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FIELD OBSERVATIONS AND ANALYSIS OF THE GENERATION OF TOTAL DISSOLVED GASES DOWNSTREAM OF THE HUGH L. KEENLEYSIDE DAM

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Abstract: Supersaturation of total dissolved gases (TDG) can occur in rivers downstream of hydropower facilities as a result of dam operations. The subsequent release of dissolved gases in downstream waters can result in fish mortality and other impacts to the aquatic environment. In order to determine the effect of different dam operations on TDG generation detailed field measurements were conducted both at and downstream of the Hugh L. Keenleyside dam on the Columbia River. TDG generation was evaluated as a result of six different operating scenarios that included releases of water through different dam structures including low-level outlet gates, the spillways, and a combination of the two types of structures. All scenarios utilized the low-level outlets and one utilized the spillways. Results indicate that the type of spill mode has significant effect on TDG generation, with southern low-level outlet gates increasing TDG 12% more than the northern low-level outlet gates for a smaller discharge. Accordingly, it is possible to optimize the spill operations in an effort to reduce TDG levels by focusing on the northern low-level outlet gates for spill discharge. In addition, the mixing of the spill water in the tailrace is important to the TDG level in the downstream river region as seemingly complete mixing occurs, decreasing the supersaturation when both southern and northern low-level outlets are operating.

1 Introduction

The act of releasing water through dam structures and the subsequent plunging and turbulent mixing of the reservoir water with the downstream river entrains a significant amount of atmospheric gases. This entrained air can create a supersaturated condition whereby there is a higher concentration of gases dissolved in the water relative to the concentration of gases in the atmosphere. If the levels of dissolved gas increase above certain thresholds, fish that inhabit the downstream river are at risk of gas bubble trauma (GBT) which can result in mortality if severe enough (Weitkamp and Katz, 1980). The zone of supersaturated gases can extend kilometers downstream of the facility possibly impacting the aquatic environment depending how gas concentration changes as a result of river hydraulics. Understanding the concentration of gases that are generated as a result of different dam operations, and how these concentrations persist downstream, is important to determine possible environmental impacts.

When air is entrained into the stilling basin at the base of a spillway, the bubbles that are formed are forced downward by the momentum of the plunging jet. Typically, in the stilling basin region, the surface area for gas transfer is along the free-surface of the river, with the introduction of many small bubbles, the surface area available for gas transfer greatly increases (Hibbs and Gulliver, 1997). As the bubble descends, the hydrostatic pressure of the water column and the dynamic pressure of the water jet acts on it to force the air from within the bubble into solution. With an increase in hydrostatic pressure, also comes an increase in saturation concentration of the gas within the bubbles and therefore, the gases ability to be dissolved in the water (Gulliver et al., 1997). Different dam operations can influence the levels of total dissolved gas in a number of ways. If water velocity at the base of a spillway is large, bubbles will be forced further down into the stilling basin increasing the hydrostatic pressure acting on the bubble. This effect is larger if the tailwater depth is also large. Different types of spill structures can create different flow patterns and levels of surface turbulence as well in the stilling basin. Low-level outlets will produce different flow patterns that impact how quickly bubbles rise to the surface. If air is entrained via low-level outlets the bubble sizes may also be different from those produced by the spillways. Bubble size distribution is an important parameter affecting TDG generation (Qu et al., 2011b) as it affects the rate of gas transfer. Modeling bubble characteristics is an important part of a physically-based predictive TDG model, as it is known that most of the gas transfer in a stilling basin will occur through the bubble-water interface. Therefore, bubble residence time and coalescence are other important parameters. Computational models have been increasingly used to model gas transfer and estimate complex hydraulic flows in the stilling basin and tailraces of dams (Politano et al., 2005; Urban et al., 2008).

Since there are many factors specific to each structure or facility that influence the generation of TDG, determining a predictive equation that applies to all dams has been challenging. However, there have been models developed to predict downstream TDG for several lower Columbia River dams in the United States (University of Washington, 2000). These models rely on coefficients determined for each of the dams the model is to be applied to, and in many cases, this requires a huge amount of effort in the way of field observations. Studies conducted by the United States Army Corps of Engineers have looked into various solutions to the problem of increased TDG levels with some success via the construction of spillway flow deflectors (USACE, 1996; Orlins and Gulliver, 2000).

As water moves downstream from the dam, the TDG concentrations may change as a result of mixing with facility generation flow and gas transfer across the surface of the water. What may also be important is if the dam operational scenario has an impact on the gradient of TDG across the width of the river or if the spill flows mix completely within the tailrace before moving downstream. This may affect measurements downstream of the tailrace where the measured values may be less than the actual TDG generated in the stilling basin.

This study will focus on the TDG issues that arise at the Hugh L. Keenleyside (HLK) Dam on the Columbia River (Figure 1). It is approximately 7 km upstream of Castlegar, BC and 60 km upstream of the Canada – United States border. It is the third and final dam on the Columbia River before flows enter the United States. The reservoir held behind HLK is the Arrow Lakes Reservoir (ALR). The main objective of this study is to quantify the TDG levels as a result of different operational scenarios (combinations of spillway and low-level outlet discharge). This study will benefit hydropower facilities in optimizing the operations of spillways and low-level outlets. Since the problem of supersaturated TDG has been difficult to correct in existing dams (USACE, 2001), predictive tools and clearer relationships between dam spill events and TDG generation will benefit designers of new facilities to meet environmental regulations. A better understanding of the operational conditions that lead to TDG increases at HLK will assist the dam operators in reducing the potential risk to fish. Another important factor in determining TDG increase across operational scenarios that utilize more than one type of spill gate is the mixing in the tailrace. Qualitative conclusions regarding the level of mixing within the tailrace may be possible as a result of the field observations. However, a computational model may be the only way to determine specific flow patterns within this region.

2 Field Program

TDG measurements were taken across several transects near the dam. The first 2 km of the river downstream of HLK are of particular interest. Additional data collected at downstream transects are available in a companion paper on TDG mixing and dissipation (Kamal et al., 2017). Measurements were also collected approximately 1.6 km upstream of the dam in the forebay.

Data collected at each transect consisted of local barometric pressure, air temperature, water temperature, total gas pressure, discharge, and velocity. Two methods were used to collect the TDG data (which included stationary continuous monitoring and spot measurements taken along transects from a boat). The probes that were used were the Pentair Point Four Lumi4 DO/TGP probe (for spot measurements) and the Pentair Point Four TGP probes (for continuous monitoring). These two types of probes have a measurement accuracy of +/- 4% saturation. Continuous monitoring stations were set up near the banks of the river at 1 km (left bank), and 4 km (right bank). Spot measurements were taken along those transects as well as at transects 0.5 km, 2 km, and for some scenarios (SC) at the end of the tailrace (around 300 m downstream of the spill gates). In all cases, the TDG probes were located approximately 1 m below the water surface for data collection. These probes were placed in a water tight container situated on a custom-built PVC frame that was anchored in the river. The monitoring stations were limited to being located near the banks of the river where the current was less strong and where it did not require extremely long lengths of chain and rope to anchor them in place.

In an effort to collect meaningful data about the TDG generation as a result of spilling operations at HLK dam, different operational scenarios were conducted and the resulting TDG measured. These scenarios consisted of different numbers of gates and patterns and were tested over a one-week period with as many measurements taken as possible at different transects. Between each scenario, the ratio of spill rate to generation flow was held nearly constant. The scenarios were chosen to give a range of specific discharges that came along with different numbers of gates operating at once. An effort was made to also ensure that all types of structures were utilized to test a large range of possible dam operations. The timing between scenarios was important because it was desirable to have the flow of a particular scenario completely replace the flow of the previous scenario, ensuring the measurements were reflective of only one scenario at a time. This also limited the number of scenarios that could be tested during the field work. A summary of the times of each scenario along with its operational combination and gate discharges are listed in table 1.

Figure 1: HLK dam site on the Columbia River and downstream river transects, tailrace (TR) measurement location, and Bruce (2016a) meter 2 (M2)

HLK dam conveys water through two different types of gates. Four radial spillway outlet gates (labeled SPOG 1 – 4) are between two sets of four low-level outlet gates (labeled LLOG 1 – 8). LLOGs labeled 1 – 4 are commonly referred to as the northern LLOGs (or NLLOGs) and those labeled 5 – 8 are the southern LLOGs (or SLLOGs), referring to their position relative to the SPOGs (see figure 1). In total, all spill gates are capable of discharging 10,500 m^3/s. Several gates may be in operation at once, with the exception of LLOGs 1 and 8. These two gates are reserved for emergency flows only. The Arrow Lakes Generation Station (ALGS) was commissioned in 2002 and is currently the main source by which flows pass through the dam. It has a discharge capacity of 1,150 m^3/s.

The continuous monitoring stations were set up over the course of two days and recorded TDG data in 2-minute intervals. Meter 2 (M2) is a continuous monitoring station tied to a berm on the south end of the tailrace and collected data at 5-minute intervals (Bruce, 2016a). The spot measurements were conducted at various transects over the course of the six different spill scenarios, but not every scenario was able to have transect TDG data collected because of the tight spill schedule and the amount of time it took to travel up and down the 20 km river reach by boat. For spot measurements taken from the boat, the TDG probe was kept in the flow for approximately 3 – 7 minutes to allow the reading to stabilize. The stabilized reading was recorded for each point. A typical data series for one spot measurement is illustrated in figure 2.

Table 1: HLK Operational Scenarios

SC	Start Time	End Time	Operational Pattern	Gate Number (m^3/s)	Spill Rate (m^3/s)	ALGS (m^3/s)
1	July 26, 12:00	July 27, 14:00	3 NLLOGs	2(186.38), 3(188.41), 4(650.81)	1025.6	1085
2	July 27, 14:00	July 27, 16:00	2 SPOGs	4,3(490.52)	981.04	1085
3	July 27, 16:00	July 28, 14:00	3 SLLOGs	5,6,7(311.58)	934.74	1085
4	July, 28, 14:00	July 28, 16:00	2 SLLOGs	5,6(644.92)	1289.84	1100
5	July 28, 16:00	July 29, 16:00	2 SLLOGs + 2 NLLOGs	5,6(277.4), 3,4(277.85)	1110.5	1100
6	July 29, 16:00	July 30, 16:00	1 SLLOG + 2 NLLOGs	5(191.71), 3(186.12), 4(645.48)	1023.31	1081

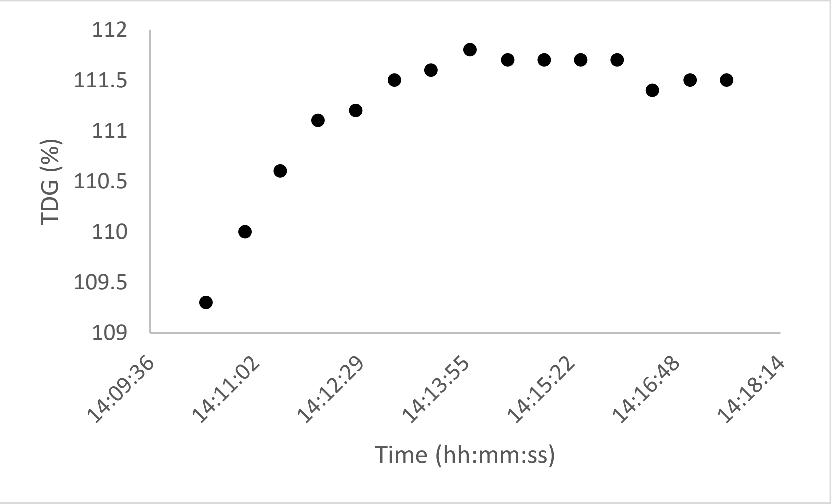

Figure 2: TDG data series for single spot measurement

There is a stabilization period between scenarios where the spill gates are in a transition between operating scenarios. With the exception of scenario 2, all scenarios had been in operation for at least 16.5 hours before the first transect measurement was taken, most scenarios began in the mid-late afternoon and the measurements were carried out the following morning. Figure 3 shows the continuous TDG data recorded at the 4 km transect (right bank) for the duration of the field work. TDG levels below approximately 109% indicate the period of time that the instrument was recording data while being in the open air before placing it into the water for the first time and taking it out at the end of the week. The vertical lines delineate the scenarios, however, at 4 km downstream these lines are slightly behind the location on the graph that would indicate the TDG level at the time the scenario's flow would have passed. It is because of this that scenario 2 appears to have the same TDG measurements as scenario 1.

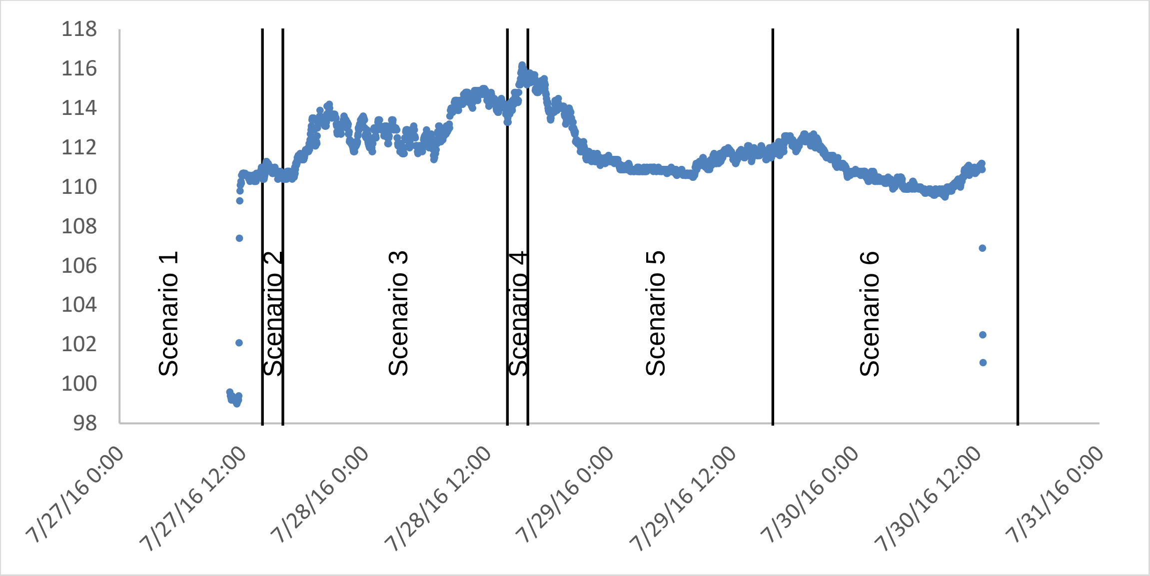

Figure 3: TDG data series for continuous monitoring station at 4 km (right bank)

3 Results and Discussion

Figure 4 illustrates the cross-sectional spot measurements recorded for each scenario for the first three transects. Table 2 is a summary of measured TDG values. The dashed lines represent straight-line interpolations between measured points. In reality, it is expected to vary with the mixing functions suggested by Kamal et al. (2017). For instance, figure 4(a) suggests that SC 3 showed an increase in TDG much closer to the left bank than other scenarios, this is simply because the second data point was not collected at the same location as other scenarios. Collecting data at consistent locations with appropriate density was a challenge due to the fact that the boat could not always select the same point of measurement between each scenario and the time constraints of the work. The right-most data point for SC 2 in figure 4(c) is likely in error, this deviates dramatically from the trend seen in other measurements.

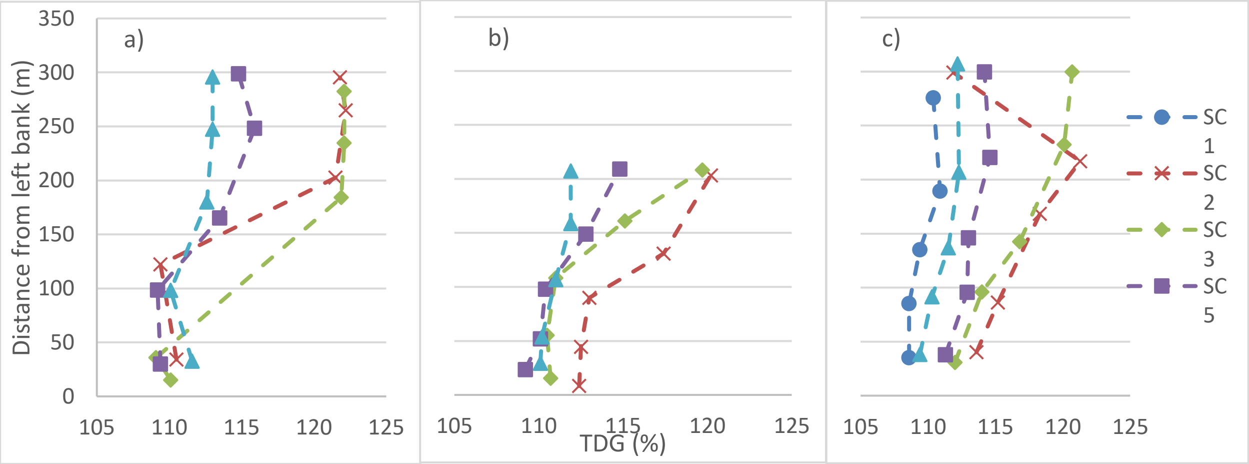

Figure 4: TDG measurements at a) 0.5 km, b) 1.0 km, and c) 2.0 km

Table 2: TDG measurements (%) recorded from the Columbia River at transects downstream of HLK Dam for six different operational scenarios

Transect	SC 1		SC 2		SC 3*		SC 4		SC 5		SC 6	
	LB	Max	LB	Max	LB	Max	LB	Max	LB	Max	LB	Max
M2	**-**	112	-	119	-	117	-	115	-	114	-	111
TR**	-	-	-	-	-	124	-	-	-	116	-	113
0.5 km	-	-	111	122	110	122	-	-	109	116	110	113
1.0 km	-	-	112	120	111	120	-	-	109	115	110	112
2.0 km	108	111	114	121	112	121	-	-	111	115	110	112

*Note that no measurements were taken for scenario (SC) 4, this was a short scenario in which not enough time was available to gather complete measurements from SC 3 in addition to measurements from SC 4. The operating patterns were also similar to SC 3 and therefore not considered to be critical.

** Tailrace measurement (TR) from boat

From figure 4, it is apparent that there is a strong TDG gradient between the left bank and the right bank of the downstream river. This is explained by the two different types of discharge in the river at these locations, the spill discharge (staying mostly near the right bank) and the ALGS discharge (staying mostly near the left bank). The two separate flows were visually distinguishable from each other during some of the measurements in the field. Another result of the measurements that can be seen in table 2 is the difference in maximum TDG levels between the scenarios. The maximum TDG (typically near the right bank are attributed primarily to spill flow) during scenarios 1, 5, and 6 are markedly less than scenarios 2 and 3. This shows a strong increase in TDG is attributed to the spillways and southern low-level outlets in particular and TDG generation by northern low-level outlets is apparently much less. Figure 5 below shows a starker comparison between the maximum TDG generated for each scenario at 0.5 km and at the tailrace (TR). The data point for SC 1 (112%) is measured from station M2 as a comparison since no measurements were taken for this scenario at 0.5 km or in the tailrace.

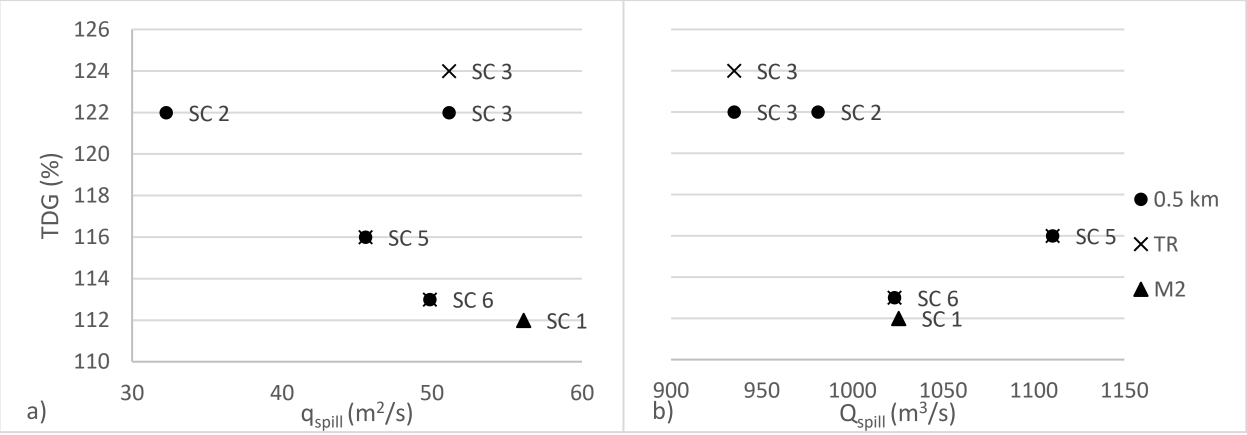

Figure 5: Maximum measured TDG vs a) specific discharge (q_{spill}) and b) total spill (Q_{spill}) for each scenario

Figure 5 takes into account the specific discharge of each scenario. Where different gate openings were used between each gate, an average specific discharge was calculated. This demonstrates the difference particularly well between the southern LLOGs and northern LLOGs. Scenarios 1 and 3 both utilize three LLOGs to spill water, yet SC 1 (3 NLLOGs) generates significantly less TDG than SC 3 (3 SLLOGs) for a greater specific discharge. SC 6 included one less northern LLOG and one southern LLOG. The specific discharge decreased and the TDG generated increased. Further, in SC 5, which consisted of 2 SLLOGs, and 2 NLLOGs, a decrease in specific discharge occurred followed by an increase in TDG. This, along with the measurements pertaining to SC 3, seems to indicate that the southern LLOGs generate much more TDG than the northern LLOGs, a difference of 10% TDG. Considering the differences between figure 5(a) and figure 5(b), another conclusion can be made that not only is TDG generation dependent on the type of structure, but the number of gates in operation as well. This has consequences for the way dam operators would prioritize gate use for spilling a given flow rate. If the same flow rate can be spilled with the use of more northern LLOGs as opposed to using southern LLOGs, this may significantly reduce TDG generation.

Another interesting note is that the SLLOGs (SC 3) were observed to produce a similar level of TDG supersaturation for a slightly less total discharge than the SPOGs (SC 2). Although the SLLOGs have a higher specific discharge than the SPOGs for these scenarios (32.271 m^3/s and 52.133 m^3/s respectively). This is contrary to conventional wisdom due to the fact that it is easily observed at the water surface much more turbulence and therefore air entrainment caused by the plunging jets of the spillways, relative to the observed entrainment due to the LLOGs. Perhaps an unseen mechanism of air entrainment is occurring between the low-level outlet gate and the stilling basin that leads to higher levels of TDG than one might expect. Anecdotal evidence of similar findings is mentioned in Johnson and King (1975) and Qu et al (2011a).

During scenarios 3, 5, and 6, tailrace measurements approximately 300 m downstream of the spill gates, were taken. These measurements are sure to contain spill water only. From figure 5 it would appear that these tailrace measurements are equivalent to the maximum measured values for the 0.5 km transect. With the exception of SC 3, which showed a slightly higher level of TDG in the tailrace. It would appear that the right bank measurements at 0.5 km give good approximations for the TDG leaving the tailrace region before entering the main flow of the river. Figure 4(a) also suggests that regardless of the spill mode, at about 100 – 110 m from the left bank, the spilled water becomes apparent. Therefore, whatever combination of spill gates are open, the individual spills mix together before 0.5 km. The fact that SC 3 seems to show an earlier increase in TDG is most likely due to the lack of measurement around 100 m. For figure 4(b and c) it can be shown that it does follow the same path as other scenarios. It can be assumed, then, that the spill flow leaving the tailrace is fully mixed before encountering the ALGS flow.

Forebay measurements upstream of the dam indicated an average of 109% TDG. This value is taken as the background TDG that remained very nearly constant and is representative of the TDG levels in the ALGS flow as indicated by left bank transect measurements and the 1 km continuous monitoring station (situated near the left bank). With this in mind, over the range of tested scenarios, the northern LLOGs generate the least amount of TDG, a 2-3% increase. The southern LLOGs increased TDG levels by a maximum of 17% and the SPOGs increased TDG by a maximum of 15%. It is possible that due to the short spill time associated with SC 2 that the maximum TDG measured may have been taken slightly ahead of the true maximum TDG flow. In the cases of SC 5 and 6, where there are two types of spill gates operating in tandem (SLLOGs and NLLOGs) an estimation of the TDG increase over 109% can be made. If the measurement from M2 (115%, or a 6% increase over background levels) is used for SC 4 (2 SLLOGs) and a 3% increase in TDG is assumed from the NLLOGs, a mass balance can be used (assuming complete tailrace mixing of the two flows) to estimate a TDG increase of 4.5% for SC 5. The total TDG generated is 113.5%, less than the maximum 116% measured at the edge of the tailrace region. Using the M2 value may underestimate the TDG in the tailrace, this was observed in all scenarios and may be a product of the instrument being different than the one used for spot measurements. Similarly, for SC 6, assuming a 6% increase from the SLLOGs and a 3% increase from the NLLOGs, the total increase is 3.5%. Yielding a total generation of 112.5%. This is closer to the maximum value measured of 113%.

Between 1992 and 1994, TDG measurements were taken downstream of HLK. The database collected has a number of useful parameters that were measured, including the operational scenarios and conditions that resulted in the generated TDG downstream, along with initial forebay measurements. The main issue with the measured TDG data is that it was collected approximately 5.7 km downstream of HLK (Bruce and Plate, 2013). Therefore, any fitted parameter would not truly capture generation mechanisms occurring in the tailrace. Furthermore, at the time of the data collection, the Arrow Lakes Generation Station had not been constructed, this means that mixing mechanisms would also play a role in predicting the TDG levels of the most recent field observations, making the verification of the predictions difficult. Nonetheless, Bruce (2016b) has utilized the existing database to determine a predictive model for TDG generation that incorporates some physical parameters such as the Froude number of the spillway jets. This model is the result of a regression analysis of pertinent parameters that has the added benefit of specifying equations for the spillway outlet gates, southern low-level outlet gates, and the northern low-level outlet gates. Then, to take into account the ALGS flow (and assuming complete mixing across the river), a mass balance is used to determine a final TDG value. The main equations used in the model are shown below.

Northern LLOG: [1] $dP_{TR} = 1.1511 \cdot dP_{FB} + 11.051 \cdot Fr_G - 10.129$

Southern LLOG: [2] $dP_{TR} = 1.1511 \cdot dP_{FB} + 11.051 \cdot Fr_G + 54.825 \cdot TWD_S - 986.67$

Where dP_{TR} is the difference in TDG pressure between water and atmosphere at the tailrace (mmHg), dP_{FB} is the difference in TDG pressure between water and atmosphere at the forebay (mmHg), Fr_G is the Froude number downstream of LLOG, and TWD_S is the tailrace depth at southern LLOG end sill (m).

Spillway: [5] $H = FB_{EL} - 424.9 - 0.5 \cdot d_G$

If $H \geq 6.30$,

[6] $TDG_{TW} = 10.84 \cdot TWD + 896.3$

If $H < 6.30$,

[7] $TDG_{TW} = -37.395 \cdot Fr_{TW} + 14.956 \cdot H + 936.28$

Where TDG_{TW} is the total dissolved gas in the tailrace below the spillway (mmHg), H is the hydraulic head upstream of SPOG (m), FB_{EL} is the forebay elevation (m), TWD is the tailrace depth at SPOG end sill (m), and Fr_{TR} is the Froude number at the tailrace surface. Table 3 lists the results of this model and gives a comparison of measured values between 4 and 7 km transects.

Table 3: TDG Predictions

Scenario	**SLLOG Generation (% TDG)**	**SPOG Generation (% TDG)**	**NLLOG Generation (% TDG)**	**ALGS Generation (% TDG)***	**TGP Mixed (% TDG)**	**Δ TDG (%)****
1	-	-	112	108	111	1
2	-	124	-	109	117	-
3	142	-	-	110	125	9
5	144	-	114	109	119	6
6	143	-	112	108	114	2

*This value was taken as the mean TDG measurement from the 1 km continuous monitoring station over the period of time the field measurements were taken for a scenario near the tailrace and is reflective of forebay TDG levels.

**This is the difference between the predicted value (TGP mixed) and the average measured value from 4 km and 7 km.

It can be seen that there is some deviation between predicted and measured values particularly for scenarios 3 and 5. This is primarily caused by the inclusion of the SLLOG in the scenario. Bruce (2016b), indicates that there was the most uncertainty in the predictive equations for the SLLOG as a result of having much fewer data points (and a narrower range of gate openings) from which to base the regression equation on. Compared to the predictions made with the NLLOG, which make for a much more reasonable agreement. Unfortunately, measurements beyond 2 km were not taken for SC 2 due to time constraints Although the left bank-right bank variability in TDG was found to be 114 – 121% at 2 km for this scenario, these numbers are unlikely to change very much by the time the flow reaches 5.7 km, putting the predicted value of 118% within reasonable proximity.

A Klohn-Crippen Integ (1994) TDG reduction study reflects many of the results observed during this field work campaign. It was found in their report that the spillways generated TDG levels up to 140% and routinely generated levels around 125%. The report also recognized that the NLLOGs generated nearly no TDG when compared to the forebay levels, which were measured to be around 110% and fluctuated mostly with time of year. The SLLOGs produced supersaturated waters up to 125%. The observed results of this past study seem to agree with the conditions found in the current work.

4 Conclusion

Field work was conducted on the lower Columbia River near Castlegar, BC to determine if operational procedures and patterns at HLK dam impact the level of total dissolved gas generated in the tailrace. Overall, it does appear that specific dam discharge structures and patterns contribute differently in generating TDG. It was found that scenarios with a significant portion of the flow attributed to SLLOG operation yielded high levels of TDG (SC 3 and SC 5). Scenarios with a significant portion of flow attributed to NLLOG operation yielded relatively low TDG levels (SC 1 and SC 6). It is suggested that from measurements taken near the tailrace that there may be a significant diluting effect caused by the operation of the NLLOGs on the high TDG levels created by the SLLOGs, this would theoretically extend to a scenario where the NLLOGs are operated in tandem with the SPOGs. If significant dilution is occurring between the SLLOGs and the NLLOGs, then it is reasonable to assume that much of the two flows are mixed before leaving the stilling basin and enter the downstream river along with the ALGS flow. Only a single scenario was tested with spillways in operation and a characteristically high level of TDG was recorded. Although different operational scenarios determine the magnitude of TDG leaving the tailrace, it has been shown that regardless of which gates are in operation, the spill flow mixes before leaving the tailrace. Because of the highly turbulent nature of the stilling basin and the narrowing geometry of the tailrace, this is perhaps to be expected.

The regression equations developed for this site have some limitations that make conclusions about generation specific results difficult. The reason for this is primarily the location of which the measurements were taken, at 5.7 km downstream of the dam on the left bank. This location and therefore the equations based on the data collected there are not true predictions of generation, however, because at the times these data were collected, ALGS was not in operation. Therefore, these values are unlikely to have changed very much and no ALGS dilution would have taken place. Instead, a mass balance equation is used to estimate this dilution. This model still seems to agree quite closely with the measured results between 4 and 7 km of the current study, taking into consideration the uncertainty in the SLLOG predictions and instrument uncertainty.

It has been determined with relative confidence based upon field measurements and initial analysis that the pattern or mode of spill discharge is an important consideration in predicting TDG generation. For future field work, more effort should be put towards ensuring hydraulic variability, not only in gate combinations but in the amount of water that is spilled (i.e. gate opening).

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