Controlling Total Dissolved Gas

Lower Clark Fork River Dams

Robert D. Sullivan [1], Don E. Weitkamp
Parametrix, Inc. 5808 Lake Washington Blvd. #200, Kirkland, WA 98033

Tim Swant, and Joe DosSantos
Avista Corp. PO Box 1469, Noxon, MT 59853

Abstract. - Studies indicate that changing the normal spill gate configurations used at the lower Clark Fork River hydroelectric projects can substantially reduce downstream total dissolved gas (TDG) supersaturation. Investigation of operational procedures at Noxon Rapids and Cabinet Gorge Dams between 1997 and 2001 demonstrated how various spill gate combinations, and other factors at the two dams influence TDG levels. Controlled spill tests at Noxon Rapids Dam indicated that spilling through gates over the central portion of the spillway could reduce TDG levels by 6% to 12% of saturation as compared to spill through the end gates equipped with flip buckets. It appears the combination of greater air entrainment with the flip buckets together with entrainment of air bubbles in the powerhouse discharge resulted in the higher TDG levels when the end gate closest to the powerhouse was used. At Cabinet Gorge Dam controlled spill tests demonstrated TDG levels could be reduced by as much as 13% of saturation using a different gate combinations. It appears gates near the powerhouse and over the deeper portion of the stilling basin allow greater entrainment of bubbles into the powerhouse discharge resulting in higher TDG levels. These observations demonstrate the unique properties of each dam that lead to higher or lower TDG levels downstream.

INTRODUCTION

In the 1990s total dissolved gas (TDG) supersaturation was recognized as a water quality concern in the lower Clark Fork River. In gathering baseline information on the hydroelectric projects for the Federal Energy Regulatory Commission relicensing, it was determined that TDG supersaturation exceeded the Montana and Idaho water quality criterion of 110% of saturation at spill levels greater than 225 m^3/s (8 thousand cubic feet per second [kcfs]) (WWP 1995). A series of investigations were initiated to determine the levels of TDG produced and the operational changes that might reduce TDG during spill periods. The observed biological effects of this supersaturation and the relevant behavior of resident fishes are presented in separate publications (Weitkamp et al. 2002a, 2002b).

Avista Corporation owns and operates the Cabinet Gorge and Noxon Rapids hydroelectric projects on the lower Clark Fork River in northern Idaho and northwestern Montana (Figure 1). The two hydroelectric dams, constructed in the 1950s, have limited hydraulic capacities of their generating units that are commonly exceeded by high river flows during the spring. The two dams, Noxon Rapids and Cabinet Gorge (Figure 1) have different hydraulic capacities. Noxon Rapids Dam has a hydraulic capacity of about 1,444 m^3/s (51 kcfs), while Cabinet Gorge Dam has a maximum hydraulic capacity of only 1,011 m^3/s (35.7 kcfs). In recent years peak spring flows in the lower Clark Fork River have commonly been in the range of 1,980-3,965 m^3/s (70-140 kcfs) substantially exceeding the hydraulic capacity of each dam. The dams also have additional characteristics that produce substantially different levels of TDG.

Noxon Rapids Dam is an earthen and concrete dam about 1,620 m long and 80 m high (Figure 2). When the hydraulic capacity is exceeded, and the forebay is at full pool elevation, excess water is spilled through a concrete gravity spillway. The spillway consists of eight gravity ogee spillbays with tainter gates that are 10.7 m high and 12.2 m wide. The spill gates are numbered from north to south; with Gate 1 located nearest the northern shoreline and Gate 8 next to the powerhouse. Water passing through gates 1, 7, and 8 discharges into flip buckets that deflect the water upward to plunge into the stilling basin. The five central gates discharge directly off the ogee into the relatively shallow stilling basin. These spillbays also have dentate columns near the downstream edge of the spill apron. The stilling basin has several large rock outcrops about 115 m from the spillway at the end nearest the powerhouse. These rocks extend to near or above the water surface influencing the flow patterns from both the powerhouse and the portion of the spillway adjacent to the powerhouse.

Downstream, Cabinet Gorge Dam is a concrete, gravity arch dam 120 m long and about 63 m high. The spillway has eight gates numbered from north to south, with Gate 1 next to the powerhouse (Figure 3). The vertical-lift crest spillway gates are 10.7 m high and 12.2 m wide. In the stilling basin a concrete apron with a splitter wall directs the free-falling spill discharge nearly parallel to the powerhouse. The powerhouse is oriented perpendicular to the arch dam and parallel to the river. The spill apron below Gates 1-3 is 14 to 17 m deeper than below gates 5-8, with a sloped transition between these elevations at Gate 4.

Total dissolved gas (TDG) supersaturation commonly occurs when large volumes of water are spilled at hydropower facilities. High spill levels produce high TDG levels primarily because spilled water entrains significant volumes of atmospheric gases that are forced into solution by the increased pressure at depth in the stilling basins. TDG supersaturation conditions persist where relatively deep reservoirs or non-turbulent river reaches offer less-effective gas dissipation than shallow, more turbulent river reaches that facilitate degassing.

High TDG levels can cause gas bubble disease (GBD) in fish and other aquatic organisms, which can be a direct or indirect cause of mortality. Although the TDG levels that these organisms can tolerate are not specifically defined, the Montana and Idaho State water quality criteria for TDG are set at 110% of saturation to protect all aquatic life. Extensive research during the 1960’s and 1970’s determined that TDG supersaturation can lead to fish mortalities in the Columbia River system (Ebel et al. 1975, Weitkamp and Katz 1980). Resulting changes in mainstem Columbia River hydroelectric project operations reduced or eliminated supersaturation in most years. In the 1990's the use of spill as a juvenile fish passage measure together with high runoff conditions in some years resulted in renewed focus on supersaturation as a potential cause of fish mortalities.

TDG supersaturation conditions were monitored during the spring runoff periods in 1996 through 2001 at Noxon Rapids and Cabinet Gorge. These TDG supersaturation conditions result from spilling water at these two projects, as well as other upstream hydroelectric projects. Noxon Rapids and Cabinet Gorge dams are operated to maximize power generation and minimize water spill volumes. However, spilling is commonly necessary, particularly in years when heavy melting snow or heavy spring rain produces high runoff.

TDG supersaturation is of greater concern at Cabinet Gorge Dam because the limited hydraulic capacity of 1,020 m^3/s (36 kcfs) is often exceeded during spring runoff resulting in substantial spill. The greater powerhouse capacity of Noxon Rapids Dam (1,444 m^3/s, 51 kcfs) results in less frequent and lower amounts of spill.

METHODS

TDG levels were measured in the lower Clark Fork River and Lake Pend Oreille during the spill season (typically April through June) from 1997 through 2001. Routine monitoring upstream and downstream from each of the lower Clark Fork dams provided nearly continuous records of the TDG conditions.

Fixed monitoring stations used Common Sensing Model TBO-L tensiometer units and Model DL-3 data loggers deployed on the upstream face of each dam (forebay). Downstream monitoring stations were established at each dam in 1997 using Common Sensing Model WTDG-2 wireless tensiometers, and changed to Model TBO-L tensiometers in 1999. All probes were deployed at a 3-m depth and programmed to record TDG and temperature measurements at 15-minute intervals. During specific spill gate evaluations however, the probes were set to record this information at one minute intervals.

A portable Common Sensing Model TBO-L tensiometer was used to measure TDG levels downstream of Noxon Rapids and Cabinet Gorge dams during controlled spill tests. Measurements were made at quarter-point intervals across the river at transect locations. These short-term controlled spill tests were conducted to assess the potential differences in the production of TDG supersaturation with different spill gate configurations. Controlled spill tests released a prescribed amount of water through pre-established gate configurations of periods of a few hours. Establishing the same conditions of total flow and spill amount through different gate combinations allows comparison of the specific TDG characteristics of each gate configuration tested.

RESULTS

The need for controlling TDG produced by the lower Clark Fork River dams has been demonstrated by recent routine monitoring. The six monitoring years encompassed a substantial range of runoff conditions in the Clark Fork River. The maximum daily discharge in 1997 (3,933 m^3/s, 139 kcfs) approximately equaled the highest daily average flow in over 40 years (1959-2001). The high runoff volumes in 1997 resulted in nearly continuous spill at both projects throughout the spring runoff period. However, spill typically occurs more frequently and in greater volumes at Cabinet Gorge Dam compared to Noxon Rapids Dam due to the lower hydraulic (powerhouse) capacity at Cabinet Gorge Dam, (Table 1). The maximum spill level in 1997 was 2,150 m^3/s (76 kcfs) at Noxon Rapids Dam, about 63% of the total flow. The average 1997 spill volume was about 1,245 m^3/s (44 kcfs). Maximum spill volume at Cabinet Gorge Dam was 3,056 m^3/s (108 kcfs) or 77% of total river flow, while the average was 1,671 m^3/s (59 kcfs).

Table 1. The percent of time that spill occurred, and the mean spill levels at Noxon Rapids and Cabinet Gorge dams, during spring runoff seasons.

	Noxon Rapids		Cabinet Gorge	
Year	**Hours of Spill (%)**	**Mean Spill Volume (m^3/s)**	**Hours of Spill (%)**	**Mean Spill Volume (m^3/s)**
1997	87	1246	100	1671
1998	6	198	53	934
1999	59	255	93	708
2000	0	0	25	396
2001	0	0	0	0

In contrast to 1997, little or no spill occurred at Noxon Rapids in 1998 and 2000, and spill did not occur at either project in 2001. Although spill occurred at least 59% of the time at the two projects in 1999, the average spill volumes were at least half as great as in 1997. Despite the relatively frequent spill at Cabinet Gorge Dam in 1998 and 2000, the average hourly spill levels were extremely variable. Individual periods of continuous spill typically lasted substantially less than 24 hours in these two years.

The TDG levels recorded in the lower Clark Fork River generally corresponded to the spill levels at the projects. The maximum TDG levels recorded during the five monitoring years (158% of saturation) occurred downstream of Cabinet Gorge Dam during the 1997 high flow year. Peak TDG levels in the other monitoring years typically remained below 130% of saturation. Even during the extensive spill periods in 1999, peak daily TDG levels downstream of Cabinet Gorge Dam typically ranged between 120% and 130% of saturation. The highly variable spill patterns in 1998 and 2000 resulted in similar daily variations in TDG levels, frequently ranging between about 105% to 120% of saturation within 24 hours.

Although the downstream TDG levels generally correspond to total spill volume, some substantial differences were noted between various spill gate configurations. These variations and the desire to control TDG levels resulted in the controlled spill tests. Evaluations were conducted at Noxon Rapids Dam in 1996 indicate that water passing through some spill gates can result in higher downstream TDG levels than for other gates. Spill volumes of between 830 and 977 m^3/s (29.3–34.5 kcfs) through Gate 1 produced TDG levels 6% of saturation lower than through Gate 7. A similar total spill volume through Gates 1 and 7 resulted in a TDG level that was intermediate of the levels for each gate individually. However, spreading the same spill volume among the five central gates (Gates 2 – 6) resulted in only slight increases (1-2% of saturation) over background levels. These results were similar to those observed during routine monitoring in 1997, with TDG levels about 8% of saturation higher with a spill configuration using Gates 1 and 7, compared to Gates 2, 3, 4, 6, and 7. Gate 8 was not included in the evaluation because it is rarely used because it tends to spray water onto the powerhouse deck.

Table 2. Noxon Rapids Dam spill gate configurations, spill volumes and resulting downstream TDG levels during controlled spill tests on June 19 and 20, 1996.

Date	Configuration	Total Spill Volume (m^3/s)	Mean TDG (% of saturation)	Standard Deviation
June 19	Gate 1	830	119.1	0.37
	Gate 7	874	124.7	0.94
June 20	Gates 1 & 7	877	122.4	0.56
	Gates 2-6	976	113.7	0.24
	Gates 1 & 7	368	112.5	0.29

Evaluations at Cabinet Gorge Dam also indicate substantial differences in TDG production among spill gate configurations. Spill through the lower numbered gates (adjacent to the powerhouse) produces TDG levels about 13% of saturation higher than a similar volume spilled through the higher numbered gates (Table 3). A spill volume of 407 m^3/s (14.4 kcfs) through Gates 2 and 3, and full powerhouse discharge, resulted in about a 24-26% of saturation increase greater than forebay TDG levels. However, a similar volume through Gates 7 and 8 produced an increase of only about 13% of saturation. The configuration using all eight gates produced about the same TDG level as the Gates 7 and 8 configuration.

Table 3. Cabinet Gorge Dam gate configurations and spill volumes evaluated on June 19 and 20, 2000, with the resulting downstream TDG levels and the time required for the TDG levels to equilibrate after initiating or changing the spill configuration.

Date	Configuration	Total Spill Volume (m^3/s)	Mean % TDG	Standard Deviation	Equilibration Time (min)[1]

June 19	Gates 2&3	405	125.7	1.19	
	Gates 4&5	416	121.5	1.11	
	Gates 7&8	425	113.7	0.81	
	Gates 1-8	422	113.9	0.61	
June 20	Gates 2&3	408	127.0	0.172	85
	Gates 4&5	408	122.2	0.156	57
	Gates 7&8	410	114.5	0.263	42
	Gates 1-8	583	118.7	0.202	44

[1] Time to equilibrate to within the 95% confidence interval of levels recorded between 1.5 and 2.0 hours after the configuration change

The increased recording frequency of TDG levels at fixed monitoring stations during the Cabinet Gorge Dam spill evaluation demonstrated that TDG levels measured about 1.6 km downstream did not stabilize until about 85 minutes after initiation of a controlled spill test. In contrast, the stabilization period when switching from one spill configuration to another, was less than one hour (42-57 minutes).

DISCUSSION

Our observations indicate that TDG levels in the lower Clark Fork River, resulting from spill at the Avista Corp. projects, can be reduced by specific project operations. Spill through the more favorable gates at Noxon Rapids Dam is likely to keep dissolved gas supersaturation in the range of 120% or less during most years, and commonly below the 110% criterion. Levels in this range are not expected to cause detectable effects in downstream fish populations (Weitkamp et al. 2002a, 2002b).

Following the spill evaluations at Noxon Rapids, the spill configuration patterns were changed from preferentially using gates 1 and 7, to spreading the spill over a greater number of gates and to minimize the use of gate 7. Even during the 1997 high flow year, TDG levels downstream of Noxon Rapids Dam were held to about 123% of saturation or less, despite spilling more than 50% of the total river volume (up to 2,100 m^3/s, 75 kcfs). In addition, these TDG levels typically represented less than a 4% of saturation increase in downstream TDG level compared to forebay TDG levels. In 1999, spilling up to 33% of the total river volume (700 m^3/s, 25 kcfs) resulted in downstream TDG levels remaining below 110% of saturation.

It is unclear whether the observed TDG reductions at Noxon Rapids Dam are the result of spreading the spill volume over a greater number of gates, minimizing the use of high TDG producing gates, or a combination of these factors. Although the Noxon Rapids Dam testing results indicate that Gate 7 produced higher TDG levels than Gate 1, there is limited information on the TDG production rates for the other gates. However, due to different construction characteristics of Gates 2 through 6, we expected they would have different TDG producing characteristics than gates 1 and 7. Gates 1, 7 and 8 are flip bucket gates that redirect the spill flow upward in an arc that plunges into the stilling basin about 20-30 m downstream from the bucket. The other gates discharge directly from the ogee near the tailrace surface resulting in less plunge. These spillbays also have dentate columns near the downstream end of the spill. The USACE (1996) reports that the effectiveness of flip bucket designs at reducing TDG was questionable because the discharge will plunge into the stilling basin rather than deflecting the discharge horizontally as with a flow deflector. Our results support this conclusion.

Several factors may contribute to the greater TDG production of Noxon Spill Gate 7 as compared to Gate 1, even though they both have the same flip bucket design. Gate 7 is located near the center of the river where the water depths are greater than downstream of Gate 1 near the shoreline. The shallower depth downstream of gate 1 limits the plunge depth thereby likely reducing the duration of the gas transfer process. Gate 7 is also located close to the powerhouse, apparently entraining air in a portion of the powerhouse discharge. Therefore, a greater portion of the total flow is initially supersaturated and less powerhouse discharge is available for diluting the supersaturated discharge as the two discharges mix downstream.

Spreading the spill volume over a greater number of gates apparently contributes to the TDG abatement at Noxon Rapids Dam. Similar results were observed at Rocky Reach Dam on the Columbia River (Weitkamp and Sullivan 2000). However, the USACE (1996) found that an even distribution of spill at two Snake River dams resulted in only slight TDG reductions (1 to 3% of saturation). USACE (1996) found that actual benefits from altered spill patterns are sometimes not the same as those expected based on spillway test results, particularly with single spill bay testing. These differences between expected and observed TDG reductions may be due to changes in depth and distribution of air bubbles together with different mixing and re-circulation processes between powerhouse and spillway discharges. The results of continuous TDG monitoring downstream of Noxon Rapids Dam in 1997 and 1999 supported the spillway test results showing that spreading the spill over a number of gates and reducing the use of Gates 1 and 7 effectively reduced downstream TDG levels.

Continuous TDG monitoring results at Cabinet Gorge Dam also indicated a distinct difference in the TDG production levels between spill gates. The data showed that spilling water through the higher numbered gates (5-8) resulted in substantially lower downstream TDG levels than with the lower numbered gates. The primary factor affecting TDG production at Cabinet Gorge Dam appears to be the depth of the tailrace below the spill gates. The spill apron below Gates 1 through 3 is 14 to 17 m deeper than below Gates 5-8, with a sloped transition between these elevations at Gate 4. The deeper stilling basin allows the spilled water to plunge deeper, where the increased pressure can force more air into solution resulting in higher TDG levels.

In addition to the deeper water downstream of the lowered numbered gates, aerated water from these gates appears to mix with and entrain more air bubbles in the adjacent powerhouse discharge, than spill from the high numbered gates. Supersaturating the powerhouse discharge reduces the available dilution that frequently occurs at other projects when powerhouse discharge with low TDG levels, mixes with spillway discharges downstream following loss of remaining air bubbles.

The spill evaluation tests conducted at Cabinet Gorge Dam in 2000 indicated about a 13% of saturation difference between gate configurations. Similar differences were observed with the routine monitoring data collected throughout the spill season, although there was considerable variability. Variations of 10-25% of saturation were recorded for many of the spill volumes that occurred during routine monitoring. Much of this variation appears to be due to the timing of the measurements relative to spill conditions. The spill evaluation tests indicate that TDG levels do not stabilize at the fixed monitoring station until about 45 minutes after a gate change, or almost 90 minutes after the initiation of spill following a non-spill period. This differential lag-time tends to result in greater variability in downstream TDG levels in moderate to low flow years, such as 1998 and 2000, because of the frequent (often daily) occurrences of no-spill periods in those years.

The data collected over five years provided information to alter the spill protocols at Noxon Rapids and Cabinet Gorge dams, and has resulted in lower TDG levels in the lower Clark Fork River. The revised spill procedures at Noxon Rapids Dam, appear capable of reducing the downstream TDG levels to below the state water quality standards (110% of saturation) in most years. Although revised spill procedures also appear effective at Cabinet Gorge Dam, the relatively low hydraulic capacity at the project limits the capacity of this process to maintain low TDG levels in most years.

REFERENCES

Ebel, W.J., H.L. Raymond, G.E. Monan, W.E. Farr, and G.K. Tanonaka. 1975. Effect of atmospheric gas supersaturation caused by dams on salmon and steelhead trout of the Snake and Columbia rivers. National Marine Fisheries Service, Northwest Fisheries Center, Seattle, Washington.

Parametrix, Inc. 2000a. Total dissolved gas monitoring Cabinet Gorge and Noxon Rapids hydroelectric projects, 2000. Report prepared for Avista Corporation, Spokane, Washington.

Parametrix, Inc. 2000b. Total dissolved gas monitoring Cabinet Gorge and Noxon Rapids hydroelectric projects, 1999. Report prepared for Avista Corporation, Spokane, Washington.

Weitkamp, D. E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society 109:659-702.

Weitkamp, D.E. and R.D. Sullivan. 2000. Analysis of total dissolved gas data – Rocky Reach Dam, 1997-2000. Report prepared for Chelan County Public Utility District No. 1, Wenatchee, Washington.

Weitkamp, D.E., R.D. Sullivan, T. Swant and J. DosSantos. 2002a

Weitkamp, D.E., R.D. Sullivan, T. Swant and J. DosSantos. 2002b

LIST OF FIGURES