Application of W2 V4.5 SYSTDG to the Bonneville Reservoir for predicting downstream total dissolved gas concentration

Zhonglong Zhang, Department of Civil and Environmental Engineering, Portland State University

Introduction

The System Total Dissolved Gas (SYSTDG) model has been used to forecast Total Dissolved Gas (TDG) concentration downstream of reservoirs and optimize hydropower system operations for the Columbia River system (Scheider and Hamilton, 2015). The spillway TDG production equations developed for SYSTDG have been validated based on extensive TDG field studies conducted for the Columbia and Snake River dams. Currently, SYSTDG is the most complete container of knowledge regarding spillway TDG generation of dams on the Columbia River. TDG simulations were improved by implementing SYSTDG algorithms into the W2 model. Application to the Bonneville reservoir on the Columbia River was used to demonstrate this new capability.

SYSTDG is an Excel-based spreadsheet model used to compute TDG saturation levels in reservoir and riverine systems. Primary use of SYSTDG has been in real-time management to assist in setting daily TDG spill caps, but has occasionally been used in a planning capacity. SYSTDG contains regression equations for gas generation at each spillway and powerhouse based on outlet flow, tailwater depth, and barometric pressure (Fig. 1).

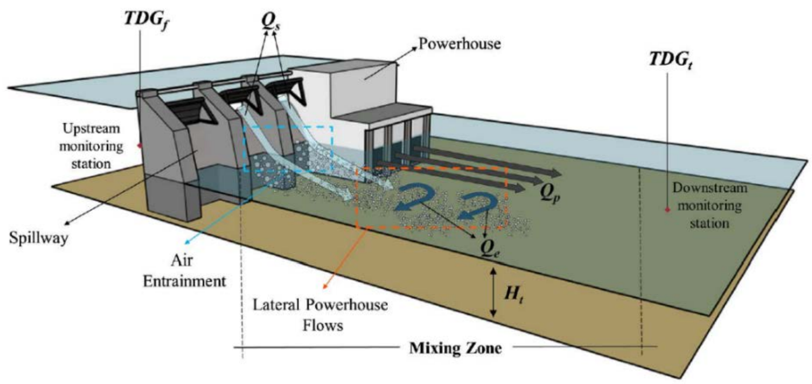

Fig.1. Physical processes of TDG production from downstream of a spillway.

The following five regression equations (Eq. 1 to 5) are included in SYSTDG for estimating gas generation at each spillway and powerhouse based on outlet flow, depth of the tailwater, and barometric pressure.

$$TDG_{sp} = P1 * \left(1 - e^{P3 * Q_{sp}}\right) + bp \quad (1)$$

$$TDG_{sp} = P1 * (twe - twce)^{P2} * \left(1 - e^{P3 * q_s}\right) + P4 + bp \quad (2)$$

$$TDG_{sp} = P1 * (twe - twce)^{P2} * {q_s}^{P3} + P4 + bp \quad (3)$$

$$TDG_{sp} = P1 * (twe - twce) + P2 \; * {q_s}^{P3} + P4 + \; bp \qquad (4)$$

$$TDG_{sp} = P1 * (1 - e^{P2 * q_s}) + P3 * (T_{tw} - P4) + \; bp \qquad (5)$$

where TDG_{sp} = spillway discharge total gas pressure (mmHg), ΔTGP_{sp} = spillway discharge gas pressure (mmHg), *bp* = observed barometric pressure (mmHg), *twe* = observed project tailwater elevation (feet), *twce* = project specific tailwater channel elevation (feet), *twe* - *twce* = tailwater channel depth (feet), T_{tw} = tailwater temperature (^{o}C), Q_{sp} = total project spillway discharge (kcfs), q_s = flow weighted specific spill bay discharge (kcfs), *P1* - *P4* = project specific coefficients (unitless).

The unit spillway discharge is a surrogate measure for the velocity, momentum, and exposure time of aerated flow associated with spillway discharge. The higher the unit spillway discharge, the greater the TDG exchange during spillway flows. Flow weighted specific spill bay discharge can be actual measured discharges through each spill bay or computed as a function of the spill pattern.

$$q_s = \frac{\sum_{i=1}^{nb} Q_i^C}{\sum_{i=1}^{nb} Q_i^{(C-1)}} \qquad (6)$$

where Q_i = discharge through spill bay i, *nb* = the number of project spill bays, *C* = spill pattern specific constant. The values of C used in SYSTDG range from 1 to 4.01 in the current set of spill patterns (SP) provided by the USACE. The larger the value of C, the more highly weighted the higher spillbay flows are.

In SYSTDG, the entrainment of powerhouse flows is computed as a simple linear function of spillway flows. As spillway flows increase relative to powerhouse flows, both bubble production and water entrainment ramp up to a point at which nearly all powerhouse flows are exposed to bubbles entrained at the spillway. The following three equations (Eq. 7 – 9) are included in SYSTDG for calculating the entrainment of powerhouse flow.

$$Q_e = E1 * Q_{sp} + E2 \qquad (7)$$

$$Q_e = min\left(\frac{Q_{tot}}{60}, 1\right) * E1 * Q_{sp} + E2 \qquad (8)$$

$$Q_e = min\left(\frac{Q_{sp}}{20}, 1\right) * E1 * Q_{sp} + E2 \qquad (9)$$

where Q_e = total powerhouse flow that is entrained in spillways (kcfs), Q_{tot} = total project discharge (powerhouse and spillway) (kcfs), *E1* - *E2* = project specific coefficients (unitless).

Downstream TDG is calculated based on two significant physical processes: TDG production through air entrainment and bubble dissolution, and the mixing of spillway flows with lateral powerhouse flows (Fig. 1). The mixing TDG pressures in the tailrace is modeled as the sum of flow weighted contributions of spillways and the powerhouse TDG pressures by:

$$TDG_{rel} = \frac{TDG_{sp}(Q_{sp}+Q_e)+TDG_{ph}(Q_{ph}-Q_e)}{Q_{ph}+Q_{sp}} \qquad (10)$$

where TDG_{rel} = project release TGP after mixing (mmHg), TDG_{sp} = spillway TGP (mmHg), TDG_{ph} = release TGP through the powerhouse turbines (mmHg), Q_{sp} = Total project spill (kcfs), Q_{ph} = Total flow through powerhouse turbines (kcfs).

Eq. 10 predicts tailrace TGP during spill events. Q_{ent}, Q_{sp}, Q_{ph} are known (gauged) or forecast. The entrained powerhouse flow was assumed to be exposed to the same conditions that spillway flows encounter and, hence, achieve the same pressures. TDG_{ph} pressures of flows released from the powerhouse are assumed equivalent to the TDG pressure in the forebay.

In W2, gate has a capability of specifying a time series data of flow rates for individual spillbays. Therefore, the TDG production equations derived by spillway operations were implemented through a gate structure in the model. Two TDG target locations were included, one for specified spill flow target, the other one for specified tailrace mixing zone target. TDG concentrations computed with the SYSTDG equations are directly written into the W2 model withdrawal output files. Withdrawal outflow files contain information with release or withdrawal TDG concentrations in time series output files. The applicability of the W2 model is general as long as the spillway TDG production coefficients can be estimated. Effects of hydraulic structures such as spillways, gates on oxygen and nitrogen gas reaeration are considered by adjusting their saturations with TDG supersaturation. Relative to their saturation concentrations, each gas concentration acts similarly to the others. Concentrations of DO and N2 released from spillbay gates are updated at the model simulation time step using the TDG supersaturation computed with SYSTDG equations.

$$N2 = N2_{sat} \cdot \%TDG \qquad (11a)$$

$$DO = DO_{sat} \cdot \%TDG \qquad (11b)$$

TDG saturation is computed below and reported as a derived water quality constituent in the W2 model output.

$$TDG\% = \left[79\frac{N2}{N2_s} + 21\frac{DO}{DO_s}\right] \qquad (12)$$

W2 model can also be used to determining if temporal and spatial distribution of spillway release TDG is being met at the right place and time for the spillway operations. This capability allows operators to allocate spill flows to minimize TDG production while meeting powerhouse maximum capacities. A constant or an external time-series of TDG targets (TDG_{ta}) is specified at spillway or tailrace (mixing zone) to represent target TDG gage location. Priority designations can be set for the spill bay to assist in choosing which spill bays are used and in determining which spill bays receive a greater proportion of the flow allocation. In the flow allocation calculation, the TDG target is assumed between TDG_{ph} and TDG_{sp}:

$$TDG_{ph} \leq TDG_{ta} \leq TDG_{sp}$$

If more than one spill bay exists, then the overall flow to the powerhouse is allocated equally from each spill bay, subject to minimum and maximum flow criteria of the powerhouse. The spill priority list is defined by the user. The numerical dichotomy method was applied to calculate the flow allocation from spill bays to the powerhouse.

Application of W2 V4.5 to the Bonneville reservoir

Bonneville reservoir on the lower Columbia River was selected as a demonstration site for validating the TDG prediction. Bonneville Dam is located on Columbia River Mile (RM) 146.1 and is a run-of-river dam (Fig. 2). The reservoir is 48 miles long, from Bonneville Dam to the foot of Dalles Dam upstream, with a surface area of 29.5 square miles, and a capacity of 537,000 acre-feet. The full forebay elevation is 77 feet, and the maximum forebay elevation is 82.5 feet. The Dam is 171 feet high and 2,477 feet long. The spillway is 1,070 feet long and contains 18 spill bays each with a 50 feet by 60 feet lift gate. Bonneville Dam is equipped with 2 powerhouse units, 18 spillbays, and 1 fish ladder (USACE, 2020a,b).

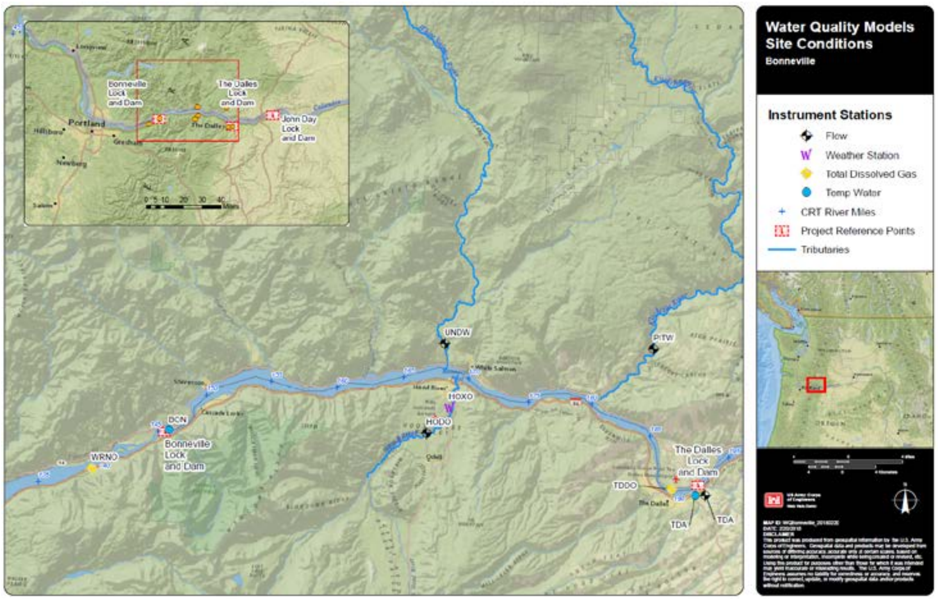

Fig. 2. Study site and lower Columbia River (USACE, 2020b)

The Bonneville W2 model domain extends upstream for 45.9 river miles to the Dalles Dam and has 75 longitudinal segments of varying widths and 56 vertical layers of varying heights. The model includes 2 powerhouse units and 18 spillbays. The spillway flow was spread across all spillbays. Powerhouse No. 1 flows were modeled as a “line” source 313 m in length. Powerhouse No. 2 flows were modeled as a “line” source 300.5 m in length, but limited to 242 m by the model’s geometry at the discharge elevation. The spillway flows were modeled as a “line” source 442 m in length, limited by the model width of 316 m at the discharge depth. The fish ladder flow and any flows not accounted for in the spillway and powerhouse were combined into a single miscellaneous flow category. Only incoming flow to the reservoir considered in the model was the upstream Columbia River, as no other significant tributaries are present in the system (USACE, 2020).

Bonneville Reservoir downstream TDG have been measured on an hourly basis at two locations: (1) WRNO Warrendale, located six miles downstream of Bonneville Dam, and (2) CCIW Bonneville Dam tailwater at the TDG gauge on Cascade Island. The TDG percent saturation was obtained by dividing the TDG pressures recorded with the local barometric pressure determined by a reference barometer at the monitoring station. Data from WRNO are compared to the blended TDG concentrations from Bonneville Dam assuming that the outflows will be well mixed before six miles downstream. Data from CCIW were used to compare with modeled releases from the spillway, as the TDG gauge was deployed to evaluate gas levels below the spillway. In general, TDG data were only recorded from March to September of each year.

Graphical comparison between W2 modeled and observed TDG at the Bonneville Dam tailwater is presented in Fig. 3. The model captures a number of distinct system characteristics well, including the range of maximum to minimum TDG throughout the system, daily and weekly fluctuations in TDG, overall system variability in TDG magnitude, and most importantly, project-specific dependence of TDG uptake on spillway flow.

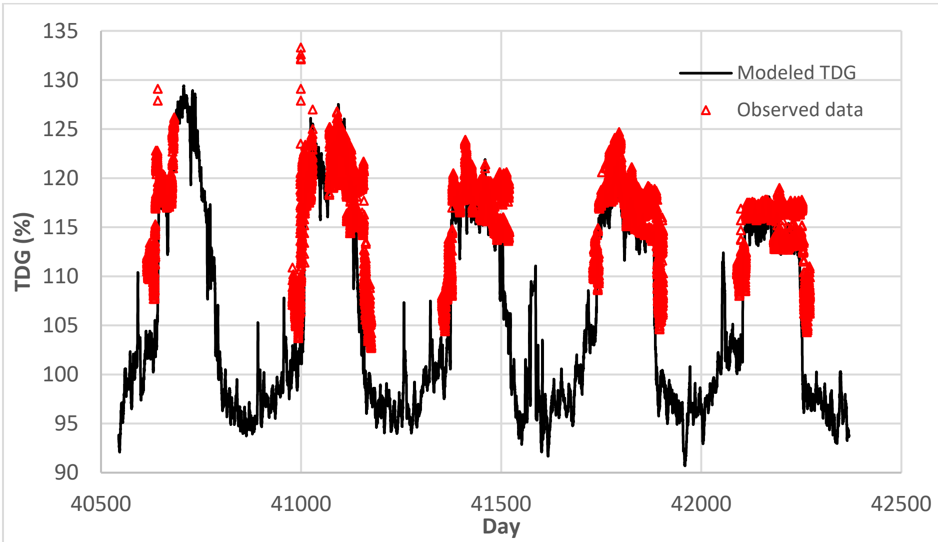

Fig. 3. Time series comparison of W2 modeled and observed TDG at Bonneville tailwater

To demonstrate the spill flow allocation capability implemented in W2, the seasonal TDG targets at the Dam tailwater set ranging from 115% to 125% shown in Fig. 4. Spillway TDG concentrations above the TDG targets occurred during the spill seasons. The W2 model was then applied to allocate spill bay flow into the powerhouse to reduce the saturation of spill TDG and achieve the TDG targets.

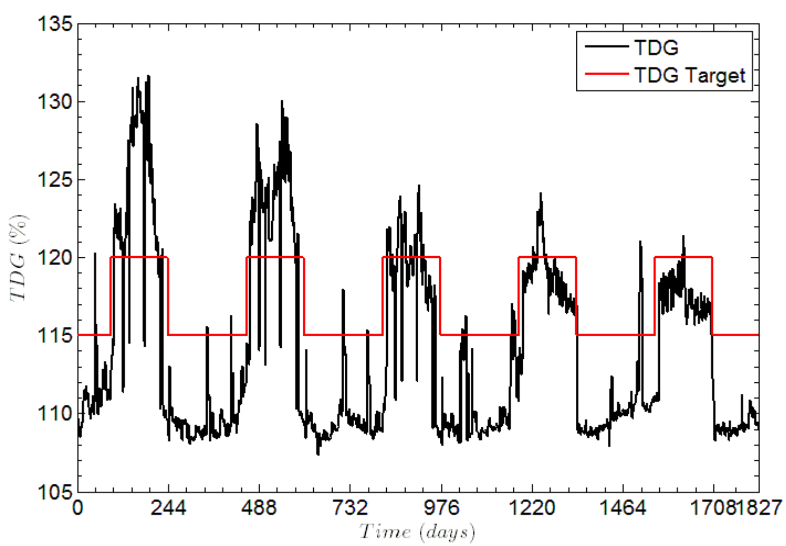

Fig. 4. Spillway TDG released from Bonneville Dam with varying TDG standard.

The existing total flow, the power house flow and spillway flows released from the Bonneville Dam are shown in Fig. 5(a). The maximum powerhouse capacity as limited by unit availability for the Bonneville Dam was 212 kcfs. Fig. 5(b) presented the updated spillway and powerhouse flows after an allocation was conducted based on the same priority for all individual spill bays. Under this assumption, a significant amount of spillway flow was allocated into the powerhouse during the spill seasons.

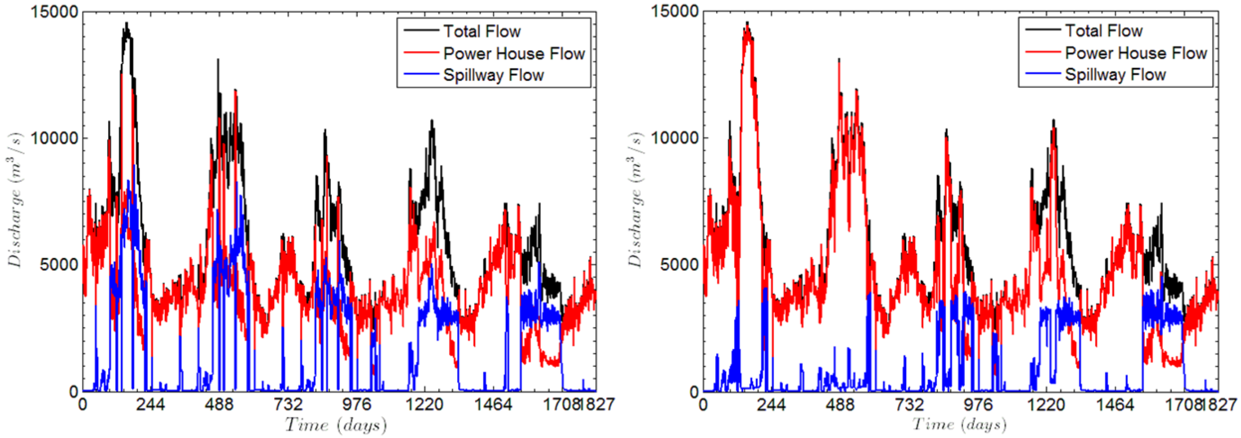

Fig. 5. Spillway and powerhouse flows released from Bonneville Dam for (a) before (b) after performing a Spill flow allocation set by the TDG target.

The predictive equations, coefficients, and constraints in SYSTDG were incorporated into W2 in support of the Columbia River System Operations (CRSO) study. The SYSTDG capabilities in W2 were validated against observed data by the CRSO modeling team, the model results showed that the SYSTDG features in the W2 model function well.

Acknowledgments

The Bonneville reservoir W2 V4.1 model was developed by the Columbia River System Operations (CRSO) water quality team: Kathryn Tackley, Dan Turner, Norm Buccola, and Tammy Threadgill of USACE.

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