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FIELD STUDY ON THE DECAY OF SUPERSATURATED TOTAL DISSOLVED GASES IN THE LOWER COLUMBIA RIVER DOWNSTREAM OF HUGH L. KEENLEYSIDE DAM

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Abstract: Reliable prediction of the decay of supersaturated total dissolved gases (TDGs) produced by hydropower operations is crucial to evaluating potential hydro-environmental-ecological impacts downstream of facilities. For quantitative prediction of TDG decay under different gate operation scenarios, detailed measurements of TDG and river hydraulics were collected in the Lower Columbia River downstream of Hugh L. Keenleyside Dam near Castlegar, British Columbia. The measured data in conjunction with an analytical approach was utilized to estimate the mixing and decay rates for four different operational conditions of low level outlet gates. For dimensionless mixing coefficients of 0.6 and 0.2 for the two sub-reaches of the river, the average decay rate was 0.017 hr^{-1}. Comparison with available decay equations and some widely used reaeration models indicated that further investigation would be useful to assess their applicability in the case of supersaturated TDGs and develop a predictive tool to estimate decay.

1 INTRODUCTION

Supersaturation of total dissolved gases (TDGs) often occurs in hydropower facilities as a result of voluntary (e.g. facilitating non-turbine fish passage) or involuntary (releasing excess water) spills, and may pose adverse environmental and ecological effects (Weitkamp, 2008). It is generally caused by the entrainment of air in the form of bubbles during spillway releases and the subsequent transfer of atmospheric gasses (primarily nitrogen and oxygen) into water. As the flows move out of the tailrace, the net mass transfer reverses resulting in TDG dissipation. Supersaturated dissolved gases dissipate through decay at the free surface and mixing with adjacent waters which are dependent on factors like velocity, turbulence, available surface area, and river depth (Geldert et al., 1998). The excess TDG decays through gas exchange in the air-water interface and requires a long time to diffuse out of the river. Therefore, elevated or even supersaturated gas levels may persist far downstream from the source of supersaturation and can result in fish mortality (e.g. gas bubble disease) and other impacts to the aquatic environment.

The decay of TDG comprises of various physical, biological, and chemical processes where the physical component is driven by gas exchange at the air-water interface. This transfer process (i.e. decay) across the gas-liquid interface is of fundamental importance to understanding the distribution of TDG in the natural environment. The process becomes more complicated when spilled water with high TDG concentrations mixes with generation discharge downstream, and with any tributary inflows. A limited number of studies have been reported on the direct quantification of TDG decay. Most of the previous studies considered the decay rate by incorporating surface gas transfer rate at the air-water interface by replacing it with semi-empirical reaeration equations based on the surface renewal or the energy dissipation model. Given the complexity of the generation and dissipation process, the decay rate should be evaluated directly in order to assess the impact of TDGs in fish, fish habitat, and the downstream environment. Therefore, the objective of the present study is to assess the decay rate of TDG for different operational conditions in hydropower facilities. This study is based on the extensive field work carried out on the Lower Columbia River downstream of Hugh L. Keenleyside Dam (HLK) at Castlegar, BC. Detailed monitoring of TDG as well as hydraulic measurements were carried out for different combinations of low level gate (LLOG) operations of the dam to assess the TDG decay rate for these conditions.

2 Theoretical Background

In general for a non-conservative substance like TDG, the depth averaged concentration (*C*) can be described by the advection-dispersion equation with a first-order decay term (Fischer et al., 1979):

[1] $$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y} = E_l\frac{\partial^2 C}{\partial x^2}+E_t\frac{\partial^2 C}{\partial y^2} - kC$$

where *u* and *v* are velocities in *x* and *y*-directions respectively; E_l and E_t are the corresponding dispersion coefficients and *k* is the decay rate. For accurate prediction of TDG distribution in the river, both mixing and decay rate should be evaluated based on field measurements. When the flow is not completely mixed, i.e. at the near and intermediate mixing zone of a river, the transverse mixing coefficient (E_t) usually governs the concentration distribution across the channel. It is usually difficult to control the quality of field data due to the non-conservative nature of the substance, inadequate number of samplings, or measurement errors. Therefore, the field data should be used in conjunction with analytical methods to estimate E_t (Zhang and Zhu, 2011). Using the concept of cumulative discharge, the simplified, steady-state distribution of a non-conservative substance can be written as (Gowda, 1984):

[2] $$\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial q^2} - \frac{kC}{U}$$

where *q* is the cumulative discharge; *U* is the mean velocity in *x*-direction and *D* is the factor of diffusion. Downstream of hydropower facilities, TDG concentrations can vary laterally and the two-dimensional distribution can be described by Eq. (2). Assuming a line source of high TDG stretching from $q = q_1$ to $q = Q$ (as in the case of spill), the analytical solution of Eq. (2) for a conservative case can be written as:

[3] $$C_i(x, q) = C_b+\left(\frac{C_o-C_b}{2}\right)\left[\mathrm{erf}\left(\frac{q-q_1}{\sqrt{4Dx}}\right)-\mathrm{erf}\left(\frac{q-Q}{\sqrt{4Dx}}\right)\right] + \text{Image sources}$$

where *Q* is the total discharge; C_o is the maximum TDG concentration at the initial section and C_b is the background concentration corresponding to generation flow or tributary inflow. Image sources were included to account for the effect of banks on concentration distribution. In order to evaluate transverse mixing coefficient (E_t), the factor of diffusion can be expressed as follows (Rutherford, 1994):

[4] $$D = \psi E_t U H^2$$

where *H* is the average depth and ψ is the dimensionless shape factor that has been reported to be in the range from 1.0 – 3.6 (Rutherford, 1994). When supersaturation occurs, the exchange of mass at the air-water interface (i.e. decay) during transport through the river system drives TDG levels towards equilibrium conditions with the atmosphere. Since the high concentrations could dissipate by both mixing and decay, Eq. (3) can be utilized to estimate the transverse variation in TDG concentration. Then the final concentration of TDG incorporating decay can be obtained as follows:

[5] $$C = C_s+(C_i-C_s)\exp(-kt)$$

where *t* is the travel time of water ($t = x/U$) and C_s is the saturation concentration and is usually 100% at atmospheric pressure. For gases of low solubility (such as nitrogen and oxygen), the decay of TDG across the air-water interface depends on the molecular and turbulent transport processes in the water layer similar to the process of reaeration. For such cases, two widely used semi-empirical treatments of gas transfer are the surface renewal model and the energy dissipation model. For isotropic turbulence, the gas transfer rate according to the simplified surface renewal model of O'Connor and Dobbins (1958) can be expressed as follows:

[6] $k \propto U^{1/2}H^{-3/2}$

In the energy dissipation model, the dependence of gas transfer on turbulent transport and diffusivity can be modeled in the form (Moog and Jirka, 1999) as follows:

[7] $k \propto Sc^{-1/2}R_*^{-n}$

where S_c is the Schmidt number and R_* is the turbulent Reynolds number. The Reynolds number exponent (n) is ½ for the large eddy model and ¼ for the small eddy model.

3 FIELD WORK

3.1 Description of the Study Site

The Hugh Keenleyside Dam (HLK) and Arrow Lakes Generating Station (ALH) form the lower-most of three Hydroelectric Projects (along with Mica Dam and Revelstoke Dam) on the Canadian portion of the Columbia River. The dam is located 7 km upstream of the City of Castlegar, BC and approximately 57 km upstream from the BC-Washington border. The 52 m high dam impounds the Arrow Lakes Reservoir and was constructed for the Columbia River Treaty in 1968, with generating capacity at ALH added in 2002. There are two styles of outlet gates at HLK - four radial spillway outlet gates (SPOGs) and eight low level outlet gates (LLOGs). Relative to the position of the spillway, the first four low level gates are referred to as northern LLOGs while the other four are denoted as southern LLOGs. These units are collectively capable of discharging up to 10,500 m^3/s (Bruce and Plate, 2013). The ALH Generating Station is located directly north of the HLK facility (Figure 1). It receives water through a power canal inlet, which was located approximately 900 m upstream of HLK. Maximum turbine discharge through ALH is 1,150 m^3/s. The confluence of the Lower Columbia River and the Kootenay River is located approximately 10 km downstream of HLK. The Brilliant Dam is the furthest downstream dam on the Kootenay River, located about 2.5 km upstream from the confluence. The region for the current field work comprised of the lower reach of the Columbia River from HLK to about 20 km downstream including the Kootenay River confluence.

Figure 1: Study site at the Lower Columbia River with measurement locations

3.2 TDG Monitoring and Hydraulic Measurement

The field work in the Lower Columbia River was conducted from July 26 to July 30, 2016 for different combinations of gate settings at the HLK. A total of four scenarios of different LLOGs operations were implemented for the present study which were operated for longer duration. Detailed measurements were carried out for these scenarios. Table 1 shows the operational conditions of different gates for these scenarios along with the flow conditions. The spill rates (Q_s) mentioned in the table were the total flow through the gates. Flow through individual units and height of gate opening were different for these scenarios. Detailed operational modes and their effect on the generation of TDG will be found in a companion paper (Billay et al., 2017).

Table 1: Various gate operational scenarios for the field work

Scenario	Gate operation	Spill rate Q_s (m^3/s)	Generation flow Q_g (m^3/s)	Kootenay R. inflow Q_K (m^3/s)
1	3 Northern LLOGs	1025.6	1085	585.21
2	3 Southern LLOGs	934.7	1100	573.33
3	2 Southern + 2 Northern LLOGs	1110.5	1100	530.43
4	1 Southern + 2 Northern LLOGs	1023.3	1081	528.50

Measurements of TDG for the operational scenarios were conducted at various locations through combination of spot measurements from the boat as well as continuous monitoring from floating platforms designed to capture temporal variation of TDG. The total gas pressure (TGP), barometric pressure (BP) and water temperature was collected by two types of probes – the Lumi4 DO-TGP probe and PT4 Smart TGP probe (manufactured by Point Four Systems Inc.). These probes are capable of recording TGP and BP readings with an accuracy of ±2 mmHg resulting in an overall accuracy of 4% for TDG measurement (Pentair Aquatic Eco-Systems, 2014).

Using floating platforms, TDG was monitored continuously at the left bank at 0.98 km; at the right banks of 4.39, 6.70, 11.30 and 19.68 km, and upstream on the Kootenay River with PT4 Smart TGP probes. In addition, two continuous monitoring stations were installed on the right bank of the HLK tailrace (courtesy: James Bruce). Before installation and deployment, each of the probes was calibrated and set to record data continuously at 2 minute intervals at about 1 m depth. The spot measurements were taken along seven transects downstream of HLK (as shown in Figure 1). In addition, measurements were also taken along a transect in the forebay and at a point close to the spillway gates in the tailrace. The spot measurements were taken by the Lumi4 DO-TGP probe at a depth of about 1 m below the water surface. For each measurement, sufficient time (5 – 15 minutes) was allowed so that the probes could acquire stable TGP readings. These measurements were carried out in all seven transects for scenarios 2 and 3. Due to time limitations and other constraints it was not possible to take measurements at 0.56 and 0.98 km for scenario 1 and at 11.30 and 19.68 km for scenario 4. In all cases, the locations of TDG measurement were recorded using a handheld GPS. Uncertainty in TDG measurements could arise due to the inaccuracy of the instruments, of the measurement, or operator error. From the recorded TDG at the continuous monitoring stations, the fluctuation in percent saturation over time for the same condition (related to precision error) was typically ≤ 0.2%. The bias error, associated TGP and BP measurements, was about 0.4%. The overall uncertainty was well within the accuracy of TDG measurement.

In order to understand TDG dissipation mechanisms and their relation to various hydraulic features, a RiverRay 600 kHz Acoustic Doppler Current Profiler (ADCP) was used to measure velocity and flow at the HLK tailrace and downstream Lower Columbia River. The ADCP was equipped with a universal mount, a trimaran and an external GPS (DGPS) to record the locations. The ADCP measurements were carried out in each of the tailrace and downstream river transects as shown in Figure 1. The measurements were completed by driving the boat slowly across the transects allowing for simultaneous measurement of velocity and discharge. Each of these transects were repeated 3 to 4 times for accuracy and comparison purposes. These measurements obtained transverse variations of velocity which were utilized to calculate cumulative flow at each transect.

During the period of field work, the HLK releases varied from 934.7 m^3/s (scenario 2) to 1110.5 m^3/s (scenario 3), while the ALH flow remained consistent at about 1081 to 1100 m^3/s resulting in a spill-to-generation flow ratio of about 1.0 for all the scenarios. The discharge measured by ADCP at the first five transects showed similar flow rates (Table 2), except for the transect at 0.98 km. In this location it was not possible to cover the whole cross section due to the presence of log booms along the right bank. As a result, about 50 m length was not measured by the ADCP and hence the discharge was found to be lower compared to other transects. At transect 11.30 and 19.68 km, the discharges were about 2630 and 2445 m^3/s, indicating the additional inflow coming from the Kootenay River. Table 2 outlines some of the basic hydraulic parameters at different transects obtained from the ADCP measurements.

Table 2: Basic hydraulic parameters collected in the transects

Reach	**Trans.** (km)	***Q*** (m^3/s)	***U*** (m/s)	***B*** (m)	***H*** (m)	S_o (×10-4)	***U**** (m/s)	***Ψ***	***Fr***
1	0.56	2069.9	0.43	309.6	15.89	0.492	0.086	2.34	0.03
	0.98	1736.0	0.61	259.5	13.18		0.078	1.63	0.05
	2.03	2111.4	0.48	338.8	13.62		0.080	2.59	0.04
	4.39	2089.9	0.48	328.9	13.42		0.080	1.89	0.04
	6.70	2086.5	0.49	409.8	10.31		0.070	1.96	0.05
2	11.30	2629.5	1.82	199.6	7.42	4.218	0.174	1.83	0.21
	19.68	2444.4	0.75	200.0	17.29		0.075	3.25	0.06

Note: Q = total discharge; U = mean velocity; B = channel width; H = mean depth; S_0 = slope of the reach; U^* = shear velocity = $(gRS_o)^{0.5}$; Ψ = shape factor; Fr = Froude number = $U / (gH)^{0.5}$

4 RESULTS AND DISCUSSION

4.1 TDG Distribution and Flow Hydraulics

In the Lower Columbia River, flows exiting from the HLK showed marked distinction in TDG concentrations between the spill and generation discharges, with spill releases containing high level of TDG compared to the powerhouse releases (Figure 2). The discharge coming from the HLK (through LLOGs) was similar to the flow rate of ALH, with similar spill-to-generation flow ratios for all the scenarios. For these scenarios, TDG concentrations near the left bank (corresponding to ALH generation flow) were comparatively low with initial TDGs (at 0.56 and 0.98 km) in the range of 108-110% which were similar to the measured TDG in the forebay. From continuous monitoring station at the tailrace, it was found that the maximum TDG for scenario 1 was 112%. Depending on the gate operation, the maximum TDG at 0.56 km, i.e. generated TDG, was 122, 116 and 113% for scenarios 2, 3 and 4 respectively. The TDG was mixed between the two flows and simultaneously decayed as the water moved downstream. As a result, the TDGs along the left bank were found to increase with distance. For most of the downstream transects, the maximum TDG was found near the right bank. At 7 km downstream, the maximum TDG was 110% for scenario 1 and 117% for scenario 2. ADCP measurements showed the cross-sectional mean velocities at the transects from 0.56 to 6.70 km varied from 0.43 to 0.61 m/s (Table 2). The Froude number in this reach ranged from 0.03 to 0.05.

The flow condition changed after the Kootenay River confluence with inflow coming from the release of Brilliant Dam. The velocity was very high at 11.30 and 19.68 km (Table 2) with this additional flow passing through comparatively narrower and shallower cross sections. At these transects, the Froude numbers were 0.2 and 0.06 respectively. Downstream of the confluence, the TDG distribution was also found to be affected by the two converging rivers with different TDG levels. Continuous monitoring and some spot measurements showed that the Kootenay inflow had TDG concentrations in the range of 106 to 109%. Spot measurements at 11.30 km showed that the maximum TDG was 114% for scenario 2 and 111% for scenario 3, while the left bank had TDGs of 109% for both cases. At 19.68 km, the maximum concentrations varied from 109-114% depending on the scenarios.

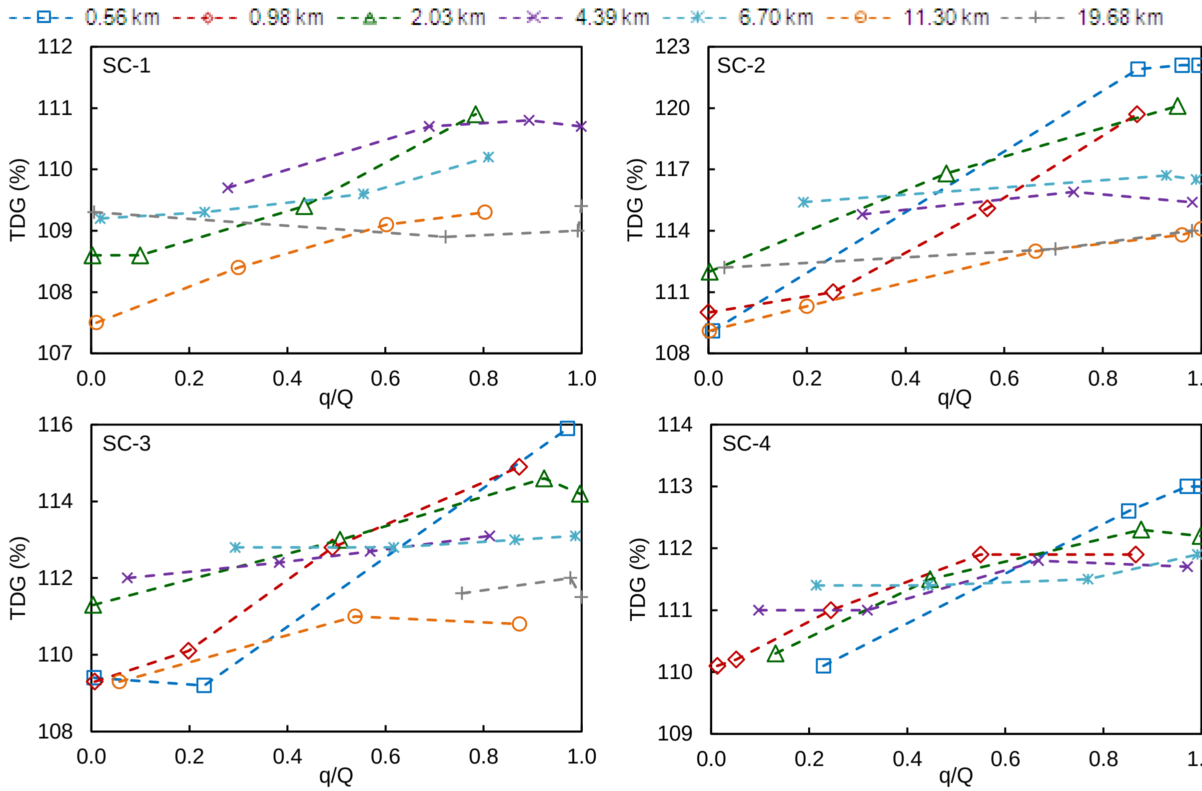

Figure 2: TDG at the downstream transects for different scenarios

4.2 Analysis on Transverse Mixing

As seen from Figure 2, the two flows of different TDG concentration changed downstream, as TDG was dissipated through mixing within the water and decay at the air-water interface. Since the release from HLK (spills) mixed with ALH flow initially and then the flow received inflow from Kootenay River, the two-dimensional distribution of TDG can be described by Eq. (2). Then using Eq. (3) and (4), the transverse mixing coefficient could be obtained from the lateral distribution of the measured TDG across the individual cross-sections. Most of the existing methods to evaluate mixing coefficient place emphasis on the use of raw field data. Because of the sparsely measured data with limited number of samplings (Figure 2) and non-conservative nature of TDG, such methods might not be useful for the current case.

In the present study, various dimensionless transverse mixing coefficients (E_t/HU^*) were assumed and compared with the measured data to obtain the mixing coefficient. In natural rivers, this dimensionless coefficient can vary from 0.3-0.6 for regular channels, 0.6-0.9 for gently meandering channels and 1-3 for sharp curved channels (Fischer et al. 1979; Rutherford 1994). Figure 3 shows theoretical concentration profiles calculated for dimensionless mixing coefficients ranging from 0.1 to 0.9 in different transects and their comparison with the measured data of scenario 2. Since the confluence of the Kootenay River adds additional flow, the study reach was divided into two sub-reaches. For these reaches, the factors of diffusion (D) were evaluated from E_t assuming the coefficients would remain same with the slightly varying discharge conditions for different scenarios. A comparison of Figure 2 and Figure 3 showed that the value of E_t/HU^* was about 0.6 and 0.2 for the two above mentioned reaches. In reach 1 (upstream of confluence), the corresponding mixing coefficient was 0.631 m^2/s, while E_t was found to be 0.313 m^2/s in reach 2 (downstream of confluence). The higher value of the mixing coefficients at the upstream reach was not surprising, considering the highly turbulent conditions in the downstream of the dam.

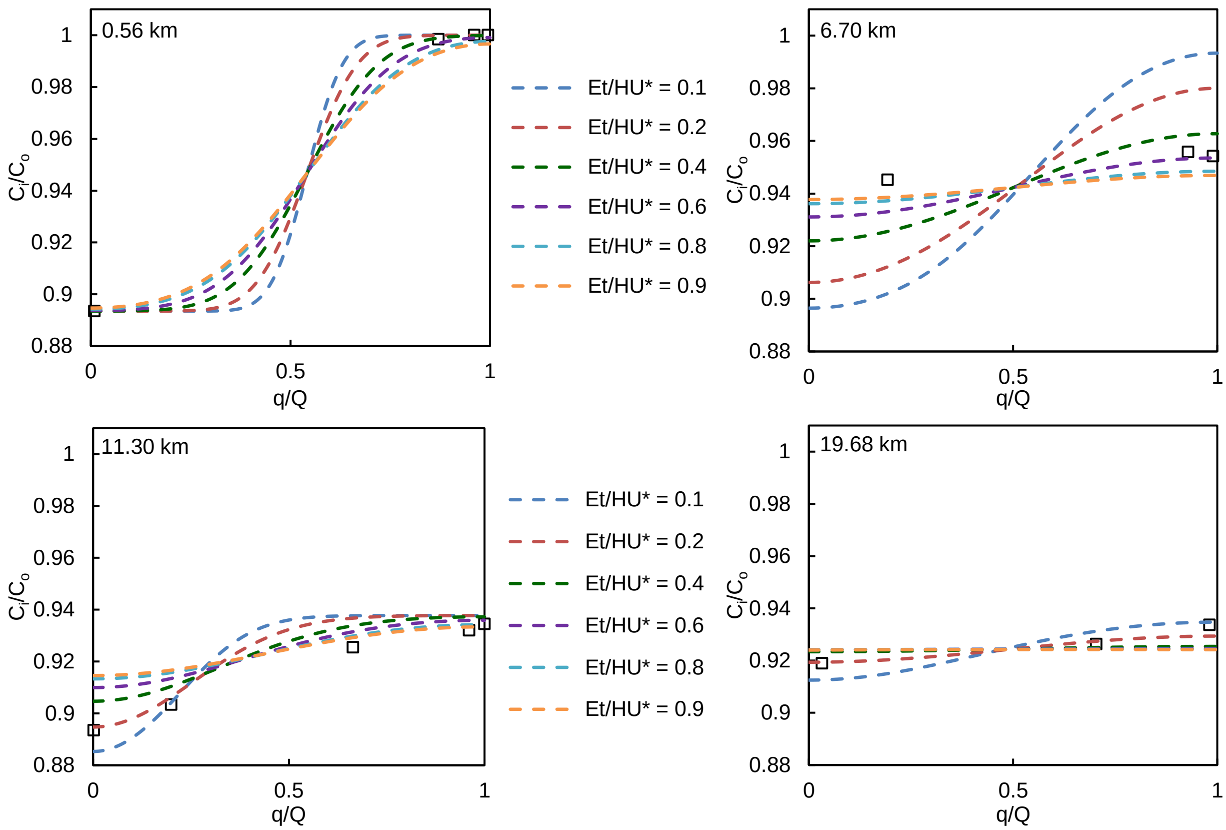

Figure 3: Analysis of transverse mixing coefficient for the two sub-reaches (square symbol represents the measured data for scenario 2)

4.3 Estimation of Decay Rate

Measurements showed that lateral gradients in TDG existed in the Lower Columbia River due to differential concentrations of spillway and powerhouse releases. However as seen from Figure 2, the change in concentrations along the river was not similar across the transects. As a result of mixing and decay, the TDGs along the left banks increased with downstream distance up to the confluence of the Kootenay River. On the other hand, TDG concentrations along the right banks (associated with high TDGs from spills) tended to decrease. Therefore in the present study, the TDG decay was estimated by following the flow of high TDG water released from the low level gates. Since the high concentrations could dissipate by both mixing and decay, Eq. (3) was utilized to estimate the transverse variation in TDG concentration. Then the final concentration of TDG incorporating decay was obtained using Eq. (5).

Since background concentration in the river was 108 to 110%, the saturation concentration was taken as 108% for the present analysis. Eq. (5) was employed to estimate the decay rate of TDG for various scenarios. TDG concentrations measured at 0.56 km was applied as the initial or reference concentration, while the mean velocities (Table 2) obtained from the ADCP measurements were used in the calculation. Then the decay rates were obtained by fitting the calculated concentrations with measured data based on the least square method. Using this method, the rates of decay were 0.012, 0.013, 0.02 and 0.019 hr^{-1} respectively for scenarios 1-4 with an average value of 0.016 hr^{-1}. Figure 4 shows the calculated TDG concentrations at various transects for scenarios 2 and 3 along the spill flows (from $q = Q_g$ to $q = Q$, where $Q_g = Q - Q_s$). These calculated profiles incorporated both mixing and decay.

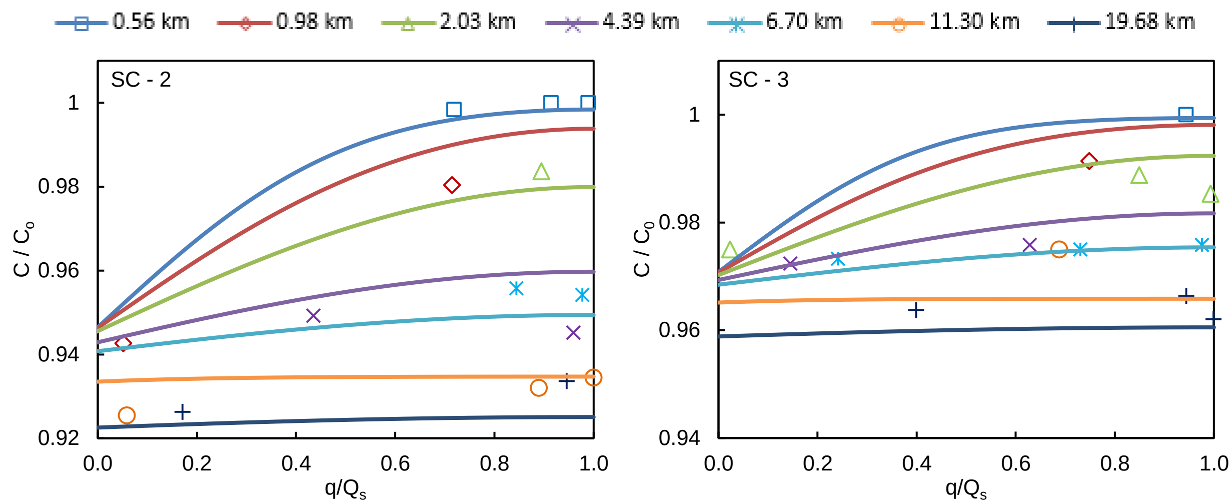

Figure 4: Calculated TDG incorporating mixing and decay for scenarios 2 and 3 with measured data

The variation of temperature could affect the rate of decay and usually it increases with rising temperature (Shen et al., 2014). Therefore the usual practice is to present decay rates corresponding to a standard temperature of 20 ^{0}C. The values of k could be temperature corrected relative to 20 ^{0}C with the simplified equation as follows –

[8] $k = k_{20}(1.0241)^{(T-20)}$

where *T* is the measured river water temperature. The temperature corrected decay rates are shown in Figure 5. The corresponding average decay rate was 0.017 hr^{-1}.

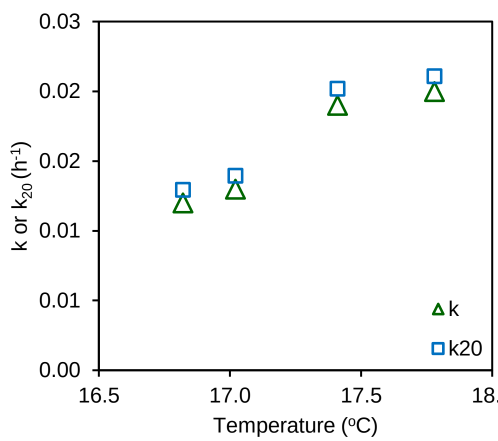

Figure 5: Decay rates for different scenarios in relation with temperature

The US Army Corps of Engineers (USACE 2001) proposed an equation to estimate decay based on surface renewal theory. Recently Feng et al. (2014) developed a semi-empirical relationship by including the effect of water depth, shear velocity, hydraulic radius, and Froude number. The decay rate obtained in the present study was found to be much higher compared to the calculated rates using these methods (Table 3). The USACE equation simply considered the velocity and depth as governing parameters which might not always be applicable for turbulent flow. The equation developed by Feng et al (2014) underestimated the decay rate as well. It might be due to the reason that the equation was formulated for relatively shallow rivers with Froude Numbers ranging from 0.11 to 0.54, which might not be applicable to deep rivers like the Lower Columbia River. However, the form of the model could be useful to relate decay with the variation of flow.

Table 3: Decay rate of TDG using different methods

Method	Equation	Decay rate, k (hr^{-1})
Present study	-	0.017
USACE (2001)	$k = \left(\frac{D_m U}{H^3}\right)^{1/2}$	0.0033
Feng et al. (2014)	$k = 0.0037\frac{U^*}{R}\left(\frac{H}{R}\right)^{2.02} Fr^{1.73}$	0.0026

4.4 Comparison with Gas Transfer Theories

Gas transfer across the air-water interface is difficult to measure in the field and therefore, empirical methods based on the fundamental gas transfer theories are generally used. Numerous equations based on mean velocity, shear velocity, channel slope, depth, and Froude number have been developed to estimate the stream reaeration coefficient, K_a. A number of studies have also included the effect of wind. In the present study, some of the most widely used formulae have been used as outlined in Table 4. These predictive equations referred to a standard temperature of 20 °C. The field data obtained from the hydraulic measurements in the Columbia River was utilized in these equations in order to determine the values of K_a and compare them with the estimated decay rate.

Analysis of the reaeration equations presented an overall poor performance, with most of the equations under or over predicting the decay rate except the equation given by Thackston and Krenkel (1969). Such variation likely resulted due to different hydraulic conditions from which the study data were collected and the fact that the principal gas transfer mechanisms could vary with hydraulic conditions. The reaeration rates calculated by the methods given by O'Connor and Dobbins (1958), Churchill et al. (1962) and Bennett and Rathbun (1972) was found to be much lower compared to the estimated decay in the current study. These equations primarily used velocity and depth as key variables which might not be always representative for turbulent flow conditions as in the case of downstream regions of hydropower facilities. The methods that incorporated channel slope (Tsivoglou and Wallace, 1972 and Moog and Jirka, 1998) over predicted the decay rate indicating that the slope might not be a governing variable for our case. According to the equation of Thackston and Krenkel (1969), the value of K_a was 0.011 hr^{-1} which was close to the estimated decay rate. This implied that addition of parameters that relate turbulence such as the shear velocity and Froude number, could be useful as predictor variables to estimate decay.

Table 4: Estimation of reaeration coefficient (K_a) using predictive equations

Reference	**Equation** (1/day at 20 °C)	**K_a (hr^{-1})**		
		Reach 1	Reach 2	Average
O'Connor and Dobbins (1958)	$K_a = 3.9\, U^{0.5} H^{-1.5}$	0.002	0.004	0.003
Churchill et al. (1962)	$K_a = 5.01\, U^{0.969} H^{-1.673}$	0.001	0.004	0.003
Thackston and Krenkel (1969)	$K_a = 24.9\,(1 + Fr^{0.5}) U^* H^{-1.0}$	0.007	0.014	0.011
Bennett and Rathbun (1972)	$K_a = 32.5\, U^{0.413} S_0^{0.273} H^{-1.408}$	0.002	0.005	0.004
Tsivoglou and Wallace (1972)	$K_a = 22500\, S_o U$	0.023	0.506	0.265
Moog and Jirka (1998)	$K_a = 1740\, U^{0.46} S_0^{0.79} H^{0.74}$	0.141	1.130	0.636

5 CONCLUSIONS

The current study presents a methodology to estimate the decay rate of supersaturated TDG in a large regulated river through a combination of field measurements and analytical modelling. Detailed field monitoring of TDG in the Lower Columbia River downstream of Hugh L. Keenleyside Dam indicated differential TDG concentrations between the spill releases and the generation flows. Variations in concentrations were also observed between the Columbia River flow and Kootenay River inflow downstream of the confluence. For four different spill scenarios of low level outlet gates with similar hydraulic condition, the maximum TDG were 112, 122, 116 and 113% while the initial concentrations corresponding to the generation flows were in the range of 108-110%. Downstream of the Kootenay River confluence, the maximum TDG varied from 111 to 114% depending on the gate operations. Analyses of the measured TDG for the operational scenarios showed that the decay rate varied from 0.013 to 0.02 hr^{-1}. For dimensionless mixing coefficients of 0.6 and 0.2 for the two sub-reaches of the river, the average decay rate was 0.017 hr^{-1} at standard temperature. Due to greater depth and low Froude Number in the river, the estimated decay rate was found to be much higher compared to the calculated rates based on other available methods. Comparison with some widely used reaeration equations indicated that shear velocity and Froude number could be considered in the predictive equations to estimate decay. However, all of these analyses were carried out for similar hydraulic conditions. TDG prediction and decay rate estimation can be improved by incorporating data for different hydraulic conditions and employing more detailed analytical and numerical approaches.

References

Bennett, J. P. and Rathbun, R. E. 1972. Reaeration in open-channel flow. *USGS Prof. Pap. 737*, U.S. Government Printing Office, Washington, DC.

Billay, G., Zhu, D., Bruce, J., Leake, A. and Crossman, J. 2017. Field Observations and Analysis of Total Dissolved Gas Generation on the Lower Columbia River Downstream of the Hugh L. Keenleyside Dam. Paper submitted to the 23rd Hydrotechnical Conference, Vancouver, Canada.

Bruce, J.A. and Plate, E. 2013. Total Dissolved Gas Supersaturation Downstream of Hugh Keenleyside Dam: A Model-based TGP Risk Assessment of Facility Operations that Reduce Reliance on Low Level Ports for Water Conveyance. *Report Prepared for BC Hydro, Burnaby BC*. Creekside Aquatic Sciences Report No. CAQ-001: 40 p + app

Churchill, M. A., Elmore, H. L. and Buckingham, R. A. 1962. The prediction of stream reaeration rates. *J. Sanit. Eng. Div*., 88(4), 1–46.

Feng, J., Ran, L., Gian, M. and Le-Le, W. 2014. Experimental and field study on dissipation coefficient of supersaturated total dissolved gas. *J. Cent. South Univ* 21:1995−2003

Fischer, H. B., List, E. G., Koh, R. C. Y., Imberger, J. and Brooks, N. H. 1979. *Mixing in Inland and Coastal Waters*. Academic Press, New York, NY.

Geldert, D.A., Gulliver, J.S. and Wilhelms, S.C. 1998. Modeling dissolved gas supersaturation below spillway plunge pools. *J. Hydrol. Eng.* 124(5): 513-521.

Gowda, T. P. H. 1984. Water quality prediction in mixing zones of rivers. *J. Environ. Eng.*, 110(4), 751–769.

Moog D. and Jirka, G. 1998. Analysis of reaeration equations using mean multiplicative error. *Journal of Environmental Engineering*, 112(2): 104–110.

Moog, D. and Jirka, G. 1999. Air-Water Gas Transfer in Uniform Channel Flow. *J. Hydraul. Eng*., 125:1(3), 3-10.

O'Connor, D. J. and Dobbins, W. E. 1958. Mechanism of reaeration in natural streams. *Trans. Am. Soc. Civ. Eng*., 123, 641–684.

Pentair Aquatic Eco-Systems. 2014. PT4 TGP Probe Technical Manual.

Rutherford, J.C. 1994. *River mixing*. John Wiley & Sons, West Sussex, England.

Shen, X., Liu, S.Y., Li, R. and Ou, Y.M. 2014. Experimental study on the impact of temperature on the dissipation process of supersaturated total dissolved gas. *Journal of Environmental Science*, 26(9), 1874-1878.

Thackston, E. L. and Krenkel, P. A. 1969. Reaeration prediction in natural streams. *J. Sanit. Eng. Div.*, 95(1), 65–94.

Tsivoglou E.C. and Wallace J.R. 1972. Characterization of Stream Reaeration Capacity. *Report No. EPA-R3-72-012*, US Environmental Protection Agency: Washington, DC.

USACE. 2001. Dissolved Gas Abatement Study: Phase II. *Technical Report*, US Army Corps of Engineers, North Pacific Division, Portland District and Walla Walla District.

Weitkamp, D.E. 2008. Total Dissolved Gas Literature 1980-2007, An Annotated Bibliography Parametrix, Bellevue, Wa.

Zhang, W. and Zhu, D. 2011. Transverse Mixing in an Unregulated Northern River. *J. Hydraul. Eng.*, 137(11), 1426-1440.