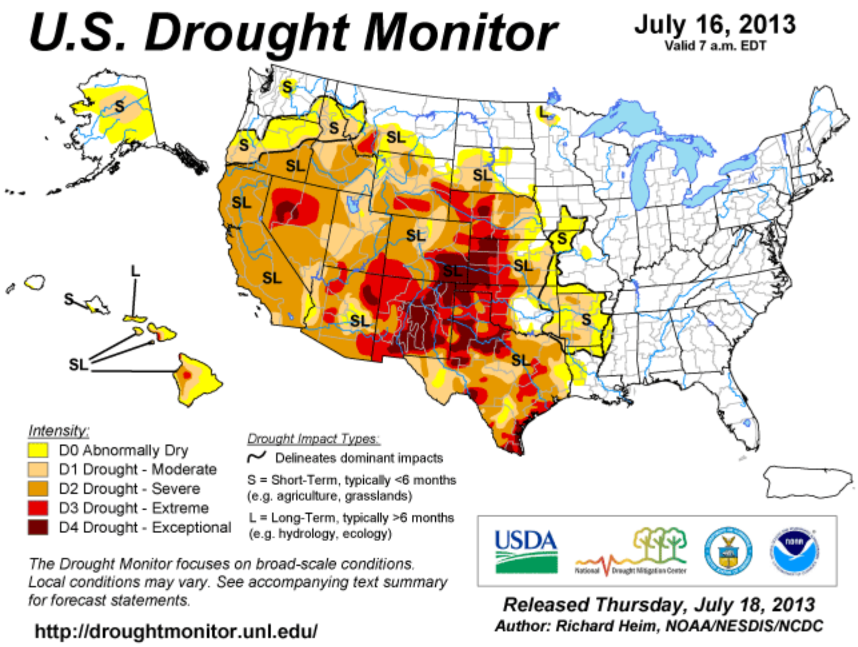

Figure 4. Midwest drought on July 16, 2013 (University of Nebraska, 2013).

Ice Storms

During summer 2012, abnormally warm air temperatures resulted in more line sag of the millions of miles of copper stretching across the United States. As copper lines heat up and stretch, that copper becomes thinner and longer thereby increasing resistance and energy use.

Late spring ice storms that damage electrical lines may cause transmission grid constraint and consequently, more spill and TDG concerns. Global climate change may cause more variability in the weather. Instead of snow storms, ice storms might become more prevalent with increases in temperature.

The Great Ice Storm of 1998 was a massive combination of five smaller successive ice storms which combined to strike a relatively narrow swath of land from eastern Ontario to southern Quebec to Nova Scotia in Canada, and bordering areas from northern New York to central Maine in the United States. During January 1998, it caused massive damage to trees and electrical infrastructure all over the area, leading to widespread long-term power outages. Millions were left in the dark for periods varying from days to weeks, and in some instances, months leading to more than 30 fatalities and a shutdown of activities. A destructive ice storm melting into a spring flood could elevate TDG concerns. Dworshak dam may provide transmission grid constraint relief if Dworshak Dam tailwater TDG can be reduced.

Parameters affecting TDG

Grand Coulee Dam, JWK pump generation plant, and Banks Lake need to be managed within system-wide operations with future wind penetration and irrigation concerns considered in conjunction with TDG management. Many variables affect system-wide TDG management. However, a simplified initial data analysis approach based on plunge pool depth, percent spill, releases, and water surface elevations is being used and those parameters are shown in Table 1.

Table 1. Initial parameters used to analyze TDG of mid-Columbia River Dams.

Parameter	Description
TDG	percent TDG in headwater and tailwater
Release rates	total spill and generation flows
Plunge pool depth	tailwater elevation minus stilling basin bottom depth
Project head	difference of headwater and tailwater elevations
Energy	generation

A list of factors that affect spill levels is given by Hamilton (updated April 13, 2012). The five main categories that influenced spill were legal, physical, and guidance factors and model forecasting and the tracking of spill rates. The 27 factors listed under those categories were listed and discussed. All factors related to daily spill caps. There are two types of spill caps: fish passage spill caps (fish flow augmentation) and lack of load spill caps (lack of market spill). The system for classifying spill variances includes six types. The types are classified as operational limits, maintenance, research related, transmission stability, navigation, and human/program error.

Potential Approaches

Currently, individual TDG equations (models) exist for individual dam sites. However, these models fall into particular classes. One class is mainstem Columbia River dams without deflectors; those with spill deflectors (flip-lips) fall into another class. Grand Coulee Dam falls into a class of its own with both drum gates and regulating (over under operations) used for spill; Grand Coulee Dam is just downstream of the Canadian border (at the top of a chain of dams on the Columbia River in the United States) and also has the ability to pump water "over the hill" via JWK pump generation plant (divert water out of the Columbia River drainage). Yet another class is Snake River dams which are smaller volume reservoirs with steep tributaries draining the long Snake River plain; Dworshak Dam, a large storage reservoir, on the North Fork of the Clearwater River (a tributary to the Snake River) provides cold water release for fish. If TDG can be reduced in Dworshak Dam tailwater, a system-wide approach to TDG, temperature, and spill management might be feasible. The input parameter similarities between classes lend itself computationally to the use of a layered connectionist approach; another residual approach would be to collapse information into simplistic relationships for more rapid computation. The most likely approach is the development of a generalized TDG equation that can be embedded within operational models; shifting storage between FDR Lake and Dworshak Reservoir, the two reservoirs with sizable useable storage (see Table 2), might be investigated based on proposed additional TDG reduction strategies to revise spill caps at Columbia River and Snake River dams (Figure 5)

Table 2. Comparison of mid-Columbia dam reservoirs and Dworshak Reservoir useable storage volume.

----- Dam -----	--Useable storage volume-- million acre-ft (cubic kilometers)
Grand Coulee	5.20 MAF (6.414 km^3)
Chief Joseph	0.12 MAF (0.148 km^3)
Wells + Rocky Reach + Rock Island + Wanapum + Priest Rapids	0.35 MAF (0.432 km^3)
total of 7 mid-Columbia Dams	5.67 MAF (6.994 km^3)
Dworshak (to Snake River)	2.02 MAF (2.487 km^3)

Figure 5. Major Columbia River and Snake River Dams

Spill cap is defined as the maximum spill amount that will keep the High 12 hour %TDG average within 115% in the forebay or 120% in the tailwater. These limits are gas caps. Gas caps are constant, whereas spill caps may vary daily depending on flow, spill operation, spill pattern, temperature, legal constraints in accordance with the Fish Operation Plan (FOP, USACE, March 2012), and other environmental conditions.

Much was learned from the mini-flood event during June 2010 in the Pacific Northwest. The system was operated to minimize TDG; however, high TDG saturation occurred in the tailwater of McNary Dam and also in the forebay of Bonneville Dam for that relatively late spring mild flooding event. That June 2010 event would be an interesting case study.

A simplified modeling methodology linking TDG models to operational models on a per-time-step basis is required for implementation of proposed operational changes for water quality improvement. A per time-step methodology for use on the Columbia River watershed modeled with mid-C RiverWare model with added Dworshak Dam and Reservoir components may eventually be tested in a following project phase.

Initially, more physical data will be added to TDG equations for individual dam sites by multi-parameter regression equation improvements. However, eventually a connectionist approach in the form of an improved mid-Columbia RiverWare model or another operational tool will be considered to incorporate the effects of pumped storage, wind integration, and irrigation on both TDG and energy production.

A residual approach is the calibration of models and equations, reduction into a simpler set of equations that require less computation time than a model, and comparison of residuals between the existing calibration and proposed alternatives output from those equations. A residual approach is mathematically challenging to develop the required reduced equations.

The proposed approach is to initially develop a multi-parameter generic regression TDG equation that can be used at multiple dam sites and potentially embedded within existing operational models such as the mid-Columbia RiverWare model with Dworshak Dam and Reservoir components added. The regression equation would be based on a select set of parameters and a reduced set of inputs based on statistical analysis of historical data from multiple dams.

Figure 6 shows that at Grand Coulee Dam spill above 30,000 cfs percent TDG is often above the 120 percent gas cap. Potential system-wide solutions for moving that spill to other Columbia-Snake River dams are being explored. Solutions at Dworshak Dam could potentially provide more operational flexibility at mid-Columbia River dams.

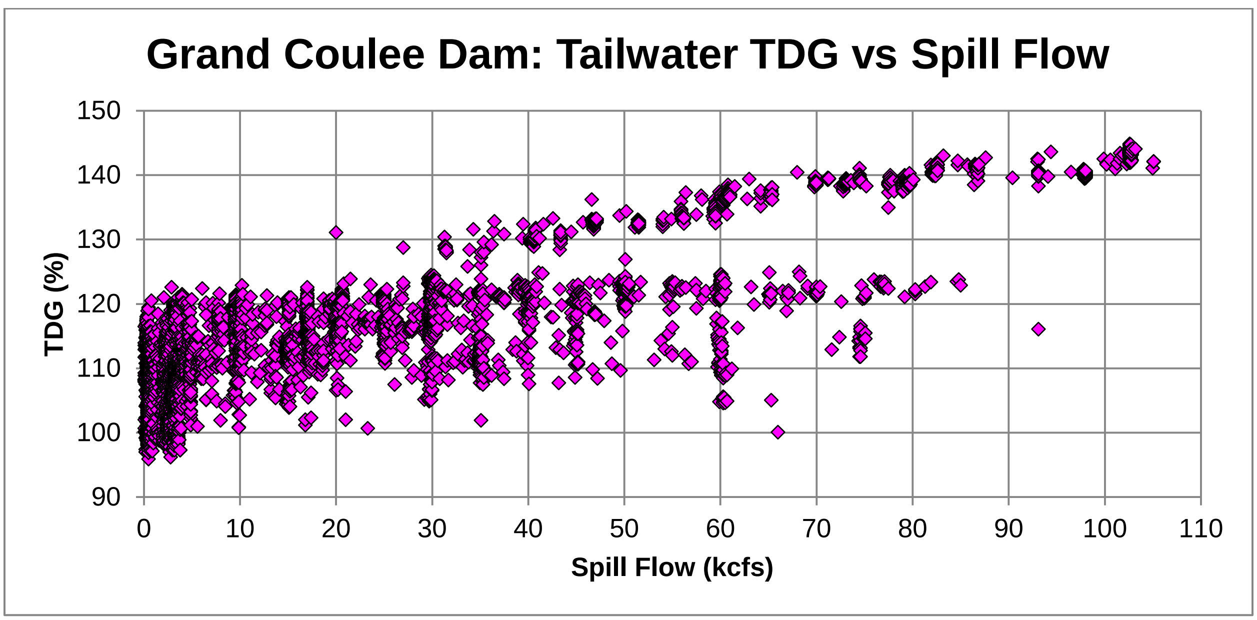

Figure 6. Grand Coulee Dam TDG as a function of spill flow, years 2004-2011.

Conclusions

Fishery managers and dam operators need to beware of late spring rain-on-snow events during cold wet and windy weather; wind storms that cause wind energy to increase and hydro generation to drop off results in increased spill and therefore TDG super saturation.

Potential Changes at Grand Coulee Dam and JWK could provide additional hydropower via wind integration/pumped storage. The existing pumps and pump generators could be utilized more effectively if FDR Lake elevations could be raised earlier in the spring season by spreading flood control to other facilities. Additional pumping of Columbia Basin project water “over the hill” for additional irrigation would provide additional energy withdrawal that would reduce the need to increase decrementing hydropower for additional wind integration. Holding less spinning and non-spinning reserves and generating more hydropower in heavy load hours has the effect of lessening spill during light load hours; this helps control TDG without asking thermal and renewable energy sources to reduce output (BPA, January 2013).

Less drawdown of FDR Lake might be accomplished by using more third powerhouse releases at Grand Coulee Dam with less dispatch of the smaller generators in the left and right powerhouses and by shifting flood control back to Dworshak (COE project) and other projects by reducing TDG in tailwaters; Dworshak is typically low on the spill priority list and therefore likely has potential for affecting system-wide TDG reduction. Storing water in off-channel impoundments for irrigation during summer might also provide additional pumping needs for load balancing during wet periods.

A system-wide approach might be based on spill, total flow, TDG measurements, and estimated TDG in the tailwaters below each dam of the mid-C reach and Dworshak Dam. More sophisticated equations may be developed as understanding increases. Approaches might focus on simplifying modeling efforts to eventually link a condensed set of detailed information from TDG models to an operational model on a per-time-step basis. A multi-parameter generic regression TDG equation is being developed for use in operational models such as an expanded mid-C RiverWare model; fine tuning of the spill priority list is a desired result.

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Biographical Sketches

Merlynn D. Bender: Mr. Merlynn Dean Bender is a hydraulic engineer and modeler at the Bureau of Reclamation, U.S. Department of Interior (DOI). Merlynn specializes in flow and water quality modeling of river and reservoir systems. He has worked for both Tennessee Valley Authority (TVA) and Reclamation. His contact information is Denver Federal Center, P.O. Box 25007, mail code 86-68220, Denver, Colorado, 80225, USA, phone: 303-445-2460, and email: mBender@usbr.gov.

Boualem Hadjerioua, PhD: Dr. Hadjerioua is the Deputy Water Power Program Manager at Oak Ridge National Laboratory (ORNL), he manages projects for Department of Energy (DOE) developing technologies, decision-support tools, and methods of analysis that enable holistic management of water-dependent energy infrastructure and natural resources. Prior to ORNL, Dr. Hadjerioua balanced stakeholder demands for the Tennessee Valley Authority (TVA). Dr. Hadjerioua (Bo) can be reached at P.O. Box 2008 MS6038, Oak Ridge, TN, 37831-6038, USA, phone: 865-574-5191 and email: Hadjeriouab@ornl.gov.