Boundary Hydroelectric Project (FERC No. 2144)

Study No. 3
Evaluation of Total Dissolved Gas and Potential Abatement Measures Final Report

Prepared for
Seattle City Light

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EXECUTIVE SUMMARY

Introduction

As part of the relicensing of the Boundary Hydroelectric Project (Project), Seattle City Light (SCL) will need to obtain water quality certification from the Washington Department of Ecology (Ecology). Developing a plan for abatement of total dissolved gas (TDG) above the 110 percent TDG saturation standard is part of this certification process. SCL is required to identify all “reasonable and feasible” (Ecology 2005) improvements that could be used to meet the state of Washington’s 110 percent TDG saturation standard by evaluating operational and/or structural modification alternatives. The standard is waived for conditions where incoming TDG is greater than that leaving the Project and for flow exceeding the 7-day, 10-year (7Q10) flow event, which is 108,300 cubic feet per second (cfs) for the Project (SCL 2006). The 7Q10 event can be put into context using the Pend Oreille River Annual Flow Duration (U.S. Geological Survey [USGS] gaging station 12396500), showing percent exceedance of approximately 0.5 percent (R2 Resource Consultants 2008) of the 7Q10 flow, which corresponds to an average occurrence of approximately 1.9 days per year based on the 1987 through 2005 period of record.

Evaluation of Historic Data

At higher flows, the Project forebay TDG level is closely linked to upstream TDG levels from Box Canyon and Albeni Falls dams. Spill from these upstream projects causes relatively high forebay TDG at flows near and slightly above the Project powerhouse capacity (55,000 cfs) (Section 5.2.2). The Project tailrace TDG begins to increase slightly over the forebay level for flows above approximately 70,000 cfs (percent exceedance of approximately 2.6 percent [R2 Resource Consultants 2008]) (Section 5.2.1 and Appendix 4 [Section 4.4]), which corresponds to an average occurrence of approximately 9 days per year. At flows greater than approximately 80,000 cfs, the incoming TDG levels decrease, due to removal of the spillway gates at Box Canyon Dam and corresponding elimination of overflow plunging into the tailwater at upstream projects at higher river flows (Section 5.2.2).

Low volume of spill flowing through either spill gates or sluice gates at the Project does not increase tailrace TDG above that in the forebay. At present river conditions, this low volume of spill is approximately 15,000 cfs or less. As upstream projects improve their TDG compliance and the TDG levels at the Project forebay decrease, the ability to pass low volumes of spill at the Project without increasing tailrace TDG will become more difficult as the downstream TDG levels become dominated by the TDG performance of the Project spill gates and not the incoming TDG level (Section 4.4 of Appendix 4 and Section 5.2.7).

Changes to Project powerhouse operations were introduced in September 2003 for the Project’s largest generating units (Units 55 and 56), resulting in a significant improvement in TDG performance, to the point where there is minimal addition of TDG by the Project powerhouse. In fact, at outflows below the Project powerhouse capacity (55,000 cfs), the Project tends to slightly reduce TDG below forebay levels (Section 5.2.3). The analysis of historic data indicates that, with the Project powerhouse operational changes initiated in 2003, TDG exceeds the regulatory limit in the Project tailrace for flows between approximately 70,000 cfs and 108,300 cfs (which corresponds to spill flows of approximately 15,000 cfs to 53,300 cfs). These flow conditions correspond to an occurrence of approximately 7.4 days per year based on the 1987 through 2005 period of record.

Table ES-1 defines the days the Project provides a benefit to the Pend Oreille River by reducing the TDG from the forebay to the tailrace. These historical data indicate that the Project reduces river TDG 9 days per year on average.

The table also indicates that the Project adds TDG to the river 7.4 days per year on average. Two days per year the river flows are greater than the 7Q10 river flow and the TDG regulatory requirement of 110 percent is not enforced.

Table ES-1. Project spill influence on TDG.

Spill (cfs)	Days/Year	% TDG Stripped (Reduced) or Added
0–5,000	3.7	7 to 5% reduced
5,000–10,000	3.0	5 to 2% reduced
10,000–15,000	2.2	2% reduced to 0% change
15,000–53,300	7.4	0% change to 24% added
53,300 +	1.9	110% TDG standard not applicable as flow is greater than 7Q10 flow

Notes:
7Q10 – 7-day, 10-year frequency flood
cfs – cubic feet per second
TDG – total dissolved gas

Evaluation of Alternatives

Six structural TDG abatement alternatives were short-listed by SCL in the Revised Study Plan (RSP) (SCL 2007). This shortlist was further developed and evaluated by knowledgeable experts in geology, dam construction, hydraulics, TDG issues, gate design, and structural design, and an additional promising alternative (Spillway Flow Splitter/Aerator) was included. The experts' qualitative evaluation included impacts on Project features and safety. Three alternatives were selected for more detailed examination (Section 5.3.4):

1. Throttle Sluice Gates (Option 1-3), which involves operation of sluice gates in partially open positions;
2. Roughen Sluice Flow (Option 3-2), which entails modification of the sluice gate outlets to break up and spread flow; and
3. Spillway Flow Splitter/Aerator (Option 2 – New), which entails modifying the spillways to aerate, break up and spread flow.

These three gate alternatives all involve spilling flow through existing outlets (the seven sluice gates and two spillway gates) into the plunge pool and rely on reduction in TDG production by spreading the flow and limiting plunging effects of the confined jets. The historical performance of these outlets at small gate openings indicates potential for successfully reducing tailwater TDG levels (Section 4.4 of Appendix 4 and Section 5.2.7).

The four remaining alternatives all employ various tunnel configurations with submerged outlets or surface jets outside the plunge pool. Although no tunnel options were selected for near-term analysis, two tunnel options may be considered in the future if the gate alternatives are shown to not perform adequately (Section 5.3.4). These two tunnel alternatives are:

- Penstock Draft Tube By-pass (Option 4-9)
- Right Abutment Tunnel with Submerged Discharge (Option 4-7)

Two alternatives will not be considered further, mainly due to performance, dam safety, and cost considerations (Section 5.3.4):

- New Left Abutment Tunnel Next to Unit 51 Intake (Option 4-10)
- Open Existing Diversion Tunnel and Add Control Structure (Option 4-8A)

Continuing Studies

Currently, activities are underway in the following areas:

- **More detailed engineering analysis of the three gate alternatives.** Analysis is focusing on flow capacity, engineering details, estimates of TDG performance based on analysis of the hydrodynamic effects of flow in the plunge pool, and cumulative effects of deploying multiple gate alternatives. Analytical tools being used include standard engineering calculations, computational fluid dynamic (CFD) modeling, and physical hydraulic model testing. Progress of the engineering program is discussed in Section 5.4.3. Progress will be reviewed with relicensing participants as development continues.
- **Modification of the sluice gates** to allow testing for potentially improved TDG performance. The 2008 spill testing and monitoring program included implementation of a prototype of the first structural abatement alternative (throttle sluice gate). Effects of operating the gates for extended periods of time in this manner are being analyzed and will be further documented in future studies.
- **Additional TDG monitoring** focusing on confirming effects of various gate operations as flow is available. TDG monitoring will utilize data from USGS gages.

Project spill is the focus of the TDG abatement strategies. Engineering studies are underway to explore promising prototype installations and field studies for the three favored alternatives, which involve spreading the spill flow to the extent possible within the Project plunge pool to minimize aerated spill flow plunging to depth. Given the complexities associated with operational changes and structural abatement alternatives, a measured, incremental, adaptive management approach is being employed. The strategy employs engineering studies to develop predicted improvement over current TDG conditions, followed by incremental prototype studies at the Project. This will also allow consideration of potential issues associated with fish entrainment and fish passage, dam safety, and operation and maintenance. The selected alternatives can be developed and implemented incrementally, allowing TDG data to be gathered and compared to predicted TDG performance, and expediting improvement to Project TDG performance, without the delays inherent in large infrastructure modifications.

The draft Clean Water Act Section 401 water quality certification application is being submitted to Ecology in May 2009 and the final application will be filed in November/December 2009. Studies of TDG operational changes and structural abatement alternatives will continue past this application for water quality certification. The TDG study team will assess the engineering and model studies, field testing, and prototype performance to determine whether further prototype and field studies are warranted to develop the three gate alternatives or whether one of the two tunnel options should be considered further. The Section 401 certification application will contain the current status of investigations as well as the strategy and a decision matrix that outlines SCL's "10-year plan" for continuing to address TDG following issuance of the new Federal Energy Regulatory Commission license for the Project. Additional developments of the continuing TDG program studies and prototype testing will be documented after the Section 401 application in annual reports that will be made available to relicensing participants.

Study No. 3: Evaluation of Total Dissolved Gas and Potential Abatement Measures
Final Report
Boundary Hydroelectric Project (FERC No. 2144)

1 INTRODUCTION

Study No. 3, Evaluation of Total Dissolved Gas (TDG) and Potential Abatement Measures, is being conducted in support of the relicensing of the Boundary Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 2144, as identified in the Revised Study Plan (RSP; SCL 2007) submitted by Seattle City Light (SCL) on February 14, 2007, and approved by the FERC in its Study Plan Determination letter dated March 15, 2007. This is the final report for the 2007 and 2008 study efforts of the evaluation of TDG and potential abatement measures.

2 STUDY DESCRIPTION

2.1. Study Objectives

The goal of the study is to identify all "reasonable and feasible" (Ecology 2005) improvements that could be used to meet the state of Washington's 110 percent TDG saturation standard by evaluating operational and/or structural modification alternatives to reduce TDG impairment at the Project in support of the Pend Oreille River total maximum daily load (TMDL) for TDG and application for Clean Water Act Section 401 certification. This goal will be accomplished by the following eight primary objectives of the study, which will be accomplished in two phases (Phase 1 was initiated in 2007, and Phase 2 was initiated in 2008):

1. Analyze hourly and 15-minute interval TDG data reported by the U.S. Geological Survey (USGS) from 1999 to 2005 for the forebay and tailrace fixed monitoring stations (FMS) relative to Pend Oreille River flow data, Project discharge and spill volumes to assess dissolved gas saturation.
2. Continue to monitor and collect Project forebay and tailrace FMS TDG data and assess the dissipation of TDG downstream of the Project.
3. Identify and provide brief summaries of the scope and results of the various TDG related studies and evaluations that have been conducted since 1998 concerning gas supersaturation at the Project.
4. Evaluate methods and controls to reduce air admission requirements for generating Units 55 and 56 to reduce TDG.
5. Identify, describe, and evaluate a shortlist of alternatives and potential combinations of alternatives consisting of operational and structural control measures for reducing TDG production relative to the established criterion.

6. Conduct a comparative analysis of the shortlist of operational and/or structural modification alternatives based on TDG reduction performance, hydraulic engineering methods, field testing, and modeling.
7. Identify the "preferred alternative modification strategy" (preferred alternative) for controlling and mitigating for TDG impairment based on the results of this study.
8. Identify the TDG and other monitoring and reporting activities that will be undertaken during the new license term, including those needed to evaluate the effectiveness of TDG control measures or other mitigation.

2.2. Study Plan

The scope of TDG studies can be classified in three basic categories:

1. Review existing information, which consists of the two major activities:
   - Review existing data and reports (annotated bibliography) (completed)
   - Retrospective data analysis (completed)
2. Conduct field studies
   - 2007 TDG field studies (completed)
   - 2007 acoustic Doppler current profile (ADCP) studies (completed)
   - 2008 TDG field studies (completed)
3. Examine structural TDG abatement alternatives
   - Examine six options from the RSP (SCL 2007) (completed)
   - Consider additional alternatives (completed)
   - Preliminary designs of alternatives (completed)
     - Layout
     - Preliminary engineering
     - Cost estimate
     - TDG performance
   - Evaluate alternatives (completed)
   - Develop details of most promising alternatives (continued into Phase 2, 2008 and beyond)
   - Use more advanced analysis to further develop designs of most promising alternatives (Phase 2, 2008 and beyond)

2.2.1. Review Existing Information

This portion of the study sets the stage for understanding the TDG problem and identifying what additional data are needed.

TDG issues have been previously studied at the Project. A review of the Project TDG studies, along with other TDG studies conducted by the scientific community and at other projects where TDG is an issue, provides an understanding of what has been developed and what needs to be done. An annotated bibliography of reference information, including its relevance to the Project, has been developed and is attached as Appendix 1 (see Sections 4.1 and 5.1 for more detail).

TDG data have been gathered at the Project since 1998. Historic data analysis at the Project has been a separate exercise from examining structural abatement alternatives. Our review is focused on the goal of achieving compliance. The historic data are described in more detail in Sections 4.2 and 5.2.

2.2.2. Conduct Field Studies

Two field seasons were available for field studies within the Integrated Licensing Process (ILP) study timeframe. The following activities have been performed:

- 2007 TDG field studies—Focus on additional tests of the effects of spillway operations on downstream TDG levels
- 2007 ADCP studies—Data for calibration of future physical and numerical models
- 2008 TDG field studies—Studies to develop understanding of performance of preferred alternatives

2.2.3. Examine Structural Abatement Alternatives

Six structural abatement alternatives were presented in the RSP (SCL 2007). These were the result of a series of meetings between SCL and an expert panel. Some additional alternatives were considered.

The SCL panel included the following:

- Henry Falvey—Hydraulic Engineering and TDG production
- Glenn Tarbox—Dam safety and Civil Design issues
- Ken Bates—Fisheries issues

A group of experts was convened on October 1 and 2, 2007, to conduct a workshop to evaluate various aspects of engineering and geology and discuss issues relevant to TDG alternatives. Items discussed included:

- Spatial layout
- Preliminary design
- Cost estimate
- TDG performance

The workshop was attended by the following:

- Keith Moen—Tetra Tech Team TDG study lead
- Prof. John Gulliver—TDG expert, alternative TDG performance
- Chick Sweeney—Hydraulics, alternative performance
- Kim deRubertis—Geology geotechnical and dam safety
- Joe Groeneveld—Hydraulics
- Christopher May—Gates and mechanical engineering
- Paul Oblander—Constructability and cost estimating
- Jim Rutherford—Structural issues and dam safety
- Bill Fullerton—Hydrology and Tetra Tech liaison

- Kim Pate—SCL TDG study lead
- Dan Kirschbaum—SCL mechanical engineering
- Paul Carson—Mechanical issues and TDG alternatives
- Randall Filbert—Recording and Long View Associates liaison

Prior to the workshop, an evaluation matrix had been developed for evaluating alternatives. During the workshop, the matrix was further refined and a first-cut evaluation of alternatives was achieved. After the workshop, further work was performed to fill in technical details and develop further detail on the alternatives. The alternatives were ranked, and the most promising ones were selected based on the results of the evaluation.

Use of more advanced analysis is anticipated to further develop designs of the most promising alternatives. This analysis will include:

- A physical hydraulic model
- Computational fluid dynamic (CFD) modeling

2.2.4. Schedule

Figure 2.2-1 shows a simplified schedule for Phase 1 and Phase 2 of Study 3.

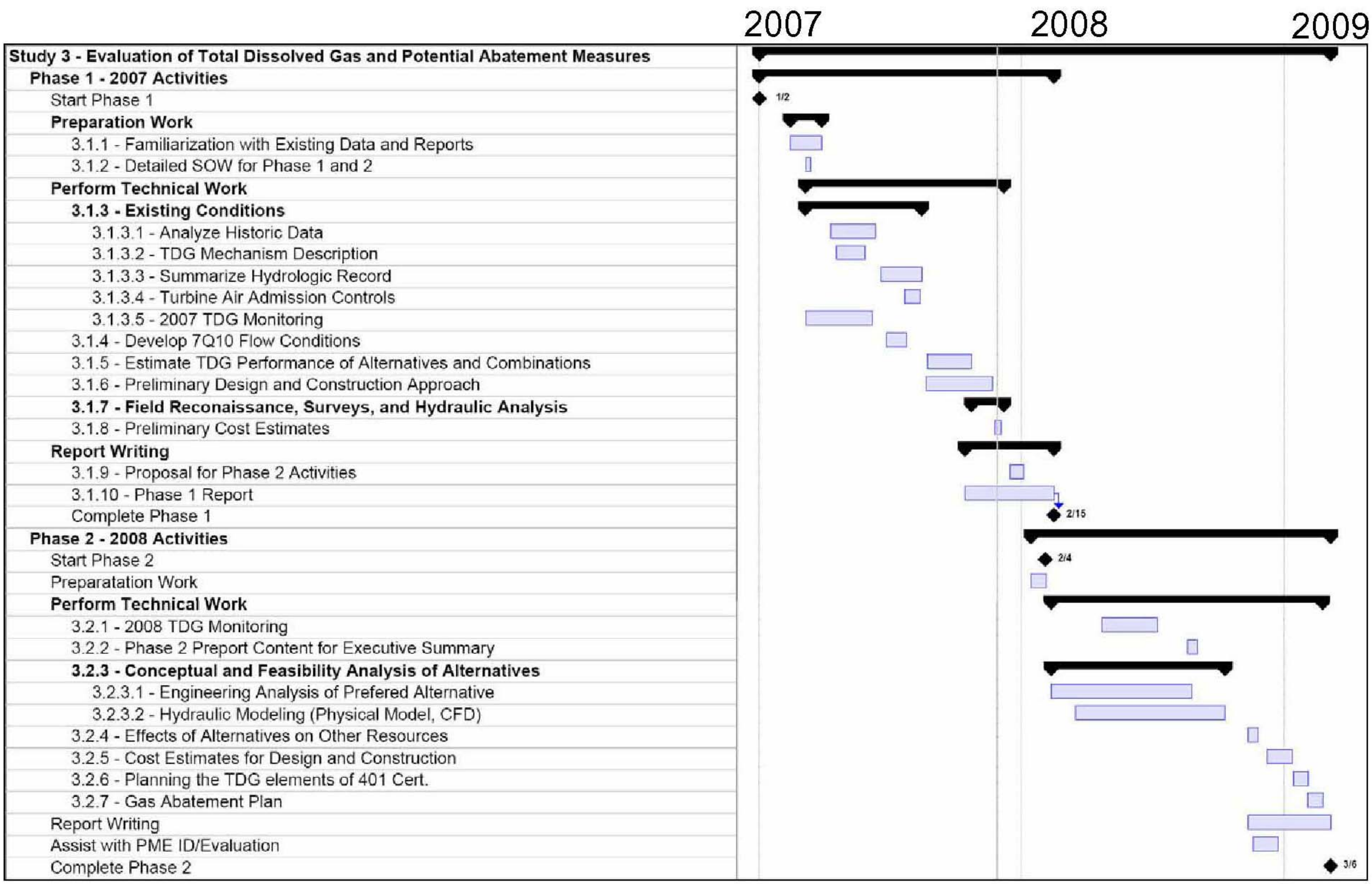


Figure 2.2-1. Study 3 TDG simplified schedule.

3 STUDY AREA

3.1. Project Location

The Project is located on the Pend Oreille River in northeastern Washington, 1 mile south of the Canadian border, 16 miles west of the Idaho border, 107 miles north of Spokane, and 10 miles north of Metaline Falls, as shown in Figure 3.1-1. Boundary Dam is the third of five dams on the Pend Oreille River. Seven Mile Dam and Waneta Dam are located downstream in Canada. Box Canyon Dam is immediately upstream of the Boundary Reservoir, and Albeni Falls Dam is 50 miles farther upstream near Newport, Washington. The Project operates in a load-following mode, generating power during peak-load hours and curtailing generation during off-peak hours; Box Canyon Dam and Albeni Falls Dam are run-of-river facilities.

TDG issues extend well beyond the immediate area of the Project and the area influenced by Project regulation. TDG produced far upstream of the Project passes through the Project and downstream to Canada, then back again to the U.S. in the Columbia River downstream to Lake Roosevelt. Current Project operations are significantly influenced by, and have influence in, the reach from Albeni Falls Dam to the Seven Mile project.

TDG monitoring and structural abatement alternatives are limited to the immediate study area surrounding the Project.

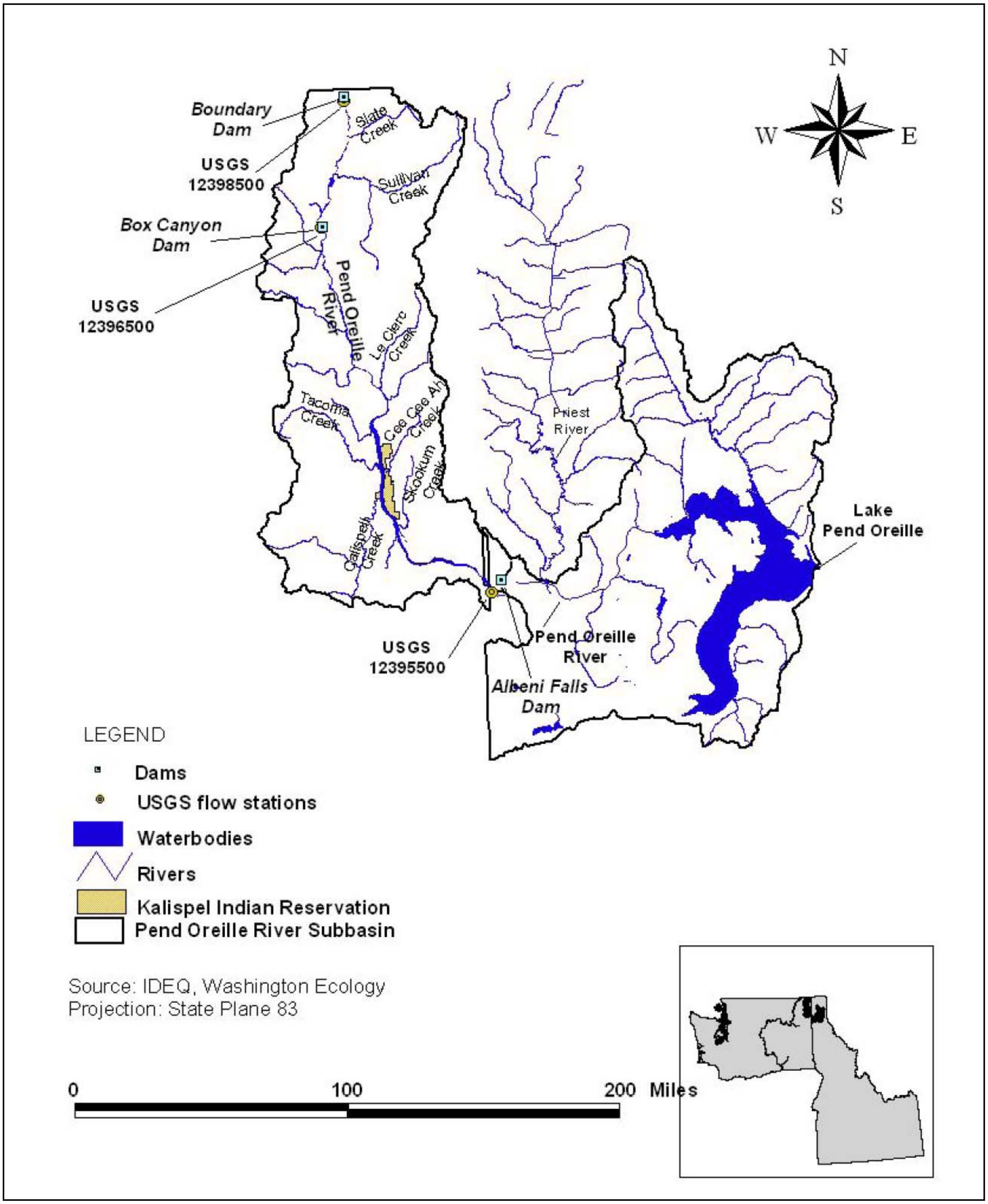


Figure 3.1-1. Project area.

3.2. Project Features

The Project, shown in Figure 3.2-1, consists of an arch dam, reservoir, and underground powerhouse. Boundary Dam is a variable-radius concrete arch dam with a structural height of 340 feet, a crest length of 508 feet, and a total length of 740 feet. It varies in thickness from 8 feet at the crest, which is at elevation 2,004 feet NAVD 88 (2,000 feet NGVD 29)[1], to 32 feet at the base at elevation 1,644 feet NAVD 88 (1,640 feet NGVD 29). The normal elevation of the river surface below the dam is 1,733 feet NAVD 88 (1,729 feet NGVD 29) based on approximately 261 feet of gross head for power purposes.

[Note: Per guidance from the Federal Energy Regulatory Commission, project facility drawings contain Critical Energy Infrastructure Information (CEII) and have therefore, been omitted from general distribution in the Updated Study Report (USR). This information has been filed with FERC with a CEII designation in Volume 6 of the USR submittal. Procedures for obtaining access to CEII may be found at 18 CFR § 388.113. Requests for access to CEII should be made to the Commission's CEII coordinator.]

Figure 3.2-1. Project site plan.

Boundary Reservoir extends 17.5 miles upstream to Box Canyon Dam. Total usable storage is approximately 41,000 acre-feet from the normal maximum water surface elevation of 1,994 feet NAVD 88 (1,990 feet NGVD 29) to 1,954 feet NAVD 88 (1,950 feet NGVD 29) as the 40-foot operating range authorized by the current license.

[1] SCL is in the process of converting all Project information from an older elevation datum (National Geodetic Vertical Datum of 1929 [NGVD 29]) to a more recent elevation datum (North American Vertical Datum of 1988 [NAVD 88]). As such, elevations are provided relative to both data throughout this document. The conversion factor between the old and new data is approximately 4 feet (e.g., the crest of the dam is 2,000 feet NGVD 29 and 2,004 feet NAVD 88).

On each abutment there is a 50-foot-wide spillway with a 45-foot-high radial gate at elevation 1,950 feet NAVD 88 (1,946 feet NGVD 29). The two spillways have a combined total maximum discharge capacity of 108,000 cfs. There is also one bascule-type (hinged-leaf) skimmer gate, 26 feet wide by 9 feet high, adjacent to the left spillway at elevation 1,982 feet NAVD 88 (1,978 feet NGVD 29) to permit passage of debris from the reservoir. In addition, there are seven low-level sluices through the dam with a head of 190 feet that provide 252,000 cfs of capacity. The sluice gates are 17-foot-wide by 21-foot-high fixed-wheel gates at elevation 1,864 feet NAVD 88 (1,860 feet NGVD 29).

The power intake facilities consist of a 300-foot-wide by 800-foot-long forebay, a trashrack structure, and a portal face with six horseshoe-shaped tunnels extending to fixed-wheel intake gate chambers. A penstock leads from each intake gate to one of the turbine-generator units in the powerhouse (six penstocks total). Each consists of a circular conduit of reinforced concrete down to elevation1,822 feet NAVD 88 (1,818 feet NGVD 29) and a steel-lined conduit below elevation 1,822 feet NAVD 88 (1,818 feet NGVD 29).

The Project powerhouse is composed of an underground machine hall, six turbine generator units, draft tubes, and transformer bays. The machine hall houses four 208,000-horsepower (hp) and two 268,000-hp Francis turbines, with four 165-megawatt (MW) and two 205-MW umbrella generators (approximate peak electrical output). Powerhouse flow capacity is approximately 55,000 cubic feet per second (cfs). The draft tubes discharge through individual short tunnels at the base of the tailrace cliff. Six transformer bays branch off the dam access gallery and daylight at the face of the cliff above the maximum tailwater.

Flows through the Project powerhouse discharge into the tailrace immediately below the dam. BC Hydro's Seven Mile Project, located 11 river miles downstream of the Project, periodically backs water up to the base of Boundary Dam. The normal maximum water surface elevation of the Seven Mile Reservoir is at approximately elevation 1,734 feet NAVD 88 (1,730 feet NGVD 29)

Further information on specific Project features can be found in the Pre-Application Document (PAD; SCL 2006).

4 METHODS

This section describes methods used to develop this report.

4.1. Existing Data and Reports

Sources of data used in developing this report are:

- SCL Boundary Project Relicensing Library
- Additional information collected by team members from other projects with TDG issues relevant to the Project
- Supporting technical information (STI) developed during FERC Part 12 studies
- Washington Department of Ecology (Ecology) literature review (Picket 2007)

Data are stored electronically in Portable Document Format and compiled into an annotated bibliography (see below Section 5.1 and Appendix 1).

The STI contains engineering data useful in evaluation of structural abatement alternatives, providing Project background, which will facilitate evaluation of the alternatives.

4.2. Retrospective Data Analysis

Further details of the analysis described in the following sections may be found in Appendix 2 (Historical TDG Data Analysis Final Report).

4.2.1. Purpose of Retrospective Data Analysis

The study analyzing historical TDG data was designed to:

- Obtain historical flow, TDG, and existing Project operations data and develop a comprehensive database for a representative time period for study.
- Identify general annual trends at the Project, operational history of the Project, impacts of upstream project operations, Project forebay to tailrace equilibrium times, and frequency of TDG standard violations at the Project.
- Determine and implement a method for detailed analysis of the impacts of Project spill, and sluice gate operations on TDG production at the Project.
- Develop predictive equations for TDG production at the Project as a function of forebay TDG, spill flow, etc.
- Identify potential operations scenarios that may improve TDG conditions at the Project, either by limiting the amount of TDG produced or promoting stripping of gas.
- Develop recommendations for further monitoring.

The retrospective TDG data analysis uses two databases: 1) a long-term database of USGS forebay and tailrace fixed monitoring station TDG measurements, and 2) a short-term database of TDG from spill and sluice gate tests conducted during spill seasons. The following sections describe the database development.

4.2.2. Long-Term USGS Database

A long-term database was developed of available data for the period from June 1, 1999, to July 25, 2005, from the USGS forebay and tailrace fixed TDG monitoring stations, current Project operations, and upstream project flows. ENSR obtained data for TDG pressure, barometric pressure, and temperature from the USGS stations in the Project forebay (USGS gaging station 12398550) and tailrace (USGS gaging station 12398600) in 15-minute intervals. Hourly water surface elevations for the forebay and tailrace, reservoir storage, and reservoir inflows, and smoothed inflows were obtained from R2 Resource Consultants via a data request on April 26, 2007. Hourly Project spill flows, sluice flows, generation flows (by unit), and Project outflow (generation flow plus spill/sluice flow), and spill and sluice gate settings were provided by SCL. Box Canyon Dam flows were obtained from the USGS gaging station 12396500 in the Box Canyon Dam tailrace.

The data were merged into a single Project database containing hourly-interval data using Microsoft® Access and exported to Excel for analysis. Prior to analysis, adjustments were made to complete missing data and remove anomalous data from the database. These adjustments included filling in forebay barometric pressure data not available in the USGS data record (prior to 2002) with corrected tailrace barometric pressure, filtering out instances of erroneous or missing TDG data, and removing the high tailrace TDG data spikes at the end of December through the beginning of January of each year other than 2002 and the high forebay TDG data spikes in November of 1999 to 2001. These spikes may be attributable to seasonal maintenance operations or instrumentation maintenance although SCL was unable to explain their origins. In addition to cleaning up the TDG data, generation flows were calculated as the sum of the unit flows provided by SCL, and the total Project outflows were calculated as the sum of the spill flow, sluice flow, and generation flow. Information on actual gate operations (spill gate number or gate setting or sluice gate number or setting) was not available at the time of writing of this report for the long-term database, only total spill or sluice flow.

4.2.3. Short-Term Spill and Sluice Gate Test Database

Data from short-term spill and sluice gate tests were obtained from SCL for 2006, 2007, and 2008. The 2008 short-term database was developed to capture TDG data corresponding to spill and sluice gate tests as an addition to the 2006–2007 short-term database. Project operations, gate operations, and provisional USGS TDG data for the forebay and tailrace fixed monitoring stations were obtained from SCL. In addition, 2008 data for TDG monitoring in the forebay and at multiple locations along three tailrace transects were obtained from Golder Associates (Golder) and integrated into the database. The database was analyzed to determine the effects of gate operations on tailrace TDG during designated test events as described in the following section. Further information on the 2006–2007 data analysis is provided in Appendix 3, and the 2008 data analysis in Appendix 4.

4.3. Field Investigations

4.3.1. Purpose of Field Investigations

The 2007 field studies were conducted to:

- Supplement existing USGS forebay and tailrace FMS TDG data for current Project operations to provide greater understanding of the impacts of operations on TDG generation by the Project;
- Assess suitability of existing USGS FMS locations relative to lateral distribution and dissipation of TDG downstream from the Project; and
- Acquire hydrodynamic (velocity and water level) data for use in calibration of hydraulic models (physical and numerical) to be used in designing and assessing TDG mitigation alternatives

4.3.2. TDG, ADCP, and Water Level Monitoring Stations

4.3.2.1. TDG Monitoring

TDG data were acquired at the stations shown in Figure 4.3-1. The forebay station supplemented and provided a check on the USGS forebay FMS (USGS gaging station 12398550), plus provided background TDG for comparison. The forebay station was designated as H9. Transect 2 (four stations) reproduced a transect used for previous studies and allowed comparison to those results, plus examined lateral distribution as a function of existing Project operations. It was located at approximately the downstream end of the frothy (gas transfer) zone on the basis of photos and video of spill, immediately downstream of the constriction point of the tailrace. The stations at transect 2 were designated H1 to H4. Transect 3 (three stations) was selected to supplement and check the USGS tailrace FMS (USGS gaging station 12398600) to determine if lateral mixing is complete and the FMS bank line station is representative. The stations at transect 3 were designated H5 to H7. Transect 4 (one station) was selected downstream from riffle in Canada to determine if the riffle reduces TDG. This station was designated as H8. Details of the TDG meter deployment locations are provided in Appendix 5.

All of the TDG meters were deployed for a test period from April 27 through July 6, 2007, and May 17 to July 17, 2008.

4.3.2.2. Velocity and Water Level Monitoring

Velocity data were acquired on approximately the same transects as TDG data (moving flow measurement transect measurements) and stations (fixed velocity measurements) shown in Figure 4.3-1. The locations were selected based on the locations of the TDG sampling locations (also shown in Figure 4.3-1), consideration for the use of the data for calibration and verification of CFD and physical hydraulic models, and consideration for characterizing the hydrodynamic conditions responsible for TDG flux. Measurement locations were designated 1 to 4 from west to east on transect 1, 5 to 8 from west to east on transect 2, and 9 to 11 from west to east on transect 3. Data were collected for two different flow conditions, a low river flow of approximately 33,000 cfs on June 20, 2007, for which only turbines were operating, and a higher river flow of approximately 52,000 cfs, on June 13, 2007, for which the turbine flows were supplemented with spill. Coordinates of the ADCP measurement stations are tabulated in Appendix 5.

Water level data were acquired at stations at either bank line on approximately the same transects employed for ADCP and TDG data collection to provide a consistent dataset to be used in association with the ADCP and TDG data. These locations were adjusted based on practical considerations, such as ability to install the water level recorders along the shore. Coordinates of the water level monitoring stations are tabulated in Appendix 5.

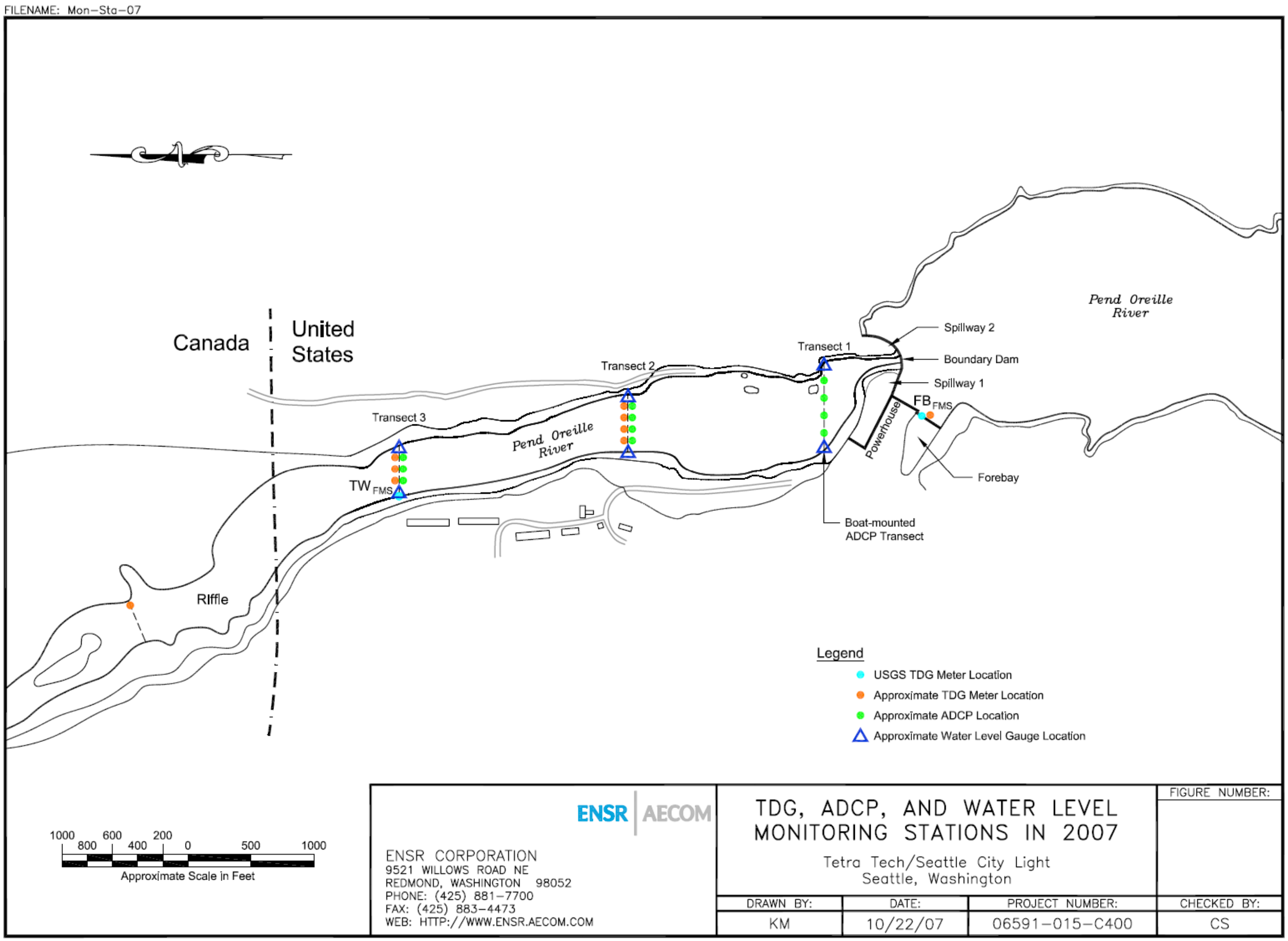


Figure 4.3-1. TDG, ADCP, and water level monitoring stations in 2007.

4.3.3. Monitoring Instruments and Deployment Methods

Methods used in acquiring the TDG, ADCP, and water level data are described in the following sections. Details of the methods used for data management, quality assurance and control, and interpretation are found in Appendix 5.

4.3.3.1. TDG Monitoring

A total of nine Hydrolab® MS5 Multiprobe® (referred to as MS5 or Minisonde hereafter) instruments with TDG, temperature, and depth sensors were purchased from Hach Company Inc. SCL also provided a single Hydrolab DS4a® (referred to as the DS4a or Datasonde hereafter).

Water quality parameters recorded during monitoring included TDG (millimeters mercury) and water temperature (ºC). To assist in data quality control, water depth (in meters) was also recorded and used in conjunction with water temperature to identify periods when the probe emerged from the water and when the probe was above the minimum TDG compensation depth.

Details of the TDG probe operation and calibration methods are found in Appendix 5.

The forebay probe, station H9, was deployed by cable in a weighted housing from the railing of the bridge across the forebay trashracks.

The tailrace probes were deployed in custom-designed and fabricated metal housings, which positioned the TDG meters above the river bottom to prevent accumulation of sand and gravel around the sensors. Floats were attached to the housings by cable to facilitate location and retrieval of the meters. In addition, radio-locator tags manufactured by Lotek, Inc., were attached to the housings to allow the probes to be found in the event of a float cable failure.

Detailed descriptions of the meter deployment housings and techniques are provided in Appendix 5.

4.3.3.2. Velocity and Water Level Monitoring

Velocity data were acquired using a 1,200 kilohertz (kHz) RD Instruments Workhorse Sentinel ADCP. This meter is capable of collecting velocity data in a profile extending from approximately 3 feet below the surface to a depth of approximately 65 feet.

ADCPs determine current velocity by measuring the frequency shift of reflected acoustic energy. The flow velocity components along the paths of three beams are used to resolve the vector and the fourth beam provides a consistency check. Each acoustic beam is a cone 3.0 degrees wide originating from the unit. The centerline of each beam projects 20 degrees from the instrument centerline resulting in a total beam spread of 43 degrees. The ADCP is capable of determining vessel motion relative to the riverbed to within ±0.02 foot per second (fps). This feature is used to provide absolute current velocity and direction with respect to the bottom by subtracting vessel motion from the resultant flow vector.

The ADCP was mounted directly to the hull of the survey boat with its beams aligned with the long axis of the boat. This facilitated the use of a gyrocompass to correct the ADCP data to a true north orientation because magnetic anomalies were likely present, especially near the powerhouse and overhead transmission lines.

The survey boat was equipped with an S.G. Brown Meridian Surveyor gyrocompass. The gyrocompass can report headings within ±0.6 degrees of true north and was interfaced to the ADCP data collection software (WinRiver) to correct measured velocity components to a true north orientation.

WinRiver was set up to collect ensembles of data at approximately 1 hertz (Hz) with one ping per ensemble. Data were collected at depth increments (bin size) of approximately 1.6 feet for the majority of the data beginning at a depth of approximately 4.6 feet. Data were acquired for approximately 10 minutes at each station, resulting in approximately 600 data points per station, from which average and standard deviations of the velocity components will be calculated.

To acquire moving transect discharge measurements, the survey boat moved along the transect line at 1 to 2 knots, during which time ADCP data were collected at approximately 1 Hz sampling rate at depth increments (bin size) of approximately 1.6 feet for the majority of the data. The distance from shore to the instrument at the beginning and end of the transect was noted. These distances were used to estimate discharge in the portions of the river too shallow for boat operation or ADCP measurement.

Water level data were acquired using RBR XR-420 CTD gauges mounted in protective polyvinyl chloride pipe housings set in concrete weighted 5-gallon buckets set securely on the river bottom at the measurement locations. The data loggers were deployed prior to on-water data collection activities and retrieved at the end of the velocity and discharge measurements. The location of water level for each data logger was surveyed in using the Trimble Differential Global Positioning System (DGPS) and a level and rod based on a nearby elevation benchmark.

Water level data were acquired at station 1 and stations 4 to 6 on June 13. During retrieval of Gauge 2, it was observed to have moved, so these data were not reported. Data were acquired from all six gauges on June 20. Water level measurements were collected continuously throughout the entire data collection program. The data loggers were set up to average 1 minute of data (60 data points at 1 Hz sampling rate) every 15 minutes.

Instrument position was determined from the survey boat, which was equipped with a Trimble AG-132 12-channel DGPS receiver capable of receiving real-time differential corrections from either the Coast Guard beacons in Appleton, Washington, or Fort Stevens, Oregon, or from a commercial OmniSTAR satellite. The DGPS antenna was mounted directly above the ADCP, so no offset correction is required in the ADCP data presentation.

The survey boat was also equipped with Hypack v. 6.2 navigational software to provide real-time positioning guidance to the boat operator by providing on-screen boat position versus target location. This aided in locating measurement stations and in station-keeping once current measurement had begun. Positions were recorded in North American Datum of 1983, Washington State Plane, North Zone, coordinates.

4.3.4. Test Conditions

4.3.4.1. TDG Data

A "playbook" prioritizing current Project operations and operations scenarios desired for tests for various ranges of flow was prepared and used by SCL staff and power planning to schedule tests, allowing them flexibility to set conditions in order of priority as river flows and power requirements allowed. Operations scenarios to be tested included the following:

- Sluice and spill tests with low forebay TDG
- Sluice gate tests at partial gate openings
- Sluice gate tests comparing single and multiple gates at similar openings
- Sluice gate tests comparing similar flows from grouped and spread gate patterns
- Spill tests emphasizing Gate 2 independent of Gate 1 at all spill levels, particularly between 5,000 and 10,000 cfs
- Spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows
- Additional tests of 20:80, 60:40, and 70:30 Gate 1 to Gate 2 ratios
- Collection of additional data during the spill season at the H1 through H9 monitoring locations to better define the spatial variation in tailrace TDG

The recommendations prioritized the sluice gate tests at partial gate openings, the sluice gate tests with single and multiple gates, and the spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows. Duration of tests required for equilibration of TDG was determined to be 4 hours. Actual test conditions achieved are summarized with the analysis of TDG data in Section 4.4 of Appendix 4.

4.3.4.2. Hydrodynamic Data

ADCP and water level data were acquired on June 13, 2007, for conditions of a total river flow of approximately 52,000 cfs, with 4,900 cfs spill through Gate 1 and on June 20, 2007, for a total river flow of approximately 33,000 cfs with no spill.

4.4. Engineering Studies

The engineering studies are of three types:

- Development of alternatives
- Evaluation of alternatives
- Estimates of effects on existing resources

Development of alternatives started with the short list of six alternatives developed previously and presented in the RSP (SCL 2007). These alternatives were examined in light of information gathered from review of existing documents and TDG data. Additional alternatives that were examined during previous studies and rejected were also reviewed to see whether further study was warranted. Other additional alternatives were also suggested by team members. The alternatives were then developed further by a group representing multiple engineering disciplines, using experience with similar projects, established design guidelines, and some simple calculations to a point where performance and construction costs could be estimated.

Evaluation of alternatives relied on a uniform criteria applied to all alternatives by use of an evaluation matrix. The criteria were developed to reflect the goals of the study. Alternatives were evaluated based on their ability to meet criteria and ranked on a numeric scale. The result was a numeric ranking of the alternatives relative to each other.

The alternatives evaluated as most favorable were then examined for their effects on Project generation and other existing resources.

5 RESULTS

This section presents the results of the engineering studies and responds to the tasks listed in the RSP (SCL 2007).

5.1. Familiarization with Existing Data and Reports

Over 70 documents have been collected and assembled in a Project TDG reference library. An annotated bibliography has been developed that includes a complete document reference, summary, and the articles' relevance to the TDG study. The annotated bibliography is included as Appendix 1. Table 5.1-1 provides a summary of the documents and their relevance to Study 3.

Additionally, documents that are part of the FERC part 12 STI have been gathered to provide technical background information on Project features. STI cannot be transmitted due to FERC Critical Energy Infrastructure Information (CEII) restrictions.

Table 5.1-1. TDG reference material collected in annotated bibliography.

Author/Date	Title	Relevance to TDG Study
Angelaccio, C.M. Bacchiega, J.D. Barrionuevo, H.D. Fattor, C.A. (1997)	Effects of the Spillways Operation on the Fishes Habitat: Study of Solutions	This is a paper on deflector design from physical hydraulic models, and discusses the South American experience with spillway deflectors. General background on the most used structural TDG remediation.
Boyer, P.B. (1973)	Gas Supersaturation Problem in the Columbia River	This paper outlines the problem and then-current research investigations for gas supersaturation and structural modifications. Historical reference.
Brocchini, M. Peregrine, D.H. (2004)	The Dynamics of Strong Turbulence at Free Surfaces	This paper discusses the source of air entrainment in surface jets. It may be valuable to understand how high speed surface jets can entrain air.
Cain, James M. (1997)	Design of Spillway Deflectors for Ice Harbor Dam to Reduce Supersaturated Dissolved Gas Levels Downstream	This paper is about the spillway deflectors, flow patterns and design for Ice Harbor Dam. This will be of relevance if similar designs are to be undertaken.
Carroll, J.H. Lemmons, J.W. Schneider, M. (2000)	Data Summary for Wanapum Dam Prototype Total Dissolved Gas Evaluation, Spillway 5, Single Spillbay Study	The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.
Columbia Basin Environmental (October 2001)	Boundary Dam Total Dissolved Gas Study, 24 to 25 September 2001, Draft Report	Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2001.
Columbia Basin Environmental (February 2002)	Boundary Dam Total Dissolved Gas Study, 24 to 25 September 2001, Pre-Decision Draft Report	Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2001.
Columbia Basin Environmental (January 2003)	Boundary Dam Spillway Evaluation, 1 May – 25 July 2002, Pre-decision Draft Report	Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2002.
Eastman, Kent B. Klein, Amy S. (2004)	Total Dissolved Gas and Temperature Monitoring at Chief Joseph Dam, Washington, Albeni Falls Dam, Idaho and Libby Dam, Montana 2004: Data Review and Quality Assurance	Monitoring studies for other dams in 2004 could develop perspective on the severity of TDG in the tailwater of Boundary Dam.
EES Consulting	Total Dissolved Gas Monitoring, Final Report 2003, Box Canyon Hydroelectric Project (No. 2042) (2003)	Monitoring studies for other dams in 2004 could develop perspective on the severity of TDG in the tailwater of Boundary Dam.
Entrix (2002)	Level 1 Assessment, WRIA 62, Prepared For: Pend Oreille Conservation District, Pend Oreille (WRIA 62) Watershed Planning Unit	Most is very general information but it can be useful to point to other more detailed documents. Provides good overview of water quality in Pend Oreille watershed.
Entrix (2002)	Phase Ii, Level 1 Assessment, WRIA 62, Prepared For: Pend Oreille Conservation District, Pend Oreille (WRIA 62) Watershed Planning Unit	Good overview of water quality in Pend Oreille River and associated tributaries. Role of tribes in watershed planning pg 1-1. Historical discussion (secondary source) pg 28.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
Fast, Don O'Riordan, Jon (1981)	Ambient Water Quality Assessment And Objectives for the Lower Columbia River Birchbank to the US Border, Overview Report	This report describes Canadian water quality objectives for the lower Columbia River from Birchbank to the international boundary in 1981.
FERC (2002)	Draft Environmental Impact Statement, Box Canyon Hydroelectric Project, Washington and Idaho, (FERC 2042-013)	Draft ESI provides comprehensive overview of water quality in Box Canyon Reservoir. Could provide background for the Project.
Framatome (2002)	Total Dissolved Gas Monitoring, Final Report, 2002, Box Canyon Hydroelectric Project (No. 2042)	Spill gate configurations could provide insight into performing similar operations at Boundary.
Geldert, Darrin A. (1997)	Parametric Relations to Predict Dissolved Gas Supersaturation Below Spillways	This thesis describes in detail a 1-D computational model for TDG supersaturation. It is applied to dissolved gas modeling on the lower Snake River and Columbia River. An eventual TDG model may utilize some gas transfer equations from this thesis.
Geldert, Darrin A. Gulliver, John S. (1996)	Prediction of Dissolved Gas Supersaturation Downstream of Hydraulic Structures	Article outlines 1-D predictive relations based on mass transfer physics. Probably not as complete as either of the other Geldert references. May provide a better description of the processes than ether of the other Geldert references, though.
Geldert, Darrin A. Gulliver, John S. Wilhelms, Steve C. (1998)	Modeling Dissolved Gas Supersaturation Below Spillway Plunge Pools	Article outlines 1-D predictive relations and fits coefficients to four dams. It was found that surface transfer was important, especially at spillways with a shallow tailwater.
Hallock , Robert J. (2004)	Fish passage feasibility study for bull trout in the Pend Oreille basin in Idaho and Washington (Battelle Study Proposal, File #34 1.1000)	Discussion of Bull Trout population at Albeni Falls Dam. Although not about TDG, this is a prime reason for TDG criteria at the Project.
Harza (March 1981)	Expansion of the Boundary Hydroelectric Project, Project Planning Report	Feasibility level study. Primarily engineering and economic information and recommendations. Contains limited water quality and fisheries information.
Holmes (1999)	State of Water Quality of Columbia River at Birchbank 1983-1997, Canada - British Columbia Water Quality Monitoring Agreement	This report discusses TDG problems on the Columbia River in Canada, downstream of the Project.
Johnson, P.L. (1976)	Hydraulic Model Studies of Navajo Dam Auxiliary Outlet Works and Hollow-Jet Valve Bypass Modifications to Reduce Dissolved Gas Supersaturation. US Bureau of Reclamation Report REC-ERC-76-5	These hydraulic model studies were on flow deflectors and hollow jet valves. Hollow jet valves or a gate alternative that has the same effect have been under consideration for the Project.
Johnson, Perry L. (1984)	Prediction of Dissolved Gas Transfer in Spillway and Outlet Works Stilling Basin Flows.	This paper is on gas transfer resulting from the plunge below spillways. It primarily focuses on stilling basins and is an early attempt to model TDG below a spillway. It is helpful to go back to see what was done.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
Johnson, Perry L. (1992)	Modification of the Stilling Basin at Arthur R. Bowman Dam, Oregon to Reduce Dissolved Gas Supersaturation.	This paper is on stilling basins with flow deflectors to reduce TDG. The solution was to decrease depth of stilling basin, to create skimming flow at high discharge due to "deflector" configuration.
Johnson, Perry L. King, Danny L. (1979)	Prediction of Dissolved Gas at Hydraulic Structures.	This paper was on dissolved gas modeling in stilling basins. It outlines general predictive techniques for determining dissolved gas levels downstream of the types of hydraulic structures employed by the Bureau of Reclamation.
Lee, Kenneth S. (1994)	Gas Supersaturation at Jennings Randolph Lake.	This paper describes the TDG supersaturation problem at Jennings Randolph Lake, North Branch Potomac River and discusses alternative measures for prevention.
Lemons, John Gunter, Mark (2000)	Boundary Dam Total Dissolved Gas Evaluation: TDG Dynamics Associated with Power Generation, 23 June - 23 July 2000.	This report discusses the history of operation effects on TDG below Boundary Dam.
Linder, W.M. (1982)	Water Quality Management at Harry S. Truman Dam and Reservoir.	This paper is on stilling basin performance on dissolved gases, as related to one spillway. Deflectors on the spillway, the construction of a skimming weir spillway and small releases were the changes recommended for the Harry S. Truman dam. Harry S. Truman Dam experienced TDG supersaturation and fish mortality before turbines were installed. This indicates that TDG are not only a concern in the northwest. Deflectors were recommended for the spillway.
Mains, E.M. (1977)	Corps of Engineers Responsibilities and Actions to Maintain Columbia Basin Anadromous Fish Runs.	This paper outlines all aspects of what the U.S. Army Corps of Engineers did to enhance fisheries, including installing spillway deflectors in the 1970s, in the Columbia and Snake rivers.
Mannheim, Carl O.M. Weber, L.J. (1997)	Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XII: Physical Model Data for Development of a Gas Concentration Computational Model	This report describes physical model data collected and used as input for numerical model described by Orlins and Gulliver (1997, 2000). Provide insight into the use of models for the Project.
Mannheim, Carl O.M. Weber, L.J. (1997)	Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design.	This paper describes a physical model study that evaluated high, low, and sloped spillway deflectors. These alternatives may be useful in planning the Project design.
Mathur, Dilip Heisey, Paul G. Skalski, John R. Hays, Steven G. (1997)	Structural Modifications at Hydro Dams: An Opportunity for Fish Enhancement.	This paper describes fish passage mortality with spillway modifications. It is one of the few sets of data on these conditions, and could be used to assess mortality in structural modifications at the Project.
Mesa, M.G. Warren, J.J. (1997)	Predator Avoidance Ability of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) Subjected to Sublethal Exposures of Gas-Supersaturated Water.	This paper provides evidence that salmon exposed to 120% supersaturation of dissolved gas are not more susceptible to predation from northern squawfish. This may be important in the argument that 110% is too strict of a standard.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
North Pacific Division (1976)	Dissolved Gas Data Report, 1975-76.	An early study on overall dissolved gases on the Columbia and Snake Rivers. This could be a historical reference for the Project.
North Pacific Division (1984)	Spillway Deflectors at Bonneville, John Day and McNary Dams on Columbia River, Oregon-Washington and Ice Harbor, Lower Monumental and Little Goose Dams on Snake River, Washington.	Model studies of spillway deflectors for the Columbia River and Snake River Corps dams. This provides background on what was planned for TDG abatement on these dams.
Orlins, Joseph J. Gulliver, J.S. (1997)	Prediction of Dissolved Gas Concentration Downstream of a Spillway.	This paper describes a numerical model of TDG at the Wanapum Dam. The model requires a physical model of flow and turbulence. A similar model could be considered for the Project.
Orlins, Joseph J. Gulliver, John S. (2000)	Dissolved Gas Supersaturation Downstream of a Spillway, II: Computational Model.	This paper describes a numerical model of TDG at the Wanapum Dam. The model requires a physical model of flow and turbulence. A similar model could be considered for the Project.
Parametrix (1997)	Total Dissolved Gas Monitoring for Spillway Modification Evaluations-Wanapum Dam, 1996.	The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface at the Project.
Parametrix (1998)	Dissolved Gas Assessment, Boundary Dam.	Data on dissolved gas concentrations in relation to different spill configurations at the Project. From testing performed in 1998.
Pelletier (1990)	Progress Report No. 1, Pend Oreille River Water Quality Study.	Excellent background information describing the habitat and water quality conditions in the Albeni Falls to Box Canyon reach of the Pend Oreille River.
Pelletier(1990)	Pend Oreille River Water Quality Study.	Report of 1990 TDG measurements upstream of the Project.
Pickett, Paul J. (2004)	Quality Assurance Project Plan, Pend Oreille River Total Dissolved Gas, Total Maximum Daily Load Technical Study, Washington State Department of Ecology, 2004.	Report of 2004 TDG measurements upstream of the Project.
Politano, M. Carrica, P. Weber, L. (2005)	Prediction Of Total Dissolved Gas Downstream Of Spillways Using A Multidimensional Two-Phase Flow Model.	This is an interesting model of bubble transport and gas transfer in a spillway tailwater. However, the assumption of negligible bubble breakup and coalescence is not correct. Getting this important characteristic wrong makes the results suspect. Provides background to TDG modeling at the Project.
Politano, M.S. Carrica, P.M. Cagri, T. Weber, L. (2007)	A Multidimensional Two-Phase Flow Model for the Total Dissolved Gas Downstream of Spillways.	This is an interesting model of bubble transport and gas transfer in a spillway tailwater. However, the assumption of negligible bubble breakup and coalescence is not correct. Getting this important characteristic wrong makes the results suspect. Provides background to TDG modeling at Project.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
RL&L (1998)	Total Gas Pressure Monitoring, At Seven Mile And Waneta Dams 1995-1997.	Total gas pressure monitoring at Seven Mile and Waneta dams from 1995-1997. This report provides background on expectations of TDG at regional dams.
RL&L (2000)	Total Gas Pressure Monitoring at Hugh L. Keenleyside Dam, 1999 Investigations.	1998 and 1999 TDG data from Keenleyside Dam provides background on TDG generation downstream of the Project.
RL&L (2000)	Kootenay River Total Gas Pressure Monitoring 1999 Investigations.	The Kootenay River is a tributary to the Columbia River in Canada. This report on the 1999 TDG data for this river provides background on the measurements at the Project.
Reese, H.O. (1980)	Gas Supersaturation at Reservoir Projects, in Proceedings of a Seminar on Water Quality Evaluation.	An early synopsis of dissolved gas problems and potential solutions. Historical reference for TDG at dams.
Roesner, L.A. Norton, W.R. (1971)	A Nitrogen Gas (N2) Model for the Lower Columbia River.	An early predictive model that identified the stilling basin as the primary source of dissolved gas super-saturation. A historical reference for TDG at dams.
Seattle City Light (1981)	Application for Amendment of License for the Boundary Hydroelectric Project, Project No. 2144, 1981.	Deals directly with Project. Virtually identical to the Review Draft of Exhibit E Environmental Report. Very general - little information available for the Project area. Provides a broad overview of water quality in Boundary Reservoir, but data are 25 years old. Historical reference for Project.
Seattle City Light (2003)	Recommendations to reduce total dissolved gas levels at Boundary, Internal memo to Mike Harrison, Mike Haynes, Mike Sinowitz and the Boundary Relicensing Team, 2003.	An internal memorandum that discusses how operations affect TDG levels in the tailwater of the Boundary Dam.
Seattle City Light (2004)	Selected Items from Doc 347, Christine Pratt's 3-Ring Binder, 2004.	Binder with miscellaneous notes, presentation handouts, and guidance documents related to water quality. Contains information relevant to 303(d) listing for Pend Oreille River.
Smith, H.A., Jr. (1974)	Spillway Redesign Abates Gas Supersaturation in Columbia River.	General information which indicates the general level of knowledge at the time. Historical reference for Project.
Sullivan, Robert D. Weitkamp, Don E. Swant, Tim DosSantos, Joe (2006)	Controlling Total Dissolved Gas, Lower Clark Fork River Dams, Report to Avista Corp., 2006.	Discussion of how operations can make a difference in TDG levels.
Tervooren, H.P. (1972)	Bonneville Spillway Test Deflector Installation in Bay 18: Preliminary Evaluation Report on Nitrogen Tests.	These tests were low spillway discharges, where there is minor plunging of the spillway flow. Minimal help to the Project because these discharges are not of concern for spillways.
Tervooren, H.P. (1973	Bonneville Spillway Nitrogen Tests, 29-30 October 1972 Test Results.	These results show that incorrect conclusions can result from an analysis of limited data, which occurred in this case.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
Turner, A. Rudder, Jr. (1992)	Fish Spill and Dissolved Gas Saturation at Columbia and Snake River Dams.	This paper provides an overview of TDG problems at Corps dams on the Columbia and Snake rivers.
Urban, A. L. Gulliver, J.S. Johnson, D. (2007)	Modeling Total Dissolved Gas Concentrations Downstream of Spillways.	This paper demonstrates that the quantity of air entrainment on a spillway surface is not of great importance to TDG in the tailwater, because the air entrained is more than enough to approach steady state TDG levels. Modeling at the Project will be adapted from the equations in this paper.
U.S. Army Corps of Engineers (1996)	Dissolved Gas Abatement Study: Phase I Technical Report, North Pacific Division, U.S. Army Corps of Engineers, 1996.	The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.
U.S. Army Corps of Engineers (1999)	Dissolved Gas Abatement Study: Phase II-60% Draft Report, North Pacific Division, U.S. Army Corps of Engineers, 1999.	The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.
U.S. Army Corps of Engineers (2004)	2004 Dissolved Gas And Water Temperature Monitoring Report Columbia River Basin.	Monitoring summary for the U.S. Army Corps of Engineers dams on the Columbia and Snake rivers.
U.S. EPA WA Dept of Ecology Spokane Tribe of Indians (2004)	Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt - Submittal Report, 2004.	TMDL on TDG for the Columbia River from the Canadian border to the Snake River confluence. Could provide the basis for settlement of TDG concerns at the Project.
Walla Walla District of the US Army Corps of Engineers (1992)	Lower Granite & Little Goose Projects: 1992 Reservoir Drawdown Test Draft Report.	Describes performance of spillway flow deflectors for reservoir drawdown conditions, including the effects of drawdown on spillway deflector performance.
Weber, Larry J. Mannheim, Carl (1997)	A Unique Approach For Physical Model Studies Of Nitrogen Gas Supersaturation.	The effects of reservoir drawdown on spillway deflector performance.
Weitkamp, D.E. Katz, M.	A Review Of Dissolved Gas Supersaturation Literature.	A classic compendium of literature published prior to 1980 on fisheries impacts of dissolved gas.
Weitkamp, Don E. Sullivan, Robert D. Swant, Tim DosSantos, Joe (2003)	Behavior of Resident Fish Relative to Total Dissolved Gas, Supersaturation in the Lower Clark Fork River.	This is one of many papers on fish behavior relative to TDG. It does attempt to explain the lack of gas bubble trauma observed in fish at 120% supersaturation in the field.
Wilhelms, S.C. Gulliver, J.S. (2005)	Bubbles and Waves Description Of Self-Aerated Spillway Flow.	This paper describes self-aerated spillway flow as entrained bubbles and air "entrapped" between the surface waves. The distinction is important because not all of the entrapped air will enter into the tailwater as entrained air.
Wilhelms, S.C. Gulliver, J.S. Parkhill, K. (1998)	Predictive Capabilities In Oxygen Transfer At Hydraulic Structures.	This paper outlines the "best" predictive models from the literature for estimating dissolved oxygen levels. The importance to dissolved gas levels is that many of the same processes are predominant in re-aeration and TDG transfer.

Table 5.1-1, continued…

Author/Date	Title	Relevance to TDG Study
Wilhelms, Steven C. Schneider, Michael L. (1997)	Total Dissolved Gas In The Near-Field Tailwater Of Ice Harbor Dam.	This paper summarizes the U.S. Army Corps of Engineers thinking on reducing TDG below dams.
Wilson, C.J. (1994)	Kenney Dam Release Facility: An Overview.	This paper presents what Alcan went through to meet strict TDG requirements.
Young, M.F. (1992)	Hydraulic Model Studies - Yellowtail Afterbay Dam Sluiceway, US Bureau of Reclamation Report GR-82-5, Denver, CO, 1982.	This report describes some of the considerations of a deflector installation.

5.2. Retrospective Data Analysis

5.2.1. Water Quality Standards, 7Q10 Flow Conditions, and Flow Duration

The water quality standards applicable to this Project are the Washington State Water Quality Standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC). These standards describe designated beneficial uses, water body classifications, and numeric and narrative water quality criteria for surface waters of the state. The revised version of the standards, adopted in 2003, applies to the Project.

The standards relevant to this study limit TDG based on the adverse impact of dissolved gas on aquatic life. TDG is the amount of air held in saturation in the water, measured in percent of saturation pressure relative to ambient barometric pressure (percent saturation). The criteria for maximum total TDG are summarized in Table 200(1)(f): Aquatic Life Total Dissolved Gas Criteria in Fresh Water.

For waters designated as salmonid spawning and rearing, the standard states that TDG shall not exceed 110 percent of saturation at any point of sample collection. This criterion is waived when the stream flow exceeds the 7Q10 frequency flood. The 7Q10 flow is the highest flow of a running seven consecutive day average using the daily average flows that may occur in a 10-year period. The 7Q10 flow at the Project is 108,300 cfs (SCL 2006).

Previous estimates of spill during the 7Q10 event have been computed based on the assumption that one of the six Project generating units is inoperable during the 7Q10 event. However, unit reliability at the Project is quite high, and maintenance schedules are developed to keep the units operational during the spring flood season. The likelihood of a combined event where the unit is offline during a 7Q10 event is very small. For the purposes of TDG abatement alternative evaluation, the target flow for passing the 7Q10 event is assumed to be 53,300 cfs (108,300 minus the Project generation capacity of 55,000 cfs).

The flow duration curve for the Pend Oreille River at USGS gaging station 12396500 below Box Canyon Dam is shown in Figure 5.2-1. The curve was developed using flows from 1987 through 2005. Table 5.2-1 shows specific exceedance values for specific flows of interest and the equivalent number of days per year that the flow volume will be exceeded.

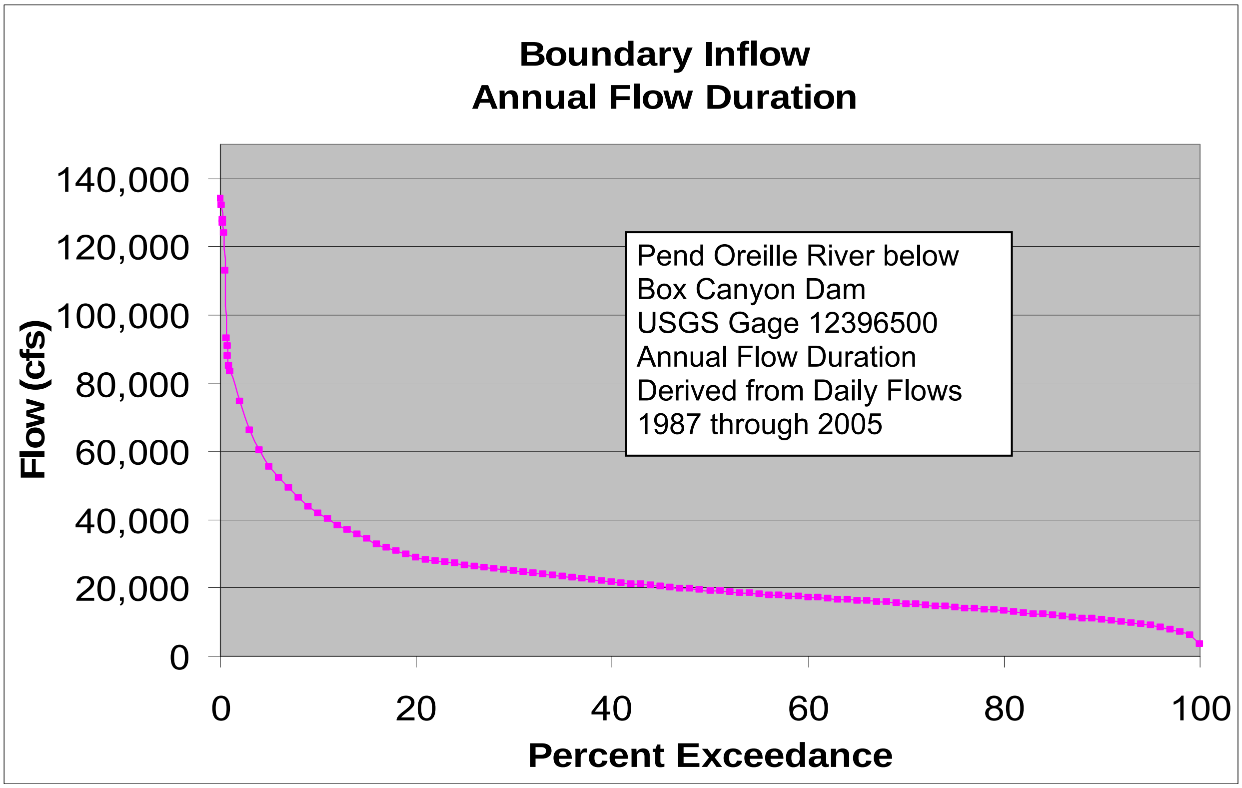


Figure 5.2-1. Flow duration curve.

Table 5.2-1. Exceedance values for specific flows of interest and equivalent number of days per year.

Flow	Percent Exceedance (%Exceed.)	Equivalent No. of Days (%Exceed x 365)
108,300	0.52	1.91
90,000	0.73	2.67
80,000	1.38	5.03
70,000	2.55	9.32
60,000	4.06	14.82
55,000	5.13	18.74
50,000	6.75	24.64
40,000	11.15	40.70

5.2.2. Representative Hydrology and Response of Forebay TDG to Upstream Operations

Current Project operations and forebay TDG are influenced by operations at the upstream Albeni Falls and Box Canyon dams due to the powerhouse hydraulic capacity of the upstream projects. Albeni Falls Dam has a powerhouse hydraulic capacity of 29,000 cfs and Box Canyon Dam has a powerhouse hydraulic capacity of 33,000 cfs. Above these river flows, both dams increase the TDG in the river and in the Project forebay as flow is passed through spill gates and plunges into the tailwater. As river flow increases, both projects pull their gates completely out of the water to pass flood flows unimpeded (Albeni Falls Dam at 74,000 cfs and Box Canyon Dam at 90,000 cfs), removing the spillway plunge and effectively eliminating their TDG contributions to the river.

This action is illustrated by plots of flow and TDG levels (Figure 5.2-1) at the Project for a representative flow year (2002) during which the previously described cycle of upstream gate operation occurred. Of the years with data in the long-term database, 2002 has the most complete data record, with flows ranging from low winter flows to spill flows from May through early July. As a benchmark, Table 5.2-1 summarizes the flows in 2002 and the approximate percent exceedance as based on the available flow frequency curves for Box Canyon Dam in the PAD. Updated hydrologic information for the Project is pending finalization of the hydrologic report from R2 Resource Consultants. The flow information in Table 5.2-2 is from the long-term database developed for the TDG data analysis.

Table 5.2-2. Summary of 2002 flow exceedances (R2 Resource Consultants 2008).

Period	2002 Max. Flow	% Exceedance	2002 Avg. Flow	% Exceedance
Annual	97,500	1	26,900	26
Jan	27,700	5	17,200	42
Feb	22,000	16	16,800	34
Mar	25,000	22	18,200	58
Apr	51,900	6	29,000	39
May	80,900	4	46,300	28
Jun	97,500	5	84,300	9
Jul	82,000	1	37,400	15
Aug	21,300	6	14,700	25
Sep	15,600	43	12,500	64
Oct	19,200	62	15,900	86
Nov	19,500	51	14,900	82
Dec	22,000	18	16,000	52

In 2002, the maximum Project inflow was approximately 95,000 cfs and the maximum spill flow approximately 45,000 cfs, as shown in Figure 5.2-2. These conditions are still considerably below, but begin to approach, the 7Q10 conditions of 108,300 cfs inflow and 53,300 cfs spill flow. The minimum Project inflow was approximately 9,000 cfs. Incoming forebay TDG was below 110 percent until the incoming flow began to increase above approximately 33,000 cfs. Then the forebay TDG increased to as high as approximately 130 percent at an incoming flow of about 80,000 cfs. This corresponds to the river flows when the upstream dams (Albeni Falls and Box Canyon dams) pull their gates to effectively remove their TDG contributions from the river. As the flow increases beyond approximately 80,000 cfs, the forebay TDG decreases to between 110 percent and 118 percent until the gates at the upstream dams are replaced and forebay TDG increases again. As the river flows taper off in late July, the forebay TDG decreases. Tailrace TDG is greater than 110 percent during the entire spill period and about a month prior to the spill season.

Tailrace TDG was generally in compliance until the forebay TDG rose above 110 percent in April to May. In late April, forebay TDG was above 110 percent, but river flows were high enough that at times Project powerhouse operations resulted in slight gas stripping and kept the tailrace TDG in compliance (shown in green in Figure 5.2-2). Flows dropped off slightly in early May, resulting in slight gassing of flows through the powerhouse before the spill season started abruptly in late May. Spill flows above 12,000 to 14,000 cfs resulted in tailrace TDG that was out of compliance with state standards, but spill below this range stripped gas and reduced tailrace TDG to less than forebay levels.

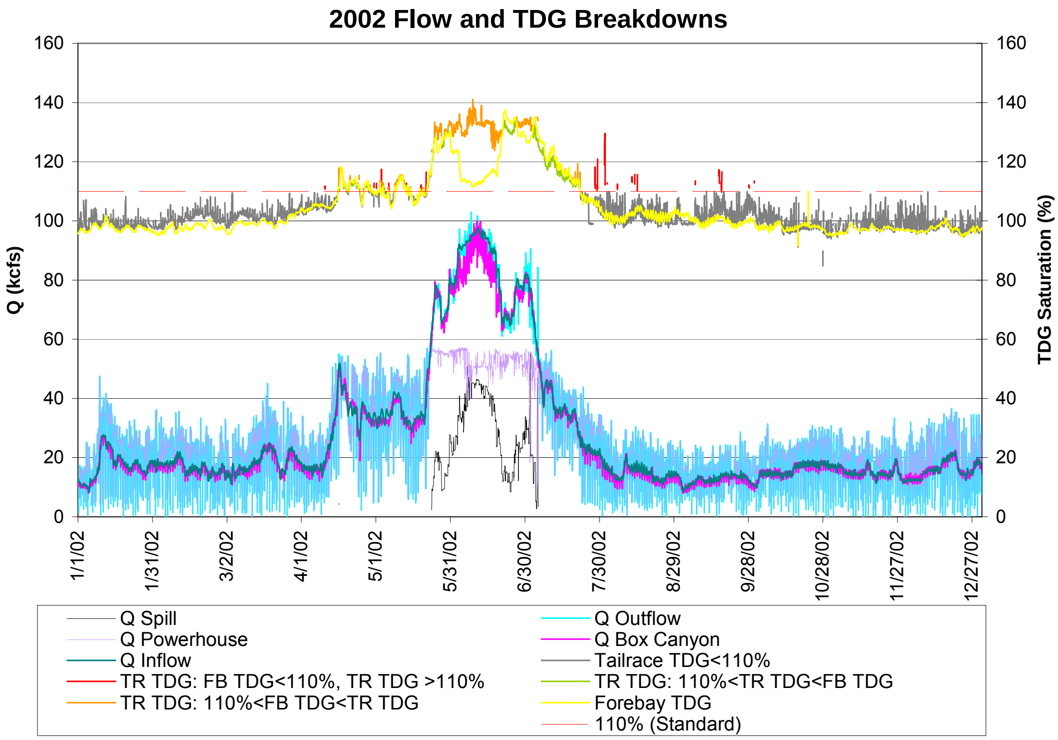


Figure 5.2-2. 2002 flow and TDG breakdowns.

Using the long-term database, ENSR developed a relationship between Box Canyon Dam tailrace flows and Project forebay TDG to predict the incoming forebay TDG at the Project as a result of upstream operations, as shown in Figure 5.2-3. The relationship between Box Canyon tailrace flows and Boundary Dam forebay TDG shows that there is a reasonably good correlation between upstream flow and forebay TDG ($R^2 = 0.78$). The correlation is likely not valid for flows above approximately 90,000 cfs or below approximately 8,000 cfs due to lack of data. It is also important to note that this correlation provides a retrospective indication of the incoming TDG at the Project forebay due to upstream operations for a range of river flows. If upstream projects improve their TDG performance with operational or structural measures, this correlation will change.

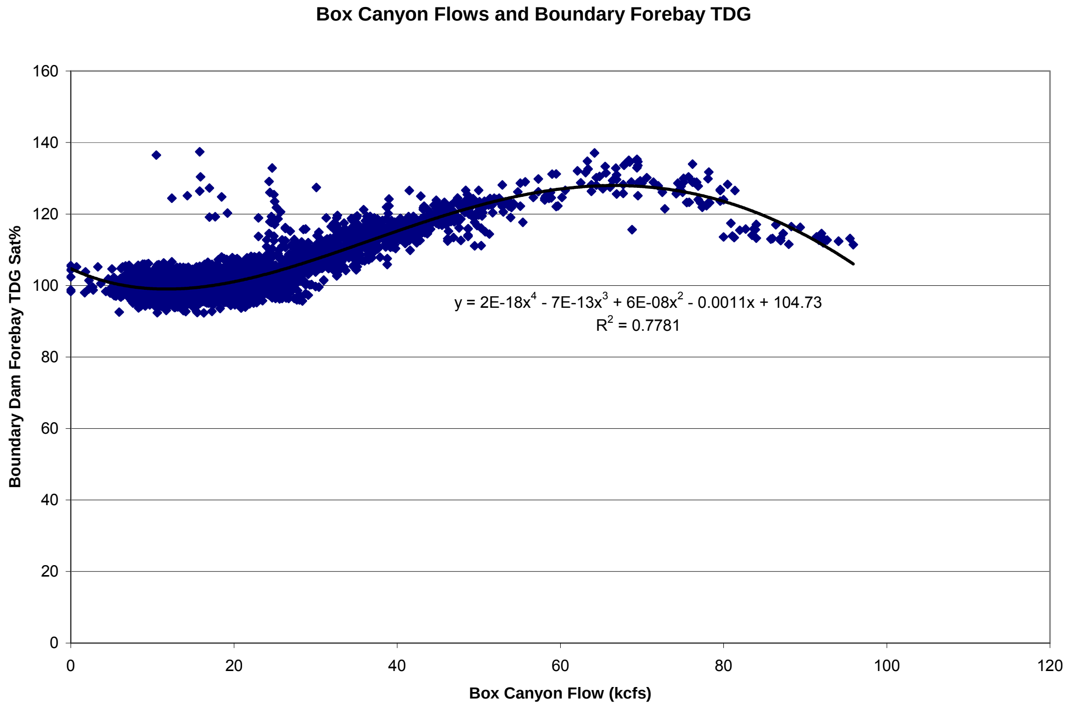


Figure 5.2-3. Box Canyon tailrace flows and Boundary Dam forebay TDG correlation (not valid at flows above approximately 90,000 cfs or below approximately 8,000 cfs).

5.2.3. Impact of Powerhouse Operations on TDG

The long-term database was filtered for Project outflows ranging from 0 to 50,000 cfs (just below Project capacity) and a second filter was applied to remove any instances of spill flow with outflow less than 50,000 cfs. The filtered dataset consisted of powerhouse-only operations for Project outflows less than 50,000 cfs. A plot of the TDG gain from forebay to tailrace as a function of Project outflow is shown in Figure 5.2-4. The data from 1999 through September 2003 are plotted in maroon and the data from September 2003 through the end of the long-term database in July 2005 is shown in blue. Based on the observations of the long-term forebay and tailrace records for 1999 through 2005 it was apparent that the change to existing Project powerhouse operations in approximately September 2003 decreased the amount of fluctuation in TDG from the forebay to the tailrace during periods of low powerhouse flows and frequent unit startup and shutdown.

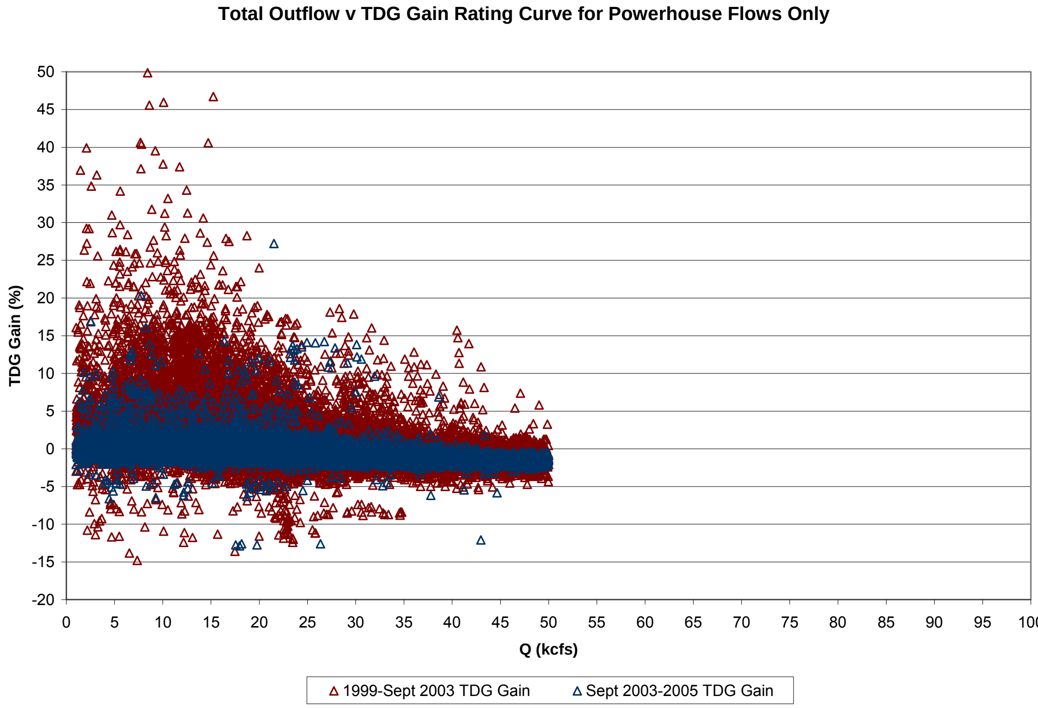


Figure 5.2-4. Long-term TDG gain for powerhouse only operations.

In 2003, SCL implemented changes in the Project powerhouse start-up and shut-down operations to reduce air admissions at Units 55 and 56. Previous testing indicated that during low flow operations, air admitted through the turbine runner contributed to spikes in tailrace TDG. This was an issue particularly during start-up and shut-down procedures when Units 55 or 56 were operated as the first powerhouse units to turn on or last units to turn off. SCL implemented procedures to limit the use of Units 55 and 56 as the first on/last off units, to improve tailrace TDG.

Based on the apparent change in Project powerhouse operations in September 2003, the database was divided into two parts, before and after September 2003, and two regression equations were developed to show the TDG production as a function of Project powerhouse flows before and after the change in Project powerhouse operations. TDG production from generation flows alone before the Project powerhouse operations procedure was adjusted in late September 2003 can be expressed by the equation $\Delta TDG = -0.00015*Q + 5.0716$ (Figure 5.2-5), where Q represents the total outflow. After the change in Project powerhouse operations, TDG production from the powerhouse decreases, especially at lower flows, and the regression equation for TDG gain as a function of powerhouse flow becomes $\Delta TDG = -0.00005*Q + 0.8178$ (Figure 5.2-5).

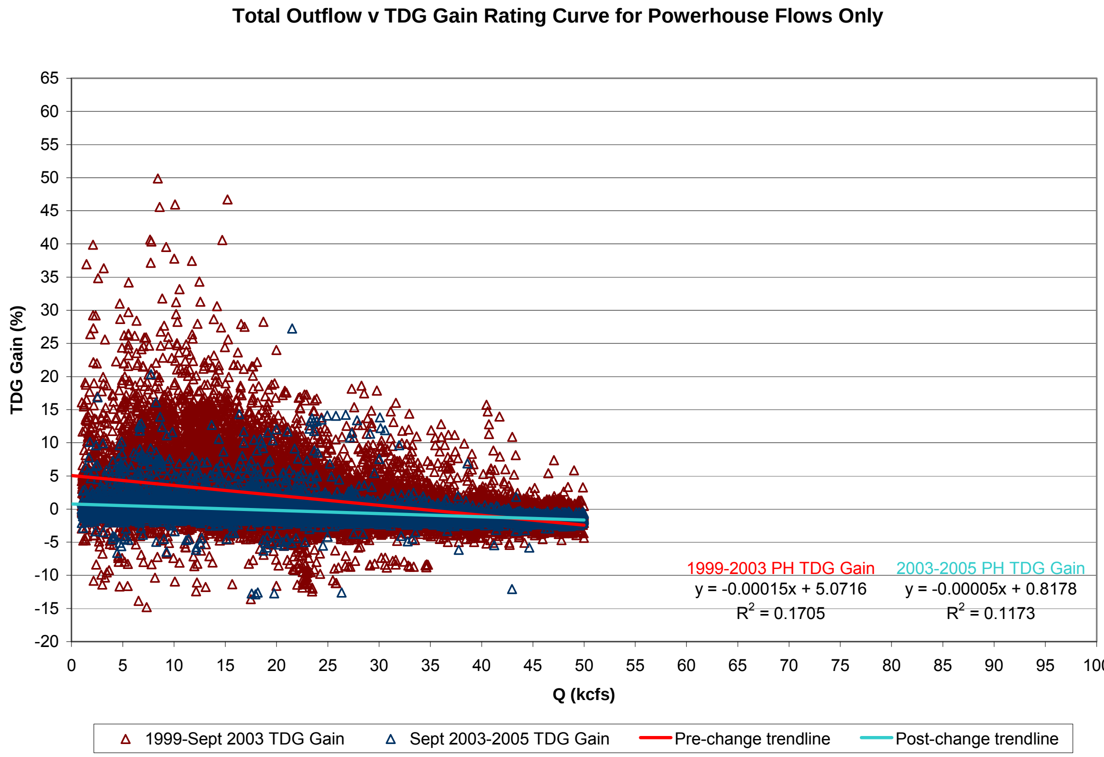


Figure 5.2-5. Regression analysis for TDG gain as a function of total flow during periods of no spill when Q<50,000 cfs prior to and following the September 2003 adjustment in standard powerhouse operations.

There should be no difference in air admissions between the two operating procedures above a certain flow, represented by the point in Figure 5.2-5 where the regression lines cross. Based on this, the change in TDG attributed to the powerhouse is assumed constant at -1.3 percent above 42,500 cfs of generation flow when using these equations in the following sections.

5.2.4. Short-Term Spill and Sluice Test Data Analysis

See Section 4.4 of Appendix 4 for discussion.

5.2.5. 2007 Hydrodynamic Data

As related in Section 4.3.2, tailrace hydrodynamic data were acquired for two different flow conditions:

- Low Flow—Total river flow of 33,600 cfs; Unit 51 at 0 cfs; Unit 52 at 5,690 cfs; Unit 53 at 5,660 cfs; Unit 54 at 5,560 cfs; Unit 55 at 8,320 cfs; Unit 56 at 8,370 cfs; Spill Gate 1 at 0 cfs; Spill Gate 2 at 0 cfs.
- High Flow—Total river flow of 53,450 cfs; Unit 51 at 6,740 cfs; Unit 52 at 6,840 cfs; Unit 53 at 6,940 cfs; Unit 54 at 8,000 cfs; Unit 55 at 9,990 cfs; Unit 56 at 10,040 cfs; Spill Gate 1 at 4,900 cfs; Spill Gate 2 at 0 cfs.

Figure 5.2-6 contains typical plots of the water surface profile data acquired during the field data collection. Complete time series of the water surface data throughout the test periods have been archived for use during calibration of future hydrodynamic models of the Project tailrace.

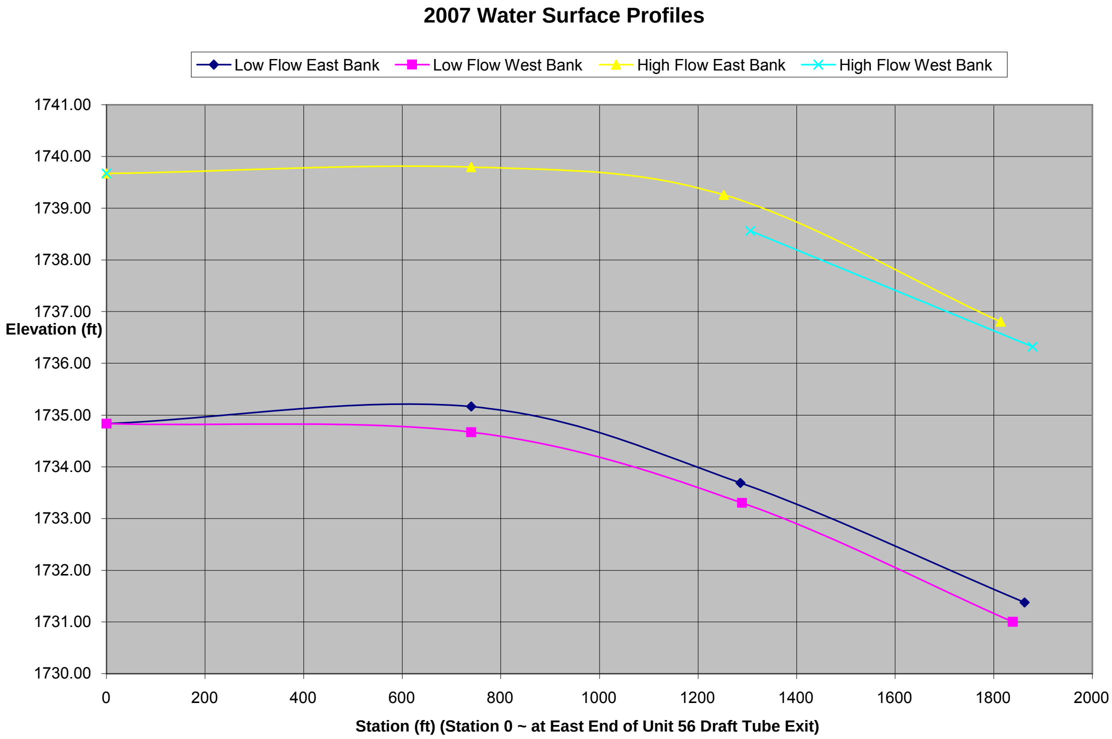


Figure 5.2-6. 2007 tailrace water surface profiles.

Figures 5.2-7 and 5.2-8 contain plots of the average velocity vectors measured at 0.6 of the river depth at the fixed measurement stations in the tailrace. These measurements are representative of the average velocities in the vertical profile. The average full three-dimensional velocity vectors and their standard deviations at 0.2, 0.6, and 0.8 of the river depth have been tabulated and archived for use during calibration of future hydrodynamic models of the Project tailrace.

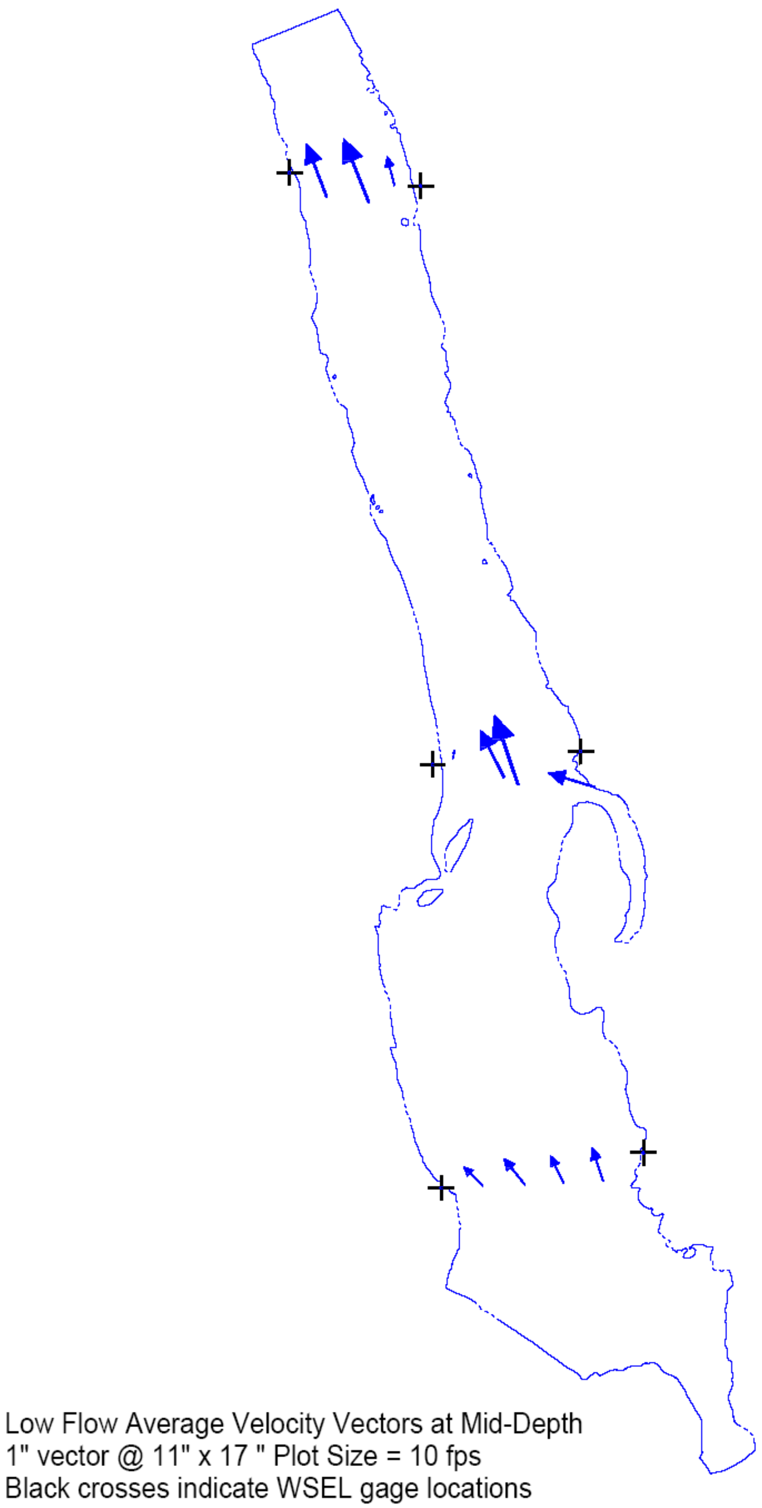


Figure 5.2-7. 2007 low-flow average velocity vectors at mid-depth (vectors not to scale) in the Project tailrace.

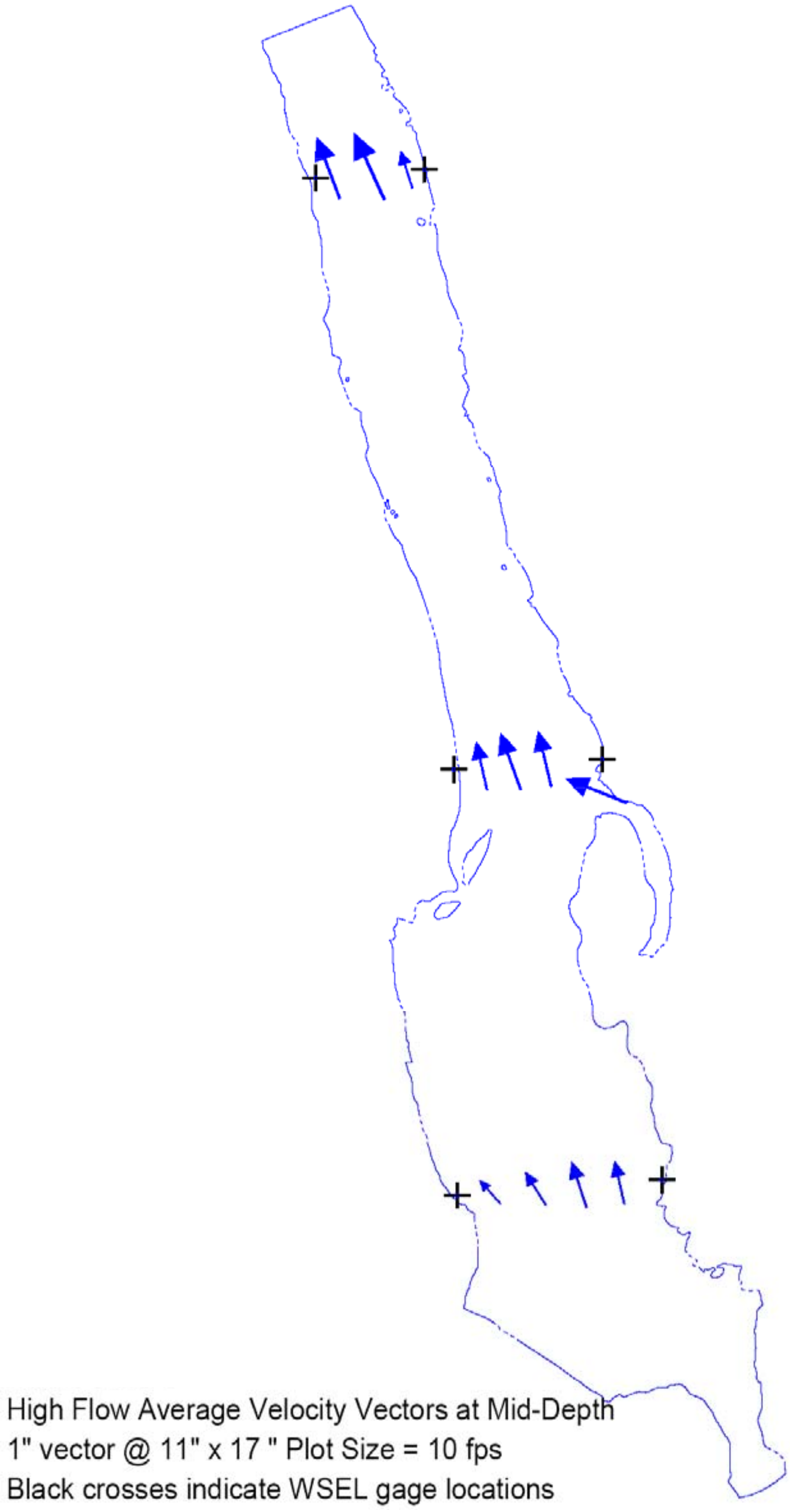


Figure 5.2-8. 2007 high-flow average velocity vectors at mid-depth (vectors not to scale) in the Project tailrace.

5.2.6. 2008 TDG Data

5.2.6.1. TDG Database

The 2008 field tests were designed as a complement to the TDG historical data analysis, which was based on a long-term database of USGS forebay and tailrace fixed monitoring station TDG measurements and a short-term database of TDG from spill and sluice gate tests conducted during the 2002 and 2003 spill seasons (see Appendix 2). The 2008 database was analyzed to develop correlations between the forebay TDG station H9, the USGS forebay fixed monitoring station, the tailrace stations H1 to H7, the USGS tailrace fixed monitoring station, and the gage installed downstream of the riffle across the Canadian border (station H8). These correlations were used to derive conclusions concerning longitudinal and lateral distributions of TDG in the tailrace and TDG stripping action of the Boundary tailrace downstream from the USGS fixed monitoring station through the riffle to station Meter H8 downstream of the Canadian border.

5.2.6.2. Summary of 2008 TDG Data Monitoring Data

See Section 4.3.1 in Appendix 4 for discussion.

5.2.6.3. TDG Distribution During Spill Flow

See Section 4.3.3 in Appendix 4 for discussion.

5.2.6.4. General Longitudinal and Lateral TDG Distribution

The following section describes the longitudinal and lateral TDG distribution and mixing trends identified from the data for stations H1 to H9 and the USGS forebay and tailrace fixed monitoring stations.

The meter at station H9 was installed in the forebay as a duplicate for the USGS fixed monitoring station. TDG data from H9 were generally strongly correlated with the USGS forebay station data. As shown in Figure 5.2-9, the data from station H9 were consistently slightly higher than the USGS data at forebay TDG levels above 110 percent. The station H9 data were nearly identical to the USGS data for forebay TDG levels between 107 percent and 110 percent, and H9 data in the lowest range were 2 to 3 percent higher than the USGS forebay meter data.

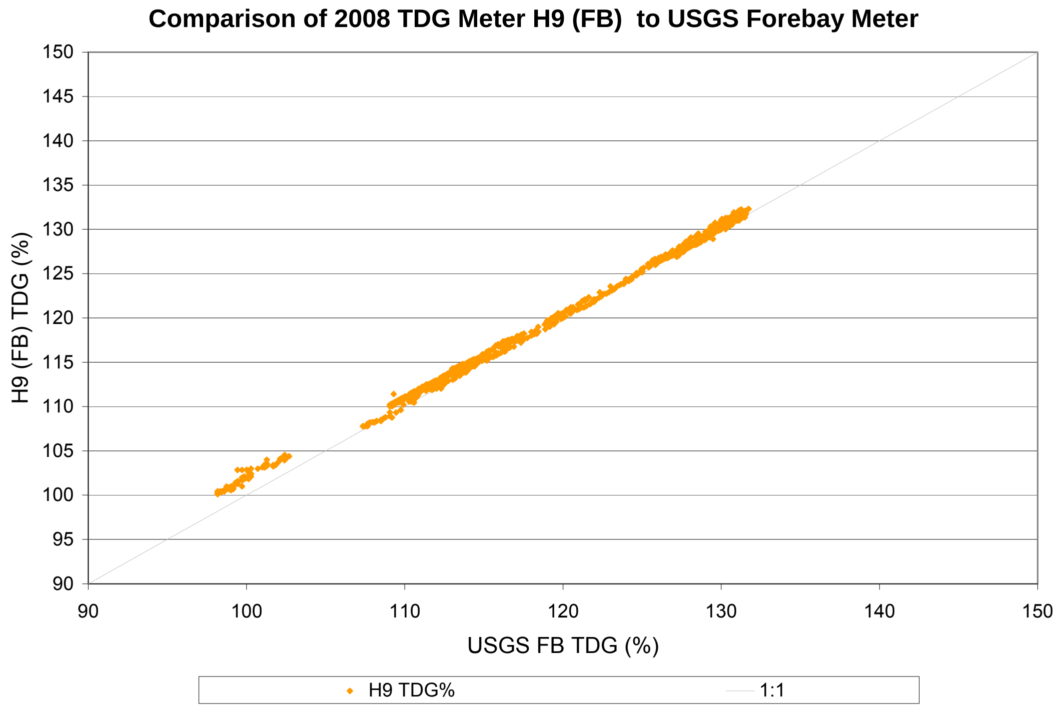


Figure 5.2-9. Station H9 to USGS forebay meter correlation.

Figures 5.2-10 and 5.2-11 compare the stations along transects 2 and 3 longitudinally and laterally with respect to river flow. In each case, the differences between the USGS tailrace fixed monitoring station TDG and the TDG station were plotted for the entire study period. Negative TDG gain in the figures indicates that the stations generally read higher TDG than the USGS fixed monitoring station at Project outflows above approximately 50,000 to 60,000 cfs, with this difference increasing from left to right across the river. As discussed in the two-week chronological plots in Section 4.3.3 of Appendix 4, this effect was observed at spill flows above approximately 12,000 cfs.

Figure 5.2-10 shows the relationship of river flow to the difference in TDG between the transect 2 stations (H1 to H4) and the USGS tailrace station. There was a distinct relationship between flow level and the difference in TDG measurements between the transect 2 stations and the USGS fixed monitoring station. At full powerhouse capacity, the transect 2 stations read approximately the same as the USGS tailrace station. As river flows increased, the transect 2 stations (H2, H3, and H4) measured higher than the USGS tailrace station by approximately 4, 5.5, and 8 percent, respectively, at 105,000 cfs. This suggests that mixing was incomplete and TDG is greater on the right side of the river at higher spill flows. Station H1 stopped recording on May 4 and produced no data above 43,000 cfs.

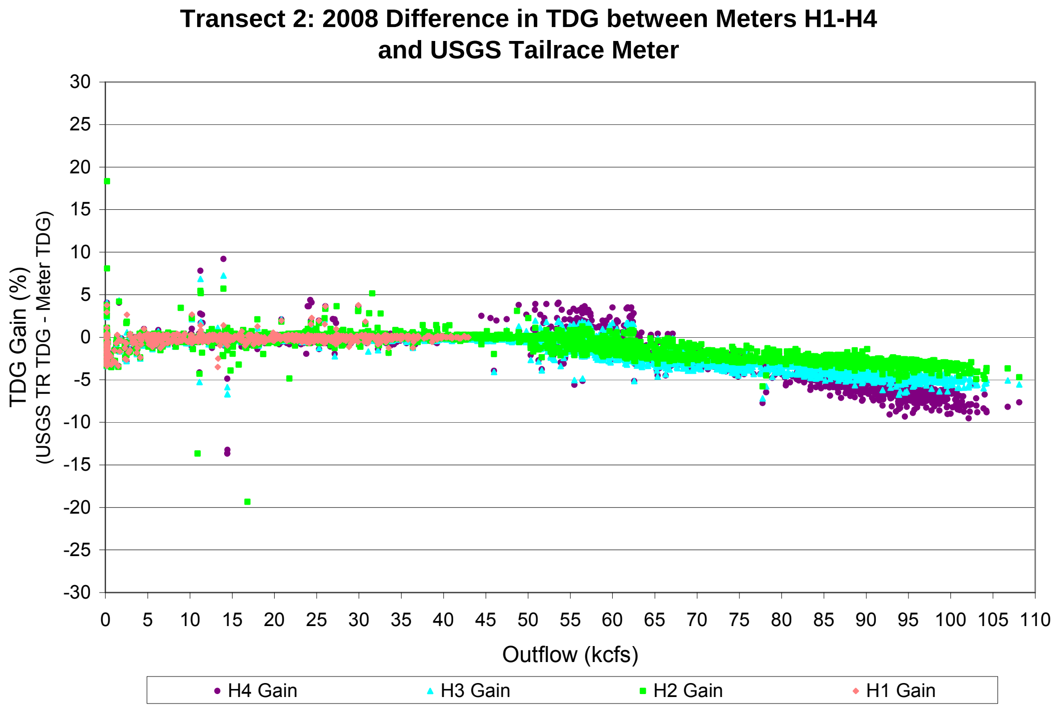


Figure 5.2-10. River flow vs. TDG difference between transect 2 meters and the USGS tailrace meter.

Figure 5.2-11 shows the relationship of river flow to the difference in TDG between the transect 3 stations (H5 to H7) and the USGS tailrace station. The transect 3 stations followed the same pattern as those on transect 2: reading higher than the USGS station at Project outflows below 12,000 cfs, neutral to 50,000 to 60,000 cfs, and increasing in difference from the USGS station to 4.5 percent at station H5 and 6 percent at station H6 at 110,000 cfs. This suggests lateral variation with higher TDG on the right side of the river on Transect 3. Station H7 recorded a limited data set until April 10 for outflows below about 36,000 cfs.

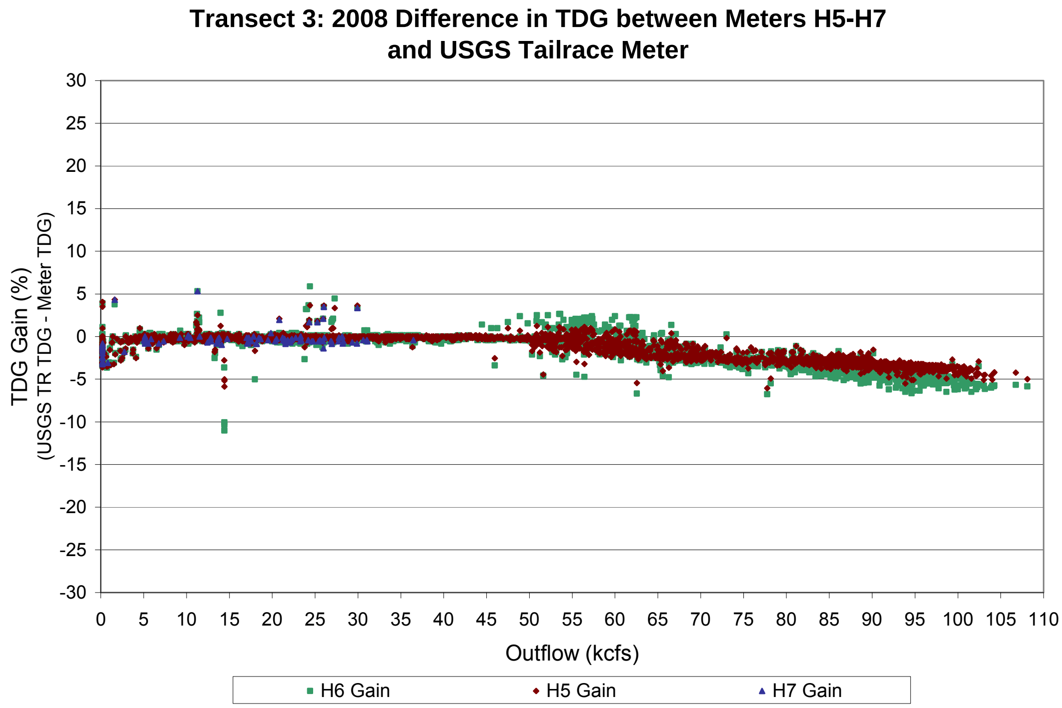


Figure 5.2-11. River flow vs. TDG difference between transect 3 meters and the USGS tailrace meter.

Figure 5.2-12 compares the downstream station H8, which is located on transect 4 at the Canadian border, to the USGS tailrace station. The 2007 data showed the TDG measured at station H8 to be slightly lower than at the USGS tailrace station, with the difference decreasing with Project outflow from -1.1 percent at 5,000 cfs to zero percent at approximately 55,000 cfs. The 2008 data show no difference between station H8 and the USGS tailrace station below 50,000 cfs, with station H8 an average of about 2 percent lower between 50,000 cfs and 62,000 cfs, then increasing to about 4 percent at 110,000 cfs. This trend of transect stations showing higher TDG readings than the USGS station at higher spill flows is consistent with the results at the upstream transects because station H8 was located near the right bank.

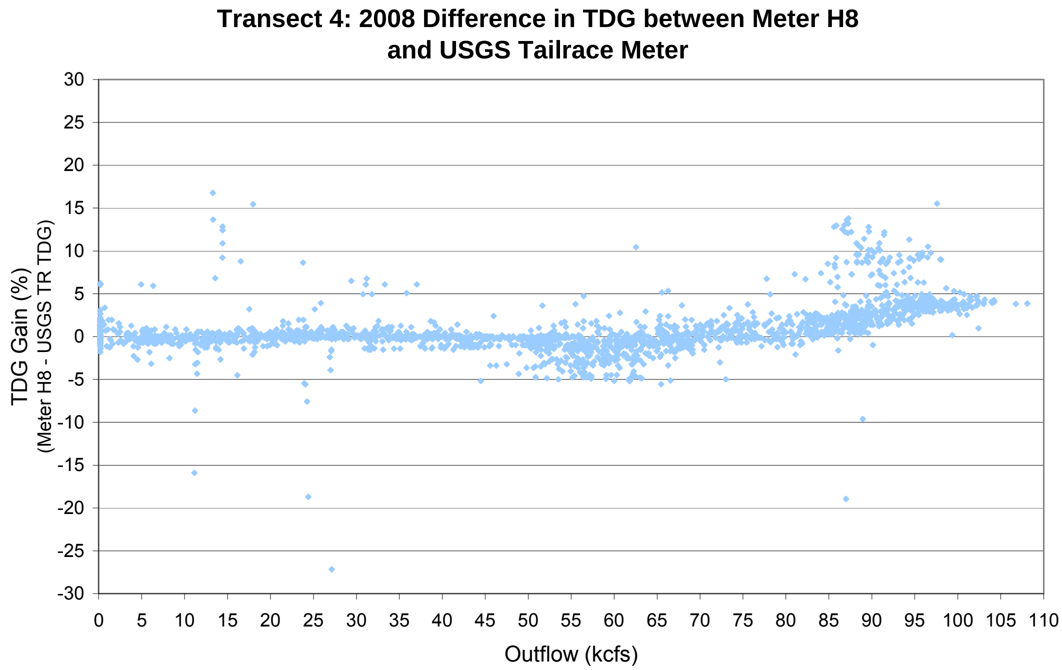


Figure 5.2-12. River flow vs. TDG gain from the USGS tailrace station to the Canadian border.

5.2.7. TDG Mechanism Description

5.2.7.1. TDG Generation Mechanisms

There are two known sources of high TDG at the Project:

1. Air admission to generating Units 55 and 56 for the lower part of the operating range (discussed in detail in Section 5.4.6)
2. Spill flow (see below)

High TDG concentrations at the Project during spill are caused by the spillway configuration: After a short time on the surface of the spillway, the flow is released into the air as a falling jet; this jet falls to the plunge pool, gaining energy as it falls. At the intersection between the plunge pool and the falling jet, a high velocity gradient entrains a substantial quantity of air into the flow, which continues as a vertically oriented jet in the water. This air is carried to the bottom of the plunge pool by the vertically oriented jet. The hydrostatic pressure on the bubbles of entrained air increases by one atmosphere for each 34 feet of depth. The bubbles are smaller under pressure, so the concentration of oxygen and nitrogen per unit volume is correspondingly higher. The local equilibrium that the water can eventually reach is based upon this higher concentration, which can be 200 percent of atmospheric saturation at 34 feet of depth, or higher at deeper depths. The local equilibrium of 110 percent occurs at 3.4 feet of depth. The rate of gas transfer from the bubbles under pressure to the water depends upon the turbulent energy of the water, the bubble surface area present, and the difference between local equilibrium and the water concentration.

There are therefore three conditions necessary to result in the high TDG concentrations of the tailwater of a spillway:

1. An energetic flow with a substantial amount of turbulent energy. This condition exists below most spillways and at most dam outlets. One of the best ways to reduce the energy in a flow is to extract it through hydroturbines. The other mechanism is to reduce the energy through head loss as it moves down the channel or conduit. This is the approach used by baffled and stepped spillways.
2. Air entrainment that occurs due to the jet falling through the air and plunging into the pool. In a high velocity, free surface flow, air entrainment is probably the most difficult of the three conditions to avoid. The devices proposed to eliminate air entrainment have all proven to be expensive and often not effective.
3. Air bubbles that are carried to depth. TDG supersaturation requires the bubbles be at depth. If most of the bubbles are kept near the surface, the dissolved gas concentration will be close to 100 percent. This is the approach used by spillway deflectors, which deflect the flow at the bottom of the spillway across the surface of the plunge pool. This is a cost-effective solution which has limitations at higher discharges, because the surface jet that is deflected will expand and carry the bubbles with it. The ~0.7 fps rise velocity of the bubbles and the high turbulent velocities in the jet results in a large portion of the bubbles being pulled to depth with the expansion of the surface jet.

The plunging jet immediately downstream of Boundary Dam has all three of these conditions. Reduction of any of the three, without increasing any of the others, will likely result in lower TDG concentrations.

5.2.7.2. Impact of Historical Operations on Compliance with TDG Standards

Regression equations were developed for TDG production as a function of Project powerhouse flows as described in Section 5.2.3. Two equations were developed for the long-term data period, one for TDG production through the powerhouse prior to September 2003 and one after September 2003 when Project powerhouse operation changes appear to decrease fluctuation of tailrace TDG during low flows and startup/shutdown operations. Because 2002 is a typical year and has a complete range of flows from low flows to spill flows, the data from the 2002 database were used to further assess the impacts of the improved Project powerhouse operations on tailrace TDG.

Table 5.2-6 shows the percentage of tailrace TDG measurements out of compliance in 2002 based on the actual data in the long-term database (either exceeding the standard of 110 percent or increased TDG above the Project forebay level when the incoming forebay is 110 percent or more). In addition, the regression equation for TDG production through the Project powerhouse prior to September 2003 and the regression equation developed for TDG as a function of flows greater than the powerhouse capacity were used to predict the tailrace TDG for the Project outflows (powerhouse and spill flow) for 2002 from the long-term database. A frequency analysis was performed on the predicted 2002 tailrace TDG values and the resulting percentages of predicted Project tailrace TDG values out of compliance are in Table 5.2-6. The tailrace TDG regression equation for the improved Project powerhouse operations after September 2003 was then applied to predict tailrace TDG values for 2002 as if the improved operations had been instituted before 2002. A frequency analysis was performed on the improved 2002 predicted TDG values; the results are shown in Table 5.2-3.

Table 5.2-3. Predicted effect of powerhouse operations change on exceedance frequency for typical year (2002).

Effect	Not in compliance	TR>110, FB<110	110<FB<TR
Actual	14.6%	1.8%	12.8%
Predicted with pre-September 2003 regression	15.3%	2.0%	13.2%
Predicted with post-September 2003 regression	10.3%	0.2%	10.1%

Notes:
FB – forebay
TR – tailrace

5.3. Estimated Performance of Alternatives and Combinations

5.3.1. Review of Alternative Shortlist and Potential Additional Alternatives

The following alternatives include the six short-listed alternatives from the RSP (SCL 2007) and the alternative ranked number 7 in previous rankings:

- Throttle Sluice Gates (No. 1-3)
- Roughen Sluice Flow (No. 3-2)
- Spillway Flow Splitter/Aerator (No. 2-8)—**New**
- Right Abutment Tunnel with Submerged Discharge (No. 4-7)
- Open Existing Diversion Tunnel and Add Control Structure (No. 4-8A)
- Penstock Draft Tube By-pass (No. 4-9)
- New Left Abutment Tunnel Next to Unit 51 Intake (No. 4-10)

5.3.1.1. Throttle Sluice Gates (No. 1-3)

This alternative involves throttling the sluice gates to pass flow with either a neutral or stripping effect on tailrace TDG (see Appendix 6, Figure A.6-1). Water is drawn from a lower portion of the reservoir where fisheries studies have indicated lower fish abundance.

This alternative would be an incremental approach to throttling flows and testing for TDG impacts. SCL has FERC approval for modification of the sluice gate seals to allow this testing (FERC 2007).

Some testing was performed in 2006 for throttled gate openings. The 2006 testing showed the discharge from the sluice gates at lower flows having a significant downward component due to the effects of the downstream edge of the gate. This testing was taken further in 2007 and 2008 as described below.

5.3.1.1.1. Gate Considerations

The sluice gates were designed to operate in either the fully open or fully closed positions. Previous tests of the sluice gates at partial openings demonstrated problems of flow interactions with the gate slot heater covers and large sprays that are disruptive for access areas above the gates and may be causing damage to concrete near the gate seals.

The gate seals are mounted on the embedded parts and are inflated/pressurized to contact a peripheral sealing plate on the upstream face of the gate. To operate and seal the gate at partial openings it is necessary to add intermediate horizontal sealing plates to provide a contact surface for the lintel seal. A series of such plates have been added to Sluice Gate No. 4 for testing purposes. The slot heater covers will be inspected to ensure integrity. Consideration will be given to changing the seal insert from PTFE to brass.

Further testing occurred during 2008 with the aforementioned sealing plates added to the gate skinplate. Although the performance was better than without the sealing plate in place, further modifications are required before the system is ready for long-tem reliable use.

Additionally, consideration is being given to deflectors within the sluice gates to direct the water away from the gate slots. Initial indications are that, considering the pressure and velocity of the flow in the sluice gates, those deflectors would need to be substantial to direct the flow away from the gate slots. Additional considerations associated with the deflectors within the sluice gates will be evaluated as part of the 2009 TDG program.

5.3.1.1.2. TDG Performance

Based on available data, it is expected that a 4-foot sluice gate opening will pass approximately 4,400 cfs with neutral TDG effect. At this point the effects of having multiple gates operating simultaneously are unclear. There is one test from 2006 that shows two gates operating simultaneously at 4-foot gate openings with possibly less effective performance. This option will provide for a range of flows from either three or four sluice gates operating at 4-foot gate openings (3 or 4 x 4,400 cfs = 13,200 to 17,600 cfs). It may also work with seven gates at 2-foot gate openings (7 x 1,700 = 11,900 cfs). Additional testing may prove that the capacity of this alternative can be increased if operation of more than four (every other) gates does not negatively impact TDG. The TDG performance of these gates is expected to be affected by upstream TDG levels, so the impact of TDG reductions upstream may make this a less viable alternative.

5.3.1.1.3. Constructability

This option works by operating the gates in various throttled positions to decrease the size of the tailwater jet thereby reducing the mass of the individual gate's impacting jet as it enters the tailwater. The flow from the throttled sluice is spread over a wider area by discharging from multiple gates, thus reducing the energy per unit surface area.

Construction for this option includes continuing with the modifications to the gate seals and heater plates and the installation of larger sealing plates on the faces of the gates. Work can be performed incrementally, spreading the associated cost over any period predetermined by SCL.

Site reconnaissance may be required to determine if there is truly any detrimental impact to the concrete on the downstream side of the gates. This situation could be remedied with the installation of additional steel or stainless steel plating on the concrete to protect it from possible degradation.

Constructability issues for this option include safe access to the gate area for work on the seals and heater plates. Because work on the heater plates and seals has been performed previously, it is assumed that there are safe working procedures in place that could be replicated for the continued work. This work could be performed any time after the freshet flows have passed for the year. Work could also be performed through the winter months because the relatively small work areas could be quite easily heated.

5.3.1.2. Roughen Sluice Flow (No. 3-2)

This alternative was depicted in the RSP (SCL 2007) as consisting of a modification to the sluice gates with an obstruction that would break up the flow downstream of the gate. The workshop group considered this option to be reliably functional only for partial gate openings and is therefore an additional step to the Throttled Sluice Gate alternative to increase the flow through the sluice gates without increasing TDG production. At full gate opening, the flow would still form jets that would likely result in high TDG due to plunging action of the jet into the plunge pool.

The addition of varied height, flip or ramp type structures to the downstream side of sluice gates is intended to add a positive vertical component to direct a portion of the flow higher than what presently occurs and to also break up and spread out the jet in an attempt to reduce the plunging mass of the jet. This will result in a longer and wider area of impact with the tailwater pool. This spreading of the energy impact area should produce a shallower plunging depth which should reduce the take-up of dissolved gas.

As shown in Appendix 6, Figure A.6-2, each device would be 30 feet long and attached to the existing downstream opening of each orifice. The end of the device consists of two teeth-shaped deflectors with gaps between them. The variable ramping of the flow exiting the orifice will follow various flow trajectories. Those trajectories going over the top of the teeth will travel a greater distance downstream than those going through the gaps between the teeth.

It is expected that the structure would be manufactured from steel as either a plate structure or as a partial box structure that could be filled with grout to increase its mass and minimize the potential for vibration or resonance to occur. Excessive vibration could potentially cause the supporting concrete structures to migrate.

It may also be possible to include open piping in the bottom of the structure or the sides of the "steps" to allow for air induction (caused by the velocity of the flow over the apertures). This would serve to provide additional aeration to the bottom and sides of the jet, which would increase the turbulence and could potentially provide some TDG stripping. Additionally, the footprint of the area where the jet strikes the water would be increased, decreasing the energy per unit area and plunge depth could be slightly reduced because the jet should become more dispersed.

Although there is some confidence that this scheme will enlarge the impact area of the jet leaving the orifice, there is no theoretical way to estimate the effectiveness of this device in reducing the uptake in TDG within the tailrace. Additionally, the effect of the relatively narrow outlet to the plunge pool area will have a limiting effect on multiple options employed in the plunge pool area. To determine the TDG effectiveness, a full-sized prototype of the orifices of this scheme would have to be built and tested at the Project site.

An alternate design has also been conceptualized. The second concept is similar in that it represents a deflector positioned below the flow from the sluice to allow it to be redirected and distributed throughout the plunge pool. It is, however, smaller in scale and positioned lower to allow continued use of the existing gate seal system. The trajectory of the discharge at small sluice gate openings is directed downward. The deflector intercepts the discharge and redirects and distributes the flow. This alternate may be considered in the future in lieu of or in combination with that described above.

5.3.1.2.1. TDG Performance

The addition of flip buckets on the downstream side of sluice gates is intended to direct the flow more horizontally than presently occurs and also break up and spread out the jet as a spray within the plunge pool. The flip buckets are expected to be constructed of steel supports attached to the downstream face of the arch dam that support a steel surface at the outlet of the gate, directing the flow. The flip buckets can also be arranged to segment the flow into smaller jets designed to break into a spray before reaching tailwater. The advantage of a spray is the reduction in inertia of each droplet, compared to the water jet, reducing the depth to which the water and entrained air plunges. At full gate opening, the flow would still form jets that would likely result in high TDG due to plunging action of the jet into the plunge pool. If the roughened sluice flow is successful, the TDG performance may be below 110 percent at discharges of 12,000 cfs with four gates operating.

5.3.1.2.2. Constructability

Construction of this option would require access to the sluice gates. Scaffolding or suspended stages would be required to allow safe worker access. The steel deflectors would have to be attached to the downstream end of the gate guide structure and supported by either welding or bolting or a combination of both to the spray deck supports. Additional support for the length of the deflectors would require bolting diagonal steel supports to the dam face. Care must be taken to avoid the tendons that tie the spray deck supports to the dam.

Work could be conducted on one or two gates to allow for field testing to confirm that the assumptions made for operation of this option are valid and potential TDG reduction is being realized. The actual gate output for a given opening would also need to be confirmed. Additional modifications or adjustments could be made to the installed members and members to be installed based on field test results.

Sequencing of the installations would have to be determined and a decision-making process would need to be in place to determine whether the modifications should be made to all gates, alternating gates, center gates only, and so on.

This option could be constructed after the runoff flows have been passed for the year. Summer construction would be easiest as the length of the deflectors would make it slightly more difficult to hoard and heat the working areas. A fairly substantial scaffold system would be required to provide a safe work area but the actual deflectors would be a relatively simple installation.

5.3.1.3. Spillway Flow Splitter/Aerator (No. 2-8)

Various options were also considered that involved the development of spillway flow splitter/aerators to aerate and modify the trajectory of the spillway jet. The options investigated may allow for some TDG stripping, offer lower costs, and are relatively easy to construct. Because the spillways are somewhat isolated on the abutments and not operated regularly, any disturbance to Project facility operations during construction would also be minimal.

The options included:

- Addition of deflectors to the end of the existing spillway structure
- Provision of air vents to the spillway chute to allow for aeration of the base of the spillway jet
- Increase the turbulence in the flow by roughening the spillway surface or providing structural elements to increase the turbulence in the flow.

These options could be implemented separately or in combination with one another. Each is described in more detail below.

Option 1: Addition of Deflectors. This scheme involves the addition of a deflector to the end of the each existing spillway chute. The purpose of this device is to cause the jet to spread longitudinally as it leaves the structure. This will result in a longer and wider area of impact with the tailwater pool. This spreading of the energy impact area will result in a shallower plunging depth which should reduce the take-up of dissolved gas.

As shown in Appendix 6, Figure A.6-3, each device is approximately 30 feet long (depending on the slope of the chute) and requires modifications to the downstream end of each chute. The end of the device would consist of three teeth-shaped deflectors with gaps between them. The variable ramping of the flow as it reaches the device will follow various flow trajectories. Those trajectories going over the top of the teeth will travel a greater distance downstream than those going through the gaps between the teeth. The additional loading created by the water pressure on these blocks/ ramps would be transferred directly through the spillway slab using rock anchors drilled into the underlying substrate.

Though there is some confidence that this scheme will enlarge the impact area of the jet leaving the spillway, there is no theoretical way to estimate the effectiveness that this device may have in reducing the uptake in total dissolved gas within the tailrace. Hence, to determine the ultimate effectiveness of this scheme, ideally a full-size prototype for one of the spillways should be built and tested at the Project site. If such testing for the similar orifice scheme had already proved successful, then there would be more confidence that this scheme would also be effective.

Option 2: Aeration of Chute. This alternative involves construction of a venting system that would help to aerate the underside of the spillway jet. The introduction of air at the base of the jet would help to initiate some stripping of the TDG and would also begin to "bulk up" up the water column. Model studies would have to be undertaken to ensure that this bulk-up of water would still be confined within the existing wall height of the spillway chute. These studies would require a model on the scale of 1:15 to evaluate the air entrainment and the bulking effects.

This option would require installation of a piping system through the walls of the spillway structures and across the floor of the spillways. Channels would be cut across the spillway floor to allow the installation of horizontal stainless steel pipes, which would supply air across the width of the structure. Care would have to be taken to ensure that the interface between the pipe and the spillway slab are appropriately sealed so water is not allowed to seep under the slab and potentially freeze. Vertical standpipes on the exterior of the spillway walls would feed air into the horizontal pipe from both ends.

Further study is required to determine the most effective air supply system. Work on this item could start any time after the freshet flows have passed. The overall schedule for this component is relatively brief so it could easily be performed in the summer months which would accelerate the work. If winter construction were required, the areas requiring concrete or grouting work are relatively small and could easily be hoarded to allow temporary heating.

Option 3: Increase Turbulence in Flow. This option would involve roughening the spillway surface or adding external structural elements to increase turbulence in the flow. Increased turbulence enhances the air exchange and gas transfer across the air/water interface. This concept also increases the impact area, which reduces the energy per unit surface area at the plunge point.

Structural analysis would have to be conducted to determine modifications that may be required to the structure to allow for the addition of structural elements. Hydraulic model studies would have to be undertaken to ensure that these modifications do not create cross waves that could potentially overtop the walls of the spillway chute.

5.3.1.3.1. TDG Performance

The purpose of this alternative is to make the jet area at the impact point as large as possible. This reduces the energy per unit surface area and thus reduces the depth to which the jet plunges. The air is added to the flow on the spillway to assist this process. Flow will not plunge as deep as the falling jet because of the reduction in inertia. Operating alone at up to 20,000 cfs, the spillway flow with splitters and aeration are predicted to perform at a TDG level of roughly 110 percent.

5.3.1.3.2. Constructability

Although it is also the most expensive, the recommended option would be Option 1, the installation of deflector blocks at the spillway outlets, because it would have the largest effect on the plunging water and the TDG. This would also have the greatest effect on the largest amount of flow. After installation of the deflectors on one of the spillways, their effectiveness could be tested prior to committing to their installation on the second spillway. The installation of these deflectors does not preclude the installation of either of the other components. Their installation could also be staged or staggered to test their effectiveness with, for example, the air induction piping being installed on one spillway and the radial gate teeth being installed on the other. Should all of the options prove through testing to have a beneficial stripping effect, all three of the modifications could eventually be installed on both spillways.

Construction of this option is more complicated than for the other two. The concrete work involved in this option, although it could be performed at any time, would be much more easily and cost effectively performed in the summer and fall to avoid freezing conditions. Winter construction would require building substantial hoarding structures and result in higher heating costs. These options are structurally complex to form and concrete and therefore expensive to construct. The transfer of deflector block loads directly through the spillway slab using rock anchors drilled into the underlying substrate could possibly lead to increased geotechnical enhancement to the foundation beneath the ends of spillway chutes with attendant higher priced labor and supervision. The schedule is short compared to an alternative such as the tunnel but the working surfaces and access on the high cliffs reduce productivity, slowing schedule and increasing costs.

Any combination of these spillway alternatives would have an effect on the TDG. Selection of any one of these options again does not preclude the addition of a second or even a third option.

5.3.1.4. Right Abutment Tunnel with Submerged Discharge (No. 4-7)

This alternative consists of a low-level tunnel excavated on the right abutment (facing downstream) of the dam. The tunnel would include an inlet facility on the upstream side, and a submerged discharge on the downstream side. Discharge through the tunnel would be mobilized during high-flow periods to reduce flows being passed through the Project spill facilities.

The right bank tunnel scheme would give the most flexibility for the development of a hydraulic arrangement for bypassing flood waters without increasing TDG. Two basic alternative arrangements were examined although other variations on each could be considered.

Option 1. Construction of a single large tunnel capable of handling the full 53,300 cfs flow. The tunnel would be equipped with flow regulating capabilities to effectively dispense any required amount of flow.

Option 2. Construction of a smaller unregulated tunnel that would be capable of passing only 26,500 cfs using a smaller tunnel operating for either a fully open or fully closed condition. Because it does not provide the target discharge value, this option would be developed in conjunction with other modifications to the spillways or the sluices gates or both.

Each option is further described below.

5.3.1.4.1. Geology

The Metaline limestone is the dominant bedrock formation at the site, and it forms the dam's foundation and the host for the underground powerhouse. Although referred to in the literature as limestone, the formation contains more dolomite than limestone. Regional tectonic and glacial forces produced several sets of joints and faults throughout the site. A rhyolite dike cuts through the forebay and was exposed in the diversion tunnel.

A reddish dolomite dominates the left abutment. The tectonic and glacial forces jumble the bedding and discontinuities so that no clear pattern is evident. Nine shear zones and faults have been identified in the left abutment, some of which daylight in the abutment. Shear zones occasionally appear open. Tendons were installed from the access tunnel to promote stability across faults that daylight in the abutment above the river. Drainage also was provided to reduce pressures in the discontinuities.

The right abutment generally is more massive, comprising interbedded limestone and dolomite. Bedrock strikes parallel with the river and strikes 50 degrees upstream. Three faults cross the abutment and pass under the dam. Joints and faults appear generally to be tight.

The powerhouse was excavated without unusual difficulty in predominantly weathered dolomite. Some support was required. Similarly, the diversion tunnel was finished without unusual difficulty, but predominantly in limestone.

In the Project archive, contained within the FERC Part 12, Supporting Technical Information document, there are 21 separate reports concerning foundations, geology, grouting, and drainage. The reports date from 1963 to 1997.

The rock formation on the right abutment of the dam is inherently more stable and thus more suitable for tunnel construction than the rock on the left abutment of the dam. This alternative also moves the construction with any potential impacts away from the Project operation facilities of the site which is focused to the left abutment.

The Bechtel-Leedshill drawing information provided circa 1963 in the information package displays four faults at or near the right abutment of the dam. The rock formation is listed as interbedded limestone and dolomite. The report also states that joints present in the rock do not appear to form prominent or significant patterns, many of the joints are re-cemented, and right abutment faults are poorly defined.

Various drilling and coring programs have been conducted through the years to determine the underlying stratigraphy of the Project site:

- The U.S. Army Corps of Engineers (USACE) performed drilling in 1944.
- SCL performed a drilling program in 1963.
- Exploratory tunnels were excavated and additional drill holes bored in 1963.

Core holes drilled by the USACE in 1944 indicate that there is very little if any overburden in the reservoir area where the intake would be proposed for this option. The SCL drilling program in 1963 also indicates that the overburden in the area of the proposed inlet works is minimal.

- Drill hole 17 starting at elevation 1,754 feet NAVD 88 (1,750 feet NGVD 29) feet indicates no significant overburden.
- Drill hole 21 in the same area near the proposed inlet starting at elevation 1,747 feet NAVD 88 (1,743 feet NGVD 29) again indicates no significant overburden.

Existing drill logs also indicate that within the river downstream of the dam the overburden on the right abutment (facing downstream) varies greatly in depth from 40 feet to 200 feet depending on the actual location of the outlet. This material consists of various sized boulders, cobbles, sands, and gravels.

Core holes drilled in the relative location of the proposed tunnel indicate that the rock seems quite competent with a composition or combination of dolomite, dolomitic limestone, and limestone. There are some shale materials present but in relatively small amounts. Some weathering of the joints is evident which is fairly typical for this type of material.

5.3.1.4.2. Option 1: Development of a High Discharge Capacity Tunnel

This option involves construction of large low-level outlet on the right abutment capable of discharging flows of up to 53,300 cfs. The tunnel would be fully regulated, and would discharge releases through a submerged outlet, designed to provide a relatively low exit velocity. Appendix 6, Figure A.6-4 provides a schematic view of this concept, and the proposed layout of the tunnel system.

The tunnel would consist of four major components:

- Intake
- Tunnel
- Regulating gates
- Outlet facility

<u>Intake</u>

The purpose of the intake structure is to draw and convey water from the reservoir into the tunnel system. Various options were initially considered for the intake structure design:

- A head gate structure in the reservoir with an open-mouthed tunnel inlet
- A bell-mouthed intake with integral gates in the reservoir
- A weir type structure with an open mouthed tunnel inlet; this option could also utilize overflow type gates
- Bell-mouthed intake with only stop logs or emergency closure gates
- Vertical blasted unfinished or unlined intake

The final design concept adopted is shown in Appendix 6, Figure A.6-4. As shown, the intake structure is located approximately 500 feet upstream of the dam axis. This structure would consist of a conventional concrete bell-mouth entrance having a square opening of approximately

37 by 37 feet, and a crown at elevation 1,919 feet NAVD 88 (1,915 feet NGVD 29). The upstream submergence is expected to be sufficient to prevent air entraining vortices. The intake structure would include a single vertical lift bulkhead gate. This gate would normally be closed for balanced flow conditions but would also be capable of closure for the full design discharge of 53,300 cfs. Alternatively, the gate size could be reduced if it were decided that a two- or three-gate scheme were more practical or cost-effective. It should be noted that because of the expected velocities through the Intake structure, it would not be possible to provide a trashrack facility for the tunnel. However, relatively little debris is expected to pass through the tunnel, given the overall depth of the intake.

For ease of construction, the inlet structure could be built in the dry in an excavation set back slightly from the reservoir. Once the structure has been completed, the guard gate would be closed, and the remaining rock between the structure and the reservoir removed as the final construction operation.

Tunnel

As shown in Appendix 6, Figure A.6-4, a square to modified horseshoe transition would be provided downstream of the Intake gate section to interface to a 37-foot-diameter concrete-lined tunnel. This tunnel would run horizontally in a northerly direction and would be approximately 700 feet long. At the design discharge the flow velocity would be approximately 50 fps. It would terminate in vertical curved section joining to a drop shaft. The drop shaft would be concrete lined with an inside diameter of 37 feet. This shaft would drop approximately 300 feet terminating in another vertical curve. The vertical curve would connect to another 37 foot horizontal tunnel approximately 300 feet long running in a westerly direction. This tunnel would terminate in a modified horseshoe to square transition and then connect to a rectangular 19.5- by 19.5-foot section housing a vertical lift regulating gate.

The high velocity flow in the tunnel would require that a concrete lining be provided to limit erosion within the tunnel. Appendix 6, Figure A.6-4 shows a typical cross-section for the tunnel. With this liner in place, the tunnel was sized to prevent velocities from exceeding approximately 50 fps. It would also be possible to use an unlined tunnel in sections upstream of the outlet control gate. However, use of an unlined tunnel would require that the velocities be limited to 20 fps or less to prevent erosion of the in situ rock mass. This would require a tunnel diameter of 58 feet, and would significantly increase excavation volumes. Based on a quick cost comparison of these tunnel concepts (lined versus unlined), it was found that use of the lined tunnel cross section provides an equally economical solution, and has been adopted for the preferred design concept.

Regulating Gates

The regulating gate would be sealed/bonneted to prevent entrainment of air. The gate and other mechanical equipment would be housed in a chamber excavated in the rock immediately above the gate location. A shaft or small tunnel would connect this chamber to the surface to allow maintenance/servicing of the operating equipment. Tunnel dewatering equipment would also be installed to allow the tunnel to be dewatered for inspections and maintenance.

The regulating gate is designed for a clear opening that is 19.5 feet wide by 19.5 feet high. The gate is assumed to be of the downstream sealing type to minimize water turbulence in the gate slot at partial gate openings.

The gate seals are assumed to be of the double stem type for the lintel seal, to prevent rolling, and of the J-seal type for the side seals. These seals are assumed to have fluorocarbon inserts to minimize friction loads.

Several conceptual arrangements have been studied for the gate slots using either fixed wheels or caterpillar rollers. The fixed wheel gate has two options, one with the wheels cantilevered from the end of the gate, and the other with the wheels supported on both sides. Table 5.3-1 outlines the feasible dimensions for each arrangement.

Table 5.3-1. Regulating gate comparison.

Component	Fixed Wheel Gate Double Support	Fixed Wheel Gate Single Support	Caterpillar Roller Gate
Number of wheels/rollers in contact per side	12	12	85
Wheel/Roller diameter	24 in	24 in	4 in
Wheel/Roller axle diameter	5.75 in	9.5 in	1 in
Required hardness	281 BHN	281 BHN	178 BHN
Guide slot depth	16.75 in	15.69 in	20 in
Guide slot wide	28 in	26 in	24.38 in
Wheel/Roller span	284.38 in	284.38 in	289 in
Seal span	277 in	277 in	276.5 in

All of the above options use sleeve type bearings to minimize required maintenance. The bearing material is assumed to be DEVA-METAL. This material has an allowable bearing strength of 18,855 pounds per square inch (psi) and a stated friction factor between 0.09 and 0.13. A friction factor of 0.12 has been adopted for design purposes.

The embedded roller track parts for the caterpillar roller gate can be of Type 304 stainless steel due to the lower hardness requirements (178 BHN). However, the wheeled gate options require age hardened stainless steel of high hardness (281 BHN) for the tracks. Because age hardened stainless steel is not weldable the hardening would need to be done after the assembly is welded.

The option for the wheel cantilevered from the end of the gate was not considered any further for the following reasons:

- The larger wheel axle diameter would lead to a more costly design.
- The wheel axle friction loads are higher.
- The savings in guide slot size are not significant.

The operating loads provided in Table 5.3-2 were calculated for these options.

Table 5.3-2. Regulating gate actuator comparison.

Element	Fixed Wheel Gate (Gravity Lowered)		Fixed Wheel Gate (Pushed Down)		Caterpillar Roller Gate	
	Fully Lowered	**Partially Opened**	**Fully Lowered**	**Partially Opened**	**Fully Lowered**	**Partially Opened**
Gate weight in air (lbf)	142,120		142,120		131,192	
Ballast weight in air (lbf)	140,000		0		0	
Wheel bearing friction (lbf)	156,159	92,218	156,159	92,218	0	0
Wheel rolling resistance (lbf)	8,090	4,778	8,090	4,778	56,882	33,591
Seal friction (lbf)	14,260	5,625	14,260	5,625	14,260	5,625
Downpull (lbf)	0	95,370	0	95370	0	95,370
Push down force	0	0	81,273	0	0	0
Required hoist capacity	480,318	504,669	378,153	402,504	232,024	311,329
Cylinder rod diameter	7.5 in.		8.1 in.		5.9 in.	
Cylinder bore	17.7 in.		16.5 in.		14.0 in.	

Note:
lbf – pounds force

Because the fixed wheel gate option uses sleeve type bearings the wheel friction is high and significantly affects the operating loads and thus requires the largest operating cylinder size. Here it should be noted that a single operating cylinder has been assumed although it would be possible to use two synchronized cylinders.

If the gate is required to lower under gravity then the wheeled gate would need to have 140,000 pounds force (lbf) of ballast. This ballast can be added as filler between the gate beams and may comprise reinforced concrete or steel billets. The addition of ballast increases the operating load.

If the gate does not need to lower under gravity then it can be pushed down by the operating cylinder. The pushing capacity of the hydraulic cylinder is, however, limited by the buckling strength of the cylinder rod. The operating loads for this option are significantly reduced and the cylinder size is thus reduced.

For the caterpillar roller option the wheel friction is eliminated but there is an increase in the resistance to rolling. However, overall, the operating loads and cylinder size is minimized.

Another option, not considered, is the use of spherical roller bearings in the gate wheels. This would reduce operating loads to about that of the caterpillar roller option. However, these bearings would need maintenance with regular greasing.

Tunnel Outlet Facility

The regulating gate would discharge into a 48-foot-diameter, 200-foot-long, concrete-lined expansion chamber with an invert at elevation 1,664 feet NAVD 88 (1,660 feet NGVD 29). This is approximately 70 feet below the tailwater level for the Project. The design of this expansion chamber would be similar in concept to that of the Mica project constructed in British Columbia. This expansion chamber would dissipate close to 200 feet of head. The geometry at the entrance to the structure would direct any cavitation bubbles away from the structure walls, so that they would harmlessly implode within the water column. The downstream end of the expansion chamber would be the exit portal of the Right Bank By-Pass Tunnel Scheme. Preliminary analysis of a simple expansion chamber model indicates an average exit velocity is indeed near about 10 m/s or 30 fps (see Figure 5.3-1). In this study, the length of the chamber has been set based on empirical charts available for prediction of flow expansion rates. However, at the next level of study, the final length for the chamber should be set based on physical or more refined numerical model studies. Forces are significant within the expansion chamber and require a silica fume, high strength concrete lining. The tailwater submergence should be sufficient to allow for effective energy dissipation without entraining air. A 48- by 48-foot floating bulkhead gate would be provided to allow for inspection and servicing the area downstream of the regulating gate.

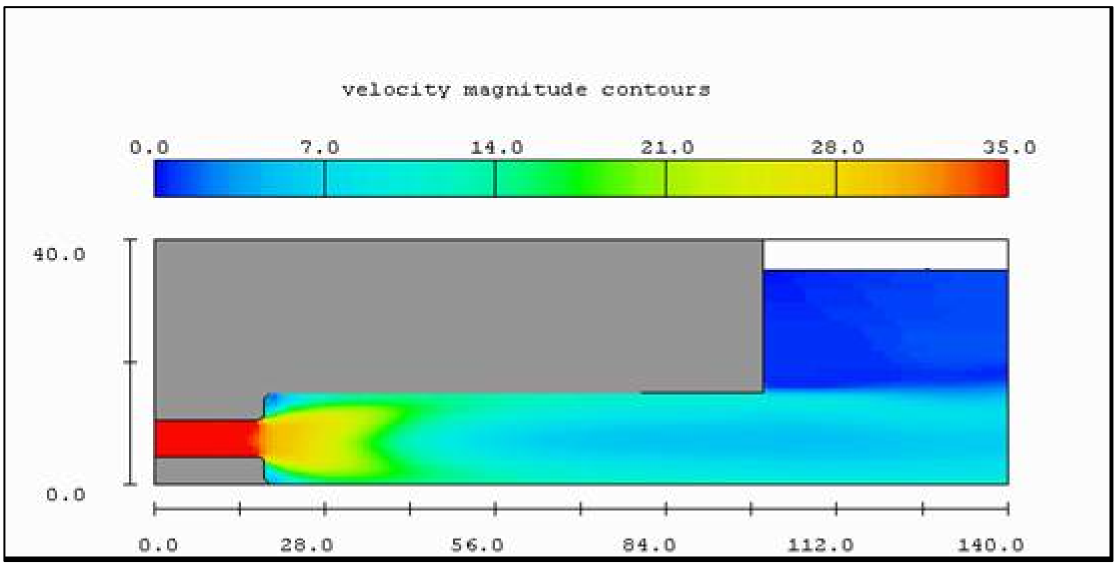


Figure 5.3-1. Computational fluid dynamic model of expansion chamber velocities (m/s).

The expansion chamber is in effect, the outlet of the tunnel. The invert of the expansion chamber when it enters the tailrace is at elevation 1,664 feet NAVD 88 (1,660 feet NGVD 29). From the expansion chamber a substantial amount of material would have to be removed from the tunnel outlet area to allow for unimpeded flows from the tunnel. As stated previously overburden on the right bank of the river has been measured as starting between elevations 1,734 feet NAVD 88 (1,730 feet NGVD 29) and 1,744 feet NAVD 88 (1,740 feet NGVD 29) and can be as thick as 200 vertical feet. Excavation in the tailrace would likely require the removal of approximately 70 vertical feet of this material in an inverted conical shape. Operation of the tunnel would typically reshape the remaining materials to more natural angles.

Most of the energy of the flow passing through this tunnel would be dissipated within the expansion chamber, though there would also be hydraulic losses due to the intake, tunnel friction, bend losses, and tailrace exit. Because the conveyance system would be sealed or would have significant submergence, the chance of ingesting air into the flow is considered to be remote. The sudden expansion of the flow from the tunnel will probably be accompanied by cavitation that would release significant amounts dissolved gas. This release of dissolved gas may be beneficial.

5.3.1.4.3. Option 2: Development of Low Discharge Tunnel

Consideration was also given to construction of a smaller unregulated tunnel that would be capable of only either full flow or no flow. This option would be capable of passing only 26,000 cfs using a smaller tunnel operating for either a fully open or fully closed condition. Although this option would only handle one half of the required flow, the reduced tunnel size requirements would diminish the costs associated with its construction because of the smaller diameter, smaller inlet gates and lack of an expensive regulating gate. Flow would be either mobilized or demobilized within the tunnel by fully raising or lowering a guard gate at the intake structure.

To avoid problems with the formation of an air-entraining hydraulic jump in the tunnel as it fills and surging flow during the transition from part full to full flow conditions, the tunnel would need to be filled slowly with no flow and only put into operation with a fully filled tunnel.

This alternative would follow the alignment of Option 1, and it is expected that the upstream gate would be reduced in size to 26 feet by 26 feet. The diameters of the tunnels and expansion chamber would be reduced to 26 and 33 feet, respectively. This option would not have a downstream regulating gate, but rather a 15.5-foot-diameter restriction would be provided immediately upstream of the expansion chamber. Forces are significant within the expansion chamber and require a silica fume, high strength concrete lining. This restriction would limit flows within the tunnel to approximately 26,000 cfs. This option would operate either fully open or fully closed using the intake gate. Care would be required during tunnel filling to ensure that large air bubbles are not trapped in the upper tunnel. The same confidence and concerns as expressed for Option 1 apply to this option.

5.3.1.4.4. TDG Performance

The experience of the planned tunnels at Cabinet Gorge indicates that high velocity tunnel construction is difficult and will have constraints. It may not be possible to submerge the tunnel by 70 feet. For this reason, both a surface tunnel and submerged tunnel will be considered.

A surface tunnel is one that is submerged by 20 feet or less, because the kinetic energy of the water flowing from the tunnel would pull the water surface down to the outlet flow, allowing the flow from the tunnel to entrain air. At Cabinet Gorge, the tunnel was designed to pass 41,000 cfs with an equivalent outlet diameter of 30 feet and an outlet velocity of 60 fps. The tunnel was assumed to entrain sufficient air to have a steady state develop between the mass transfer of bubbles near the surface and those at depth. This steady-state value was 133 percent of saturation. The predicted values corresponded with that measured with spillway deflectors at high flow (Carroll et al. 2000; USACE 1996, 1999), which are presumed to have similar characteristics. The proposed approach would pass 53,300 cfs through a tunnel with an equivalent diameter of 45 feet, and a flow velocity at the outlet of 35 fps. This outlet velocity would entrain less air and have lower turbulence levels than that proposed for Cabinet Gorge, although the larger equivalent diameter would carry the bubbles to a similar or greater depth than the 30-foot equivalent diameter tunnel. The downstream TDG levels below a surface discharging tunnel would probably be between 125 percent and 130 percent of saturation. Pool TDG levels would make little difference in this value.

It is uncertain whether a submerged tunnel is possible. Submergence to an invert of 1,660 feet would discharge the jet without entraining air at the discharge point. Given the 0.35 rise/run of the tailwater bottom at this location, the jet would reach the surface at approximately 250 feet downstream. The core of the jet would still have a speed of approximately 35 fps, because this is close to the end of the zone of flow establishment (Fischer et al. 1979, Fig. 9.5). The temporal mean velocity profile would then be given by the equation (Fischer et al. 1979, Table 9.2, Equation. 9.27):

$$u = u_m \exp(-(y/28ft)^2)$$

where u is temporal mean velocity, u_m is the maximum u at a given x, and y is transverse distance from the jet centerline in feet. At the jet centerline, the vertical velocity component would be 11.6 fps, which would cause a water boil with 2 feet of hydrostatic head. The turbulent velocities at this point would be 4.6 fps (Fischer et al. 1979, Fig. 9.4), which would cause short waves with a height of 0.3 feet. There may be breaking waves when the jet reaches the surface of the tailwater pool, which would entrain air at the surface. Any air entrained at the surface would be distributed throughout the depth by the turbulence of the jet, causing relatively high TDG levels. It is anticipated that the TDG level of a discharge submerged for these conditions would be between 115 percent and 130 percent. This performance may be adequate for current conditions with high forebay TDG levels for spill flow volumes up to 25,000 cfs; however, this alternative is not expected to achieve TDG levels at or below 110 percent.

5.3.1.4.5. Constructability

Other alignments for the tunnel could also be explored that would reduce the length of the horizontal components. These options would require that the tunnel inlet be moved closer to the right abutment spillway.

Although the upper horizontal portion of the tunnel could be created using a Tunnel Boring Machine (TBM) it would not be practical due to the short length of this segment of tunnel. It is more likely that the entire tunnel would be excavated in a typical drill and blast fashion.

The regulating gate access tunnel would have to be built early in the process to allow access for equipment, manpower, and mucking of the excavated materials from the lower horizontal section. The vertical section of the tunnel could be excavated either top down or vertical rising. After the tunneling is complete and the regulating gate is installed the last plug of material would be blasted to open the downstream end of the tunnel to tailwater. Upon completion of the inlet structure the final rock berm between the inlet and the reservoir would be removed creating a channel from the reservoir to the inlet.

Tunneling work is not as reliant on weather and could therefore take place regardless of the season. The inlet structure could be constructed in the warmer spring to fall months. Excavation in the river for the tunnel outlet could be limited by various biological constraints, such as periods when vulnerable fish life stages are present.

5.3.1.5. Open Existing Diversion Tunnel and Add Control Structure (No. 4-8A)

In an attempt to develop a lower-cost tunnel option, a number of schemes were investigated that would involve remobilization of the existing diversion tunnel. The existing diversion tunnel for the Project is located along the left abutment of the dam and consists of a 42-foot-diameter horseshoe-shaped tunnel. This tunnel was plugged with concrete over a 120-foot section following completion of the Project. The intake for the diversion tunnel is located within the reservoir, at an invert elevation of 1,704 feet NAVD 88 (1,700 feet NGVD 29). This is approximately 290 feet below the normal forebay water surface elevation of 1,994 feet NAVD 88 (1,990 feet NGVD 29). In addition, the invert is currently covered with over 60 feet of silt and mud. The diversion tunnel is also plugged at a point where it meets the mucking tunnel. There is a plug approximately 20 feet long in the mucking tunnel. The existing tunnel discharge invert is at elevation 1,691 feet NAVD 88 (1,687 feet NGVD 29), which is approximately 44 feet below the normal tailwater water surface elevation.

It became clear early in these investigations that it would not be possible to re-use the existing intake facility for this tunnel. The intake is too deep and covered in a deep layer of sediment. Rather, a scheme was devised in which the intake was located at a point approximately midway along the tunnel, and therefore only the downstream half of the abandoned tunnel would be remobilized. The tunnel was designed to discharge flood flows of up to 53,300 cfs.

This scheme is similar in concept to Alternative 4-7, and is shown in Appendix 6, Figure A.6-5. As shown in this layout drawing, this scheme would include a morning glory intake structure located on a submerged promontory between the Left Spillway and the Powerhouse Intake Channel. This structure would have a throat diameter of approximately 40 feet, and the ogee crest would be set at elevation 1,919 NAVD 88 (1,915 feet NGVD 29). With this opening, the submergence provided (60 feet) is expected to be sufficient to prevent the formation of air entraining vortices when the bypass is operating. This opening would be capable of being closed by a floating circular gate that when lowered over the opening would act like a “cork in a bottle” vertical lift bulkhead gate. This gate would be closed for balanced flow conditions. It should be noted that because of the expected velocities through the intake structure, it would not be possible to provide a trash rack facility for the tunnel. However, relatively little debris is expected to pass through the tunnel, given the overall depth of the intake.

5.3.1.5.1. Geology

The Bechtel-Leedshill drawing information provided in the information package, circa 1963, displays a group of six faults at or near the left abutment of the dam. The rock formation is listed as massive limestone and dolomite. The report states that considerable faulting in the abutment has shifted the bedding such that only the general bedding and strikes and dips can be established. The dolomite, which is reddish brown to brownish gray, is weaker than the massive gray limestone. The report also states that core holes and exposures in the exploratory tunnel show that most of these faults are tight, but some do contain clay or shale.

Drill hole 36 indicates a widely varying array of materials from clay seams to rhyolite porphyry, dolomite, limestone with weathered seams, and slickensides.

This alternative may initially be, as with all of the left abutment tunnel options, looked upon negatively for dam safety reasons because of the known condition of the left abutment rock and their proximity to the Project operational facilities of the site.

- Drill hole 34 indicates that the upper layers from elevation 1,982 feet NAVD 88 (1,978 feet NGVD 29) are moderately to highly fractured. Lower layers have shaley seams, rhyolite porphyry, and limestone.
- Drill hole 31 indicates highly fractured limestone and dolomite layers with shaley seams and slickensided fractures and small voids.

5.3.1.5.2. Hydraulics

At the design discharge the flow velocity within the aperture/tunnel would be approximately 45 fps. The bottom of the morning glory would transition into a concrete lined drop shaft with an inside diameter of 37 feet. This shaft would drop approximately 300 feet and terminate in a vertical curve. This curve would connect the drop shaft to the existing horseshoe shaped tunnel. The horseshoe-shaped section would be approximately 350 feet long. Although the original tunnel was unlined, this section of the tunnel would be steel lined to ensure water tightness within the rock mass. This section of the tunnel would then terminate in a horseshoe to square transition. This transition would connect to a 19.5-foot square section housing a vertical lift regulating gate. The regulating gate would discharge into a 48-foot–diameter, 200-foot-long concrete-lined expansion chamber constructed to an invert elevation of 1,664 feet NAVD 88 (1,660 feet NGVD 29). Given that the existing invert at the discharge end of the tunnel is at elevation 1,690 feet NAVD 88 (1,686 feet NGVD 29), this would require deepening of the existing invert by approximately 26 feet.

This expansion chamber would dissipate close to 200 feet of head. The downstream end of the expansion chamber would be the exit portal for the diversion tunnel. Assuming full expansion, the exit velocity would be approximately 30 fps and the submergence should be sufficient to induce energy dissipation without entraining air. This assumption of full expansion should be confirmed as a part of future studies using either numerical or physical models. The length of the expansion chamber can then be refined as required to provide adequate performance. Forces are significant within the expansion chamber and require a silica fume, high strength concrete lining. A 48- by 48-foot floating bulkhead gate would be provided to seal the outlet and allow for inspection and servicing the area downstream of the regulating gate.

There is reasonable confidence that this scheme would be able to pass spill flows from the forebay to the tailrace but there is some concern that it would not be as efficient as the other bypass schemes in preventing an increase in TDG. Most of the energy of the flow passing through this tunnel would be dissipated within the expansion chamber, although other losses would occur due to form loss at the intake, tunnel friction, bend losses, and the tailrace exit loss. Because the control gate is offset from the centerline of the expansion chamber, energy dissipation would not be as efficient. Because the conveyance would be sealed or would have significant submergence, the chance of ingesting air into the flow is remote. However, the downstream submergence is not as great as for the other tunnel bypass schemes. Hence, there would be a greater chance of some air being drawn in from the energy dissipation in the tailrace.

5.3.1.5.3. TDG Performance

The TDG performance of this alternative would be similar to Alternative 4-7.

5.3.1.5.4. Constructability

Tunnel Intake

The intake for this option would require the construction of a work area in the reservoir above the headpond water level. This construction would be quite straightforward as access to the area is excellent. The geographical location of the vertical shaft allows easy walk-on construction access from the land to the west. Additionally, construction activities at the outlet may place Unit 56 out-of-service during construction of the exit tunnel to allow placement of a coffer dam.

Construction of this option would require an island or land extension to be built on the plateau at elevation 1,934 feet NAVD 88 (1,930 feet NGVD 29). Using any one of a variety of grouting techniques this island could be solidified enough to build an inlet structure, most likely using a piling system that could extend into the bedrock.

The vertical shaft through the imported material could be finished with a concrete or steel liner to maintain the stability of the mass and the integrity of the shaft. Alternately a smaller submerged island could be constructed to use as a base for a sinking steel liner/cofferdam. The steel liner would be used to advance down through the fill as the material in the center of the liner is excavated. As the excavation proceeds, additional plates and stiffeners would be added to the top of the construction until it rests soundly on the bottom.

The concrete liner would effectively alleviate pressure concerns for the surrounding rock during tunnel operation. During inoperative periods the downstream regulating gate could remain closed and the tunnel dewatered. Alternately it could remain open and allow pressure from the tailwater head similar to the existing state.

Tunnel

The vertical shaft would be 37 feet in diameter and be capable of handling the required 53,300 cfs flow.

A new concrete plug would be required in the original diversion tunnel upstream of the intersection between the new shaft and the old tunnel. The existing diversion tunnel outlet would be bulkheaded or cofferdammed off to allow for removal of the existing tunnel plug, installation of the regulating gate and the excavation of the expansion chamber.

The existing concrete plug would have to be removed and the existing mucking tunnel could be used during the excavation and or tunnel lining work.

Although the length of the tunnel is relatively short, a 250-foot-long expansion chamber would be included at the outlet to allow for expansion of the water column to reduce exit velocities.

Concrete protrusions would be constructed from the existing tunnel walls to transition to rectangular and then to square for the regulating gate. Downstream of the gate the tunnel would transition rapidly into the expansion chamber.

Particular care would be required to retain high pressure flow within the tunnel and not allow leakage to cause pressures to build in the abutment.

The regulating gate would require excavation of a chamber above the existing tunnel which would hold the operating systems as well as the gate when in the open position. The gate would be approximately 20 feet square.

Tunnel Outlet

The expansion chamber would be the outlet of the tunnel. Rather than the expansion chamber being constructed to the same centerline as the horizontal tunnel component it would use the same top of tunnel elevation and be excavated deeper to increase submergence. Forces are significant within the expansion chamber and require a silica fume, high strength concrete lining.

5.3.1.6. Penstock Draft Tube Bypass (No. 4-9)

This alternative involves the construction of a bypass tunnel from the turbine penstock down to the draft tube, as shown in Appendix 6, Figure A.6-6. The tunnel would be formed in steel, and would re-enter just downstream of the draft tube elbow.

Normally, this bypass would be closed, and flow would pass through the turbine-generator unit. During times of flood however, the bypass would be mobilized, allowing higher flow volumes to circumvent the unit while it is being operated. The design discharge for this concept is for each modified unit to be able to pass 10,000 cfs. To do so, it is estimated that each bypass tube would need to be 10.5 feet in diameter. A 10.5-foot-diameter ring follower gate would be installed near the exit to the turbine bypass in order to mobilize and demobilize flow through the bypass. It should be noted that this system would only operate for either fully open or fully closed conditions.

5.3.1.6.1. Geology

The geology of the left abutment rock is described in Section 5.3.1.5.1.

5.3.1.6.2. Hydraulics

There are a number of hydraulic constraints and concerns associated with this concept which must be carefully considered. These include the following:

- This concept would result in an additional flow through the powerhouse of approximately 20,000 cfs, assuming two units are retrofitted. This would result in additional head loss across the intake trashracks when the unit is in operation. The reduction in generation due to these losses is not likely a concern, but it should be noted that the trash rack loadings would increase. It is estimated that at present, the structural integrity of the trashracks would not be compromised until the trash rack was at least 81 percent blocked with debris. However, with the addition of 20,000 cfs through the powerhouse, the structural integrity would begin to be compromised with blockage ratios of only 74 percent.
- At present, submergence on the unit intake structure is approximately 43 feet. If an additional flow of 10,000 cfs is being drawn though a unit, then it is estimated that a minimum submergence depth of 33 feet should be provided to prevent the development of air entraining vortices. Therefore, standard hydraulic calculations indicate submergence for this alternative is adequate. Other hydrodynamic factors influence submergence, and model testing would be required to determine if inlet submergence is adequate or if a vertex prevention system would be required.
- There would be a minor additional head loss created at the intake of the bypass tube. This loss would occur for current Project operations (i.e., without mobilization of the bypass), as flows would likely create a circulating eddy within the bypass tube at the junction location. It is estimated the additional head loss would be approximately 1 foot when the unit is operating at full capacity.
- When the bypass is mobilized, the regulating gate would be fully opened. These resulting flow velocities within the bypass tube would be in excess of approximately 115 fps. These high velocities would create low pressure zones within the bypass tube, particularly at the entrance to the tube. However, based on preliminary analyses, it appears that the potential for significant cavitation to occur in this area is limited. Therefore it is considered unlikely that the formation of cavitation bubbles within the flow stream would begin to choke the overall capacity of the bypass tunnel.
- Flow velocities in the reach of the penstock upstream of the junction would also be increased. This would lead to some additional headloss when both the units and bypass are operating. The additional friction loss is estimated to be approximately 3 feet. This upstream headloss would be offset by 5 feet of suction head on the underside of the turbine. This may, however, increase the cavitation potential on the runner blades.
- The flow velocity entering the downstream draft tube would be in the order of 115 fps. It is estimated that the total head drop from the bypass discharge expansion into the draft tube would be 185 feet, meaning the total energy dissipated in the draft tube would be approximately 125 MW. The dissipation of this energy would cause rapidly varying pressures on the turbine blades. The acceptability of these flow conditions and pressure fluctuations should be confirmed with manufacturers to ensure it would be acceptable to operate the unit for these conditions. Concerns include the draft

head and potential turbine cavitation. A physical model may be necessary to understand the effects on the turbine.

- The high velocity jet exiting the bypass tunnel may also result in some erosion/ cavitation damage to the nose of the draft tube pier. This pier nose may need to be reshaped and/or steel-lined to mitigate against this.
- The velocity exiting the draft tube would be significantly higher than the current condition. Given the relatively short length of the draft tube, it is expected that the high velocity jet exiting from the bypass tube would likely not fully expand prior to exiting the draft tube. Therefore, velocities along the bottom of the draft tube may be significantly higher than currently occur. This would create some additional surface turbulence, and may reduce the overall effectiveness of the scheme in reducing TDG.

5.3.1.6.3. TDG Performance

The flow pattern in the draft tube would depend upon the swirl in the draft tube and the particulars of the draft tube design. It is assumed that this alternative would have minimal effect upon intake TDG levels, similar to the hydroturbines. Thus, upstream TDG concentration would be passed through to the tailwater.

5.3.1.6.4. Constructability

Although this alternative does have some merit because of the small size of the tunnel, it would be challenging to construct. The tunnel would require full steel lining because of velocity and cavitation issues as well as the condition of the left abutment rock.

Construction would require that each unit be taken offline for the duration of the construction work. The penstock inlet and the draft tube would both have to be sealed. The re-entry point of the bypass tunnel into the draft tube would be determined based on the effect on the turbine. The penstock liner would have to be cut open to allow access to the rock for excavation.

Mucking would be an issue with the material having to be removed either through the dismantled unit or by tunneling from the lower mucking tunnel. Because of the proximity to the operating equipment the tunneling must proceed very cautiously. The most likely method would be the use of a road header, because blasting in this circumstance would be unacceptable.

A chamber would have to be created under the unit to allow for the installation of a regulating gate and space for the gates operating equipment. After the tunnel had been excavated a full steel liner would have to be installed and grout or concrete used to fill the void between the steel and rock. Because the construction would require that the unit remain offline it would be best performed during a major scheduled shutdown or other such period. Tunneling machines would have to work from both ends of the tunnel simultaneously to shorten the construction duration. The effect on the function of the turbine is currently being determined.

5.3.1.7. New Left Abutment Tunnel Next to Unit 51 Intake (No. 4-10)

This option would involve construction of large low level outlet on the left bank that would be capable of discharging flows of up to 53,300 cfs. This left abutment bypass tunnel scheme is very similar in concept to Alternative 4-7 discussed in Section 5.3.4. The tunnel would be fully regulated, and would discharge releases through a submerged outlet, designed to provide a relatively low exit velocity. Appendix 6, Figure A.6-7 provides a schematic view of this concept, and the proposed layout of the tunnel system.

The tunnel would consist of three major components:

- Intake
- Tunnel
- Outlet

As shown in Appendix 6, Figure A.6-7, the intake structure would be located at the extreme left of the powerhouse forebay pond, and would be positioned so as to avoid the grounding grid buried in this area. This structure would consist of a conventional concrete bell-mouth entrance having a square opening of 37 by 37 feet with a crown at elevation 1,919 feet NAVD 88 (1,915 feet NGVD 29) feet. The upstream submergence is expected to be sufficient to prevent air entraining vortices. This opening would be capable of being closed by a vertical lift bulkhead gate. This gate is typically closed for balanced flow conditions, but must also be capable of closure for full design discharge.

5.3.1.7.1. Geology

The Bechtel-Leedshill drawing information provided in the information package, circa 1963, displays a group of six faults at or near the left abutment of the dam. The rock formation is listed as massive limestone and dolomite. The report states that considerable faulting in the abutment has shifted the bedding such that only the general bedding and strikes and dips can be established. The dolomite, which is reddish brown to brownish gray, is weaker than the massive gray limestone. The report also states that core holes and exposures in the exploratory tunnel show that most of these faults are tight, but some do contain clay or shale.

- Drill hole 68 indicates an area near the proposed tunnel that contains fractured limestone and dolomite with weathered seams and slickensides on most fractured surfaces. Small shale seams are also present.
- Drill hole 31 indicates highly fractured limestone and dolomite layers with shaley seams and slickensided fractures and small voids.
- Drill hole 13 near the proposed outlet indicates brecciated and recrystallized dolomitic material with weathered joints.

5.3.1.7.2. Hydraulics

This design would require that an additional 53,300 cfs be drawn through the existing track rack structure. The additional flow would lead to an increase in head loss across the structure and increased loadings. As a part of this review, the trashrack loadings were assessed for both the existing condition, as well as this option. It is estimated that at present, the structural integrity of the trashracks would not be compromised until the trash rack was at least 81 percent blocked with debris. However, with the addition of 53,300 cfs through the powerhouse, the structural integrity would begin to be compromised with blockage ratios of only 65 percent. In both cases, this equates to a total head differential of approximately 6.8 feet across the trashrack. It should also be noted that with clean trashracks, the theoretical headloss across the trashrack increases from the original design value of 1.2 inches to 4.5 inches. The current condition of existing trash rack commonly shows an average water level change of about 1 foot at the Project capacity (55,000 cfs). The corresponding headloss at higher flows may require trash rack modifications or at a minimum a through cleaning and possible removal of accumulated debris.

The 1963 hydraulic study identified numerous problems with the forebay layout and required a number of different layouts for a flow of 55,000 cfs. Some forebay modifications are anticipated to accommodate the different inlet conditions to the units and the potential for increased forebay vortex generations. Modifications to the forebay will be complicated by the presence of a seam of weak rock material within the forebay.

Downstream of the gate section, the intake would transition to a round, 37-foot-diameter lined tunnel. This tunnel would run horizontally in an easterly direction and would be approximately 200 feet long. At the design discharge the flow velocity would be approximately 50 fps. It would terminate in vertical curved section joining to a drop shaft. The drop shaft would be concrete-lined with an inside diameter of 34 feet. This shaft would drop approximately 300 feet, terminating in another vertical curve. The vertical curve would connect to another 34-foot horizontal tunnel approximately 500 feet long running in a westerly direction. This tunnel would terminate in a round to square transition. This transition would connect to a 19.5-foot square section housing a vertical lift regulating gate.

The high velocity flow in the tunnel would require that a lining be provided to limit erosion within the tunnel. As well, available geological information indicates the rock mass is weaker than the rock on the right abutment, and its permeability is less than desirable. Consideration was given to providing either a concrete lining or steel lining within the tunnel. To ensure water tightness, the final design selected utilizes a steel lining from the intake through to the control structure.

The regulating gate would be sealed/bonneted to prevent entrainment of air. The gate and other mechanical equipment would be housed in a chamber excavated in the rock immediately above the gate location. A shaft or small tunnel would connect this chamber to the surface to allow maintenance/servicing of the operating equipment. Tunnel dewatering equipment would also be installed to allow the tunnel to be dewatered for inspections and maintenance.

The regulating gate would discharge into a 48-foot-diameter, 200-foot–long, concrete-lined expansion chamber with an invert at elevation 1,664 feet NAVD 88 (1,660 feet NGVD 29). This expansion chamber would dissipate close to 200 feet of head, and would be capable of safely handling any cavitation that might occur immediately downstream of the regulating gate restriction. The geometry at the entrance to the structure would direct any cavitation bubbles away from the structure walls, so that they would harmlessly implode within the water column. The downstream end of the expansion chamber would also be the exit portal back into the river. It should be noted that some channel excavation would be required to develop a suitable tailrace channel to convey expansion chamber releases back up into the river channel. This tailrace channel would gradually rise at a 1V:4H slope from the expansion chamber invert elevation of 1,664 feet NAVD 88 (1,660 feet NGVD 29) to meet the existing river bed level of approximately 1,710 feet. The exit velocity would be about 30 fps and the submergence should be sufficient to induce energy dissipation without entraining air. Velocities of 30 fps are sufficient to move sizeable material. Hydraulic model studies would be required to estimate the extent of scour and depth and areas of deposition. A 48- by 48-foot floating bulkhead gate would be provided to allow for inspection and servicing the area downstream of the regulating gate.

The discharge associated with the bypass tunnel flows would be relatively turbulent, and may result in some additional fluctuations in tailwater at the powerhouse units. Given the close proximity of the expansion chamber exit to the powerhouse draft tubes, the potential for this to adversely affect current Project powerhouse operation should be reviewed in future studies.

Most of the energy of the flow passing through this tunnel would be dissipated within the expansion chamber, although there would also be some hydraulic loss due to the intake, tunnel friction, bend losses, and tailrace exit. Since the conveyance would be sealed or would have significant submergence, the change of ingesting air into the flow is remote.

5.3.1.7.3. TDG Performance

The TDG performance would be similar to the surface tunnel for Alternative 4-7. If the tunnel is a similar cross section as Alternative 4-7, the TDG levels are anticipated to be between 115 percent and 130 percent of saturation.

5.3.1.7.4. Constructability

Intake

Construction of the intake structure for this option could be done "in the dry" by excavating to the west of the existing headpond. The material between the structure and the headpond would be removed last creating a channel from the existing headpond to the intake structure. Accommodation would have to be made for the access roadway on the west side of the headpond. The structure would be a concrete bell mouth with gates to allow dewatering of the tunnel. A trash rack would not be required because of the existing headpond trashrack. Because the regulation of flows is controlled by the in-tunnel regulating gate the intake gate system could be relatively simple. The intake closure could also be stop logs. Modifications to the forebay will be complicated by the presence of a seam of weak rock material within the forebay that was treated with a large concrete infill during original construction.

Tunnel

Because of the short horizontal and vertical segments of the tunnel it would be impractical to use a TBM for this tunnel. Excavation could be performed with a combination of drill and blast and roadheader equipment although the proximity to the powerhouse would likely preclude blasting. The tunnel would be 37 feet in diameter to be capable of handling the required 53,300 cfs flow.

Once the tunnel reaches its lower horizontal component the shape of the tunnel would transition to rectangular then square for the regulating gate. Downstream of the regulating gate the tunnel would rapidly transition to the expansion chamber, then discharge to tailwater. The regulating gate would require excavation of a chamber above the tunnel which would hold the operating systems as well as the gate when in the open position. The gate would be approximately 20 feet square.

Particular care would be required to retain high pressure flow within the tunnel and not allow leakage to cause pressures to build in the abutment. Additional concerns require additional exploration. Among these are rock quality along the proposed alignment and the needs for support and drainage.

Although the length of the tunnel is relatively short a 250-foot-long expansion chamber would be included at the outlet to allow for expansion of the water column to reduce exit velocities.

Outlet

The expansion chamber would be the outlet of the tunnel. Because this would be a new excavation the expansion chamber could maintain the same centerline as the tunnel and regulating gate. Forces are significant within the expansion chamber and require a silica fume, high strength concrete lining. The excavation of the lower part of the tunnel may require coffer dams which could potentially have some effect on the current Project powerhouse operation because of flow velocities from Units 51, 52, and 53 (see Appendix 6, Figure A.6-7).

5.3.2. Criteria for Evaluating Gas Abatement Alternatives

This section presents the methodology for evaluation of each alternative. The key feature of the evaluation was an "Alternative Evaluation" workshop meeting. This workshop involved knowledgeable experts in geology and arch dam construction, hydraulics, TDG issues, gate design, and structural design reviewed the short listed concepts qualitatively, and evaluated impacts on Project features and safety.

The following items were used in the ranking of the alternatives:

- Evaluation criteria – See below for description of criteria
- Weighting factors – Each criterion category is given a rating factor as a function of its importance to the study. The total weighting is summed to 100 for all rated categories (see below for weighting factors).
- Confidence factors – The degree of confidence placed in the qualitative rating given to each evaluation criterion is given a confidence factor, with low confidence given a factor of 1, moderate confidence a 2, and high confidence a factor of 3. A higher confidence score may enhance an alternative relative to one with an equivalent weighted total criteria score and vice-versa.

5.3.2.1. Evaluation Criteria

Biological Performance

Potential biological performance excluding TDG performance is rated for two categories that allow evaluation of both potential risks associated with structural or operational changes as well as potential enhancements:

Risk of Biological Injury – This criterion evaluates risk of injury to fish passing through any proposed structure or due to changes in existing Project operations, with performance being given numerical values from 5 to 0, with low risk getting the highest score.

- 5 Points – No injury risk
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – Significant injury risk

TDG Performance

Flow Capacity – Rating for this criterion evaluates the capacity relative to that required to pass the 7Q10 flow, with full required spill capacity being given a numerical value of 5 and no capacity a 0 with values in between being prorated according to the actual capacity:

- 5 Points – 7Q10 capacity (53,300 cfs = 108,300 – 55,000 cfs)
- 4 Points – (40,000 cfs)
- 3 Points – (30,000 cfs)
- 2 Points – (20,000 cfs)
- 1 Point – (10,000 cfs)
- 0 Points – No spill flow capacity

Compatibility – Rating for this criterion evaluates the compatibility of the alternative with other alternatives to result in an increased overall capacity achieving the 7Q10 flow, i.e., total compatibility being given a 5 and absolutely no compatibility a 0:

- 5 Points – Totally compatible
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – No compatibility

Projected TDG Performance

An alternative that will actually reduce (strip) TDG is rated with a 5, while an alternative which increases discharged TDG above 125 percent is rated 0.

- 5 Points – Strips incoming TDG, passes incoming TDG (neutral impact), discharges TDG 100 to 110 percent
- 3 Points – Discharges TDG 110 to 120 percent
- 1 Point – Discharges TDG 120 to 125 percent
- 0 Points – Discharges TDG greater than 125 percent

Technical Feasibility

Technical feasibility is rated for several categories, each on relative scales which measure relative difficulty on a scale of 5 to 0, with 5 being the least difficult or problematic and 0 being the most:

- 5 Points – Least difficult
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – Most difficult

Permitting – This criterion rates the ease of acquiring permits for the Project and addresses such issues as whether there are shoreline modifications requiring a Section 404 Permit from the Corps of Engineers, whether there is in-water work required, etc.

Schedule – This criterion rates relative length of time that will be required to complete the necessary work to implement the final solution.

Constructability – This criterion rates construction difficulty, taking into account the amount of in-water work, cofferdam construction, dive time, unknown or bad foundation conditions, unprecedented construction techniques, etc.

Dam Safety

An alternative that poses no dam safety risks through construction processes or operation procedures is rated highest. An alternative that poses a significant dam safety risk is not acceptable and further consideration is contingent on resolution of dam safety concerns.

- 5 Points – No dam safety risk
- 3 Points – Questionable, but still considered for ranking
- 2-0 Points – Significant dam safety risk, consideration is contingent on resolution of dam safety concerns

Design and Construction Cost

The alternatives are rated on a relative cost scale from 5 for the least expensive to 0 for the most expensive (ranges of cost may be applied to these ratings once preliminary cost estimates have been developed or maximum cost commitment levels established).

- 5 Points – Least expensive
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – Most expensive

Maintenance and Access

Alternatives are rated relatively on the basis of maintenance and access with those requiring little or no increase in maintenance being rated a 5 to those with extensive regular maintenance requirements and/or those where access for maintenance is problematic, being given a 0 rating.

- 5 Points – No increase in maintenance
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – Extensive maintenance required or access for maintenance is problematic

Impact on Existing Project Operations

Alternatives that have no impact on existing Project operations are given a rating of 5, while those that result in varying increasing impacts on operations are rated from 4 to 0.

- 5 Points – No impact on power production
- 4 Points
- 3 Points
- 2 Points
- 1 Point
- 0 Points – High impact on power production

Ability to Prototype Test

Alternatives for which TDG performance can be field tested and confirmed through prototype testing of a lower cost temporary facility are given a rating of 5; those that can be phased to prove concept without complete implementation are given a 3; while those that must be fully implemented to test are given a 0, with varying degrees of ability to test rated in-between.

- 5 Points – Ability to field test through a low cost prototype
- 4 Points
- 3 Points – Ability to phase implementation
- 2 Points
- 1 Point
- 0 Points – No ability to prototype test or phase implementation

Ability to Adjust on Basis of Performance

Alternatives for which there is an ability to adjust major parameters affecting TDG performance post construction/implementation to improve or in-some other way fine-tune performance are given a rating of 5, while those that have varying reduced degrees of adjustability or operational flexibility are rated from 4 to 0 for no flexibility.

- 5 Points – Highly adjustable or flexible
- 4 Points
- 3 Points
- 2 Points

- 1 Point
- 0 Points – No adjustability or flexibility

5.3.2.2. Weighting Factors

Each criterion category was given a rating factor as a function of its perceived importance to the study, as shown in Table 5.3-3. The total weighting sums to 100 for all rated categories. Heaviest weight was placed on projected TDG performance as that is the purpose of this exercise. Dam safety was also weighted heavily with the added provision that no alternative can be advanced without significant dam safety concerns being resolved.

Table 5.3-3. Evaluation matrix weighting factors.

Criterion		Weighting Factor
Biological Performance:	Risk of Biological Injury	4
TDG Performance:	Flow Capacity	8
	Compatibility	6
	Projected TDG Performance:	19
Technical Feasibility:	Permitting	4
	Schedule	4
	Constructability	8
Dam Safety:		15
Design and Construction Cost:		10
Maintenance and Access:		4
Impact on Existing Project Operations:		6
Ability to Prototype Test:		6
Ability to Adjust on Basis of Performance:		6
	Sum	**100**

5.3.3. Preliminary Cost Estimates

The costs shown in Table 5.3-4 provide information on the engineers' opinion of the comparative costs for the construction of the alternatives. These estimates are based on "screening level" alternative layouts and intended for comparison purposes only. There is limited information available on site conditions and the layout of Project features rely on previous experience of similar and rule of thumb design guidelines. Estimates were developed with a range of contingencies (50 to 150 percent), and those presented in Table 5.3-4 use a contingency of 100 percent. Costs are presented in 2007 U.S. dollars. More detailed estimate tables are provided in Appendix 7.

Table 5.3-4. Summary of engineers' opinion of cost.

Alternative	Conditions	Engineers' Opinion of Cost[1]
Sluice Gate Throttle (No. 1-3)	Single gate	$1,297,000
	Four gates[1]	**$5,188,000**
Roughen Sluice Flow (No. 3-2)	Single gate	$4,509,000
	Three gates	$13,527,000
	For three gates w/ throttle gate modifications[1]	**$18,715,000**
Spillway Modifications (No. 2-8)	Deflector (single spillway)	$864,000
	Air induction piping (single spillway)	$931,000
	Increase turbulence (single spillway)	$1,119,000
	Two spillways deflector and air induction[1]	**$3,590,000**
Right Abutment Tunnel (No. 4-7)	53,000 cfs capacity tunnel[1]	**$152,383,000**
	26,500 cfs capacity tunnel	$95,839,000
Left Abutment Tunnel (No. 4-8A)	Use existing diversion tunnel[1]	**$139,885,000**
Penstock Draft Tube Bypass (No. 4-9)	Single unit bypass	$60,780,496
	Bypass both Units 55 and 56[1]	**$121,561,000**
Left Abutment Tunnel Next to Unit 51 (Option 4-10)	Concrete liner[1]	**$179,514,000**
	Steel liner	$196,530,000

Note:
1 Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.

5.3.4. Evaluation of Alternatives

The design and construction approach for each alternative is further developed as suggested during the "Alternative Evaluation" workshop meeting. The alternatives are ranked using an evaluation matrix (see Appendix 8).

5.3.4.1. Throttle Sluice Gates (No. 1-3)

Biological Performance:

- Risk of Biological Injury – Given the depth of the gates in the reservoir, there is little likelihood of fish presence near the intakes. There will be a shear zone in the sluice flow, but the impact should be minimal. (4 points, confidence Level 3)

TDG Performance:

- Flow Capacity – 7Q10 is (53,300 cfs) capacity, assuming no units down. Flow capacity approx. 12,000 – 18,000 cfs. (2 points, confidence level 3).
- Compatibility – No issues except potential for interaction with flow from the spillways. There is a minimal likelihood of this. (5 points, confidence level 3)
- Projected TDG Performance. (4 points, confidence Level 1—limited test data to date)

Technical Feasibility:

- Permitting – SCL has received initial permit and will need more permits as iterations continue. This should be achievable. (5 points, confidence level 3—SCL has been through the permitting already)
- Schedule – No major schedule constraints. (5 points, confidence level 3—SCL has done some of this work and testing already.)
- Constructability – Construction is performed on the spray deck with good access. The gate seal modification needs to be done properly so that the gates will close completely. Incremental inspections and tests will be required to make sure there is no operational difficulty. (5 points, confidence level 3—SCL has done some of this work and testing already.)

Dam Safety: No concerns. (5 points, confidence level 3)

Design and Construction Cost: Relative to others, this alternative will be inexpensive. (5 points, confidence level 3—SCL has done some of this work already and understands the costs.)

Maintenance and Access: This alternative may have a fair amount of maintenance and operations to test, repair, replace seals, and maintain the sluice gates for the throttled openings. (3 points, confidence level 2).

Impact on Existing Project Operations: No expected impact on existing Project operations but there is a significant risk to existing Project operations due to a partially stuck open sluice gate. This risk is unknown, and therefore results in a confidence level of 1. This would impact existing Project operations and costs. Sluice maintenance gate can pass in front of the operating gates at 1,000 cfs. (5 points, confidence level 1)

Ability to Prototype Test: SCL will is currently able to do limited prototype testing and will be able to fully prototype after modification to the existing gates including welding clips and fixing the sluice gate seal heaters prior to the testing. If this is done, the confidence would be improved. (5 points, confidence level 3—based on possible approaches to testing)

Ability to Adjust on Basis of Performance: Through incremental approach and/or testing, seal design can be modified to adjust gate opening. (5 points, confidence level 3).

5.3.4.2. Roughen Sluice Flow (No. 3-2)

Biological Performance:

- Risk of Biological Injury – Given the depth of the gates in the reservoir, there is little likelihood of fish presence near the intakes. There will be a shear zone in the sluice flow, but the impact should be minimal. (4 points, confidence level 3)

TDG Performance:

- Flow Capacity – Assume 4 sluice gates can be modified with capacity of 4,000 - 5,000 cfs each for a total of 16,000 - 20,000 cfs. (2 points, confidence level 2)
- Compatibility – No issues except potential for interaction with flow from the spillways. There is a minimal likelihood of this. (5 points, confidence level 3)
- Projected TDG Performance (4 points, confidence level 1—limited test data to date)

Technical Feasibility:

- Permitting – Permits expected to be relatively simple. (4 points, confidence level 3—SCL has been through the permitting of sluice gate already, which is similar)
- Schedule – No major schedule constraints, (4 points, confidence level 3—SCL has done some of this work and testing already).
- Constructability – Construction is difficult, on the face of the dam, and exposed. The gate seal modification needs to be done properly so that the gates will close completely. Incremental inspections and tests will be required to make sure there is no operational difficulty. (5 points, confidence level 3—SCL has done some of this work and testing already)

Dam Safety: No concerns. (5 points, confidence level 3)

Design and Construction Cost: Relative to others, this one will be inexpensive, but slightly more expensive than sluice gate throttling. (4 points, confidence level 3—easy access and straight-forward construction methods)

Maintenance and Access: This alternative may have a fair amount of maintenance and operations to test, repair, replace seals, and maintain the sluice gates for the throttled openings. (3 points, confidence level 2)

Impact on Existing Project Operations: No expected impact on existing Project operations but there is a significant risk to existing Project operations due to a partially stuck open sluice gate. This risk is unknown, and therefore results in a confidence level of 1. This would impact existing Project operations and costs. Sluice maintenance gate can pass in front of the operating gates at 1,000 cfs. (5 points, confidence level 1)

Ability to Prototype Test: SCL will be able to prototype test one gate at a time. (5 points, confidence level 3)

Ability to Adjust on Basis of Performance: Through incremental approach and/or testing, seal design can be modified to adjust gate opening. (5 points, confidence level 3).

5.3.4.3. Spillway Flow Splitter/Aerator (No. 2-8)

Biological Performance:

- Risk of Biological Injury – The actual biological risk is not known at this point, (3 points, confidence level is a 2).

TDG Performance:

- Flow Capacity – 10,000 - 15,000 cfs/spillgate for a total of 20,000 – 30,000 cfs. (2 points, confidence level 2—untested)
- Compatibility – No issues. (5 points, confidence level 3)
- Projected TDG Performance (4 points, confidence level 1—no data available, will need to test)

Technical Feasibility:

- Permitting – No permitting expected for this alternative. (5 points, confidence level 3)
- Schedule – While the conditions are challenging, it will have a short duration construction relative to other projects. (5 points, confidence level 3)
- Constructability – Construction access is simple, most of construction is in the dry. (5 points, confidence level 3)

Dam Safety: None (5 points, confidence level 3)

Design and Construction Cost: Relative to others, this one will be inexpensive. (5 points, confidence level 3)

Maintenance and Access: Accessible, visible, not many components to maintain. (5 points, confidence level 3)

Impact on Existing Project Operations: No expected impact on existing Project operations. (5 points, confidence level 3)

Ability to Prototype Test: One spillway will be modified, but the second can be phased. Both can be modified. (3 points, confidence level 3)

Ability to Adjust on Basis of Performance: Easily modified after installation, easy access for modification. (5 points, confidence level 3)

5.3.4.4. Right Abutment Tunnel with Submerged Discharge (No. 4-7)

Biological Performance:

- Risk of Biological Injury – At a shallow enough depth that there is a potential to entrain some fish into the intake. (3 points, confidence level 2)

TDG Performance:

- Flow Capacity – Some uncertainty in the design at this point; this can be updated as the design progresses. (5 points, confidence level 2)
- Compatibility – This alternative is compatible with other alternatives and operations. (5 points, confidence level 3)
- Projected TDG Performance – Looking at about 35 fps leaving the tunnel. If the tunnel is shallow, there will be air entrainment. If it is deep, it will have less air entrainment but will be much more complicated. (3 points – Discharges TDG 115-130 percent, confidence level 1—no data available at this point)

Technical Feasibility:

- Permitting: 1 point, confidence level 2
- Schedule – This project will likely take two construction years. (1 point, confidence level 3)
- Constructability – This project involves constructing a tunnel, underwater work for the intake and discharge structures, gate construction, etc. (2 points, confidence level 3)

Dam Safety: Additional exploration would be required to improve the confidence level and determine whether a dam safety risk is involved. The potential to introduce high pressures into the abutment would be the major uncertainty to be resolved. (3 Points, confidence level 2)

Design and Construction Cost: 1 point, confidence level 3

Maintenance and Access: Cavitation repair, gate maintenance and repair, access road will be available from construction. (3 points, confidence level 2)

Impact on Existing Project Operations: No impacts on existing Project operations. (5 points, confidence level 3)

Ability to Prototype Test: No ability to prototype test for this alternative. (0 points, confidence level 3)

Ability to Adjust on Basis of Performance: There may be some potential for adjustability in the design, such as adjusting flows or adding flow vanes to the discharge structure. The final structure may be proven to perform at a lower flow range than designed. (1 point, confidence level 3)

5.3.4.5. Open Existing Diversion Tunnel and Add Control Structure (No. 4-8A)

Biological Performance:

- Risk of Biological Injury – The location of the intake is shallow enough that there is a potential to entrain some fish into the intake. (3 points, confidence level 2)

TDG Performance

- Flow Capacity – Some uncertainty in the design at this point, this can be updated as the design progresses, use a flow range 53,300–26,500. (5 points, confidence level 2)
- Compatibility – This alternative is compatible with other alternatives and operations. (5 points, confidence level 3)
- Projected TDG Performance – Looking at about 35 fps leaving the tunnel. If the tunnel is shallow there will be air entrainment. If it is deep, it will have less air entrainment but will be much more complicated. (3 points, confidence level 1—no data available at this point)

Technical Feasibility:

- Permitting – Permitting will be extensive for this project. (1 point, confidence level 2)
- Schedule – This project will likely take 2 construction years. (2 points, confidence level 3)
- Constructability – This project involves constructing a vertical shaft with a cofferdam in front of the spill gates, lining the existing tunnel, removing the concrete plug. (3 points, confidence level 2)

Dam Safety: There is a significant dam safety risk for this alternative with the construction and tunnel through the dam. The original tunnel was not designed for pressure flow. Additional exploration would be required to improve the confidence level and confirm that a dam safety risk is involved. The potential to introduce high pressures into the abutment would be the major uncertainty to be resolved. The main difference between this alternative and alternatives involving tunnels on the right bank is that the rock on the left abutment is of much lower quality. This alternative will not be considered further without resolution of dam safety concerns. (1 point, confidence level 3)

Design and Construction Cost: This alternative will be likely less expensive than the right abutment cost in terms of length of tunnel, but the steel lining will be expensive. In addition there are costs associated with minimizing contractor risk due to dealing with the existing bulkhead. (1 point, confidence level 3)

Maintenance and Access: This alternative has limitations for access and maintenance due to the outlet control and inability to independently dewater the tunnel upstream of the outlet gate control structure. (1 point, confidence level 3)

Impact on Existing Project Operations: May have cost impacts because Unit 56 would likely need to be shut down during a portion of the construction. (3 points, confidence Level 3)

Ability to Prototype Test: No ability to prototype test for this alternative. (0 points, confidence level 3)

Ability to Adjust on Basis of Performance: There may be some potential for adjustability in the design, such as adjusting flows. The final structure may be proven to perform at a lower flow range than designed. (1 point, confidence level 3)

5.3.4.6. Penstock Draft Tube Bypass (No. 4-9)

Biological Performance:

- Risk of Biological Injury – Reasonably significant risk of injury to fish through the bypass and where it re-enters the draft tube. (1 point, confidence level 3)

TDG Performance:

- Flow Capacity – Some uncertainty in the design at this point, this can be updated as the design progresses. Need to determine the capacity of the trashrack to handle additional flows use range of 10,000 to 20,000 cfs. (2 points, confidence level 1)
- Compatibility – This alternative is compatible with other alternatives and operations. (5 points – Totally compatible, confidence Level 3)
- Projected TDG Performance – The discharge will be through the existing draft tubes and should perform similarly to the existing powerhouse. However, the velocities coming out the draft tubes will be likely more than twice the existing velocities and may result in slightly poorer performance than the existing units. (4 points, confidence level 1 – no data available at this point)

Technical Feasibility

- Permitting – Permitting will be minimal for this project. (4 points, confidence level 3)
- Schedule – This project will likely take 1 construction year. (3 points, confidence level 2)
- Constructability – This project involves constructing a bypass tunnel under the existing Project powerhouse during operations. (4 points, confidence level 3)

Dam Safety: There are no significant dam safety risks for this alternative. (5 points—No dam safety risk; confidence level 3)

Design and Construction Cost: This alternative will likely be less expensive than the right and left abutment cost in terms of length of tunnel, but the bypass construction will be expensive. (3 points, confidence level 2)

Maintenance and Access: This alternative can be accessed by closing the headgate and the draft tube gates and dewatering the draft tubes. There will be some limitations for as to access and maintenance due to limited sized access portals. (2 points, confidence level 2)

Impact on Existing Project Operations: There is a potential for loss of generation due to potential for interaction with turbines. Units will need to be out of service during construction. (2 points, confidence level 1)

Ability to Prototype Test: No ability to prototype test for this alternative, but the implementation can be phased. The alternative would be developed in conjunction with turbine replacement and would with a comprehensive engineering study and analysis that would include physical and numeric modeling that may provide information as to the expected performance. (3 points, confidence level 3)

Ability to Adjust on Basis of Performance: There may be some potential for adjustability in the design, such as adjusting flows. The final structure may be proven to perform at a lower flow range than designed. (1 point, confidence level 2)

5.3.4.7. New Left Abutment Tunnel Next to Unit 51 Intake (No. 4-10)

Biological Performance:

- Risk of Biological Injury – At a shallow enough depth that there is a potential to entrain some fish into the intake. (3 points, confidence level 2)

TDG Performance:

- Flow Capacity – Some uncertainty in the design at this point, this can be updated as the design progresses. Need to determine the capacity of the trashrack to handle additional flows, use flow range 26,500 to 53,300. (3 points, confidence level 1)
- Compatibility – This alternative is compatible with other alternatives and operations. (5 points, confidence level 3)
- Projected TDG Performance – This tunnel will have to have a surface discharge due to depth constraints on the left bank. (1 point, confidence level 1—no data available at this point)

Technical Feasibility

- Permitting – Permitting will be extensive for this project. (1 point, confidence level 2)
- Schedule – This project will likely take 2 construction years. (2 points, confidence level 3)
- Constructability – This project involves constructing a tunnel, potentially enlarging the forebay, potential modifications to the trashrack, and work under the powerhouse. (2 points, confidence level 3)

Dam Safety: There is a significant dam safety risk for this alternative with the construction and tunnel near the dam. Additional exploration would be required to improve the confidence level and confirm that a dam safety risk is involved. The potential to introduce high pressures into the abutment would be the major uncertainty to be resolved. The main difference between this alternative and alternatives involving tunnels on the right bank is that the rock on the left abutment is of much lower quality. There is also the potential to destabilize the rock mass between the new shaft and the existing penstock shafts. (1 point, confidence level 3). This alternative will not be considered further without resolution of dam safety concerns.

Design and Construction Cost: This alternative will be likely less expensive than the right abutment cost in terms of length of tunnel, but the steel lining will be expensive. (1 point, confidence level 3)

Maintenance and Access: This alternative has access for maintenance using upstream stoplogs and regulating gates at the downstream side. The area upstream of the stoplogs and downstream of the regulating gates is more challenging for maintenance. (3 points, confidence level 2)

Impact on Existing Project Operations: There is a potential for loss of generating head due to increased flow in the forebay and headloss across the trashrack. There may be power outages required during construction. (1 point, confidence level 1)

Ability to Prototype Test: No ability to prototype test for this alternative. (0 points, confidence level 3)

Ability to Adjust on Basis of Performance: There may be some potential for adjustability in the design, such as adjusting flows. The final structure may be proven to perform at a lower flow range than designed. (1 point, confidence level 3)

5.3.4.8. Summary of Evaluation of Alternatives

Evaluation of TDG abatement alternatives has indicated that three are favored for more detailed examination:

- Throttle Sluice Gates (No. 1-3), flow capacity 12,000 to 18,000 cfs;
- Roughen Sluice Flow (No. 3-2), flow capacity 16,000 to 20,000 cfs; and
- Spillway Flow Splitter/Aerator (No. 2-8), flow capacity 20,000 to 30,000 cfs.

All of the above-mentioned alternatives can be used in combination. Modifying the sluice gates as required for the Throttle Sluice Gate alternative would be the first step for the Roughen Sluice Gate alternative. Observations indicate that the location of contact for the gate discharge for the throttled sluice gate would quite different from what is expected with the deflectors used in the Roughen Sluice Flow alternative (see Figure 5.3-2).

Figure 5.3-2. Operation of throttled sluice gate illustrating angle of jet.

Following is a potential configuration:

- Four Throttled Sluice Gates (without Roughen Sluice Flow modifications), operating at a range of 2 feet (with estimated flow of 1,700 cfs/gate) to 4 feet (with estimated flow of 4,400 cfs/gate) for a flow capacity of 6,800 to17,600 cfs;
- Three Roughened Sluice Flow Gates, with an estimated capacity of 4,000 to 5,000 cfs each for a total flow capacity of 12,000 to 15,000 cfs (utilizing all the remaining sluice gates); and
- Modifications to both spillways for at total flow capacity of 20,000 to 30,000 cfs.

These alternatives all involve spilling flow through existing outlets (the seven sluice gates and two spillway gates) into the plunge pool and rely on reduction in TDG production by spreading the flow and limiting plunging effects of the confined jets. The relatively modest area of plunge pool where spill and sluice gates discharge and the constrained outlet from the pool to the downstream river, may limit the spill flow that may be released by combinations of alternatives without TDG increasing to a level higher than the combined output of alternatives operating individually. Addition of the flow ranges for combinations of alternatives is approximately 40,000 cfs to 60,000 cfs; however, the total capacity is expected be less than this range due to the constrained plunge pool outlet.

5.4. Further Analysis of Alternatives and Interactions with the Project

5.4.1. Assess additional Field Data Requirements

The three favored alternatives are located in areas where significant information is available.

Knowing the shape of the existing plunge pool is necessary for physical hydraulic and numerical modeling. Recent bathymetric information will supplement the existing information on the shape of the plunge pool and area near the tailrace.

Further analysis may uncover field data gaps; however, at this time no additional field data are anticipated beyond further TDG testing.

5.4.2. Design Details of New Alternatives

5.4.2.1. Throttle Sluice Gates (No. 1-3)

As originally designed and constructed, the seven sluice gates operate either fully opened or fully closed. One objective of the TDG study plan is to operate a sluice gate at a throttled position to determine the maximum possible flow that may be passed while not causing TDG impairment. This approach provides a means to seal the gate at intermediate positions and should help minimize vibration during throttled openings of Sluice Gate 4 for assessing TDG concentrations during spill conditions. The design and operation of this modification will not significantly alter the function or operation of Sluice Gate 4. The modification will not alter the structural integrity or design basis of the gate.

The seven low-level sluices through the dam at a head of approximately 190 feet provide 252,000 cfs of the total 360,000 cfs discharge capacity of the dam at reservoir elevation 1,994 feet NAVD 88 (1,990 feet NGVD 29). The sluice gates are fixed-wheel gates, 17 feet wide by 21 feet high, operated by cable hoists located on a hoist deck along the downstream face of the dam at elevation 1,864 feet NAVD 88 (1,860 feet NGVD 29). A sluice maintenance bulkhead, 35 feet wide by 57 feet high, can be moved into position on the upstream face of the dam over a sluice entrance and utilized for dewatering the sluices for maintenance purposes.

The sluices are steel-plate lined, including the entrance transitions that incorporate a surface against which the maintenance bulkhead seals. Electric seal heaters are located on the downstream fixed seal surfaces against which the operating gates seat. Seals are hydraulically inflated using anti-freeze fluid supplied from an elevated tank and deflated by bleeding the fluid and pumping it back to storage.

Major components of the work for this approach are as follows:

- Sealing off upstream entrance of Sluice Gate 4 with the sluice maintenance gate to provide a safe work environment (completed in 2007)
- Installation of 3/8-inch-thick by 8-inch-wide stainless steel (SS-304L) plates on sluice gate 4 to provide a sealing surface during throttling operations at 1.4, 3.5, and 4.7 feet (completed in 2007)
- Designing and installing deflectors within the sluice gates to direct the water away from the gate slots (ongoing)
- Testing to confirm adequate sealing and acceptable vibration and fatigue analysis (ongoing)

The components of the sluice gate system, including the heater covers, have presented problems during testing that need to be addressed. Additionally, potential water cutting of the sluice gate seals is a concern. Further analysis is required to address dam safety and vibration concerns.

5.4.2.2. Roughen Sluice Flow (No. 3-2)

Two concepts have been developed for this alternative. Both involve deflecting the flow from the sluice to allow it to be redirected and distributed throughout the plunge pool.

The first concept has been developed furthest and is the basis for cost estimates. The sluiceway flow deflector would be configured as a 30-foot-long upward contoured surface extending from the face of the dam below the sluiceway invert (see Appendix 6, Figure A.6-2).

The following constraints were considered in selecting the structural configuration of the deflector:

- The piers that extend on each side of the sluiceway each contain two 30-foot-high curtains of post-tensioned reinforcement anchored in the main body of the dam. Because of the presence of the post-tensioned reinforcement, the piers are considered to be critical existing structures that would be sensitive to modifications. Hence, no high load structural interfaces are permitted on the piers in the post-tensioned zone.
- On several of the sluiceways, the piers extend unequal distances on each side.
- The downstream face of the sluiceways are extended at various distances from the main body of the dam and the varying geometry of the lower ledge beveled transitions precludes the use of braces attached between the lower body of the dam and the upward sloped deflector structure. The useable heights of the lower downstream faces of the sluiceways vary, with the least height being approximately 13.5 feet.

Given the difficulties and constraints in using a braced structure, a cantilevered structure was selected for development in this study. The structure consists of several major elements, as described below.

Attachment Frames. The two attachment frames provide the structural interface between the body of the dam and the cantilevered deflector structure. They are required to transfer the moment and vertical shear from the cantilevered deflector structure to the dam. Each frame would be attached to the lower downstream face of the sluiceway by a set of post-tensioned anchor rods installed and developed within the main body of the dam. See Appendix 6, Figure A.6-2. The upper part of the frame would be anchored by eight high strength steel anchors that develop the tension component of the reaction couple. The lower part of the frame transfers the compression component of the reaction couple directly to the dam concrete face. A set of shear keys attached to the mid section of the frame and grouted into horizontal slots cut into the dam face provide the shear reaction force. The frame would be attached, grouted, and post-tensioned prior to construction/installation of the remaining deflector structure.

Box Girders. The two tapered box girders provide the main support structure for the deflector. The box section provides high torsional stiffness not otherwise obtained using open girder sections. It is believed that high torsional stiffness is advantageous in avoiding fluid-structural dynamic interaction. Also, when the deflector side walls are of different lengths (as when two different pier lengths bound the sluiceway), there is a significant torsional moment due to the imbalanced load on the differential side wall length. The box girders would connect to the attachment frames by flange and web bolted splice plates.

Deflector Floor and Side Wall Frames. Support of the deflector floor would be provided by W-shape beams spanning across and connected to flanges of the box girders. The beams transfer the total vertical hydrostatic and hydrodynamic loads from the deflector floor to the girder. Support of the deflector side walls would be provided by vertical cantilevered W-shape beams rigidly connected to ends of the floor beams and simply connected to the girder web. This connection combination provides a stiffer vertical beam than if the beam is connected only to the floor beam or to the girder. The need for tension ties connecting the tops of the vertical beams is to be assessed. Without a deflector ceiling (i.e., a totally enclosed deflector conduit), the tension ties may be subject to detrimental flow impingement. Until further hydraulic modeling is complete, only hydrostatic loading on the side walls is being considered.

Deflector Floor and Side Walls. The deflector floor would be configured to spread the sluiceway flow using a pair of progressively increasing height trapezoidal ramps integrated into the deflector floor. See Appendix 6, Figure A.6-2. The floor profile would be developed using a set of profiled rib plates attached to the top of each transverse floor beam. The profile is such that floor plates are either flat or formed in single curvature. The side walls would attach to the vertical beams to full height. The side wall plates can be considered to act compositely with the vertical beams (providing additional effective flange width and thickness) such that the side walls have greater strength and stiffness than determined using the vertical beams alone. Both the floor and the sides would be appropriately sealed to the face of the dam (requirements are to be determined).

The deflector concept has several issues that need to be addressed by further study:

1. Determine hydrodynamic loads on deflector structure.
2. Determine whether fluid-structural dynamic interaction will induce flutter or other oscillatory instabilities.
3. Determine the fatigue loading conditions and design criteria.
4. Determine the need for top of beam cross ties.
5. Determine the need for a totally enclosed deflector conduit.
6. Determine the need for top of side wall bracing to piers.

The second concept is similar in that it represents a deflector positioned below the flow from the sluice to allow the flow to be redirected and distributed throughout the plunge pool; however, it is smaller in scale and positioned lower to allow continued use of the existing gate seal system. The trajectory of the discharge at small sluice gate openings is directed downwards. The deflector intercepts the discharge and redirects and distributes the flow.

5.4.2.3. Spillway Flow Splitter/Aerator (No. 2-8)

This alternative involves developing spillway flow splitter/aerators to aerate the jet off the spillway and improve the TDG performance of the spillways at higher spill flows. The alternative includes venting to provide air to the flow and "turbulence elements" on the spillway surface to roughen or separate the surface flow. The flow capacity for this alternative is estimated to be 20,000 cfs (based on the results of spillway gate testing). There is the potential of some additional capacity.

This option may allow for some TDG stripping with lower cost and ease of construction. Because the spillways are somewhat isolated on the abutments and not operated as part of the regular regime, the disturbance to the operation of the facility would be minimal.

Three distinct components are part of this option.

Option 1: Addition of a Deflector Device. This scheme involves the addition of a deflector to the end of the each existing spillway chute. These devices have been preliminarily sized at approximately 30 feet long.

The additional loading created by the water pressure on these blocks/ramps would be transferred directly through the spillway slab using rock anchors drilled into the underlying substrate. Details of attachment to the rock and spillway slab require development.

The deflectors will behave similarly to the flip bucket on the end of Spillway 1 that will tend to break up the jet, which should be slightly better for smaller fish and slightly worse for larger fish (see Section 5.4.3, below). The deflector design should be developed to direct the flow into the plunge pool and not onto rock abutments. The variable ramping of the deflectors requires refinement to direct the flow trajectories. Those trajectories going over the top of the teeth will travel a greater distance downstream than those going through the gaps between the teeth. Both should be tuned to enlarge the impact area of the jet leaving the spillway.

Option 2: Aeration of Chute. This alternative involves construction of a venting system that would help to aerate the underside of the spillway jet. The introduction of air at the base of the jet would help to initiate some stripping of the TDG, and would also begin to "bulk-up" the water column. Model studies would have to be undertaken to ensure that this bulk-up of water would still be confined within the existing wall height of the spillway chute.

This option would require installation of a piping system through the walls of the spillway structures and across the floor of the spillways. Air demand for the spillway needs to be determined. Channels cut across the spillway floor to allow air supply across the width of the structure. Care would have to be taken to ensure that the interface between the pipe and the spillway slab are appropriately sealed so water is not allowed to seep under the slab and potentially freeze. Vertical standpipes on the exterior of the spillway walls would feed air into the horizontal pipe from both ends. Further study is required to determine the most effective air supply system.

Option 3: Increase Turbulence in Flow. This option would involve roughening the spillway surface or addition of an external structural element to increase turbulence in the flow. Increased turbulence enhances the air exchange and gas transfer across the air/water interface

5.4.3. Analysis Plan and Progress for Preferred Alternatives

5.4.3.1. Engineering Studies

5.4.3.1.1. Study Goal

The engineering study goals are to further develop the structural abatement alternatives using standard engineering analysis. These studies are in support of and in addition to the CFD and physical model analysis described below to provide a comparative basis and foundation for decision making as the TDG study plan progresses.

5.4.3.1.2. Engineering Tasks Completed or in Progress

As of November 2008, engineering tasks completed or in progress include the following:

- Holding a workshop for the TDG engineering team to develop a common understanding of the scope of work and brainstorm concepts for modifications to spill operations that will reduce TDG including spillway modifications (aeration of flow, flip buckets) and sluice gate modifications (flip buckets, gate modifications)
- Developing a three-dimensional CAD model of the dam, spill and sluice gates, and Project topograph and bathymetry for use in analysis of alternatives (see Figure 5.4-1)
- Examining existing sluice gate seals and expected flow conditions during testing to confirm modifications made to improve reliable operation during testing
- Preparing a trajectory analysis of existing spill and sluice gates using hydraulic calculations
- Comparing trajectory analysis against observations of spill testing (as well as physical model and CFD model results)
- Analyzing hydraulic capacity of alternatives
- Examining effects of potential operational changes associated with more frequent use of sluice gates and spillway gates, including; winches, cables and other subsystems of the gates

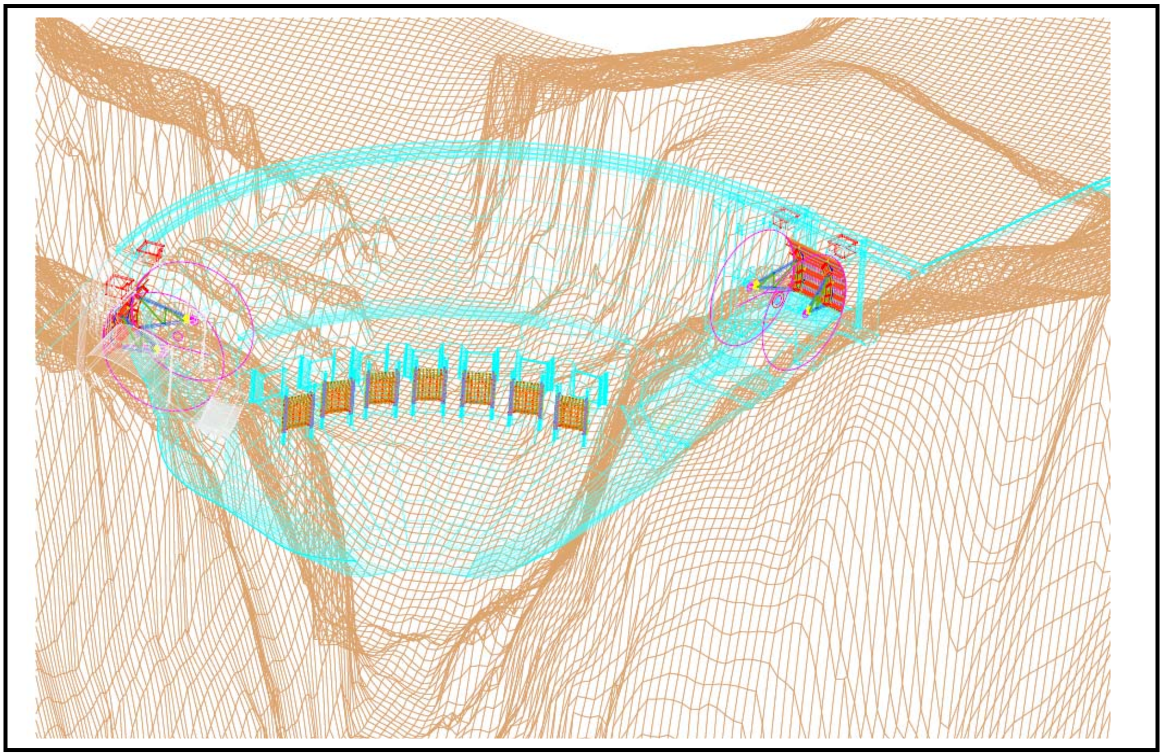


Figure 5.4-1. View of 3D CAD model of Project area.

5.4.3.1.3. Future Engineering Tasks

Future engineering tasks include the following:

- Developing design details of favored alternatives including potential interactions with existing features of the Project (existing structural components of dam, sluice gates, and spillway).
- Further investigating existing conditions and potential interactions with existing structures including structural components and dam abutments.
- Developing more detailed drawings that can provide better concept understanding and basis for cost estimates.
- Developing more detailed cost estimates and construction sequencing for favored alternatives.
- Implementing the favored alternative as a prototype at the Project in a manner that allows confirmation of performance prior to fully implementing the concept.
- Monitoring the performance of the prototype to confirm and refine prediction of TDG performance.

5.4.3.2. CFD

Resolution of many of the hydraulic design issues will rely heavily on the results of both physical and numerical hydraulic models. Both models will be used in complementary roles to maximize their particular strengths. The greatest strength of the numerical model is the capability it offers designers to explore, develop, and compare various design concepts relatively quickly and easily. Modifications can be made quickly in the "numerical flume," and tested to ensure a proposed design alteration performs as expected. The model will also be used (eventually) to assist in predicting the relative TDG performance of each of these alternatives.

5.4.3.2.1. Study Goal

The goal of the CFD model studies will be to develop a model of the sluices and spillways that can be:

- Used to analyze, in conjunction with the physical model, modifications to the sluices and spillways to provide greater dispersion of the jets and lower jet momentum entering the tailwater;
- Verified versus physical model results; and
- Incorporated into an overall model of the plunge pool area and downstream river at a later date to provide the hydrodynamic framework for an overall TDG predictive model for the Project.

5.4.3.2.2. CFD Model Description and Program

The final model will extend from the immediate forebay area down to a point approximately 5,000 feet downstream of the main dam. The upstream boundary for the model will consist of a specified reservoir level for the Project, whereas the downstream boundary will consist of a specified tailwater level (see Figure 5.4-2).

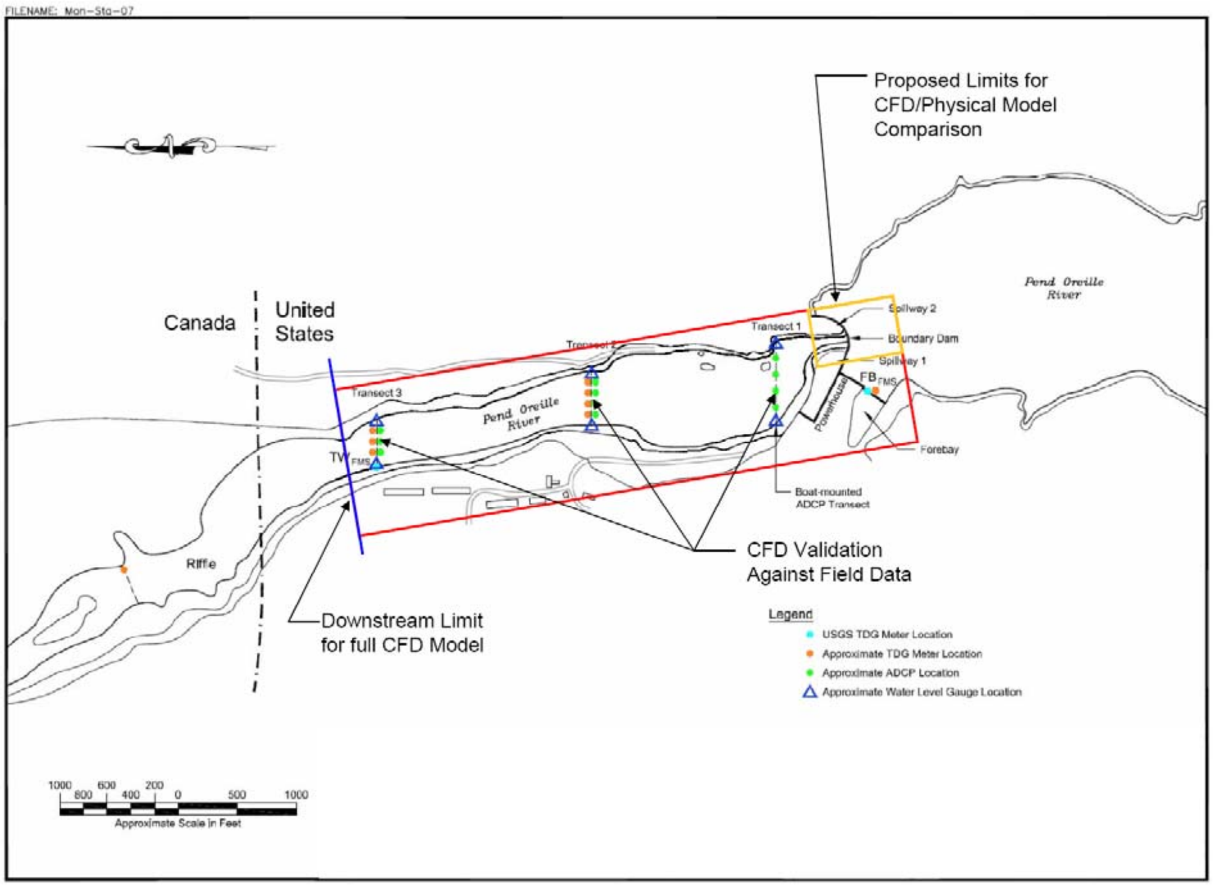


Figure 5.4-2. Limits of model for CFD analysis.

After development of individual models, a series of runs will be undertaken to calibrate and validate the CFD model results. Prototype data are ideal for this purpose; however, the plunge pool is a challenging location for data collection and prototype data in the plunge pool are limited to qualitative observations and photos taken during historical operation of the sluiceways/spillways. Although it is important to compare the model against this type of data, a more detailed comparison can be made by replicating actual physical model study tests and performing a more in-depth comparison between the CFD and physical model results. With this in mind, validation of the model is carried out using a two-phase approach:

- While the physical model is being constructed, the CFD model is being set up and used to replicate a known discharge condition for both a single sluice gate and a single spillway gate. The model results will then be compared to prototype observations to ensure a reasonable match.
- Once physical model test results are available, an additional series of tests will be performed to compare the CFD model results directly to physical model test results at physical model scale. These validation tests will be performed for a single operating bay (either sluiceway or spillway). The CFD model will first be translated into a model scale to ensure complete compatibility with the physical model results. Then both models will be run for an identical test. For the sluiceway, this will involve the

partial opening of a single sluice gate to provide a flow of 4,400 cfs. For the spillway, this will involve the operation of single spillway gate to discharge 10,300 cfs.

Once both models have been run, the TDG study team will conduct a more rigorous comparison between model results. This will include a comparison of:

- Downstream flow patterns and velocities
- Jet trajectory measurements
- Dimensions of jet impact area
- Qualitative observations of depth and extent of air entrainment

As required, pertinent CFD model parameters may be adjusted to achieve a better match with those of the physical model. Once a suitable match is obtained, both models will be rerun at a prototype scale to identify and document any scaling effects in moving to the larger prototype dimensions. These results will be compared to prototype observations to ensure a continued good fit between the CFD and prototype results.

Once a suitable match has been obtained and the models have been validated, the final model results will then form the “baseline” for operation of a single sluiceway and single spillway bay. These runs will form the baseline data against which the performance of other modifications can be compared.

Following completion of the baseline and validation runs, the models will be changed to include the operational and structural modifications proposed for potential TDG structural abatement at the sluiceway and spillway structures. The initial design for each will be based on concepts developed in the conceptual design report, but these will be modified as required to optimize overall hydraulic design. CFD analysis will be performed iteratively with the design team to test the performance of various concepts.

Initial runs will involve a single gate test developing into multiple spill and sluice gate tests as the study progresses. At the completion of each run, comparisons will be made with the baseline runs to determine the overall impacts on jet trajectory, impact area, and calculated air entrainment. These comparisons will be used to rank various alternative designs, in the search for an optimal solution.

It should also be noted that as a continued validation exercise, these CFD test results would also be compared with results emerging from the concurrent physical model study.

5.4.3.2.3. CFD Model Tasks Completed or in Progress

Model Development and Setup. The grid structure of the individual spillway and sluice models is being developed with a common overall coordinate system so that individual components can be easily joined in a larger model later. To ensure this compatibility between components, the following tasks were completed or are being completed in developing the model grids:

- Bathymetry and structure drawings were acquired in a common datum in three-dimensional CAD files that are compatible with the grid building software. These drawing are converted into appropriate digital files for import into the FLOW-3D software (refinement of model topography and bathymetry is challenging due to steep slopes) (see Figure 5.4-3).

- A rough overall model grid is being developed to be used as the framework for the nested detailed model grids.
- The individual nested (detailed) model grids of the sluices have been developed.
- The detailed model grid of the spillways will be developed.

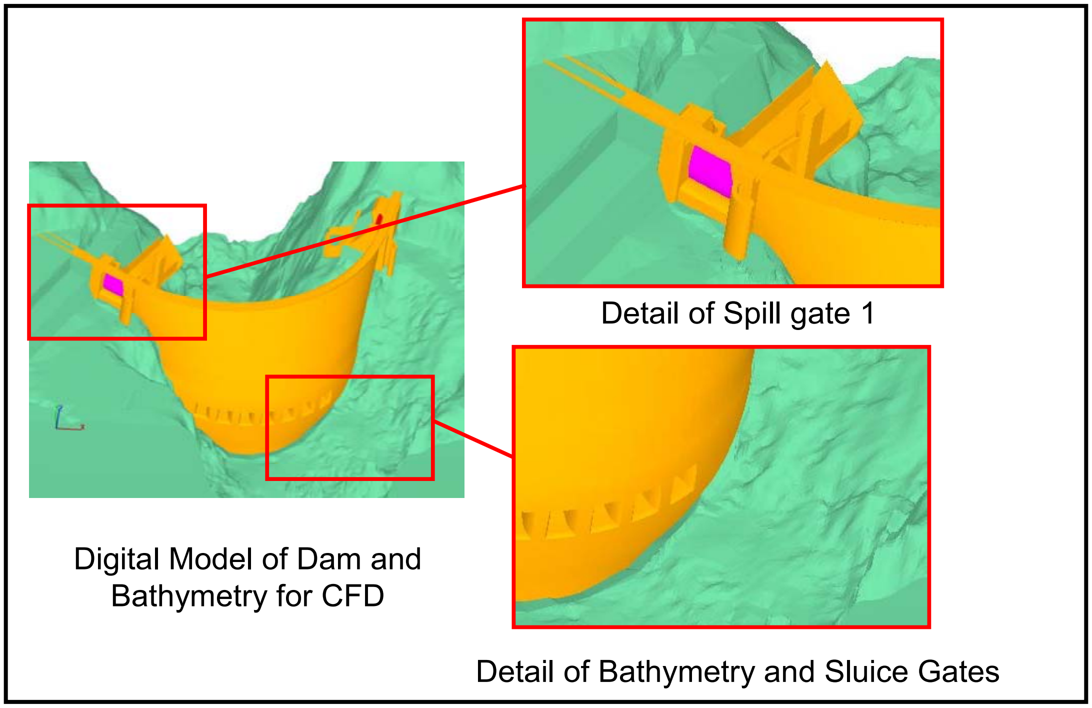


Figure 5.4-3. Views of digital model for CFD analysis.

Validation Tests. Validation tests of the sluice gate model have been initiated using available data. Near field validation tests include replication of a sluiceway field tests (FSL = 1986 feet, TWL = 1745 feet and sluiceway no. 4 open by 4 feet). Elements of comparison include comparison of jet width/length for 4-foot opening (see Figure 5.4-4), gate discharge comparisons, and examination of hydraulic effects gate guide (see Figure 5.4-5).

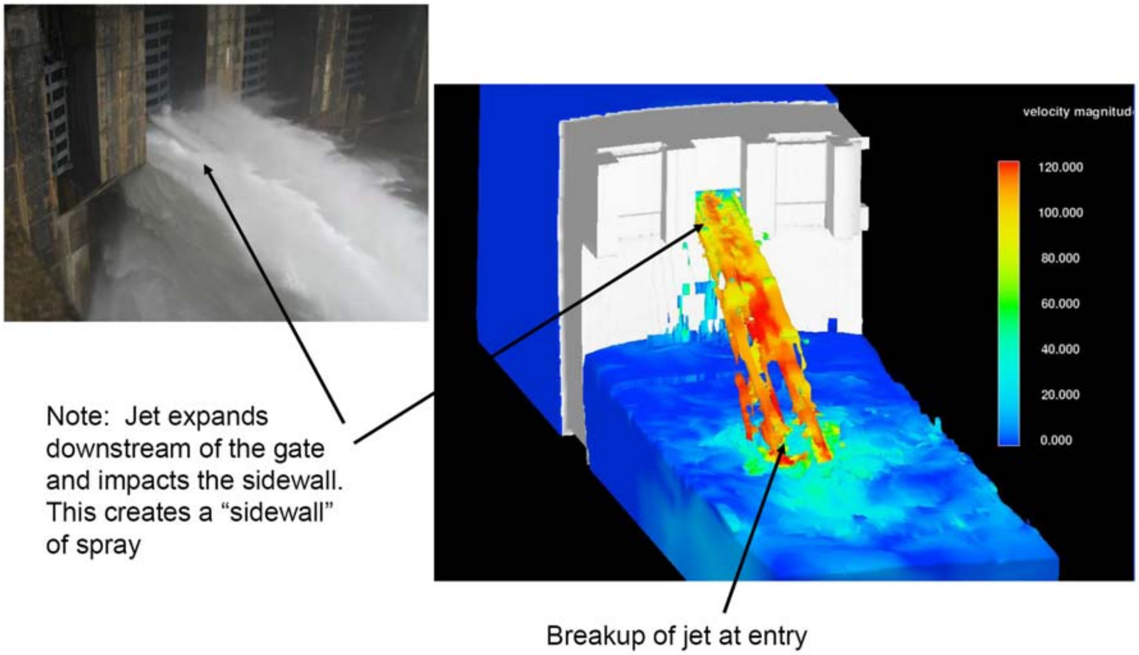
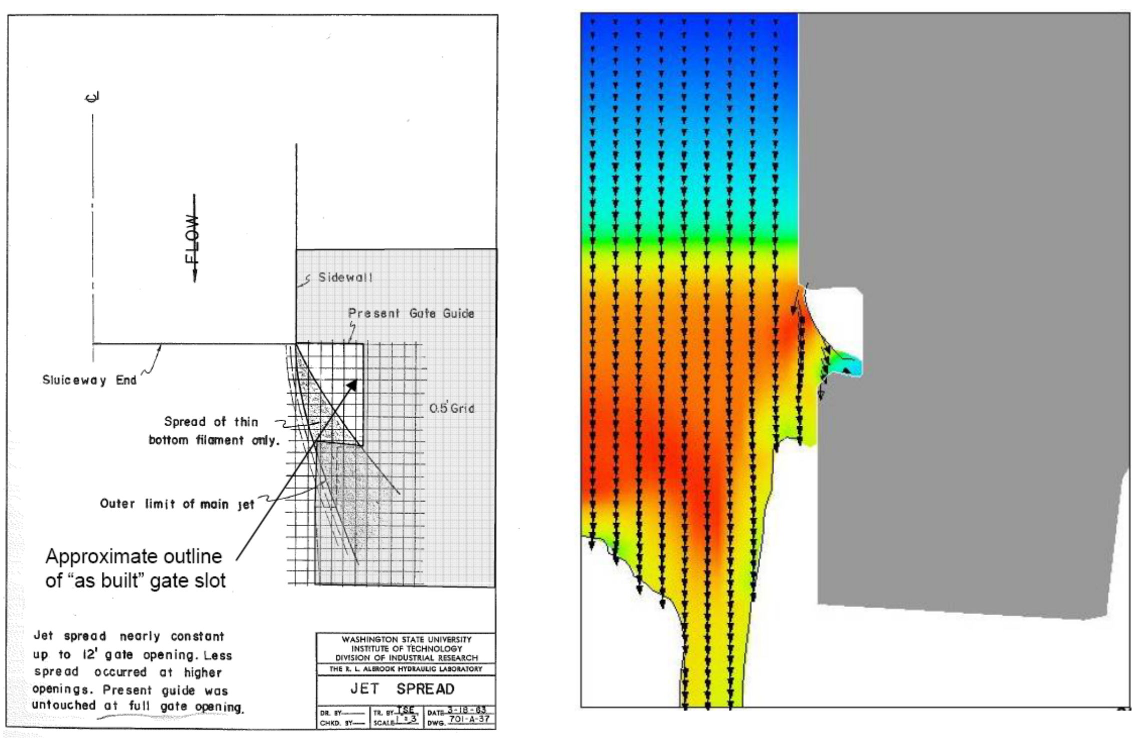


Figure 5.4-4. Validation tests of sluice gates—CFD analysis.



1963 Physical model study - Jet spread in gate slot

4 ft gate opening CFD model (velocity) jet spread in gate slot

Figure 5.4-5. Validation tests of sluice gate slots—CFD analysis vs. 1963 model study.

5.4.3.2.4. Future CFD Model Tasks

Future CFD model tasks will include the following:

- Spillway model grid development
- Near field spillway tests and validation tests versus field observations
- Validation tests of both sluice and spillway models versus the physical model
- Validation of the final far field model results versus field data
- Application of near and far field models to examine hydrodynamic performance of TDG mitigation alternatives

5.4.3.2.5. Development of TDG Predictive Model

In addition to predicting the transient flow field to aid in design of structural modifications, eventually the CFD model will be used to predict TDG. The CFD model simulation of TDG will involve four main steps:

1. Entrainment of air into the flowing water
2. Transfer of air into solution (TDG) as a function of pressure, temperature, and physical properties of air and water, and the turbulence that bubbles will experience
3. Transport of the TDG by the flow field
4. Transfer of excess TDG from the dissolved phase to the atmosphere

Though many commercial CFD software packages are currently available, none of the software packages has incorporated the source/sink terms necessary for simulating all the physical processes important to TDG.

One of the key components of the numerical modeling exercise will be the eventual application of these CFD models to help predict the final TDG performance associated with each of the proposed modifications.

At this time, the TDG study team proposes to adopt and compare two separate approaches to TDG simulation. The first is the most comprehensive and allows for the continuous computation of TDG directly within the FLOW-3D model, requiring some customization of the FLOW-3D software. The second approach involves application of the models in which TDG calculations were performed independently outside of the actual FLOW-3D code. It is proposed that both approaches be used and the results compared to provide a cross-check on predictions. Each approach is described in more detail below.

Approach 1—Direct Modeling of TDG. In 2009, the CFD models will be modified to predict the TDG contribution of the Project. Although not part of the immediate scope, this ultimate use of the models must be kept in mind in the development of the hydrodynamic and air entrainment and transport computational model.

Source/sink terms will be incorporated in the mass transport algorithm of FLOW-3D to simulate TDG. These source and sink terms represent the generation of TDG and also the escape of excess TDG at the free surface. FLOW-3D's existing capabilities will be utilized to determine the volume of entrained air, shear stress, and pressure in the water phase. The simulation of TDG within the water column will be accomplished by implementing the following steps:

1. Determine the number and size of air bubbles and their corresponding surface area in each computational cell as a function of shear stress and volume of entrained air.
2. Determine the transfer of air mass to the dissolved phase as a function of pressure, temperature, air/water interface area, and initial (background) TDG concentration.
3. Apply a boundary condition on the free surface to allow release of excess dissolved air into the atmosphere.
4. Utilize the existing transient Large Eddy Simulation (LES) capability of FLOW-3D to transport TDG throughout the flow field by solution of an advection-diffusion equation and simple "mass" transport.

Equations relating flow characteristics with the number and size of bubbles, transfer of air from bubbles to water, and release of dissolved gas into the atmosphere will be obtained from the work performed by Professor Gulliver and reported by Urban et al. (2008). Therefore, no new research work will be involved in developing source/sink terms. However, incorporation of these processes into a transient three-dimensional CFD model will represent significant improvements over currently available methods.

Approach 2—Use of Discrete Particle Tracking. The second approach proposed is considerably simpler in nature, and similar to a technique developed and used for studies of the Cabinet Gorge project to simulate TDG transfer. The technique provided reasonable estimates of TDG performance at Cabinet Gorge as compared to actual field data.

This technique involves the "sprinkling" of a representative number of history particles within the air-entraining area of the jets entering the tailwater. These particles are given a buoyancy equivalent to a standard air bubble, and then their position is tracked as they move throughout the computational domain. The CFD model tracks time, pressure, air entrainment fraction, and velocities experienced by these "bubbles" as they move through the mesh.

This CFD-computed information is then exported from the FLOW-3D model and imported into a special spreadsheet model developed by Professor Gulliver to estimate gas transfer. This spreadsheet estimates the amount of gas transfer that might occur for each bubble based on the pressure and velocity hydrographs experienced by each. The gas transfer associated with each bubble is then integrated to determine a total TDG percentage for the main flow field.

5.4.3.3. Physical Model

5.4.3.3.1. Study Goal

The goal of the physical model studies is to develop a model that will:

- Provide a tool that can be used to test various sluice and spill gate operational scenarios and visualize the resulting jet interactions, water surface impact areas, and subsurface flow conditions and mixing in the plunge pool (this operational testing can be more readily done and results interpreted more intuitively using a physical model than using a CFD model).

- Provide a basis for verification of CFD models of the project flow release structures.
- Model limits and scale.

5.4.3.3.2. Model Limits

To examine the interaction of flows from the spill and sluice gates, all must be included in the model, plus the plunge pool area and outlet. An appropriate downstream limit will be the necking of the channel at the right bank at the upstream end of the powerhouse. The forebay model will be developed to characterize approach flow to the spillway gates and outlets. Appendix 9, Figure A.9-1 illustrates the necessary model limits.

5.4.3.3.3. Physical Model Description

A model scale of 1:25 is the maximum that can be built within the vertical height constraints of the laboratory, while allowing the full plunge pool depth. This scale achieves Reynolds Numbers less than an order of magnitude less than the values suggested by the American Society for Civil Engineers for simulation of air entrainment by a deflected jet. As long as care is taken in the qualitative evaluation of air transport by the model convective velocities, this model should provide valuable insights into the hydrodynamics of the jet trajectories, interactions, and plunge pool action.

See Appendix 9 for drawings of the physical model.

5.4.3.3.4. Physical Model Tasks Completed or in Progress

The model construction includes the following elements:

- Steel head tank (completed).
- Acrylic dam, sluice, and spillway structures and gates (in progress).
- Fixed bed sand-cement bathymetry molded to templates (in progress) based on bathymetric data provided by SCL.
- Metered flow supply from a dedicated 20 cfs capacity pumping system in the laboratory sump. This flow system is capable of delivering flows to the model in excess of the simulated 53,300 cfs 7Q10 spill capacity requirement.

5.4.3.3.5. Future Physical Model Tasks

Performance Criteria

Relative performance of the varying operations and modifications of the outlets will be judged on the depth and amount of air entrainment and the distance downstream that entrained air is carried. Both entrainment and transport should be reduced by maximizing the surface area of jet impact.

Instrumentation and Data Collection

To a large degree, the relative performance will be judged on the basis of qualitative observations. However, there will be some quantifiable data collected as well. At a minimum, the following information will be collected for each test:

- Metered inflow using orifice flow meters in supply piping
- Flow through each outlet (sluice and spillway gate based on ratings for each developed in the model)
- Water levels and wave action using point gauges and capacitance wire probes
- Jet trajectories documented through point gauge measurements, photography, and video
- Jet impact zones on water surface through visual assessment, photography, and video
- Air entrainment through visual assessment, photography, and underwater video
- Selected velocities using acoustic Doppler velocimeters and miniature propeller current meters

Test Conditions

The leading TDG mitigation alternative combination described in the interim report to meet the 7Q10 spill flow capacity of 53,300 cfs was:

- Four sluices operating at partial gate openings at a discharge of 4,400 cfs each for a total of 17,200
- Three sluices with roughened discharges of 5,000 cfs each for a total of 15,000 cfs
- Two modified spillways with discharge capacities of approximately 10,000 cfs each for a total of 20,700 cfs

Table 5.4-1 shows a possible sequence of test conditions that would cover the range of flow up to the 7Q10 spill requirement using these flow increments. These test conditions would be employed in model testing at a minimum. Additional test conditions would be added on the basis of observations in the model.

Table 5.4-1. Possible model test conditions.

Test Condition No.	Simulated Flows (kcfs)											
	Spillway Gates		Sluice Gates							Total Spill Flow	Power-house Flow	Total River Flow
	1	2	1	2	3	4	5	6	7			
1						5				5	55	60
2					4.4		4.4			8.8	55	63.8
3				5		5		5		15	55	70
4			4.4		4.4		4.4		4.4	17.6	55	72.6
5	10.3		4.4	5	4.4		4.4		4.4	32.9	55	87.9
6	10.3	10.4	4.4		4.4		4.4		4.4	38.3	55	93.3
7	10.3	10.4	4.4	5	4.4		4.4		4.4	43.3	55	98.3
8	10.3	10.4	4.4	5	4.4		4.4	5	4.4	48.3	55	103.3
9	10.3	10.4	4.4	5	4.4	5	4.4	5	4.4	53.3	55	108.3

Note:
kcfs – thousand cubic feet per second

Structural Configurations

The structural configurations to be tested in the model include the following:

- Existing (to provide a baseline for comparison of modifications)
- Modified spillway gates (to provide greater aeration and dispersion of the flow)
- Roughened sluices (to provide better dispersion of flow)
- Other configurations suggested by test results

These configurations will be tested in an iterative manner to develop the best final configuration.

5.4.4. Estimate Fish Survival through Favored Alternatives

Estimates of fish survival through existing Project features were developed as part of the Early Information Development for the relicensing studies (R2 Resource Consultants 2006). The following text is taken from this source, with addition of comments on the expected qualitative changes to the original fish survival estimates due to modifications associated with the three favored TDG abatement alternatives.

The fish survival evaluation examines issues associated with fish passage through alternatives; however, risk is a product of consequence and probability. The sluice gates alternatives have relatively low risk because it is unlikely that many fish will be subjected to them. Few fish are likely to occur at the depth of the sluiceway intakes. Studies are currently underway by SCL to assess species composition and relative abundance of fish at depth in the forebay.

The risk of injury or mortality associated with fish passage through a dam is a function of consequence and probability. The hydraulic conditions that would be experienced by the fish during passage and upon reintroduction to the river in the tailrace are the consequence of fish passage. The probability reflects the expected numbers of fish subjected to the consequence. The following sections describe hydraulic conditions that could affect fish passing downstream through the Project facilities.

5.4.4.1. Conditions Potentially Damaging to Fish

Fish have been shown to experience injury or mortality when exposed to particular extreme hydraulic or physical conditions upon passage through hydroelectric facilities. These conditions include:

- Strike – Physically contacting solid structures at high velocity. This could include striking solid objects protruding into spillway or sluiceway passages, contacting the leading edge of turbine runner blades, or contacting rock upon reentry into the river downstream of the dam.
- Shear – Exposure to a transition zone of steep velocity gradient between two regions in a body of water that are moving at different velocities.
- Grinding – Getting caught between moving and stationary mechanical components of a turbine or gate.
- Turbulence – This is generally associated with downstream portion of passage where energy is dissipated through rapid mixing of flows, typical in and downstream of draft tubes, plunge pools, and stilling basins. Exposure to turbulent conditions can result in disorientation of the fish leaving them exposed to a greater risk of predation from larger fish or avian predators.
- Cavitation – In localized areas of extreme high velocities the effective water pressure can fall to well below atmospheric pressure and drive gas out of solution, forming small air bubbles in the flow. As these bubbles move back into more typical pressure zones they rapidly collapse which results in localized shock waves that can at times be strong enough to cause pitting in the steel blades of turbines.
- Pressure Changes – Rapid pressure changes typical in passage through turbines can result in bursting of the swim bladder or blood embolisms. Some species of fish are more susceptible to these effects than others due to their physiology, with salmonids being more resistant to problems associated with pressure changes than are perch or bass, for example. The rapid change in pressure due to cavitation seems to be the primary cause of fish mortality when passing through a turbine.
- Dissolved Gas Levels – The presence of supersaturated TDG levels, can be a biological concern for any species living in the river, not just those that pass through the Project, due to potential for gas bubble trauma, where the gas comes out of solution and forms bubbles in the tissues of the organism when the organism enters a region of lower pressure.

5.4.4.2. Spillways

5.4.4.2.1. Existing Spillways

Of the seven potentially damaging conditions listed in above, the two that are major considerations associated with existing Project spillways are shear and strike. Damaging shear occurs when the plunging spill flow enters the tailrace and there is a substantial difference in velocities where the plunging jet enters the more quiescent tailrace. Strike can occur if the spill flow comes in contact at high velocity with projections within the spillway chute, or with rock along the bank or the bottom of the plunge pool. Although the flip bucket at the end of the Spillway 1 chute represents a projection into the flow path it is well rounded and the flow should generally follow the shape of the chute floor without producing damaging strike potential. No projections are readily apparent within the chute of Spillway 2. A secondary consideration may be gas bubble trauma. Gas bubble trauma may result from local TDG levels that may reach as high as 140 to 150 percent saturation at the water surface. However, the relative gas saturation level decreases approximately 10 percent for each meter of depth attained, so as long as average flow depths of 12 to 15 feet below the water surface are available in the immediate tailrace area and downstream, the likelihood of injury due to gas bubble trauma is reduced.

Turbulence in the tailrace for the fish that survive the plunge could be a concern because the fish are likely to be initially disoriented upon entry into the tailrace and less likely to avoid predators; however, the extent to which predators are present in the Boundary tailrace is poorly understood, although studies are currently underway by SCL to develop a more thorough assessment of fish species composition in the tailrace. Please refer to the Study 9, Fish Distribution, Timing, and Abundance Study Final Report (SCL 2009), for a more complete discussion of the current fish abundance studies in the Boundary tailrace.

The greatest impact on fish passing through spill would be expected to occur upon entrance of the plunging flow into the tailrace.

A major factor to consider when applying the laboratory shear study results to real world spillways is the size and shape of the discharge jet. Typical field results show greater mortality for small magnitude spills and reduced mortality with larger spill flows since the zone of high shear around the periphery of the jet occupies a larger percent of the jet area for the smaller spill flow magnitude. Another factor is the dissipation of the jet as it passes through the air in its trajectory to the plunge pool. The more the jet breaks up and becomes aerated and less coherent, the greater the percentage of the fish that will leave the jet and freefall into the tailrace. Smaller fish are relatively resistant to the effects of a freefall into water, and were commonly stocked in alpine lakes by being dropped from planes or helicopters. However, larger fish (above 300 mm) experience higher rates of mortality when freefalling from the height of the Boundary spillway discharges (R2 Resource Consultants 1998). Therefore, larger fish are likely to fare better if they stay in the jet, as long as the jet flow cross-sectional area is large enough to contain them in the jet core where they will not be exposed to high shear stresses, whereas smaller fish would fare better if they fully leave the jet and freefall into the tailrace.

Based on the review of previous studies at other projects and laboratory studies concerning the effects of shear forces on fish, the following assumptions are made concerning the impact on fish of passing through the spill flow at the Project:

1. Relatively low spill flow rates, but high enough that the majority of the flow reaches the plunge pool: The assumption here is that roughly half the jet is broken up before reaching the tailrace, and half the fish leave the flow and freefall in air to the tailrace. In this case the small fish (approximately 100 mm) are estimated to experience an

overall 60 to 70 percent mortality rate. Small fish that remain in the jet experience near 100 percent mortality due to exposure to shear, while small fish that leave the jet and freefall to the tailrace experience low mortality. The larger salmonids (approximately 600 mm) might experience similar or slightly smaller mortality rates of 40 to 50 percent but for the opposite reasons, with the fish that leave the jet experiencing very high mortality and those that remain in the jet fairing better due to a greater resistance to shear forces. Likelihood of exposure to gas bubble trauma is reduced at these flows as the local TDG levels in the tailrace are not as high.

2. Larger spill flows where the large majority of the flow remains in a coherent jet to the tailrace: Assuming the fish do not impact the bottom of the plunge pool, the major source of mortality would be due to the shear effects on fish near the periphery of the jet. The greater the magnitude of the spill the more likely the fish will be in the body of the flow and not exposed to the peripheral shear effects so there is a range of mortality probability, with decreasing estimated mortality associated with increasing spill flow rates. For smaller fish this range is estimated to be about 50 to 80 percent, similar to the results of field studies at Upper Baker Dam, whereas for larger fish the mortality could be as low as 20 to 40 percent. Large spill flows that increase local TDG levels are the primary concern for injury through the gas bubble trauma process.

It needs to be qualified that these are just estimates based on field studies at other sites, laboratory tests of the effect of shear, looking at the spillway with no spill flow during a site visit, drawings of the spillway shape, and photographs of the spill flow. No actual field studies estimating mortality have been performed at the Project. Results of spillway mortality field studies have varied and do not always correspond to what one might expect to find. There tend to be individual features of the spillways, stilling basins, and plunge pools at each project that complicate a predictive model. Therefore, actual mortality rates for fish passing through the Boundary spillway cannot be known without actually performing field tests at the spillway.

The flip bucket on the end of the spillway tends to lift and spread out the flow from Spillway 1 more than is the case for Spillway 2. This tends to break up the flow and drive more of the flow, and presumably a greater percentage of the fish, out of the main jet and into a freefall condition, which should be slightly better for smaller fish and slightly worse for larger fish than is the case for Spillway 2. This flow dynamic will also tend to reduce TDG levels.

5.4.4.2.2. Spillways After Modifications

Fish passage mortality associated with the proposed Spillway Flow Splitter/Aerator (No. 2-8) options are discussed below:

Option 1: Addition of a Deflector Device—The deflectors will behave similarly to the flip bucket on the end of Spillway 1 and will tend to break up the jet, which should be slightly better for smaller fish and slightly worse for larger fish as compared to existing conditions. The deflector design would be developed such that flow is directed into the plunge pool and not onto rock abutments.

Option 2: Aeration of Chute—Aeration may increase turbulence and could potentially lead to increased probability of strike; it may also increase the shear damage on a fish.

Option 3: Increase Turbulence in Flow—Roughening elements on the spillway or obstructions on the gate's toe increase turbulence may cause some marginal increase to the strike potential for fish passing through the spillway; however, the shear will by definition be increased.

All of the proposed modifications are intended to reduce TDG and therefore reduce the risk of gas bubble trauma.

5.4.4.3. Sluiceways

5.4.4.3.1. Existing Sluiceways

Boundary Dam includes seven sluiceways located at about mid-height of the dam that discharge into the plunge pool below the dam. The sluiceways are generally used to supplement the spill flow during extreme high-flow events. The sluiceways are submerged on the upstream side of the dam and are rectangular in shape, with a reducing area in the downstream direction through the dam. At the discharge end, on the downstream face of the dam, the sluiceways are 21 feet high by 17 feet wide. The flow capacity of each of the seven sluiceways is approximately 35,000 cfs with the forebay at 1,994 feet NAVD 88 (1,990 feet NGVD 29) (normal maximum water surface elevation). The invert of the sluiceway outlet is at elevation 1,795.5 feet NAVD 88 (1,791.5 feet NGVD 29). The sluiceways are controlled by gates on the downstream discharge end.

The flow exiting the sluiceways should be fairly well confined as a jet, and the jet should remain fairly well confined all the way to the tailwater. This will result in a greater percentage of the entrained fish remaining in the body of the flow and not exposed to the shear conditions of the periphery as the jet enters the tailwater.

The mortality of entrained fish in the sluiceway flow should be lower than is estimated for the spill flow assuming the same magnitude of flow.

Although no studies have been performed to investigate the actual mortality rates for fish passing through the sluiceways at Boundary Dam, the conditions would seem to imply that mortality should be somewhat lower than for the spillways. It is estimated that if alternate sluiceways are used, the jets should plunge into the tailrace before they would come in contact with each other. This would reduce potential for mutual interference and break-up of the jets and would seem to be a better condition for entrained fish if multiple sluiceways need to be used. It also should be noted that sluiceways are deep and few fish are expected to be present at that depth.

5.4.4.3.2. Sluiceways After Modifications

Two of the favored alternatives include modifications to the sluiceways: Throttle Sluice Gates (No. 1-3) and Roughen Sluice Flow (No. 3-2). For both options there are expected to be operational changes that will allow the gates to operate in a throttled position (gate partly opened). The Roughen Sluice Flow (No. 3-2) alternative includes deflectors to redirect the flow. The anticipated effects are described below:

Throttled Sluiceway Flow—Throttled flow will increase the shear surface between the jet and the air. It will also reduce the impact of the jet on the plunge pool surface. The combined effect of these two conditions on fish is difficult to predict.

Sluiceway Deflectors—The deflectors will behave similarly to the flip bucket on the Spillway and tend to break up the jet, which should be slightly better for smaller fish and slightly worse for larger fish. The presence of the deflectors may also increase the strike potential; however, the shape will be hydraulically designed to avoid intrusion into the flow.

5.4.4.4. Summary

Table 5.4-2 shows the original R2 Resource Consultants fish mortality predictions (R2 Resource Consultants 2006) for the spillway and sluiceway with the expected qualitative effect of the TDG abatement modifications.

Table 5.4-2. Fish survival estimate.

Passage Route	**Range of Estimated Mortality by Fish Length**			**Comments**
	100 mm	**250 mm**	**600 mm**	
Existing Spillways (R2 Resource Consultants 2006)	**50–80%**	**35–65%**	**20–50%**	• **Depends on spill flow rate** • **Spillway 1 better for smaller fish** • **Spillway 2 better for larger fish**
Added Spillways Deflectors	Better	Difficult to predict	Worse	• Increase Strike Potential • Increase flow dispersal • Broken, less coherent jet
Added Spillways Aerators	Better	Difficult to predict	Worse	• May increase turbulence • Increase flow dispersal • Broken, less coherent jet
Added Spillways Roughness	Marginally worse	Marginally worse	Marginally worse	• Marginal increase in strike potential

Table 5.4-2, continued…

Passage Route	Range of Estimated Mortality by Fish Length			Comments
	100 mm	250 mm	600 mm	
Existing Sluiceways (R2 Resource Consultants 2006)	**40–70%**	**25–55%**	**10–40%**	• **Speculative based on assumed reduction from spill estimates** • **Assumes adjacent sluiceways are not operated simultaneously**
Throttled Sluice Operation	Difficult to predict, expect slightly better for small fish	Difficult to predict	Difficult to predict expect slightly worse for large fish	• Operation in throttled condition assumed to increase shear surface • Jet impact reduced due to lower flow volume and increased dispersal, more broken, slightly less coherent jet
Roughened Sluiceway (deflectors)s	Better	Difficult to predict	Worse	• Effects of roughened flow is similar to deflectors on the spillway • Broken, less coherent jet

The estimated fish survival through the new favored alternatives can be generalized as focused on spreading the spill flow over the area of the existing plunge pool. As such, they are somewhat better for small fish and worse for large fish.

It should be noted that the analysis has been conducted without consideration of the abundance of fish during expected spill and the distribution of fish with depth adjacent to the reservoir, so the numbers of fish likely to be entrained and their size distribution for the various alternatives is absent from the estimate.

5.4.5. Assess Flow Interactions During Major Flood

There are no anticipated water level changes with the favored alternatives during major floods because the function and interaction between the spill gates and sluice gates and powerhouse are not expected to change.

5.4.6. Assess Effects on Powerhouse Operations

There are no anticipated effects on existing Project powerhouse operation with the favored alternatives.

5.4.7. Turbine Air Admission

This section presents existing understanding of issues associated with air admission and high TDG levels associated with operation of Units 55 and 56, potential modifications that may improve the situation, suggested investigations, and recommendations for mitigation. The task was completed using available information and industry standards without any additional field data acquisition or site visits.

5.4.7.1. Air Admission Background

At certain times TDG levels in the river downstream of the Project exceed state standards. It has been determined that air admission through the Francis turbines at the Boundary powerhouse is a primary cause of the excessive gas levels. A review of the turbine operating conditions and air admission characteristics has been made, including methods and controls to minimize air admission with the aim to reducing TDG levels. This section presents the results of the evaluation.

Boundary powerhouse contains six generating units numbered 51 to 56 that operate at a nominal gross head of 252 feet. The Project began operation in 1967.

The turbines are vertical shaft Francis type, with spiral cases and elbow draft tubes. Units 51 to 54 were part of the original installation and manufactured by Nohab. These units were upgraded in the late 1990s with new runners designed and supplied by Noel (now Andino). Each of these four units has a maximum output of approximately 170 MW.

Units 55 and 56 are newer units manufactured by Toshiba, and installed in the 1986. These units each have a maximum power of 200 MW.

To minimize the effects of rough operation the Units 55 and 56 turbines require air admission when the output of the units is less than approximately 125 MW. Rough operation of Francis turbines at low to medium loads is a common phenomenon, and one method of mitigating the effect of rough operation is aspiration or injection of air into the draft tube. Air admission is often via air valves in the turbine head cover and vent holes in the runner crown, or through the center bore of the shaft.

Units 51 to 54 also have air vents for admission of air into the draft tubes. However, it has been found that with the new runners installed as part of the upgrade air is no longer required. Therefore, the air admission valves on Units 51 to 54 are now closed at all power levels.

Previous site tests have definitively shown that air admission into the turbine draft tubes increases TDG levels. Tests are documented in two reports by Columbia Basin Environmental:

- Boundary Dam Total Dissolved Gas Study, June 23 to July 23, 2000 (CBE 2000)
- Boundary Dam Total Dissolved Gas Study, September 24 to September 25, 2001 (CBE 2002)

There are also internal SCL memoranda discussing dissolved gas measurements in September 2003 (SCL 2003a and 2003b).

The basic problem is that water in the Boundary Reservoir upstream of the powerhouse is often at 100 percent saturation, and admission of air into the runner and draft tube moves the TDG to the supersaturated levels. Water quality standards require that the TDG not exceed 110 percent saturation. This level is exceeded when there is air admission into the Unit 55 or 56 turbines.

Turbine air admission only occurs when Units 55 or 56 are operated below 125 MW load (i.e., below 62.5 percent full load). The units can operate above this load without a material impact on the load following capabilities of the facility. Furthermore, below 125 MW the turbines are at less than optimum efficiency and would not typically be operated in this regime even without the TDG issues. The main concern with excessive TDG levels is during turbine startup and shutdown. The effect on startup is less pronounced than shutdown, as on startup the subsequent operation of the unit at higher loads where there is no air admission tends to dilute the high TDG water. On shutdown, if there are no other units remaining in operation, the water with high TDG levels remains in the tailrace until the next time a unit is started and flushes out the “stagnant” water. The unit startup and shutdown times are approximately 30 minutes (each way).

To minimize the effect of air admission of TDG levels in the tailrace, the current operating policy is:

- Do not continually operate Units 55 and 56 below 125 MW.
- To ensure flushing of tailrace water with high TDG levels, operate Units 55 and 56 as “last on” and “first off.”

5.4.7.2. Effect of Air Injection on TDG

The effect of the open air valves on TDG is shown on Figure 5.4-6. These data are from the 2002 report by Columbia Basin Environmental. Turbine air valve flow and water flow are also shown in the figure. These data are from SCL and were taken at different times. The water flow is approximate based on the power level and estimated turbine efficiency. Although the data are from different sources and may not be directly comparable, they do provide an indication of the relationship between air flow, water flow, and TDG.

The actual TDG in the tailrace is less than in the gate slot due to additional degassing that occurs after the water leaves the turbine draft tube. From measurements documented by Columbia Basin Environmental (2002), it appears that TDG levels in the tailrace are roughly 85 percent of those in the draft tube.

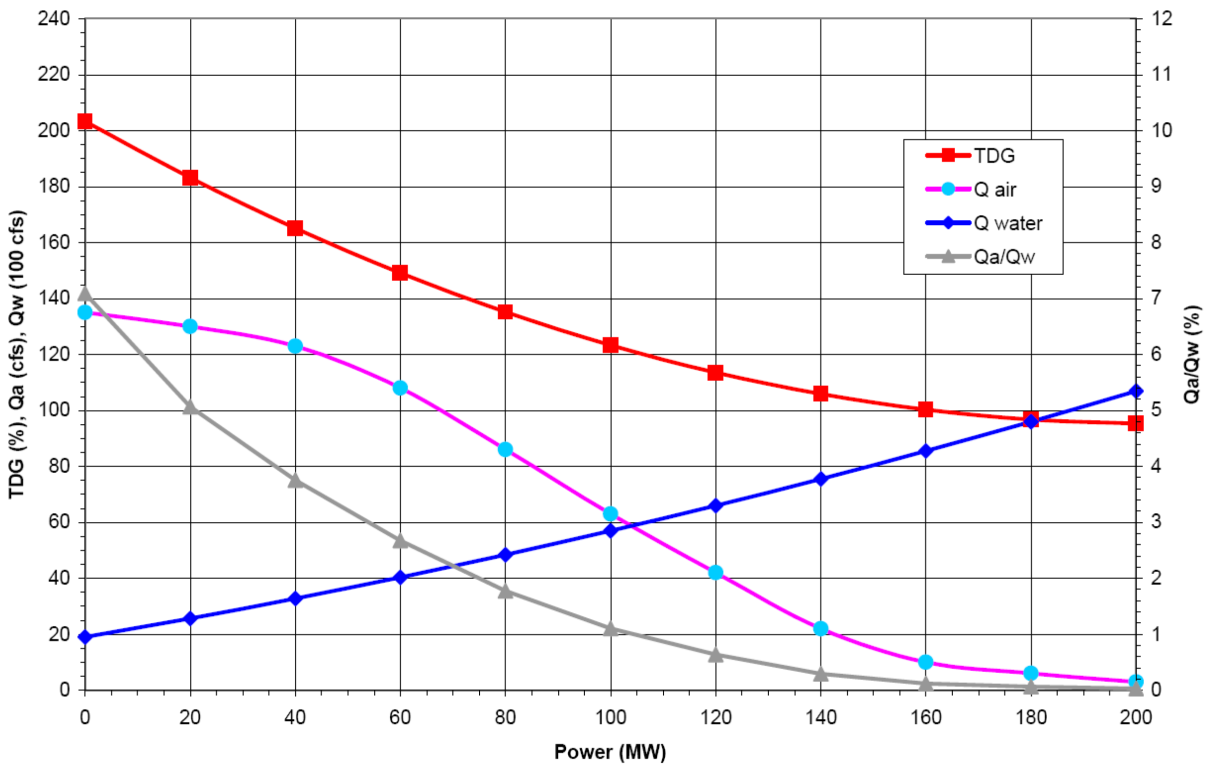


Figure 5.4-6. Boundary Units 55 and 56 air admission and TDG.

5.4.7.3. Requirement for Air Admission

As mentioned in Section 5.4.7.2, the air admission is required to reduce the turbine rough operation at part load. Table 5.4-3 presents site observations (made by Daniel Kirschbaum of SCL) on Unit 56 that provide a good assessment of the turbine with and without air admission.

Table 5.4-3. Comparison of unit operation with air valves open and closed.

Power (MW)	Air Valves Open		Air Valves Closed	
	Draft Tube Pressure (psi)	**Observations**	**Draft Tube Pressure (psi)**	**Observations**
200	10	Steady	10	Steady; slightly more noise
150	10	Steady	11 – 20	Noise level slightly lower than at 200 MW
100	13 – 22	Quieter; slow swishing sound	13 – 23	Loud cavitation noise (cement mixer)
50	12 – 18	Louder roar gone; still hear “gravel” going through the machine	13 – 18	Even louder than at 100 MW; very bad cavitation noise; roar
0 (SNL)	15 – 18	Very quiet	14 – 17	Cavitation like crazy

From the summary above a few comments can be made:

- The air admission does smooth out the unit operation, and is judged to be essential at low loads.
- The noise that is heard is likely a combination of cavitation and a vortex that forms below the runner at part load. The frequency of the vortex is generally 30 to 45 percent of the rotational speed of the unit. Certainly the “swishing” and the “cement mixer” would be the sound of the draft tube vortex moving past the draft tube door. At lower loads the cavitation noise is presumed to be due to inter-blade vortices streaming down from the leading edge of the blade near the crown down along the draft tube liner.
- The air injection does little to reduce variations in the draft tube pressure below the runner. This is consistent with observations on other turbines.
- The phenomena described are sources of rough operation but, in spite of their severity, would not necessarily be a cause of cavitation damage to the runner or other parts of the turbine. The noise at 100 MW would likely not be a source of cavitation damage. Air admission to Francis turbines is common, but is more often done to avoid unacceptably rough operation than to prevent cavitation damage, particularly when the situation is transient in nature (i.e., startup and shutdown)
- Even if the audible cavitation is not a source of cavitation pitting, the air admission is still beneficial in reducing rough operation. Rough operation is also associated with power swings that are detrimental to the electrical system.

5.4.7.4. Reducing TDG by Modifying Method of Operation

TDG reaches super-saturation levels when the air is being admitted into the turbine draft tubes below the runner. Air admission is required only on Unit 55 and 56 and only when these units are at or below 125 MW power. As mentioned in Section 5.4.7.2, the occurrence of elevated TDG levels has been minimized by operating above 125 MW and also operating Units 55 and 56 on a “last on, first off” basis.

With the above operating rules, TDG becomes a problem only when starting up or shutting down the units. The TDG could be further minimized by starting or shutting down the units more rapidly. Start-up and shut-down times are reported to be 30 minutes. From a machine condition point of view it should be possible to start up or shut down in 5 minutes or less, which would imply a six-fold reduction in the volume of air admitted into the draft tube. However, there may be flow ramping issues that limit the rate by which the units can be loaded or unloaded.

Ramping issues could possibly be overcome by decreasing load on one of the Unit 51 to 54 turbines simultaneous with startup of Unit 55 or 56. A similar but reverse process would be used for shutdown. Units 55 and 56 would have to become the second-to-last shutoff if the scenario is to be satisfactory. A possible loading and unloading sequence is shown in Table 5.4-4.

Table 5.4-4. Operation modification that may modify TDG performance.

Present Operating Conditions		Modified Operating Conditions	
Activity	**Load Change**	**Activity**	**Load Change**
A. Startup		**A. Startup (Figure 5.4-7)**	
Load Unit 51 to 150 MW at a rate of 9 MW/min	9 MW/min	Load Unit 51 to 150 MW at a rate of 9 MW/min	9 MW/min
Load Unit 55 to 250 MW at 9 MW per min	9 MW/min	Load Unit 55 to 125 MW at a rate of 25 MW/min, and simultaneously reduce Unit 51 load to 70 MW at a rate of 16 MW/min	9 MW/min
		Load Unit 55 to 250 MW at a rate of 9 MW/min	9 MW/min
		Load Unit 51 to 150 MW at a rate of 9 MW/min	9 MW/min
B. Shutdown		**B. Shutdown (Figure 5.4-8)**	
Reduce Unit 55 load to zero at rate of 9 MW/min	9 MW/min	Reduce Unit 51 load to 50 MW at a rate of 9 MW/min	9 MW/min
Reduce Unit 51 load to zero at rate of 9 MW/min	9 MW/min	Reduce Unit 55 load to 125 MW at a rate of 9 MW/min	9 MW/min
		Reduce Unit 55 load to zero at a rate of 25 MW/min, and simultaneously load Unit 51 to 130 MW at a rate of 25 MW/min	9 MW/min
		Reduce Unit 51 load to zero at a rate of 9 MW/min	9 MW/min

The modified operating scenario is more complex; however, it would be possible with automatic ramping controls through SCADA. There would be some added wear and tear on Units 51 to 54 that would have to be considered with such an operating scenario.

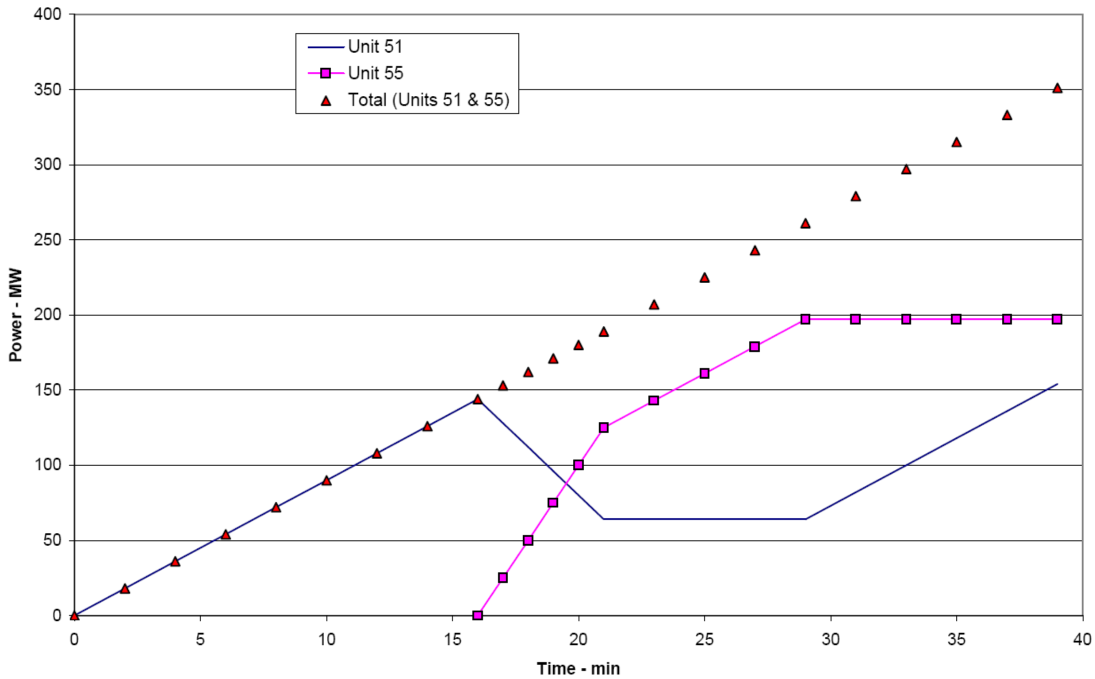


Figure 5.4-7. Loading of Units 55 and 56.

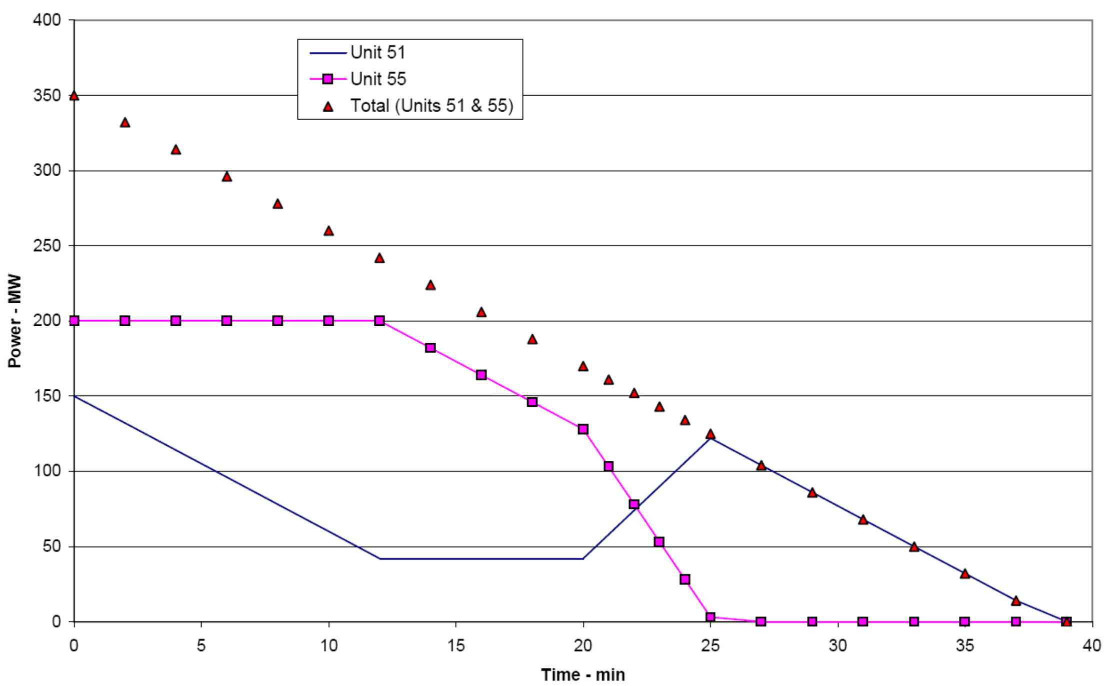


Figure 5.4-8. Unloading of Units 55 and 56**.**

5.4.7.5. Reducing TDG by Reducing the Amount of Air Admission

It should be possible to reduce the amount of air admission during a particular machine startup or shutdown. Options are discussed below.

1. Partially close the air valves to reduce the amount of air admission:

   Figure 5.4-6 shows that the air to water ratio varies from approximately 7 percent at speed-no-load to 0.6 percent at 125 MW. Tests on other turbines have shown that turbine operation can be made much smoother with air to water ratios in the order of 0.3 percent. The reduced air-to-water flow would reduce the TDG levels.

   This could be confirmed by site tests. For any tests, efforts should be made to obtain a quantitative measure of roughness. Examples of measurements are shaft runout, head cover (bearing housing) vibration, draft tube door vibration, noise level in the turbine pit, and noise level at the draft tube door. The turbine tests should include power output and penstock pressure and rotational speed, the gate opening.

2. Reduce the range of gate openings over which the air valves operate:

   Although air admission requirements are often specific to the turbine design, it is typically applied at the 30 to 65 percent gate range to minimize rough operation. At low gate openings air is often not necessary even if it does reduce the amount of cavitation noise at the draft tube door. As mentioned in Section 5.4.6.4, for a start-up and shut-down operation cavitation damage is often not a consideration, and cavitation noise at the draft tube door is not necessarily evidence that cavitation damage is occurring.

   A site test, as described in above, could be made to assess the gate range for air admission. Admittedly, the absence of cavitation damage can only be confirmed through longer term operation and dewatered inspection of the turbine. There are cavitation monitoring devices, but they are largely still experimental in nature when it comes to determining actual cavitation damage.

3. More rapid startup and shutdown of the units.

5.4.7.6. Eliminating Air Admission

There are options for eliminating the requirement for air admission to Units 55 and 56. These are discussed below.

1. Draft Tube Fins

   Fins welded to the side of the draft tube liner are an alternative to air admission for reducing turbine rough operation. A typical arrangement is shown in Figure 5.4-9. However, the concept has generally been avoided in modern turbines because the fins often have a negative effect on turbine efficiency. Cavitation damage to the draft tube liner in the area of the fins can also be an issue.

Such an option would be relatively expensive to implement even on a trial basis, and would be experimental in nature without site or model testing.

2. Cylindrical Extension to the Runner Cone

   On some turbines a cylindrical extension to the runner cone has been shown to effectively confine the vortex that forms below the runner at part load, and reduce rough operation. The concept is shown in Figure 5.4-9.

   Like the draft tube fins, such an option would be relatively expensive to implement and would be experimental in nature. The effect on efficiency would have to be assessed through site testing.

3. New Turbine Runners

   When Units 51 to 54 were upgraded with new runners, it was found that there was no longer a requirement for air admission. It is possible that a new runner design for Units 55 and 56 would also eliminate the need for air admission.

   This is a very costly option. However, it could be considered if the current turbines require a major overhaul for life extension reasons, or if a significant improvement in performance would be possible with a new runner design.

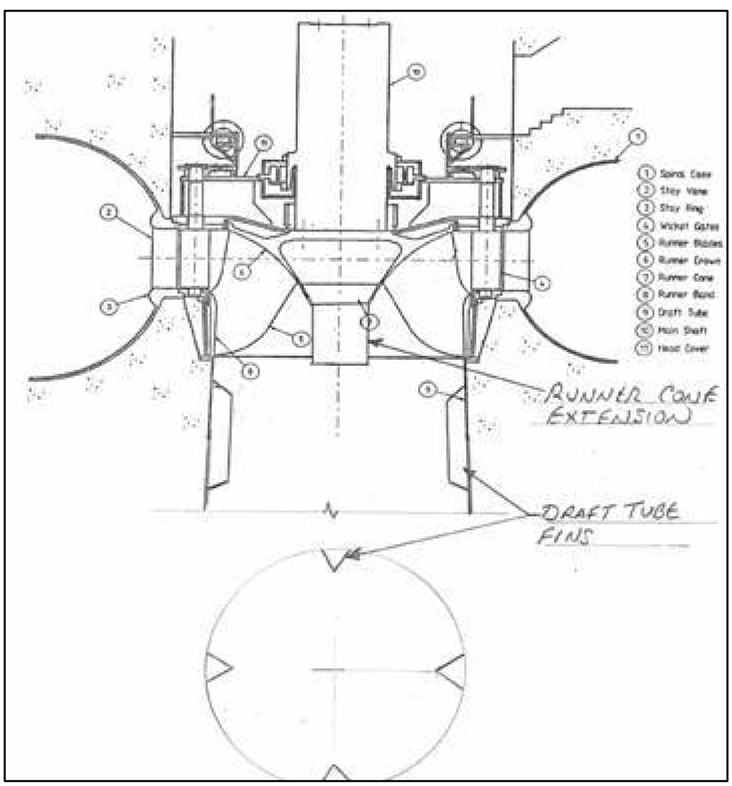


Figure 5.4-9. Concept sketch of draft tube fins.

5.4.7.7. Conclusions on Air Admission Issues

Admission of air into the turbine draft tube through the runner is a source of elevated TDG levels in the tailrace. The problem is limited to Units 55 and 56 because the other four turbines can be operated with their air valves closed. The high TDG levels have been minimized by operating Units 55 and 56 on a “last on” and “first off” basis and also by operating these units above 125 MW except during startup and shutdown.

Although the issue has been largely addressed by changes in operation, the effect of Units 55 and 56 on TDG levels can be further reduced by:

- Faster startup and shutdown of the turbines;
- Limiting the air flow rate; and/or
- Limiting the range over which air is admitted into the draft tube.

The latter two options would require site tests to assess any proposed changes.

It may be possible to completely eliminate air admission requirements by:

- Addition of draft tube fins
- Addition of a runner cone extension
- New runner design

The fins and runner cone extension would be experimental in nature, could reduce efficiency, and would be costly to test. A new runner would have major cost implications. Considering the effectiveness of the operational changes, implementation of any of these measures would not be warranted based on the current level of TDG increase due to air admission at the Project.

6 CONCLUSIONS

6.1. Existing Data and Reports

Existing reports and documents in the Project TDG reference library can be placed in the following categories:

- Scientific background on TDG production and conditions that cause TDG production
- Studies specific to the Project that document existing conditions and effects of modifications to operational procedures
- TDG field studies and documentation of TDG abatement at other projects

Previously performed TDG testing provided some guidance as to Project TDG performance during existing Project operation and during some spill events. There was limited testing during spill events and using sluice gates.

Many projects along the Columbia River have undergone structural modifications for addressing TDG. Most of these modifications have involved adding deflectors to spillways. However, these projects have spillway configurations with high flows and a smaller plunge that are substantially different from the Project.

These existing documents provide background on the conditions that cause TDG at the Project and provide some guidance on the factors that lead to high TDG levels, but provide only limited guidance on methods of reducing TDG through structural modifications to the Project.

6.2. Summary of Retrospective Analysis of Historical TDG Data

The following sections summarize the conclusions from the analysis of the historical long-term TDG data and short-term TDG data.

6.2.1. Historical Data

Comprehensive long- and short-term databases were developed for Project TDG and operations for 1999 through 2005 in support of the historical TDG data analysis objectives. The databases were analyzed to observe annual trends, describe Project hydrology and TDG trends for each year, and document the impacts of upstream project operations on incoming forebay TDG. The following conclusions were drawn from the 1999–2005 TDG long-term data analysis:

- Project forebay TDG was found to be closely linked to upstream project operations at Box Canyon and Albeni Falls dams.
- The TDG study team developed a predictive equation for Project forebay TDG as a function of Box Canyon Dam tailrace flow. Obtaining available TDG data in the Box Canyon tailrace is recommended to develop a correlation between Box Canyon tailrace TDG and Project forebay TDG.
- An improvement was observed in Boundary Dam tailrace TDG variability in the long-term database in September 2003, likely from improved Project operations for preventing air admission at Units 55 and 56.
- Predictive equations were developed for TDG production by powerhouse operations prior to September 2003 and after September 2003. The equations demonstrate the impact of the powerhouse on tailrace TDG before and after the Unit 55 and 56 operational change.
- Over the long-term database period from 1999 to 2005, spill occurred only 4.4 percent of the hours for which data are available. In 2002, spill occurred slightly more frequently, 11.8 percent of the hours with data for 2002, with the majority of the spill flows in 2002 above 15,000 cfs.

6.2.2. Short-Term Data

See Section 5.1 in Appendix 4 for discussion.

6.3. Field Studies

6.3.1. Summary of 2007 and 2008 Field Studies

In 2007 two different types of field data were collected in support of the TDG studies: 1) hydrodynamic data for use in calibration of future hydrodynamic models of the Project tailrace and 2) TDG data to provide further insights into the effects of spill operations on TDG production.

The hydrodynamic data consisted of water surface profile measurements from three gauges along either bank of the tailrace and velocity measurements at 11 fixed stations on three transects in the tailrace at varying distances downstream from the powerhouse. The hydrodynamic data were acquired for two different flow conditions: a low flow of approximately 33,600 cfs total river flow that occurred on June 20, 2007, and during which Units 52 through 56 operated with no spill; and a high flow of approximately 53,500 cfs total river flow that occurred on June 13, 2007, and during which all units operated and 4,900 cfs spill passed through spillway Bay 1. The hydrodynamic data were reduced to engineering units and archived for future use. Summary plots of both water surface profiles and the average velocity vectors were prepared and are included in this report.

TDG data were acquired using a total of nine meters. One was installed on the forebay trashrack, four on a transect just downstream of the extent of the frothy gas transfer zone downstream from the powerhouse, three on a transect at the location of the USGS tailrace fixed monitoring station, and one below a riffle in the river channel just across the Canadian border. Data were recorded by these instruments from April 27 through July 26, 2007. During the instrument deployment, a playbook of desired test conditions was employed by SCL staff in establishing Project powerhouse and spill operations that would be compatible with river flows and provide supplementary data on the effect of spill operations on TDG production. The TDG data were reviewed, reduced to total gas saturation percentages at atmospheric pressure, and combined with powerhouse operations data into a comprehensive database. A total of 13 distinct spill test conditions that met the criterion of being maintained for the 4 hours required to achieve equilibrated TDG readings were identified in the resulting database. These tests satisfied 9 of the 16 desired conditions established in the playbook, as shown in Table 6.3-1.

Table 6.3-1. 2007 spill test summary.

Requested		Obtained
Q (cfs)	**Gate 1:Gate 2 Ratio**	**Number of Tests**
5,000	100:0	5
5,000	0:100	1
5,000	50:50	1
5,000	20:80	1
10,000	100:0	1
10,000	0:100	1
10,000	50:50	1
10,000	20:80	1
15,000	100:0	–
15,000	0:100	–
15,000	50:50	1
15,000	20:80	–
20,000	100:0	–
20,000	0:100	–
20,000	50:50	–
20,000	20:80	–

Note:
cfs – cubic feet per second

The results of the 2008 field program are presented in Appendix 4. These results can be briefly summarized as follows:

- Developed an understanding of low forebay TDG performance
- Confirmed previous spillgate tests and developed further understanding of effects of spill gate operation on TDG
- Examined the distribution of TDG in the river at different flows:
  - No spill flow—little variation in TDG across the river
  - Less than 10,000 cfs spill—the USGS meter reads highest of all meters along the same transect
  - More than 15,000 cfs spill—the USGS meter reads lowest of all meters along the same transect

6.3.2. Proposed 2009 Field Program

The 2009 TDG monitoring program will develop data to improve understanding of the contributions of both spillway gate operations and sluice gate operations to TDG production in the Boundary Dam tailrace. Additional tests of single and multiple sluice gates with Spill Gate No. 2 operations are desired at various river flows and levels of forebay TDG.

Additional field tests will help develop a further understanding of issues associated with extended use of the sluice gates to allow operational use of the sluice gates to improve TDG performance.

See Section 5.2 in Appendix 4 for a more complete discussion.

6.4. Engineering Studies

Three TDG abatement alternatives are favored and will be the focus of more detailed examination in the studies planned for 2009 and beyond:

- Throttle Sluice Gates (No. 1-3), flow capacity 12,000–18,000 cfs;
- Roughen Sluice Flow (No. 3-2), flow capacity 16,000–20,000 cfs; and
- Spillway Flow Splitter/Aerator (No. 2-8), flow capacity 20,000–30,000 cfs.

These alternatives are favored for their ability to meet the following criteria:

- Low risk of fish injury
- High likelihood of improving TDG conditions downstream
- Technically feasible for construction and permitting;
- Minimal dam safety concerns
- Lower cost for implementation
- Maintenance and access are not impaired
- Existing Project operations are not impacted
- Has the ability to prototype test concept without full implementation
- Phased implementation and adjustment are possible based on the performance of the concept

The above-mentioned alternatives can be used in combination. The modifications to the sluice gates required for the Throttle Sluice Gate alternative constitute the first step for the Roughen Sluice Gate alternative. Observations of the discharge from throttled sluice gates indicate the location of contact for the gate discharge for the throttled sluice gate is quite different from what is expected with the deflectors used in the Roughen Sluice Flow alternative. Following is an initial estimate of total flow through the Project with a combination of the above alternatives in the following configuration:

- Four Throttled Sluice Gates (without Roughen Sluice Flow modifications) operating at range of 2 feet (with estimated flow of 1,700 cfs/gate), to 4 feet (with estimated flow of 4,400 cfs/gate) for a flow capacity of 6,800 to17,600 cfs;
- Three Roughen Sluice Flow gates with an estimated capacity of 4,000 to 5,000 cfs each for a total flow capacity of 12,000 to 15,000 cfs.; and
- Modifications to both spillways for a total flow capacity of 20,000 to 30,000 cfs.

The three gate alternatives all involve spilling flow through existing outlets (the seven sluice gates and two spillway gates) into the plunge pool and rely on reduction in TDG production by spreading the flow and limiting plunging effects of the confined jets. The relatively modest area of plunge pool where spill and sluice gates discharge and the constrained outlet from the pool to the downstream river, may limit the spill flow that can be released by combinations of alternatives without TDG increasing to a level higher than the combined output of alternatives operating individually. Addition of the flow ranges for combinations of alternatives is approximately 40,000 to 60,000 cfs; however, the total capacity may be less than this range.

The four remaining alternatives all employ various tunnel configurations with either submerged outlets or surface jets discharging outside the plunge pool. Although no tunnel options were selected for near-term analysis, two tunnel options may be considered in the future if the gate alternatives are shown to not perform adequately (Section 5.3.4). These two tunnel alternatives are:

- Penstock Draft Tube By-pass (Option 4-9)
- Right Abutment Tunnel with Submerged Discharge (Option 4-7).

Two alternatives will not be considered further, mainly due to performance, dam safety, and cost considerations (Section 5.3.4):

- New Left Abutment Tunnel Next to Unit 51 Intake (Option 4-10)
- Open Existing Diversion Tunnel and Add Control Structure (Option 4-8A).

Engineering studies for 2009 and beyond include the following:

- Continue conceptual and feasibility analysis of alternatives to develop the incremental approach to TDG abatement. Further feasibility analysis will require geotechnical/geologic, structural, and mechanical (gates) quantitative analyses at a feasibility level to further the qualitative analyses and develop more detailed cost estimates. Important tasks include:
    - Determining hydraulic capacity analysis of alternatives
    - Developing design details of favored alternatives
    - Further investigating existing conditions and potential interactions with existing structures
    - Developing more detailed drawings that can provide better concept understanding and basis for cost estimates
    - Estimating which alternative will provide the most effective incremental TDG benefit to the Project

- Continue development of the physical hydraulic model of the structures and the three gate alternatives.

- Continue development of the CFD modeling of the structures and Project tailrace. This model will be calibrated to simulate both flow field hydrodynamics documented in the 2007 field testing and TDG results from both the 2007 and 2008 field tests and then used to predict TDG performance of the leading TDG structural mitigation alternatives. The data collected after installation of prototype abatement alternatives will allow calibration of the predictive tool, which should improve the ability of the tool to inform the selection of subsequent prototype abatement alternatives.

- Estimate TDG performance for incremental installations of the three favored gate alternatives individually and in combination. The relatively modest area of plunge pool where spill and sluice gates discharge, and the constrained outlet from the pool to the downstream river, may limit the spill flow that can be released by combinations of alternatives without TDG increase to a level higher than the combined output of alternatives operating individually.

- Implement prototype installations of the most highly favored alternatives incrementally, monitor the performance, and use the results of the monitoring to improve the ability to predict future performance.

The draft Clean Water Act Section 401 water quality certification application is being submitted to Ecology in May 2009 and the final application will be filed in November/December 2009. Studies of TDG operational changes and structural abatement alternatives will continue past submittal of the application for water quality certification. The TDG study team will assess the engineering and model studies, field testing, and prototype performance to determine whether further prototype and field studies are warranted to develop the three gate alternatives or whether one of the two tunnel options should be considered further. The Section 401 certification application will contain the current status of investigations as well as the strategy and a decision matrix that outlines SCL's plans for addressing the TDG issue following issuance of the new FERC license.

Given the complexities associated with operational changes and structural abatement alternatives, a measured, incremental, adaptive management approach is being employed. The strategy employs engineering studies to develop predicted improvement over current TDG conditions, followed by incremental prototype studies. This strategy will also allow consideration of potential issues associated with fish entrainment and fish passage, dam safety, and operation and maintenance. Once evaluated, the measure(s) can be implemented to improve water quality. This method has been employed effectively with modification on the turbine operating sequence to address the turbine air admission issue (see Section 5.4.7), with the result of practically eliminating the TDG effects due to turbine air admission.

Project spill is the focus of future TDG abatement strategies. The three favored alternatives involve spreading the spill flow to the extent possible within the Project plunge pool to minimize aerated spill flow plunging to depth.

Examining the hydrologic record allows an estimate of the conditions (under current operating conditions) under which Project spill leads to TDG level in excess of the water quality standard. This can be described as the equivalent of 7.4 days per year (Tables ES-1 and 5.2-1). The TDG team will develop alternatives to incrementally work toward reducing both the amount of time the Project exceeds the standard and the extent by which the standard is exceeded.

7 VARIANCES FROM FERC-APPROVED STUDY PLAN AND PROPOSED MODIFICATIONS

There are no known variations from the FERC-approved study plan.

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USACE. 1999. Dissolved Gas Abatement Study: Phase II-60% Draft Report. North Pacific Division, U.S. Army Corps of Engineers.

Appendix 1: Annotated Bibliography

Angelaccio, C.M.; Bacchiega, J.D.; Fattor, C.A.; Barrionuevo, H.D. 1997. *Effects of the spillways operation on the fishes habitat: Study of solutions.* pp. 465-470 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Community. vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: The massive mortality of fishes that took place downstream of Yacyreta Dam, resulting from supersaturation of total dissolved gasses, generated diagnosis studies of the causes and possible corrective solutions to avoid re-occurrence. The causes of the environmental conflict are detailed, and changes in the original geometry of the spillway are analyzed through physical modeling, in order to reduce the supersaturation.

Comment: This is a paper on deflector design from physical hydraulic models, and discusses the South American experience with spillway deflectors. General background on the most used structural TDG remediation.
Reviewer: JSG 5/22/2007

Boyer, P.B. 1973. *Gas supersaturation problem in the Columbia River.* pp. 104-113 in Water for the Human Environment: Proceedings of the First World Congress on Water Resources. vol. 3, Chicago, IL.

Abstract: Gas supersaturation, which causes fish embolism, is the most serious water quality problem in the Columbia River. The phenomenon is attributed to spillway-stilling basin action. The plunging water carries with it the entrained air deep into the basin where, under hydrostatic pressure, the constituents of the air go into solution in excess of the ambient saturation concentration. The continuous operation of the spillways during spring-summer flood keeps the river supersaturated for nearly 100 days. Field and laboratory investigations are being carried for two major categories: (1) engineering research to provide scientific background for operational and structural modifications that might reduce gas supersaturation levels without significant mechanical damage to fish; and (2) biological research leading to an assessment of the adverse effects of gas supersaturation on fish of various sizes and species for various exposure time, swim depth, and water temperature.

Comments: This paper outlines the problem and then-current research investigations for gas supersaturation and structural modifications. Historical reference.
Reviewer: JSG, 5/22/2007

Brocchini, M, and Peregrine, D.H. 2004. *The dynamics of strong turbulence at free surfaces. Part 1: Description*. Journal of Fluid Mechanics, Vol. 449, 225-254.

Abstract: A free surface may be deformed by fluid motions; such deformation may lead to surface roughness, breakup, or disintegration. This paper describes the wide range of free-surface deformations that occur when there is turbulence at the surface, and focuses on turbulence in the denser, liquid, medium. This turbulence may be generated at the surface as in breaking water waves, or may reach the surface from other sources such as bed boundary layers or submerged jets. The discussion is structured by consideration of the stabilizing influences of gravity and surface tension against the disrupting effect of the turbulent kinetic energy. This leads to a two-parameter description of the surface behaviour which gives a framework for further experimental and theoretical studies. Much of the discussion is necessarily heuristic, and is often limited by a lack of appropriate experimental observations. It is intended that such experiments be stimulated, to test the value or otherwise of our two-parameter description.

Comment: This paper discusses the source of air entrainment in surface jets. It may be valuable to understand how high speed surface jets can entrain air, such as given below.

A `rooster tail' generated by a Seacat. The lower right of the photograph is where the highly turbulent propulsive jet has just come out from beneath a hull.

Reviewer: JSG 6/02/2007

Cain, James M. 1997. *Design of Spillway Deflectors for Ice Harbor Dam to Reduce Supersaturated Dissolved Gas Levels Downstream.* pp. 607-612 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Community. vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: Dissolved gas supersaturation occurs downstream of the eight Federal dams on the lower Snake and Columbia Rivers when spillway flows are released. This paper describes a new approach to optimize spillway deflector performance to reduce supersaturation levels downstream of Ice Harbor Dam.

Comment: This paper is about the spillway deflectors, flow patterns and design for Ice Harbor Dam. This will be of relevance if similar designs are to be undertaken.
Reviewer: JSG, 5/24/2007

Carroll, J.H., J.W. Lemmons and M. Schneider. 2000. *Data summary for Wanapum dam prototype total dissolved gas evaluation, spillway 5, single spillbay study*. Waterways Experiment station, U.S. Army Corps of Engineers.

Abstract: This study describes tests to measure TDG on a single deflectored spillway.

Comment: The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.

Reviewer: JSG 4/11/2007

Columbia Basin Environmental. 2001. "*Boundary Dam Total Dissolved Gas Study 24 to 25 September 2001.* Draft Report, October 2001, prepared for Seattle City Light.

Abstract: This study was designed to supplement previous work by better defining the operating range resulting in elevated TDG pressures. From these data, a generation to gas production relationship would be defined and the influence of the air admission system on gas production identified.

Comments: Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2001.

Reviewers: JL HEC 2/17/2005, JSG 4/11/07

Columbia Basin Environmental. February 2002. *Boundary Dam Total Dissolved Gas Study, 24 to 25 September 2001.* Pre-Decision Draft Report, prepared for Seattle City Light.

Abstract: Studies conducted in the Boundary Dam tailwater had identified the presence of elevated total dissolved gas (TDG) pressures resulting from project generation at low to medium (1-100 megawatts) ranges. It was theorized that operation of the air admission system (snorkel tube) was responsible for the elevated TDG pressures. The air admission system injects air into the turbines to minimize cavitation at low generation levels. The 2000 study had identified Units 55 and 56 as likely contributors to elevated tailwater TDG pressures. The purpose of the 2001 study was to define a gas production relationship and to determine the extent that the air admission system influenced gas production.
Comments: Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2001.
Reviewers: JL HEC 2/17/2005, JSG 4/11/07

Columbia Basin Environmental. January 2003. *Boundary Dam Spillway Evaluation, 1 May – 25 July 200.* Pre-decision Draft Report prepared for Seattle City Light.

Abstract: Although spill at Boundary occurs relatively infrequently, and typically is less than a month in duration, elevated total dissolved gas (TDG) pressures of 150-160 percent had been identified during spill periods. This study was undertaken to evaluate TDG pressures attributable to spill at the project and to begin to identify possible amelioration techniques, if warranted. The study had two objectives. The first was to identify if dividing total spill volume between Boundary spillways resulted in lower TDG pressures than directing the same volume over a single spillway. Split spill operation resulted in TDG saturations that were approximately 3 percent lower than non-split spill. Benefits were greater at lower spills and tended to disappear at spill to flow ratios >50 percent. The second objective was to identify the presence and degree of entrainment of powerhouse release water by the Boundary Dam spillway, which may lead to TDG pressures approaching, or equaling, those of spilled water. Estimates of this entrainment were ambiguous, indicating that entrainment was not occurring or represented a small volume if it did exist. Recommendations were given for future project operation and study.

Comments: Total dissolved gas study for Boundary Dam. Data from monitoring conducted in 2002.
Reviewers: TLN R2 2/14/2005, JSG 5/23/07

Eastman, Kent B., Klein, Amy S. 2004. "*Total Dissolved Gas and Temperature Monitoring at Chief Joseph Dam, Washington, Albeni Falls Dam, Idaho and Libby Dam, Montana 2004: Data Review and Quality Assurance.* US Army Corps of Engineers, Seattle District

Abstract: Intro and Scope (verbatim from document)
The Columbia River drains over 259,000 square miles of the Pacific Northwest in the United States and Canada. The Snake, Kootenai, and Pend Oreille-Clark Fork systems are the largest tributaries of the Columbia River. The Seattle District Corps of Engineers (CENWS) operates three dams in the Columbia River Basin: Chief Joseph Dam on the Columbia River in Washington, Libby Dam on the Kootenai River in Montana, and Albeni Falls Dam on the Pend Oreille River in Idaho (Figure 1). These dams are operated to provide flood control, hydropower production, recreation, navigation, and fish and wildlife habitat.

Total dissolved gas (TDG), water temperature, and associated water quality processes are known to impact anadromous and indigenous fishes in the Columbia River system. Dams may alter a rivers water quality characteristics by increasing TDG levels due to releasing water through the spillways and by altering temperature gradients due to the creation of reservoirs. Spilling water at dams can result in increased TDG levels in downstream waters by plunging the aerated spill water to depth where hydrostatic pressure increases the solubility of atmospheric gases. Elevated DG levels generated by spillway releases from dams can promote the potential for gas bubble trauma in downstream aquatic biota (Weitkamp and Katz 1980; Weitkamp et al. 2002). Water temperature has a significant impact on fish survivability, TDG saturations, the biotic community, chemical and biological reaction rates, and other aquatic processes.

The Seattle District Corps of Engineers monitored total dissolved gas (TDG) and temperature at Chief Joseph Dam, Albeni Falls Dam, and Libby Dam during the 2004 spill season, which lasted from April 1 - September 15, 2004. The purpose of the monitoring program was to provide real-time TDG data to the U.S. Army Corps of Engineers (USCOE) to allow for the understanding and management of flow and spill at dams on the Columbia River system. This report describes the TDG and temperature quality assurance (QA) results and associated data for the Chief Joseph Dam, Albeni Falls Dam, and Libby Dam monitoring programs.

Comments: Monitoring studies for other dams in 2004 could develop perspective on the severity of TDG in the tailwater of Boundary Dam.
Reviewers: AO R2 6/15/2005, JSG 5/23/07

EES Consulting. *Total Dissolved Gas Monitoring, Final Report 2003, Box Canyon Hydroelectric Project (NO. 2042)*. Prepared for Pend Oreille PUD.

Abstract: SUMMARY (taken verbatim from document)
-Total dissolved gas saturation exceeded the water quality standard of 110 percent saturation at Box Canyon Forebay for 2 percent and 38 percent of the observations in May and June, respectively.
-Total dissolved gas saturation exceeded the water quality standard of 110 percent at the Box Canyon tailrace for 50 percent, 93 percent, and 89 percent of the observations in April, May, and June, respectively.
-Levels of total dissolved gas exhibited a slight decrease from Newport to Box Canyon forebay.
-Total dissolved gas increased with higher spill. The increase in total dissolved gas was less when spill ranged from 3,000-5,000 cfs as compared to spill in the range of 0-3,000 cfs.
-Total dissolved gas saturation in excess of 120 percent saturation was observed at Box Canyon tailrace, only.
Comments: Monitoring studies for other dams in 2004 could develop perspective on the severity of TDG in the tailwater of Boundary Dam.
Reviewers: AO R2 7/5/2005, JSG 5/23/07

Entrix. 2002. L*evel 1 Assessment, Wria 62, Prepared For:Pend Oreille Conservation District, Pend Oreille (Wria 62) Watershed Planning Unit.* Prepared For, Pend Oreille Conservation District, Pend Oreille (Wria 62) Watershed Planning Unit.

Abstract: The primary objective of this Level 1 assessment were to produce an initial summary and evaluation of technical information for the Watershed Resource Inventory Area (WRIA) 62, characterizing the watershed and its subbasins; and to identify data gaps and document those areas where data are insufficient for addressing issues and making recommendations for watershed planning. Sections of the report included: an Overview of Watershed Characterization, driving factors of change, hydrology and geohydrology, water quality, fish and aquatic habitat, and water quantity. Most of the specific information given concerns smaller tributaries, or watershed administrative units (WAUs). There are few specific references to Boundary Dam; most mainstem Pend Oreille examples given are in regards to Box Canyon Dam. Recommendations for the WRIA 62 Phase 2 watershed assessment are provided for both the entire WRIA, as well as individual WAUs. No specific recommendations are given for the Boundary Dam or Reservoir.

This report presents a narrative watershed characterization drawn from existing information gathered from local, state, and federal sources in the areas of climate, hydrology, water rights, and water use. This report does not attempt to critique or reconcile differences among existing sources, or to extend the existing information base with new research or analysis. The purposes of the Level 1 report are to provide an initial watershed characterization that the Planning Unit may build upon and expand in preparing a full Phase 2 watershed assessment, and to identify data gaps and highlight their significance. This report contains the watershed characterization and illustrates the presence of data gaps wherever insufficient information exists to adequately characterize watershed resources. The priority areas summarized in this report include fish and habitat, local control, growth, regional watershed management, water quality, mainstem Pend Oreille, small streams, and water quantity.

Comments: Most is very general information but it can be useful to point to other more detailed documents. Provides good overview of water quality in Pend Oreille watershed.
Reviewers: TLN R2 2/14/2005, JL HEC 2/17/2005, JSG 5/23/07

Entrix. 2002. *Phase Ii, Level 1 Assessment, Wria 62, Prepared For: Pend Oreille Conservation District, Pend Oreille (Wria 62) Watershed Planning Unit.* Prepared For Pend Oreille Conservation District, Pend Oreille (Wria 62) Watershed Planning Unit.

Abstract: This report focuses on Tasks 4 and 5 of the Phase 2, Level 1 Technical Assessment which was begun by the WRIA 62 Planning Unit as part of the 2514 watershed planning process. Task 4 included an assessment of the validity and adequacy of the existing database, and Task 5 included the preparation of a Level 1 Technical Assessment Report. As a component of Task 4, this report provides summaries of priority issues of concern to WRIA 62 planning unit members, addressing database information available on water quantity, water quality, habitat and other data categories. This report incorporates the findings of Task4 as two data/information matrices. These matrices provide detailed information and comments for each document, identification and summary of all the data sources reviewed, limitations of the data, and recommendations for the Phase 2, Level 2 Assessment, where appropriate. This report summarizes the comprehensive characterization of the physical, biologic, human, and regulatory elements of the WRIA, based on the current level of documentation and understanding.

Comments: Good overview of water quality in Pend Oreille River and associated tributaries. Role of tribes in watershed planning pg 1-1. Historical discussion (secondary source) pg 28.
Reviewers: NG LAAS 4/29/2005, AO R2 2/14/2005, JL HEC 2/17/2005, JSG 5/23/07

Fast, Don, O'Riordan, Jon. 1981. *"Ambient Water Quality Assessment And Objectives for the Lower Columbia River Birchbank to the US Border, Overview Report*. Prepared Pursuant To Section 2(E) Of The Environment Management Act.

Abstract: Summary (Taken verbatim from document)
This document is one in a series that describes ambient water quality objectives for British Columbia. It has two parts: the following overview and a technical appendix that was prepared by a consultant as a separate document and published by Environment Canada in 1997. The overview provides general information about water quality in the lower Columbia River between Birchbank and the international boundary, and provides explanations as to differences in water quality objectives in this document compared to the technical appendix. The technical appendix presents the details of the water quality assessment for this area, and forms the basis of the recommendations and most of the objectives that are presented in the overview.

The overview is intended for both technical readers and for readers who may not be familiar with the process of setting water quality objectives. Tables listing water quality objectives and monitoring recommendations are included for those readers requiring data about these water bodies. A separate report has been published which describes the water quality assessment and objectives for the lower Columbia River from the Hugh Keenleyside Dam to Birchbank.

The Columbia River is an important trans-boundary river system that generates a host of benefits to people in Canada and the United States. In addition to in-stream water uses (i.e., fish and aquatic life), the Columbia River provides an important source of raw water for municipal water supplies, irrigation, livestock watering, and industrial water uses. The Columbia River and its tributaries have also been impounded extensively to support hydroelectric power production, water storage, and flood control. Recreation and aesthetics represent important uses of the aquatic environment that generate both social and economic benefits to area residents.

Concerns related to water quality conditions in the Columbia River are primarily related to discharges of industrial and municipal wastes. Discharges of heavy metals from the Cominco lead-zinc smelter in Trail and chlorinated substances from the Celgar Pulp Company pulp mill in Castlegar have represented the main sources of contaminants. However, discharges of treated municipal sewage from the City of Trail (primary) and the City of Castlegar (secondary) and various non-point sources also contribute to contaminant loading to the lower Columbia River. Elevated levels of dissolved gases and fluctuating water levels are also significant concerns in this system, being generated at dams on the system.

This report describes water quality objectives for the lower Columbia River from Birchbank to the international boundary. These water quality objectives specify the characteristics of water, sediment, and fish muscle tissues necessary to protect aquatic life, wildlife, livestock watering, irrigation, recreation and drinking water supplies in this portion of the river.

Comments: This report describes Canadian water quality objectives for the lower Columbia River from Birchbank to the international boundary in 1981.
Reviewers: AO R2 7/15/2005,JSG 5/23/07

FERC. 2002. *Draft Environmental Impact Statement, Box Canyon Hydroelectric Project, Washington and Idaho, (FERC 2042-013).*

Abstract: EXECUTIVE SUMMARY (Taken verbatim from document)
In this draft environmental impact statement (draft EIS), we, the staff of the Federal Energy Regulatory Commission (FERC or Commission), evaluate the potential natural resource benefits, economic costs, and the environmental effects associated with relicensing the Public Utility District No. I of Pend Oreille County (PUD) Box Canyon Project on the Pend Oreille River, in Pend Oreille County, Washington, and Bonner County, Idaho, neat- lone, Washington. The PUD proposes to continue to operate the existing 72-megawatt (MW) hydroelectric run-of-river project that lies between the upstream Albeni Falls dam (operated by the U.S. Army Corps of Engineers) and downstream Boundary dam. The project generates an average of 452,000 megawatt hours (MWh) per year. Of the 3,200-acre project area, more than 700 acres are federal

lands, about 500 of which are within the Kalispel Indian Reservation arid 200 within the Colville National Forest

The PUD filed its application for a new license on January 21, 2000. In its application, the PUD proposes to upgrade all four turbines with new, high- efficiency runners and rewound generators to increase capacity to 22.5 MW each, which would yield an additional 31,000 to 35,000 MWh per year of energy. The PUD does not propose any major construction. The PUD also proposes reservoir drawdown limitations, erosion monitoring, water quality monitoring, tributary habitat restoration, wildlife monitoring, purchase of lands to achieve zero net loss, cottonwood enhancement, aquatic plant management, and development of a Recreation Resource Management Plan and a Cultural Resources Management Plan (CRMP).

In response to the Commission's September 4, 2001, notice, the U.S. Forest Service (FS) arid the U.S. Department of the Interior (Interior) filed preliminary conditions for Section 4(e) of the Federal Power Act (FPA). Also in response to that notice, Interior filed a prescription for fishways at Box Canyon dam and the Calispell Creek Pumping Plant for Section 18 of the FPA, and the states of Washington and Idaho and the Kalispel Tribe filed recommendations for license provisions for Section 10 of the FPA. The FS's preliminary 4(e) conditions include provisions for boundary surveys; shoreline and visual management; recreational improvements; erosion monitoring; erosion control, prevention, and remediation; bald eagle/osprey/cormorant/ heron monitoring; mitigation for inundation of riparian an, upland, and native amphibian habitats., fish passage; restoration of resident fish habitat; meeting water quality standards; management of non-native aquatic vegetation; integrated weed management; and sensitive plant species management. Interior's preliminary 4(e) conditions include provisions for reservoir drawdown limitations with associated monitoring, compliance with water quality standards with associated monitoring, total dissolved gas abatement, no-net loss in trout production including a trout assessment and remediation fund, no net loss of average annualized habitat units, a CRMP, and enhancement of recreation resources on tribal lands. Interior's Section 18 prescription included provisions for interim trap-and haul-fishways, permanent downstream volitional fishways, permanent upstream volitional fishways, and plans for effectiveness evaluations.

In this draft EIS, we analyze and evaluate the environmental and economic effects of continuing to operate the project. The alternatives examined in the draft EIS include (1) the PUD Proposal, (2) the Staff Alternative, and (3) No-action. The Staff Alternative consists of the PUD Proposal with additional or modified environmental measures, which include Section 18, 4(e), 10(j), and 10(a) measures, or modifications thereof.

Based on our analysis, we recommend licensing the project for the Staff Alternative.

Comments: Draft ESI provides comprehensive overview of water quality in Box Canyon Reservoir. Could provide background for the Boundary project.
Reviewers: NG LAAS 4/29/2005, AO R2 2/14/2005, JL HEC 2/17/2005, JSG 5/23/07

Framatome. 2002. *Total Dissolved Gas Monitoring, Final Report, 2002, Box Canyon Hydroelectric Project (No. 2042)*. Prepared for Pend Oreille PUD.

Abstract: INTRODUCTION (verbatim from document)
The Pend Oreille Public Utility District No. 1 of Pend Oreille County filed a Final License Application for the Box Canyon Hydroelectric Project (FERC No. 2042) with the Federal Energy Regulatory Commission (FERC) in January 2000. In FERC's Additional Information Request dated February 27, 2001 (FERC Docket No. P-2042-013), FERC requested the District to file 60-day progress reports inclusive of electronic data for the ongoing total dissolved gas monitoring. The 2002 dissolved gas monitoring season extended from March 28, 2002 through August 5, 2002, which encompasses the entire spill season for the Spring 2002 runoff. In 2002, the District filed 60-day progress reports on June 6, 2002 and August 9, 2002, which covers the 2002 monitoring season. Data in those reports was marked as preliminary. This report includes final data for 2002 as well as a description of study methods, results and analysis of spill gate configurations relative to dissolved gas generation.

Comments: Spill gate configurations could provide insight into performing similar operations at Boundary.
Reviewers: AO R2 7/5/2005, JSG 5/23/07

Geldert, Darrin A. 1996. *Parametric Relations to Predict Dissolved Gas Supersaturation Below Spillways.* M.S. Thesis, University of Minnesota, Minneapolis, MN.

Abstract: A comprehensive physically based relationships have been developed to predict dissolved gas supersaturation below spillways. Coefficients in the relations are fit to field data collected at four dams on the Columbia and Snake Rivers. The predictive technique accounts for changes in the dissolved gas concentration that may occur on the spillway face, in the stilling basin, and in the immediate river reaches downstream of the structure. In addition, both transfer across the water surface and transfer across the bubble interface are considered. The inclusion of physical parameters will allow for the evaluation of operation and design of the structures, and may provide insight for efforts to lower the dissolved gas concentration downstream of such structures. The relationships are applied to one structure to demonstrate the usefulness of the technique.

Comment: This thesis describes in detail a 1-d computational model for TDG supersaturation. It is applied to dissolved gas modeling on the lower Snake River and Columbia River. An eventual TDG model may utilize some gas transfer equations from this thesis.
Reviewer: JSG, 5/23/2007.

No pdf.

Geldert, Darrin A.; Gulliver, John S. 1996. *Prediction of Dissolved Gas Supersaturation Downstream of Hydraulic Structures.* pp. 298-304 in Water Quality '96: Proceedings of the 11th Seminar, WES Miscellaneous Paper W-96-1, USACOE Waterways Experiment station, Vicksburg, MS.

Abstract (from introduction): To better understand and model the dissolved gas levels throughout the Columbia and Snake river systems, improved field data and current gas transfer research have been used as the basis for developing new physically based relationships to model dissolved gas levels downstream of spillways. Independent consideration of air entrainment, a detailed consideration of transfer across the water surface and across the bubble-water interface, and the effect of both the tailwater depth and downstream river depth on saturation will be considered herein. In addition, field data were specifically collected for use in deriving new predictive relationships.

Comment: Article outlines 1-d predictive relations based on mass transfer physics. Probably not as complete as either of the other Geldert references. May provide a better description of the processes than ether of the other Geldert references, though.
Reviewer: JSG, 5/23/2007.

Geldert, Darrin A.; Gulliver, John S.; Wilhelms, Steve C. 1998. *Modeling dissolved gas supersaturation below spillway plunge pools.* Journal of Hydraulic Engineering. 124: 5 513-521.

Abstract: Excessive supersaturation of dissolved gasses, primarily nitrogen and oxygen, can cause gas bubble disease, and eventual mortality, in fish. This potential threat is currently a concern in efforts to aid anadromous fish survival in the northwestern United States. In an effort to better understand dissolved gas supersaturation and assist in its mitigation, physically based relationships have been expanded and developed to predict dissolved gas supersaturation that occurs because of the stilling basin and the river reaches immediately downstream of the structure. Gas transfer across both the water surface and the bubble interface are considered. Extensive field data from three spillways on the Columbia and Snake Rivers is used to fit coefficients that the predictive relationships require. The inclusion of more physically based parameters will allow for the evaluation of the operation and design of the structures and may provide insight for efforts to mitigate high dissolved gas concentrations downstream of such structures.

Comments: Article 1-D predictive relations and fits coefficients to four dams. It was found that surface transfer was important, especially at spillways with a shallow tailwater.
Reviewer: JSG, 5/23/2007.

Hallock , Robert J. February 6, 2004. *Fish passage feasibility study for bull trout in the Pend Oreille basin in Idaho and Washington (Battelle Study Proposal, File #34 1.1000.* Letter to Seattle District, U.S. Army Corps of Engineers.

Abstract: Letter to Evan Lewis of the US Army Corps of Engineers, Seattle, recommending compliance with the USFWS biological opinion (BO) that identifies measures and time lines to address the take of bull trout with regards to Albeni Fall Dam and that portion of the Pend Oreille River. Specifically, "the action agencies shall evaluate the feasibility of reestablishing bull trout passage at Albeni Falls Dam. If the information warrants consideration of modifications to the Albeni Falls facility, then the Service will work with the action agencies to implement these measures, as appropriate." The letter further outlines that a feasibility study for reestablishment of two way passage of bull trout at Albeni Falls Dam should be conducted by

October 1, 2004, with results by October 1, 2005, as well as an evaluation and report on total dissolved gas concentrations downstream of Albeni Falls Dam by October 1, 2004. The letter also summarizes Battelle's 2003 draft report "Movement and Survival of Radio-Tagged Bull Trout Near Albeni Falls Dam" (see Doc. 378) and how it pertains to the BO recommendations to the Corps.

Comments: Discussion of Bull Trout population at Albeni Falls Dam. Although not about TDG, this is a prime reason for TDG criteria at Boundary.
Reviewers: TLN R2 2/14/2005, JSG 5/21/07

Harza. March 1981. *Expansion of the Boundary Hydroelectric Project.* Project Planning Report. Prepared for Seattle City Light.

Abstract: Reviews preferred and three alternatives for expansion of hydropower facilities in the Project. Limited discussion of environmental impacts associated with expansion scenarios.

Comments: Feasibility level study. Primarily engineering and economic information and recommendations. Contains limited water quality and fisheries information.

[From CA of HEC:]
This report presents the results of a study conducted by Harza Engineering Company on the technical and economic feasibility of the installation of two additional units at the Boundary Hydroelectric Project, as well as the environmental impact of the proposed installation. The report advocates the installation of units 55 and 56 as an attractive economic option with minimal adverse environmental impacts. The report provides only a brief and general summary of the water quality within the boundary reservoir and in the Pend Oreille River downstream of the dam. The reservoir is determined to function more like a river than a lake, with no thermocline. Comparison of numerous water quality parameters at Newport, Washington and at the International Boundary monitoring station indicate consistent water quality throughout this reach of the Pend Oreille River. Provides summary of water quality data from 1974 to 1978 from monitoring station on Pend Oreille River at International Boundary. Data collected by USGS and summarized by Harza Engineering Company.

[From RT:]
Forest near the proposed expansion is Douglas-fir with smaller amounts of fir-hemlock forest associations (RARE-II). The area is within the Columbia Forest Ecoregion according to (Bailey 1976). Some deciduous forest--mainly aspen--occurs. Riparian habitat is very limited due to the steep topography, except upstream of Metalline. There, the riparian forest is heavily disturbed by agriculture. A table with wetlands by Township, Range, Section is provided for the entire region. Deer population densities are less than 100 per sq. mile. Annual deer harvest is 6-9 deer per sq. mile south of Metalline Falls (Zender, pers. comm.). Deer do winter in the valley. Elk winter next to reservoir with 50-60 animals. Harvest of elk is 3-4 per year. Moose occur in the surrounding area but typically only cross the reservoir due to lack of marsh areas. Black bear are relatively common. River otters occur near Slate Creek. Nearly 150 species of birds occur near Boundary Reservoir. Bald eagles winter along river. Osprey have increased since Project construction.

Fourteen species of amphibians and reptiles occur (6 amphibians, 1 turtle, 2 lizards, and 5 snakes).

Recreational facilities and recreational use of the area around Boundary Dam and Reservoir are limited in variety and density. SCL maintains a picnic area and boat launch in the forebay area of Boundary Dam and 2 visitor centers (1 in the powerhouse and 1 across the river on a point overlooking the dam and powerhouse. There are no estimates of existing use at the Project, but use is likely similar to that at Sullivan Lake (approximately 41,000 visitor days per year). Recreational activities in the area include hunting, fishing, hiking, berrypicking, and snowmobiling. The majority of lands surrounding the Boundary Dam and Reservoir is part of the Colville National Forest. The forest is extensively managed for timber production. The aesthetic quality of the reservoir area is considered to be high quality. Primary modifications to the scenic character of the Boundary Dam and Reservoir include the towns of Metaline and Metaline Falls, Highway 31 bridge between the two towns, mine tailings disposal areas downstream of Metaline Falls, transmission lines, and other facilities associated with the hydroelectric project.

In 1976, the population of Pend Oreille County was approximately 8,000. The age structure of the population showed an excess of individuals in the 0-25 and over 65 age groups. Agriculture and the timber industry, along with mining and milling provide the economic base for the area. The unemployment rate in Pend Oreille County is 2-3 times the national average and often exceeds 20 percent during the winter months.

Review98: Study reviews the optimum size of units that can be feasibly installed in existing skeleton bays at the Boundary Hydroelectric Project. Report contains the method of analysis, determination of additional sustained peaking capacity and secondary energy available at Boundary, evaluation of costs and benefits from three alternatives to expansion, and the environmental impacts of recommended expansion.

Comments: One of the alternatives at Boundary is the addition of power generation units to remove energy from the flow while subsequently generating some energy. The tunnel concept brings a new benefit to this concept.
Reviewers: JL HEC 2/15/2005, RT EDAW 2/16/2005, RJ R2 7/22/1996 , JSG 5/21/07

Holmes. September 1999. S*tate of Water Quality of Columbia River at Birchbank 1983-1997, Canada - British Columbia Water Quality Monitoring Agreement.* Water Quality Section, Water Management Branch, Environment and Resource Management Department, Ministry of Environment, Lands and Parks, Aquatic Science Section, Environmental Conservation Branch, Environment Canada Pacific and Yukon Region.

Abstract: Executive Summary (taken verbatim from document)
The water quality site on the Columbia River at Birchbank is about 24 km downstream from the community of Castlegar and approximately 25 km north from the international border. The drainage area for the Columbia River at Birchbank is 88,100 km2 (Figures 1 and 2).

Water quality in this reach of the Columbia River has been influenced by the Hugh Keenleyside Dam, the Kootenay River, and major effluent discharges from the Celgar pulp mill and the City of Castlegar. The designated water uses for Columbia River water at Birchbank are: irrigation, livestock watering, primary-contact recreation (i.e., swimming), drinking water with partial treatment and disinfection, industry, wildlife, and aquatic life.

We concluded that:
· Total aluminum and total iron had environmentally significant decreasing trends over time, possibly due to the trapping effect of upstream dams and reservoirs.
· Total phosphorus had a declining trend during 1968-78, possibly due in part to the trapping effect of upstream dams and reservoirs and waste abatement. Phosphorus appeared to have reached a steady state during 1983-97, because the evidence for a declining trend was weak and contradictory for this period.
· Total chromium and total manganese had decreasing trends over time, but they were not environmentally significant because they were below guidelines or objectives, and the result of improvements in measurement methods.
· Objectives were met for pH, ammonia, arsenic, cadmium, chromium, colour, copper, lead, thallium, and zinc.
· Total dissolved gas values exceeded the objective (_110 percent saturation) about 50 percent of the time between 1994 and 1996 due to air entrainment at the Keenleyside Dam. This can stress fish. BC Hydro has been trying to minimize the water spilled at the dam in recent years to minimize the duration and extent of dissolved gas supersaturation. A powerhouse is being built at the Keenleyside Dam, which will significantly reduce dissolved gas levels in the Columbia River.
· Fecal coliform values indicate that objective was probably met, although the values were collected less frequently than required to evaluate the attainment of the objectives rigorously.
· Water hardness was lower than the optimum range for drinking water, but was still quite acceptable.
· The river had a low sensitivity to acid inputs.
· Suspended sediments (non-filterable residue, turbidity) values were lower than those in other rivers in the Kootenay region because of the lakes and reservoirs on the Columbia and Kootenay rivers, which allow suspended sediments to settle out.
· Columbia River water at Birchbank must be treated to remove turbidity and disinfected prior to drinking.
· Water temperature of the Columbia River at Birchbank was cool enough to be aesthetically pleasing for drinking, except during the summer when it was warm enough for swimming.

We recommend that monitoring be continued on the Columbia River at Birchbank. Water quality data collected at this site would be used to: determine the effects of the major effluent discharges to this reach of the Columbia River (e.g., Celgar pulp Mill, City of Castlegar), check the attainment of water quality objectives, and provide upstream water quality information, as a control site, for the lower reaches of the Columbia River.

Comments: This report discusses TDG problems on the Columbia River in Canada, downstream of the Boundary Project.
Reviewers: AO R2 7/6/2005, JSG 5/23/07

Johnson, P.L. April 1976. *Hydraulic Model Studies of Navajo Dam Auxiliary Outlet Works and Hollow-Jet Valve Bypass Modifications to Reduce Dissolved Gas Supersaturation*. US Bureau of Reclamation Report REC-ERC-76-5, Denver, CO.

Abstract: Operation of the auxiliary outlet works and the 762-mm (30-inch) hollow-jet valve bypass at Navajo Dam results in high levels of dissolved gas supersaturation in released waters. These high dissolved gas levels, which are caused by the deep penetration of the flow into the spillway stilling basin pool, have had adverse effects on the fishery. Structural modifications were considered which included a flattening of the trajectory of the jet from the 762-mm (30-inch) bypass and the addition of a deflector or flip lip to the auxiliary outlet works. A 1:48 scale hydraulic model was used to refine and evaluate these modifications. Depth of jet penetration, degree of energy dissipation, strength of back eddies returning into the stilling basin, potential for cavitation development below the flip lip, and simplicity of design were factors considered in the evaluation.

Comment: These hydraulic model studies were on flow deflectors and hollow jet valves. Hollow jet valves or a gate alternative that has the same effect have been under consideration for the Boundary Project.
Reviewer: JSG, 5/23/2007

Johnson, Perry L. 1984. *Prediction of dissolved gas transfer in spillway and outlet works stilling basin flows*. pp. 605-612 in Gas Transfer at Water Surfaces. (Brutsaert, W.; Jirka, G.H., eds.) D. Reidel Publishing Company, Dordrecht, Holland.

Abstract: An empirical model developed from field data collected at 24 different structures is presented. The model predicts oxygen and nitrogen transfer to and from flows through hydraulic structure energy dissipators and thus may be used to evaluate a structure's potential for reaeration and dissolved gas supersaturation development. The model may be applied to many types of spillway and outlet works stilling basins. Considered in the analysis are the velocity, cross sectional shape, and orientation of flow entering the basin; stilling basin length, width, depth, and shape; and tailwater depth. An example application is included.

Comment: This paper is on gas transfer resulting from the plunge below spillways. It primarily focuses on stilling basins, and is an early attempt to model TDG below a spillway. It is helpful to go back to see what was done.
Reviewer: JSG, 5/24/2007

Johnson, Perry L. 1992. *Modification of the stilling basin at Arthur R. Bowman Dam, Oregon to reduce dissolved gas supersaturation.* pp. 311-316 in Hydraulic Engineering: Saving a Threatened Resource. (Jennings, Marshall; Bhowmik, Nani G., eds.) ASCE, New York.

Abstract: A physical model study was conducted in the Hydraulics Laboratory of the US Bureau of Reclamation to develop a modification for the stilling basin at Arthur R. Bowman Dam, Oregon. Flow through the existing stilling basin generates supersaturated dissolved gas levels that exceed state standards. Alternative stilling basin designs were considered. Resulting

dissolved gas levels, modified energy dissipation, and potential structure and river bottom and bank erosion were evaluated.

Comment: This paper is on stilling basins with flow deflectors to reduce TDG. The solution was to decrease depth of stilling basin, to create skimming flow at high discharge due to 'deflector' configuration.
Reviewer: JSG, 5/17/2007

Johnson, Perry L.; King, Danny L. 1979. ***Prediction of Dissolved Gas at Hydraulic Structures.*** **pp. 76-90 in Symposium on Aeration Research. (ed. by Committee on Research, ASCE Hydraulics Division) ASCE, New York.**

Abstract: (Taken from the conclusions) Given the velocity head of the inflow jet at the tailwater surface, the angle of penetration of the jet into the tailwater, the shape of the jet, the basin length and depth, the water temperature, the barometric pressure, and the initial dissolved gas levels in the reservoir, the dissolved gas levels that will result from the passage of flow through a hydraulic structure can be predicted with reasonable accuracy. Model studies can be used to great advantage in defining the hydraulic characteristics to be used in the analysis.

Comment: This paper was on dissolved gas modeling in stilling basins. It outlines general predictive techniques for determining dissolved gas levels downstream of the types of hydraulic structures employed by the Bureau of Reclamation.
Reviewer: JSG, 6/1/2007

Lee, Kenneth S. 1994. ***Gas supersaturation at Jennings Randolph Lake.*** **pp. 33-39 in Water Quality '94: Proceedings of the 10th Seminar. USACOE Waterways Experiment station, Vicksburg, MS. ([WES Miscellaneous Paper W-95-1].**

Abstract: An unexpected event occurred in the tailwater of the Jennings Randolph Lake project in late May 1990. Severe fish kills were observed in the fish-rearing pens within the stilling basin even though the project was only discharging 4,200 cfs. First, it was assumed that chemical toxicity, especially aluminum and pH, had caused the problem, but later it was found that gas supersaturation had caused the fish kill.

Comment: This paper describes the TDG supersaturation problem at Jennings Randolph Lake, North Branch Potomac River and discusses alternative measures for prevention.
Reviewer: JSG, 5/25/2007.

Lemons , John and Gunter, Mark. 2000. ***Boundary Dam Total Dissolved Gas Evaluation: TDG Dynamics Associated with Power Generation, 23 June - 23 July 2000.*** **Prepared for Seattle City Light by Columbia Basin Environmental.**

Abstract: Seattle City Light contracted Columbia Basin Environmental to conduct a study of total dissolved gas (TDG) dynamics downstream of Boundary Dam for non-spill operation. Previous sampling had established the presence of elevated TDG concentrations for certain generation levels and this effort was intended to determine relationships between generator operation and TDG concentrations downstream of the project.

An array of multiparameter data loggers programmed to record temperature and TDG concentration was deployed in the tailwater of Boundary Dam from 23 June to 23 July 2000. These data were incorporated with Project powerhouse operations data and examined for relationships between TDG concentrations and Project generation.

Elevated TDG concentrations (in excess of atmospheric pressure) were recorded during periods when a turbine operated at less than 100 megawatts (MW). These periods were limited in duration, thus limiting the volume of water affected. Exceptions were noted when a turbine operated for an extended period at low to medium levels or at the end of a generation cycle. In the case of the former, the highest TDG concentrations recorded during the study coincided with two or more turbines simultaneously operating at less than 100 MW. In the case of the latter, water characterized by high TDG concentrations resulting from ramping turbines from full to no generation at the end of an operation cycle appeared to persist until cleared by the subsequent cycle. As the Project powerhouse "peaks" to match power requirements, periods of no operation may last for several hours.

Data collected laterally across the river at the tailwater TDG fixed monitor system (FMS) indicated that its location along the west shore represented the lowest values of the cross-section. Comparisons of the TDG FMS data to adjacent instruments, indicated good agreement, with both reporting lower values than instruments biased to the eastern side of the river. It is unclear if this relationship would hold during spill discharge, as the flow regime may differ.

Comments: This report discusses the history of operation effects on TDG below Boundary Dam. Reviewers: CA HEC 2/14/2005, JSG 5/25/07

Linder, W.M. 1982. *Water Quality Management at Harry S. Truman Dam and Reservoir.* pp. 245-271 in: Proceedings of a Seminar on Attaining Water Quality Goals through Water Management Procedures February 17-18, 1982. USACOE Waterways Experiment station, Vicksburg, MS.

Abstract: During the four and one-half years that have elapsed since the closure of the Harry S. Truman Dam, in west-central Missouri, several water quality problems have occurred. These have been corrected either by structural modifications or by adjustments in operation. The occurrence of downstream supersaturation was substantially reduced by the construction of deflectors or ' flip-lips ' on the downstream face of the spillway and by limiting the amount of spillway discharges until completion of the construction of power facilities. Adaptation of the upstream haul road as a skimming weir should reduce the amount of deoxygenated water released during high reservoir levels and may totally prevent the occurrence during typical pool levels. Depression of downstream D.O. levels during periods of non-generation may be avoided by making small releases from the spillway during certain time of day.

Comment: This paper is on stilling basin performance on dissolved gases, as related to one spillway. Deflectors on the spillway, the construction of a skimming weir spillway and small

releases were the changes recommended for the Harry S. Truman dam. Harry Truman dam experienced TDG supersaturation and fish mortality before turbines were installed. This indicates that TDG are not only a concern in the northwest. Deflectors were recommended for the spillway.
Reviewer: JSG, 5/25/2007.

Mains, E.M. 1977. *Corps of Engineers Responsibilities and Actions to Maintain Columbia Basin Anadromous Fish Runs*. pp. 40-43 in Columbia River Salmon and Steelhead, Proceedings of a Symposium. vol. . (Schweibert, E., ed.) American Fisheries Society, Bethesda, MD.

Abstract: The Fish and Wildlife Coordination Act requires that the Corps of Engineers coordinate its water resource activities with the federal and state fish and wildlife agencies. Over the past 25 years, the Corps has funded a Fisheries-Engineering Research Program to collect information for use in construction and operation of fish facilities and projects. Research has identified primary problem areas as the loss of juvenile fish - in turbines, from water supersaturated with atmospheric gases in the spillways, increased predation, and perhaps the loss of migratory motivation due to impoundments. Spillway deflectors have been developed and installed to eliminate the problem of supersaturation with gases. A transport system has been developed. Future programs are aimed at providing assistance to fish runs of the Snake River drainage.

Comment: This paper outlines all aspects of what the Coops did to enhance fisheries, including installing spillway deflectors in the 1970's, in the Columbia and Snake rivers.
Reviewer: JSG, 5/25/2007

Mannheim, Carl O.M.; Weber, L.J. 1997. *Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XII: Physical Model Data for Development of a Gas Concentration Computational Model.* IIHR LD Report No. 265. Iowa Institute of Hydraulic Research, Iowa City, IA.

Abstract (From Executive Summary): Concurrent with physical model studies aimed at developing some means for reducing gas supersaturation that occurs below the Wanapum Project during spillway operation, Public Utility District No. 2 of Grant County authorized Dr. John S. Gulliver of the University of Minnesota to attempt the development of a computerized analytical predictive model. To accomplish such a development Dr. Gulliver requested that the physical model be used to develop flow paths for the various spillway modification designs along with their associated turbulence characteristics. In addition he suggested that gas bubble distribution patterns might be simulated in the physical model by plastic beads.

This report describes physical model data collected and used as input for numerical model described by Orlins & Gulliver (1997, 2000). Provide insight into the use of models for the Boundary Project.
Reviewer: JSG, 25/25/2007.

No pdf.

Mannheim, Carl O.M.; Weber, L.J. 1997. *Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design*. IIHR Limited Distribution Report No. 264. Iowa Institute of Hydraulic Research, Iowa City, IA.

Abstract (From Executive Summary): Studies conducted on a physical model were performed to develop spillway deflectors that should reduce the gas supersaturation that occurs below Wanapum Dam due to spillway discharge operations. The studies used a three bay 1:21.5 scale model which included 860 ft. of tailrace.

Comment: This paper describes a physical model study that evaluated high, low, and sloped spillway deflectors. These alternatives may be useful in planning the Boundary Project design. Reviewer: JSG, 6/24/2007.

Mathur, Dilip; Heisey, Paul G.; Skalski, John R.; Hays, Steven G. 1997. *Structural modifications at hydro dams: An opportunity for fish enhancement.* pp. 358-323 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Economy. vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: Spillways and sluiceways at hydroelectric dams were constructed strictly as conduits for transporting excess river flow or debris with little focus on potential for safe fish passage. However, the declining salmonid populations have helped emphasize a critical re-examination of spillways and sluiceways as effective fish passage routes. Consequently, spillways at some hydro dams have been modified either to take advantage of surface oriented behavioral patterns of fish via installation of prototype overflow weirs or installed with flow deflectors to reduce total dissolved gas levels in the river. These spillway modifications have opened up a new set of fish passage survival issues. Controlled tag-recapture experiments at hydroelectric dams on the Columbia River show that not all spillway structural modifications are 100 percent fish friendly; differences in survival at unmodified spillbays between sites also occurred. Estimated survival of juvenile chinook salmon in spillway passage ranged from 95.5 to 100 percent. It appears that depth of the tainter gate opening, amount of gate opening, discharge volume, obstructions in the flow path (e.g., dentates, end walls), excessive turbulence, presence of boulders, etc. may affect fish survival. Hydraulic modeling and detailed physical examination of the spillways, in combination with fish survival information, may open new opportunities and economic impetus to incorporate appropriate structural modifications that can afford safer fish passage at spillways.

Comment: This paper describes fish passage mortality with spillway modifications. It is one of the few sets of data on these conditions, and could be used to assess mortality in structural modifications at the Boundary Project.
Reviewer: JSG, 6/25/2007.

Mesa, M.G. and Warren, J.J. 1997. *Predator avoidance ability of juvenile Chinook salmon (Oncorhynchus tshawytscha) subjected to sublethal exposures of gas-supersaturated water*. Can. J. Fish. Aquat. Sci. 54: 757-764.

Abstract: To assess the effects of gas bubble trauma (GBT) on the predator avoidance ability of juvenile chinook salmon (*Oncorhynchus tshawytscha*), we created groups of fish that differed in prevalence and severity of gas emboli in their lateral lines, fins, and gills by exposing them to 112 percent total dissolved gas (TDG) for 13 days, 120 percent TDG for 8 h, or 130 percent TDG for 3.5 h. We subjected exposed and unexposed control fish simultaneously to predation by northern squawfish (*Ptychocheilus oregonensis*) in water of normal gas saturation in 6, 18, and 10 tests using prey exposed to 112, 120, and 130 percent TDG, respectively. Only fish exposed to 130 percent TDG showed a significant increase in vulnerability to predation. The signs of GBT exhibited by fish sampled just prior to predator exposure were generally more severe in fish exposed to 130 percent TDG, which had the most extensive occlusion of the lateral line and gill filaments with gas emboli. Fish exposed to 112 percent TDG had the most severe signs of GBT in the fins. Our results suggest that fish showing GBT signs similar to those of our fish exposed to 130 percent TDG, regardless of their precise exposure history, may be more vulnerable to predation.

Comment: This paper provide evidence that salmon exposed to 120 percent supersaturation of dissolved gas are not more susceptible to predation from northern squawfish. This may be important ithe argument that 110 percent is too strict of a standard.
Reviewer: JSG 5/30/2007.

North Pacific Division. *Dissolved Gas Data Report, 1975-76.* USACOE North Pacific Division, Portland, OR.

ABSTRACT: The data regarding the dissolved gas content on the Snake and Lower Columbia Rivers for 1975 and 1976 are reported. The effectiveness of the spillway deflectors is discussed. The deflectors at McNary, Little Goose, Lower Monumental and Lower Granite Dams have helped reduce the dissolved gases below these projects to a tolerable level. The deflector at Bonneville Dam did not reduce the gas levels as expected.

Comment: An early study on overall dissolved gases on the Columbia and Snake Rivers. This could be a historical reference for the Boundary Project.
Reviewer: JSG, 5/26/2007.

No pdf.

North Pacific Division. 1984. *Spillway Deflectors at Bonneville, John Day and McNary Dams on Columbia River, Oregon-Washington and Ice Harbor, Lower Monumental and Little Goose Dams on Snake River, Washington.* USACOE North Pacific Division Hydraulics Laboratory, Bonneville, OR. Technical Report No. 104-1.

Abstract: Highly aerated water flowing over the spillways and plunging into the deep stilling basins of dams increases the nitrogen levels of the rivers to a supersaturated condition hazardous to migrating fish. The report presents data and results of model studies conducted in development of spillway deflectors for six projects on the lower Snake and Columbia Rivers. The deflectors prevent the plunging action and cause a more skimming-type flow near the surface of stilling basin resulting in reduced nitrogen saturation levels. The models were used to design the deflector geometries and to assist in evaluating their effect on fishway attraction flow near downstream fishway entrances at each project. Prototype measurements indicate that the deflectors have been effective in reducing nitrogen levels at the projects.

Comment: Model studies of spillway deflectors for the Columbia River and Snake River Corps dams. This provides background on what was planned for TDG abatement on these dams. Reviewer: JSG, 5/28/2007.

Orlins, Joseph J.; Gulliver, J.S. 1997. *Prediction of dissolved gas concentration downstream of a spillway,"* pp. 524-529 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Community. Vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: The increase in dissolved gas concentration downstream of hydraulic structures such as dam spillways can be harmful to juvenile salmonids. Such increases have been noted at Wanapum Dam on the Columbia River in Washington State. Modifications to the spillways at this dam will be installed to help lower the concentration of total dissolved gas downstream of the dam. These modifications were designed and optimized using a combination of physical and numerical models. The physical model provided information about the hydraulics associated with different spillway modifications. The numerical model calculated the concentration of total dissolved gas based upon hydrodynamic data from the physical model and mass transport relations for air-water flows. This article describes the numerical model development and application. A companion article [Weber and Mannheim, 1997] describes the physical modeling efforts and field measurements made to evaluate the performance of the modifications installed at the dam.

Comments: This paper describes a numerical model of TDG at the Wanapum dam. The model requires a physical model of flow and turbulence. A similar model could be considered for the Boundary Project.
Reviewer: JSG, 6/1/2007.

Orlins, Joseph J.; Gulliver, John S. 2000. *Dissolved gas supersaturation downstream of a spillway, II: Computational Model.* Journal of Hydraulic Research, 38(2), 151-159.

Abstract: The increase in dissolved gas concentration downstream of hydraulic structures such as dam spillways can be harmful to most fish species. Such increases have been noted at numerous hydroelectric dams on the Columbia and Snake Rivers in Washington State, and there is fear that this total dissolved gas (TDG) "supersaturation" will increase mortality in juvenile and adult salmonids. Modifications to the spillway and/or its tailrace at some of these dams have or will be installed to help lower the concentration of total dissolved gas downstream of the dams. At Wanapum Dam on the mid-Columbia River, spillway modifications were designed and evaluated using a combination of physical and numerical models. The physical model provided information about the hydraulics associated with different spillway modifications. The numerical model calculated the concentration of total dissolved gas based upon hydrodynamic data from the physical model and mass transport relations developed for air-water flows. This article describes the numerical model development and application. A companion article

(Mannheim and Weber, 1998) describes the physical modeling efforts made to evaluate the performance of the proposed spillway modifications at the dam.

Comments: This paper describes a numerical model of TDG at the Wanapum dam. The model requires a physical model of flow and turbulence. A similar model could be considered for the Boundary Project.
Reviewer: JSG, 6/1/2007.

Parametrix, Inc. 1997. *Total dissolved gas monitoring for spillway modification evaluations-Wanapum dam, 1996*. Final report, Kirkland, Washington.

Abstract: This study describes tests to measure TDG on a single deflectored spillway.

Comment: The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface at the Boundary Project.
Reviewer: JSG 4/12/2007

Parametrix. July 1998. *Dissolved Gas Assessment, Boundary Dam 1998*. Prepared for Seattle City Light.

Abstract: This report presents the results of an investigation of dissolved gas supersaturation in the Pend Oreille River immediately downstream from Boundary Dam during the spring runoff period of 1998. The initial objectives were to 1) determine where routine monitoring should occur, and 2) to determine if supersaturation can be limited through some operation scheme. Due to the 1998 spring runoff being substantially below average, supersaturation tests had to be conducted after the Bonneville Power Administration was requested to release spill on May 31st, 1998. With about two thirds of the river flow (45,000 cfs) passing through the spillway, total dissolved gas (TDG) levels downstream were in the range of 131-148 percent of saturation.

Monitoring of TDG at the USGS Gauge location appeared to be accurate for determining the levels of supersaturation occurring downstream of Boundary Dam. Preliminary data also suggested that certain spill configurations produce higher levels of TDG than others. Less dissolved gas was produced when water was discharged through Sluice Gate 1 than Sluice Gate 4. Gate 2 produced slightly lower levels of supersaturation than Gate 1. Results suggest that splitting the discharge evenly between Gates 1 and 2 might produce slightly lower gas levels than using a single gate. However, the amount of data available was deemed inadequate for supporting firm conclusions.

Comments: Data on dissolved gas concentrations in relation to different spill configurations at the Boundary Project. From testing performed in 1998.
Reviewers: JL HEC 2/17/2005, JSG 6/10/07

Pelletier. March, 1990. *Progress Report No. 1, Pend Oreille River Water Quality Study.* Washington State Department of Ecology.

Abstract: A study was conducted by the Washington State Department of Ecology to address water quality concerns of the Pend Oreille River between Albeni Falls and Box Canyon dams. Five stations were sampled every three weeks between July and November 1988. Water quality is generally good and well below the threshold of eutrophic conditions. Phytoplankton species were typical of oligotrophic to mesotrophic waters. Periphyton concentrations were well below nuisance levels for aesthetic impairment. Macrophytes are responsible for water quality violations for pH and total dissolved gases during the peak of the growing season. There was no significant difference between sample stations for nutrients, suggesting macrophyte occurrence and sediments do not elevate instream nutrient loads. Brackett Creek, Skookum Creek, and South Fork Lost Creek exceeded Class A water quality standards for fecal coliform.

Comments: Excellent background information describing the habitat and water quality conditions in the Albeni Falls to Box Canyon reach of the Pend Oreille River.

Review98: In Washington, the Pend Oreille River between Albeni Falls Dam (RM 90) and Box Canyon Dam (RM 34) is a slow-moving, relatively flat reach with a worsening Eurasian water milfoil problem. Migration of Eurasian milfoil upstream from RM 72 is occurring at a rate of approximately 6 miles per year, probably due to boating activities (Water 1988). Water quality was well below the threshold indicative of eutrophic conditions. Nitrogen and phosphorous may be limiting. Dissolved oxygen and pH were in violation of water quality standards in 33 and 31 percent of all measurements, respectively. Twenty two tributaries inputs discharging a total of 97 +/- 15 cfs were identified in the study area. Inputs of total N and total P from tributaries within the study area accounted for less than four percent of the total river loading. The Newport Waste treatment Plant, the only permitted NPDES source with the reach, contributes 8 percent total local N and 50 percent of total local P. Calispell Creek contributes approximately half of the total N load and 18 percent of the local total P load. Trimble Creek contributes approximately 20 percent of the local total N load and six percent of the local total P load. Periphyton concentrations generally were well below nuisance levels for aesthetic impairment. Phytoplankton community structure was indicative of unpolluted waters. The general composition of phytoplankton present are indicative of oligotrophic to mesotrophic water quality, which is consistent with the generally low nutrient and chlorophyll a concentrations in the water column.

Comments: Report of 1990 TDG measurements upstream of the Boundary Project.
Reviewers: KB R2 7/22/1996, JSG 6/10/07

Pelletier. March 1990. *Pend Oreille River Water Quality Study.* Washington State Department of Ecology.

Abstract: A study was conducted by the Washington State Department of Ecology to address water quality concerns of the Pend Oreille River between Albeni Falls and Box Canyon dams. Five stations were sampled every three weeks between July and November 1988. Water quality is generally good and well below the threshold of eutrophic conditions. Phytoplankton species were typical of oligotrophic to mesotrophic waters. Periphyton concentrations were well below nuisance levels for aesthetic impairment. Macrophytes are responsible for water quality violations for pH and total dissolved gases during the peak of the growing season. There was no significant differences between sample stations for nutrients, suggesting macrophyte occurrences and sediments do not elevate instream nutrient loads. Brackett Creek, Skookum Creek, and South Fork Lost Creek exceeded Class A water quality standards for fecal coliform.

Review98: Representative water quality parameters were sampled in the Pend Oreille River at five stations between Albeni Falls Dam and Box Canyon Dam at three week intervals between July 1988 and November 1988. Routine sampling of index tributaries and point sources, and random sampling of other inputs were also conducted. Samples of macrophyte and periphyton tissue were collected from four stations. Water quality was generally found to be good and below the threshold for eutrophic conditions. Phytoplankton species were typical of oligotrophic and mesotrophic waters and periphyton concentrations were well below nuisance levels. Macrophytes are responsible for water quality violations for pH and total dissolved gases during peak growing season.

Comments: Report of 1990 TDG measurements upstream of the Boundary Project.
Reviewers: JL HEC 7/2/1996, JSG 6/10/07

Pickett, Paul J. 2004. *Quality Assurance Project Plan, Pend Oreille River Total Dissolved Gas, Total Maximum Daily Load Technical Study*. Washington State Department of Ecology.

Abstract: Abstract (taken verbatim from document)
This Quality Assurance (QA) Project Plan describes monitoring for Total Dissolved Gas (TDG) in the Pend Oreille River in Washington State, to be used in development of a TDG Total Maximum Daily Load (TMDL). TDG will be monitored continuously in the Pend Oreille River near Ruby, about halfway between Newport and Box Canyon Dam. TDG will also be measured at regular intervals from April through July as paired readings with other meters operated by dam owners above Newport and at Box Canyon and Boundary Dams, as well as at the Ecology meter. Data quality, analytical, and reporting procedures are also described.

Comments: Comments: Report of 2004 TDG measurements upstream of the Boundary Project.
Reviewers: AO R2 7/5/2005, JSG 6/10/07

Politano, M., Carrica, P. and Weber, L. November 2005. *Prediction Of Total Dissolved Gas Downstream Of Spillways Using A Multidimensional Two-Phase Flow Model,*” Mechanica Computacional XXIV, Ed. By A. Larreteguy, Buenos Aires, Argentina.

Abstract: Elevated supersaturation of total dissolved gas concentration in water (TDG), which may cause gas bubble disease in fish, constitutes an important negative environmental effect of dams. Spillway discharges at hydropower dams are the main source for TDG supersaturation in the Columbia and Snake basins in the Northwest USA. The most important source for the TDG is the gas transferred from the bubbles, therefore a proper model for TDG prediction must account for the two-phase flow generated in the stilling basin. Most of the numerical studies on TDG downstream of spillways found in the literature are based on experimental correlations for the gas volume fraction. A better approach involves the use of a multiphase flow model that rely less on empirical information. In this work, an algebraic slip mixture model that accounts for the drag and turbulent dispersion forces and employs the modified $k-\varepsilon$ model for the turbulence is used to calculate the gas volume fraction and velocity of the bubbles. A bubble number density transport equation is implemented to predict the bubble size, which can change due to bubble/liquid mass transfer and pressure. The TDG is calculated with a two-phase transport equation whose source is the bubble/liquid mass transfer which is a function of the gas volume fraction and bubble size. The equations of the proposed model were implemented into the commercial code FLUENT using the available multiphase flow algorithm based on the finite-volume method. The multidimensional fields of TDG, gas volume fraction, bubble sizes and velocities of the bubbles are presented and discussed. Quantitative agreements between the numerical results and field data for the TDG in the stilling basin of Wanapum Dam on the Columbia River are obtained.

Comment: This is an interesting model of bubble transport and gas transfer in a spillway tailwater. However, the assumption of negligible bubble breakup and coalescence is not correct. Getting this important characteristic wrong makes the results suspect. Provides background to TDG modeling at the Boundary Project.
Reviewer: JSG 6/11/2007.

Politano, M.S., Carrica, P.M., Cagri, T. and Weber, L. 2007. *A multidimensional two-phase flow model for the total dissolved gas downstream of spillways.* Journal of Hydraulic Research, 45(2), 165-177.

Elevated levels of dissolved gas in the spillway stilling basin, which are responsible for gas bubble disease in fish, constitute an important negative environmental effect of dams. Bubbles, entrained when a plunging jet impacts the tailwater pool, plunge beneath the surface and transfer mass to the liquid, causing an increase in the total dissolved gas (TDG) concentration. Most of the numerical studies on TDG downstream of spillways found in the literature are based on experimental correlations for the gas volume fraction. A better approach involves the use of a two-phase flow model. In this paper, a two-fluid model is used to calculate the gas volume fraction and velocity of the bubbles. A polydisperse model is used in which a Boltzmann transport equation predicts the bubble size distribution, to account for the different bubble sizes found in the flow downstream of spillways. The bubble mass is discretized considering groups of bubbles of variable mass, with the mass of the bubbles changing due to bubble/liquid mass transfer and pressure. A two-phase transport equation for the TDG is presented, whose source is the bubble/liquid mass transfer, which is a function of the gas volume fraction and bubble size distribution. Two-dimensional numerical results of TDG, gas volume fraction, bubble number density, and velocities are presented and discussed. The predictions of TDG downstream of a spillway are compared against field data in the stilling basin of Wanapum Dam, on the Columbia River.

Comment: This is an interesting model of bubble transport and gas transfer in a spillway tailwater. However, the assumption of negligible bubble breakup and coalescence is not correct. Getting this important characteristic wrong makes the results suspect. Provides background to TDG modeling at Boundary Project.
Reviewer: JSG 6/11/2007

RL&L. 1998. *Total Gas Pressure Monitoring, At Seven Mile and Waneta Dams 1995-1997.* Prepared for BC HYDRO, Castlegar, BC.

Abstract: To obtain a better understanding of temporal and spatial variation of dissolved gas pressure (TGP) in the Pend d'Oreille River during peak flow (freshet) conditions, a summary of all TGP data was prepared for data collected during 1995, 1996, and 1997 at Waneta and Seven Mile dams. Continuous and spot measurements were obtained upstream and downstream of each dam at selected locations. At each monitoring location, a TGP station was established. TGP stations typically consisted of a weather-proof box to house and protect the meter. With the exception of the Seven Mile Dam and Waneta Dam tailrace stations, the same locations were used over the three year monitoring period.

Comments: Total gas pressure monitoring at seven mile and Waneta dams from 1995-1997. This report provides background on expectations of TDG at regional dams.
Reviewers: JL HEC 2/17/2005, JSG 6/22/07

RL&L. 2000. *Total Gas Pressure Monitoring at Hugh L. Keenleyside Dam, 1999 Investigations.* Prepared for Columbia River Integrated Environmental Monitoring Program, Nelson, B.C.

Abstract: SUMMARY AND RECOMMENDATIONS (taken verbatim from document)
A preliminary analysis of the 1999 TGP monitoring data has confirmed many of the findings reported in previous reports (Aspen Applied Sciences Ltd. 1995; Millar et al. 1996; R.L. & L. 1999a, 1999b). Typically, the highest downstream TGP concentrations were always associated with spillway discharge from HLK, with Spillway 1 producing the highest TGP levels. When low level ports were the primary discharge mechanism, downstream TGP levels were substantially lower, with LLO 3 and LLO4 producing the least amount of TGP. As with previous TGP investigations downstream of HLK, a 13 hour delay was observed between an operational change at HLK and equilibrium TGP readings at the Robson station. Sufficient data were not available to determine whether or not this delay was flow dependent.

A cursory examination of the data found one episode when a single low level port (LLO 4) was used exclusively and discharge was held constant for more than 13 hours. Normal dam operations typically used a combination of low level ports and spillways to discharge water. Further analysis of the data may yield additional individual or paired gate settings that were maintained for the minimum 13 hour equilibrium period.

These data have been transferred to Aspen Applied Sciences Ltd. to check against the existing HLK model and to determine if further monitoring is necessary to resolve modeling discrepancies. These data are also being used to compare monitoring data from the Brilliant tailrace with the DOE Columbia River station near Waneta to determine if mass balance gas estimates from upstream sites consistently predict downstream gas levels.

Preliminary examination of 1998 data from HLK by Aspen Applied Sciences Ltd. suggests the current model may underestimate TGP measurements with certain gate combinations but accurately reflects others. The incorporation of the 1999 extended data set into the model may help resolve these issues. The existing monitoring database for HLK extends over many years and encompasses a large range of flow and operational conditions. Gas production models using HLK operations are quite complex and it is yet to be established if steady state models can accurately predict TGP formation at HLK. However, it is obvious from this and other monitoring data, that any use of spillways at HLK results in TGP values that exceed B.C. water quality guidelines.

In past years during some flow conditions (i.e., when the head differential exceeds 17.5 m and discharge via the ports can only be accomplished at fully open gate settings), small incremental changes in flows would have been accomplished by switching to spill discharge, thereby substantially increasing downstream TGP levels. In 1999, several instances occurred where these types of small incremental changes in discharge from HLK were avoided. This was achieved through BC Hydro efforts to consolidate small changes in flow into larger incremental changes that allowed the continued use of low level ports to meet the target volume releases. This type of consolidation resulted in major TGP reduction benefits and should be encouraged in the future.

Comments: 1998 and 1999 TDG data from Keenleyside Dam provides background on TDG generation downstream of the Boundary Project.
Reviewers: AO R2 7/6/2005, JSG 6/22/07

RL&L. 2000. *Kootenay River Total Gas Pressure Monitoring 1999 Investigations.* Prepared For Columbia River Integrated Environmental Monitoring Program, Nelson, B.C.

Abstract: SUMMARY (taken verbatim from document)
From this presentation of the time series of the 1999 spring and summer TGP monitoring data, some conclusions can be drawn. TGP levels entering the Kootenay River from Kootenay Lake are generally below the provincial water quality guidelines and provide minimal contribution to the basin TGP load. During low flow periods in April, the majority of discharge from Kootenay Lake is diverted into Kootenay Canal to supply the Kootenay Canal powerplant. A minimum of 142 m3/s (5000 cfs) must be released through Corra Linn to provide water to downstream hydroelectric facilities on the mainstem Kootenay River and prevent dewatering of the river channel. Generation discharge from Corra Linn Dam in April ranged between 140 and 170 m3/s. Spill was minimized during the low flow period; however, the combined discharge of Kootenay Canal, Corra Linn Dam, and the Slocan River frequently exceeded the generation discharge capacity of Brilliant Dam which forced spills of excess water at this site. Increases in TGP levels upstream of Brilliant during low flow (non-spill) periods were attributed to minor gas entrainment during power generation at upstream facilities.

During medium and high discharge periods, when total discharge from Kootenay Lake exceeded maximum Kootenay Canal discharge (581 m3/s), spillways at Corra Linn Dam were used to release excess discharge. Use of spillways at this dam and at all downstream facilities increased TGP, but the major contributions were from the Lower Bonnington Dam and Brilliant Dam spillways. The test at Lower Bonnington between flows over the dam spillways and the natural cascade showed that discharge over the natural falls reduced TGP levels. This spillway operational change reduced TGP, but at the expense of reduced energy generation at the City of Nelson and Upper Bonnington plants because of increased tailwater elevation. Dilution of Lower Bonnington spill by low TGP discharge from Kootenay Canal and the Slocan River reduced the amount TGP measured downstream and reduced the possibility of detrimental effects on fish (i.e., gas bubble trauma). The amount of TGP generated by Kootenay Canal was relatively low when compared to Lower Bonnington; however, based on data from the medium flow monitoring session, all TGP produced by generation at Kootenay Canal appeared to be associated with only one of the four turbines. On 5 July, the suspect turbine was temporarily disengaged, reducing total discharge from approximately 800 to 600 m3/s. This resulted in a reduction of Kootenay Canal tailrace TGP by approximately 50 mm Hg to a level identical to the Corra Linn forebay. Subsequent reactivation of the turbine, Kootenay Canal tailrace TGP increased to the pre-deactivation level as reservoir head and power production approached maximum capacity on 6 July. The reason for increased production of TGP by this unit is unknown.

A cursory examination of the cumulative gate setting at Brilliant Dam indicated that altering Spillway 1 gate settings produced acute changes in downstream TGP levels. In the absence of discharge from Spillway 1, the effects of manipulating other spillways on the downstream TGP data were more pronounced. Overall, Spillways 6, 7, and 8 appeared to produce less TGP, and when run in conjunction with other spillways, reduced downstream TGP levels through dilution. Spills at Brilliant Dam for the operational characteristics that existed during this study, apparently do not result in TGP increases in the tailrace above a threshold level of about 128 percent of saturation, even though the volume of spillwater increased. This suggests that at Brilliant Dam, spill management by selective use of spillways will be beneficial in obtaining lower TGP levels.

Further analysis of the monitoring data by Aspen Applied Sciences Ltd. and R.L. & L. as part of the Brilliant Expansion Project should provide a more quantitative analysis as to the contribution of each facility.

Comments: The Kootenay RIlver is a tributary to the Columbia River in Canada. This report on the 1999 TDG data for this river provides background on the measurements at the Boundary Project.
Reviewers: AO R2 7/6/2005, JSG 6/22/07

Reese, H.O. 1980. *Gas Supersaturation at Reservoir Projects.* In Proceedings of a Seminar on Water Quality Evaluation. (ed. by Committee on Water Quality) US Army Corps of Engineers, Washington, DC.

Abstract: Gas supersaturation has been identified as a potential environmental problem associated with releases from Army Corps of Engineers impoundment projects. Incidents of fish mortality have been attributed to this dissolved gas problem. Fish mortality has been experienced below projects on the Snake and Columbia Rivers, and downstream of the partially completed Harry S. Truman project on the Osage River. The degree of gas supersaturation below a hydraulic structure is primarily dependent on the type of structure, depth of water in plunge pool, and magnitude of flow. Nitrogen, oxygen, argon, carbon dioxide and other gases of air become dissolved in water under pressure when air is entrained with water as small bubbles and subsequently placed under pressure. Laboratory tests show that fish mortality from gas bubble disease is related to the level of total dissolved gas pressure and the time of exposure. Tolerance to supersaturation varies between fish species. The major fish kills experience resulted from gas saturation levels in the range of 120 to 140 percent.

Comment: An early synopsis of dissolved gas problems and potential solutions. Historical reference for TDG at dams.
Reviewer: JSG, 6/1/2007.

Roesner, L.A.; Norton, W.R. 1971. *A Nitrogen Gas (N2) Model for the Lower Columbia River*. Water Resources Engineers, Walnut Creek, CA.

Abstract: (from introduction): The objective of the study reported herein was to develop a mathematical model of the behavior of dissolved nitrogen (N2) in the lower Columbia and Snake Rivers. The model was to be formulated on physical principles to the maximum possible extent, and to be specifically designed to simulate the absorption and desorption of dissolved nitrogen gas in the lower Columbia and Snake River systems. The mathematical model was to be incorporated into a computer program written in the FORTRAN IV programming language for numerical solution. Results from the mathematical model were to be compared to dissolved nitrogen observations taken from a prototype situation operating under a known set of hydraulic and hydrologic conditions. This comparison was to be made on the basis of available sampling and engineering data for John Day Dam and The Dalles Reservoir and was to be used to establish the accuracy and confidence which can be placed on the model.

Comment: An early predictive model that identified the stilling basin as the primary source of dissolved gas super-saturation. A historical reference for TDG at dams.
Reviewer: JSG, 6/1/2007.

Seattle City Light. 1981. *Application for Amendment of License for the Boundary Hydroelectric Project, Project No. 2144*.

Abstract: This document presents the results of the environmental investigations conducted for the proposed expansion of the Boundary Dam Hydroelectric Project, Pend Oreille County, Washington. These investigations were conducted in compliance with Federal Energy Regulatory Commission (FERC) regulations governing applications for License of Major Projects - Existing Dams (Federal Register, Vol. 44, No. 229, 67644-67655, Tues., Nov. 27, 1979).

Comments: Deals directly with Boundary Project. virtually identical to the Review Draft of Exhibit E Environmental Report. Very general - little information available for the project area. Provides a broad overview of water quality in Boundary Reservoir, but data is 25 years old. Historican reference for Boundary.

Review98: Limited to fisheries only. A partial list of fish species found in Boundary Reservoir includes the following species: largemouth bass, brown trout, dolly varden (bull trout), mountain whitefish, lake whitefish, pygmy whitefish (possible) yellow perch (dominant species found), rainbow trout, cutthroat trout, carp, suckers, squawfish, tench, and shiners. Two concerns were expressed by resource agencies: 1) related to the potential impact of reservoir fluctuations on shoreline spawning fishes and 2) the impact of powerhouse releases on downstream fish populations primarily through gas supersaturation.
Reviewers: AO R2 2/14/2005,JL HEC 2/17/2005, KB R2 7/23/1996, JSG 6/20/07

Seattle City Light. 2003. *Recommendations to reduce total dissolved gas levels at Boundary, Internal memo to Mike Harrison, Mike Haynes, Mike Sinowitz and the Boundary Relicensing Team*.

Comment: An internal memorandum that discusses how operations affect TDG levels in the tailwater of the Boundary Dam.
Reviewer: JSG 6/22/07

Seattle City Light. 2004. *Selected Items from Doc 347, Christine Pratt's 3-Ring Binder*.

Abstract: This binder includes miscellaneous notes, presentation handouts, and guidance documents related to water quality. Included are the title page of a 2004 Washington State Department of Ecology (WSDOE) Quality Assurance Project Plan entitled the "Pend Oreille River Total Dissolved Gas Total Maximum Daily Load Technical Study", by Paul J. Pickett. This study describes the monitoring for Total Dissolved Gas (TDG) in the Pend Oreille River in Washington State, to be used in development of a TDG Total Maximum Daily Load (TMDL). The electronic version of this document can be downloaded from:
http://www.ecy.wa.gov/pubs/0403107.pdf

The binder also includes a title page from a 2004 WSDOE Final Draft Guidance Manual entitled "Water Quality Certifications for Existing Hydropower Dams". This manual spells out Ecology's expectations of applicants who want Ecology to certify that a hydropower project meets Washington's water quality standards. The manual is intended to help license applicants, tribes, and the public understand and participate in the Department of Ecology's (Ecology) water quality review process for re-licensing hydropower projects for use by utilities, tribes, the public and Ecology staff. The electronic version of the document can be downloaded from:
http://www.ecy.wa.gov/biblio/0410022.html

Comments: Binder with miscellaneous notes, presentation handouts, and guidance documents related to water quality. Contains information relevant to 303(d) listing for Pend Oreille River.
Reviewers: JL HEC 2/17/2005 JSG 6/20/07

Smith, H.A., Jr. 1974. *Spillway Redesign Abates Gas Supersaturation in Columbia River*. Civil Engineering. 44: 9 70-73.

Abstract: The Corps of Engineers and other agencies are exploring several possible solutions to the gas supersaturation problem. These include more headwater storage, installation of additional power units to reduce the amount of spilling, new spillway stilling basin designs and collection and transportation around the supersaturated stretches of Columbia and Snake River Basins. Spillway deflectors seem to be the most promising solution.

Comment: General information which indicates the general level of knowledge at the time. Historical reference for Boundary Project.
Reviewer: JSG, 6/3/2007.

Sullivan, Robert D., Weitkamp, Don E., Swant, Tim and DosSantos, Joe. 2006. *Controlling Total Dissolved Gas, Lower Clark Fork River Dams*. Report to Avista Corp.

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 percent to 12 percent 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 percent 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.
Comments: Discussion of how operations can make a difference in TDG levels.
Reviewers: CFY R2 5/5/2006, JSG 6/20/07

Tervooren, H.P. 1972. *Bonneville Spillway Test Deflector Installation in Bay 18: Preliminary Evaluation Report on Nitrogen Tests*. USACOE North Pacific Division, Portland, OR.

Abstract: A series of tests were conducted to define dissolved nitrogen conditions under low spill conditions and to provide a comparison of deflector results with identical conditions prior to installation of the test deflectors. Studies were also made of deflector efficiency when forebay saturation levels were 112 percent to 118 percent. Test results indicate that deflectors remove about half of the surplus of dissolved nitrogen. The nitrogen content of the Bonneville forebay is dependent upon upriver spill conditions.

Comment: These tests were low spillway discharges, where there is minor plunging of the spillway flow. Minimal help to the Boundary Project because these discharges are not of concern for spillways.
Reviewer: JSG, 6/2/2007.

Tervooren, H.P. 1973. *Bonneville Spillway Nitrogen Tests, 29-30 October 1972 Test Results.* USCOE North Pacific Division, Portland, OR.

Abstract: The tests of 15 November 1972 confirm the conclusions that deflectors in all bays at Bonneville Dam would reduce excess nitrogen in the spillway fall water by 50 percent. It is reasonable to anticipate that for future Bonneville spill conditions with 100 percent forebay conditions the nitrogen content would not exceed 110 percent if deflectors are installed.

Comment: These results show that incorrect conclusions can result from an analysis of limited data, which occurred in this case.
Reviewer: JSG, 6/2/2007.

Turner, A. Rudder, Jr. 1992. *Fish spill and dissolved gas saturation at Columbia and Snake River dams*. pp. 44-53 in Water Quality '92: Proceedings of the 9th Seminar. WES Miscellaneous Report W-92-3, USACOE Waterways Experiment station, Vicksburg, MS.

Abstract (from introduction): The Corps of Engineers implements substantial water management and project operations measures each year, and conducts research to enhance salmonid survival at its dams on the Columbia and Snake Rivers in the Pacific Northwest Region. These actions include (a) operating adult and juvenile fish passage facilities; (b) collecting and transporting juvenile fish past main stem dams; (c) releasing water from storage reservoirs to flush fish downstream; (d) providing voluntary spill to allow spillway passage; (e) monitoring fish migrations and water quality; (f) operating main stem reservoirs to reduce fish travel time; and (g) conducting fisheries research to improve project passage conditions and increase survival. Fish spill is provided based on the assumption that fish passage mortality is lower for spillway than turbine passage routes. Fish spill management must consider water quality impacts, as total dissolved gas concentrations can approach lethal levels for fish downstream of spillways if not carefully controlled.

Comment: This paper provides an overview of TDG problems at Corps dams on the Columbia and Snake rivers.
Reviewer: JSG, 6/2/2007.

Urban, A. L., Gulliver, J.S. and Johnson, D. 2007. *Modeling total dissolved gas concentrations downstream of spillways.* In Press, Journal of Hydraulic Engineering.

Abstract: Dams are often operated to facilitate downstream juvenile anadromous fish migration over the spillways, but such operation can cause high dissolved concentrations of oxygen and nitrogen that can be harmful to fish. The concentration of total dissolved gas in the flow changes with distance downstream of the spillway crest and depends on the geometric configuration of the spillway and on hydraulic and operating conditions. Quality field measurements are difficult to obtain and can only be used within the field conditions of the measurements. This paper presents a model that simulates the physical processes of gas transfer with the goal of having an accurate and more widely applicable model. Sensitivity analyses demonstrate which physical processes are important for accurate total dissolved gas predictions. This effort will aid other physically-based modeling efforts and eventually reduce the extensive fieldwork that is currently required at each dam.

Comment: This paper demonstrates that the quantity of air entrainment on a spillway surface is not of great importance to TDG in the tailwater, because the air entrained is more than enough to approach steady state TDG levels. Modeling at the Boundary Project will be adapted from the equations in this paper.
Reviewer: JSG 6/11/2007.

US Army Corps of Engineers. 1996. *Dissolved Gas Abatement Study: Phase I Technical Report.* North Pacific Division, U.S. Army Corps of Engineers.

Abstract: This study describes tests to measure TDG on a single deflectored spillway.

Comment: The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.

Reviewer: JSG 5/16/2007.

US Army Corps. 1999. *Dissolved Gas Abatement Study: Phase II-60% Draft Report.* North Pacific Division, U.S. Army Corps of Engineers.

Abstract: This study describes tests to measure TDG on a single deflectored spillway.

Comment: The results may be helpful to estimate the TDG levels that would result from a spillway tunnel released at or near the tailwater surface.

Reviewer: JSG 5/23/2007.

US Army Corps of Engineers. December 2004. *"2004 Dissolved Gas And Water Temperature Monitoring Report Columbia River Basin,"* Columbia Basin Water Management Division Reservoir Control Center Water Quality Unit.

Abstract: (Taken verbatim from Section 1 of Report)
This report describes the Corps' Columbia River Basin Water Quality Monitoring Program for 2004 and was developed to meet the Corps water quality program responsibilities. The report provides information consistent with the total dissolved gas variance issued by the state of Oregon and the rule modification by the state of Washington, meeting the objectives of the NOAA Fisheries Biological Opinion.

The report focuses on the water quality monitoring of total dissolved gas (TDG) and temperature at the 12 US Army Corps of Engineers (Corps) dams in the Columbia River Basin (which includes Bonneville, The Dalles, John Day, McNary, Chief Joseph, Albeni Falls, Libby, Ice Harbor, Lower Monumental, Little Goose, Lower Granite and Dworshak).
Comments: Monitoring summary for the U.S. Army Corps dams on the Columbia and Snake rivers.
Reviewers: CFY R2, JSG 6/20/07

U.S. EPA, Washington State Department of Ecology, and Spokane Tribe of Indians. 2004. *Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt - Submittal Report.*

Abstract: Abstract (taken verbatim from document)
This Total Maximum Daily Load (TMDL) study addresses total dissolved gas (TDG) in the mainstem Columbia River from the Canadian border to the Snake River confluence. Washington State has listed this area on its federal Clean Water Act 303(d) list due to TDG levels exceeding state water quality standards.

EPA is issuing this TMDL for all waters above Grand Coulee Dam and for all tribal waters. Washington State is issuing this TMDL for state waters below Grand Coulee Dam and submitting it to EPA for approval.

Elevated TDG levels are caused by spill events at seven dams on the Mid-Columbia River and by other sources upstream of the international border and in the Spokane River. Water plunging from a spill generates TDG at high levels, which can cause "gas bubble trauma" in fish. Voluntary spills are provided to meet juvenile fish passage goals. Involuntary spills are caused by lack of powerhouse capacity for river flows.

This TMDL sets TDG loading capacities and allocations for the Mid-Columbia River and Lake Roosevelt, both in terms of percent saturation for fish passage and excess pressure above ambient for non-fish passage. Allocations are specified for each dam and for upstream boundaries. Fish passage allocations must be met at fixed monitoring stations. Non-fish passage allocations must be met in all locations, except for an area below each dam (other than Grand Coulee) from the spillway downstream to the end of the aerated zone. Attainment of allocations will be assessed at monitoring sites in each dam's forebay and tailrace and at the upstream boundaries.

A Summary Implementation Strategy prepared by the Washington State Department of Ecology and the Spokane Tribe describes proposed measures that could be used to reduce TDG levels in the Columbia River. Short-term actions primarily focus on meeting Endangered Species Act requirements, while long-term goals address both Endangered Species Act and TMDL requirements.

Comments: TMDL on TDG for the Columbia River from the Canadian border to the Snake River confluence. Could provide the basis for settlement of TDG concerns at the Boundary Project.
Reviewers: AO R2 7/6/2005, JSG 6/20/07

Walla Walla District. 1992. *Lower Granite & Little Goose Projects: 1992 Reservoir Drawdown Test Draft Report.* USACOE, Walla Walla District, Walla Walla, WA.

FROM INTRODUCTION: The report presents 1) background material on the salmon runs and the effects of dam operations; 2) what was accomplished during the drawdown test, including implementation; 3) monitoring and evaluation objectives and procedures, and 4) the data that were obtained.

Comments: Describes performance of spillway flow deflectors under reservoir drawdown conditions, including the effects of drawdown on spillway deflector performance.
Reviewer: JSG 6/4/2007.

Weber, Larry J., Mannheim, Carl. 1997. *A unique approach for physical model studies of nitrogen gas supersaturation.* pp. 518-523 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Community. vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: High levels of dissolved gas downstream of Wanapum Dam on the Columbia River have required Public Utility District Number 2 of Grant County (the District) to investigate various approaches to reduce gas supersaturation levels. To evaluate the effectiven the effects of drawdown on spillway deflector performance The model was used to both qualitatively and quantitatively assess the performance of the flow deflectors. The qualitative evaluation was performed by visual observation of the flow patterns generated by each flow deflector downstream of the spillway. Whereas, the quantitative evaluation was performed by collecting an extensive data set describing the velocity fields and bubble distributions. This data set was then analyzed numerically to predict the downstream concentration of gas supersaturation. The purpose of this paper is to describe the physical model study and the qualitative evaluation of the flow deflectors. A companion paper by Orlins and Gulliver (1997) describes the numerical model developed to analyze the velocity and bubble data.

Comment: The effects of reservoir drawdown on spillway deflector performance.
Reviewer: JSG, 6/4/2007.

Weitkamp, D.E.; Katz, M. *A review of dissolved gas supersaturation literature.* Transactions of the American Fisheries Society. 109: 6, 659-702.

Abstract: A literature review is presented of articles on dissolved gas supersaturation, a condition that results from natural and human-caused processes. Supersaturation can cause gas bubble disease, which has occurred in a wide variety of fishes and invertebrates. The causes are discussed, as well as the organisms affected, factors affecting susceptibility of aquatic organisms, and other related topics. The role of nitrogen partial pressures versus total dissolved gas pressure in causing the disease is treated extensively. The tolerance of various species to supersaturation has been investigated. Tolerance studies have investigated the effects of life stage, temperature , and genetics on development of the disease in fish. Case histories have been compiled, including the famous Columbia River incidents. Various solutions to the problem have been suggested, including passing water through baffles placed at the head of a trough and spillway deflectors.

Comment: A classic compendium of literature published prior to 1980 on fisheries impacts of dissolved gas.
Reviewer: JSG, 6/4/2007.

Weitkamp, Don E., Sullivan, Robert D., Swant, Tim, DosSantos, Joe. 2003. *Behavior of Resident Fish Relative to Total Dissolved Gas, Supersaturation in the Lower Clark Fork River.* Transactions of the American Fisheries Society: Vol. 132, No. 5, pp. 856-864.

Abstract: The behavior of resident fish exposed to total dissolved gas (TDG) supersaturation in Pacific Northwest rivers greatly influences the degree of supersaturation these fish actually experience. Because TDG supersaturation is a physical condition that is moderated by hydrostatic pressure, the depths occupied by fish during supersaturation conditions determine the biological effects experienced by members of the exposed population. Data obtained from fish equipped with depth-sensing radio tags showed that many of the fish spent sufficient time at depths of several meters or more, where they are not exposed to TDG supersaturation. These depths also provide an opportunity to recover from the short-term exposure to supersaturation experienced by the fish during the periods they occupy shallower depths. Most species tagged had median and average depth distributions of about 2 m or more, providing compensation for TDG supersaturation in the range of 120 percent of saturation or more. Tagged rainbow trout Oncorhynchus mykiss generally remained in the river for only brief periods before returning to

Lake Pend Oreille or to the tributaries of the lower Clark Fork River, where they were no longer exposed to TDG supersaturation.

Comments: This is one of many papers on fish behavior relative to TDG. It does attempt to explain the lack of gas bubble trauma observed in fish at 120 percent supersaturation in the field. Reviewers: AFO R2, JSG 6/11/2007

Wilhelms, S.C. and Gulliver, J.S. 2005. *Bubbles and waves description of self-aerated spillway flow.* Journal of Hydraulic Research, 43(5), 522-531.

Abstract: The "continuum" description of self-aerated spillway flow has adequately served to describe spillway bulking, but encounters difficulties when applied to other physical phenomena, such as cavitation and gas transfer. The continuum description is adapted to separate air being transported by the flow as bubbles ("entrained" air), and air transported with the flow in the roughness or waves of the water surface ("entrapped" air). Results from flume experiments on aerated flow are used to develop an analysis procedure and mathematical description of entrained and entrapped air for flow along a spillway face. Entrapped air is found to a constant at a void ratio, with a vertical distribution analogous to the "intermittent" region of a turbulent boundary layer. Entrained air gradually increases to a maximum value depending on slope. Cain's dimensionless distance is used to collapse entrained air data from several unit discharges with the same slope to a single relationship. The analysis procedure and dimensionless parameter provide a means of analyzing a large store of additional literature data. Observations from a full-scale spillway provide verification of the procedure.

Comment: This paper describes self-aerated spillway flow as entrained bubbles and air "entrapped" between the surface waves. The distinction is important because not all of the entrapped air will enter into the tailwater as entrained air.
Reviewer: JSG 6/11/2007.

Gulliver, J.S.; Wilhelms, S.C.; Parkhill, K. 1998. *Predictive capabilities in oxygen transfer at hydraulic structures*. Journal of Hydraulic Engineering, 124 (7) 664.

Abstract: Low-head hydraulic structures within the Corps of Engineers are generally associated with navigation projects. These structures are usually "run-of-the-river" and have the objective of maintaining a constant upstream pool elevation. The effect of the deeper, slower pools is to reduce oxygen transfer as compared to the open river. Biological and chemical oxygen demands may accumulate and concentrate in the impoundment and thereby degrade the DO concentration in the stored water (because of the excess demand compared to reaeration capability). Without sufficient reaeration, release of this water may pose an environmental and water quality concern. The objective of this paper is to report results of an extensive review of predictive models for a variety of low-head structures. Based on the reported data, predictions from several models were evaluated based on the uncertainty of their predictions. The "best" prediction models are recommended for application to "generic" hydraulic structures.

Comment: This paper outlines the 'best' predictive models from the literature for estimating dissolved oxygen levels. The importance to dissolved gas levels is that many of the same processes are predominant in reaeration and TDG transfer.
Reviewer: JSG, 6/11/2007.

Wilhelms, Steven C.; Schneider, Michael L. 1997. *Total dissolved gas in the near-field tailwater of Ice Harbor Dam.* pp. 513-517 in Proceedings: XXVIIth IAHR Congress: Water for a Changing Global Community. vol. D (Gulliver, J.S., ed.) ASCE, New York.

Abstract: Total dissolved gas (TDG) saturation levels were measured and recorded along 3 lateral transects in the immediate area downstream of the Ice Harbor Spillway. The dissolved gas levels were dependent on total spillway discharge and spill pattern, reaching nearly 140 percent at the navigation lock guide wall for the largest discharge. The data showed significant and rapid gas absorption in the stilling basin, with a maximum TDG level of 162 percent at the stilling basin endsill for the largest discharge. A rapid desorption of TDG occurred over the next 200 ft of tailrace, reducing saturation to that measured at the end of the guide wall. These results provide a basis to develop alternative designs to reduce TDG produced at hydraulic structures.

Comments: This paper summarizes the USACE thinking on reducing TDG below dams.
Reviewer: JSG, 6/11/2007.

Wilson, C.J. 1994. *Kenney Dam Release Facility: An overview.* pp. 1-17 in Electricity '94: A new energy order. (ed. by Hydraulic Structures Subsection) Canadian Electrical Assn., Montreal, Quebec.

ABSTRACT: The Kenney Dam Release Facility Will Be Constructed as part of Alcan's Kemano Completion Project in British Columbia to make the fisheries releases to the Nechako River required by a 1987 agreement signed with the Federal and Provincial Governments and to release the majority of excess flood inflow to the reservoir. The design had to meet strict temperature and dissolved gas criteria and was subject to agency review and approval. This paper presents an overview of the facility, including the design objectives and the key features incorporated in the design to achieve those objectives.

Comment: This paper presents what Alcan went through to meet strict TDG requirements.
Reviewer: JSG, 6/11/2007.
No pdf.

Young, M.F. 1982. *Hydraulic Model Studies - Yellowtail Afterbay Dam Sluiceway.* US Bureau of Reclamation Report GR-82-5, Denver, CO.

Abstract: Yellowtail Afterbay Dam is on the Big Horn River 3.5 km below Yellowtail Dam and Powerplant. Releases from the afterbay dam are used to provide uniform daily flow in the Big Horn River, leveling the peaking power generation from Yellowtail Powerplant. At times, gas supersaturation has occurred downstream from Yellowtail Afterbay Dam, resulting in serious fish kills. A 1:24 scale model of Yellowtail Afterbay sluiceway was constructed to study the placement of flow deflectors designed to keep the water jets issuing from the sluiceway gates near the tailwater surface. Deflector plates installed on the curved invert of the sluiceway will reduce jet submergence, a cause of supersaturation. Measurements show no subatmospheric pressures present on the flow deflector lips. Waves within the stilling basin will be larger with the deflectors in place than with the existing configuration, while waves outside the basin will be the same size or smaller. With the flow deflectors in place, the largest velocities, and therefore the most flow, occur near the surface where the pressure is close to atmospheric. With the deflectors in place, material will not be brought back into the basin, although any material thrown into the basin will remain there.

Comment: This report describes some of the considerations of a deflector installation.
Reviewer: JSG, 6/11/2007.

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Appendix 2: Historical TDG Data Analysis Final Report

Boundary Hydroelectric Project (FERC No. 2144)

Historical TDG Data Analysis
Final Report

Prepared for
Seattle City Light

Prepared by
Charles E. "Chick" Sweeney, P.E., Elizabeth W. Roy, P.E.,
Sonia Balsky
ENSR

January 2008

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Boundary Hydroelectric Project (FERC No. 2144)

1 INTRODUCTION

The Total Dissolved Gas (TDG) Historical Data Analysis is being conducted by ENSR in support of the relicensing of the Boundary Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 2144, as identified in the Revised Study Plan (RSP; SCL 2007) submitted by Seattle City Light (SCL) on February 14, 2007 and approved by the FERC in its Study Plan Determination letter dated March 15, 2007. This is the final report for the 2007 study efforts of the TDG Historical Data Analysis at Boundary Dam. This report describes the study objectives, Project background, long-term TDG database development, data analysis through 2006 data, and conclusions and recommendations of the study for 2007 data collection. A supplemental report will describe our analysis of the 2007 TDG data, conclusions, and recommendations for further data collection in 2008.

2 STUDY OBJECTIVES

The objectives of the TDG Historical Data Analysis are as follows:

- Obtain historical flow, TDG, and Project operations data and develop a comprehensive database for a representative time period for study.
- Analyze the data in the historical TDG database for general annual trends, operational history, impacts of upstream operations, forebay to tailrace equilibrium times, and frequency of TDG standard violations.
- Determine and implement a method for detailed analysis of the impacts of Project, spill, and sluice gate operations on TDG production at Boundary Dam.
- If possible, develop predictive equations for TDG production at Boundary Dam as a function of forebay TDG, spill flow, etc.
- Identify potential Project operations that may improve TDG conditions at Boundary Dam, either by limiting the amount of TDG produced or promoting stripping of gas.
- Develop recommendations for further monitoring.

3 PROJECT BACKGROUND

Background information on the Boundary Project location, features and relevant water quality standards is provided in the following sections and was generally obtained from SCL's Pre-Application Document (PAD) (SCL 2006).

3.1. Project Location

Boundary Dam is located on the Pend Oreille River in northeastern Washington, 1 mile south of the Canadian border, 16 miles west of the Idaho border, 107 miles north of Spokane, and 10 miles north of Metaline Falls, as shown in Figure 3.1-1. Boundary Dam is the third of five dams on the Pend Oreille River. Seven Mile Dam and Waneta Dam are located downstream in Canada. Box Canyon Dam is immediately upstream of the Boundary Reservoir, and Albeni Falls Dam is 50 miles farther upstream near Newport, Washington. Boundary Dam operates as a peaking power generation plant; Box Canyon Dam and Albeni Falls Dam are run-of-river facilities.

TDG issues extend well beyond the immediate area of the Boundary Dam Project and the area influenced by Project regulation. TDG produced far upstream of the Project passes through Boundary Dam and downstream to Canada, then back again to the U.S. in the Columbia River downstream to Lake Roosevelt. Project flows and operation are significantly influenced, and have influence in, the reach from Albeni Falls Dam to the Seven Mile project.

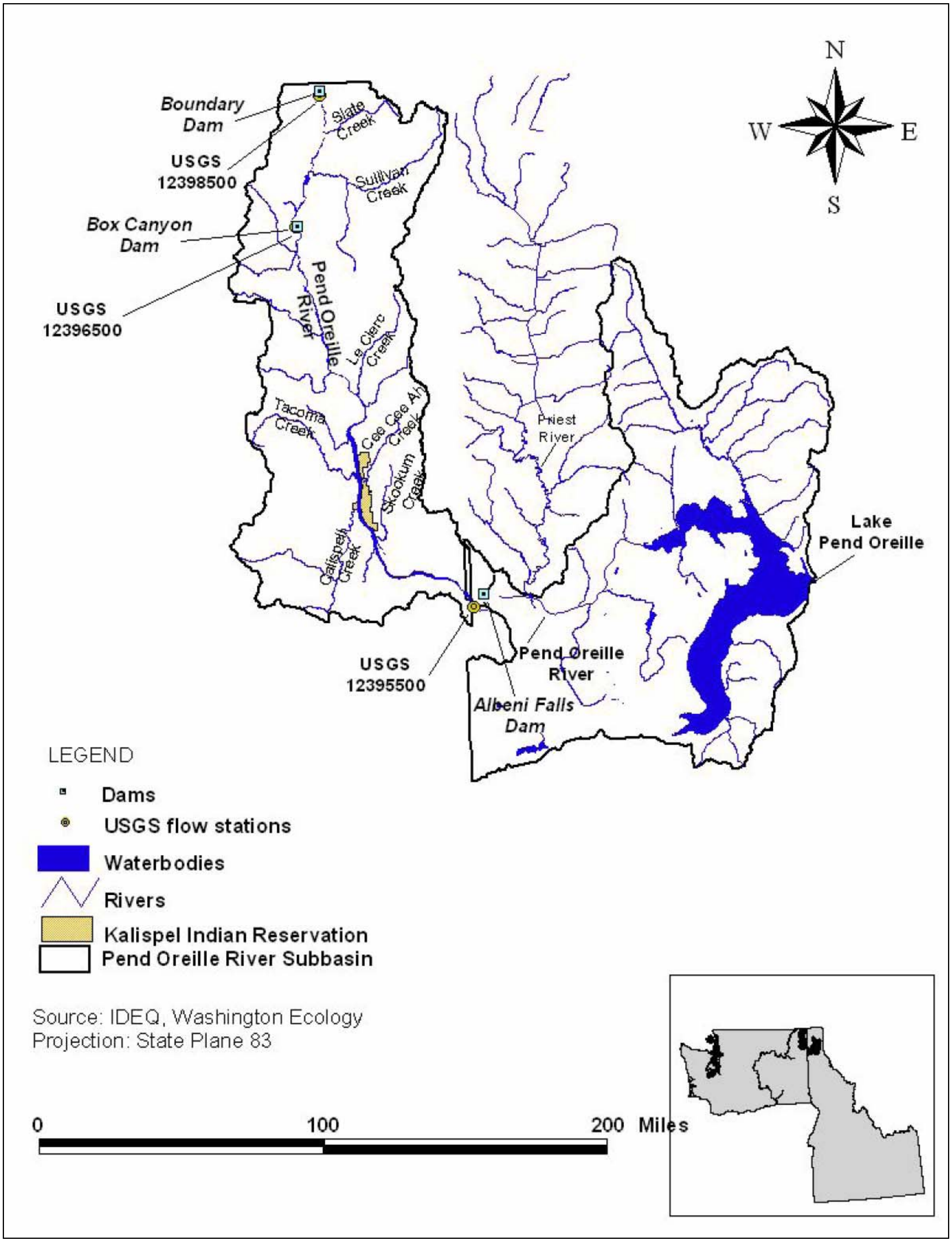

Figure 3.1-1. Project area.

3.2. Project Features

The Project, shown in Figure 3.2-1, consists of an arch dam, reservoir, and underground power plant. Boundary Dam is a variable-radius concrete arch dam with a structural height of 340 feet, a crest length of 508 feet and a total length of 740 feet. It varies in thickness from 8 feet at the crest, which is at elevation 2,004 feet NAVD 88 (2,000 feet NGVD 29[1]) , to 32 feet at the base at elevation 1,644 feet NAVD 88 (1,640 feet NGVD 29). The normal elevation of the river surface below the dam is 1,729 feet NAVD 88 (1,725 feet NGVD 29), resulting in approximately 261 feet of gross head for power purposes.

Boundary Reservoir extends 17.5 miles upstream to Box Canyon Dam. Total storage in the reservoir is approximately 95,000 acre-feet at a normal high water elevation of 1,990 feet NAVD 88 (1,986 ft NGVD 29), and total useable storage is approximately 43,000 acre-feet given the 40-foot maximum reservoir drawdown authorized by the current license.

On each abutment there is a 50-foot-wide spillway with a 45-foot-high radial gate at elevation 1,946 feet NAVD 88 (1,942 feet NGVD 29). The two spillways have a combined total maximum discharge capacity of 108 thousand cubic feet per second (kcfs). In addition, there are seven low-level sluices through the dam under a head of 190 feet that provide 252 kcfs of capacity. The sluice gates are 17-foot-wide by 21-foot-high fixed-wheel gates at elevation 1,860 feet NAVD 88 (1,856 feet NGVD 29). There is also one bascule-type (hinged-leaf) skimmer gate, 26 feet wide by 9 feet high, adjacent to the left spillway at elevation 1,982 feet to permit passage of debris from the reservoir.

The power intake facilities consist of a 300-foot-wide by 800-foot-long forebay, a trashrack structure, and a portal face with six horseshoe-shaped tunnels extending to fixed-wheel intake gate chambers. A penstock leads from each intake gate to one of the turbine-generator units in the power plant (six penstocks total), each consisting of a circular conduit of reinforced concrete down to elevation 1,818 feet NAVD 88 (1,814 feet NGVD 29) and a steel-lined conduit below elevation 1,818 feet NAVD 88 (1,814 feet NVGD 29).

The Project power plant is composed of an underground machine hall, six turbine generator units, draft tubes, and transformer bays. The machine hall houses four 208,000-horsepower (hp) and two 268,000-hp Francis turbines, with four 165-megawatt (MW) and two 205-MW umbrella generators (approximate peak electrical output). Project flow capacity is approximately 55,000 cubic feet per second (cfs). The draft tubes discharge through individual short tunnels at the base of the tailrace cliff. Six transformer bays branch off the dam access gallery and daylight at the face of the cliff above the maximum tailwater.

Flows through the power plant discharge into the tailrace immediately below the dam. BC Hydro's Seven Mile Project, located 11 river miles downstream of Boundary Dam, extends to

[1] SCL is in the process of converting all Project information from an older elevation datum (National Geodetic Vertical Datum of 1929 [NGVD 29]) to a more recent elevation datum (North American Vertical Datum of 1988 [NAVD 88]). As such, elevations are provided relative to both data throughout this document. The conversion factor between the old and new data is approximately 4 ft (e.g., the crest of the dam is 2,000 feet NGVD 29 and 2,004 feet NAVD 88).

Boundary Dam, and the Seven Mile Project periodically backs water up to the base of Boundary Dam. The normal maximum level of the Seven Mile Reservoir is at approximately elevation 1,730 feet NAVD 88 (1,726 feet NGVD 29).

Further information on specific Project features can be found in the PAD (SCL 2006).

[Note: Per guidance from the Federal Energy Regulatory Commission, project facility drawings contain Critical Energy Infrastructure Information (CEII) and have therefore, been omitted from general distribution in the Updated Study Report (USR). This information has been filed with FERC with a CEII designation in Volume 6 of the USR submittal. Procedures for obtaining access to CEII may be found at 18 CFR § 388.113. Requests for access to CEII should be made to the Commission's CEII coordinator.]

Figure 3.2-1. Project site plan.

3.3. Relevant Water Quality Standards

The water quality standards applicable to the Boundary Project are the Washington State Water Quality Standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC). These standards describe designated beneficial uses, water body classifications, and numeric and narrative water quality criteria for surface waters of the state. The revised version of the standards, adopted in 2003, applies to the Boundary Project.

The standards relevant to this study limit total dissolved gas (TDG) based on the adverse impact of dissolved gas on aquatic life. TDG is the amount of air held in saturation in the water, measured in percent of saturation pressure relative to ambient barometric pressure (percent saturation). The criteria for maximum total TDG are summarized in Table 200(1)(f): Aquatic Life Total Dissolved Gas Criteria in Fresh Water.

For waters designated as salmonid spawning and rearing, the standard states that TDG shall not exceed 110 percent of saturation at any point of sample collection. This criterion is waived when the stream flow exceeds the seven-day, ten-year (7Q10) frequency flood. The 7Q10 flow is the highest flow of a running seven consecutive day average using the daily average flows that may occur in a 10-year period. The assumed 7Q10 flow at Boundary Dam is 108,300 cfs (SCL 2006). This estimate of the 7Q10 flow may be refined on the basis of hydrological investigations presently being performed by R2 Resource Consultants.

Previous estimates of spill during the 7Q10 event have been computed based on the assumption that one of the six Boundary Project units is inoperable during the 7Q10 event. However, unit reliability at the Boundary Project is quite high, and maintenance schedules are developed to keep the units operational during the spring flood season. The likelihood of a combined event where the unit is offline during a 7Q10 event is considered very small. For the purposes of TDG abatement alternative evaluation, the target flow for passing the 7Q10 event is assumed to be 53,300 cfs (108,300 minus the Project generation capacity of 55,000 cfs).

4 DATABASE DEVELOPMENT

ENSR conducted a TDG Historical Data Analysis based on two databases, a long-term database of USGS forebay and tailrace fixed monitoring station TDG measurements and a short-term database of TDG from spill and sluice gate tests conducted during spill seasons. The following sections describe the database development.

4.1. Long-Term USGS Database

ENSR developed a long-term database of available data for the period from June 1, 1999, to July 25, 2005, from the USGS forebay and tailrace fixed TDG monitoring stations, Boundary Project operations, and upstream project flows. ENSR obtained data for TDG pressure, barometric pressure, and temperature from the USGS stations in the Boundary Dam forebay (USGS gage No. 12398550) and tailrace (USGS gage No. 12398600) in 15-minute intervals. Hourly water surface elevations for the forebay and tailrace, reservoir storage, and reservoir inflows, and smoothed inflows were obtained from R2 Resource Consultants via a data request on April 26, 2007. Hourly Project spill flows, sluice flows, generation flows (by unit), and Project outflow (generation flow plus spill/sluice flow), and spill and sluice gate settings were provided by SCL. Box Canyon Dam flows were obtained from the USGS gage No. 12396500 in the Box Canyon Dam tailrace.

The data were merged into a single database containing hourly-interval data using Microsoft Access and exported to Excel for analysis. Prior to analysis, adjustments were made to complete missing data and remove anomalous data from the database. These adjustments included filling in forebay barometric pressure data not available in the USGS data record (prior to 2002) with corrected tailrace barometric pressure, filtering out instances of erroneous or missing TDG data, and removing the high tailrace TDG data spikes at the end of December through the beginning of January of each year other than 2002 and the high forebay TDG data spikes in November of 1999-2001. These spikes may be attributable to seasonal maintenance operations or instrumentation maintenance although SCL was unable to explain their origins. In addition to cleaning up the TDG data, generation flows were calculated as the sum of the unit flows provided by SCL, and the total Project outflows were calculated as the sum of the spill flow, sluice flow, and generation flow. Information on actual gate operations (spill gate number or gate setting or sluice gate number or setting) was not available for the long-term database as of the writing of this report, only total spill or sluice flow.

4.2. Short-Term Spill and Sluice Gate Test Database

Data from short-term spill and sluice gate tests were obtained from SCL for 2002, 2003, 2005, and 2006. These data were analyzed to determine the effects of gate operations on tailrace TDG during designated test events. The data were filtered to identify and categorize tests and were merged with the full long-term database where possible on an hourly basis in Access. Data for 2006 and 2007 were not merged with the full long-term database, because the USGS flow and TDG information for the long-term database after August 2005 is not yet available. Provisional data for TDG is currently being used in the short-term database for 2006.

5 PRELIMINARY RESULTS

5.1. Long-Term TDG Data Analysis

5.1.1. Summary of Long-Term Data

The following section provides annual plots with Project flows on the primary axis and TDG on the secondary axis. The Project inflows are from the database provided by R2 and are the smoothed inflows in all years except 2005, where smoothed inflows were not available in the R2 database. All Project outflows in the long-term database fall below the 7Q10 frequency flood of 108,300 cfs and are subject to the Washington State water quality standard criteria detailed in Section 3.3. General trends for flows and TDG for each year of the long term data record are described. In each plot, the forebay TDG is indicated in yellow and the tailrace TDG timeseries are color coded to indicate whether the tailrace TDG is in compliance. The tailrace TDG is in compliance with the water quality standards when the tailrace TDG is below 110 percent saturation (indicated by gray). We have assumed the tailrace TDG is also in compliance when the tailrace TDG is greater than 110 percent but less than the incoming forebay TDG, meaning the Project is stripping gas (indicated by light green). The tailrace TDG is out of compliance when the tailrace TDG is greater than 110 percent and greater than the forebay TDG (indicated by red when the forebay is less than 110 percent and orange when the forebay is greater than 110 percent).

In 1999 the long-term database begins in May due to availability of USGS data for TDG as shown in Figure 5.1-1. In this partial record, the maximum spill flow was approximately 44,000 cfs and the maximum Project inflow was approximately 76,000 cfs. The minimum Project inflows occurred in September and were as low as approximately 10,000 cfs. During the spill season, the tailrace TDG was out of compliance during the higher spill flows (above approximately 12,000 cfs). Note the tailrace TDG was less than the forebay TDG, indicating stripping of gas, during low spill flows less than approximately 12,000 to 14,000 cfs. This occurred over a range of forebay TDG values from greater than 120 percent in early June to 110-120 percent in early July as the spill season came to an end.

It is also important to note the significant fluctuation in the tailrace TDG during times when the incoming forebay TDG was lower (<110 percent) and there was no spill flow. This is likely due to the startup/shutdown operations of the powerhouse units during low flows. The effect of the unit startup/shutdown operations is described further in Section 5.1.3.

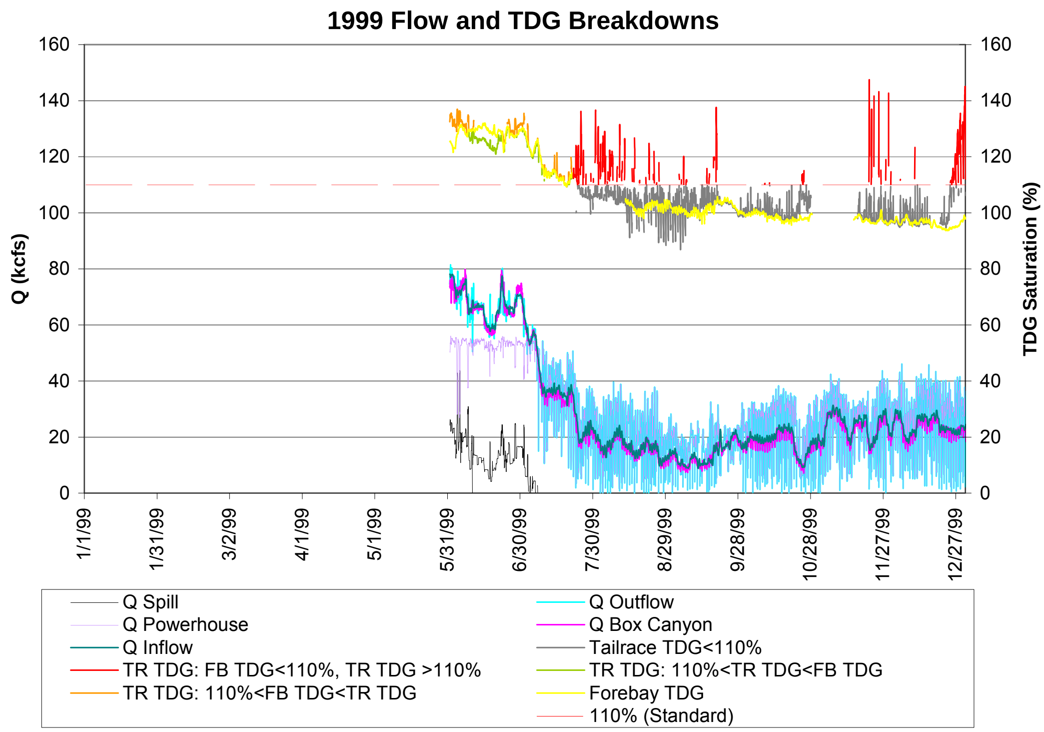

Figure 5.1-1. 1999 flow and TDG breakdowns.

In 2000, there was no spill flow and the maximum Project inflow was approximately 55,000 cfs as shown in Figure 5.1-2. The minimum Project inflow was approximately 8,000 cfs during early September. The tailrace TDG was generally in compliance during times of no spill except occasionally when fluctuations from powerhouse operations increased it to above 110 percent and during a low flow period in August when tailrace TDG values increased to above 130 percent. It is important to note that the powerhouse strips TDG during high powerhouse flows as demonstrated by the tailrace values plotted in green during April, May, and June. A more detailed discussion of the impacts of powerhouse operations is provided in Section 5.1.3.

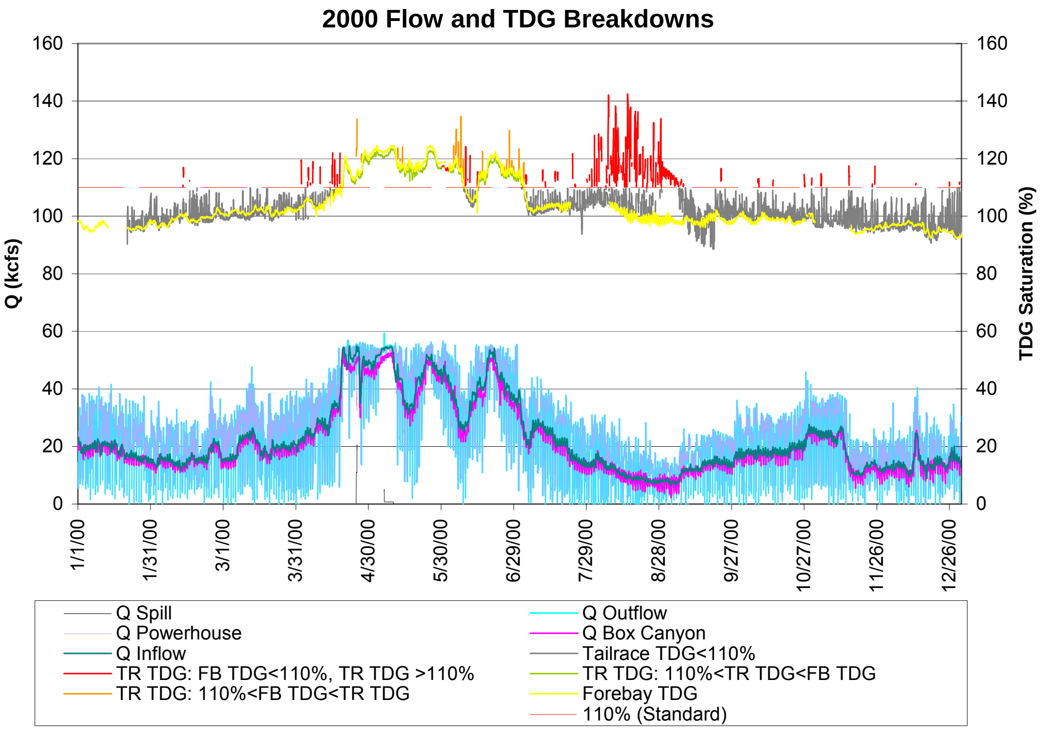

Figure 5.1-2. 2000 flow and TDG breakdowns.

In 2001 the maximum inflow to Boundary Reservoir was approximately 30,000 cfs and there was no spill flow through the Project as shown in Figure 5.1-3. The minimum Project inflow of approximately 8,000 cfs occurred during late winter and late summer. Therefore, all of the TDG production through the Project was due to flow through the powerhouse. The tailrace TDG was out of compliance during the times indicated in red and orange in the plot, corresponding generally to lower powerhouse flows. There was very little incidence of gas stripping by the powerhouse, due to low flows.

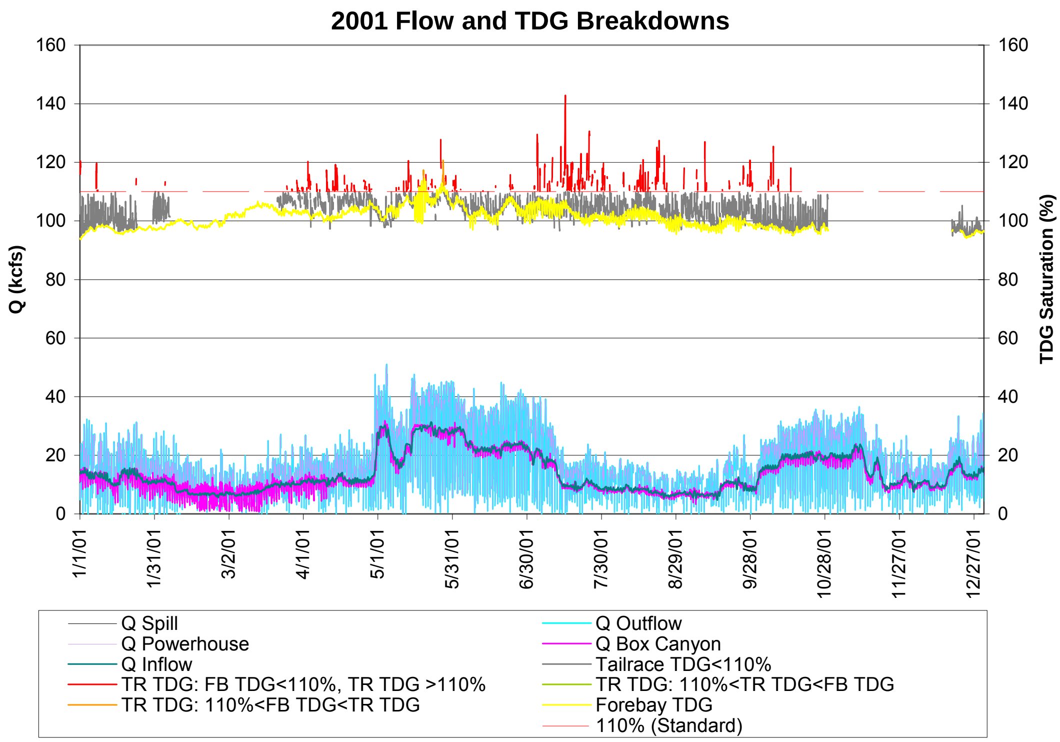

Figure 5.1-3. 2001 flow and TDG breakdowns.

In 2002, the maximum Project inflow was approximately 97,000 cfs and the maximum spill flow was approximately 45,000 cfs as shown in Figure 5.1-4. These conditions are still considerably below, but begin to approach, the 7Q10 conditions of 108,300 cfs inflow and 53,300 cfs spill flow. The minimum Project inflow was approximately 9,000 cfs. Incoming forebay TDG was below 110 percent until the incoming flow began to increase above approximately 33,000 cfs. The forebay TDG increased to as high as approximately 130 percent at an incoming flow of about 80,000 cfs. This corresponds to the river flows when the upstream dams (Albeni Falls and Box Canyon dams) pull their gates to effectively remove their TDG contributions from the river. As the flow increased beyond approximately 80,000 cfs, the forebay TDG decreased to between 110 percent and 118 percent until the gates at the upstream dams were replaced and forebay TDG increased again. As the river flow tapered off in late July, the forebay TDG decreased. Tailrace TDG is greater than 110 percent during the entire spill period and about a month prior to the spill period.

Tailrace TDG was generally in compliance until the forebay TDG rose above 110 percent in April to May. In late April, forebay TDG was above 110 percent but river flows were high enough that at times powerhouse operations resulted in slight gas stripping and kept the tailrace TDG in compliance (shown in green). Flows dropped off slightly in early May, resulting in slight gassing of flows through the powerhouse before the spill season started abruptly in late May. Spill flows above 12,000 to 14,000 cfs resulted in tailrace TDG that was out of compliance with state standards, but spill below this range stripped gas and reduced tailrace TDG to less than forebay levels. The details of the effects of spill and powerhouse operations on gas production the tailrace TDG at the USGS fixed monitoring station are discussed in Sections 5.1.3 and 5.2.2.1.

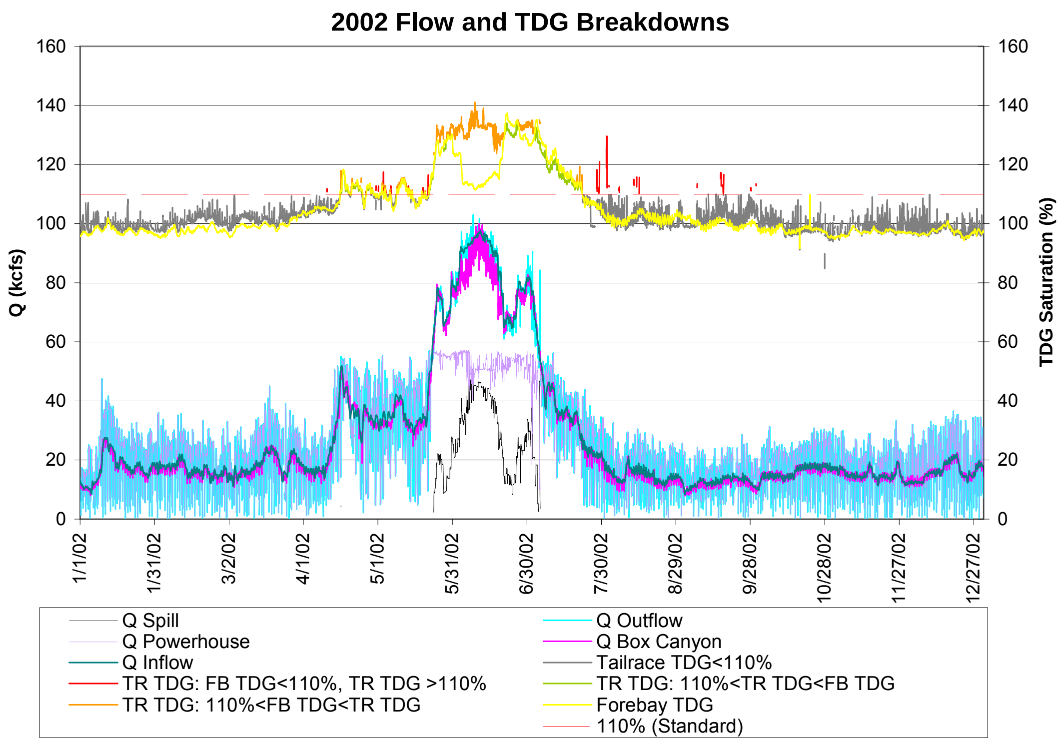

Figure 5.1-4. 2002 flow and TDG breakdowns.

Of the years with data in the long-term database, 2002 has the most complete data record, with flows ranging from low winter flows to spill flows from May through early July. As a benchmark, Table 5.1-1 summarizes the flows in 2002 and the approximate percent exceedance as based on the available flow frequency curves for Box Canyon Dam in the PAD. Updated hydrologic information for Boundary Dam is pending a draft hydrologic report from R2.

Table 5.1-1. Summary of 2002 flow exceedances.

Period	2002 Max Flow	% Exceedance	2002 Avg Flow	% Exceedance
Annual	97,500	1%	26,900	26%
Jan	27,700	5%	17,200	42%
Feb	22,000	16%	16,800	34%
Mar	25,000	22%	18,200	58%
Apr	51,900	6%	29,000	39%
May	80,900	4%	46,300	28%
Jun	97,500	5%	84,300	9%
Jul	82,000	1%	37,400	15%
Aug	21,300	6%	14,700	25%
Sep	15,600	43%	12,500	64%
Oct	19,200	62%	15,900	86%
Nov	19,500	51%	14,900	82%
Dec	22,000	18%	16,000	52%

In 2002, maximum inflow was approximately 97,000 cfs and spill flows were passed through the Project during the period from May 23rd to July 5th. The maximum monthly flow exceedance for the spill season ranged from 1 to 5 percent and the monthly average flow exceedance for the spill season ranged from 9 to 25 percent.

In 2003, the maximum inflow was approximately 68,000 cfs, with a period of spill flow of about 10 days and a maximum spill flow of approximately 20,000 cfs as shown in Figure 5.1-5. The minimum inflow was approximately 5,000 cfs in early September. The forebay TDG ranged from approximately 100 percent to 132 percent and the upstream dams did not appear to pull their gates during this period, due to low river flows (less than 70,000 cfs). Tailrace TDG was above 110 percent during the period when the forebay TDG was greater than 110 percent, but the powerhouse appears to strip TDG during most of this period (mid-April through start of spill on May 31st). Several isolated occurrences of TDG above 110 percent are scattered during the period when forebay TDG was less than 110 percent and was likely due to powerhouse startup and shutdown operations. It is apparent from the tailrace TDG data that a change in powerhouse startup and shutdown operations to reduce TDG production likely was implemented in September or October due to the visible decrease in fluctuation in tailrace TDG on a daily basis. This trend continues through the 2004 and 2005 data, and is apparent in the reduction in occurrences of TDG greater than 110 percent in the frequency analysis in Section 5.1.4 after 2003.

Spill flows less than approximately 14,000 cfs appear to strip TDG (indicated in green). The few instances of spill greater than approximately 14,000 cfs in early June result in gas production and tailrace TDG out of compliance and as high as approximately 130 percent.

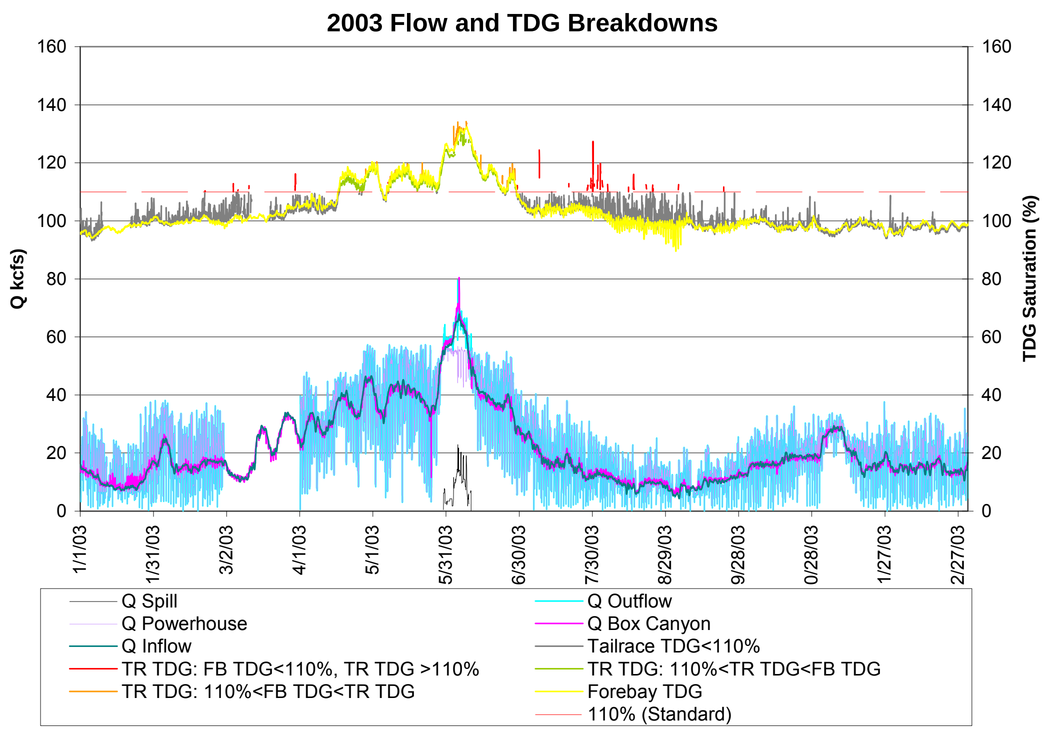

Figure 5.1-5. 2003 flow and TDG breakdowns.

In 2004, the maximum inflow was approximately 50,000 cfs and there was no spill flow through the Project as shown in Figure 5.1-6. Forebay TDG was generally below 110 percent except during inflows greater than approximately 35,000 cfs. Tailrace TDG was also generally below 110 percent except when inflows exceeded approximately 35,000 cfs and forebay TDG was above 110 percent. However, depending on operations the powerhouse generally strips TDG at flows above 35,000 cfs, resulting in tailrace TDG in compliance.

Note the decreased fluctuation in tailrace TDG from forebay TDG in 2004 as compared to previous years. It is likely that this is due to changed startup/shutdown procedures and improvement to the air admission issues at Units 55 and 56 described in the PAD (SCL, 2006). In early July through September, the fluctuation appears to return during low flow periods. However, the flows in January through February were just as low, and did not result in as much fluctuation in tailrace TDG as in the summer months. It is possible that the operating scenario for maintaining pool elevation for summer recreation differs from the winter operation and impacts TDG differently.

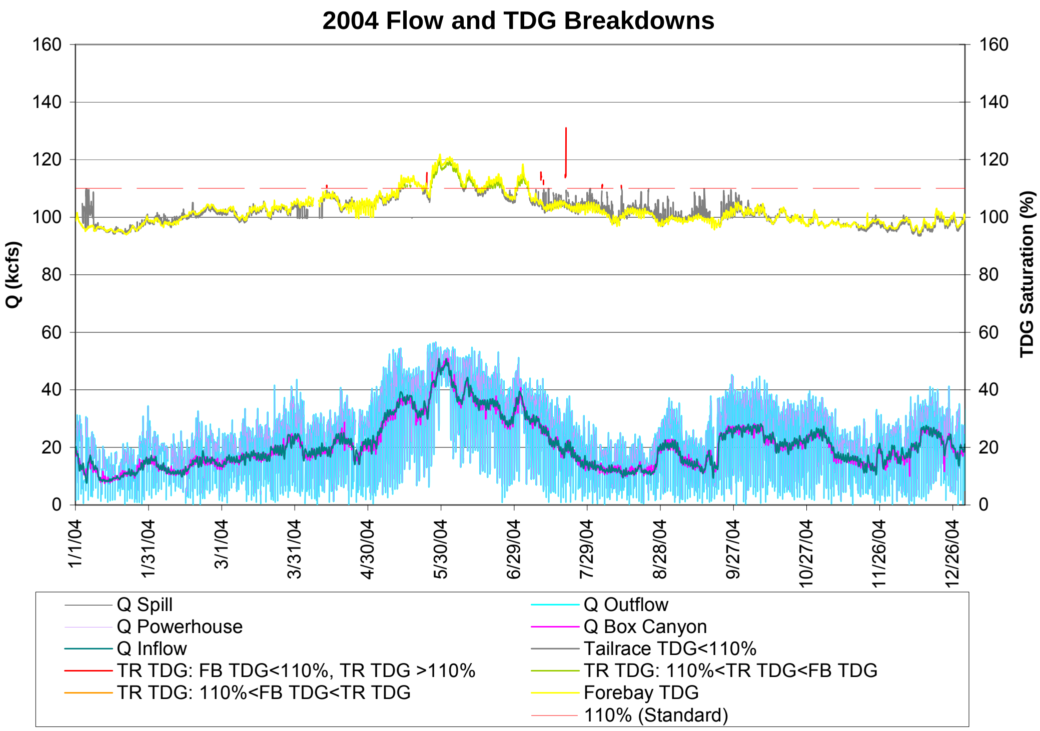

Figure 5.1-6. 2004 flow and TDG breakdowns.

Due to the availability of USGS data for the forebay and tailrace TDG meters, the long-term database ends after July 2005 as shown in Figure 5.1-7. For this portion of the year the smoothed inflows were not available in the R2 database and the unsmoothed Project inflows are shown instead. For the period of record, the maximum unsmoothed Project inflow was approximately 60,000 cfs and the minimum unsmoothed Project inflow was approximately 4,000 cfs. Several days of spill occurred in early June, with a maximum spill flow of approximately 24,000 cfs.

Note that the tailrace TDG fluctuation is similar to that for 2004 until the spill season. Tailrace TDG was in compliance until spill peaked between approximately 12,000 and 24,000 cfs. The variability in tailrace TDG picked back up after flows dropped off in July after the spill season and may be following the same trend seen for 2004. Additional long-term data will be required to investigate this trend further after the 2005 data is fully released by USGS.

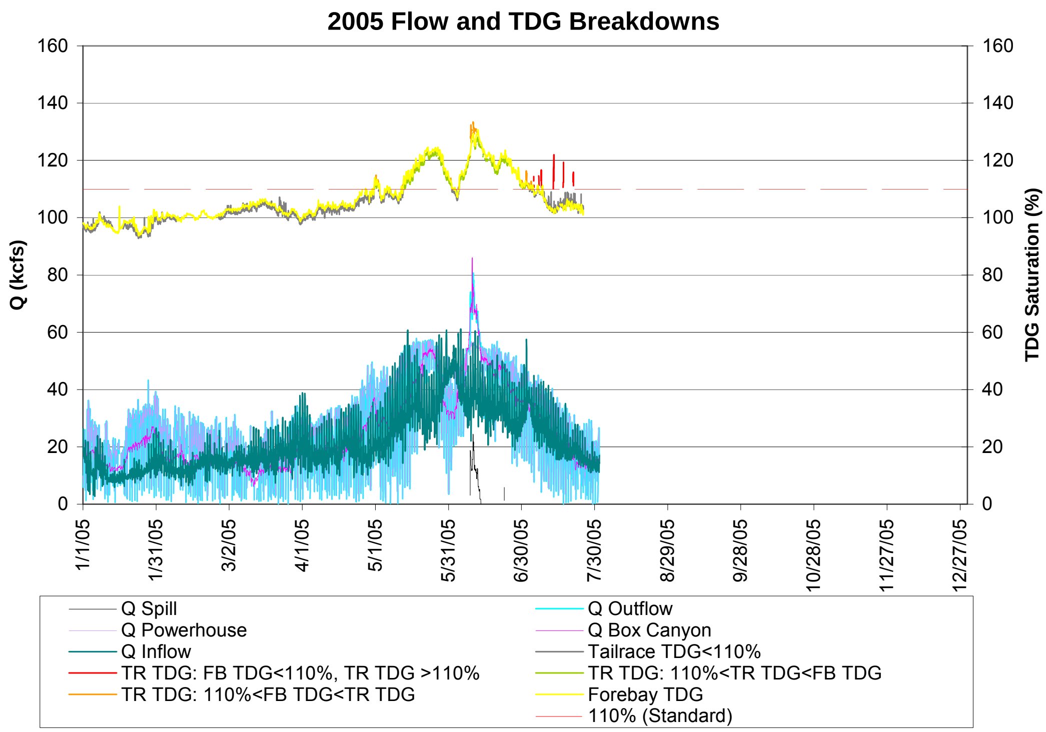

Figure 5.1-7. 2005 flow and TDG breakdowns.

5.1.2. Relationship of Forebay TDG to Upstream Operations

Boundary Dam forebay TDG is influenced by upstream project operations at Albeni Falls and Box Canyon dams due to the hydraulic capacity of the upstream projects. Albeni Falls Dam has a hydraulic capacity of 29,000 cfs and Box Canyon Dam has a hydraulic capacity of 33,000 cfs. Above these river flows, both dams increase the TDG in the river and in the Boundary Dam forebay as flow passes through spill gates and plunges into the tailwater. As river flow increases, both projects pull their gates completely out of the water (Albeni Falls Dam at 74,000 cfs and Box Canyon Dam at 90,000 cfs), removing the plunge to pass flows unimpeded and effectively eliminate their TDG contributions to the river.

Using the long-term database, ENSR developed a relationship between Box Canyon Dam tailrace flows and Boundary Dam forebay TDG to predict the incoming forebay TDG at Boundary Dam as a result of upstream operations, as shown in Figure 5.1-8 on the following page. The relationship between Box Canyon tailrace flows and Boundary Dam forebay TDG shows that there is a reasonably good correlation between upstream flow and forebay TDG (R^2 = 0.78). The correlation is likely not valid for flows above approximately 90,000 cfs or below approximately 8,000 cfs due to lack of data. It is also important to note that this correlation provides a retrospective indication of the incoming TDG in the Boundary Dam forebay due to upstream operations for a range of river flows. If upstream projects improve their TDG performance with operational or structural measures, this correlation will change.

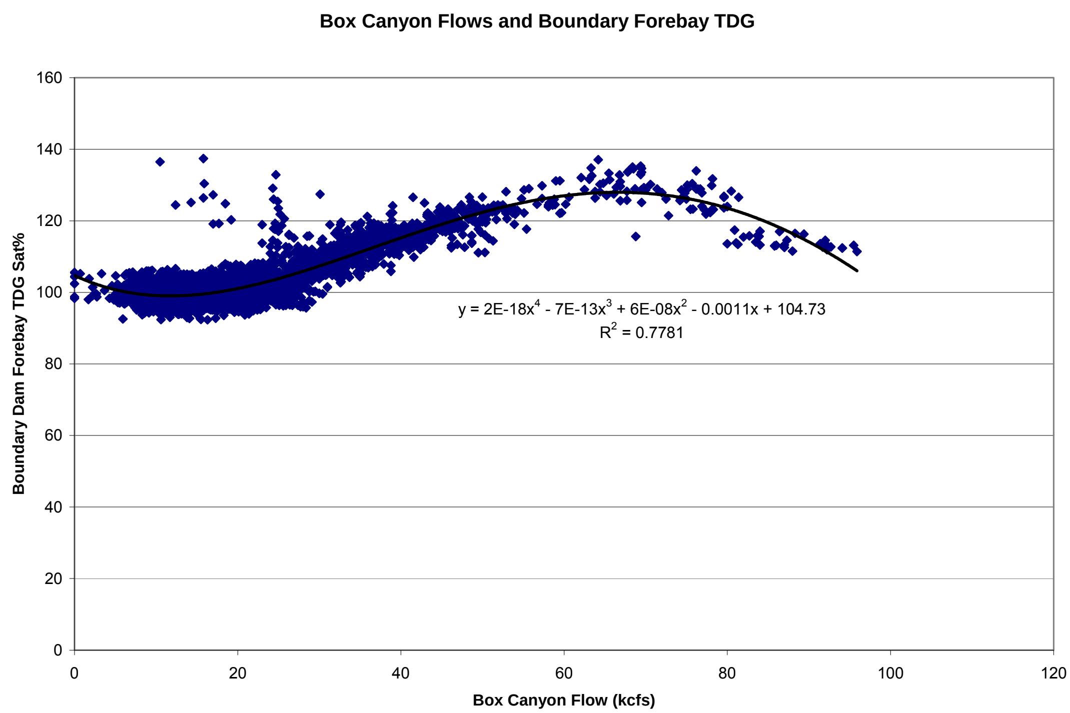

Figure 5.1-8. Box Canyon Tailrace Flows and Boundary Dam Forebay TDG Correlation (note: this correlation is not valid at flows above approximately 90,000 cfs or below approximately 8,000 cfs).

An important correlation would be to determine the amount of change in TDG that occurs from the Box Canyon Dam tailrace to the Boundary Dam forebay over a range of river flows due to natural river processes. This correlation would be useful for predicting the implications of future improvement to upstream operations on the incoming forebay TDG at Boundary Dam. At the time of this study, long-term tailrace TDG data was not available for the USGS station at Box Canyon Dam.

5.1.3. Development of Long-Term Tailrace TDG Regression Equations

ENSR developed regression equations from the long-term database to describe the change in TDG levels between the forebay and tailrace during times when the Project outflow is at or below powerhouse capacity and there is no spill flow, and another regression equation to describe the change in TDG levels as a function of Project outflow during times when there is spill flow from the Project. These equations were determined using the long-term database as described in the following sections for the powerhouse and spill flows. The long-term powerhouse TDG regression equations were then used to remove the effects of the powerhouse from short-term spill test data to determine the effects of gate settings and operations on TDG production as described in Section 5.2.2.

5.1.3.1. Powerhouse Operations TDG Regression Equations

The long-term database was filtered for Project outflows ranging from 0 to 50,000 cfs (just below Project capacity) and a second filter was applied to remove any instances of spill flow with outflow less than 50,000 cfs. The filtered dataset consisted of powerhouse only operations for Project outflows less than 50,000 cfs. A plot of the TDG gain from forebay to tailrace as a function of Project outflow is shown in Figure 5.1-9. The data from 1999 through September 2003 is plotted in maroon and the data from September 2003 through the end of the long-term database in July 2005 are shown in blue. Based on the observations of the long-term forebay and tailrace records for 1999 through 2005 it was apparent that an operational change in approximately September 2003 decreased the amount of fluctuation in TDG from the forebay to the tailrace during periods of low powerhouse flows and frequent unit startup and shutdown.

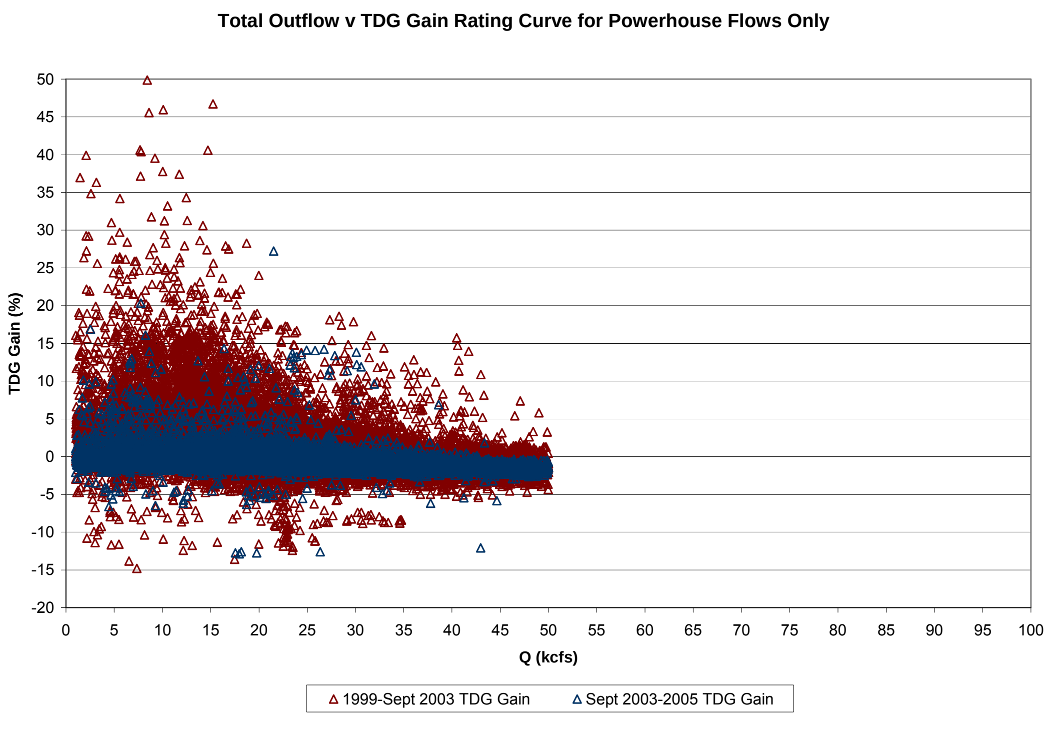

Figure 5.1-9. Long-term TDG gain for powerhouse-only operations.

SCL implemented changes in powerhouse startup and shutdown operations to reduce air admissions at Units 55 and 56. Previous testing indicated that during low flow operations when the units are throttled, air admitted through the turbine runner contributed to spikes in tailrace TDG. This was an issue particularly during startup and shutdown procedures when Units 55 or

56 were operated as the first units on or last units off. SCL implemented procedures to limit the use of Units 55 and 56 as the first on/last off to improve tailrace TDG.

Based on the apparent shift in operations in September 2003, the database was divided into two parts, before and after September 2003, and two regression equations were developed to show TDG production as a function of powerhouse flows before and after the shift in Project operations. TDG production from generation flows alone before the standard powerhouse operations procedure was adjusted in late September 2003 can be expressed by the equation $\Delta TDG = -0.00015*Q + 5.0716$ (Figure 5.1-10), where Q represents the total outflow. After the operations change in approximately September 2003, TDG production from the powerhouse decreases, especially at lower flows, and the regression equation for TDG gain as a function of powerhouse flow becomes $\Delta TDG = -0.00005*Q + 0.8178$ (Figure 5.1-10).

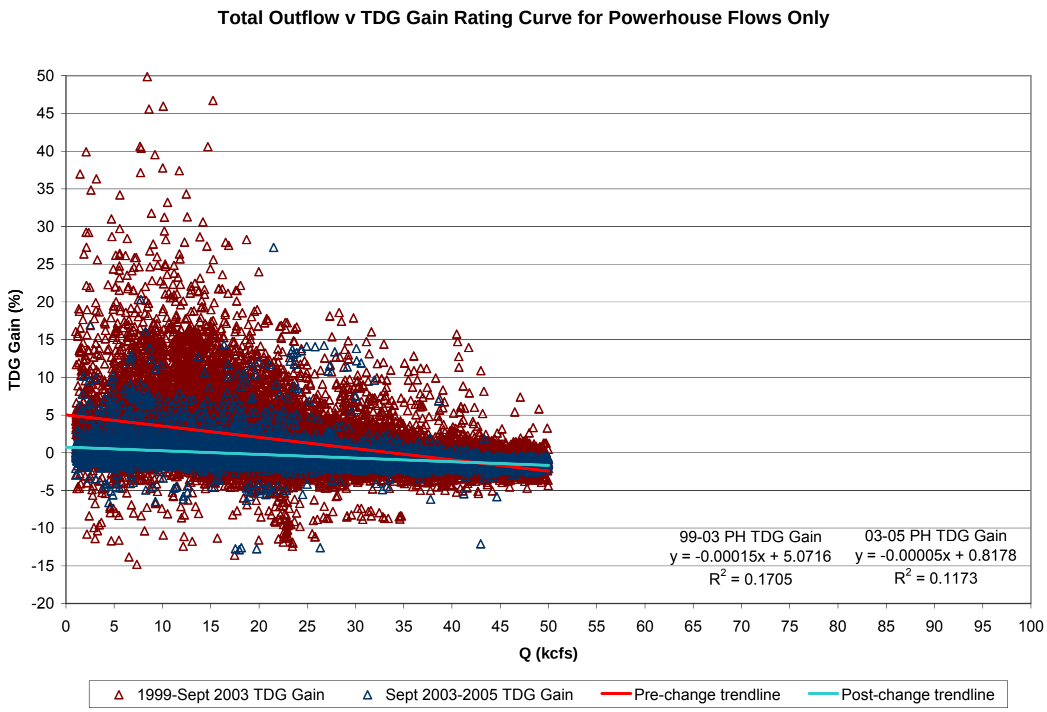

Figure 5.1-10. Regression analysis for TDG gain as a function of total flow during periods of no spill when Q<50,000 cfs prior to and following the September 2003 adjustment in standard powerhouse operations.

There should be no difference in air admissions between the two operating procedures above a certain flow, represented by the point in Figure 5.1-10 where the regression lines cross. Based on this, the change in TDG attributed to the powerhouse is assumed constant at -1.3 percent above 42,500 cfs of generation flow when using these equations in the following sections.

5.1.3.2. Spill Operations TDG Regression Equations

The full long-term database was filtered for instances when spill flow was greater than zero, generally for Project outflow greater than the powerhouse capacity of 55,000 cfs. For river flows above about 55,000 cfs, the cumulative effects of powerhouse and spill flow on tailrace TDG at the fixed monitoring station can be roughly described using the equation $\Delta TDG = 0.000625*Q - 41.7955$, where Q represents the total Project outflow and includes both powerhouse and spill flows as shown in Figure 5.1-11. The long-term neutral point resulting in no net TDG production from forebay to the tailrace USGS fixed monitoring station for the combined powerhouse and spill flows is approximately 67,000 cfs and reached as high as approximately 79,000 cfs.

Further analysis was performed above the powerhouse capacity when spill effects are dominant to attempt to separate the TDG stripping action of the powerhouse units from the influence of the spill gates. The following mass balance equation was used to isolate the TDG saturation expected to result from spill flow from the long-term database:

$$TDG_{spill} = \left(TDG_{TR}Q_{outflow} - TDG_{PH}Q_{PH}\right) / Q_{spill} \quad \text{(Equation 1.0)}$$

Where:

TDG_{TR} = tailrace TDG from long-term database
$Q_{outflow}$ = total Project outflow (spill flow plus powerhouse flow)
TDG_{PH} = FB TDG + ΔTDG due to powerhouse (from regression equation in Section 5.1.3.1
Q_{PH} = powerhouse flow from long-term database
Q_{spill} = spill flow from long-term database

The resulting TDG_{spill} was used to calculate a TDG gain from the forebay to the tailrace due to spill alone as shown in Figure 5.1-11 for flows above approximately 60,000 cfs. It is important to note that use of Equation 1.0 assumes the mass balance equation is a valid representation of the interaction of powerhouse flows and spill flows. We are using the TDG regression equations developed for powerhouse flow only and applying them to situations when spill is present as well, assuming that the powerhouse flow is mixed with the spill flow and is not gassed-up considerably by the spill flow. This assumption will provide conservative estimates of the TDG gain due to spill flow and is likely most relevant at low spill flows when the spill flow is not likely to entrain powerhouse flow.

The results of the mass balance in Figure 5.1-11 are not realistic at low flows and over-represent the stripping of TDG from the flow due to the spill gates. At low spill flows there is significant variability in the measured delta TDG from the forebay to the tailrace due to combined powerhouse and spill flows. At low flows, some of the measured delta TDG values for total outflow fall below the estimated delta TDG from the powerhouse regression equation, but within the powerhouse delta TDG variability, and cause the results of the mass balance to indicate more TDG stripping than is likely by the spill gates (delta TDG as high as 20 percent).

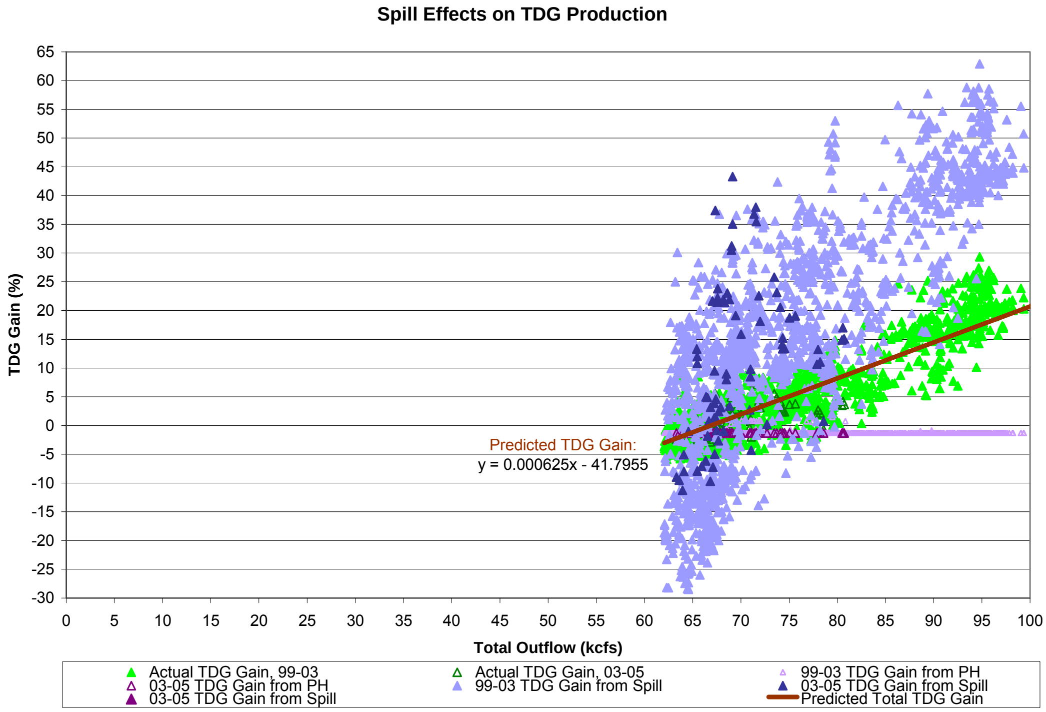

Figure 5.1-11. Regression analysis of TDG production due to spill flow, with powerhouse flow contribution removed.

The estimated TDG gain due to spill flow alone for higher flows (above approximately 75,000 cfs total outflow) provides a range of conservative values for TDG gain due to spill as a check for analysis of individual gate tests in Section 5.2.2.1. Based on this analysis, the TDG gain due to spill flow appears to reach a maximum at approximately 60 percent as total outflow increases beyond approximately 85,000 cfs. Additional detailed analysis of the impacts of gate operations on tailrace TDG are described in Section 5.2.2.1.

To provide a frame of reference for spill frequency, Table 5.1-2 summarizes the amount of time the Project was spilling below 5,000 cfs, at 5,000-10,000 cfs, at 10,000-15,000 cfs, and above 15,000 cfs over the historical data record and the corresponding forebay and tailrace TDG levels. Table 5.1-3 presents the same information for 2002, the year we are considering a representative year. Over the long-term database period from 1999 to 2005 spill occurred during only 4.4 percent of the hours for which data were available. In 2002, spill occurred slightly more frequently, during 11.8 percent of the hours with data for 2002, with the majority of the spill flows in 2002 above 15,000 cfs.

Table 5.1-2. Spill behavior, 1999-2005.

Category	Hours	% of Total	% of Spill	Avg FB TDG	Avg TR TDG	Avg TDG Gain
Spill	2358	4.4%		128.0	128.0	0.0
No spill	51555	95.7%		103.4	106.0	1.7
Spill >15 kcfs	1203	2.2%	51.6%	127.9	131.4	3.5
Spill 10-15 kcfs	544	1.0%	23.3%	128.7	127.3	-1.4
Spill 5-10 kcfs	308	0.57%	13.2%	128.6	124.5	-4.1
Spill 1-5 kcfs	275	0.51%	11.8%	123.9	122.2	-1.7

Table 5.1-3. Spill behavior, 2002.

Category	Hours	% of Total	% of Spill	Avg FB TDG	Avg TR TDG	Avg TDG Gain
Spill	1034	11.8%		123.4	131.4	8.0
No spill	7726	88.2%		101.6	103.0	1.3
Spill >15 kcfs	825	9.4%	79.8%	121.7	132.2	10.5
Spill 10-15 kcfs	140	1.6%	13.5%	131.3	129.8	-1.5
Spill 5-10 kcfs	56	0.64%	5.4%	128.1	126.0	-2.2
Spill 1-5 kcfs	13	0.15%	1.3%	126.1	124.0	-2.2

5.1.4. TDG/Flow Frequency Analysis

For each year we conducted a frequency analysis to determine the percentage of measurements of forebay and tailrace TDG greater that the water quality standard of 110 percent. The percentage of measurements in compliance and exceeding the standard, along with several subcategories, are shown in Figure 5.1-12 for each year in the long-term database. The percentage removes the influence of missing or poor quality data. The percentage of tailrace measurements in compliance (solid blue circles) and out of compliance (red +'s and orange x's) sum up to 100 percent for a given year. The analysis demonstrates the trend of an increasing percentage of tailrace TDG measurements in compliance over the long term study period (solid blue circles).

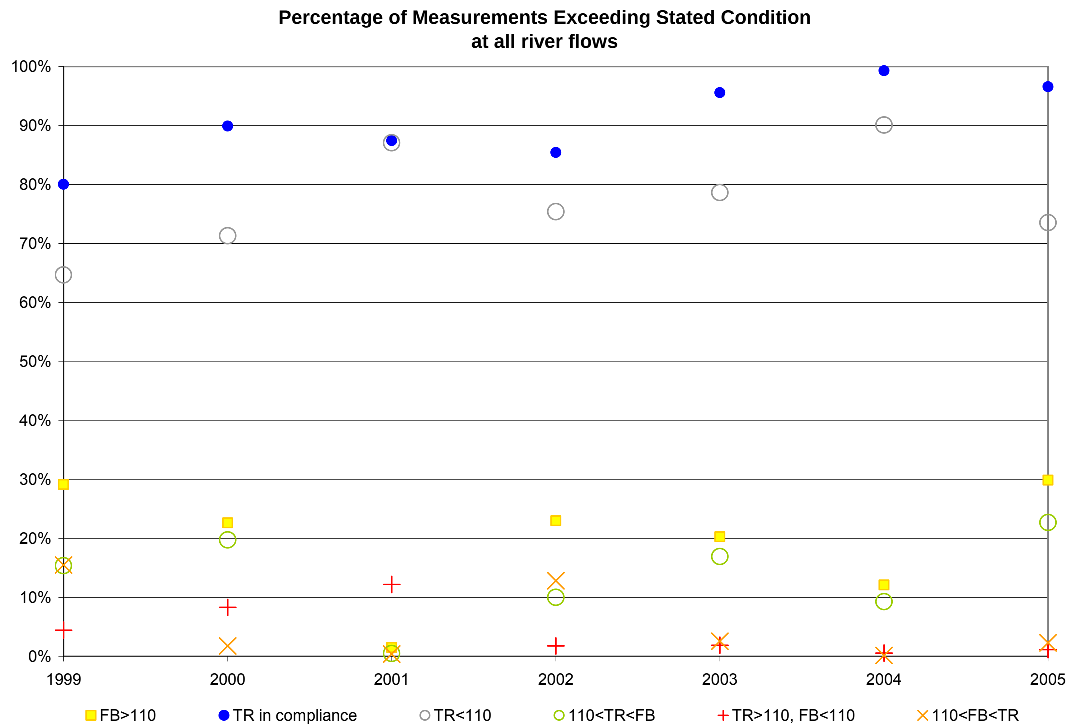

Figure 5.1-12. Frequency analysis of TDG compliance at all Project outflows.

To isolate a possible reason for the trend and the potential for improvement in tailrace TDG, the data were separated by Project outflows into two categories: powerhouse only (0-50,000 cfs) and spill (50-80,000 cfs) flows and the frequencies were recalculated based on the subset data. The results of the exceedance frequency analysis for powerhouse only flows are shown in Figure 5.1-13. The trend of improvement in tailrace TDG during low flows after 2002 likely is a result of the change in Project operations in 2003 in terms of powerhouse first on/first off operations. The total percentage of measurements showing TDG production through the powerhouse (orange x's) and resulting in tailrace TDG >110 percent (red +'s) decreases through 2003.

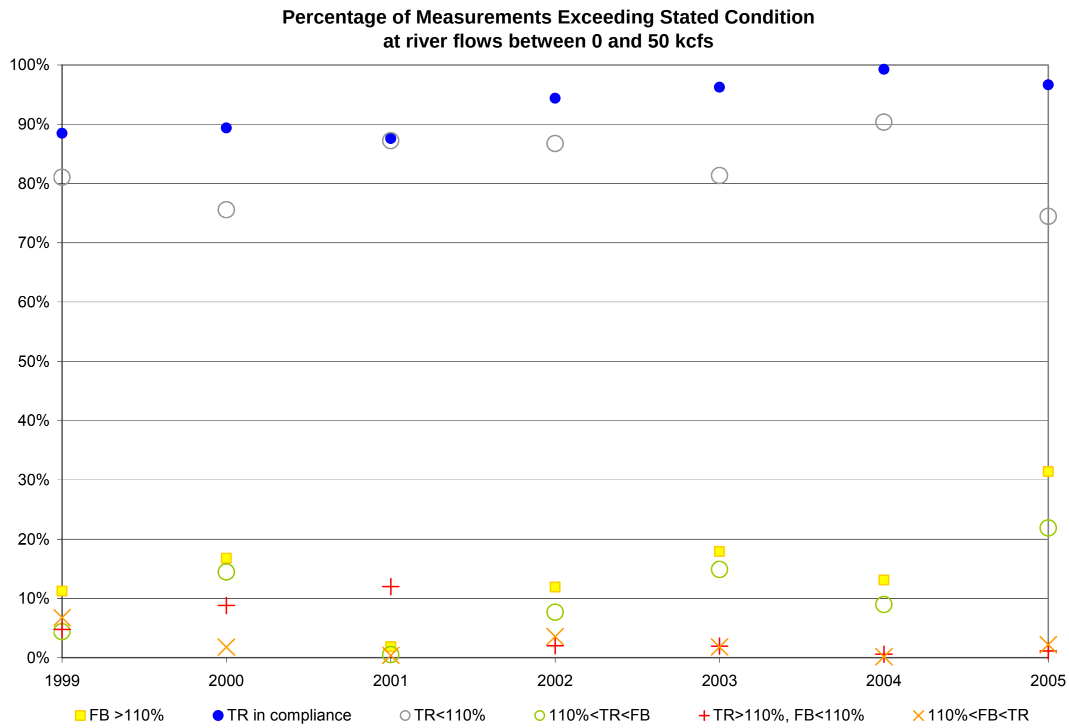

Figure 5.1-13. Frequency analysis of TDG compliance at low Project outflows (no spill).

In order to relate the exceedances due to spill flow for each year, we filtered the long term database for periods where the Project outflow was greater than 50,000 cfs, when there is generally spill flow above the powerhouse capacity, but less than 80,000 cfs to eliminate the influence of operations at Box Canyon and Albeni Falls dams. The frequencies were recalculated based on the subset spill season data and are shown in Figure 5.1-14. During years when spill flow was present (1999, 2000 very briefly, 2002, 2003, and 2005), at river flows above 50,000 cfs the tailrace TDG is generally in compliance (solid blue circles) due to stripping (green circles) from 45 to 95 percent of the spill season, depending on the year and the range of spill flows. The orange x's and red +'s indicate the percentage of measurements during the spill season when TDG is produced, and may indicate a condition where there is potential for improvement through operations or structural modifications.

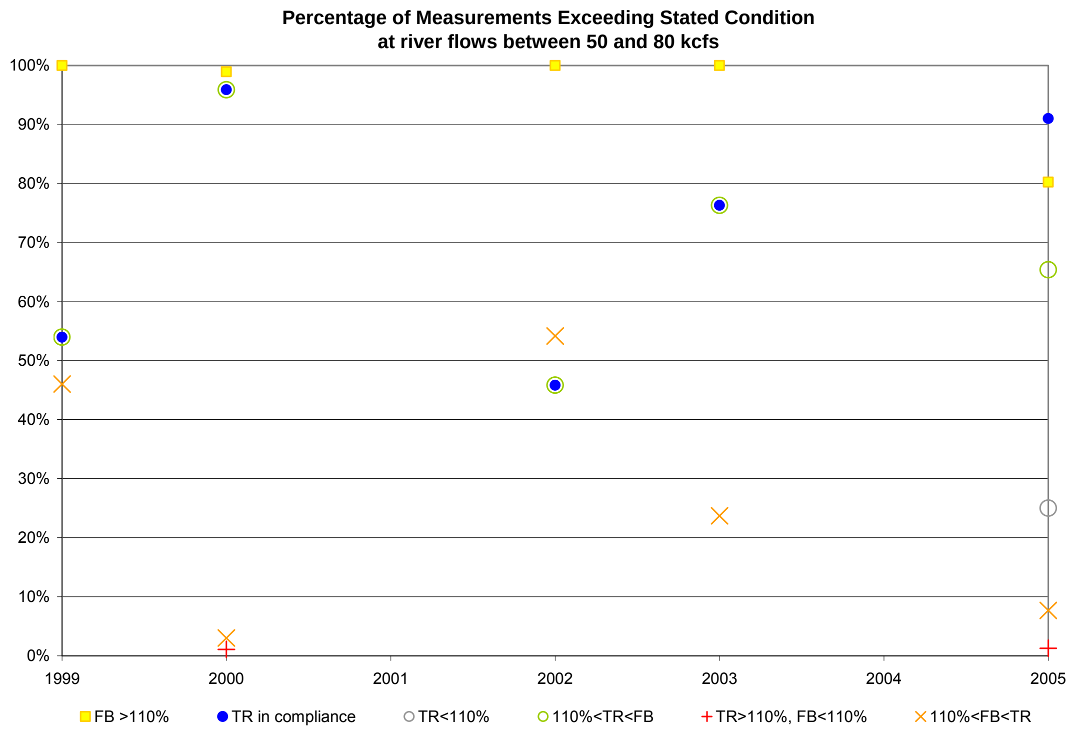

Figure 5.1-14. Frequency analysis of TDG compliance during spill season.

5.1.5. Impact of Project Operations on TDG/Flow Frequency Analysis

ENSR developed regression equations for TDG production as a function of powerhouse flows as described in Section 5.1.3.1. Two equations were developed for the long-term data period, one for TDG production through the powerhouse prior to September 2003 and one after September 2003 when powerhouse operation changes appear to decrease fluctuation of tailrace TDG during low flows and startup/shutdown operations. Because 2002 has a complete range of flows from low flows to spill flows, we used the data from the 2002 database to further assess the impacts of the improved powerhouse operations on tailrace TDG.

Table 5.1.5-1 shows the percentage of tailrace TDG measurements out of compliance in 2002 based on the actual data in the long-term database (either exceeding the standard of 110 percent or increased TDG above the forebay level when the incoming forebay is 110 percent or more). In addition, we used the regression equation for TDG production through the powerhouse prior to September 2003 and the regression equation developed for TDG as a function of flows greater than the powerhouse capacity to predict the tailrace TDG for the Project outflows (powerhouse and spill flow) for 2002 from the long-term database. A frequency analysis was performed on the predicted 2002 tailrace TDG values and the resulting percentages of predicted tailrace TDG values out of compliance are in Table 5.1-4. We then applied the tailrace TDG regression equation for the improved powerhouse operations after September 2003 to predict tailrace TDG values for 2002 as if the improved operations had been instituted before 2002. A frequency analysis was performed on the improved 2002 predicted TDG values and the results are shown in Table 5.1-4.

Table 5.1-4. Predicted effect of powerhouse operations change on exceedance frequency for 2002.

	Not in compliance	TR>110, FB<110	110<FB<TR
Actual	14.6%	1.8%	12.8%
Predicted with pre-September 2003 regression	15.3%	2.0%	13.2%
Predicted with post-September 2003 regression	10.3%	0.2%	10.1%

5.2. Short-Term Data Analysis

5.2.1. TDG Equilibrium Time

ENSR conducted an analysis of the equilibrium time required for the tailrace TDG levels at the USGS tailrace TDG station to stabilize following a major operations change (spill gate setting change, sluice gate setting change). We found that the time required for equilibration was approximately 4 hours when TDG is increasing and three hours when TDG is decreasing, based on a visual analysis of the gate operations data for 2002.

5.2.2. Summary of Spill and Sluice Test Data

5.2.2.1. Spill Operations

On the basis of the equilibration time analysis in Section 5.2.1, we filtered the short-term database described in Section 4.2 to find instances when the same gate settings were maintained for at least the equilibrium time, and extracted these “tests” into a subset database for the purpose of gate operations analysis. In the 1999-2005 period for which we have a complete data set, spill flows occurred for 2.5 months in 2002 from the beginning of May to the middle of July, as well as during the first week of June in both 2003 and 2005. These data translate into 57 tests in 2002 and six tests in 2003, of which 12 tests contain flow from Gate 1 only, 3 tests contain flow from

Gate 2 only, and 48 tests contain both Gate 1 and Gate 2 flow. The ratio of Gate 1 to Gate 2 flow in the tests when both gates are spilling is predominantly 50:50, aside from six tests at 60:40 and one test at 75:25. The spill flow in 2005 did not contain any tests as defined above, so all spill tests drawn from the short-term database occurred before the presumed change in powerhouse operations procedure. The spill tests for 2006 were analyzed in conjunction with the 2007 tests to assess the impacts of spill during similar powerhouse operations and will be described in a supplemental memorandum.

The following plots show the average measured TDG gain (forebay TDG minus tailrace fixed monitoring station TDG) from the short-term database during the spill tests for Gate 1 only (Figure 5.2.2-1), Gate 2 only (Figure 5.2.2-2), and Gate 1 and Gate 2 operating together (Figure 5.2.2-3). The measured forebay TDG (magenta squares), tailrace TDG at the fixed monitoring station (dark blue diamonds), and total TDG gain from the forebay to the tailrace (green open and solid triangles) are shown in each plot. In addition, each figure shows the approximate linear regression equation for total TDG gain as a function of spill flow. For the Gate 1 only and Gate 2 only tests, the plots show the total TDG gain as a function of spill flow per bay. For the Gate 1 and Gate 2 combined tests, the data and regression curves are for total spill flow and spill flow should be divided by two to get comparable flow per bay. It is important to note that the average measured total TDG gain for each test was calculated for the duration of the spill test and that there was some variability in TDG during the tests.

For all gate operations, it was necessary to remove the effects of the powerhouse from the total TDG gain to assess the impacts of spill flow on TDG gain during different powerhouse flows. We applied the powerhouse regression equations to estimate the TDG_{PH} in the mass balance (Equation 1.0) from the measured forebay TDG and powerhouse flow. Using Equation 1.0, we calculated the expected TDG due to spill flow and the associated TDG gain from the forebay due to spill alone and plotted the resulting predicted TDG gains from spill for each test with light blue triangles. The mass balance analysis is particularly valuable for comparing spill gate tests when spill is “forced” at the expense of powerhouse flow when river flows are less than the powerhouse capacity.

For flow through Gate 1 only in 2002 and 2003 (Figure 5.2-1), the Project appears to strip TDG from 0 to approximately 11,000 cfs of spill flow under the combined action of spill gate and powerhouse operations. This effect decreases with increasing spill flow, with the maximum measured combined stripping of 4 percent occurring around 3,500 cfs. Due to spill alone, spill flow of approximately 9,000 cfs results in an estimated TDG gain of 0 percent. At spill flows of 10,000-15,000 cfs the estimated TDG gain due to spill alone ranges from 5 percent to 20 percent. There are no tests between 20,000 cfs and 38,000 cfs, at which time the gates at the upstream dams have been pulled and the forebay TDG decreases to 113 percent from its prior 126 percent. This decrease in forebay TDG corresponds to a decrease in tailrace TDG from 133 percent to 130 percent in absolute terms, which is an increase in TDG production from 7 percent to 16 percent. This hints at the possible presence of a "reset" effect in the higher spill flow ranges. After the influence of the powerhouse was removed, the TDG gain due to spill flow alone at approximately 37,000 cfs was approximately 47 percent. This is consistent with the long-term spill flow regression equation described in Section 5.1.3.2.

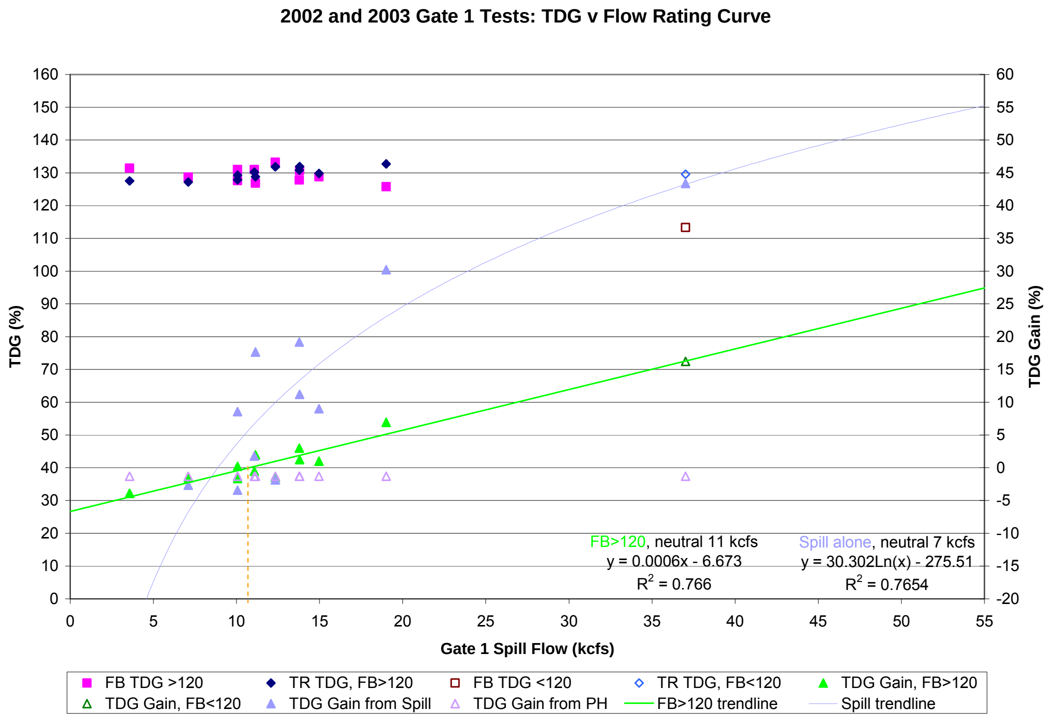

Figure 5.2-1. Summary of 2002-2003 test data for Gate 1 only.

As shown in Figure 5.2-2, Gate 2 was only operated alone for one test in 2002, which stripped about 2.5 percent of TDG at approximately 9,000 cfs of spill flow when combined with the powerhouse and produced approximately 2.5 percent when the effects of the powerhouse were removed. The other two 2002 Gate 2 tests included 35,000 cfs of sluice gate flow, and the total outflow for those tests is above the level when the upstream Projects pull their gates and reduce their TDG output into the forebay. The tailrace TDG for the Gate 2 plus sluice gate tests is about 136 percent, with significant TDG production of approximately 47 to 55 percent for the sluice gates alone. There is not enough data for Gate 2 alone to determine whether it produces more or less TDG than Gate 1 alone.

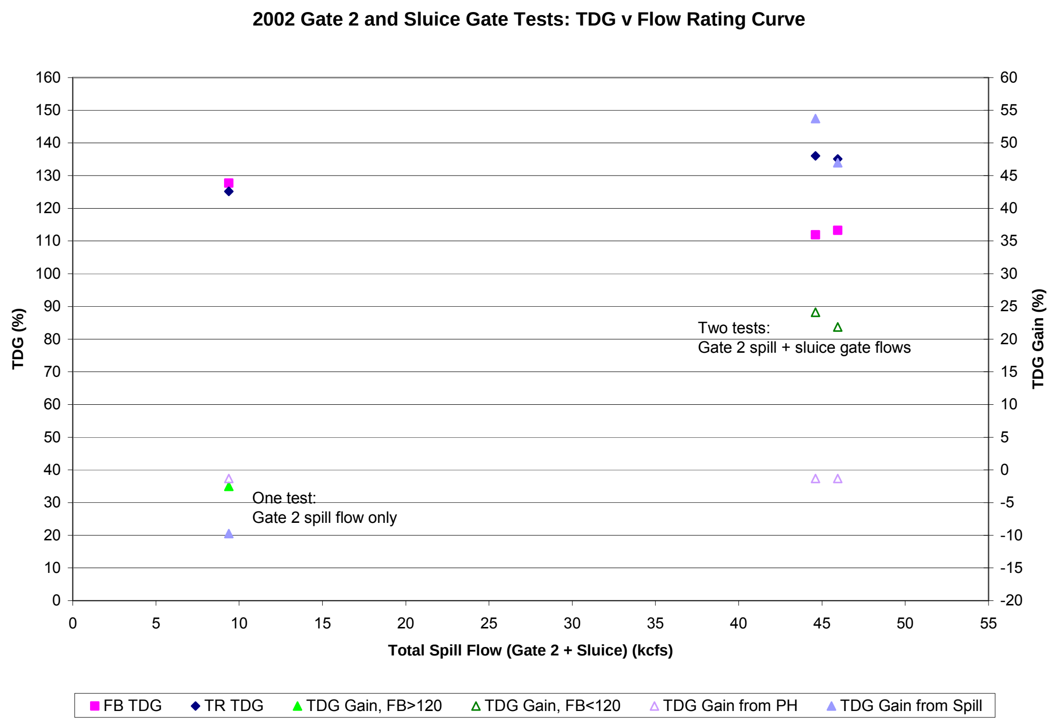

Figure 5.2-2. Summary of 2002-2003 test data for Gate 2 only and Gate 2 plus sluice gate flow.

The majority of gate tests in 2002 and 2003 occur during periods of split flow with both gates approximately equally open as shown in Figure 5.2-3. There are limited tests in the spill flow range below 15,000 cfs and at low forebay TDG for Gate 1 and Gate 2 operating together. The forebay TDG shows the influence of the upstream dams as the incoming forebay TDG is generally above 120 percent for spill flows below approximately 35,000 cfs. As river flow increased to above 80,000 cfs (generally corresponding to spill flows greater than 35,000 cfs) the gates were pulled at the upstream dams and the forebay TDG reduced to below 120 percent.

The neutral point including powerhouse operations for flow through both gates with high incoming TDG is a spill flow of approximately 16,500 cfs. Based on the limited tests available, the neutral point for spill flow only through both gates after accounting for the influence of powerhouse operations is approximately 15,500 cfs, compared to 9,000 cfs for Gate 1 alone.

TDG production increases with increasing combined Gate 1 and Gate 2 spill flow. At 31,000 cfs of spill flow, TDG production due to spill flow alone is approximately 28 percent. Above 31,000 cfs of spill flow, the gates were pulled at Box Canyon and Albeni Falls, and the forebay TDG decreased to 113-118 percent. TDG production for total Project flow increased to about 15 percent at 35,000 cfs and 21 percent at 54,000 cfs, which combined with decreasing forebay TDG resulted in a fairly constant tailrace TDG increasing only from about 129 percent at 35,000 cfs to 133 percent at 54,000 cfs.

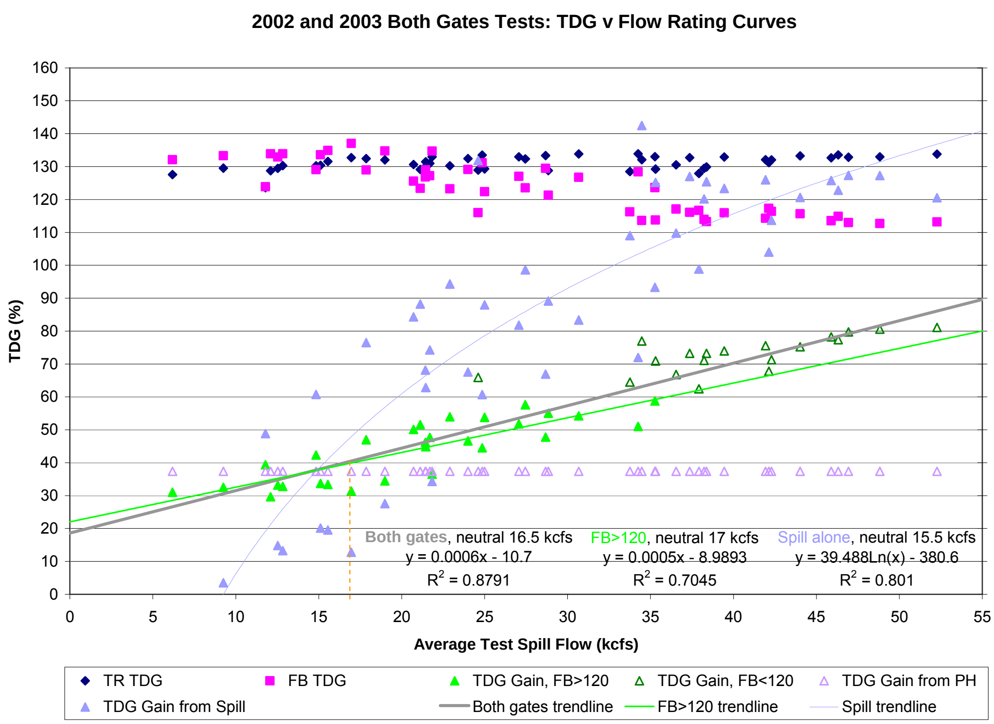

Figure 5.2-3. Summary of 2002-2003 test data for both gates operating simultaneously, grouped by incoming TDG level.

Figure 5.2-4 shows the same split flow tests as the previous plot separated by gate ratios rather than forebay TDG. From the seven tests that are not 50:50 gate splits, it may be possible to infer that higher flow from Gate 1 creates more TDG than splitting flow equally between Gate 1 and Gate 2 in the spill flow range from 15,000 to 25,000 cfs.

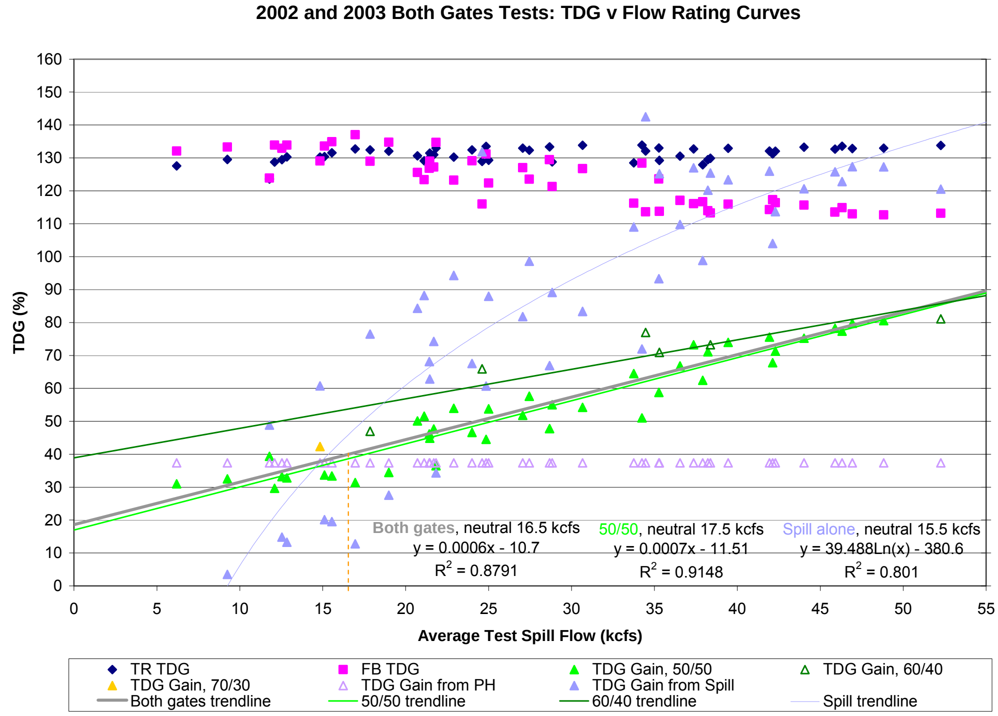

Figure 5.2-4. Summary of 2002-2003 test data for both gates, grouped by Gate 1:Gate 2 ratio.

5.2.2.2. Sluice Operations

Limited results from the 2002 gate tests suggest that sluice operation at full gate opening introduces large amounts of TDG. Two 2002 Gate 2 tests included 35,000 cfs of sluice flow, resulting in a tailrace TDG of approximately 136 percent, with significant TDG production of approximately 40 percent for the sluice gates alone. Sluice tests for 2006 will be discussed in a supplemental report on the 2006 and 2007 TDG data.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

ENSR developed both comprehensive long- and short-term databases for Boundary Dam TDG and Project operations for 1999 through 2005 in support of the Historical TDG Data Analysis objectives. We analyzed the databases to observe annual trends, describe Project hydrology and TDG trends for each year, and document the impacts of upstream Project operations on incoming forebay TDG.

The following conclusions were drawn from the TDG analysis:

- Boundary Dam forebay TDG was found to be closely linked to upstream Project operations at Box Canyon and Albeni Falls dams. ENSR developed a predictive equation for Boundary Dam forebay TDG as a function of Box Canyon Dam tailrace flow. We recommend obtaining TDG data in the Box Canyon tailrace to develop a correlation between Box Canyon tailrace TDG and Boundary Dam forebay TDG.
- We observed a change in tailrace TDG variability in the long-term database in September 2003 likely due to improved Project operations for preventing air admission at Units 55 and 56.
- ENSR developed predictive equations for TDG production by powerhouse operations prior to September 2003 and after September 2003. The equations demonstrate the impact of the powerhouse on tailrace TDG before and after the Units 55 and 56 operational change.
- We developed preliminary regression equations for TDG production as a function of spill flow for a range of gate operations based on the short-term database. Additional data from 2006 and 2007 will be used to update these regression equations. Equations were developed using the short-term database and the powerhouse regression equations to isolate the effects of spill flows on tailrace TDG.
- Over the long-term database period from 1999 to 2005 spill occurs only 4.4 percent of the hours for which data is available. In 2002, spill occurs slightly more frequently, 11.8 percent of the hours with data for 2002, with the majority of the spill flows in 2002 above 15,000 cfs.
- The preliminary analysis of the long-term database indicates that the spill gates can pass approximately between 9,000 cfs (Gate 1 only) and 15,500 cfs (Gate 1 and 2 together) with a neutral effect on TDG. However, there is not enough information to determine the relationships of TDG production to spill for low forebay TDG, or to optimize gate operations.
- Preliminary analysis of the sluice gate tests indicate the potential for use of the sluice gates at openings 4 feet or less to pass flow with a neutral or stripping effect on TDG. Further analysis of the 2006 sluice gate tests will be provided in a supplemental memo with the 2007 data analysis.

6.2. Recommendations for 2007 and 2008 Field Programs

The objective of the 2007 TDG field study was to provide additional data to determine what can be achieved operationally using the spill gates to either reduce or minimize TDG production as a supplement to other mitigation options. This information will be critical to the development and analysis of TDG mitigation schemes.

To meet this objective it will be necessary to develop relationships between TDG production and spill flow for spill flows for various gate operations, i.e., Gate 1, Gate 2 and Gate 1 and 2 split flows, both below and above the spill level where TDG production of the Project is increased. This report described our efforts to develop the necessary relationships through mining of existing data sets, including the long-term database from 1999-2005, plus data that were acquired in 2002, 2003, 2005, and 2006 for the specific purposes of evaluating spill performance.

Based on our historical data analysis, the following observations have been made with respect to data gaps:

- We have not been successful in getting spill gate operations data to go with the long-term FMS data. We only know the spill flow, not the split.
- We filtered the 2006 data to determine if there were any low spill (<20,000 cfs), low incoming TDG (< 125 percent) spill gate tests. There was only one 2.5 hour test period, indicating a need for more low spill, low forebay TDG level tests. We performed an analysis of forebay TDG versus Box Canyon flow, described in Section 5.1.2, and determined that if we want to get data with forebay TDG less than 125 percent, we need tests with total river flow less than ~55,000 cfs or greater than ~85,000 cfs.
- Sluice and spill gate openings are not available for the long-term database and there is little data available to infer anything about long-term spill gate operations. We are relying on the short-term database for spill and sluice gate test data.

As a result of the analysis described above we feel that we have inadequate data to meet the study objectives without further spill gate testing in 2007. Specifically, we recommend testing to fill the following data gaps during 2007 and 2008:

- The previous (and future) analyses need to take into account the forebay TDG level. To do this we need additional data at low forebay TDG levels in order to discern the impact of increasing forebay TDG on TDG production at low spills; most of the existing spill data were acquired for forced spill conditions where the river flows were in excess of powerhouse capacity and therefore greater than the 55,000 cfs threshold for lower forebay TDG.
- There are almost no data emphasizing Gate 2 operations either alone or with split operations skewed toward Gate 2. Data for these conditions are necessary to determine the optimum split to minimize TDG production. We know there are some dam safety concerns associated with Gate 2 operation, but also understand that that analysis has been proposed that may address this concern.
- There are not enough data at small spill gate openings and low spills to meet the objective of determining the threshold spill level/s and gate operations for TDG impacts.

We suggested that at a minimum we should acquire data for the spill operations with low forebay TDG shown in Table 6.2-1.

Table 6.2-1. Proposed TDG spill test conditions.

Test Condition #	Spill Flow (kcfs)	Gate 1 Flow %	Gate 2 Flow %
1	5	100	0
2	5	0	100
3	5	50	50
4	5	20	80
5	10	100	0
6	10	0	100
7	10	50	50
8	10	20	80
9	15	100	0
10	15	0	100
11	15	50	50
12	15	20	80
13	20	100	0
14	20	0	100
15	20	50	50
16	20	20	80

These low forebay level TDG tests may be acquired in three different ways, depending on available flows and SCL management decisions concerning cost of power and risk of not acquiring the necessary data:

- Option 1 – Acquire the data on the increasing freshet hydrograph before total river flows exceed 55,000 cfs and powerhouse capacity. This option will require manufacturing spill. This may be achieved without reducing power generation flows, but at the cost of spilling (wasting) water by drafting the reservoir. ENSR prepared a spreadsheet tool, using the spill gate ratings and the reservoir stage versus storage model provided by SCL, which can be used to prepare a table of spill gate openings versus time given a starting reservoir level and balance between Project inflow and power generating flow to maintain spill constant within a specified tolerance. These types of tests will need to be held for approximately 3 to 4 hours to ensure equilibrated TDG readings.
- Option 2 – Acquire the data near the peak of the freshet, assuming the peak will exceed ~85,000 cfs, so the incoming TDG levels will drop as a result of pulling the gates at Albeni Falls and Box Canyon dams. If this option is chosen there is a risk the data will not be acquired if the flows are not high enough. This is likely considering the predicted freshet peak for this year. Choosing this option and not achieving the necessary flow will force adoption of Option 3.
- Option 3 – Acquire the data on the receding freshet hydrograph once total river flow drops below ~55,000 cfs. This option will require manufacturing spill similarly to Option 1. However, the manufactured spill may be more costly with higher power prices during the summer and the fact that test durations may need to be longer, on the order of 4 to 6 hours, to ensure equilibrated TDG readings. TDG equilibrates more slowly on decreasing flows and TDG. Another cost factor will be the requirement for leaving the meters in the water longer and having to perform additional servicing to maintain battery power and gas membrane condition.

Besides acquiring the tabulated data for low forebay TDG, it is recommended that at least part of the tests be repeated at the peak freshet flow, as long as it exceeds ~55,000 cfs and powerhouse capacity with the accompanying higher forebay TDG, to confirm previous spill test performance. These additional high forebay TDG tests can be performed using the forced spill without the consideration of lost power generation revenues.

In addition to the spill gate tests recommended above, we recommend additional testing for the sluice gates. The tests performed to date indicate that the sluice gates produce high levels of TDG when fully open. The initial tests performed at lower gate openings in 2006 show some promise for stripping at lower sluice gate openings and warrant further investigation. For 2007 or 2008 we recommend performing duplicate sluice gate tests at sluice gate openings ranging from 2 to 6 feet open, testing multiple sluice gates to determine the combined effects of sluice gates operating near each other, and perhaps testing a sluice gate with a modified sill structure to improve performance at low gate settings and potentially increase the amount of flow passable without producing TDG.

7 REFERENCES

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Kirschbaum, Dan, SCL, personal communication with Liza Roy and Chick Sweeney of ENSR, June 2006, Re: Unit 55 and 56 startup/shutdown operations improvements.

Appendix 3: 2006 and 2007 TDG Data Analysis Final Report

Boundary Hydroelectric Project (FERC No. 2144)

2006 and 2007 TDG Data Analysis
Final Report

Prepared for
Seattle City Light

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ENSR

January 2008

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1 INTRODUCTION

This is an addendum to the final report on the Total Dissolved Gas (TDG) Historical Data Analysis at Boundary Dam submitted January 2008 under separate cover (ENSR 2008; see Appendix 2 of the Study 3 Interim Report). The purpose of the original document was to describe ENSR's efforts to analyze historical TDG data in support of the relicensing of the Boundary Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 2144, as identified in the Revised Study Plan (RSP; SCL 2007) submitted by Seattle City Light (SCL) on February 14, 2007 and approved by the FERC in its Study Plan Determination letter dated March 15, 2007. This supplemental memo documents the analysis of the 2006 and 2007 short-term spill and sluice gate operations data. Please refer to ENSR (2008) for details on the study background and historical data analysis.

2 STUDY OBJECTIVES

The objectives of the 2006 and 2007 short-term analysis are as follows:

- Obtain spill and sluice gate data collected during periods of spill flow during 2006 and 2007 and develop a short-term database for this period.
- Analyze the data for general trends and longitudinal and lateral TDG distribution.
- Ascertain whether the 2006 and 2007 data support the predictive equations developed in the November report for TDG production at Boundary Dam as a function of forebay TDG and spill flow, and refine the equations as necessary.
- Develop recommendations for further monitoring in 2008.
- Identify potential Project operations that may improve TDG conditions at Boundary Dam, either by limiting the amount of TDG produced or promoting stripping of gas.

3 SHORT-TERM DATABASE DEVELOPMENT

The 2006-2007 short-term database was developed to capture TDG data corresponding to spill and sluice gate tests. For the short-term spill and sluice gate tests in 2006 and 2007, Project operations, gate operations, and provisional US Geological Survey (USGS) TDG data for the forebay and tailrace fixed monitoring stations were obtained from SCL. In addition, data for 2007 TDG monitoring in the forebay and at multiple locations along three tailrace transects were obtained from Golder Associates (Golder) and integrated into the database. The database was analyzed to determine the effects of gate operations on tailrace TDG during designated test events as described in the following section.

4 DATA ANALYSIS AND RESULTS

4.1. Summary of 2006 and 2007 Data

The following figures show chronological flow and TDG data for the summer spill seasons in 2006 (Figure 4.1-1) and 2007 (Figure 4.1-2). In each plot, the forebay TDG is indicated in yellow and the tailrace TDG time series are color-coded to indicate whether the tailrace TDG is in compliance. The tailrace TDG is in compliance with water quality standards when the tailrace TDG is below 110 percent saturation (indicated by gray). The tailrace TDG is also considered in compliance when the tailrace TDG is greater than 110 percent but less than the incoming forebay TDG, meaning the Project is stripping gas (indicated by light green). The tailrace TDG is out of compliance when the tailrace TDG is greater than 110 percent and greater than the forebay TDG (indicated by red when the forebay is less than 110 percent and orange when the forebay is greater than 110 percent).

In 2006 the short-term database begins in April and ends in the beginning of September as shown in Figure 4.1-1. In this partial record, the maximum spill flow was approximately 44,000 cfs and the maximum Project outflow was approximately 99,000 cfs. As Project outflows increased and forebay TDG increased to above 110 percent the powerhouse stripped TDG at flows above approximately 38,000 cfs. The minimum Project outflows for the period of record occurred in September and were as low as approximately 5,000 cfs. During the spill season, the tailrace TDG was out of compliance during the higher spill flows (above approximately 12,000 cfs).

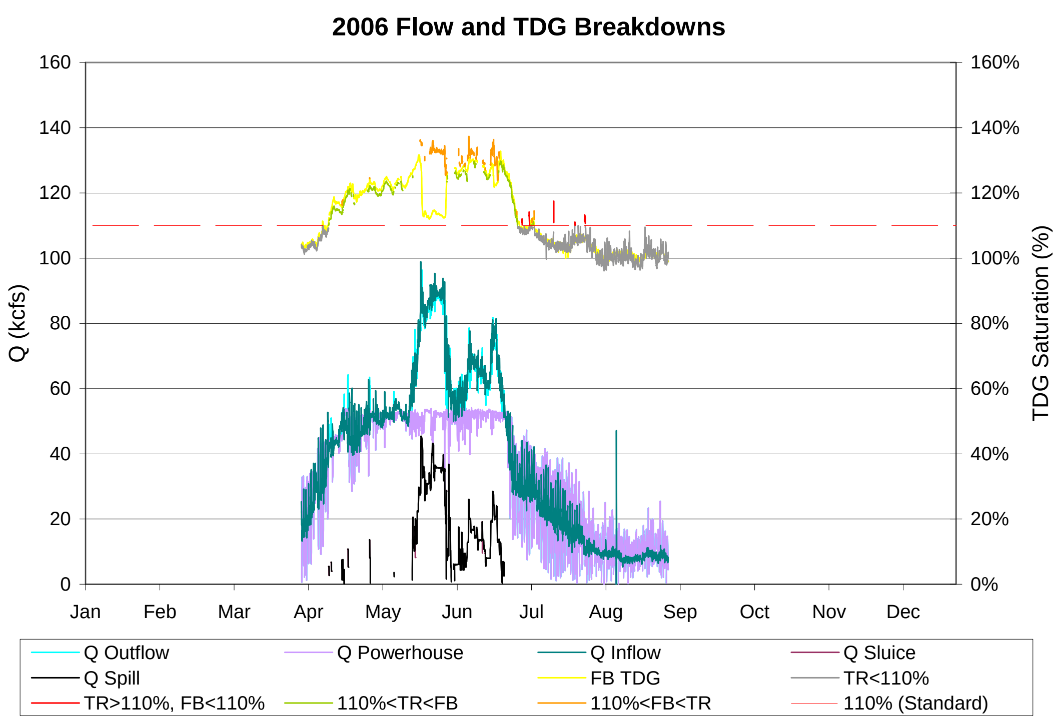

Figure 4.1-1. 2006 flow and TDG breakdowns.

The short-term database for 2007 begins in March and ends in November (Figure 4.1-2). The maximum Project outflow during this period was approximately 57,000 cfs and the minimum project outflow was approximately 5,000 cfs. A brief period of spill occurred in late March, with a maximum spill flow of approximately 12,000 cfs. An intermittent spill period of about two weeks occurred during early June with a maximum spill of approximately 14,000 cfs. The tailrace TDG variability appeared to increase during the summer months during low powerhouse flows.

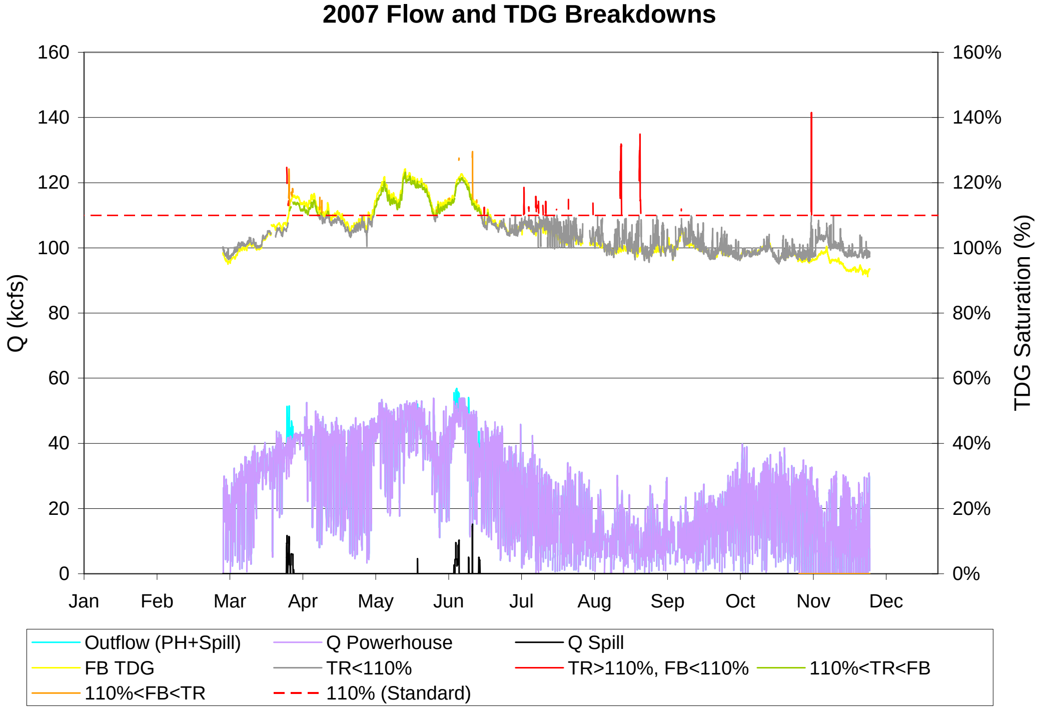

Figure 4.1-2. 2007 flow and TDG breakdowns.

4.2. Overview of 2007 Spill Testing Program

In the revised playbook rationale memorandum to Hatch Energy, dated May 10, 2007, ENSR reviewed the long-term database for missing categories of data and suggested tests to be performed during the 2007 spill season to complete the database. As detailed in the memo, the long-term database lacks data of the following types:

- Low spill (<20,000 cfs), low forebay TDG (<125 percent). Low forebay TDG occurs when the total river flow is below about 55,000 cfs and when the total river flow is above about 85,000 cfs. The spill tests filtered from the historical database contain only those data for high total river flow because there is generally no spill at the lower river flows.
- Gate 2 operating alone or with low Gate 1 operation (Q_{spill} <20,000 cfs)
- Sluice and spill gate openings were not available for the long-term database as of the writing of this memo. We are relying on the short-term database for spill and sluice gate test data.

Based on the above analysis, ENSR recommended data at these conditions in 2007: low forebay TDG levels (<125 percent), spill flow emphasizing Gate 2, small spill gate openings and low spills, and duplicate tests at the peak freshet flow to confirm previous spill test conclusions. Table 4.2-1 compares the specific tests requested in the memo to the tests performed during the 2007 field study.

Table 4.2-1. 2007 spill test summary.

Recommended for 2007		Obtained
Q (cfs)	**Gate 1:Gate 2 Ratio**	**Number of Tests**
5,000	100:0	5
5,000	0:100	1
5,000	50:50	1
5,000	20:80	1
10,000	100:0	1
10,000	0:100	1
10,000	50:50	1
10,000	20:80	1
15,000	100:0	
15,000	0:100	
15,000	50:50	1
15,000	20:80	
20,000	100:0	
20,000	0:100	
20,000	50:50	
20,000	20:80	

All 2007 tests had forebay TDG below 125 percent and spill flows below 20,000 cfs. The addition of these tests to the full short-term database allowed refinement of the spill flow versus TDG gain regression equations. However, there were not enough tests with low Gate 1 flow to make further determinations on optimal gate operation procedures.

4.3. 2007 Longitudinal and Lateral TDG Trends

The 2007 TDG monitoring data obtained from Golder include measurements from nine TDG meters (H1-H9) placed on four transects along the Pend Oreille River as a supplement to the USGS forebay and tailrace fixed monitoring stations as shown in Figure 4.3-1. Meter H9 provided a duplicate for the USGS forebay fixed monitoring station. Transect 2 (H1-H4, numbered from left to right, looking downstream) is immediately downstream of the tailrace constriction point. Transect 3 (H5-H7) is at the same cross-section as the USGS tailrace gage, and Transect 4 (H8) is across the international border in Canada. The actual coordinates of the instrument locations as deployed are provided in Golder's monitoring report (Golder 2007). The following sections describe the longitudinal and lateral TDG distribution and mixing trends identified from the data for H1-H9 and the USGS forebay and tailrace fixed monitoring stations.

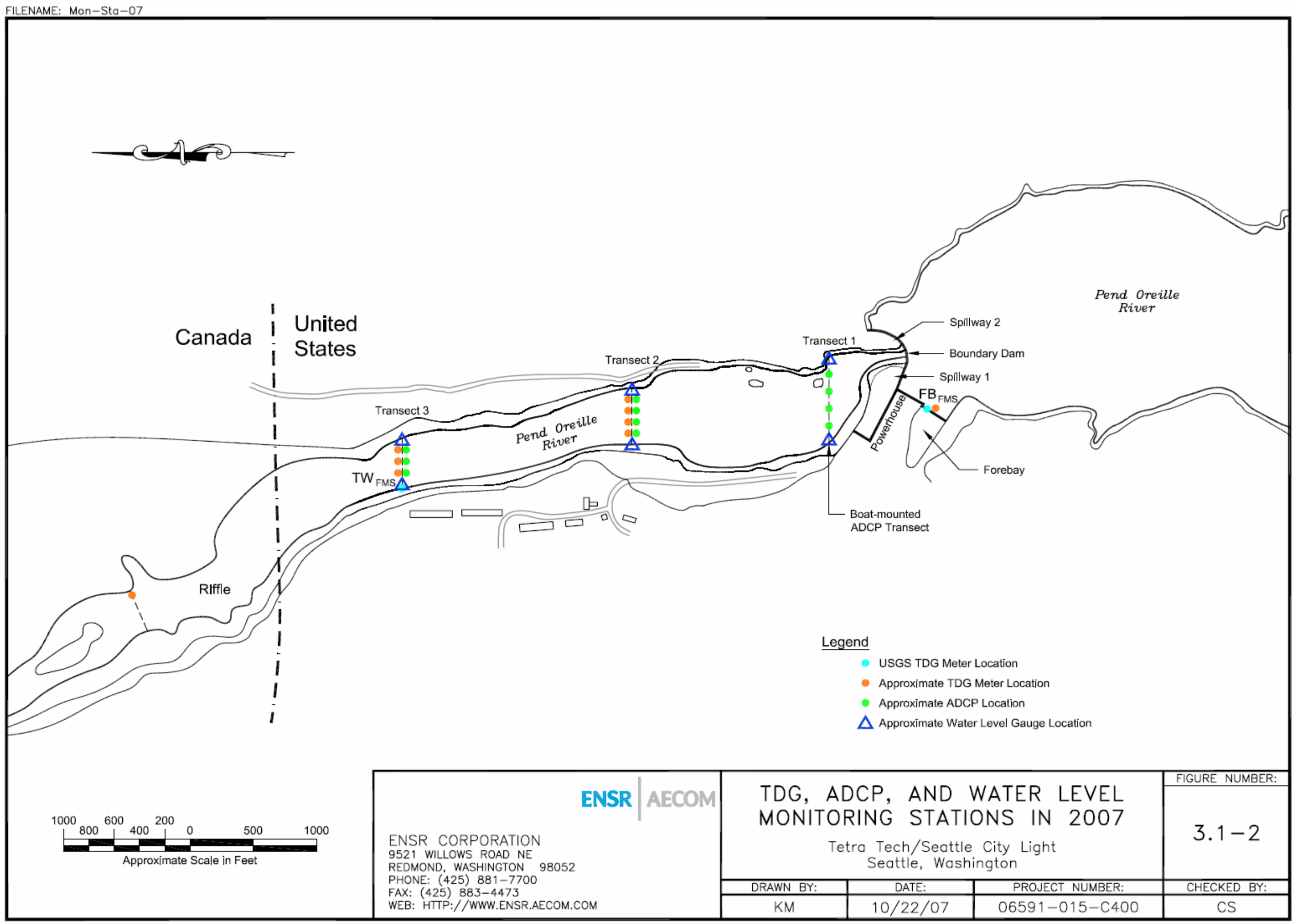

Figure 4.3-1. 2007 TDG monitoring locations.

The following three plots display the USGS tailrace and forebay TDG chronologically along with the meters at Transects 2, 3, and 4 in Figures 4.3-2 through 4.3-4, respectively. In general, the meters followed the same general trend and all tailrace meters recorded higher TDG levels during the spill periods.

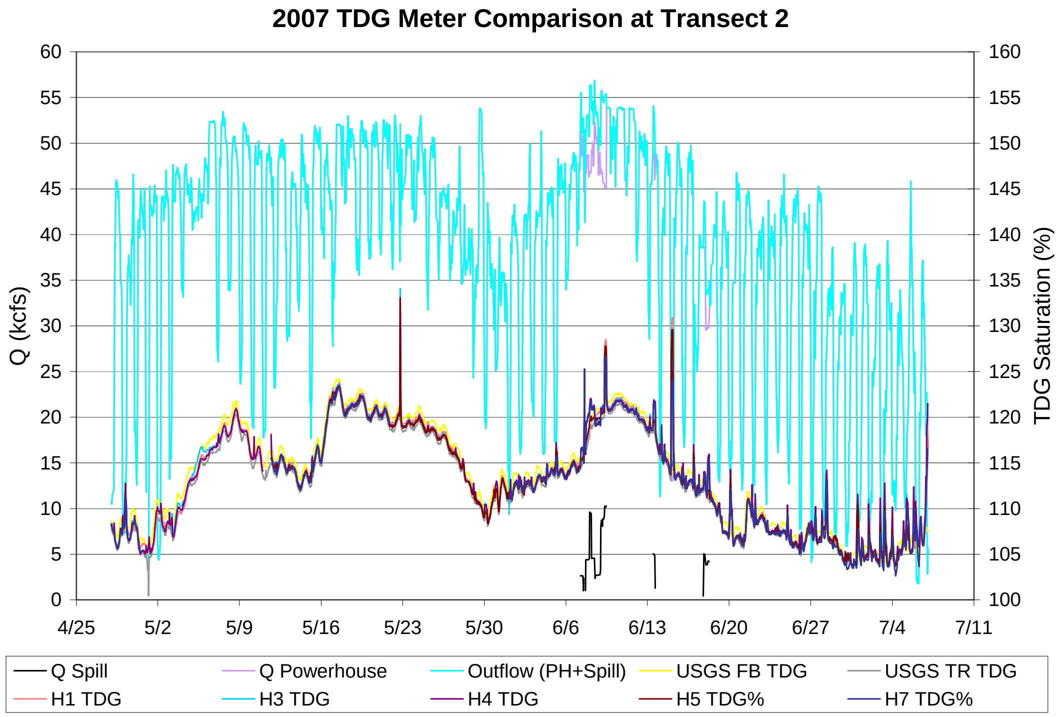

Figure 4.3-2. Transect 2 and USGS TDG measurements.

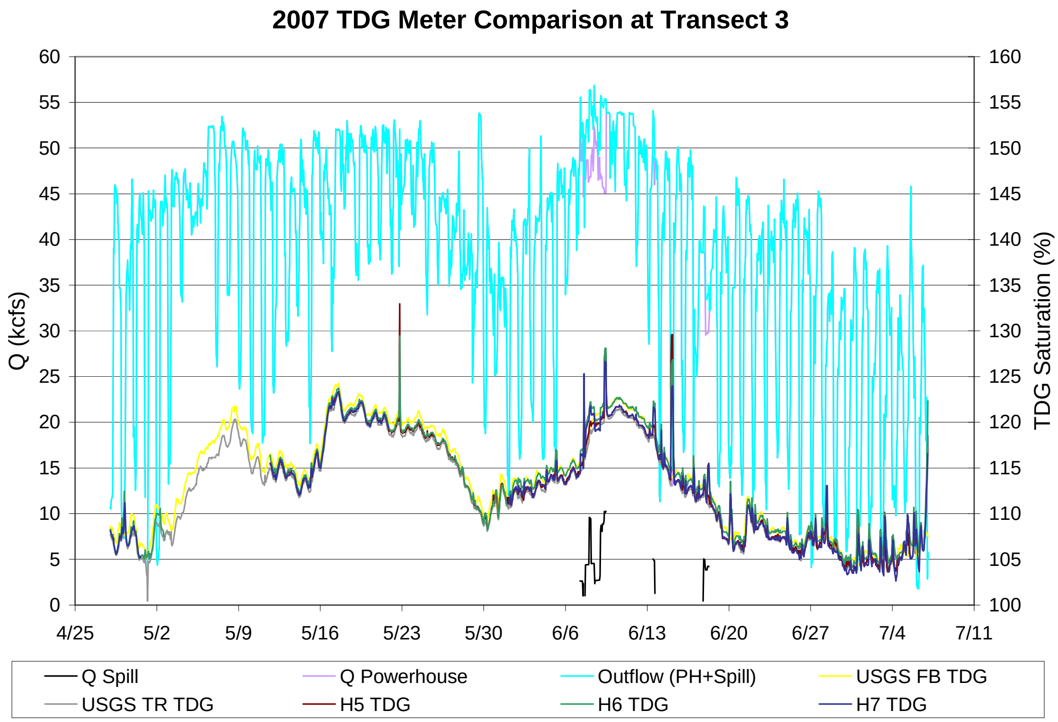

Figure 4.3-3. Transect 3 and USGS TDG measurements.

Figure 4.3-4 demonstrates that the TDG generally decreased from the forebay to the USGS tailrace fixed monitoring station except during periods of spill. TDG also generally decreased from the USGS fixed monitoring station to the Meter H8 station near the Canadian border, as expected, especially at low flows when the riffle upstream of H8 likely strips gas.

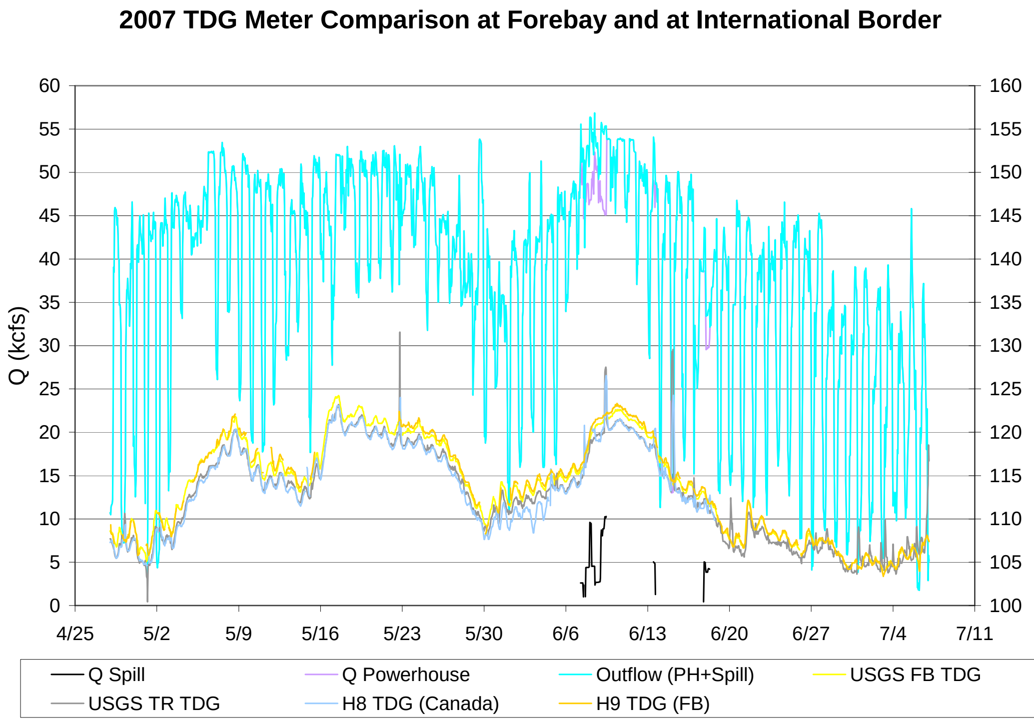

Figure 4.3-4. Transects 1 and 4 and USGS TDG measurements.

Meter H9 was installed as a duplicate for the USGS fixed monitoring station. TDG data from meter H9 are generally strongly correlated with the USGS forebay meter data. As shown in Figure 4.3-5, the H9 data are nearly identical to the USGS forebay data for low TDG levels up to about 112 percent. As forebay TDG increases above approximately 112 percent, the data from meter H9 are consistently slightly higher than the USGS data. Golder's data report for Meter H9 mentioned that there was some uncertainty in the upper pressure range calibration for Meter H9, but they did not correct the data for the meter. Golder recommended factory calibration of the meter prior to the 2008 season. The average difference in TDG between the USGS forebay meter and Meter H9 is slight and increases with flow (Figure 4.3-6), from –0.1 percent at 0 cfs to 0.5 percent at 60,000 cfs, but is within the expected instrument accuracy.

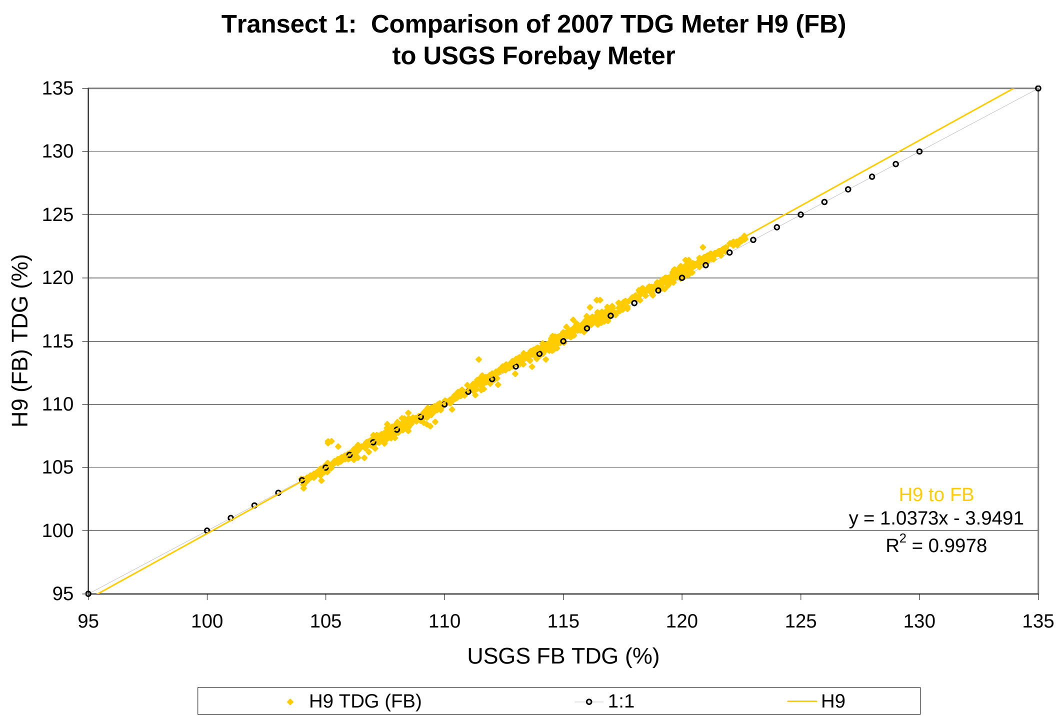

Figure 4.3-5. Transect 1 to USGS forebay meter correlation.

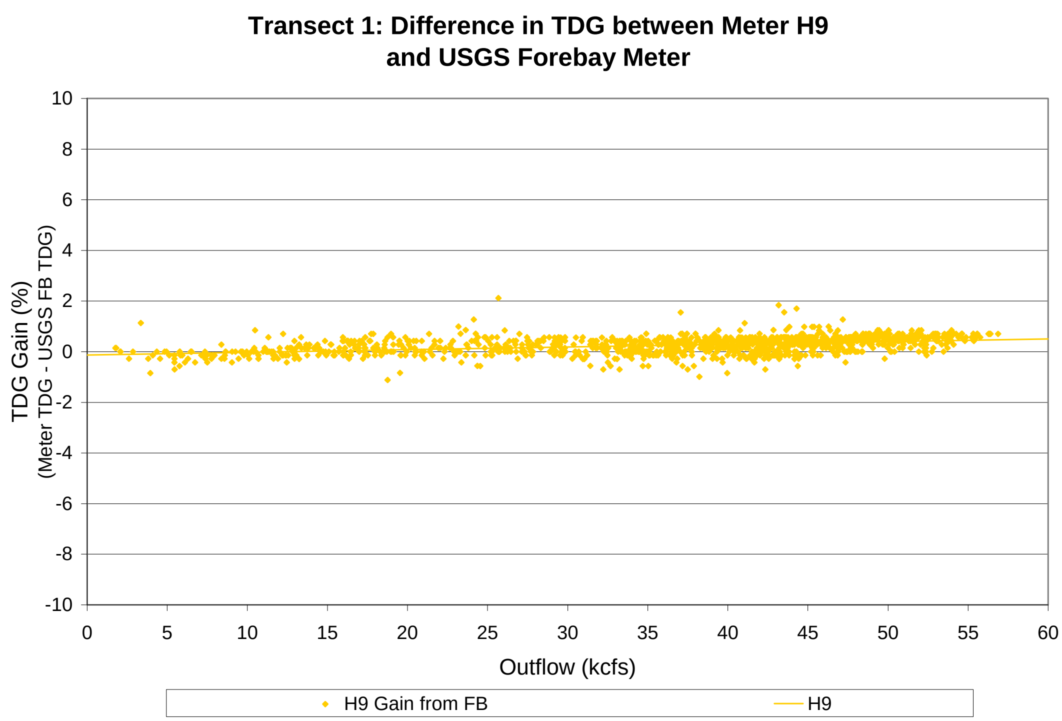

Figure 4.3-6. River flow vs. the difference in TDG between Meter H9 and the USGS forebay meter.

The following plots compare the meters along Transects 2 and 3 longitudinally and laterally with respect to river flow. In each case, the differences between the USGS tailrace fixed monitoring station TDG and the meter TDG were plotted for the entire study period. Then a regression line was fitted for the delta TDG for each meter to show the trend between each meter and the USGS fixed monitoring station. Negative TDG gain in the figures indicates that the meters generally read very slightly higher TDG than the USGS fixed monitoring station.

Figure 4.3-7 shows the relationship of river flow to the difference in TDG between the Transect 2 meters (H1-H4) and the USGS tailrace meter. In Figure 4.3-8 the same regression lines are shown, but the delta TDG points were removed for clarity. All Transect 2 locations generally measure slightly higher TDG at all flow levels than the USGS tailrace (negative gain) by approximately 0.5 to 1.0 percent, aside from Meter H2 at flows above 54,000 cfs. It is important to note that Meter H2 had a limited duration of testing (11 out of 70 days) as compared to the other meters. The general trend is for TDG at Transect 2 to approach the TDG measured at the USGS tailrace meter as powerhouse flows increase to capacity, indicating well-mixed tailrace flows. However, when spill flows occur, there appears to be a minor longitudinal and lateral distribution of TDG along the tailrace that is dependent on spill flow, gate operation, and powerhouse flow. An example is shown in Figure 4.3-9. The USGS fixed monitoring station, Transect 2 Meter H1, and Transect 3 Meter H5 (all left bank meters) appear to have the highest TDG during single gate spill flows above approximately 10,000 cfs. At lower single gate spill flows between 5,000 and 10,000 cfs, there appears to be a shift in the tailrace dynamics, and slightly higher TDG values were recorded by Meter H7 on the right bank (maximum of 2.7 percent higher during full powerhouse flow). During split spill operations, the lateral variation was minimized and the Transect 3 meters generally recorded within 1 percent of the USGS meter. This is important to note, because future spill operations are expected to be split spill operations and the lateral gradient is within instrument accuracy during split spill operations.

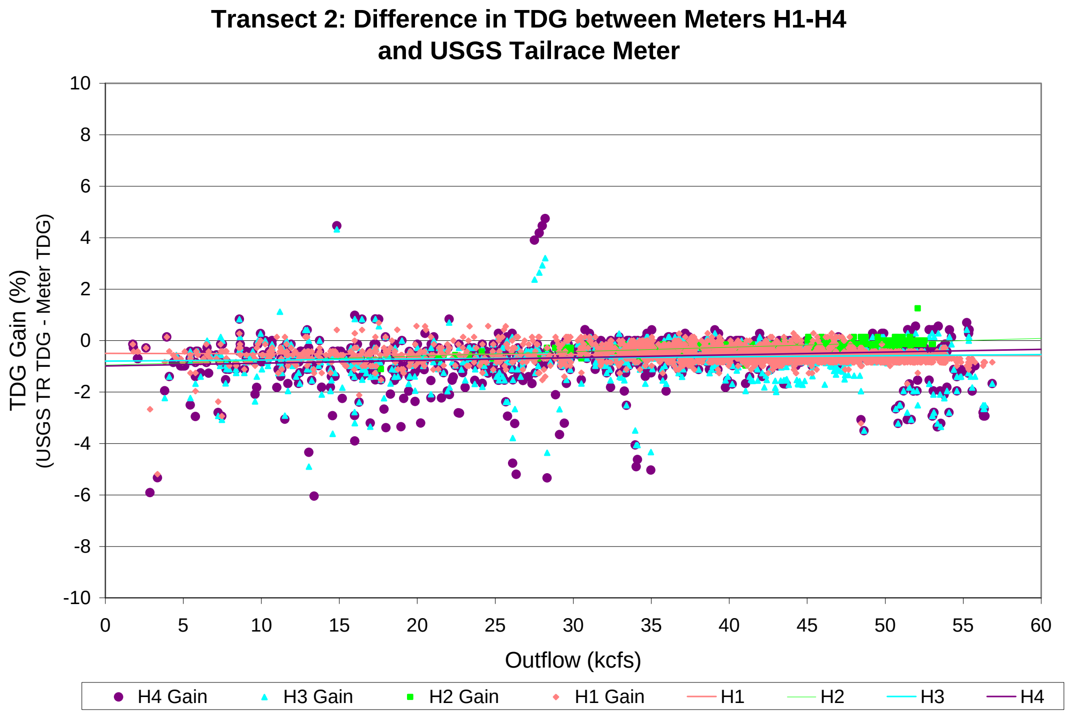

Figure 4.3-7. River flow vs. TDG difference between Transect 2 meters and the USGS tailrace meter.

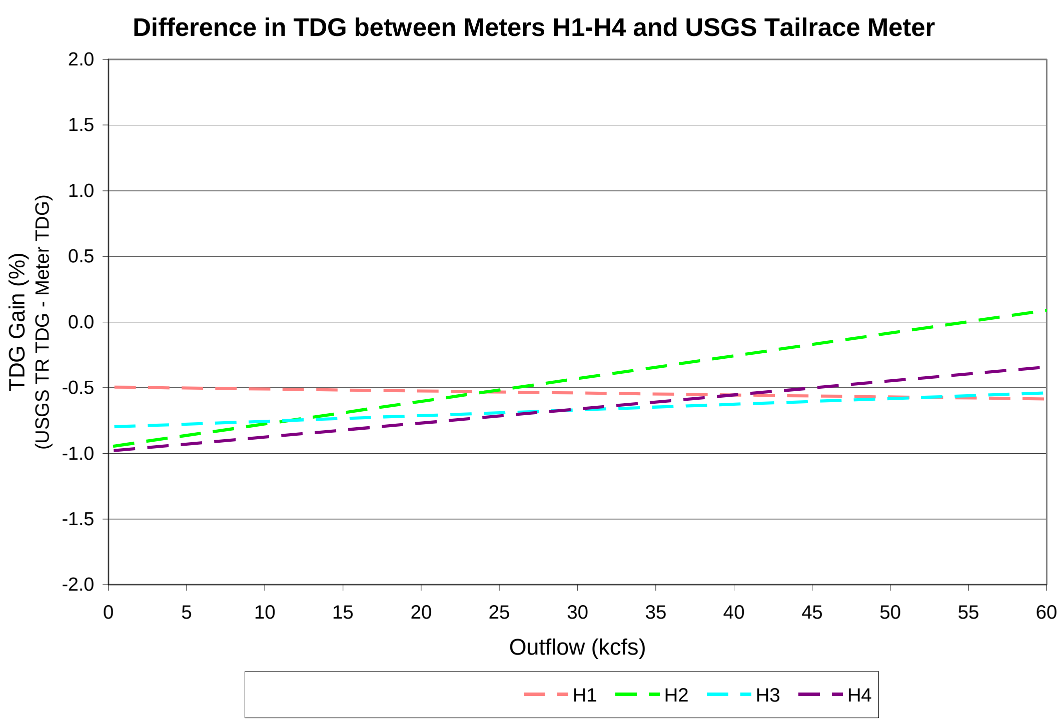

Figure 4.3-8. River flow vs. average difference in TDG between Meters H1-H4 and USGS tailrace meter.

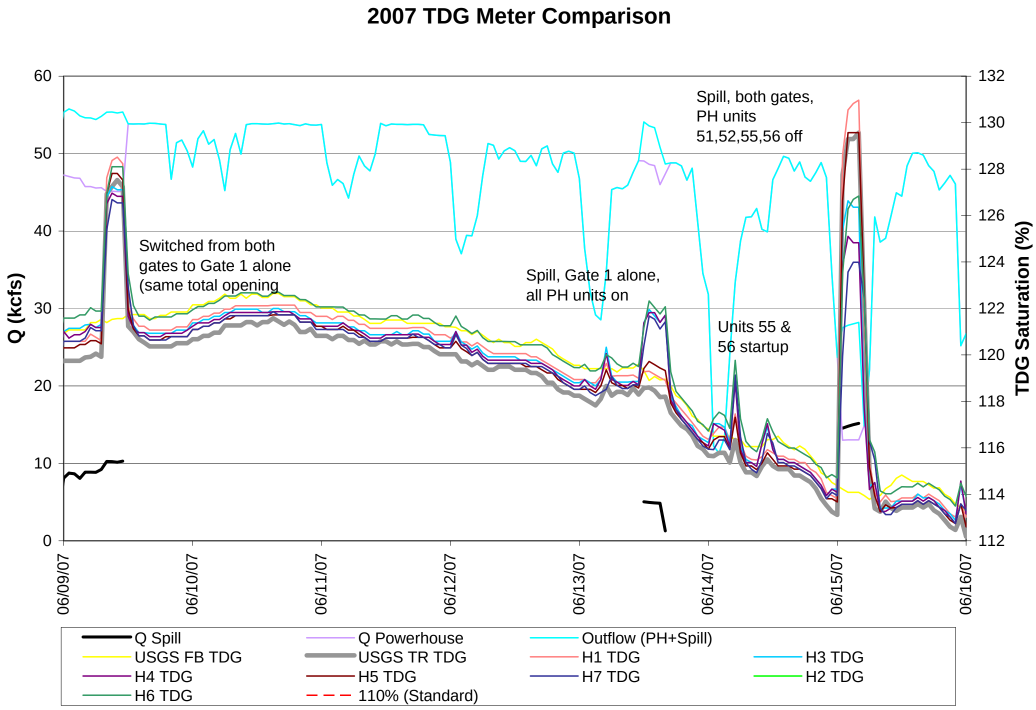

Figure 4.3-9. Example of tailrace TDG during 2007 spill season.

Figure 4.3-10 shows the relationship of river flow to the difference in TDG between the Transect 3 meters (H5-H7) and the USGS tailrace meter. In Figure 4.3-11 the same regression lines are shown, but the delta TDG points were removed for clarity. All Transect 3 locations generally measure higher TDG at all flows below approximately 55,000 cfs than the USGS tailrace (negative gain). During periods of no spill with a fully mixed river, the H5 and H7 meters consistently read 0.3 percent higher than the USGS tailwater meter. The USGS calibration records from March 2007 to July 2007 indicate excellent meter accuracy.

Meter H6 displays the greatest difference from the USGS tailrace meter, from -1.1 percent at 0 cfs to about -0.8 percent at 55,000 cfs. During data collection, Golder observed that Meter H6 was reading high, but the calibration factor applied to the data does not appear to remove the effect entirely. If the TDG in mid-channel at Meter H6 were truly significantly higher than at the USGS fixed monitoring station on the left bank, this trend would be apparent at Transect 2 mid-channel at Meters H2 and H3 as well. This trend is not evident in the Transect 2 data. We suspect that the Meter H6 data have some calibration error despite correction during data processing.

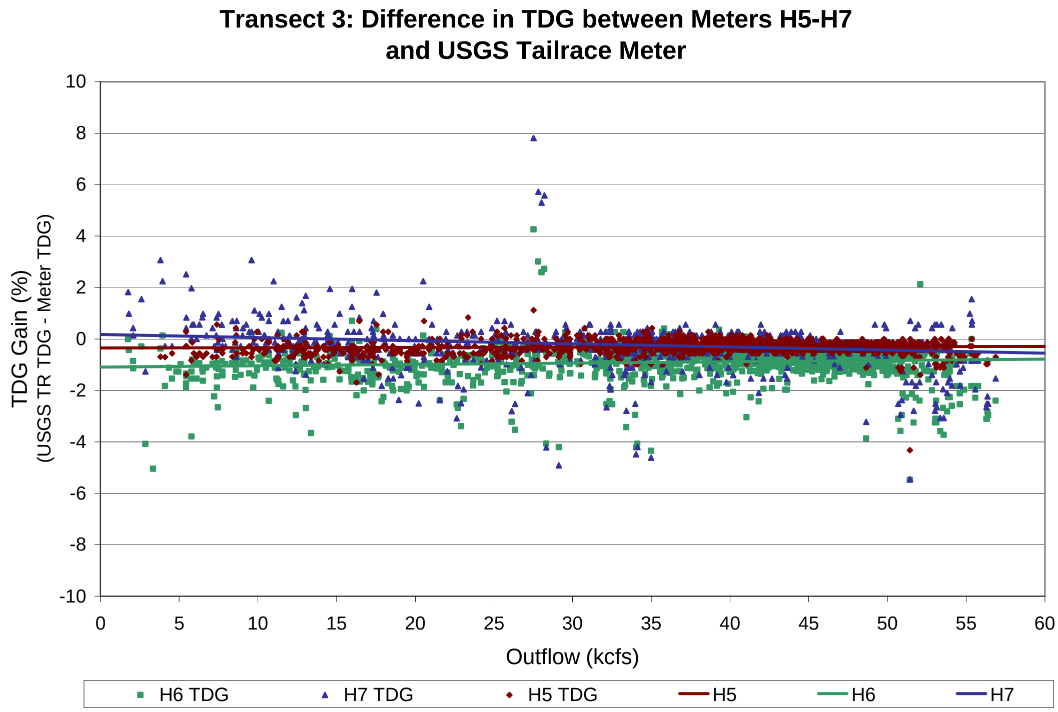

Figure 4.3-10. River flow vs. TDG difference between Transect 3 meters and the USGS tailrace meter.

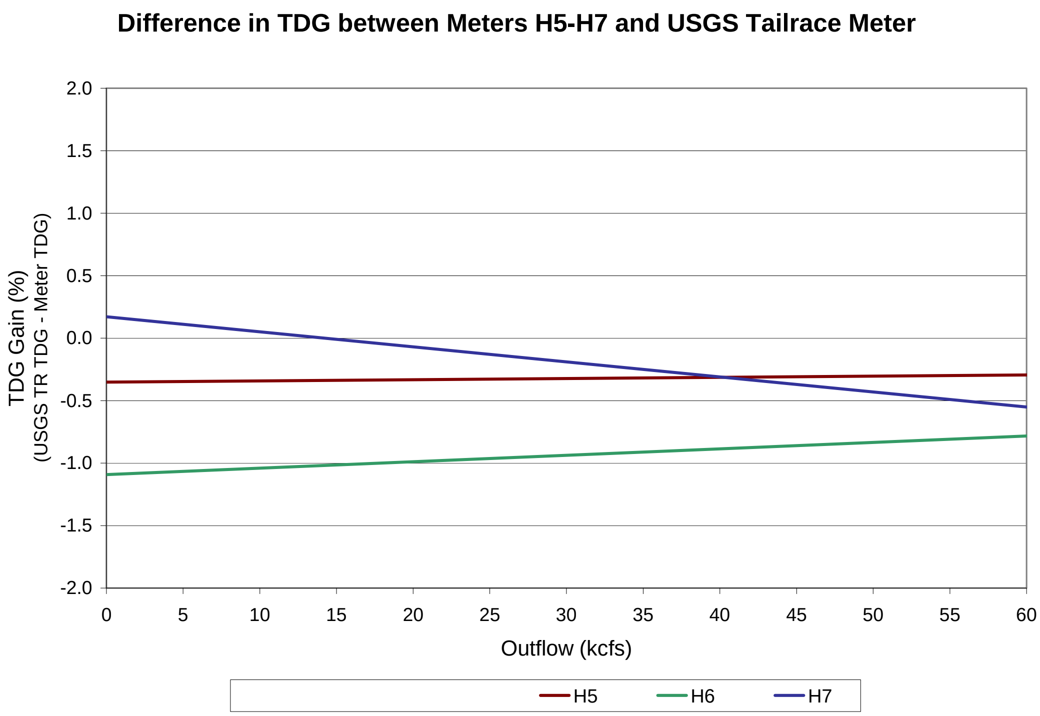

Figure 4.3-11. River flow vs. the average difference in TDG between Meters H5-H7 and the USGS tailrace meter.

Figure 4.3-12 compares the downstream meter at the Canadian border to the USGS tailrace meter. TDG measured at Meter H8 is slightly lower than at the USGS tailrace meter, likely due to slight stripping of TDG as flow moves downriver through the riffle downstream of the tailrace meter. The average change in TDG from the USGS tailrace meter to Meter H8 decreases with flow (Figure 4.3-13), from -1.1 percent at 5,000 cfs to 0 percent at approximately 55,000 cfs. This indicates that the TDG in the river at the Canadian border will be lower than what is measured at the tailrace USGS fixed monitoring station for flows below 55,000 cfs. Additional data at the Meter H8 location should be obtained for higher flows to confirm the trend beyond 55,000 cfs.

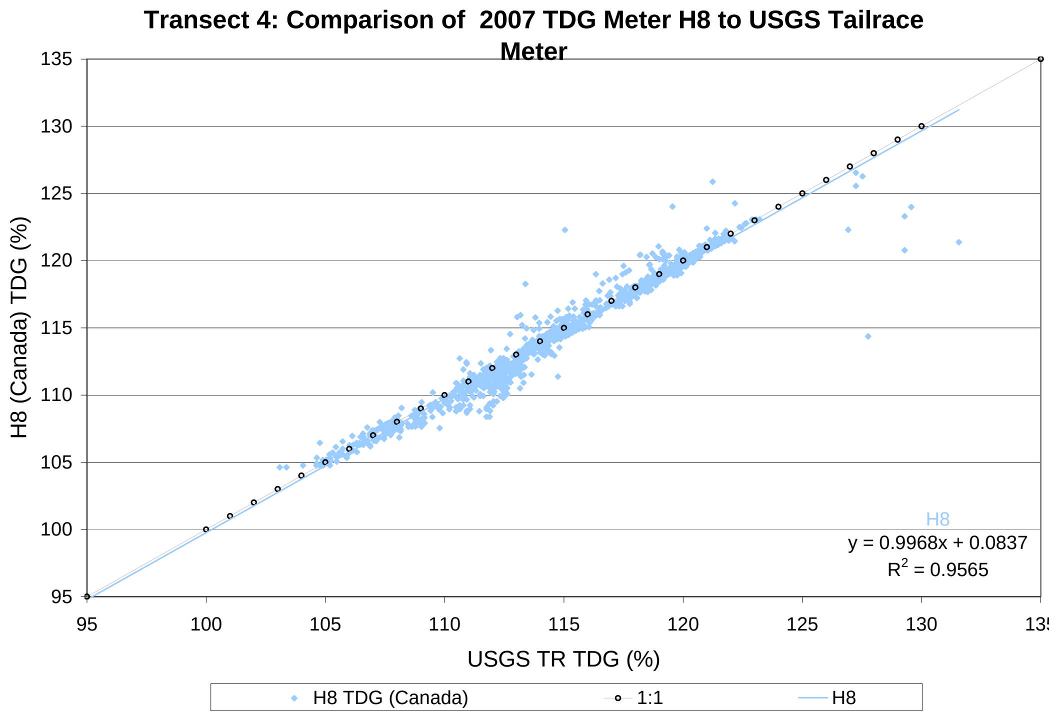

Figure 4.3-12. Transect 4 to USGS tailrace meter correlation.

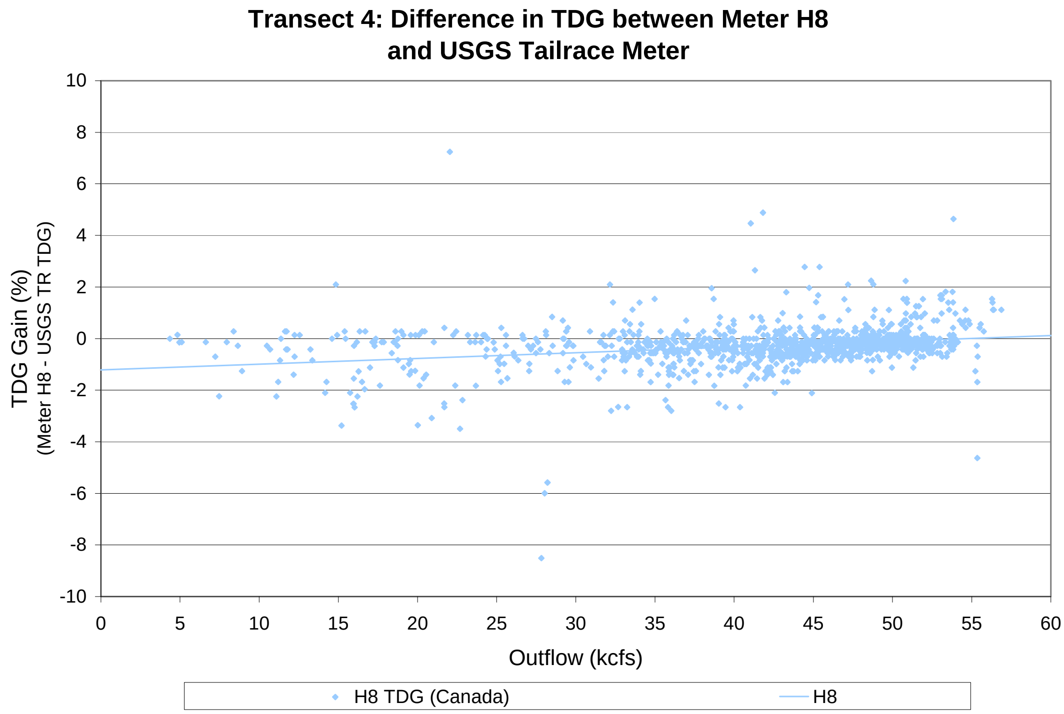

Figure 4.3-13. River flow vs. TDG gain from the USGS tailrace meter to the Canadian border.

4.4. Long-term TDG Regression Equations

ENSR developed regression equations from the long-term database to describe the change in TDG levels between the forebay and tailrace during times when the Project outflow is at or below powerhouse capacity and there is no spill flow. These equations were determined using the long-term database as described in Section 5.1.3.1 and 5.1.3.2 of the November 2007 TDG Historical Data Analysis (ENSR 2008; see Appendix 2 of the Study 3 Interim Report). The long-term powerhouse TDG regression equations were then used to remove the effects of the powerhouse from short-term spill test data to determine the effects of gate settings and operations on TDG production as described in Section 5.2.2 of that memo. The same powerhouse TDG production equations were used for the 2006 through 2007 short-term analysis and updated equations were developed for the spill flow TDG production for each gate test category as described in Section 4.3.

4.5. Summary of Spill and Sluice Test Data

4.5.1. Spill Operations

On the basis of the equilibration time analysis conducted as part of the November 2007 analysis, we filtered the short-term databases for 2006 and 2007 to find instances when the same spill or sluice gate settings were maintained for at least four hours and extracted these "tests" into a subset database for the purpose of gate operations analysis. Spill flow occurred in 2006 on April 18 and from May 18 through June 4, and in 2007 from June 7-18 as shown in the chronologic figures in Section 4.1. For 2006 and 2007 combined, there are 18 tests of Gate 1 alone, two tests of Gate 2 alone, 27 tests of both gates, and nine sluice gate tests. Of the tests with both spill gates open, three tests have a 20:80 ratio of Gate 1 to Gate 2 spill, 11 are split 50:50, eight are split 60:40, and five are split 70:30.

The gate test data for 2006 and 2007 were added to the database of gate tests identified for 2002 and 2003. The following plots show the average measured TDG gain (forebay USGS fixed monitoring station TDG minus tailrace USGS fixed monitoring station TDG) from the 2002 through 2007 short-term database during the spill tests for Gate 1 only (Figure 4.5-1), Gate 2 only (Figure 4.5-2), and Gate 1 and Gate 2 operating together (Figures 4.5-3 and 4.5-4). The measured forebay TDG (magenta squares), tailrace TDG at the fixed monitoring station (dark blue diamonds), and TDG gain from the forebay to the tailrace (triangles) are shown in each plot. In addition, each figure shows the approximate linear regression equation for TDG gain as a function of spill flow. The average measured TDG gain for each test was calculated for the duration of the spill test, and there was some variability in TDG during the tests.

For all gate operations, it was necessary to remove the effects of the powerhouse on TDG to assess the impacts of spill flow on tailrace TDG and provide a comparison for tests done and different powerhouse flows. We applied the powerhouse regression equations developed in the November 2007 TDG Historical Data Analysis (Section 5.1.3.1 in ENSR 2008) to estimate the TDG_{PH} in the following mass balance equation:

$$TDG_{spill} = \left(TDG_{TR}Q_{outflow} - TDG_{PH}Q_{PH}\right) / Q_{spill} \quad \textbf{(Equation 1.0)}$$

Where:

TDG_{TR} = tailrace TDG from long-term database
$Q_{outflow}$ = total project outflow (spill flow plus powerhouse flow)
TDG_{PH} = FB TDG + ΔTDG due to powerhouse (from regression equation in Section 5.1.3.1
Q_{PH} = powerhouse flow from long-term database
Q_{spill} = spill flow from long-term database

The resulting TDG_{spill} was used to calculate a TDG gain from the forebay to the tailrace due to spill alone. Use of Equation 1.0 assumes that the mass balance equation is a valid representation of the interaction of powerhouse flows and spill flows. We are using the TDG regression equations developed for powerhouse flow only and applying them to situations when spill is present as well, assuming that the powerhouse flow is mixed with the spill flow and is not gassed-up by the spill flow. This assumption will provide conservative estimates of the TDG gain due to spill flow and is likely representative of actual conditions at lower spill flows. At higher spill flows, powerhouse flows are likely entrained and gassed up. The resulting predicted TDG gains from spill for each test are plotted on Figures 4.5-1 through 4.5-4 with light blue triangles.

Figure 4.5-1 depicts the gate tests with flow through Gate 1 alone, filtered by forebay TDG. For flow through Gate 1 only (Figure 4.5-1), the Project appears to strip TDG at spill flows from 0 to approximately 8,000 cfs under the combined action of spill gate and powerhouse operations.

Before the 2006 and 2007 data were added, flow through Gate 1 only was estimated to strip TDG at spill flows up to 11,000 cfs. This effect decreases with increasing spill flow, with the maximum combined stripping of 4 percent occurring around 3,500 cfs as in the 2002-03 short-term dataset, though the additional data makes it clear that stripping of 1 percent to 1.5 percent is more typical for spill flow between 2,500 and 7,000 cfs. The powerhouse and spill flows combine with a neutral effect at spill flows of approximately 8,000 cfs. Above 8,000 cfs, TDG production due to total outflow increases with spill to about 7 percent at 19,000 cfs and 16 percent at 37,000 cfs, which is the maximum test spill flow as in the 2002-03 dataset. The additional 2006-07 data are entirely in the low spill range below 13,000 cfs, and the TDG gain is generally slightly lower for comparable spill flows than observed in 2002-03. This may be due to lower incoming forebay TDG, but additional data at low flow with low forebay TDG will be needed to confirm this.

After addition of the 2006 and 2007 gate test data, the neutral point for spill effects alone after discounting powerhouse effects becomes 4,500 cfs, in contrast to 9,000 cfs for the 2002-03 data.

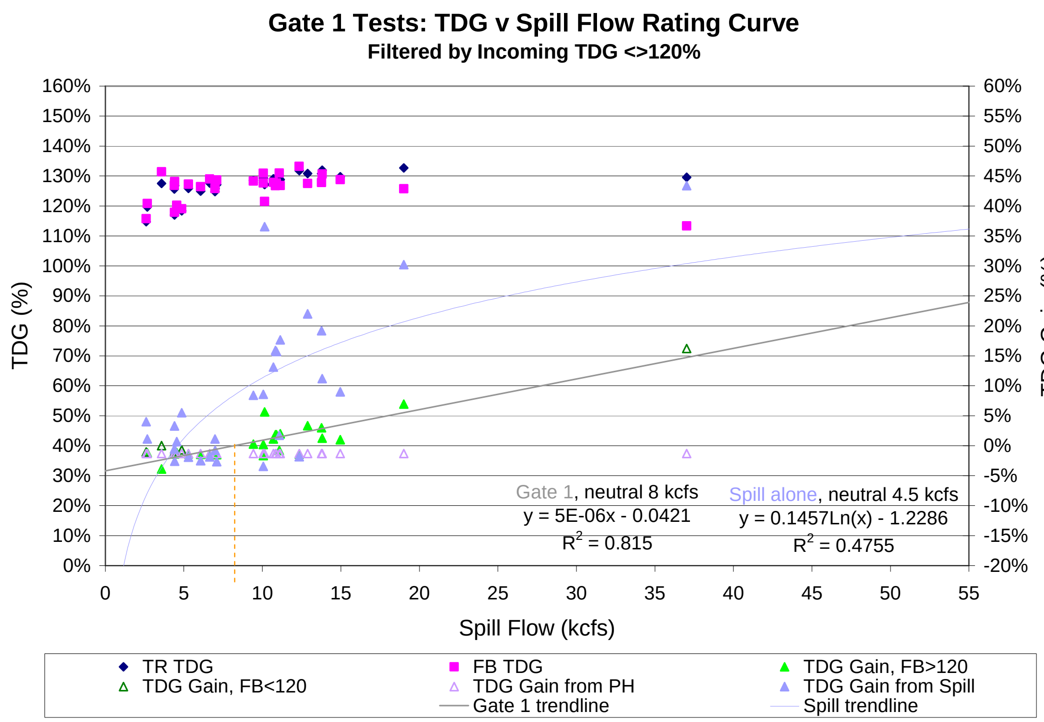

Figure 4.5-1. Summary of 2002-07 test data for Gate 1 only.

Two tests of Gate 2 alone were conducted in 2007 at 5,000 and 10,000 cfs of spill flow, resulting in TDG stripping of 0.5 and 0.7 percent. When combined with the 2002-03 data in Figure 4.5-2, including two tests with high total spill consisting of Gate 2 flow around 10,000 cfs plus sluice gate flow of 35,100 cfs, Gate 2 is estimated to strip TDG below approximately 9,500 cfs for combined powerhouse and spill flows. The neutral point for spill effects alone after removing the powerhouse contribution is about 7,500 cfs.

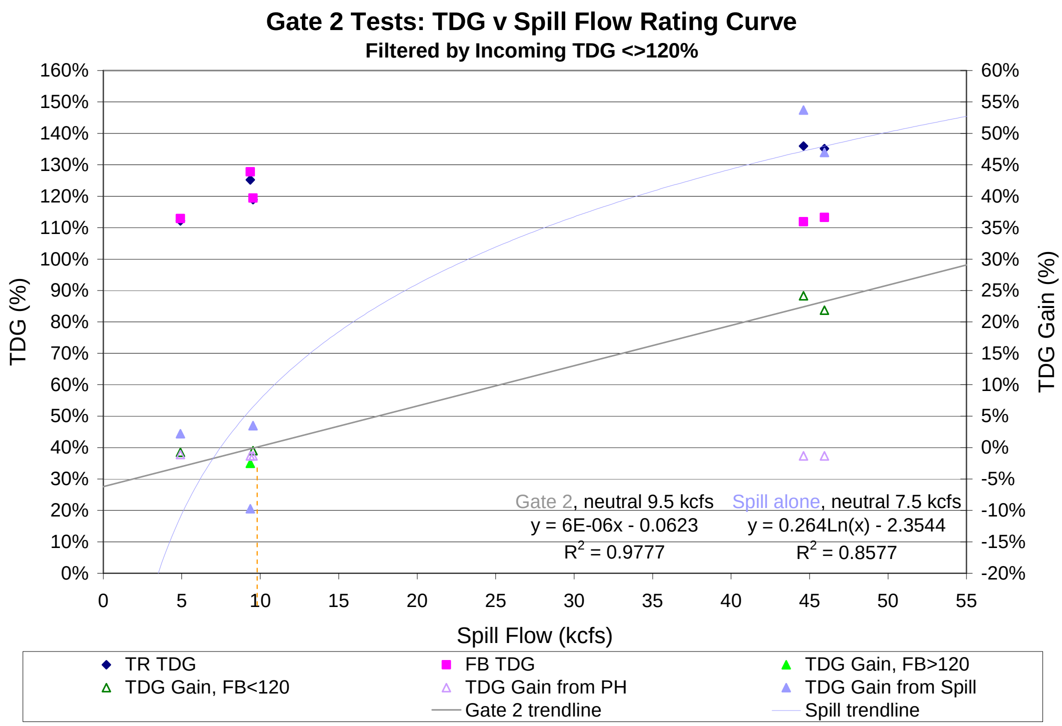

Figure 4.5-2. Summary of 2002-07 test data for Gate 2 only.

Figure 4.5-3 shows the TDG production regression equation for flow through both gates. The 2006-07 tests at low spill flows were particularly helpful in refining the regression equation for both gates operating together, as there were few tests in 2002-03 with spill flow below 15,000 cfs and forebay TDG below 120 percent. The neutral point including powerhouse operations for flow through both gates is approximately 13,000 cfs, or approximately 6,500 cfs per bay. This is less than the Gate 1 spill flow for a neutral TDG production for total Project outflow. The preliminary analysis of the 2002 and 2003 tests indicated the opposite, which shows the sensitivity of the database to the addition of new test data, especially at low and high spill flows.

For incoming TDG above 120 percent, TDG is stripped for spill flows below approximately 15,000 cfs. The neutral point for spill flow only through both gates at all forebay TDG levels after removing the influence of powerhouse operations through the mass balance analysis is approximately 11,000 cfs, or approximately 5,500 cfs per bay compared to 4,500 cfs for Gate 1 alone. These are comparable within the variability of the powerhouse stripping effect expected at full or near-capacity flows (1 to 2 percent) and significant conclusions about whether single gate or dual gate operation is better at low flows cannot be drawn from this analysis. The regression lines for combined powerhouse and spill flows indicate in general that at low flows combined gate operation may be beneficial, but at higher flows this benefit diminishes.

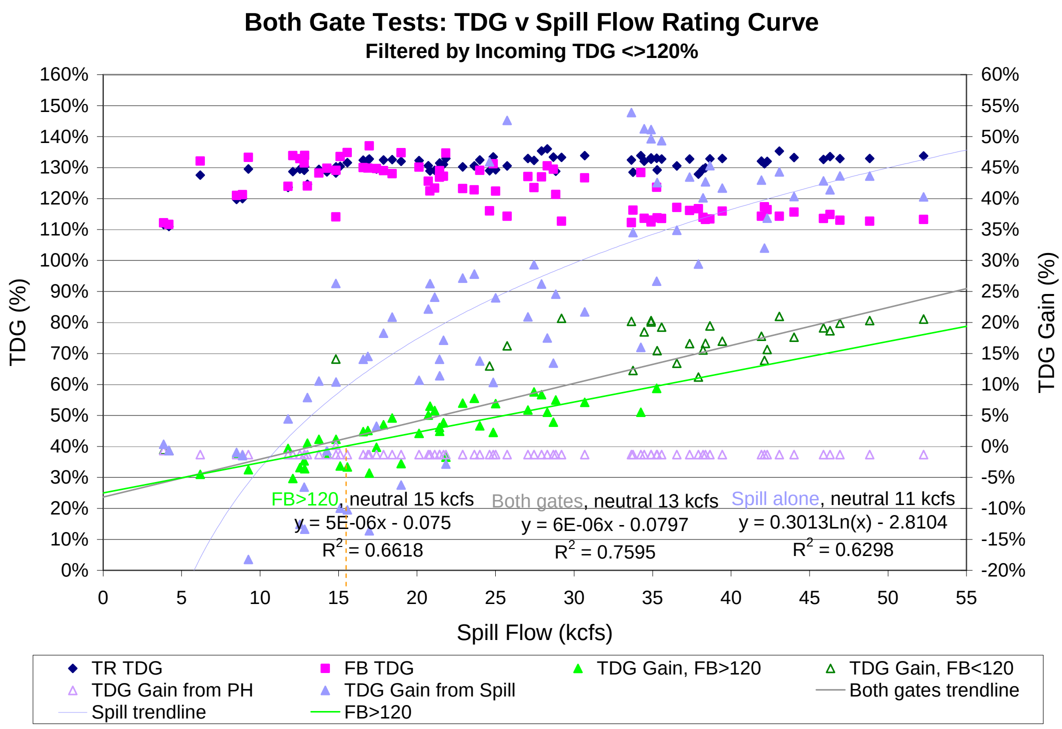

Figure 4.5-3. Summary of 2002-07 test data for both gates, grouped by incoming TDG level.

TDG production increases with spill flow and at 31,000 cfs, or 16,500 cfs per bay, TDG production due to spill flow alone is approximately 30 percent. This compares to TDG production of 18 percent for Gate 1 alone at a spill flow of approximately 16,500 cfs. The tailrace TDG reaches a reset point at high spill flows above about 37,000 cfs. In this spill range, gate operations do not affect TDG production because increased spill flow does not increase air entrainment. TDG gain is high in this spill range since the spillway gates at the upstream dams have been pulled so forebay TDG is low. Below the reset point around 37,000 cfs of spill flow, TDG gain will be higher for Gate 1 alone than for Gate 2 operating together at flow level, as shown in Figure 4.5-4.

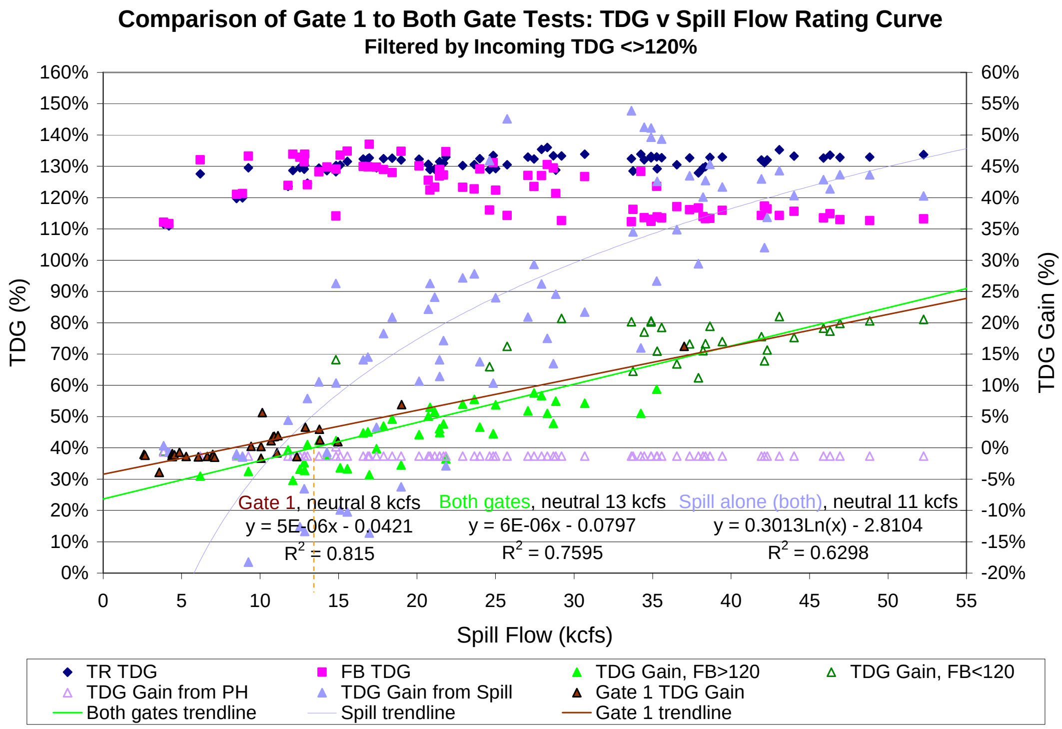

Figure 4.5-4. Comparison of single- and dual-gate operations.

Figure 4.5-5 shows the same split flow tests as Figure 4.5-3 separated by gate ratios rather than forebay TDG. The majority of split flow tests occur with Gates 1 and 2 approximately equally open. At all spill levels, TDG gain for combined powerhouse and spill flow is highest for flows split 60:40 towards Gate 1. However, the 70:30 tests are not differentiable from the 50:50 tests, so it is not possible to conclude that increasing Gate 1 proportion will increase TDG gain. Additionally, the three 20:80 tests are within the range of variability of the 50:50 tests. The TDG gain attributed to spill flow appears to follow the same pattern as the total TDG gain measured in the Project outflow.

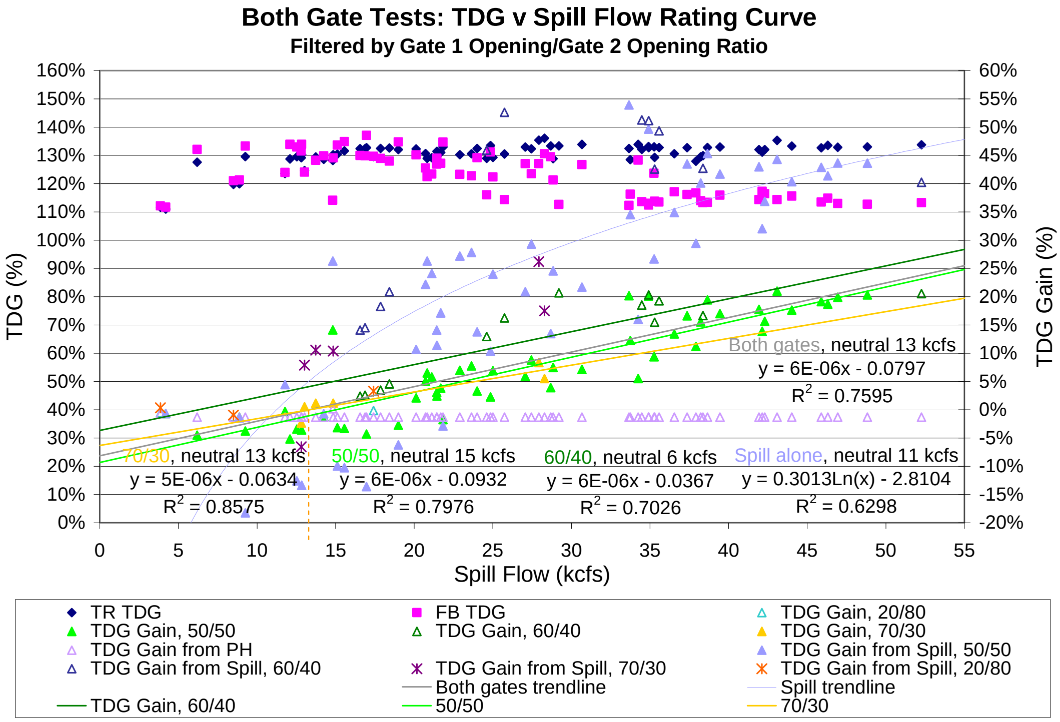

Figure 4.5-5. Summary of 2002-07 test data for both gates, grouped by Gate 1:Gate 2 ratio.

4.5.2. Sluice Operations

Table 4.5-1 and Figure 4.5-6 depict nine of the sluice gate tests conducted in 2006, with flow between 1,500 cfs and 17,100 cfs and incoming TDG between 112 and 127 percent. Overall TDG production for all tests is fairly neutral and increases uniformly with spill regardless of forebay TDG, with maximum stripping of 1.8 percent and maximum generation of 1.1 percent for combined powerhouse and sluice flow. These sluice gate tests show promise for stripping TDG up to gate openings of approximately 4 feet, but beyond that there is the potential for TDG production. We recommend collection of additional sluice gate test data during 2008 to continue to study the interaction between multiple gates, optimize gate opening, and perhaps test modifications to the sluice sill that would allow passage of higher flows without producing TDG.

Table 4.5-1. 2006 Sluice Flows and TDG Gain

# of Gates Open	Sluice Gate 3		Sluice Gate 4		Sluice Gate 5		Total Sluice Flow	TDG Gain
	(cfs)	(ft)	(cfs)	(ft)	(cfs)	(ft)	(cfs)	(%)
1	4,309	4					4,309	-1.7
1	1,583	2					1,583	-1.8
1	5,639	5					5,639	-1.4
1	2,916	3					2,916	-1.8
2	4,262	4	4,262	4			8,524	-1.1
2	1,548	2	1,548	2			3,096	-1.5
2	5,684	5	5,684	5			11,368	0.0
2	2,940	3	2,940	3			5,880	-1.2
3	5,715	5	5,715	5	5,715	5	17,145	1.1

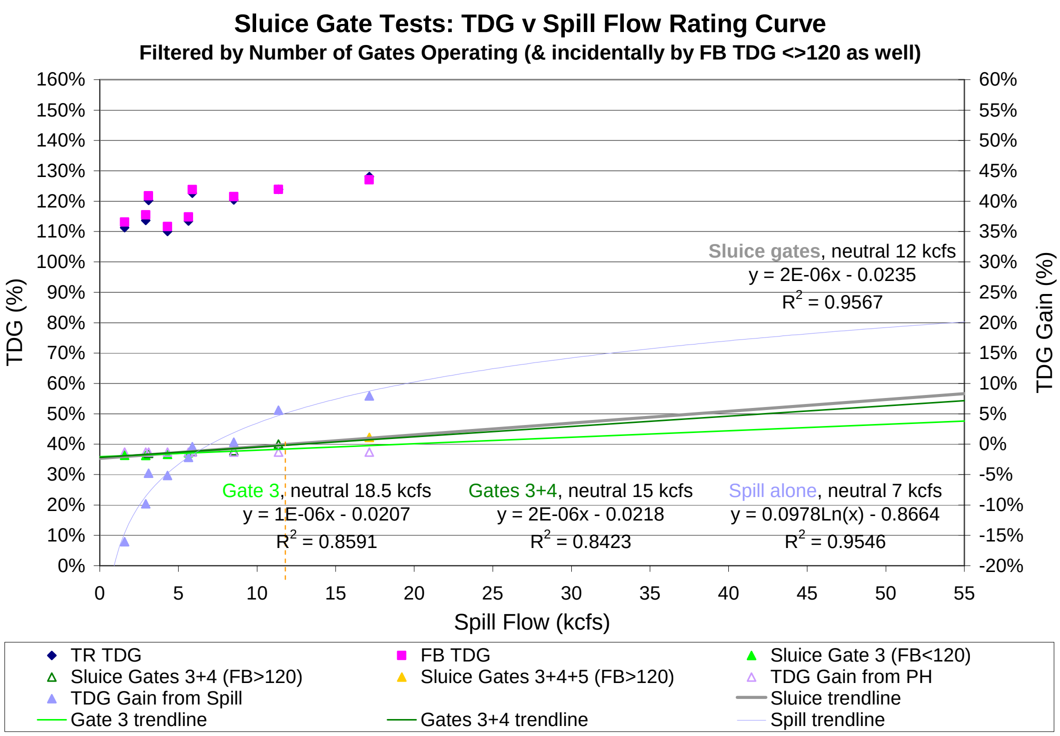

Figure 4.5-6. Summary of 2006 sluice gate test data.

Three additional tests were identified that were not included in the above analysis and should be included in further analysis with data from 2008:

- On May 18, Gates 3, 4, and 5 were opened 4 feet for 4 hours.
- On May 31, Gates 3, 4, and 5 were opened 7 feet for 4 hours.
- On June 16, Gate 4 was opened 7 feet for 4 hours.

Some of these tests were during periods when the USGS tailrace meter did not report data, but data are available for a secondary USGS meter and these data can be used for further analysis.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

ENSR developed short-term databases for spill and sluice gate tests in 2006 and 2007 from data obtained from SCL and the 2007 TDG field program. Data were analyzed to supplement understanding of spill and sluice gate operation impacts on TDG production presented in the previous report on historical data analysis.

Data for the 2007 spill season were analyzed for the H1-H9 TDG measurement locations and the following conclusions were drawn from the results:

- The forebay monitoring station H9 generally matched the USGS forebay fixed monitoring station well during low forebay TDG and river flows. At higher forebay TDG and river flows, a calibration error in the instrument may have resulted in approximately 0.5 percent difference between the Meter H9 readings and the fixed monitoring station; this is well within the expected TDG instruments accuracy.
- In general, as powerhouse flow neared capacity, the TDG measured at the tailrace monitoring stations approached that measured by the USGS fixed monitoring station.
- At flows below approximately 55,000 cfs there is little lateral variation in TDG at Transects 2 and 3, aside from Meter H6, which appears to have had a calibration error.
- During spill flows, there is a minor lateral gradient in TDG at Transect 3 that appears to be dependent on spill flow, gate operation, and powerhouse operation and is generally within the expected instrument accuracy.
- For flows during the study period, TDG is generally stripped from the flow over the distance from the USGS fixed monitoring station to the Meter H8 location near the Canadian border, with the greatest stripping occurring at low flows.

The range of spill and sluice gate operation conditions in the expanded short-term dataset allowed some refinement of the analysis of the effects of gate operations, but did not allow us to draw any firmer conclusions concerning the best operation procedures to minimize TDG production than we were able to derive from the previous historic data analysis. Conclusions on the spill and sluice gate performance are as follows:

- For spill through Gate 1 alone in combination with powerhouse flows, the Project appears to strip TDG for spill flows up to about 8,000 cfs as compared to 11,000 cfs for the previous analysis.
- For spill through Gate 2 alone in combination with powerhouse flows, the Project appears to strip TDG for spill flows up to about 9,500 cfs. However, this conclusion is based on limited data and the resulting regression is highly leveraged by two high spill flow tests (≈45,000 cfs) with no intermediate flow data (10,000-45,000 cfs).
- For spill through both gates in combination with powerhouse flows, the Project appears to strip or have neutral impact on TDG for spill flows up to about 13,000 cfs, when forebay TDG is less than 120 percent. When forebay TDG is greater than 120 percent, the range of stripping action increases up to a spill flow of 15,000 cfs.

- The TDG advantage of operation of two gates versus one for a given spill flow diminishes as spill flow increases and is essentially non-existent for spill flows above about 37,000 cfs. Above this reset point, tailrace TDG produced by spillway operation appears to be independent of forebay TDG or gate operations.
- There is no discernable difference in TDG production as a result of varying the ratio of spill flow from Gates 1 and 2.
- Sluice gate operation appears not to produce TDG for gate openings below about 4 feet and for total sluice flows below about 15,000 cfs. However, all data for multiple sluice gate operations have the sluice gates blocked in adjacent groups, so the impact of other patterns of operation is not known.

5.2. Recommendations for 2008 Field Program

From the analysis to date, we have determined that TDG production through the Project is dependent on incoming TDG, river flow, spill flow, spill operations, and powerhouse operations. The relative importance of each of these factors in predicting tailrace TDG for a given set of initial conditions varies significantly. It is therefore necessary for the database to contain data for each possible combination of forebay TDG level, spill flow, and spill gate opening to develop effective gate operations procedures over the full range of operating conditions. Duplicate tests are also useful in making predictions with confidence, due to variability in the field data.

To this end, we recommend collection of data for the following additional tests:

- Sluice and spill tests with low forebay TDG. While these tests are not indicative of present conditions during spill due to the impact of TDG production at upstream projects, and therefore must be "manufactured", the results will be important in determining how the Project should be operated if upstream project operations are modified so they comply with the TDG standard;
- Sluice gate tests at partial gate openings, independent of spill flow;
- Sluice gate tests comparing single and multiple gates at similar openings;
- Sluice gate tests comparing similar flows from grouped and spread gate patterns;
- Spill tests emphasizing Gate 2 independent of Gate 1 at all spill levels, particularly between 5,000 and 10,000 cfs, if possible without dam safety concerns;
- Spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows as described in the recommendations for the 2007 field program in the December 2007 memo (ENSR 2008);
- Additional tests of 20:80, 60:40, and 70:30 Gate 1 to Gate 2 ratios; and
- Collection of additional data during the spill season at the H-1 through H-9 monitoring locations to better define the spatial variation in tailrace TDG. Hydrodynamic data from physical or numerical modeling may be required to understand the dynamics of tailrace TDG during a range of spill flows.

We understand it may not be possible to collect all of these data during the 2008 field season and therefore recommend that the sluice gate tests be given priority. In addition, the spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows will provide useful information on the optimum split spill operation.

6 REFERENCES

ENSR. 2008. Historical TDG Data Analysis Final Report. Prepared for Seattle City Light by ENSR. January 2008.

Golder Associates (Golder). 2007. Final 2007 Interim Study Report Field Investigation Methods Appendix. December 2007.

Seattle City Light (SCL). 2007. Revised Study Plan for the Boundary Hydroelectric Project (FERC No. 2144). Seattle, Washington. February 2007. Available online at: http://www.seattle.gov/light/news/issues/bndryRelic/br_document.asp

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Appendix 4: 2008 TDG Data Analysis Final Report

Boundary Hydroelectric Project (FERC No. 2144)

2008 TDG Data Analysis

Final Report

Prepared for
Seattle City Light

Prepared by
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November 2008

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1 INTRODUCTION

This report documents the analysis of the 2008 total dissolved gas (TDG) and operations data at Boundary Dam. This report follows two prior reports on the subject: the final report on the TDG historical data analysis at Boundary Dam submitted January 2008 (see Appendix 2 of the Study 3 final report), hereafter the "historical report"; and the addendum to the final report covering the 2006-2007 TDG data analysis also submitted January 2008 (see Appendix 3 of the 2007 Study 3 final report), hereafter the "short-term report." The purpose of the original documents was to describe the TDG study team's efforts to analyze historical and short-term TDG data in support of the relicensing of the Boundary Hydroelectric Project (Project), Federal Energy Regulatory Commission (FERC) No. 2144.

The following background information on the Project location, features, and relevant water quality standards was generally obtained from Seattle City Light's (SCL's) Pre-Application Document (PAD) (SCL 2006). Boundary Dam is located on the Pend Oreille River in northeastern Washington and is the third of five dams on that river. Seven Mile and Waneta dams are located downstream in Canada. Box Canyon Dam is immediately upstream of the Boundary Reservoir, and Albeni Falls Dam is 50 miles farther upstream. Boundary Dam operates as a peaking power generation plant; Box Canyon and Albeni Falls dams are run-of-river facilities. Project flows and operation are significantly influenced by, and have influence in, the reach from Albeni Falls Dam to the Seven Mile Project.

The Project consists of an arch dam, reservoir, and underground power plant. There are spillways located on each abutment, with a combined total maximum discharge capacity of 108,000 cubic feet per second (cfs). In addition, there are seven low-level sluices through the dam with a total of 252,000 cfs of capacity. The Project power plant contains four 208,000-horsepower (hp) and two 268,000-hp Francis turbines, with four 165-megawatt (MW) and two 205-MW umbrella generators (approximate peak electrical output). Project powerhouse flow capacity is approximately 55,000 cfs. Flows through the power plant discharge into the tailrace immediately below the dam.

The water quality standards applicable to the Project are the Washington State Water Quality Standards, set forth in Chapter 173-201A of the Washington Administrative Code (WAC). The standards relevant to this study limit TDG based on the adverse impact of dissolved gas on aquatic life. For waters designated as salmonid spawning and rearing, the standard states that TDG shall not exceed 110 percent of saturation at any point of sample collection. This criterion is waived when the stream flow exceeds the seven-day, ten-year (7Q10) frequency flood. The 7Q10 flow is the highest flow of a running seven consecutive day average using the daily average flows that may occur in a 10-year period. The assumed 7Q10 flow at Boundary Dam is 108,300 cfs. For the purposes of TDG abatement alternative evaluation, the target flow for passing the 7Q10 event was assumed to be 53,300 cfs (108,300 minus the Project generation capacity of 55,000 cfs).

2 STUDY OBJECTIVES

The objectives of the 2008 short-term analysis were as follows:

- Obtain TDG and Project operations data during periods of spill flow during 2008 and add these data to the database developed for the 2006 and 2007 spill periods.
- Analyze the data for general trends and longitudinal and lateral TDG distribution.
- Develop a method for analyzing spill and sluice gate operation tests to determine the relative impacts of tested operations and future operations or improvements on TDG.
- Analyze the spill and sluice gate tests to determine preferred operations for optimizing TDG performance over a range of forebay TDG and river flows.
- Analyze available data to assess the potential for powerhouse flow to be gassed up by spill flow over a range of forebay TDG and spill flows.
- Develop recommendations for further monitoring in 2009.

The overall long-term objective of the study is to identify potential Project operations that may improve TDG conditions at Boundary Dam, either by limiting the amount of TDG produced or promoting stripping of gas.

3 SHORT-TERM DATABASE DEVELOPMENT

The 2008 short-term database was developed to capture TDG data corresponding to spill and sluice gate tests as an addition to the 2006-2007 short-term database. Project operations, gate operations, and provisional U.S. Geological Survey (USGS) TDG data for the forebay and tailrace fixed monitoring stations were obtained from SCL and Golder Associates (Golder) (Golder 2008). In addition, 2008 data for TDG monitoring in the forebay and at multiple locations along three tailrace transects were obtained from Golder (2008) and integrated into the database. The database was analyzed to determine the effects of gate operations on tailrace TDG during designated test events as described in the following section.

4 DATA ANALYSIS AND RESULTS

4.1. Summary of 2008 Data

Figure 4.4-1 shows chronological Project flows and TDG data from the long-term USGS forebay and tailrace monitoring stations for 2008. USGS tailrace data were missing or invalid from April 23 to May 2 and from May 22 to June 5. Data from these periods were replaced with TDG values synthesized from one of the Golder transect stations as described in Section 4.3. In each plot, the forebay TDG is indicated in yellow and the tailrace TDG time series are color-coded to indicate whether the tailrace TDG was in compliance. The tailrace TDG was in compliance with water quality standards when the tailrace TDG was below 110 percent saturation (indicated by gray in Figure 4.4-1). The tailrace TDG was also considered in compliance when the tailrace TDG was greater than 110 percent but less than the incoming forebay TDG, meaning the Project was stripping gas (indicated by light green). The tailrace TDG was out of compliance when the tailrace TDG was greater than 110 percent and greater than the forebay TDG (indicated by red when the forebay was less than 110 percent and orange when the forebay was greater than 110 percent).

The 2008 data record begins on January 1 and ends on July 31, as shown in Figure 4.1-1. In this partial record, the maximum spill flow was approximately 63,000 cfs and the maximum Project outflow was approximately 108,000 cfs, approximately equal to the 7Q10 flow for the Project. During periods with no spill, as Project outflows increased and forebay TDG increased to above 110 percent, the powerhouse stripped TDG at flows above approximately 38,000 cfs. The minimum Project outflows for the period of record occurred in January through April when the powerhouse flow shut down to below 200 cfs at night. During the spill season, the tailrace TDG was out of compliance during the higher spill flows (above approximately 12,000 cfs).

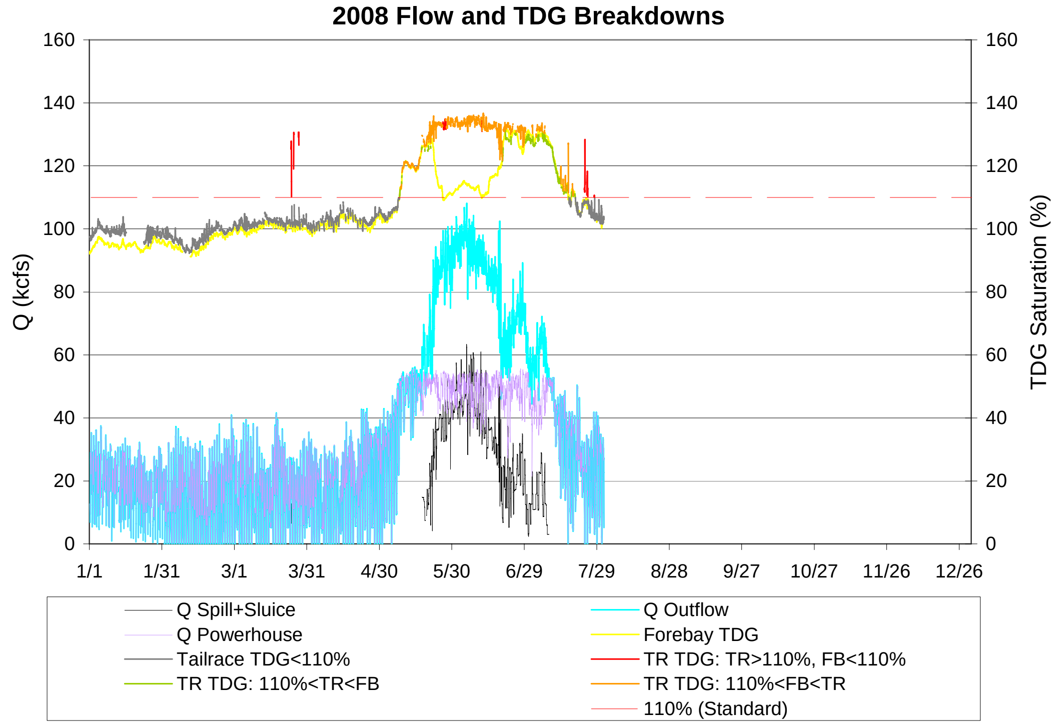

Figure 4.1-1. 2008 flow and TDG breakdowns.

4.2. Overview of 2008 Spill Testing Program

In the short-term report, the TDG study team reviewed the 2006-2007 short-term database for data gaps and recommended tests to be performed during the 2008 spill season to supplement the database as follows:

- Sluice and spill tests with low forebay TDG
- Sluice gate tests at partial gate openings
- Sluice gate tests comparing single and multiple gates at similar openings
- Sluice gate tests comparing similar flows from grouped and spread gate patterns

- Spill tests emphasizing Gate 2 independent of Gate 1 at all spill levels, particularly between 5,000 and 10,000 cfs
- Spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows
- Additional tests of 20:80, 60:40, and 70:30 Gate 1 to Gate 2 ratios
- Collection of additional data during the spill season at the H-1 through H-9 monitoring locations to better define the spatial variation in tailrace TDG

The recommendations prioritized the sluice gate tests at partial gate openings, the sluice gate tests with single and multiple gates, and the spill tests comparing Gate 1 to Gate 2 ratios at low and medium spill flows.

The 2008 spill season occurred from May 17 to July 17 as shown in Figure 4.1-1. The combined 2006 and 2008 sluice tests are summarized in Table 4.2-1. The 2008 sluice gate tests included two tests with low forebay TDG, which were “manufactured” by reducing the powerhouse flow and forcing spill early in the year. These tests were intended to provide information on the impact of the sluice gate operations if upstream project operations are modified so they comply with the TDG standards. Five sluice gate tests were obtained at partial gate openings at flows from 2,200 to 6,100 cfs per gate with three gates open. All of the 2008 tests were obtained for combined operation of Gates 2, 4, and 6 at different gate openings. Additional tests were obtained containing single and multiple sluice gates at similar openings in combination with flow from the spill gates up to flows of 63,000 cfs.

Table 4.2-1. 2006 and 2008 sluice-only tests, sorted by sluice flow per gate.

Date	# of Gates Open	Sluice Gate 2 (cfs)	Sluice Gate 3 (cfs)	Sluice Gate 4 (cfs)	Sluice Gate 5 (cfs)	Sluice Gate 6 (cfs)	Total Sluice Flow (cfs)	Sluice Flow per Gate (cfs)	Total Outflow (cfs)	% of Total Q per Gate (%)	FB TDG (%)	TR TDG (%)	TDG Gain (%)
4/20/06	2		1,548	1,548			3,096	1,548	53,507	2.9%	121.8	120.3	-1.5
4/12/06	1		1,583				1,583	1,583	45,067	3.5%	113.1	111.3	-1.8
3/24/08	3	2,200		2,200		2,200	6,600	2,200	21,058	10.4%	100.8	111.3	10.4
4/13/06	1		2,916				2,916	2,916	47,079	6.2%	115.5	113.7	-1.8
4/29/06	2		2,932	2,932			5,864	2,932	56,646	5.2%	123.8	122.6	-1.2
5/17/06	3		2,972	2,972	2,972		8,916	2,972	57,992	5.1%	127.1		
5/19/08	3	3,400		2,200		3,400	9,000	3,000	62,676	4.8%	126.8	127.3	0.5
4/20/06	2		4,250	4,250			8,500	4,250	61,411	6.9%	121.5	120.4	-1.1
4/12/06	1		4,309				4,309	4,309	47,800	9.0%	111.7	110.0	-1.7
5/18/06	3		4,332	4,332	4,332		12,996	4,332	66,984	6.5%	127.7		
3/25/08	3	4,500		4,500		4,500	13,500	4,500	24,829	18.1%	100.6	122.2	21.7
5/19/08	3	4,500		4,500		4,500	13,500	4,500	64,963	6.9%	126.8	128.4	1.6
6/19/08	3	4,500		4,500		4,500	13,500	4,500	64,955	6.9%	120.5	126.3	5.8
4/13/06	1		5,639				5,639	5,639	49,805	11.3%	114.8	113.4	-1.4
4/29/06	2		5,669	5,669			11,338	5,669	60,057	9.4%	123.9	123.9	0.0
5/17/06	3		5,715	5,715	5,715		17,145	5,715	65,887	8.7%	127.0	128.1	1.2
5/21/08	3	6,100		6,100		6,100	18,300	6,100	69,858	8.7%	127.9	131.3	3.4
5/31/06	3		8,390	8,390	8,390		25,170	8,390	78,649	10.7%	123.5	128.6	5.1
6/16/06	1			8,390			8,390	8,390	61,053	13.7%	127.1	126.0	-1.1

The 2008 spill gate tests were mainly with even-split spill through Gate 1 and Gate 2. There were 62 tests of even-split spill, along with one test with a 40:60 Gate 1 to Gate 2 ratio, 18 tests with a 60:40 Gate 1 to Gate 2 ratio, and three tests with a 70:30 Gate 1 to Gate 2 ratio. The 2008 tests had a range of forebay TDG from 100 percent to 132 percent and spill flows up to 55,000 cfs. Tables 4.2-2 and 4.2-3 summarize the frequency of spill flow and corresponding forebay and tailrace TDG levels that occurred during 2008 and during the full data record from 1999 to 2008, respectively.

Table 4.2-2. Spill behavior, 2008.

Category	Hours	% of Spill	Avg FB TDG	Avg TR TDG	Avg TDG Gain	Hours of + Gain	Hours of - Gain
Spill/Sluice flow (any)	1269	100%	119.3	131.5	12.1	981	233
Spill flow only	869	68.5%	120.7	131.4	11.0	636	189
Sluice flow only	26	2.0%	117.0	124.7	7.7	26	0
Spill and sluice flow	374	29.5%	119.5	131.9	12.4	319	44
Spill >15 kcfs	669	77.0%	118.2	132.7	14.8	613	28
Spill 10-15 kcfs	129	14.8%	126.5	127.9	1.4	20	98
Spill 5-10 kcfs	45	5.2%	128.5	127.4	-1.0	2	38
Spill 1-5 kcfs	26	3.0%	128.9	127.6	-1.3	1	25
Sluice >15 kcfs	5	19.2%	127.9	131.3	3.4	5	0
Sluice 10-15 kcfs	13	50.0%	114.8	125.4	10.7	13	0
Sluice 5-10 kcfs	8	30.8%	113.9	119.3	5.5	8	0
Sluice 1-5 kcfs	0	0%	--	--	--	0	0
Spill + Sluice >15 kcfs	321	85.8%	118.1	132.9	14.7	306	4
Spill + Sluice 10-15 kcfs	33	8.8%	127.8	126.9	-0.8	12	21
Spill + Sluice 5-10 kcfs	20	5.3%	127.2	125.7	-1.5	1	19
Spill + Sluice 1-5 kcfs	0	0%	--	--	--	0	0

Table 4.2-3. Spill behavior, 1999–2008.

Category	Hours	% of Spill	Avg FB TDG	Avg TR TDG	Avg TDG Gain	Hours of + Gain	Hours of - Gain
Spill/Sluice flow (any)	4570	100%	124.2	128.8	4.6	2780	1526
Spill flow only	4103	89.8%	125.0	128.7	3.7	2426	1447
Sluice flow only	85	1.9%	120.2	121.3	2.0	35	35
Spill and sluice flow	382	8.4%	119.6	131.9	12.4	319	44
Spill >15 kcfs	2331	56.8%	123.5	132.0	8.5	2013	145
Spill 10-15 kcfs	877	21.4%	128.0	127.7	-0.4	308	469
Spill 5-10 kcfs	574	14.0%	126.6	124.3	-2.4	90	444
Spill 1-5 kcfs	321	7.8%	122.7	121.3	-1.4	15	389
Sluice >15 kcfs	17	20.0%	125.9	129.6	4.1	10	1
Sluice 10-15 kcfs	20	23.5%	118.6	124.9	6.9	16	1

Table 4.2-3, continued…

Category	Hours	% of Spill	Avg FB TDG	Avg TR TDG	Avg TDG Gain	Hours of + Gain	Hours of - Gain
Sluice 5-10 kcfs	31	36.5%	120.7	120.6	0.5	9	17
Sluice 1-5 kcfs	17	20.0%	115.7	113.8	-1.1	0	16
Spill + Sluice >15 kcfs	321	85.8%	118.1	131.4	13.3	306	4
Spill + Sluice 10-15 kcfs	33	8.8%	127.8	126.9	-0.8	12	21
Spill + Sluice 5-10 kcfs	20	5.3%	127.2	125.7	-1.5	1	19
Spill + Sluice 1-5 kcfs	0	0%	--	--	--	0	0

4.3. 2008 TDG Monitoring Data Analysis

4.3.1. Summary of 2008 TDG Data Monitoring Data

The 2008 TDG monitoring data obtained from Golder included measurements from nine TDG stations (H1 to H9) placed on four transects along the Pend Oreille River as a supplement to the USGS forebay and tailrace fixed monitoring stations as shown in Figure 4.3-1. Meter H9 provided a duplicate for the USGS forebay fixed monitoring station. Transect 2 (H1-H4, numbered from left to right, looking downstream) was immediately downstream of the tailrace constriction point. Transect 3 (H5 to H7) was at the same cross section as the USGS tailrace gage, and transect 4 (H8) was across the international border in Canada. The actual coordinates of the instrument locations as deployed were provided in Golder (2008) and were similar to the 2007 placement.

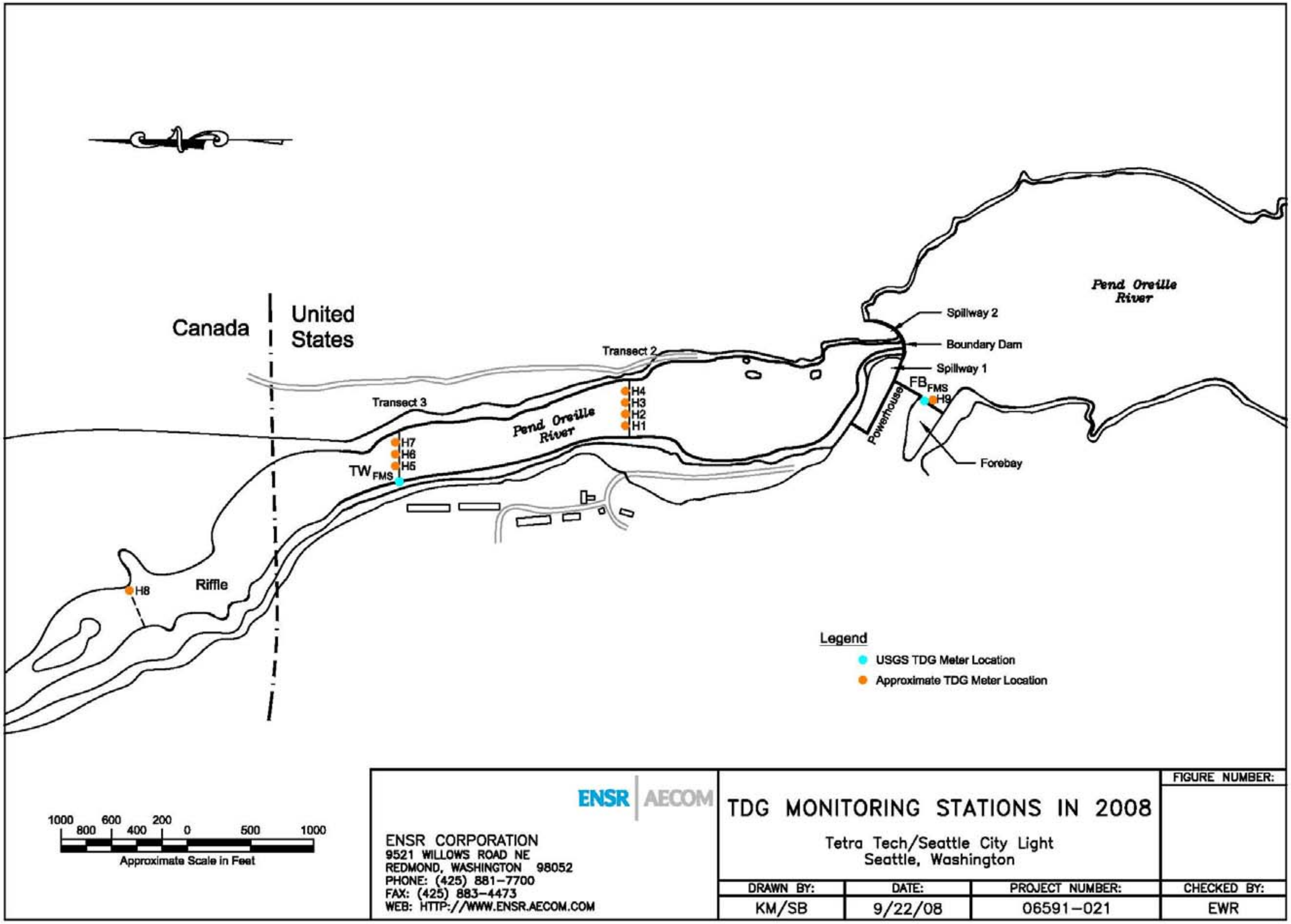

Figure 4.3-1. 2008 TDG monitoring locations.

Figures 4.3-2 through 4.3-4 display the USGS tailrace and forebay TDG chronologically along with the stations at Transects 2, 3, and 1 and 4, respectively.

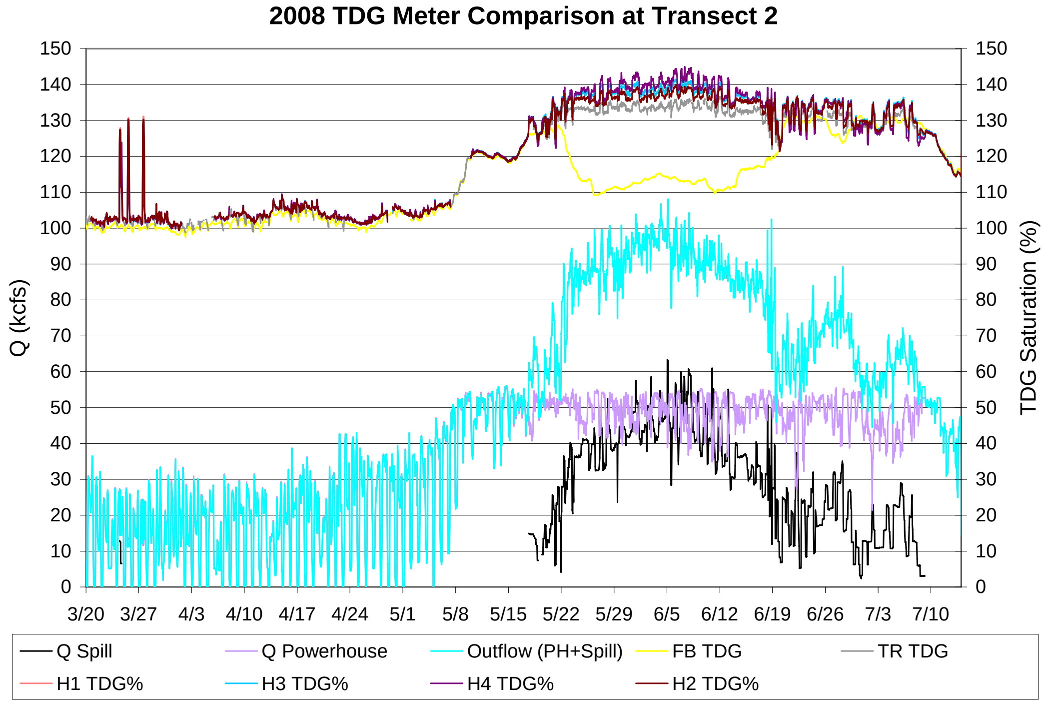

Figure 4.3-2. Transect 2 and USGS TDG measurements.

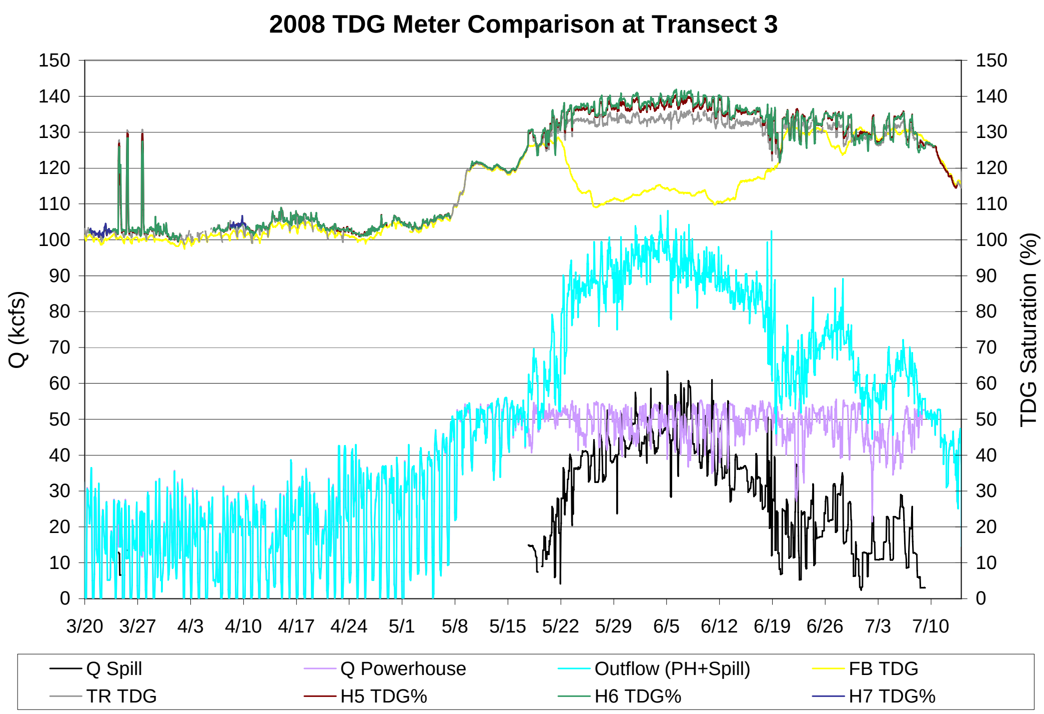

Figure 4.3-3. Transect 3 and USGS TDG measurements.

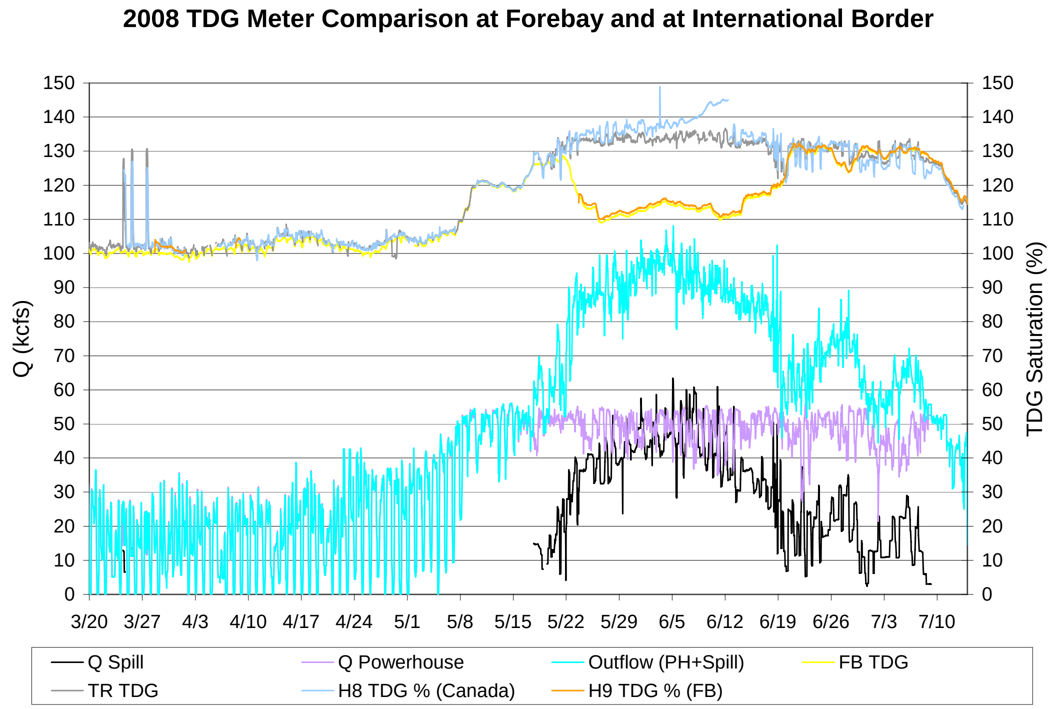

Figure 4.3-4. Transects 1 and 4 and USGS TDG measurements.

Figure 4.3-3 demonstrates that the TDG generally decreased from the forebay to the USGS tailrace fixed monitoring station except during periods of spill. During times of no spill, TDG at station H8 near the Canadian border (Figure 4.4-4) was similar to or slightly lower than at the USGS fixed monitoring station. In early June when spill was above approximately 30,000 cfs, the station H8 data were suspect, as they indicated significantly higher TDG than previously and higher than the TDG measured by the USGS fixed monitoring station. The TDG study team will review these data with Golder to confirm that station H8 was operating correctly during this two- to three-week period in June.

4.3.2. Synthesis of Replacement USGS Tailrace Data

The 2008 database was compiled from USGS forebay and tailrace station TDG data and Golder transect station TDG data. USGS tailrace data were missing or invalid from April 23 to May 2 and from May 22 to June 5, 2008. The USGS tailrace station is located on transect 3 along with Golder stations H5, H6, and H7 (listed from left bank to right bank; see Figure 4.3-1). The chronological plot in Figure 4.3-3 shows that all transect 3 stations were comparable prior to the spill season. Data for station H7 were limited and ended before the spill season. During periods of spill, a lateral TDG distribution developed as a function of spill flow.

In order to fill in the USGS tailrace station data gaps, a correlation between the USGS tailrace station and the closest transect 3 station, station H5, was developed. A representative subset of the H5 and USGS tailrace TDG data from June 5 (when the USGS station returned to normal output) to June 24 (when the stations came back together at the end of the spill season) was used to determine the relationship between the stations. For the range of spill flows during the period from June 5 through June 24, the data showed a linear relationship between total spilled flow and the difference in TDG measurements between station H5 and the USGS tailrace station (Figure 4.3-5). The resulting equation, USGS tailrace TDG = H5 station TDG - 0.00008*(Spill + Sluice Flow), was entered into the overall database to synthesize USGS tailrace TDG for the data gaps from April 23 to May 2 and May 22 to June 5. Instances of missing USGS tailrace data at other times were left blank. At times when barometric pressure data at the USGS tailrace station were unavailable, barometric pressure from the USGS forebay station was used after adjusting by 7 millimeters mercury (mmHg) to account for the difference in elevation between the meter locations. All plots in this report include the synthesized USGS tailrace data.

June 2008: Comparison of H5 to USGS TR TDG

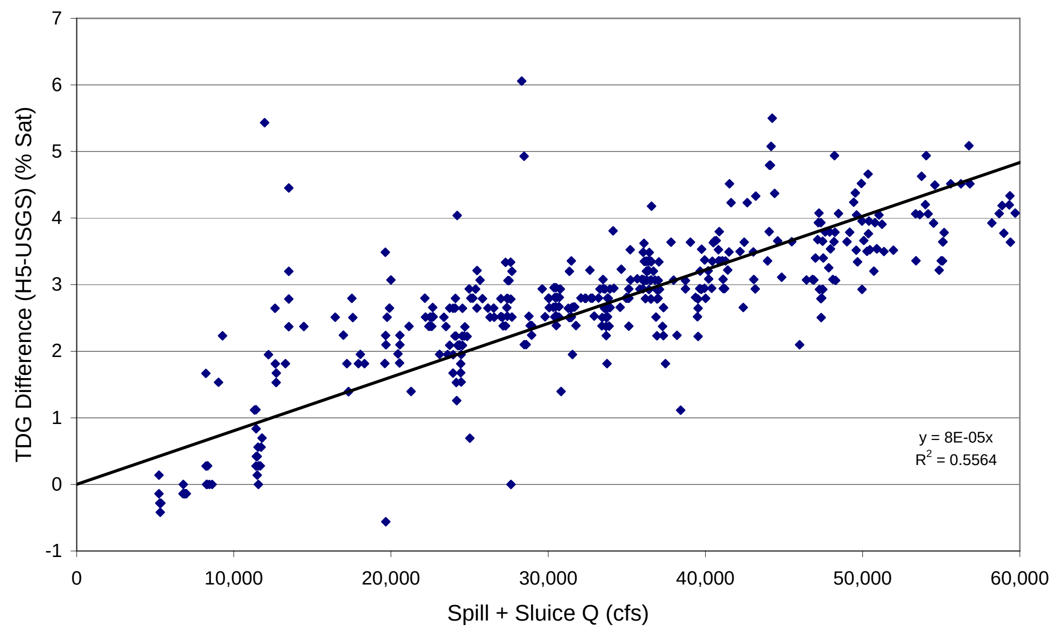

Figure 4.3-5. Comparison of station H5 to USGS tailrace station in June 2008 for May USGS data replacement.

4.3.3. TDG Distribution During Spill Flow

Figures 4.3-6 to 4.3-10 present a chronological record of the TDG data collected at transects 2 and 3 (stations H1 to H7 and the USGS tailrace station), along with the USGS forebay station and Project flows, during the spill season. The data were separated into two-week intervals for ease of viewing. The general trend was for TDG at transect 2 to approach the TDG measured at the USGS tailrace station as powerhouse flows increased to capacity, indicating well-mixed tailrace flows. However, when spill flows occurred, there appeared to be a longitudinal and lateral distribution of TDG along the tailrace that was dependent on spill flow.

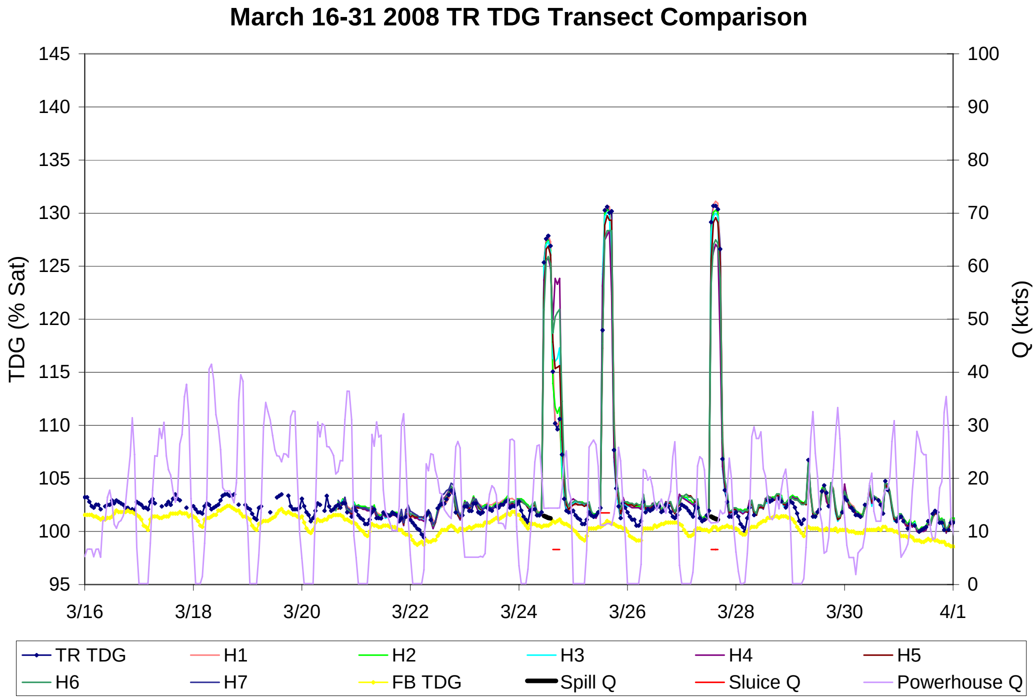

Figure 4.3-6. Project flows and TDG at Transect stations H1–H7 and USGS stations, March 16–31, 2008.

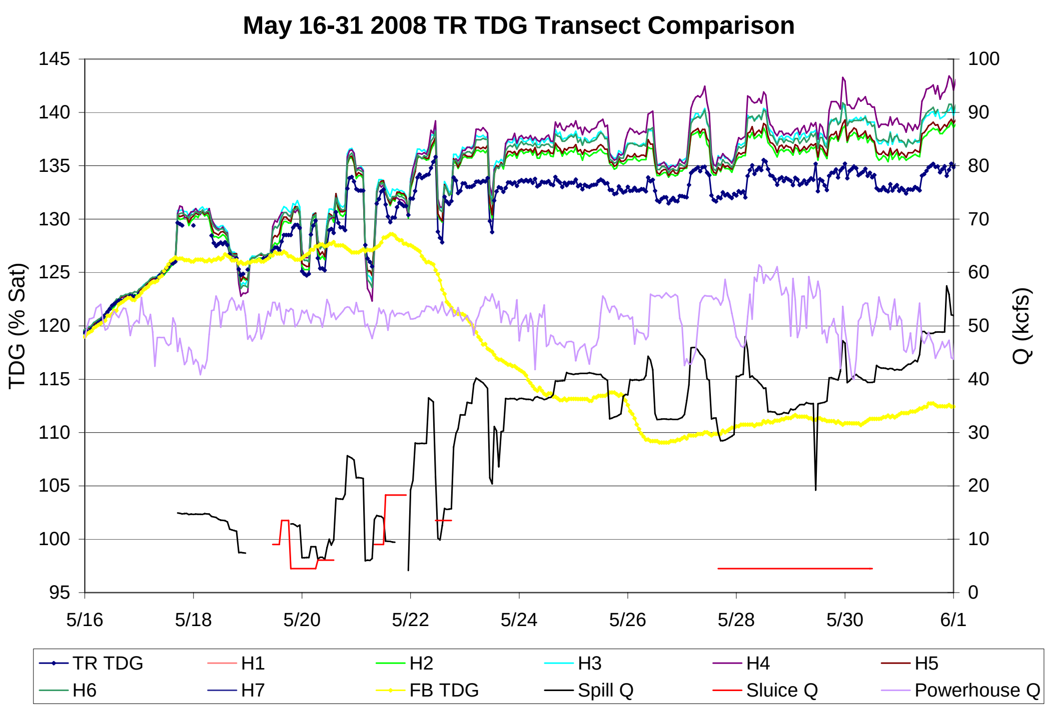

Figure 4.3-7. Project flows and TDG at Transect stations H1–H7 and USGS stations, May 16–31, 2008.

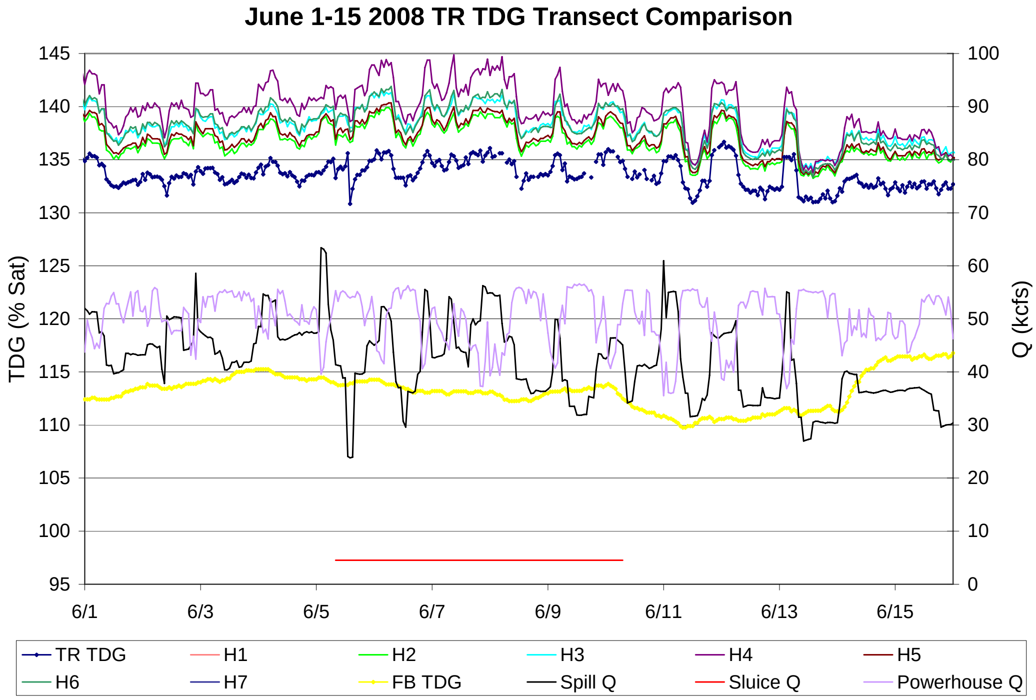

Figure 4.3-8. Project flows and TDG at Transect stations H1–H7 and USGS stations, June 1–15, 2008.

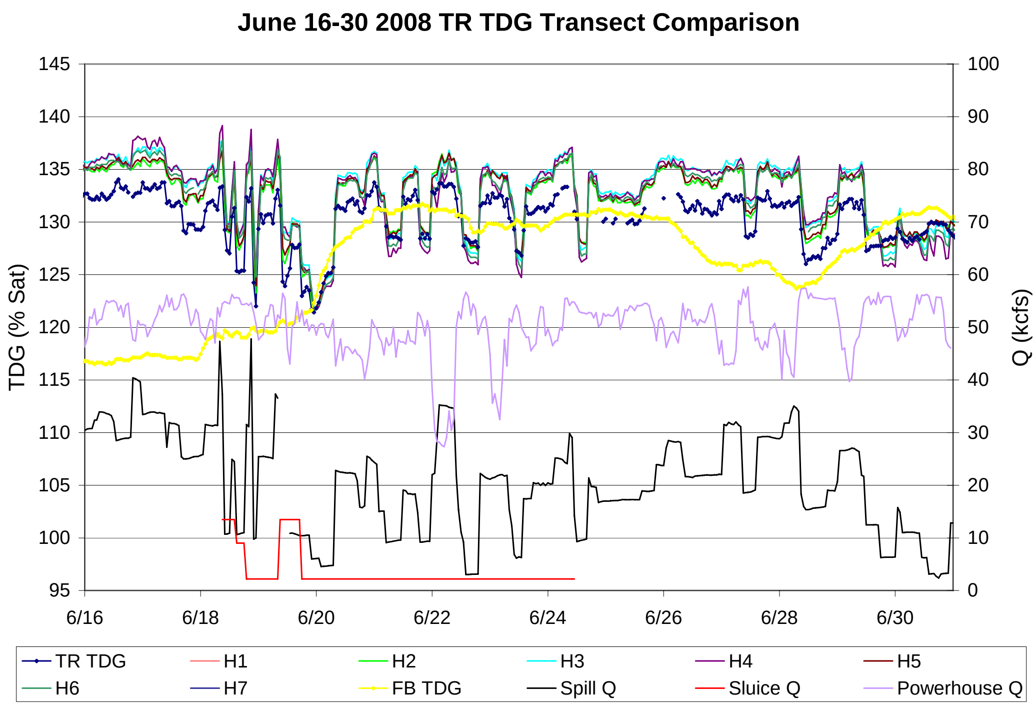

Figure 4.3-9. Project flows and TDG at Transect stations H1–H7 and USGS stations, June 16–30, 2008.

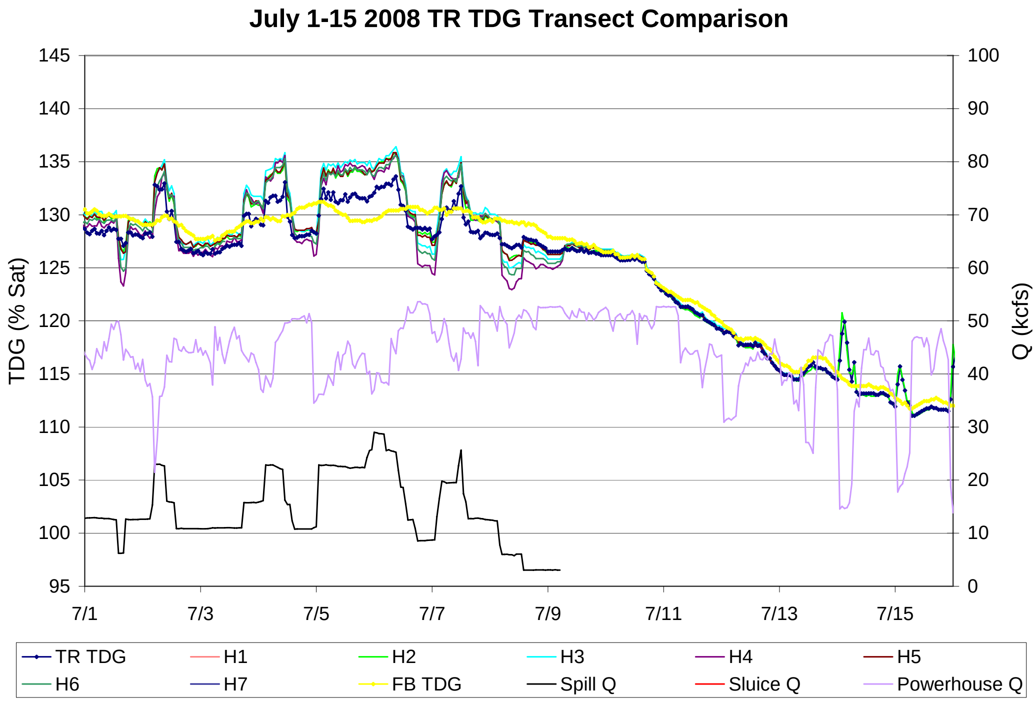

Figure 4.3-10. Project flows and TDG at Transect stations H1–H7 and USGS stations, July 1–15, 2008.

As shown in Figure 4.3-6, spill occurred during four tests in March, resulting in visible spikes of TDG in all tailrace stations. These instances of spill were produced by reducing powerhouse flow, for the purpose of collecting data for sluice gate performance at low forebay TDG levels. TDG measurements varied between the stations, and in general were higher on transect 2 and at the USGS station than on the remainder of transect 3.

Figure 4.3-7 shows TDG data at the beginning of the spill season. Until spill flows started on May 17, all tailrace stations measured similar TDG levels. For spill flows below approximately 12,000 cfs, the USGS station read higher TDG than the transect stations. As spill increased above approximately 12,000 cfs, the USGS station read lower than the transect stations, with TDG increasing from left (stations H2 and H5) to right (stations H4, H3, and H6) across the river. This suggests that the lateral TDG distribution varies with spill flow. Figure 4.3-7 also depicts the forebay TDG "inversion" that occurred after May 22, when total river flow rose above the hydraulic capacity of the upstream projects and their gates were pulled, effectively eliminating their contribution to TDG.

Figure 4.3-9 shows increased forebay TDG when the upstream projects replaced their gates as the river flows dropped off. Figure 4.3-10 shows the end of the spill season. Note that the lateral variation between the meters effectively disappeared when spill flow ceased. This confirmed that this effect was not due to a meter calibration or other data collection error.

4.3.4. General Longitudinal and Lateral TDG Distribution

The following section describes the longitudinal and lateral TDG distribution and mixing trends identified from the data for stations H1 to H9 and the USGS forebay and tailrace fixed monitoring stations.

Meter H9 was installed in the forebay as a duplicate for the USGS fixed monitoring station. TDG data from station H9 were generally strongly correlated with the USGS forebay station data. As shown in Figure 4.3-11, the data from station H9 were consistently slightly higher than the USGS data at forebay TDG levels above 110 percent. The station H9 data were nearly identical to the USGS data for forebay TDG levels between 107 and 110 percent, and station H9 data in the lowest range were 2 to 3 percent higher than the USGS forebay station data.

The average difference in TDG between the USGS forebay station and station H9 was slight and increased with flow (Figure 4.3-12), from neutral at 0 cfs to 0.9 percent at 110,000 cfs. This is consistent with the 2007 findings and the variation is within the expected instrument accuracy. There is also a subset of data showing a 2 percent gain in the lower outflow ranges below 35,000 cfs, which will be confirmed with Golder. These data points occurred during late March and early April, while the data points at this level of outflow in July fit the expected trendline.

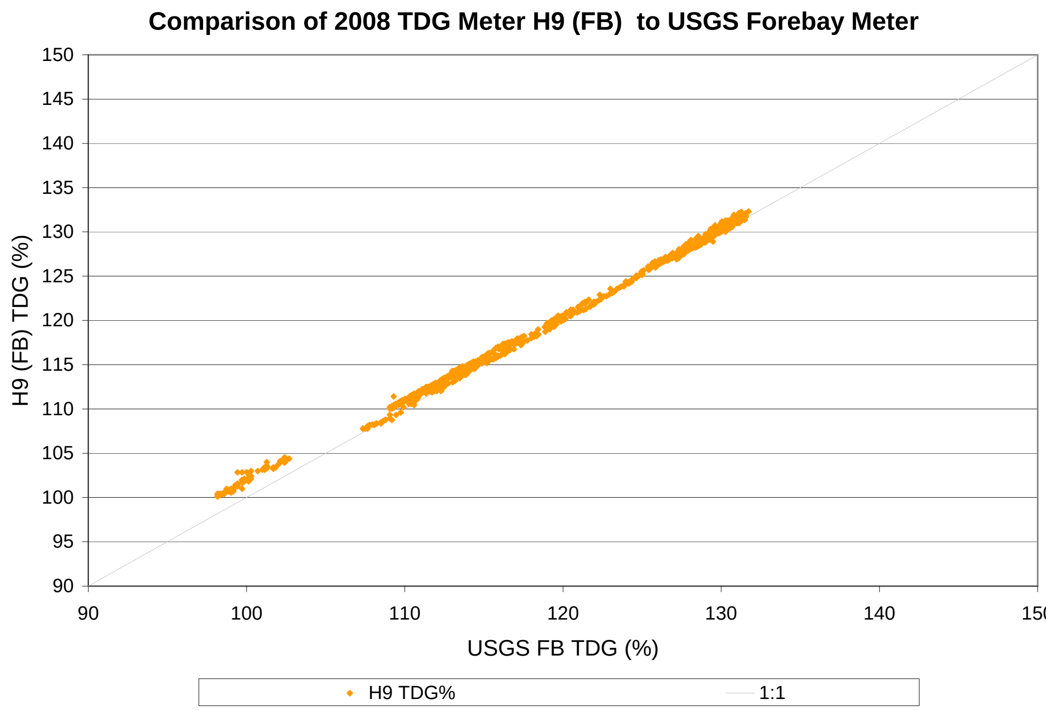

Figure 4.3-11. Station H9 to USGS forebay station correlation.

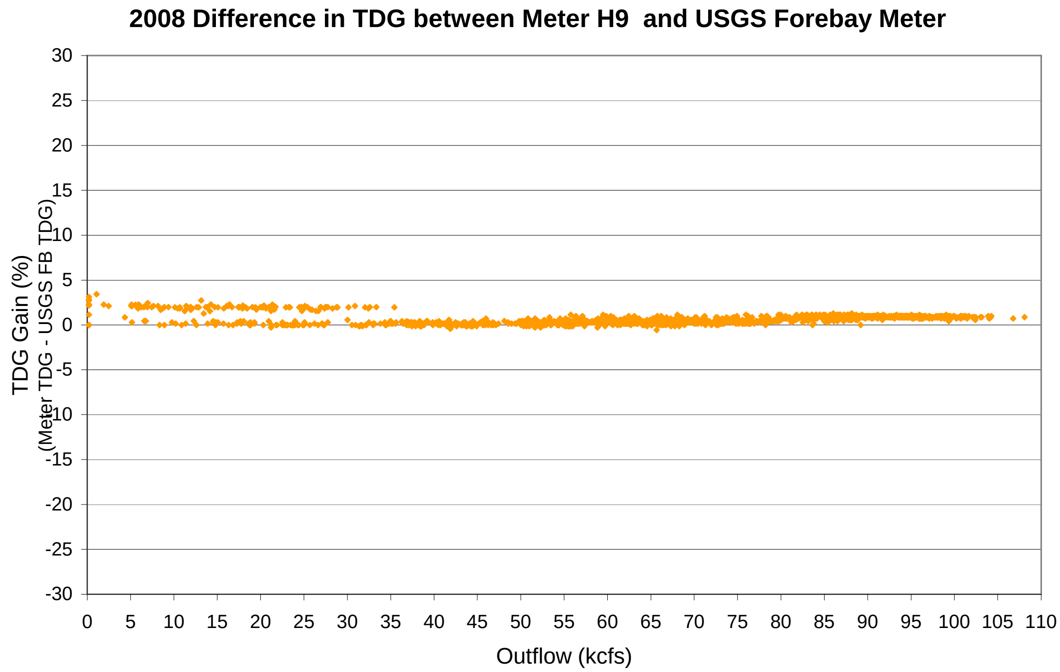

Figure 4.3-12. River flow vs. the difference in TDG between station H9 and the USGS forebay station.

Figures 4.3-13 and 4.3-14 compare the stations along transects 2 and 3 longitudinally and laterally with respect to river flow. In each case, the differences between the USGS tailrace fixed monitoring station TDG and the station TDG were plotted for the entire study period. Negative TDG gain in the figures indicates that the stations generally read higher TDG than the USGS fixed monitoring station at Project outflows above approximately 50,000 to 60,000 cfs, with this difference increasing from left to right across the river. As discussed in the two-week chronological plots in Section 4.3.3, this effect was observed at spill flows above approximately 12,000 cfs.

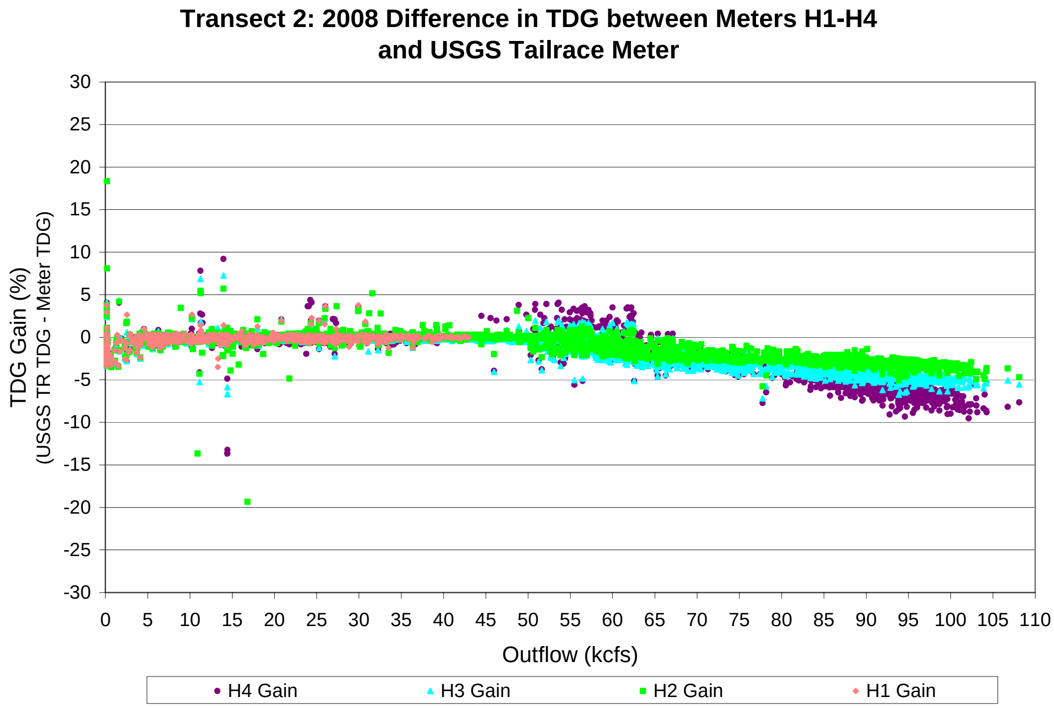

Figure 4.3-13. River flow vs. TDG difference between Transect 2 stations and the USGS tailrace station.

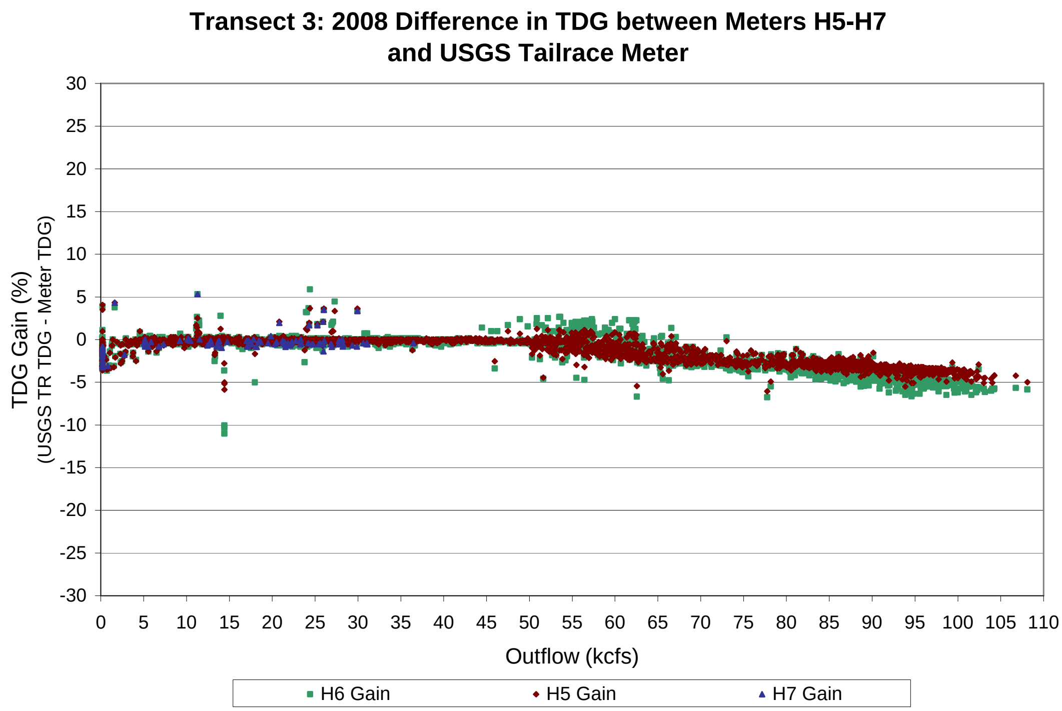

Figure 4.3-14. River flow vs. TDG difference between Transect 3 stations and the USGS tailrace station.

Figure 4.3-13 shows the relationship of river flow to the difference in TDG between the transect 2 stations (H1-H4) and the USGS tailrace station. There was a distinct relationship between flow level and the difference in TDG measurements between the transect 2 stations and the USGS fixed monitoring station. At full powerhouse capacity, the transect 2 stations read approximately the same as the USGS tailrace station. As river flows increased, the transect 2 stations measured higher than the USGS tailrace station by approximately 4, 5.5, and 8 percent for stations H2, H3, and H4 respectively at 105,000 cfs. This suggested that mixing was incomplete and TDG was greater on the right side of the river at higher spill flows. Station H1 stopped recording on May 4 and produced no data above 43,000 cfs.

Figure 4.3-14 shows the relationship of river flow to the difference in TDG between the transect 3 stations (H5-H7) and the USGS tailrace station. The transect 3 stations followed the same pattern as the transect 2 stations: reading higher than the USGS station at Project outflows below 12,000 cfs, neutral to 50,000 to 60,000 cfs, and increasing in difference from the USGS station to 4.5 percent at station H5 and 6 percent at station H6 at 110,000 cfs. As for transect 3, this suggested lateral variation with higher TDG on the right side of the river. Station H7 recorded a limited data set until April 10, for outflows below about 36,000 cfs.

Figures 4.3-15 and 4.3-16 compare the downstream station H8, which is located on transect 4 at the Canadian border, to the USGS tailrace station. The 2007 data showed the TDG measured at station H8 to be slightly lower than at the USGS tailrace station, with the difference decreasing with Project outflow from -1.1 percent at 5,000 cfs to zero percent at approximately 55,000 cfs. The 2008 data show no difference between station H8 and the USGS tailrace station below 50,000 cfs, with station H8 an average of about 2 percent lower between 50,000 cfs and 62,000 cfs, then increasing from there to about 4 percent higher at 110,000 cfs. This trend of higher TDG readings than the USGS station at higher spill flows was consistent with the results at the upstream transects as station H8 was located near the right bank.

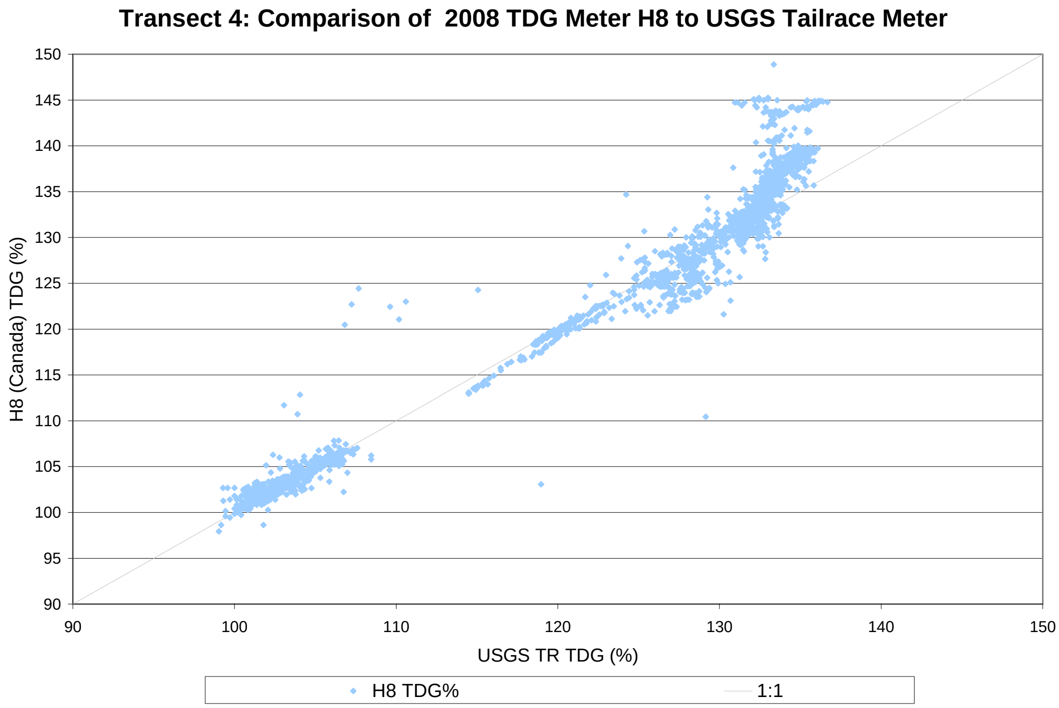

Figure 4.3-15. Transect 4 to USGS tailrace station correlation.

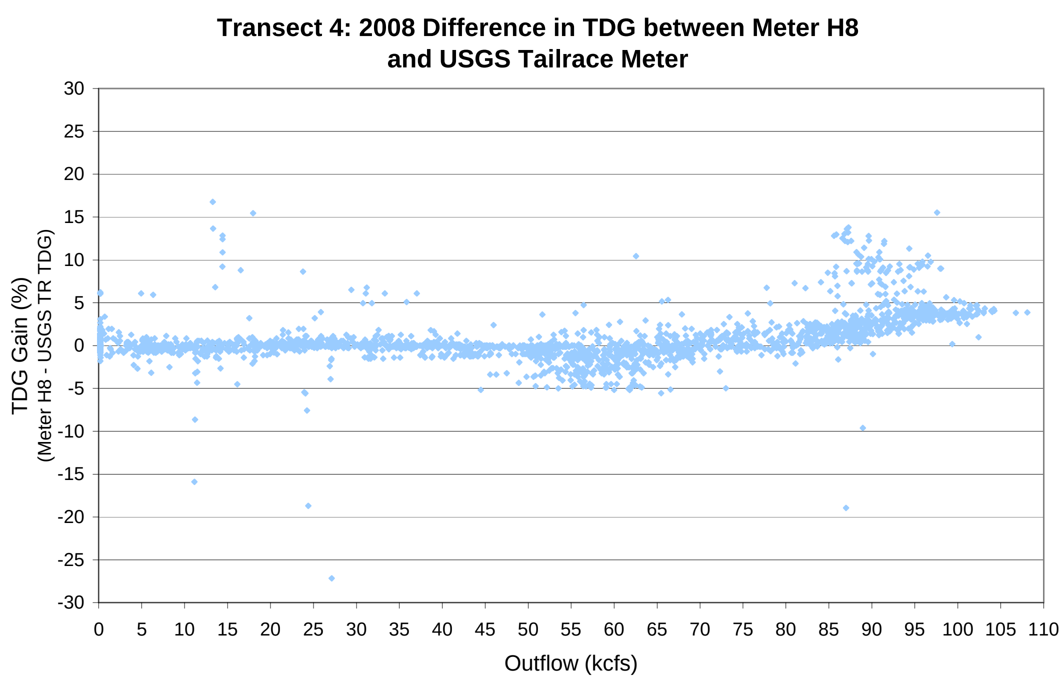

Figure 4.3-16. River flow vs. TDG gain from the USGS tailrace station to the Canadian border.

4.4. Short-Term Spill and Sluice Test Data Analysis

4.4.1. Short-Term Database

On the basis of the equilibration time analysis conducted as part of the historical report, the data from the 2008 spill season were filtered to find instances when the same spill or sluice gate settings were maintained for at least 4 hours. These "tests" were extracted into a short-term database for the purpose of gate operations analysis.

The sluice and spill gate test data for 2008 were added to the 2006 and 2007 gate test data to complete the short-term database. The short-term gate test database contained 208 planned and incidental gate tests over a range of incoming forebay TDG as shown in Table 4.4-1. In an attempt to isolate variable test conditions, the tests were arranged by the percent spilled flow (% Spill), or percentage of total river flow that was passed over spill gates and/or through sluice gates, and then grouped by forebay TDG. From the table it was apparent that during low percent spill, and low spill flow conditions (0 to 10 percent spill) the tests occurred over a range of forebay TDG as river flows increased over powerhouse capacity and TDG increased from upstream project influences. As river flow increased so that spill flows are 15 to 30 percent of the total river flow, forebay TDG was typically above 125 percent due to influence of upstream projects. At river flows of 80,000 to 90,000 cfs, the upstream projects reached their hydraulic capacities, pulled gates, and reduced the Project forebay TDG. When river flows were approximately 90,000 cfs, resulting in percent spill in the 35 to 45 percent range, the majority of the gate tests were for forebay TDG less than 120 percent.

Table 4.4-1. Summary of short-term database test conditions.

% Spill (Q_{spill}/Q_{total})	Number of Tests by Forebay TDG				Total Tests	Spill Flow Range for Tests to Date (cfs)
	<115%	115-120%	120-125%	>125%		
0 to 10	4	6	1	8	19	1,600 to 5,300
10 to 15	5	3	3	15	26	3,800 to 9,200
15 to 20	0	1	3	16	20	9,000 to 12,800
20 to 25	1	1	4	14	20	11,000 to 17,100
25 to 30	0	1	1	15	17	14,700 to 21,500
30 to 35	4	1	6	7	18	20,700 to 27,200
35 to 40	7	6	1	13	27	22,600 to 33,600
40 to 45	13	3	2	2	20	Range for FB up to 120% was 33,700 to 43,100
45 to 50	21	1	1	0	23	39,700 to 47,500
50 to 60	17	0	0	1	18	45,200 to 59,500
Total	72	23	22	91	208	1,600 to 59,500

To compare the effects of gate operations, percent spill, and spill flow on tailrace TDG, average values were calculated for the duration of each test for USGS forebay TDG, USGS tailrace TDG, TDG gain from the forebay to the tailrace, spill flow, sluice flow, and powerhouse flow. Figure 4.4-1 presents the average TDG gain for each spill test as a function of the forebay TDG and shows the distribution of spill tests over the range of forebay TDG as described above. The tests were grouped in categories by percent spill range as in Table 4.4-1. "Forced spill" tests obtained in March 2008 are not included in the figure.

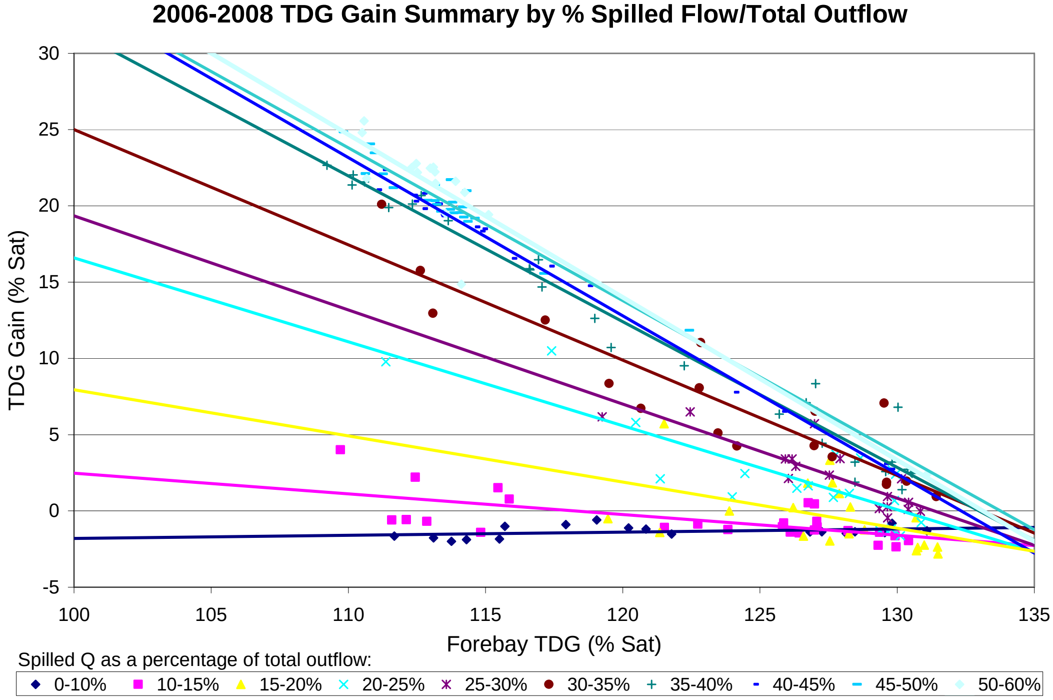

Figure 4.4-1. TDG gain summary, by spilled flow as a percentage of outflow.

Figure 4.4-1 shows that for a given percent spill range, the TDG gain from the forebay to the tailrace varied as a function of incoming forebay TDG. In addition, the figure shows that TDG varied differently over the forebay TDG range for each percent spill category. At low percent spill (0 to 10 percent), TDG gain did not vary significantly as a function of forebay TDG, indicating that when the spill flow was a relatively low percentage of powerhouse flow, gassing of powerhouse flow by spill flow was minimal over the entire forebay TDG range. As percent spill increased, the potential for powerhouse flow to be gassed up by the spill flow increased, particularly when the forebay TDG was low. At higher percent spill flows the TDG gain increased as forebay TDG decreased, indicating that as percent spill increased and forebay TDG decreased the potential for powerhouse flow gassing increased.

4.4.2. Spill and Sluice Operations Analysis

After developing the TDG gain summary in Figure 4.4-1 for the gate tests as a function of forebay TDG for all of the percent spill ranges, subplots were developed to compare gate operations within each percent spill range as shown in Figures 4.4-2 through 4.4-12. Within each percent spill category, the gate tests were arranged along the x-axis according to forebay TDG during the test, with the spill or sluice gate flows and total spill flow on the primary axis and TDG gain on the secondary axis for each test. All values were averaged over the test duration as described above.

Based on the additional data for a range of forebay TDG in 2008 it was confirmed that the forebay TDG, powerhouse flow gassing, and percent spill flow were all significant variables in determining tailrace TDG. Therefore, developing a statistically meaningful analysis of the gate database to determine the relative effects of different gate operations with a limited number of tests was not possible. In order to assess the impacts of operations on TDG gain, the tests within each percent spill range were compared to determine the preferred sluice or spill or sluice/spill combination operation for the range of forebay TDG. Notes are shown on the figures to aid in viewing gate test pairs or highlight observations from the analysis. After completing the analysis for all of the percent spill ranges, common observations on preferred operations and recommendations for additional testing were summarized in Table 4.4-2. Percent spill categories that contained tests with operations that were in compliance with the TDG standard are highlighted in green. Operations that are borderline compliant are highlighted in yellow. Ranges where there were no compliant operations tested are highlighted in orange.

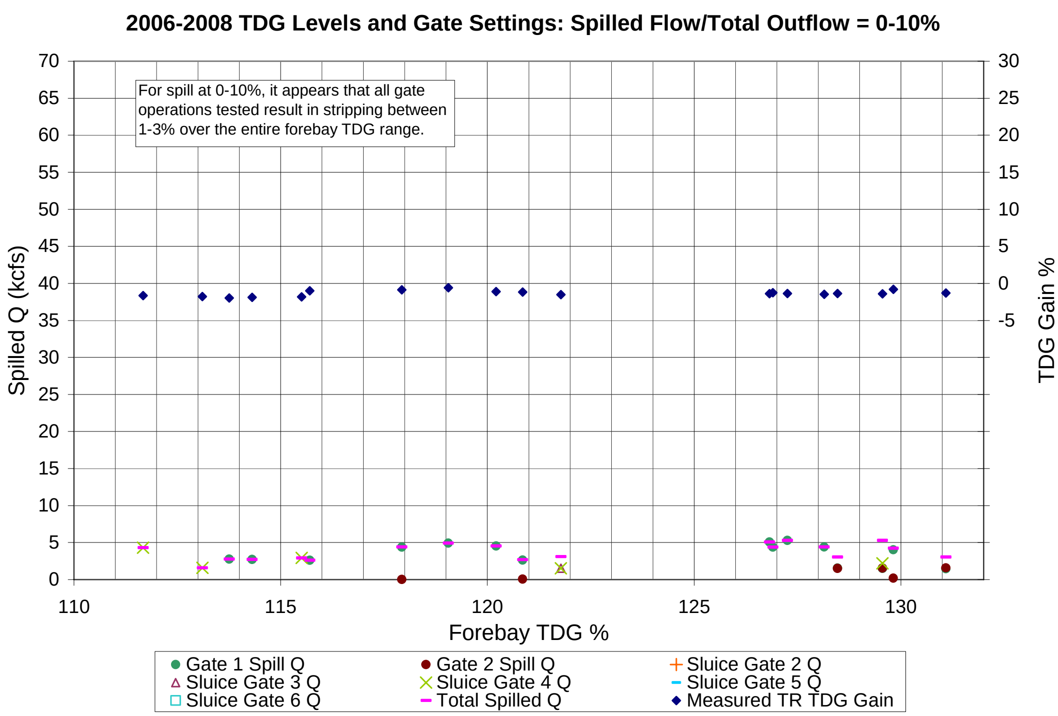

Figure 4.4-2. 2006-2008 TDG levels and gate settings for Spill=0-10%.

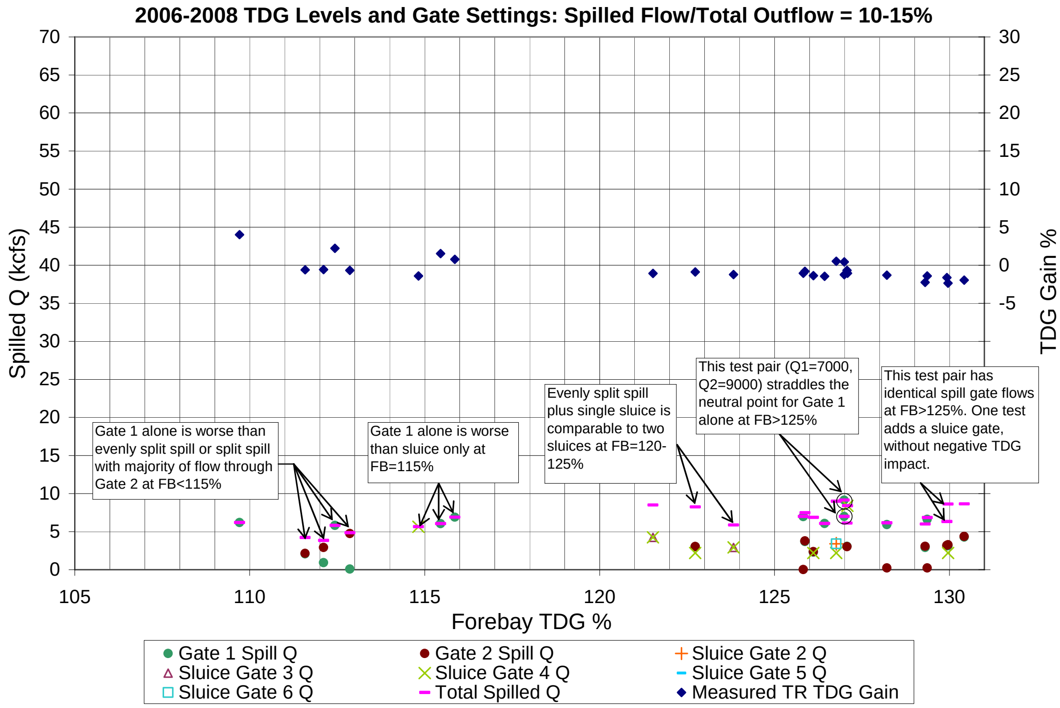

Figure 4.4-3. 2006-2008 TDG levels and gate settings for Spill=10-15%.

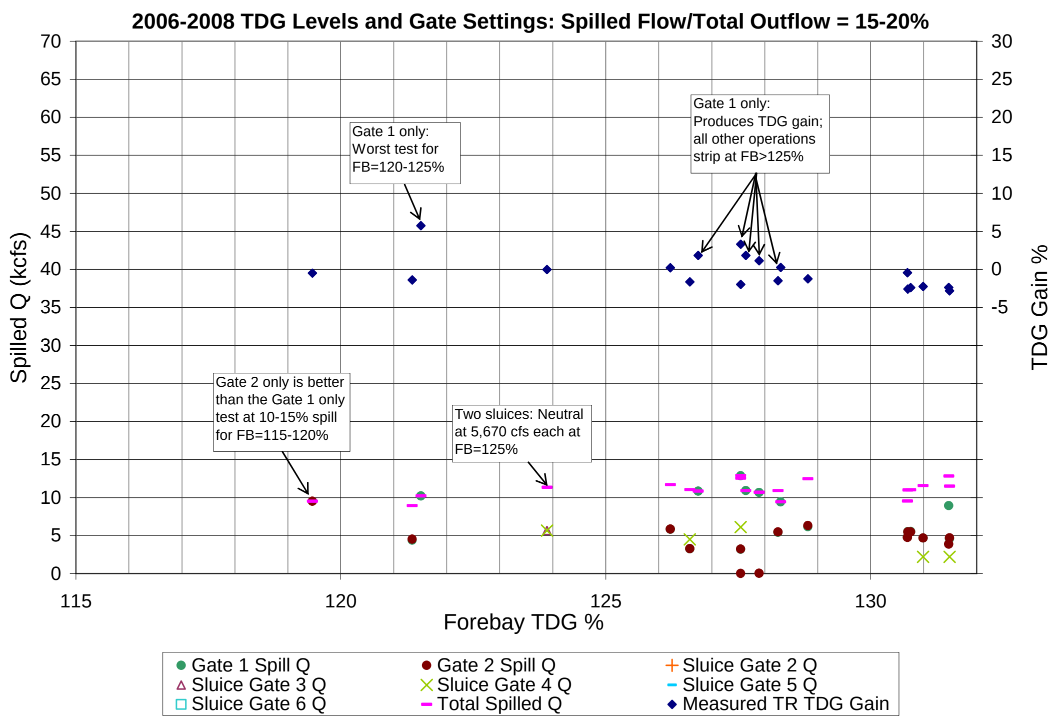

Figure 4.4-4. 2006-2008 TDG levels and gate settings for Spill=15-20%.

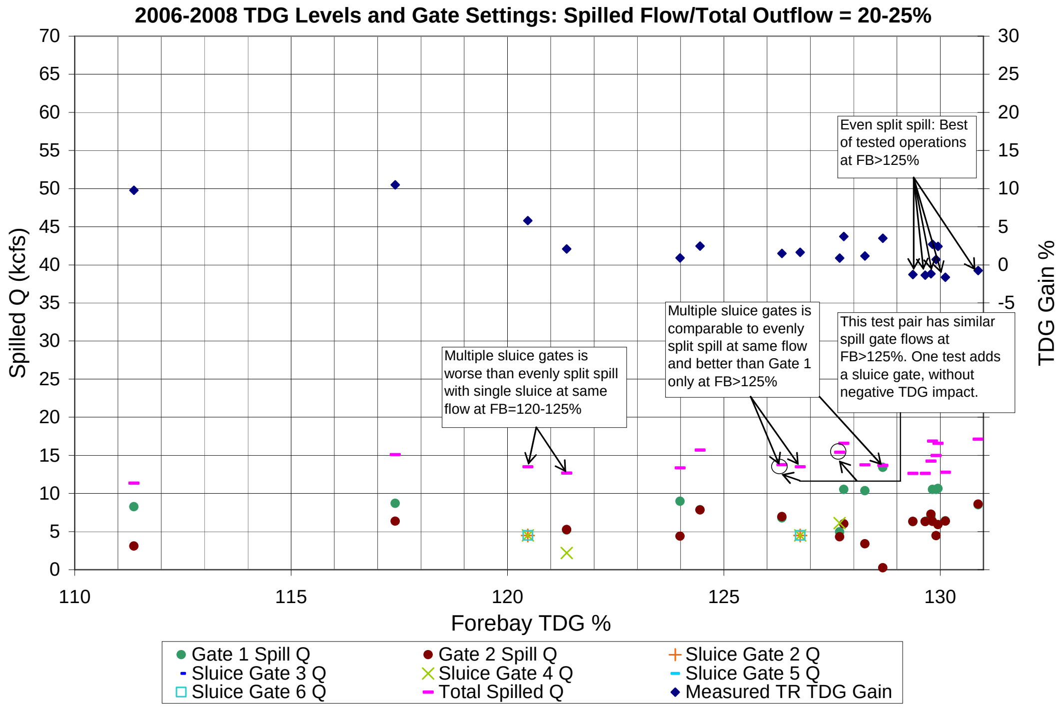

Figure 4.4-5. 2006-2008 TDG levels and gate settings for Spill=20-25%.

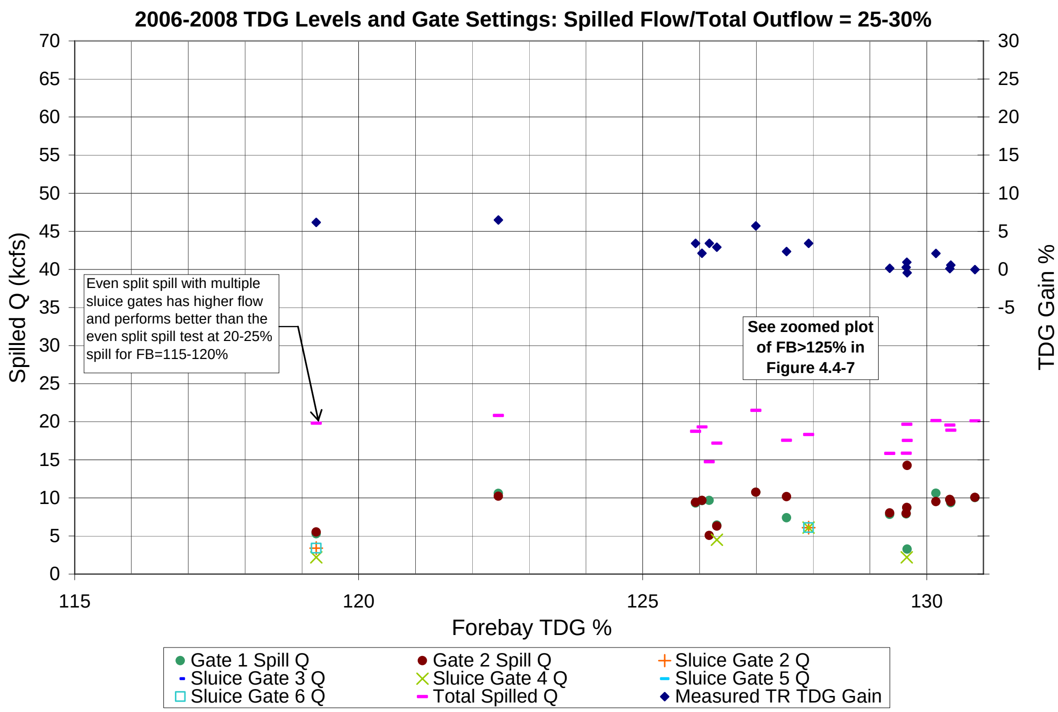

Figure 4.4-6. 2006-2008 TDG levels and gate settings for Spill=25-30%.

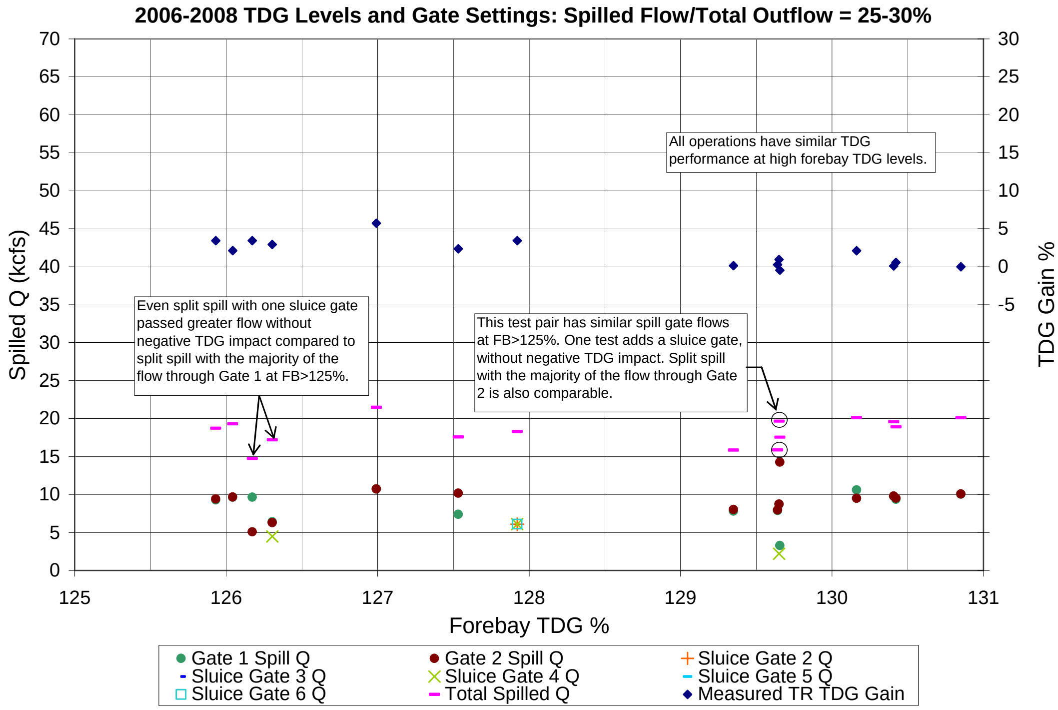

Figure 4.4-7. 2006-2008 TDG levels and gate settings for Spill=25-30%, zoomed to FB>125%.

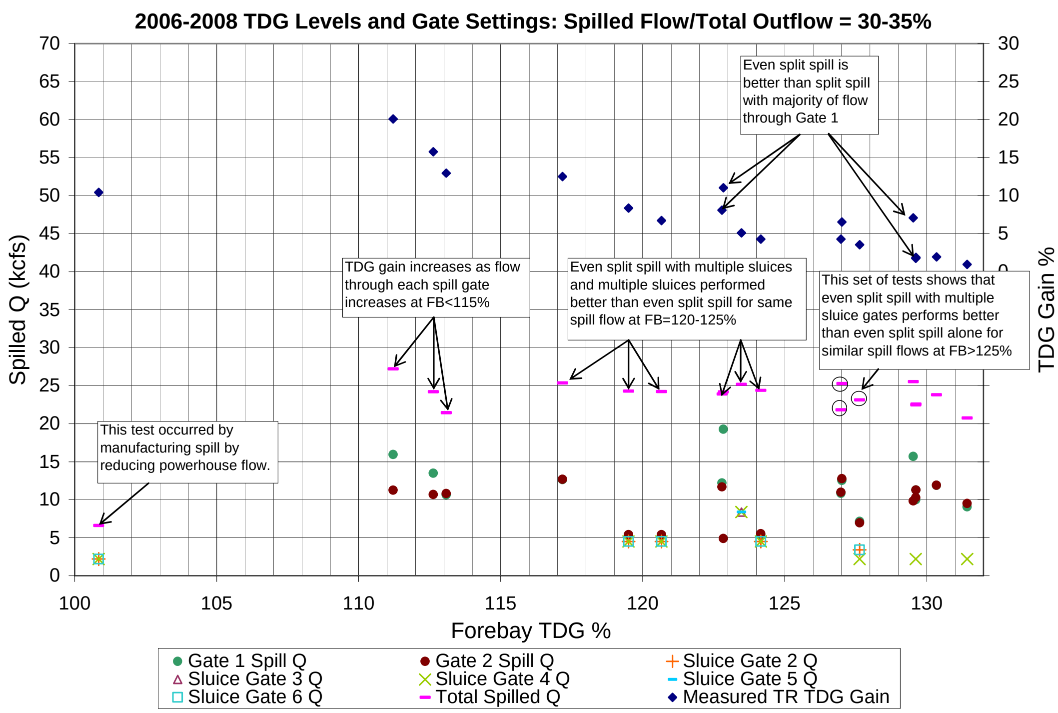

Figure 4.4-8. 2006-2008 TDG levels and gate settings for Spill=30-35%.

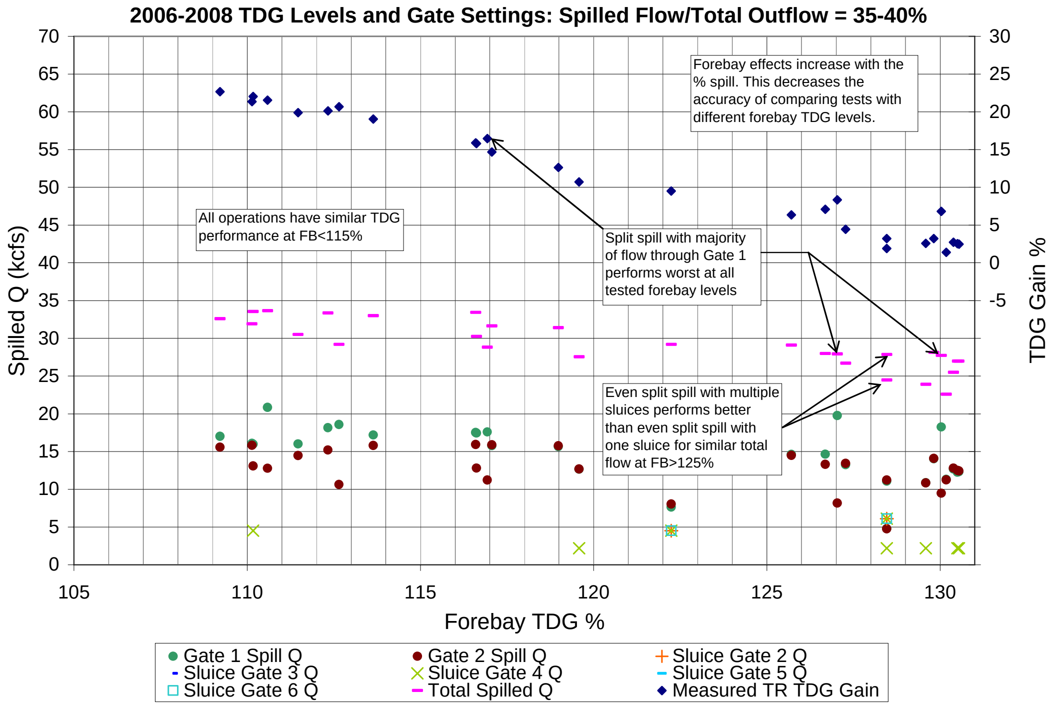

Figure 4.4-9. 2006-2008 TDG levels and gate settings for Spill=35-40%.

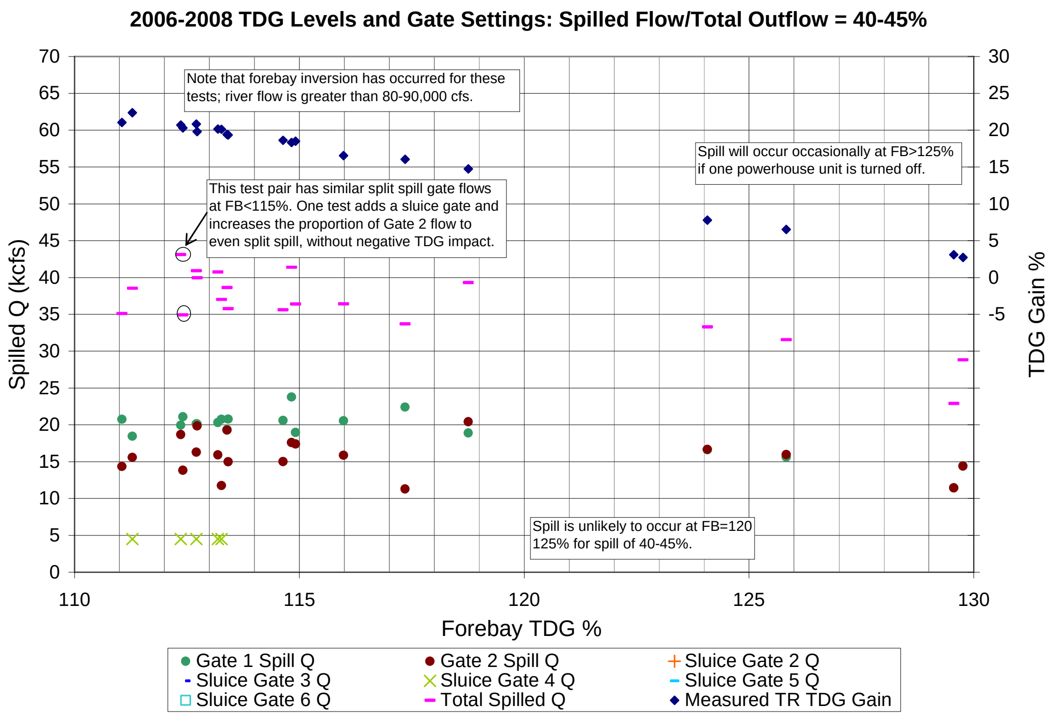

Figure 4.4-10. 2006-2008 TDG levels and gate settings for Spill=40-45%.

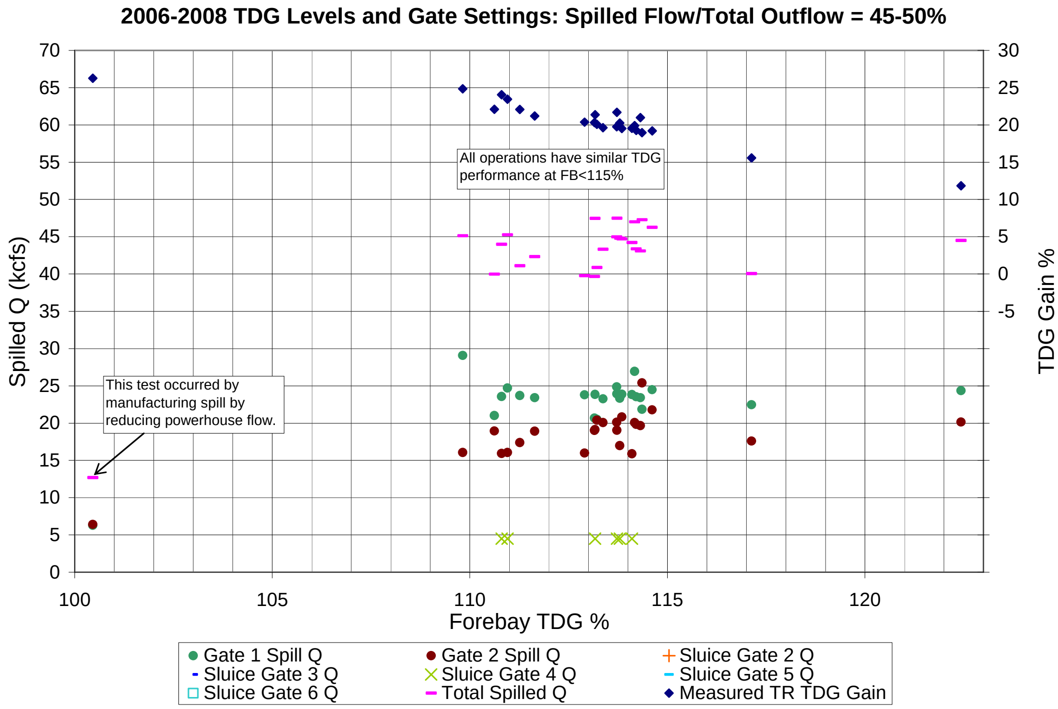

Figure 4.4-11. 2006-2008 TDG levels and gate settings for Spill=45-50%.

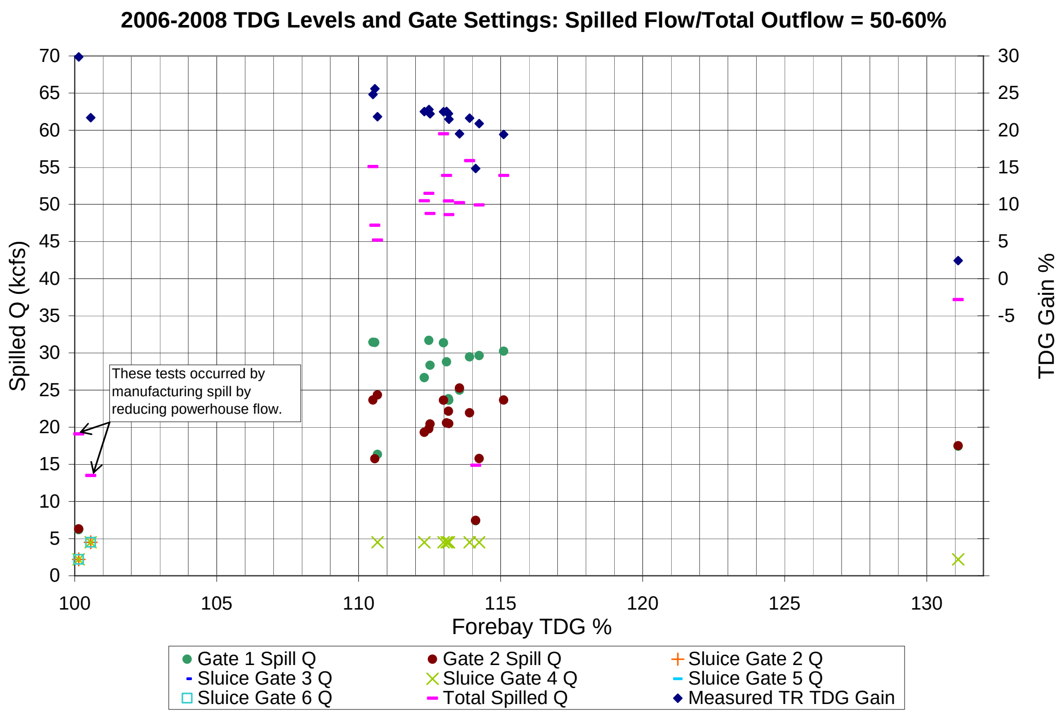

Figure 4.4-12. 2006-2008 TDG levels and gate settings for Spill=50-60%.

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Table 4.4-2. Summary of gate operations analysis by percent spill and forebay TDG range.

% Spill	Number of Tests by Forebay TDG				Preferred Operations by Forebay Range				Total Tests	Spill Flow Range for Tests to Date (cfs)	Further Tests Recommended
	<115%	115-120%	120-125%	>125%	<115%	`115-120%	120-125%	>125%			
0 to 10	4	6	1	8	Any of the tested ops (single sluice, Gate 1 only, majority Gate 1 spill flow). Likely other ops (even-split spill, spill gates plus sluice) would be adequate upon testing	Any of the tested ops (single sluice, Gate 1 only, majority Gate 1 spill flow). Likely other ops (even-split spill, spill gates plus sluice) would be adequate upon testing	Any of the tested ops (single sluice, Gate 1 only, majority Gate 1 spill flow). Likely other ops (even-split spill, spill gates plus sluice) would be adequate upon testing	Any of the tested ops (single sluice, Gate 1 only, majority Gate 1 spill flow). Likely other ops (even-split spill, spill gates plus sluice) would be adequate upon testing	19	1,600 to 5,300	May be beneficial for future operations to confirm Gate 2 operations in this percent spill flow range.
					Stripping up to 2.3%	Stripping up to 2.3%	Stripping up to 2.0%	Stripping up to 1.8%			
10 to 15	5	3	3	15	Spill gates even split, more flow to Gate 2, Sluice only	Sluice only, likely same as <115% but need tests for even split or more Gate 2 to confirm	Sluice only, spill plus single sluice, even-split spill and spill plus multiple sluice possible with further testing	For flows <= 8,000 cfs any tested operations ok, even-split spill or even spilt plus single sluice best	26	3,800 to 9,200	FB 115-125% need tests with spill plus sluice, perhaps spill plus multiple sluice
					Stripping up to 0.7%	Stripping up to 1.4%	Stripping 0.9 to 1.2%	Stripping up to 2.4%			
15 to 20	0	1	3	16	Unknown, No tests	Gate 2 only, no other tests, likely same ops as above	Even split spill, or multiple sluices	Even split spill plus sluice, even split also ok	20	9,000 to 12,800	Need further testing for even spill with multiple sluices (2 or more), even spill w single sluice FB 120 to 125% to confirm performance, lacking tests below FB 125%.
						Stripping of 0.5%	Stripping up to 1.4%	Stripping up to 2.8%			
20 to 25	1	1	4	14	Unknown, only test is for majority of flow through Gate 1 and performance is not optimized	Unknown, only test is for majority of flow through Gate 1 and performance is not optimized	Even split spill, even-split spill with single sluice, or possibly majority through Gate 1 up to approx. 9,000 cfs through Gate 1	Even split spill, even-split spill with single sluice	20	11,000 to 17,100	Need further testing for even spill with multiple sluices (2 or more) at all FB levels, even spill and even spill w single sluice FB <125%.
					Gain of 9.8%	Gain of 10.5%, but likely significantly less if operations optimized	Gain as low as 0.9%	Stripping up to 1.6%			
25 to 30	0	1	1	15	Unknown, No tests	Unknown, only test is for even split with multiple sluices. Performance for this single test was better than comparable test in %Spill 20 to 25 range	Unknown, only test is for even-split spill	Even split spill, even-split spill with single sluice, potential for multiple sluices	17	14,700 to 21,500	Need further testing for even spill with multiple sluices (2 or more) at all FB levels, even spill and even spill w single sluice FB <125%.
						Gain of 6.2%	Gain up to 6.5%	Stripping up to 0.5%			
30 to 35	4	1	6	7	Unknown, likely need spill flow plus sluice flow to keep spill flow below neutral point for each gate	Unknown only test is for even-split spill.	Even split spill with multiple sluices or multiple sluices	Even split spill with multiple sluices, possibly multiple sluices with no spill gates but no tests	18	20,700 to 27,200	Need further testing for even-split spill and even-split spill with sluice at FB < 125%, tests for multiple sluices with no spill gates for all FB.
					Gain as low as 13.0%	Gain of 12.5%	Gain as low as 4.3%	Gain as low as 0.9%			
35 to 40	7	6	1	13	Even split spill or even-split spill with single sluice. Even split w/ multiple sluice not tested.	Even split spill or even-split spill with single sluice. Even split w multiple sluice not tested.	Unknown based on single test, but likely even-split spill with multiple sluice to minimize spill gate flow	Even split spill with multiple sluices	27	22,600 to 33,600	Need tests for even-split spill with multiple sluice at higher sluice flows and greater number of sluices operating to minimize spill gate flow.
					Gain as low as 19.0%	Gain as low as 10.7%	Gain of 9.5%	Gain as low as 1.4%			
40 to 45	13	3	2	2	Based on tests to date, split spill or split spill with single sluice are comparable. Further testing with minimized spill gate flow and multiple sluices may optimize performance.	Unknown based on limited tests for slightly uneven spill.	Unlikely to need to spill at 40 to 50% river flow in this forebay range	Unlikely to need to spill at 40 to 50% river flow in this forebay range, only happens if spilling with one unit off.	20	Range for FB up to 120% was 33,700 to 43,100	Need tests at FB < 120% for even-split spill with multiple sluice at higher sluice flows and greater number of sluices operating to minimize spill gate flow.
					Gain as low as 18.3%	Gain as low as 14.8%	N/A	N/A			
45 to 50	21	1	1	0	Based on tests to date, split spill or split spill with single sluice are comparable. Further testing with minimized spill gate flow and multiple sluices may optimize performance.	Unknown based on single test.	Unlikely to need to spill at 45 to 50% river flow in this forebay range.	Unlikely to need to spill at 45 to 50% river flow in this forebay range.	23	39,700 to 47,500	Need tests at FB < 120% for even-split spill with multiple sluice at higher sluice flows and greater number of sluices operating to minimize spill gate flow.
					Gain as low as 19.0%	Gain as low as 15.6%	N/A	N/A			
50 to 55	17	0	0	1	Based on tests to date, even-split spill or split spill with single sluice are comparable. Further testing with minimized spill gate flow and multiple sluices may optimize performance.	Unknown, no tests	Unknown, no tests	Unlikely to need to spill at 50 to 60% river flow in this forebay range.	18	45,200 to 59,500	Need tests at FB < 120% for even-split spill with multiple sluice at higher sluice flows and greater number of sluices operating to minimize spill gate flow.
					Gain as low as 19.0%						

Notes:
Green highlighting indicates categories containing tested operations that compiled with the TDG standard
Yellow highlighting indicates categories with tested operations that were borderline with respect to TDG standard compliance
Orange highlighting indicates categories with tested operations that did not comply with the TDG standard
No highlighting indicates categories with tested operations that are unlikely or for which no tests were available
cfs – cubic feet per second
FB – forebay
N/A – not applicable

For percent spill from 0 to 10 percent (Figure 4.4-2) there were 19 tests for spill flows ranging from 1,900 cfs to 5,300 cfs. The gate operations tested were primarily Gate 1 only (or significant majority of flow through Gate 1) with a few sluice only tests and one spill gate plus sluice test. When percent spill was 0 to 10 percent, the TDG gain from the forebay to the tailrace did not vary significantly with forebay TDG. All of the gate operations tested resulted in negative TDG gain, indicating slight stripping of TDG from the forebay to the tailrace in this spill flow range.

As spill flow increased to 10 to 15 percent of river flow, TDG gain varied slightly as a function of forebay TDG as shown in Figure 4.4-3, so the tests were compared only when they occurred within similar forebay ranges as summarized in Table 4.4-1. For example, five tests for forebay TDG <115 percent were grouped together and compared to each other to determine the preferred gate operations within that forebay range for this percent spill range. As the analysis progressed, patterns were observed in the gate operations results, even though tests were not directly comparable across all percent spills, spill flows, and forebay ranges.

In general, for 10 to 15 percent spill, the gate tests showed stripping from forebay to tailrace for forebay TDG greater than 120 percent for all tested operations except two tests: spill flow above 9,000 cfs through Gate 1 only and 3 sluices operating together. For forebay below 120 percent, Gate 1 only tests generally result in positive TDG gain, while split spill combinations and sluice operations resulted in minor stripping (up to 1.4 percent).

As the spill flow increased to 15 to 20 percent of river flow (Figure 4.4-4), few tests were available for forebay TDG <125 due to the influence of upstream projects on forebay TDG. As seen in lower percent spill ranges, spill through Gate 1 only generally produced the greatest TDG of all the tested combinations in this percent spill range. Even-split spill with sluice flow appeared to be the best operation tested for forebay TDG >125 percent. In addition, even-split spill and multiple sluices showed potential in this percent spill range.

Due to the influence of upstream projects on incoming forebay TDG, only two tests were available for forebay less than 120 percent for spill flows between 20 and 25 percent of river flow (Figure 4.4-5). Both were with the majority of flow through Gate 1. These tests resulted in TDG gain of approximately 10 percent and based on results at other percent spills were not likely indicative of optimal operations. For forebay greater than 120 percent, even-split spill and even-split spill with single sluice tests performed the best. Note the range of TDG gain as a function of forebay increased over the previous percent spill category. It is also important to note that individual tests should be compared with total spill flow in mind.

In the 25 to 30 percent spill category (Figure 4.4-6), the even-split spill tests with multiple sluice gates at forebay 119.2 percent resulted in less TDG gain for higher total spill flow than the even-split spill flow test in the same forebay TDG range for 20 to 25 percent spill in Figure 4.4-5. In general for forebay TDG less than 125 percent, the preferred operations could not be determined from two tests, but the potential for even-split spill with multiple sluices should be confirmed through further testing. The results for forebay TDG greater than 125 percent are shown on a larger scale in Figure 4.4-7 for ease of viewing. For forebay TDG greater than 125 percent, even-split spill and even-split spill with sluice were the preferred operations in this percent spill range, with the potential for multiple sluices to perform well upon further testing. At this percent spill range, two tests show the potential for Gate 2 passing a higher percentage of the flow to perform as well as the even-split spill tests or even-split spill with sluice.

The tests for spill flow of 30 to 35 percent of river flow are summarized in Figure 4.4-8. In general the TDG gain as a function of forebay TDG followed an approximately linear trend for all the gate tests combined, with TDG gain decreasing as forebay TDG increased. It is therefore important to compare tests in this percent spill range with comparable forebay TDG and total spill flow. For forebay TDG less than 115 percent, three tests were available for approximately even-split spill, or with slightly more flow through Gate 1. As the spill flow increased, and the Gate 1 flow increased, the TDG gain increased, as expected. The tests in the forebay TDG range from 120 to 125 percent provided multiple tests at comparable total spill to demonstrate that even spilt spill with multiple sluices or multiple sluices were the preferred operations in this range. The tests for forebay TDG above 125 percent also showed potential for even-split spill with multiple sluices, with the TDG gain as low as 0.9 percent at the higher end of the forebay TDG range.

As percent spill reached 35 to 40 percent, the spill flows for the tests in Figure 4.4-9 ranged from 22,600 to 33,600 and corresponded to the transitional river flows just before and just after the upstream projects reached hydraulic capacity and pulled/replaced their gates. As shown in Figure 4.4-9, the tests with lower total spill flow (indicating lower river flow as well) occurred during higher forebay TDG due to the influence of the upstream projects. The tests with higher total spill flow (indicating higher river flow) occurred at lower forebay TDG after the upstream projects pulled their gates and removed their contribution to Boundary forebay TDG.

As confirmed over other percent spill ranges, split spill with the majority of flow through Gate 1 generally resulted in the greatest TDG gain at all tested forebay levels for percent spill from 35 to 40 percent. Based on the range of tests available for this percent spill range, even-split spill or even-split spill with single sluice were the preferred operations. Additional tests are needed to confirm this operation in the forebay TDG 120 to 125 percent range. One test for forebay TDG >125 percent showed the potential for even-split spill with multiple sluices to perform as well as even-split spill with a single sluice, but additional tests are required to confirm performance.

Figure 4.4-10 shows the tests that occurred after the river flows increased above the upstream projects' hydraulic capacities and forebay TDG decreased. A few tests in higher forebay TDG occurred with less than full powerhouse flow and at lower river flow. The overall TDG gain ranged from approximately 22 percent at forebay TDG levels below 115 percent to approximately 3 percent when the forebay TDG was 130 percent. Spill is unlikely to occur for forebay TDG greater than approximately 120 percent under current upstream project operations in this percent spill range, unless the Project spills with one or more powerhouse units off for significant duration.

Based on the tests, even-split spill or even-split spill with a single sluice operations were comparable. Further tests to minimize spill gate flow and put additional flow through multiple sluices may optimize performance based on tests in other percent spill categories.

Figures 4.4-11 and 4.4-12 show the tests for percent spill in the 45 to 50 percent and 50 to 60 percent river flow ranges, respectively. In both percent spill ranges, the majority of the tests occurred during river flows above the hydraulic capacity of the upstream projects and during forebay TDG between 110 percent and 115 percent. In this range, the majority of the tests were incidental spill tests, captured in the database as periods when spill operations remained steady for at least four hours. The tests were generally even-split spill or split spill with slightly more through Gate 1, along with a group of tests during a period when Sluice Gate 4 was opened for a long duration mechanical test. Because of the relatively high variation in TDG gain as a function of forebay TDG, along with varying total spill flows during these incidental tests, it was difficult to identify many comparable test pairs in these percent spill ranges. General conclusions from the incidental tests were that the split spill tests with sluice appeared to perform as well as the split spill. Spill flow in these percent spill ranges may benefit from reducing spill flow through the gates and passing additional flow through multiple sluices, but no tests have been done to date for greater than 45 percent spill.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The TDG study team developed a short-term database for spill and sluice gate tests in 2008 from data obtained from SCL and the 2008 TDG field program. Data were analyzed in combination with the 2006 and 2007 short-term database to supplement understanding of spill and sluice gate operation impacts on TDG production presented in the previous reports on historical and short-term data analysis.

Data for the 2008 spill season were analyzed for the station H1 to H9 TDG measurement locations and the following conclusions were drawn from the results:

- The forebay monitoring station H9 generally matched the USGS forebay fixed monitoring station well, though data for forebay TDG of 100 to 105 percent were approximately 2 to 3 percent higher than the USGS fixed forebay monitoring station data.
- At flows below approximately 50,000 cfs with no spill there was little lateral or longitudinal variation in TDG at transects 2 and 3, as observed in 2007.
- During spill, there was a lateral TDG gradient at transects 2 and 3, which appeared to be a function of spill flow. For river flows below approximately 60,000 cfs, the USGS meter read higher TDG than did the transect meters. As river flow increased above approximately 60,000 cfs, the USGS meter read lower than the transect meters, with TDG increasing from left (meters H2 and H5) to right (meters H4, H3, and H6) across the river.
- At flows below 50,000 cfs, there was no noticeable difference between TDG levels at the USGS fixed monitoring station and the station H8 location near the Canadian border. At river flows below approximately 60,000 cfs, the USGS tailwater meter

generally measured higher TDG than meter H8. Above approximately 60,000 cfs of river flow, TDG was generally greater at meter H8 than at the USGS tailwater meter. This is consistent with the shift in the lateral TDG gradient observed at other transects when river flows exceeded approximately 60,000 cfs.

The range of spill and sluice gate operation conditions in the updated short-term database for 2008 allowed for refinement of the analysis of the effects of gate operations. In addition preliminary recommendations can be made for preferred gate operations as a function of percent spill and forebay TDG. The recommendations are based on available test data, and further potential improvement may be made through structural improvement or testing of operations not tested to date. The analysis provided in Table 4.4-2 and Figures 4.4-2 through 4.4-12 provides a basis for comparison of future gate test performance for similar percent spills and forebay TDG.

Based on the tests available to date, the following general conclusions describe the overall behavior of the spill and sluice gate operations:

- TDG gain from the forebay to tailrace varied as a function of forebay TDG and percent spill in addition to varying with changes in spill and sluice gate operations as shown in Figure 4.4-1. Therefore, spill and sluice gate tests were comparable only when considered with respect to the percent spill, forebay TDG, and total spill during which they occurred.
- At higher percent spills (above approximately 20 percent), the TDG gain increased significantly as forebay TDG decreases. As percent spill increased and forebay TDG decreased, the potential for gassing up the powerhouse flow increased.
- Throughout the tested forebay TDG range and for spill flows up to the capacity of the spill gate, tests with spill through Gate 1 only generally produced the worst TDG performance compared to other operations.
- Fewer tests were available for Gate 2 operating with more flow than Gate 1, but these tests showed potential for Gate 2 to perform better than Gate 1 in an uneven-split spill operation. Further testing may confirm this operation.
- The neutral point of the spill gates is expected to vary over the tested forebay TDG range and cannot be determined from the existing tests.
- As summarized in Table 4.4-2, even-split spill and even-split spill plus a single sluice were the best performing tested operations for the range of percent spill up to 20 percent of total river flow (spill flow range for tests = 9,000 to 12,800 cfs). In general the preferred operations for percent spill up to 20 percent of river flow resulted in negative TDG gain from forebay to tailrace, and indicated the potential for Project compliance over the expected range of forebay TDG at this percent spill, as indicated in the green cells in Table 4.4-2.
- In addition, even-split spill and even-split spill with single sluice were the preferred operations for percent spill from 20 to 30 percent for forebay TDG > 125 percent and indicated the potential for Project compliance in this range. The spill flow range for these tests was 11,000 to 21,500 cfs.
- Even-split spill and even-split spill with single or multiple sluices performed with TDG gain less than 3 percent for at least one test for percent spill 20 to 25 percent (forebay TDG 120 to 125 percent) and percent spill 30 to 40 percent (forebay TDG >

125 percent. These operations (indicated in yellow in Table 4.4-2) may be optimized through further testing of even-split spill with multiple sluices or multiple sluices only to bring TDG gain within compliance.

- Operations in the categories shown in orange in Table 4.4-2 for percent spills greater than 20 percent and forebay TDG less than 125 percent may be optimized through further testing to minimize the TDG gain during spill. Based on tests to date, even-split spill with single or multiple sluices shows potential.

5.2. Recommendations for 2009 Field Program

Based on the analysis to date, TDG production through the Project depends on incoming TDG, river flow, spill flow, spill operations, and powerhouse operations. It is therefore necessary for the database to contain data for comparable forebay TDG levels, spill flows, percent spills, and spill and sluice gate opening in order to recommend preferred gate operations over the full range of operating conditions. Duplicate tests are also useful in making predictions with confidence, due to variability in the field data.

To this end, collection of data for the following additional tests is recommended:

- For spill less than 10 percent of river flow:
  - Test Gate 2 only or majority flow to Gate 2 at any forebay TDG.
- For spill between 10 and 20 percent of river flow:
  - For forebay TDG 115 to 125 percent, test even spill plus sluice and/or even spill plus multiple sluice.
  - Test Gate 2 only or majority of flow to Gate 2.
- For spill between 20 and 30 percent of river flow:
  - Test even spill plus multiple sluices and multiple sluices only at all forebay TDG levels.
  - Test even spill and even spill plus single sluice at forebay TDG less than 125 percent.
- For spill between 30 and 40 percent of river flow:
  - For forebay TDG <125 percent test even-split spill and even-split spill with sluice.
  - For all forebay TDG levels test even-split spill with multiple sluices at higher sluice flows and/or greater number of sluices to minimize spill gate flow and multiple sluices with no spill gates.
- For spill greater than 40 percent of river flow:
  - Test multiple sluices at higher sluice flows and greater number of sluices operating to minimize spill gate flow.

The TDG study team understands the limitations of collecting all of this data during the 2009 field season, particularly for sluice tests. The team will work with SCL to prioritize the tests given the available testing resources and data gaps in the database.

6 REFERENCES

Golder (Golder Associates). 2008. Study 3.1 TDG Monitoring System Data Transmittal. August 2008.

SCL (Seattle City Light). 2006. Pre-Application Document for the Boundary Hydroelectric Project (FERC No. 2144). May 2006.

Appendix 5: Field Investigations Methods

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Field Investigation Methods

A.5.1 SELECTION OF TDG, ADCP, AND WATER LEVEL MONITORING STATIONS

A.5.1.1. TDG Monitoring

Total dissolved gas (TDG) data were acquired at stations summarized in the following:

- The forebay (FB) station was selected to supplement and check the U.S. Geological Survey (USGS) forebay Fixed Monitoring Station (FMS) (USGS gage 12398550), plus provide background TDG for comparison. The forebay station was designated as H9.

- Transect 2 (four stations) was selected to reproduce a transect used for previous studies and allow comparison to those results, plus examine lateral distribution as a function of Project operations. It was located at the approximate downstream end of frothy (gas transfer) zone on basis of photos and video of spill, immediately downstream of the constriction point of the tailrace. The stations at transect 2 were designated H1 to H4.

- Transect 3 (three stations) was selected to supplement and check the USGS tailrace FMS (USGS gage 12398600) to determine if lateral mixing is complete and the FMS bank line station is representative. The stations at transect 3 were designated H5 to H7.

- Transect 4 (one station) was selected downstream from a riffle in Canada to determine if the riffle reduces TDG. This station was designated as H8.

Details of the TDG station locations for both 2007 and 2008 are presented in Table A.5-1.

Table A.5-1. TDG monitoring station locations (easting and northing values are in Washington State Plane, North Zone, NAD 1983, feet).

Station	2007 [1]			2008 [2]		
	Easting	Northing	Deployment Depth (m)	Easting	Northing	Deployment Depth (m)
H1	2476198	746170	4.2	2476224	746108	2.9
H2	2476298	746193	7.7	2476294	746183	5.8
H3	2476434	745992	12.0	2476337	746231	6.2
H4	2476447	746198	5.5	2476381	746250	5.0
H5	2475856	747828	8.3	2475853	747892	8.1
H6	2475949	747874	7.0	2475926	747885	8.4
H7	2476033	747869	4.9	2475967	747876	7.3
H8 [3]	2474819	750084	4.0	2474819	750084	4.0
H9 [4]	2472925	744298	4.0			

Notes:

1 In 2007, meters were deployed at stations H1 to H7 on April 20, H8 on April 23, and H9 on April 27. The easting and northing positions for H1, H2, and H5 are at sub-meter accuracy as indicated by percent dilution of position (PDOP) values of less than 4.0. PDOP values greater than 4.0 at H3, H4, H6, and H7 were due to poor satellite reception. A Garmin 12 GPS was used to obtain UTM coordinates for Station H8; this unit did not report PDOP.

2 In 2008, meters were deployed at stations H1 to H7 on March 20, H8 on March 24, and H9 on March 28. All Easting and Northing positions are at sub-meter accuracy as indicated by PDOP values of less than 4.0.

3 At station H8, the meter was deployed at the same location in 2007 and 2008. The depth was visually estimated, and appeared to be deeper in 2008 than in 2007.

4 Station H9 was located approximately 50 feet south of the USGS Boundary forebay station. The depth was visually estimated.

Global Positioning System (GPS) coordinates were obtained for stations H1 to H7 with a Trimble® GeoXT®. The main GPS features of this unit included integrated Satellite Based Augmentation System (SBAS) and RTCM real-time correction support that enabled sub-meter accurate measurements in real-time.

In 2007, all of the TDG meters were deployed for a test period from April 27 through July 6. In 2008, TDG was monitored between March 20 and July 24.

A.5.1.2. Velocity and Water Level Monitoring

Velocity data were acquired on approximately the same transects as TDG data (moving flow measurement transect measurements) and stations (fixed velocity measurements). The locations were selected based on the locations of the TDG sampling locations, consideration for the use of the data for calibration and verification of CFD and physical hydraulic models, and consideration for characterizing the hydrodynamic conditions responsible for TDG flux. Measurement locations were designated 1-4 from west to east on transect 1, 5-8 from west to east on transect 2, and 9-11 from west to east on transect 3. Data were collected for two different flow conditions, a low river flow of ~33,000 cubic feet per second (cfs) on June 20, 2007, for which only turbines were operating, and a higher river flow of ~52,000 cfs, on June 13, 2007, for which the turbine flows were supplemented with spill. Coordinates of the measurement locations are included in Table A.5-2.

Table A.5-2. Stationary velocity profile and moving transect discharge measurement locations (easting and northing values are in Washington State Plane, North Zone, NAD 1983, feet).

Flow Condition	Measurement Location			Data Collection	
	Station	**Easting [1]**	**Northing [1]**	**Date in 2007**	**Time**
High	Moving transect 1 east to west			June 13	11:33
High	Moving transect 1 west to east			June 13	11:42
High	1	2476269	744705	June 13	11:51
High	2	2476404	744715	June 13	12:08
High	3	2476533	744727	June 13	12:27
High	4	2476653	744733	June 13	12:43
High	Moving transect 2 west to east			June 13	14:41
High	Moving transect 2 east to west			June 13	14:44
High	5	2476244	745994	June 13	14:28
High	6	2476330	746008	June 13	14:17
High	7	2476431	746016	June 13	14:04
High	8	2476584	745920	June 13	13:51
High	Moving transect 3 west to east			June 13	14:50
High	Moving transect 3 east to west			June 13	14:55
High	9	2475789	747806	June 13	14:59
High	10	2475911	747810	June 13	15:12
High	11	2476021	747801	June 13	15:25
Low	Moving transect 1 east to west			June 20	08:07
Low	Moving transect 1 west to east			June 20	08:17
Low	1	2476275	744699	June 20	09:06
Low	2	2476402	744713	June 20	08:52
Low	3	2476534	744720	June 20	08:39
Low	4	2476659	744736	June 20	08:26
Low	Moving transect 2 east to west			June 20	09:32
Low	Moving transect 2 west to east			June 20	09:37
Low	5	2476214	745998	June 20	11:21
Low	6	2476333	746002	June 20	10:51
Low	7	2476377	746014	June 20	10:07
Low	8	2476579	745921	June 20	09:47
Low	Moving transect 3 east to west			June 20	11:41
Low	Moving transect 3 west to east			June 20	11:45

Table A.5-2, continued...

Flow Condition	Measurement Location			Data Collection	
	Station	Easting [1]	Northing [1]	Date in 2007	Time
Low	9	2475791	747803	June 20	12:35
Low	10	2475913	747803	June 20	12:23
Low	11	2476020	747801	June 20	11:57

Note:
1 Average for station.

Water level data were acquired in 2007 for stations at either bank line on approximately the same transects employed for acoustic Doppler current profile (ADCP) and TDG data collection to provide a consistent data set to be used in association with the ADCP and TDG data. These locations were adjusted based on practical considerations, such as the ability to install the water level recorders along the shore. The gauge locations are indicated in Table A.5-3.

Table A.5-3. Water level measurement locations (easting and northing values are in Washington State Plane, North Zone, NAD 1983, feet).

Flow Condition	Transect	Bank	Gauge Number	Easting	Northing
Low	1	West	2	2476171	744695
Low	1	East	1	2476779	744742
Low	2	West	4	2476161	745984
Low	2	East	3	2476602	746016
Low	3	West	6	2475752	747776
Low	3	East	5	2476074	747802
High	1	West	2	2476176	744663
High	1	East	1	2476801	744772
High	2	West	4	2476149	745969
High	2	East	3	2476607	746009
High	3	West	6	2475707	747796
High	3	East	5	2476113	747755

A.5.2 MONITORING INSTRUMENTS AND DEPLOYMENT METHODS

A.5.2.1. TDG Monitoring

A total of nine Hydrolab® MS5 Multiprobe® (referred to as MS5 or Minisonde hereafter) instruments with TDG, temperature, and depth sensors were purchased from Hach Company Inc.

The MS5s are self-contained data loggers powered by an internal battery pack consisting of eight AA batteries. The MS5 dimensions are as follows: 74.9 centimeters (cm) long (29.5 inches), outer diameter 4.4 cm (1.75 inches), and total weight with battery pack 1.3 kilograms (kg) (2.9

pounds). The MS5 internal memory allowed recording of up to 120,000 measurements. Seattle City Light (SCL) also provided a single Hydrolab® DS4a® (referred to as the DS4a or Datasonde hereafter) for use during the project. The DS4a dimensions were as follows: 58.4 cm long (23 inches), outer diameter 8.9 cm (3.5 inches), and approximate total weight with 8 C batteries 3.35 kg (7.4 pounds). Similar to the MS5, the DS4 is a self-contained logger and can log up 120,000 records.

Water quality parameters recorded during monitoring included TDG (millimeters mercury [mmHg]) and water temperature (°C). To assist in data cleaning, water depth (m) was also recorded and used in conjunction with water temperature, to identify periods when the meter emerged from the water and when the meter was above the minimum TDG compensation depth. The range, accuracy, and resolution of each parameter are provided in Table A.5-4. Internal battery voltage was also recorded to monitor power consumption and determine battery replacement requirements. In order to record data at the 15-, 30-, 45-, and 60-minute marks each hour, logging was delayed until the beginning of the next 15-minute period and logged at 15-minute intervals.

Table A.5-4. Accuracy and resolution of parameters recorded during the 2007 and 2008 TDG monitoring study.

Parameter	**Range**	**Accuracy**	**Resolution**
Total Dissolved Gas	400 to 1300 mmHg	±0.1 % of span	1.0 mmHg
Temperature	-5 to 50°C	±0.10°C	0.10°C
Depth (0-25 m)	0 to 25 m	±0.05 m	0.01 m

The two main methods to operate the MS5 were through an RS-232 cable connection from the unit to either the Hydras 3 L T® software (Hydras) installed on a laptop computer or a hand-held Hydrolab® Surveyor®. The user interface of the Hydras software allowed configuration of all aspect of the MS5, including 1) setup of basic sonde identification (e.g., site name), 2) online monitoring and the display and recording of select parameters in real-time, 3) initializing data logging and downloading of data log files, 4) configuration of parameters, 5) parameter calibration, and 6) configuration of communication and software settings. Similar control options were also possible through the hand-held Surveyor; however, due to limitations of the Surveyor interface, particularly when entering names and numerical values, the Surveyor was primarily used during calibration to display real-time barometric pressure data when connected to either the MS5 or DS4.

At the onset of the field component in 2007, Golder was notified by SCL that a DS4a was to be installed in the Boundary Dam forebay and was to monitor dissolved oxygen (DO) in addition to the three primary parameters (i.e., TDG, temperature, and depth). Upon inspection of the DS4a by Golder, the DO sensor was dry and required servicing. In the process of trying to calibrate the DO sensor, a communication problem between the Hydras software and the unit could not be resolved. An attempt was made to try to calibrate the DO sensor by using the Surveyor. However, unlike the software calibration program, the only calibration option available when using the Surveyor was calibrating DO to a known standard (e.g., based on testing a standard against Winkler DO test results). A known DO standard was not available and the DS4a DO sensor could not be calibrated. The primary use of the DS4a was to provide barometric pressure data. However, since this unit had not been recently factory calibrated in 2007, three or more identical barometric pressure readings from new factory calibrated MS5s was considered a more reliable source of barometric pressure data against which the remainder of the MS5s could be calibrated. In 2008, the DS4a was factory calibrated, used as a portable unit, and the source of barometric pressure data against which all the MS5s were calibrated against.

A.5.2.1.1. Boundary Tailrace Station Deployment Method

During past TDG monitoring efforts in the Boundary Dam tailrace, bottom-anchor deployed TDG meters could fail for a variety of reasons, the most common of which was puncturing of the silastic membrane as a result of abrasion from suspended material (Figure A.5-1). Floats and ropes used to retrieve bottom anchor stations also routinely failed due to damage of the rope or floats during high flows. In an attempt to prevent failure of the meters or the float retrieval mechanism during the 2007 and 2008 studies, custom-designed metal housings were fabricated to position the sensor component of the TDG meter above the river bottom to reduce or prevent the accumulation of sand and small gravel around the sensors. The final design fabricated was based on initial discussions that Hydrolab Datasondes were to be purchased for the project. Based on this knowledge, each housing consisted of a 32-inch length of 4-inch-diameter steel well-casing pipe, to which three pieces of 18-inch length by 5/8-inch diameter steel rod were welded at evenly spaced positions around the circumference of the pipe (i.e., interior angles were approximately 120°), approximately 4 inches from the downstream end of the housing. When deployed, the steel rods (legs) elevated the downstream end of the housing approximately 10 to 12 inches above the river bottom. The housing legs, combined with hydraulic pressure due to the angled profile of the housing, also served to force the legs into the substrate and stabilize the housing.

Figure A.5-1. TDG meter packed with debris.

Two 1 1/2-inch-wide by 6-inch-long slots were cut on opposite sides of the housing, approximately 6 inches from the downstream end, to allow water to circulate around the probe sensors. A welded metal plate was used to seal the upstream end of the housing to prevent the accumulation of sediment and debris in the housing. The upstream end of the housing was perforated with two ¾-inch holes to allow water to escape from the housing during retrieval and to allow the Minisonde to be secured within the housing by a ¼-inch metal cable. Two ¾-inch holes drilled through either end of the housing, approximately 1 in from the edge of the pipe, served as the attachment point for the anchor line and float line bridles. Two additional holes drilled at the downstream end of the housing allowed insertion of a carriage bolt and ABS blocker as a secondary method to prevent loss of the Minsonde should the attachment cable fail.

The anchor cable bridle at the upstream end of the housing consisted of a loop of ¼-inch braided steel cable secured with four cable clamps. The float line bridle at the downstream end of the housing consisted of the loop of braided metal cable to which an additional length of metal cable or stringer was attached. The purpose of the stringer was to minimize damage to the float line by keeping it away from the housing and the river bottom (Figure A.5-2).

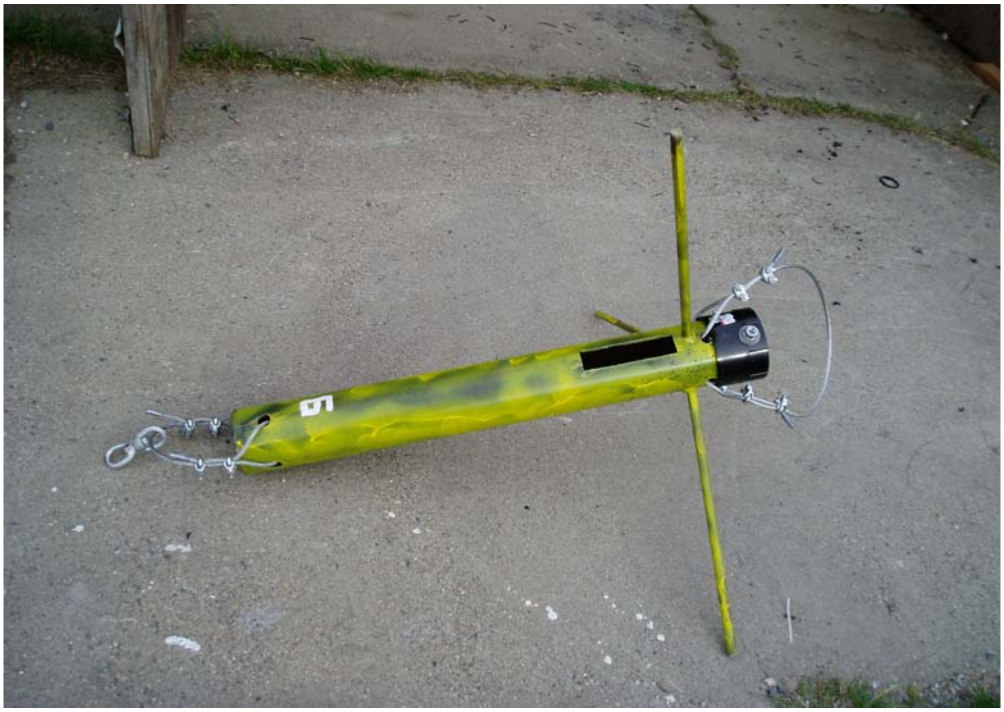

Figure A.5-2. Housing with cable bridles.

With the purchase of Minisondes as opposed to the Datasondes, modification to the housings was required to accommodate the longer length of the Minisondes and still allow the installation of a carriage bolt and ABS blocker. As a solution, a 4-inch ABS pipe coupler was attached as a collar to the downstream end of the housing. This coupler was held in place by friction and three ¼-inch bolts drilled through the pipe. The addition of this collar increased the total housing length to approximately 34 inches and allowed installation of an ABS block (Figure A.5-3). As a precaution, radio locator tags (manufactured by Lotek Inc.) were used to enable relocation of the housing should the anchor line or float line fail. These radio tags were placed in a hard plastic case and were attached to the ABS block on the outside of the housing (Figure A.5-4). The thinner Minisondes also required use of closed-cell foam to fill the space between the housing wall and the sonde and thereby prevent movement and vibration (Figure A.5-5).

Figure A.5-3. Collar and blocker.

Figure A.5-4. Locator tag housing.

Figure A.5-5. Foam padding to protect Minisonde.

Cut 3-foot sections of railway were used to anchor and hold the housings in position at each transect. Each rail piece weighed between 75 to 80 pounds and had 1-inch holes burned through either end as an attachment point. Each anchor consisted of four rail pieces connected with a 4-foot length of ½-inch braided metal cable secured with four cable clamps (Figure A.5-6). Braided 3/8-inch steel anchor cables, ranging from 15 to 25 meters (m) long, were used to connect the housing to the anchor. Float lines ranging from 15 to 25 m long and single or paired Polyform® LD2® floats or round floats were attached to the bridle stringer of the housing. Carabineers were attached to the anchor and float line to allow the housing to be quickly removed and reattached during retrieval and deployment. Inline swivels were also added to prevent twisting of the anchor cable and float line. The depths at which the housings were deployed are listed in Table A.5-1.

Figure A.5-6. Anchor.

A.5.2.1.2. Boundary Forebay Deployment System

Station H9 in the Boundary forebay consisted of 30 m length of 3/8-inch braided metal cable attached to the inside concrete railing of the causeway above the trash racks. The bottom of the cable was weighted with a 70-pound concrete anchor. The MS5 was housed in a perforated 5-foot length of 4-inch diameter ABS pipe, sealed at the bottom end. A 10-pound lead weight was attached to the bottom end to assist in deploying the housing to depth. Closed-cell foam was used to pad the sonde and prevent movement/vibration. Braided metal cable and cable clamps were used to secure the sonde within the pipe. U-brackets and carabineers were used to attach the bottom and top of the pipe to the metal cable. To retrieve and deploy the meter, a 30-m length of gold-braid rope was attached to a bracket on the outside of the housing. When deployed, the sensors of the MS5 were estimated to be at depth of at least 4 m in both 2007 and 2008.

A.5.2.1.3. Boundary Tailrace (Canada)

The MS5 at station H8, located downstream of Boundary Dam in Canada, was housed in an identical metal housing as used in the Boundary tailrace and was secured in an identical manner. The housing was then deployed with an approximately 30-m long braided metal cable attached to a tree on shore. A 15-m float retrieval line was attached to the float-line bridle of the housing. When deployed, the depth of the TDG sensor was estimated to be at least 4 m.

A.5.2.2. Velocity and Water Level Monitoring

- Velocity data acquisition:
  - A 1200 kHz RD Instruments Workhorse Sentinel ADCP was used to collect current profiles on all measurement lines. This meter is capable of collecting velocity data in a profile extending from approximately 3 feet below the surface to a depth of approximately 65 feet. ADCPs determine current velocity by measuring the frequency shift of reflected acoustic energy. The flow velocity components along the paths of three beams are used to resolve the vector and the fourth beam provides a consistency check. Each acoustic beam is a cone 3.0 degrees wide originating from the unit. The centerline of each beam projects 20 degrees from the instrument centerline resulting in a total beam spread of 43 degrees. The ADCP is capable of determining vessel motion relative to the riverbed to within ±0.02 feet per second (fps). This feature is used to provide absolute current velocity and direction with respect to the bottom by subtracting vessel motion from the resultant flow vector.
  - The ADCP was mounted directly to the hull of the survey boat with its beams aligned with the long axis of the boat. This facilitated the use of a gyrocompass to correct the ADCP data to a true north orientation since magnetic anomalies were likely present, especially near the powerhouse and overhead transmission lines.
  - The survey boat was equipped with an S.G. Brown Meridian Surveyor gyrocompass. The gyrocompass can report headings within ±0.6 degrees of true north and was interfaced to the ADCP data collection software (WinRiver) to correct measured velocity components to a true north orientation.
- Water level data acquisition:
  - Water level data were acquired using RBR XR-420 CTD gauges mounted in protective PVC pipe housings set in concrete weighted five-gallon buckets set securely on the river bottom at the measurement locations. The data loggers were deployed prior to on-water data collection activities and retrieved at the end of the velocity and discharge measurements.
- Instrument position:
  - The survey boat was equipped with a Trimble AG-132 12-channel Differential Global Positioning System (DGPS) receiver capable of receiving real-time differential corrections from either the Coast Guard beacons in Appleton, Washington, or Fort Stevens, Oregon, or from a commercial OmniSTAR satellite. The DGPS antenna was mounted directly above the ADCP, so no offset correction was required in the ADCP data presentation.
  - The survey boat was also equipped with Hypack v. 6.2 navigational software to provide real-time positioning guidance to the boat operator by providing on-screen boat position versus target location. This aided in locating measurement stations and in station keeping once current measurement had begun. Positions were recorded in NAD 83, Washington State Plane, North Zone, coordinates.

- The location of each water level data logger was surveyed using the Trimble DGPS and a level and rod based on a nearby elevation benchmark.

A.5.3 CALIBRATION AND MAINTENANCE

A.5.3.1. TDG Instruments

Based on the original scheduled 21-day deployment period for 2007 as outlined in the Revisd Study Plan (RSP), calibration of TDG meters relied on accurate factory calibration in conjunction with field verification, calibration, and maintenance at deployment and retrieval. However, low flow in 2007 resulted in extending the planned 21-day deployment period to approximately 78 days (April 20 to July 7). As a result, additional maintenance and servicing of Boundary forebay and tailrace meters (stations H1–H7 and H9) was conducted in 2007 on May 10–11 and May 31 to June 1. Servicing of the H8 station in Canada was conducted on May 14 and June 4. Furthermore, meter deployment through the peak freshet period subjected the tailrace housings, cable attachment, and float retrieval lines to substantially more force than originally anticipated. Consequently, float lines and anchor lines in the tailrace were eventually damaged and lost. Between July 1 and 6, 2007, divers were required to re-attach floats and retrieval lines to stations H2, H3, H4, H5, and H6. Stations H1, H7, H8 and H9 were recovered without diver intervention. All calibration records for deployments, service sessions, and retrieval conducted in 2007 are provided in Attachment 1, Tables A.1-1 to A.1-11.

During 2008, melting of the extremely high snow pack resulted in higher flows and a longer deployment period than in 2007. TDG meters were deployed between March 20 and middle to late July depending on the station. Extremely high flows through the peak freshet period subjected the tailrace housings, cable attachment, and float retrieval lines to a substantial amount of force resulting in the loss of the H2 float line. During a scheduled outage at Boundary Dam, divers were able to locate the H2 housing and attach a float line to facilitate retrieval of the housing and MS5 at a later date. On July 24, Golder retrieved the H2 housing and MS5 successfully. All calibration records for the 2008 deployments, service sessions, and retrieval are provided in Attachment 1, Tables A.1-12 through A.1-17.

A.5.3.1.1. Pre- and Post-Deployment Calibration

In the absence of a hand-held factory calibrated barometer, TDG pressure readings from new, recently factory calibrated MS5s were assumed to be accurate in 2007. In 2008, all the MS5s and the DS4a were sent to Hach for factory calibration prior to beginning the 2008 TDG monitoring season. All MS5s had similar barometric pressure readings. Therefore, an arbitrary meter, at station H8, was selected as the standard for the remaining MS5s and SCL's DS4a during the initial pre-deployment calibration.

Two-point pressure tests of the TDG sensor of the MS5s were conducted during pre- and post-deployment calibration sessions in both 2007 and 2008 by pressurizing the TDG sensor with a sphygmomanometer. A two-point pressure test was also performed on the DS4a during the pre-deployment calibration in 2007 and 2008 and post-deployment calibration in 2008. Although the two-point tests were useful for a relative comparison, only one-point TDG calibration could be performed using the Hydras software interface. Consequently, any corrections based on difference between the two-point tests were applied during the screening and cleaning of the collected data.

During the 2007 study, two different sphygmomanometer pressure gauges were used. For the pre-deployment calibration, a 300 mmHg pressure gauge with an accuracy of ± 3 mmHg was used. For the post-deployment calibration, a more accurate pressure gauge was available (± 0.5 mmHg). In the 2008 study, the more accurate sphygmomanometer pressure gauge (± 0.5 mmHg), was used for both the pre-deployment and post-deployment calibrations.

A.5.3.1.1.1. Pre-Deployment Calibration

Pre-deployment calibration and testing of the MS5s was conducted in both 2007 and 2008 to ensure that the logger clock was set to the correct date and time, confirm that each meter could log and download data, and confirm that the TDG and temperature sensors were calibrated by verifying that similar readings were recorded within the accuracy range of the sensors when deployed under identical conditions. The pre-deployment calibration was conducted in two parts: 1) two-point pressure testing of the TDG sensor, and 2) mass calibration field testing of TDG meters at equal depth under elevated TDG conditions.

Two-point testing of the TDG sensors was conducted on April 20, 2007, and March 18-19, 2008, at water level in the tailrace of Boundary Dam. The TDG sensor with the membrane removed was tested at ambient barometric pressure against a recently calibrated barometer, and at 200 mmHg greater than ambient pressure. To perform the 200-mmHg pressure test, a sphygmomanometer was attached to the TDG sensor with a custom-made fitting, and then the sensor was pressurized until the sphygmomanometer pressure gauge read 200 mmHg, upon which the MS5's TDG pressure sensor reading was recorded. Mass calibration of the tailrace MS5s was conducted in the tailrace of Boundary Dam prior to deployment in 2007 and 2008. The patency of each silastic membrane was confirmed by slightly pressurizing the membrane and confirming that a pressure change was registered. Each unit was delay started to start at the same time and set to log data at one-minute intervals. All units were then tied together and deployed from the back of the boat so that all the silastic membranes were at a depth of 2 m below the surface. Deploying the meters from the boat compensated for fluctuations in tailrace elevation resulting in the meters remaining at a constant depth. After a total deployment period of approximately one hour, the units were downloaded and TDG, water temperature, depth, and interval battery voltage were recorded at 30 and 50 minute interval. Based on these data, it was confirmed that temperature and TDG sensors were properly calibrated. Depth readings, however, were higher than expected. Since depth was to be recorded as a general reference parameter, the difference between each meter's sensor depth and the actual deployment depth was noted for later correction of the data, if required.

A.5.3.1.1.2. Post-Deployment Calibration

Upon retrieval on July 7, 2007, all units were transferred back to the Ione, Washington, field house where they were removed from their housings. Prior to calibration, each MS5 was cleaned and new batteries were installed, if required. The temperature sensor of the unit was then placed in the water bath and compared to temperature recorded with a mercury calibration thermometer. The patency of the silastic membrane was then assessed and the membrane was removed. With the sensor exposed to ambient atmospheric pressure, the TDG sensor readings were compared to barometric pressure readings from a second calibrated unit. The TDG sensor was then pressurized 200 mmHg greater than atmospheric pressure and the reading recorded. If the meter had experienced a power loss, the voltage of the eight individual AA cells from the battery pack were tested and recorded. Finally, the internal clock in each TDG meter was calibrated against a GPS clock. The difference between the two clocks was recorded to allow correction of time-series plots if required. The same post-deployment calibration procedure was followed in 2008.

A.5.3.1.2. Maintenance and Servicing

During each service period, each meter and its housing were retrieved and the pull time was recorded. The meters were subsequently transported to shore and removed from the housings. Depending on the condition of the meter, it was either serviced at the tailrace and redeployed the same day or it was taken to the Ione field house, serviced, and redeployed the following day. Each servicing procedure entailed verification of logging status and confirmation of data download, the start and end dates for logged data, and the data file name and location. In cases where the meter had lost power, the meter’s batteries were replaced and the old batteries tested individually. If the meter was still operational upon retrieval, the old batteries’ voltages were recorded and then the new batteries were installed and their voltages recorded.

Patency of the old membrane was then confirmed, followed by removal of the membrane, which was then cleaned and allowed to dry. With the sensor exposed to air, the barometric pressure was recorded and compared to the other meters or a second calibrated meter when available. A one-point calibration was conducted if the sensor barometric pressure reading differed from the other meters or the calibrated meter by more than 2 mmHg. It was also assumed that the meter barometric readings could be compared to real-time barometric pressure readings at the USGS stations and that the data could be adjusted in the office if required. Once calibrated, a new membrane was installed and the patency tested and confirmed. Air temperature, depth and internal battery voltage was also recorded. Temperature was only calibrated during the pre- and post-deployment calibrations in 2007. Since the MS5s had received factory maintenance shortly before the 2008 study, temperature readings were considered sufficient for this study. Depth was not a required parameter hence only the relative values were recorded.

Initiation of data logging involved synchronizing the computer and logger clocks, selection of the parameters to log, confirmation of the log interval (15 minutes), and setting the delay log start time to the nearest quarter hour interval (i.e., 15-, 30-, 45- or 60-minute mark each hour). Of critical importance, the logging end date was changed from the default end date of 24 hours after start up, to a new end date of one year after start up. To confirm log initiation, the audible tone feature was selected so that each meter emitted a series of beeps prior to logging and single beeps while in standby mode. Upon confirmation of logging, the meter was re-installed, secured in the housing, redeployed, and the deployment time was recorded.

Servicing station H8, which is located in Canada, followed essentially the same procedure, with the exception that a second barometric pressure reading was not available for direct comparison during servicing of the station. At this location, TDG data quality was reliant on initial factory calibration, routine silastic membrane exchanges, and post-correction of data based on comparing barometric pressure recorded by the meter during calibration and real-time barometric pressure recorded upstream at the USGS Boundary tailrace station.

A.5.3.2. Velocity and Water Level Instruments

The ADCP has a manufacturer specified procedure for checking the electronic circuitry and transducer transmitting frequency that was performed prior to deployment. This procedure was performed as necessary to assess instrument operation. In addition, the fourth ADCP acoustic beam is used to measure differential error to establish whether the bin measurements are affected by spatial variations in the field and interference from flow boundaries. A significant differential error indicates that the bin is not adequately homogenous, which may indicate that the meter's ability to resolve all three velocity vectors is compromised.

The gyroscopic compass has no factory-specified checks, other than turning the equipment on and making sure it works and transmits data properly. The gyroscopic compass requires significant start-up time to reach stability, up to three hours. The gyrocompass was started and checked for operation prior to the start of data collection. No field calibration can be performed, but its output can be checked against a known baseline heading, such as a dam face.

The vertical position of the ADCP was determined by measured water surface elevations for each flow condition.

The DGPS has no factory-specified checks, other than turning the equipment on and making sure it works and transmits data properly.

A.5.4 DESCRIPTION OF THE FIELD PROGRAM

A.5.4.1. TDG Monitoring

At the start of the project, it was assumed that the meters would be deployed and serviced during daylight hours. However, upon deployment of the anchor and float retrieval lines on April 19, 2007, followed by deployment of the meters within the housings on April 20, 2007, it became apparent that retrieval of the housings would not be possible at flows in excess of 30 thousand cubic feet per second (kcfs). Consequently, all subsequent services were conducted at night between 2300 and 0600 hours when Boundary Dam generation was minimal. To operate at night, Golder's two electrofishing boats, both with external bow lights, were used to pull and deploy the tailrace meters. Upon retrieval and depending on the conditions of the meter, the meters were downloaded and serviced on shore at the tailrace boat launch. Upon redeploying the tailrace meters, the forebay meter was retrieved and serviced. If the meters had significant problems that could not be addressed in the field, all the meters, including the forebay meter were brought to the lone field house for servicing and were redeployed the following day. The H8 station, which is located in Canada, was serviced independently from the other stations, which are located in the U.S. The MS5 at station H8 was deployed from shore and could be retrieved at all flows and during daylight hours by using a car-top boat or larger river boat.

Tailrace Station Deployment and Retrieval Procedure

In the spring of 2007, TDG meters were deployed at tailrace stations (H1 to H7) in two stages using a crew of three and a 21-foot Jet-drive Valco riverboat. The first stage involved positioning and deploying the anchor and float line. Three or four rail pieces were rested on the starboard gunnel of the boat near the stern. These pieces were then cabled together with a loop of ½-in braided steel cable secured with a cable clamp. The anchor cable and float lines were then attached and were coiled into separate buckets so that they would spool out smooth once the anchor was deployed. Depending on the water velocity and expected anchor drift, anchors were deployed approximately 25 to 35 m upstream of the location of the transect so that the housing, when attached, would be positioned approximately on the transect where the ADCP transect had been conducted. The spacing of TDG stations across the transect was based on visual position estimates with the objective of deploying the meters uniformly across the transect. During deployment, the boat was slowly moved into position and the anchor was pushed off the gunnel, followed by the anchor cable and float retrieval line. In 2007, deploying H3, which is located in a high-velocity mid-channel location on transect 2, was complicated by the high flows combined with the steep-sloped river bottom causing the anchor to move closer to the H2 station than planned. This resulted in the float being forced below the surface and not re-surfacing. This required deployment of a new H3 anchor, which was located approximately 100 m upstream on April 27, 2007. In 2008, the anchor systems were deployed on station without any major complications.

Once an anchor system was deployed, the housing containing the TDG meter was deployed by retrieving the anchor cable via the float retrieval line and attaching it to the upstream and downstream bridles of the housing. The housing then was lowered into the water by the float line while drifting slowly downstream, and the deployment time was recorded. The housings were retrieved and redeployed in the same manner during each service period in 2007 and 2008.

A.5.4.2. Velocity and Water Level Monitoring

- Water level data were acquired at stations 1 and 4–6 on June 13, 2007. During retrieval of gage 2, it was observed to have moved, so these data were not reported. Data were acquired from all six gages on June 20, 2007.
- The data collection software, WinRiver, was set up such that ensembles of data were collected at approximately 1 Hz with 1 ping per ensemble. Data were collected at depth increments (bin size) of approximately 1.6 feet for the majority of the data beginning at a depth of approximately 4.6 feet. Data were acquired for approximately 10 minutes at each station, resulting in approximately 600 data points per station, from which average and standard deviations of the velocity components were calculated.
- The ADCP was attached to a staff that could be lowered and tilted to ensure the instrument was vertical.
- To acquire moving transect discharge measurements, the survey boat moved along the transect line at 1-2 knots, during which time ADCP data were collected at approximately 1 Hz sampling rate at depth increments (bin size) of approximately 1.6

feet for the majority of the data. The distance from shore to the instrument at the beginning and end of the transect was noted. These distances were used to estimate discharge in the portions of the river too shallow for boat operation or ADCP measurement.

- Water level measurements were collected continuously throughout the entire velocity monitoring collection program. The data loggers were set up to average 1 minute of data (60 data points at 1 Hz sampling rate) every 15 minutes.

A.5.5 TEST CONDITIONS

A.5.5.1. Targeted Project Operations—TDG Data

A "playbook," which prioritized Project operations desired for tests for various ranges of flow, was prepared and modified to utilize flow conditions that were available.

Duration of tests required for equilibration of TDG was determined to be 4 hours.

The playbook was used by SCL staff and power planning to schedule tests, allowing them flexibility to set conditions in order of priority as river flows and power requirements allowed.

A total of 18 tests were performed in 2007 and 136 in 2008, either planned as specified in the test plan playbooks, or incidental tests defined by maintenance of constant project operations for the required 4 hour duration. These tests included operations of Spill Gate 1 only; Spill Gate 2 only; varying ratios of Spill Gate 1:Spill Gate 2; Sluice Gate 2 only; Sluice Gate 4 only; Sluice Gate 6 only; equal ratios of Sluice Gates 2 and 4 or 2, 4, and 6; varying ratios of Sluice Gates 2, 4, 6, 2 and 4, 2, 4 and 6 with Spill Gates 1 and/or 2; and all of the above in combination with varying powerhouse flows and unit operations. Total river flows varied up to just over 108,000 cfs and spill flows up to just over 61,660 cfs, both of which nearly match the 7Q10 conditions of 108,300 and 63,300 cfs.

A.5.5.2. Targeted Project Operations—Hydrodynamic Data

ADCP and water level data were acquired on June 13, 2007 for conditions of a total river flow of approximately 52,000 cfs, with 4,900 cfs spill through Gate 1 and on June 20, 2007 for a total river flow of approximately 33,000 cfs with no spill.

A.5.6 DATA MANAGEMENT

A.5.6.1. TDG Data Analysis and Processing

For each station, all data recorded were summarized into a single file. TDG% values were calculated for the tailrace stations (H1 to H8) by temporarily matching their TDG data with corresponding barometric pressure data from the USGS Boundary tailrace station. TDG% was calculated for the forebay station (H9) in a similar manner with the exception of using the USGS forebay station instead of tailrace station. Following these calculations, TDG% for stations H1 to H8 were compared to corresponding TDG% for the USGS tailrace station and TDG% for station H9 was compared to corresponding TDG% for the USGS forebay station. For each station's data set, TDG% was plotted in combination with temperature and depth data. During periods when temperature and depth data suggested that the probe was exposed above the water's surface, these suspect data were removed from the data set prior to further analyzes. Rapid changes in TDG that tracked with depth data indicated failure of the silastic membrane; these data also were removed from the ongoing data set. The voltage status of the meter was also used to identify questionable data; data recorded during period of low or erratic voltage were flagged as suspect.

A common database was developed and used to merge TDG data with operations, USGS, and Box Canyon data according to data and time.

A.5.6.2. Hydrodynamic Data Storage, Analysis, and Processing

The primary storage of collected velocity data was on the internal hard drive of the data acquisition computers. The data were also backed up onto removable USB flash drives on a daily basis. Once back in the office, established protocols were employed to provide safe backup data storage.

The DGPS, velocity, and water level data were reviewed upon return to the office and obvious data outliers were excluded from further analysis. The data were then transformed into consistent engineering units and combined into a single time series for each measurement location. The results were independently reviewed for accuracy. Transect discharge data were processed using the WinRiver software and resulting discharge computations were compared to the total flows reported by the powerhouse control room. The fixed location velocity data were analyzed to calculate the average and standard deviation of the velocity vector magnitude, azimuth, and dip angle at each velocity bin elevation and horizontal location, and stored for later use.

A.5.7 QUALITY ASSURANCE/QUALITY CONTROL

Parameter calibration was verified prior to deployment with one-point calibration against a calibrated source, group comparison, and in situ mass calibration testing at depth. In addition, the TDG sensor underwent two-point range testing. Pre-deployment testing also included calibration and verification tests for time and date and testing of logging and data downloading. Prior to deployment, field staff recorded parameter selection, logger setting, and confirmation of logging status.

During each service period, maintenance and service involved one-point TDG calibration, group TDG comparison, and comparison to a calibrated TDG source. Field staff recorded differences between the instruments, as a group, and the calibrated source for subsequent correction of the data set. Time checks were conducted and batteries were replaced during each service. Patency of the new silastic membrane was checked and confirmed. Prior to redeployment, field staff recorded parameter selection, logger setting, and confirmation of logging status.

At final retrieval for each year, field staff recorded the logging status, power supply status and general condition of the meters. One-point calibration was conducted against a calibrate source and group comparison of parameters. Field staff conducted a two-point range test of the TDG sensor and temperature sensor.

During all service periods and during the final retrieval, TDG data were downloaded to a portable laptop computer. Due to the relatively slow maximum download speed, two separate computers were used to allow two sondes to be downloaded at the same time. Upon completion of download, the data file was briefly inspected in the field for completeness and the start and end date of the data file recorded. As a precaution, these data were also copied to a USB drive as a backup.

A.5.7.1. Measurement Quality Objectives

Measurement Quality Objectives (MQOs) answer the question of how accurate the measurements must be in order to get accurate data. The U.S. Environmental Protection Agency (EPA) refers to MQOs as "acceptance criteria" for the quality attributes measured by project data quality indicators (EPA 2006). The MQOs are based on methods and the Data Quality Objectives, which guide how accurate data need to be in order to make correct decisions. MQOs include precision, bias, and accuracy guidelines against which the laboratory and some field quality control results are compared. The MQOs for this study are reported in Table A.5-5.

Table A.5-5. Calculated relative standard deviation (RSD) for H1-H9 relative to MQO for barometric pressure (BP), BP+200, TDG, and temperature during 2007 TDG monitoring (Study 3).

Meter and Site IDs	RSD or Difference from group average								MQO			RSD or difference - MQO (positive values denote exceedance of MQO)							
	BP[1]	BP+200[2]		TDG[3]		Temperature[3]			BP/BP+200 mmHg	TDG	Temp	BP[1]	BP+200[2]		TDG[3]		Temperature[3]		
	(mmHg)	Pre-Deployment (mmHg)	Post-Deployment (mmHg)	30-Min (mmHg)	50-Min (mmHg)	30-Min (ºC)	50-Min (ºC)	Post-Deployment (ºC)	(mmHg)	(mmHg)	(ºC)	(mmHg)	Pre-Deployment (mmHg)	Post-Deployment (mmHg)	30-Min (mmHg)	50-Min (mmHg)	30-Min (ºC)	50-Min (ºC)	Post-Deployment (ºC)
045070 (H1)	0.7	1.0	4.0	2.0	0.5	0.0	0.0	0.1	2.0	5.0	0.5	-1.3	-1.0	2.0	-3.0	-4.5	-0.5	-0.5	-0.4
045074 (H2)	1.4	1.0	1.0	0.0	0.5	0.0	0.0	0.2	2.0	5.0	0.5	-0.6	-1.0	-1.0	-5.0	-4.5	-0.5	-0.5	-0.3
045073 (H3)	0.5	1.0	0.0	2.0	1.5	0.0	0.0	0.1	2.0	5.0	0.5	-1.5	-1.0	-2.0	-3.0	-3.5	-0.5	-0.5	-0.4
045075 (H4)	0.7	1.0	1.0	3.0	2.5	0.0	0.0	0.3	2.0	5.0	0.5	-1.3	-1.0	-1.0	-2.0	-2.5	-0.5	-0.5	-0.3
045076 (H5)	1.3	2.0	0.0	4.0	2.5	0.0	0.0	0.0	2.0	5.0	0.5	-0.7	0.0	-2.0	-1.0	-2.5	-0.5	-0.5	-0.5
045084 (H6)	3.0	1.0	5.0	3.0	2.5	0.0	0.0	0.1	2.0	5.0	0.5	1.0	-1.0	3.0	-2.0	-2.5	-0.5	-0.5	-0.4
045085 (H7)	0.9	0.0	1.0	1.0	1.5	0.0	0.0	0.2	2.0	5.0	0.5	-1.1	-2.0	-1.0	-4.0	-3.5	-0.5	-0.5	-0.3
045088 (H8)	4.3	2.0	1.0	1.0	0.5	0.0	0.0	0.1	2.0	5.0	0.5	2.3	0.0	-1.0	-4.0	-4.5	-0.5	-0.5	-0.4
045095 (H9)	1.1	1.0	3.0	n/a	n/a	n/a	n/a	0.0	2.0	5.0	0.5	-0.9	-1.0	1.0	n/a	n/a	n/a	n/a	-0.5
RSD combined	2.0	1.2	2.4	2.5	1.9	0.0	0.0	0.1	2.0	5.0	0.5	0.0	-0.8	0.4	-2.5	-3.2	-0.5	-0.5	-0.4

[1] Pooled RSD calculated from BP record at station and at USGS station during service period and removal.

[2] Calculated differences of point measurement at +200 mmHg between and expected and observed values.

[3] Calculated difference of point measurement and group average during *in situ* calibration at 30 and 50 minute equilibration times; post-deployment readings were based on the difference between the meter and calibration thermometer in a water bath.

Precision is estimated as the standard deviation of the results of n replicate measurements. If more than one estimate of the standard deviation of a population is available, a pooled estimate may be calculated based on m pairs of duplicate results as:

$$sp = \sqrt{\frac{\sum D^2}{2m}}$$

where: sp = pooled standard deviation

D = difference between two paired results

Precision is often reported as the relative standard deviation (RSD) of the results of replicate measurements (Ecology 2001), which is calculated as a percentage of the mean by:

$$RSD = (s_x/x_m)*100$$

Where: x_m is the sample mean of the replicate measurements and s_x is the standard deviation

Ecology (2001) describes accuracy as a measure of the magnitude of the total error which consists of bias (difference from the true value) and a random component, and suggests using the following formula to estimate accuracy.

Accuracy = Bias + 2 * RSD when accuracy and bias are expressed as percentages of the true value and RSD is the percent relative standard deviation.

Typical instrument precision limits are also listed in Table A.5-5. Precision limits are defined as the minimum value at which there is 95 percent confidence that the instrument value is within one standard error of the actual value for a sample.

MQOs for TDG Measurements

After initially calibrating all meters to a common barometric pressure during the pre-deployment calibration, the field MQO for pressure readings from TDG sensor in air (i.e., silastic membrane off with the TDG sensor at ambient barometric pressure) during the service period was ± 2 mmHg from the calibrated standard. The MQO was compared to RSD calculated based on paired measurements from each meter when the meters were serviced at the field house in Ione, Washington. RSD values were also calculated for all meters combined based on the TDG value recorded during two-point testing at 200 mmHg above ambient barometric pressure and compared to an MQO of ±2 mmHg. Paired in situ TDG measurements at the station deployment locations were not possible during the study. Consequently, during mass calibration of all meters in the tailrace, a relative standard deviation was calculated based on TDG data recorded at 30-minute and 50-minute equilibration times. This value was compared to an MQO of 1 percent or 5 mmHg.

For 2007, RSDs were calculated for all meters combined based on temperature data recorded from the pre-deployment mass calibration data and post-deployment comparison to a mercury calibration thermometer, and then compared to an MQO of 0.5°C. Results of the RSD and comparisons to MQOs are presented in Table A.5-5 for 2007 and Table A.5-6 for 2008.

Table A.5-6. Table Calculated relative standard deviation (RSD) for meters relative to MQO for barometric pressure (BP), BP +200, TDG, and temperature during 2008 TDG monitoring (Study 3).

	RSD or Difference From Group Average			MQO		RSD or Difference - MQO (Positive values denote exceedance of MQO)		
	BP[1]	BP+200[2]		BP/BP+200 mmHg	TDG	BP[1]	BP+200[2]	
Meter and Site IDs	(mmHg)	Pre-Deployment (mmHg)	Post-Deployment (mmHg)	(mmHg)	(mmHg)	(mmHg)	Pre-Deployment (mmHg)	Post-Deployment (mmHg)
45070 (H1)	0.7	9.0	25.0	2.0	5.0	-1.3	7.0	23.0
45073 (H3)	1.0	1.0	1.0	2.0	5.0	-1.0	-1.0	-1.0
45074 (H2)	1.6	9.0	1.0	2.0	5.0	-0.4	7.0	-1.0
45075 (H4)	1.6	1.0	1.0	2.0	5.0	-0.4	-1.0	-1.0
45076 (H9)	1.0	0.0	n/a	2.0	5.0	-1.0	-2.0	n/a
45084 (H6)	0.7	49.0	1.0	2.0	5.0	-1.3	47.0	-1.0
45085 (H7 & H9)	1.0	9.0	16.0	2.0	5.0	-1.0	7.0	14.0
45088 (H8)	4.1	25.0	9.0	2.0	5.0	2.1	23.0	7.0
45095 (H5)	1.0	4.0	0.0	2.0	5.0	-1.0	2.0	-2.0
RSD combined	1.4	3.4	2.6	2.0	5.0	-0.6	1.4	0.6

[1] Pooled RSD calculated from BP recorded at station and at USGS tailrace station during service period and removal. Post-monitoring two-point test conducted on July 25, 2008 confirms that MS5 45088 TDG in air was low by 4 mmHg.

[2] Calculated differences of point measurement at +200 mmHg between expected and observed values.

A.5.8 FIELD QUALITY CONTROL FOR TDG DATA COLLECTION

Quality control in the field was assured by accurately and thoroughly completing quality assurance/quality control (QA/QC) forms for calibration. Calibration of field instruments was performed according to the manufacturer's instructions at each instrument servicing, prior to and subsequent to deployment.

A.5.8.1. Field Quality Control for Hydrodynamic Data Collection

Prior to each day’s on-water activities, the internal clocks on all equipment were synchronized to a standard time that remained consistent throughout the data collection program. The diagnostic checks of the software for the ADCP were performed prior to deployment on a daily basis.

Velocity data were reviewed in real-time as they were collected to ensure that the boat position was maintained within the 10-foot radius of the target location, and that the velocity profiles were consistent with expected values. In addition, if the differential correction on the DGPS was lost, the navigation software displayed a visual alarm on the navigation computer screen. The velocity data sampling time was then adjusted to compensate for the lost time without differential correction to the GPS signal.

Water level measurements were field checked at the time the instrument housings were surveyed for elevation. Data were downloaded and reviewed at the end of the field deployment.

A.5.8.2. Position and Heading

The horizontal precision of the DGPS in dynamic mode (moving boat) is approximately ±1 meter or ±3 feet.

The precision of the instantaneous horizontal position of the ADCP was also ±3 feet, as the antenna for the DGPS was attached vertically above the ADCP. The precision of location of each final measurement point was diluted somewhat by boat movement and depends on a number of factors, including current speed and eddies. In an attempt to define precision, the boat driver was provided with a 10-foot radius computer screen target, within which to hold boat position. An initial estimate of the accuracy of the ADCP location is approximately:

$$PE = \sqrt{\Sigma(ie)^2} = \sqrt{\Sigma(\pm DGPS)^2 + (\pm boat)^2} = \sqrt{\Sigma(\pm 3)^2 + (\pm 5)^2} = \pm 6 \text{ feet}$$

assuming only data within a 5-foot radius of the target is used.

The precision of vertical position of the ADCP was within ±1 foot. The ADCP was set to a vertical resolution (bin-size) of approximately 6.6 feet. The accuracy of the velocity measurement decreases with increasing resolution.

The gyro compass provided a dynamic accuracy of ±0.6 degree.

A.5.8.3. Current Speed and Direction

RDI claims a current speed measurement accuracy for the 1200-kHz ADCP of ±0.25 percent of the water velocity relative to the instrument plus ±0.1 inch per second. Current direction as computed by the ADCP relative to the instrument is a function of the velocity magnitude accuracy. Direction data were reduced from the magnitudes of each velocity component to provide azimuth and dip angle information.

A.5.8.4. Water Level

The accuracy of the WaterLOG DH-21 water level data loggers is approximately 0.03 foot water depth.

A.5.9 INTERPRETATION OF DATA

TDG reported as total gas pressure and percent saturation from:

%TDG = TDGP/BP*100,

Where:

%TDG = total gas saturation percent
TDGP = total gas pressure (mm Hg)
BP = ambient atmospheric pressure (mm Hg)

Data were tabulated and plotted as time series to allow identification of specific test treatments and determination of equilibrated TDG values for the treatment.

A.5.10 REFERENCES

Ecology (Washington Department of Ecology). 2001. Guidelines for Preparing Quality Assurance Project Plans for Environmental Studies. February 2001. Ecology Publication No. 01-03-003.

EPA (U.S. Environmental Protection Agency). 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process. February 2006. EPA QA/G-4. 111 pp.

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Attachment 1: Calibration Records

Table A-1. Dissolved gas two-point calibration and membrane patency testing, April 2007.

Location Boundary TR Crew PG/TO/CK

MS5 Serial No.	Site ID	Calibration Date	TDG in Air Uncorr (mmHg)	BP (mmHg)[1]	TDG Correction (mmHg)	TDG in Air Corrected (mmHg)	TDG +200 mmHG (mmHg)[4]	Silastic Membrane No.	Membrane Patent	Logger Clock/PC Clock Time Synch	Locator Tag Code	Depth in Air at Water Level (m)
045070	H1	4/20/07	714	713	-1	713	914	1	y	y	22	1.27
045074	H2	4/20/07	712	713	1	713	912	2	y	y	19	0.86
045073	H3[2]	4/20/07	713	713	0	713	912	3	y	y	14	1.11
045075	H4	4/20/07	713	713	0	713	912	4	y	y	20	1.12
045076	H5	4/20/07	711	713	2	713	911	5	y	y	15	1.01
045084	H6	4/20/07	712	713	1	713	914	6	y	y	16	1.01
045085	H7	4/20/07	714	713	-1	713	913	7	y	y	21	0.98
045088	H8	4/20/07	713	713	0	713	915	8	y	y	12	0.99
045095	H9	4/24/07	713	711[2]	-2	711	912	9	y	y	5	0.96
n/a	DS4a	4/19/07	700	705[3]	5	705	897	n/a	n/a	n/a	n/a	n/a

[1] H1-H7 TDG (in air) was compared to concurrent H8 TDG (in air)

[2] H9 TDG (in air) was compared to concurrent H3 TDG (in air)

[3] DS4a TDG (in air) was compared to concurrent H9 TDG (in air)

[4] Two-point test conducted after 1-point calibration. Pressure gauge used was a 300 mmHg sphygmomanometer (Batra Group China Co. Ltd) accuracy approx. +/- 3 mmHg.

Table A-2. H1-H8 TDG meter mass-calibration test after 30- and 50-minute deployment periods at 2.0 meter depth in the Boundary Tailrace, April 20, 2007 at 1104-1211 hours.

Date: 20-Apr-07 Start Time: 11:04 End Time: 12:11
Location: Boundary TR Crew: PG/TO/CK

	30-minute equilibration				50-minute equilibration			
Site ID	TDG (mmHg)	Temperature (ºC)	Depth in Air at Water Level (m)	Internal Battery (v)	TDG (mmHg)	Temperature (ºC)	Depth in Air at Water Level (m)	Internal Battery (v)
H1	771	8.07	3.12	11.80	771	8.08	3.10	11.8
H2	769	8.05	2.75	11.80	770	8.07	2.75	11.8
H3	771	8.08	2.98	11.70	772	8.10	2.99	11.7
H4	766	8.11	2.96	11.80	768	8.12	2.95	11.8
H5	765	8.08	2.90	12.00	768	8.10	2.90	11.9
H6	772	8.06	2.84	12.00	773	8.07	2.84	11.9
H7	770	8.08	2.79	12.00	772	8.09	2.77	12.0
H8	768	8.06	2.86	11.60	770	8.07	2.88	11.6
Average	769	8.07			771	8.09		
Standard Deviation	2.5	0.02			1.9	0.02		
Standard Error	0.9	0.01			0.7	0.01		

Table A-3. Data log settings and initiation confirmation, April 2007.

Location Boundary TR Crew PG/TO/CK

Site ID	Deployment Location	Deployment Date	Delay Log Start Time	15 min Log Interval	2008 Log End Date	Log Start Confirmed	Deployment Time
H1	Boundary tailrace Transect 2	4/20/07	n	y	y	y	16:32
H2	Boundary tailrace Transect 2	4/20/07	n	y	y	y	16:41
H3	Boundary tailrace Transect 2	4/27/07	15:00	y	y	y	18:35
H4	Boundary tailrace Transect 2	4/20/07	n	y	y	y	16:49
H5	Boundary tailrace Transect 3	4/20/07	n	y	y	y	17:04
H6	Boundary tailrace Transect 3	4/20/07	n	y	y	y	17:13
H7	Boundary tailrace Transect 3	4/20/07	n	y	y	y	17:18
H8	Boundary tailrace Canada	4/23/07	11:00	y	y	y	18:35
H9	Boundary forebay	4/27/07	11:45	y	y	y	11:54

Table A-4. Recovery and logging status on May 11and May 14, 2007.

Crew PG/DF/CK (10-11 May 07) PG/CK (14 May 07)

MS5 Serial No.	Site ID	Retrieval Date	Pull Time	Logging Ok	Old Battery Voltage (v)
045070	H1	5/11/07	00:00	y	8.5
045074	H2	5/11/07	00:04	n	0
045073	H3	5/11/07	00:08	n	0
045075	H4	5/11/07	00:10	y	10.2
045076	H5	5/11/07	00:21	n	0
045084	H6	5/11/07	00:18	n	0
045085	H7	5/11/07	00:15	n	0
045088	H8	5/14/07	17:40	y	10.1
045095	H9	5/11/07	02:20	y	10.1

Table A-5. Meter calibration check and service log, May 11 and May 14, 2007.

MS5 Serial No.	Site ID	Calibration Date[2]	Time	New Battery Voltage (v)	Data Download Ok	TDG in Air Old (mmHg)[1]	TDG in Air New (mmHg)	TDG Correction (mmHg)	Box Canyon Forebay BP (mmHg)	Temp in Air (°C)	Depth (m)	Old Silastic Membrane No.	Old Membrane Patent	New Silastic Membrane No.	New Membrane Patent	Logger Clock/PC Clock Time Synch
045070	H1	5/11/07	13:04	12.7	y	708	708	0	708	20.28	1.24	1	y	14	y	y
045074	H2	5/11/07	13:34	12.7	y	706	706	0	708	21.08	1.18	2	y	13	y	y
045073	H3	5/11/07	13:18	12.8	y	708	708	0	708	19.81	1.05	3	y	12	y	y
045075	H4	5/11/07	13:27	12.7	y	708	708	0	708	20.59	1.09	4	y	11	y	y
045076	H5	5/11/07	13:42	12.6	y	708	708	0	708	21.03	1.31	5	y	17	y	y
045084	H6	5/11/07	13:48	12.5	y	708	708	0	708	20.39	0.94	6	y	18	y	y
045085	H7	5/11/07	13:56	12.3	y	707	707	0	708	20.61	0.92	7	y	16	y	y
045088	H8	5/14/07	18:34	13.5[3]	y	725	725	0	720	15.82	1.13	8	y	10	y	y
045095	H9	5/11/07	14:07	12.7	y	708	708	0	708	21.43	0.92	9	y	19	y	y

[1] TDG (in air) of H1-H7 & H9 compared to calibrate meter. TDG correction only perform if TDG difference was in excess of +/-2 mmHg. Real-time barometric pressure comparsion not availabe in H8 in Canada.

[2] Meters calibrated at Ione field house. Box Canyon forebay barometric pressure calculated for comparison (equal to Boundary forebay barometric pressure - 1 mmHg).

[3] Higher voltage due to replacement of old batteries with new Nickel Oxy Hydroxide batteries.

Table A-6. Data log settings and initiation confirmation, May 11 and May 14, 2007.

Location Boundary TR Crew PG/DF/CK

Site ID	Deployment Location	Deployment Date	Delay Log Start Time	15 min Log Interval	2008 Log End Date	Log Start Confirmed	Deployment Time
H1	Boundary tailrace Transect 2	5/11/07	13:15	y	y	y	16:19
H2	Boundary tailrace Transect 2	5/11/07	13:45	y	y	y	16:17
H3	Boundary tailrace Transect 2	5/11/07	13:30	y	y	y	16:24
H4	Boundary tailrace Transect 2	5/11/07	13:45	y	y	y	16:22
H5	Boundary tailrace Transect 3	5/11/07	14:00	y	y	y	16:00
H6	Boundary tailrace Transect 3	5/11/07	14:00	y	y	y	16:13
H7	Boundary tailrace Transect 3	5/11/07	14:15	y	y	y	16:08
H8	Boundary tailrace Canada	5/14/07	18:45	y	y	y	19:10
H9	Boundary forebay	5/11/07	14:15	y	y	y	16:50

Table A-7. Recovery and logging status on May 31, June 1, and June 4, 2007.

Crew PG/DF/CK (31 May-1 June 07) CK/SW (4 June 07)

MS5 Serial No.	Site ID	Retrieval Date	Pull Time	Logging Ok	Old Battery Voltage (v)
045070	H1	5/31/07	22:57	y	10.9
045074	H2	could not retrieve	n/a	n/a	n/a
045073	H3	5/31/07	23:05	n	0
045075	H4	5/31/07	23:01	y	10.8
045076	H5	could not retrieve	n/a	n/a	n/a
045084	H6	5/31/07	23:20	y	10.9
045085	H7	5/31/07	23:13	n	0
045088	H8	6/4/07	13:50	y	12.8
045095	H9	6/1/07	04:02	y	10.8

Table A-8. Meter calibration check and service log, June 1 and June 4, 2007.

MS5 Serial No.	Site ID	Calibration Date	Time	New Battery Voltage (v)	Data Download Ok	TDG in Air Old (mmHg)	TDG in Aair New (mmHg)	TDG Correction (mmHg)	BP at USGS TR (FB) (mmHg)	Temp in Air (ºC)	Depth in Air (m)	Old Silastic Membrane No.	Old Membrane Patent	New Silastic Membrane No.	New Membrane Patent	Logger Clock/PC Clock Time Synch
045070	H1	6/1/07	01:13	12.8	y	715	715	0	714	12.57	1.29	14	y	1	y	n/a
045074	H2	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a
045073	H3	6/1/07	00:22	12.5	y	715	715	0	714	12.93	1.08	12	y	3	y	n/a
045075	H4	6/1/07	01:18	12.8	y	715	715	0	714	12.49	1.14	11	y	4	y	n/a
045076	H5	n/a	n/a	n/a	n/a	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a
045084	H6	6/1/07	00:24	12.8	y	719 (717)	713	-4	714	12.75	1.02	18	y	6	y	n/a
045085	H7	6/1/07	01:52	12.7	y	715	715	0	714	12.16	1	16	y	7	y	n/a
045088	H8	6/4/07	14:54	12.6	y	717	717	0	712	20.89	0.99	10	y	8	y	n/a
045095	H9	6/1/07	04:34	12.7	y	708	708	0	(707)	12.14	0.9	19	y	9	y	n/a

[1]TDG (in air) of H1-H7 & H9 compared to calibrated meter. TDG correction only performed if TDG difference was in excess of +/-2 mmHg. Real-time barometric pressure comparsion not availabe in H8 in Canada.

Table A-9. Data log settings and initiation confirmation, June 1 and June 4, 2007.

Location Boundary TR Crew PG/DF/CK

Site ID	Deployment Location	Deployment Date	Delay Log Start Time	15 min Log Interval	2008 Log End Date	Log Start Confirmed	Deployment Time
H1	Boundary tailrace Transect 2	6/1/07	01:45	y	y	y	02:39
H2	Boundary tailrace Transect 2	n/a	n/a	n/a	n/a	n/a	n/a
H3	Boundary tailrace Transect 2	6/1/07	00:45	y	y	y	02:44
H4	Boundary tailrace Transect 2	6/1/07	01:45	y	y	y	02:47
H5	Boundary tailrace Transect 3	n/a	n/a	n/a	n/a	n/a	n/a
H6	Boundary tailrace Transect 3	6/1/07	01:00	y	y	y	02:57
H7	Boundary tailrace Transect 3	6/1/07	02:15	y	y	y	02:59
H8	Boundary tailrace Canada	6/4/07	15:30	y	y	y	15:37
H9	Boundary forebay	6/1/07	05:00	y	y	y	05:04

Table A-10. Recovery and logging status on June 25 and July 7, 2007.

Crew CK/SW (25 June 07) PG/CK/SW (7 July 07)

MS5 Serial No.	Site ID	Retrieval Date	Pull Time	Logging Ok	Old Battery Voltage (v)
045070	H1	7/7/07	01:14	y	10.8
045074	H2	7/7/07	01:18	n	0.0[1]
045073	H3[2]	7/7/07	01:24	n	0.0[2]
045075	H4	7/7/07	01:27	y	10.8
045076	H5	7/7/07	01:37	y	10.2
045084	H6	7/7/07	01:44	y	11.1
045085	H7	7/7/07	01:46	y	11.0
045088	H8	6/25/07	13:05	y	11.2
045095	H9	7/7/07	02:45	y	10.8

[1] Power drain of AA cells in backpack not uniform; voltages were as follows: 1.11V, 1.06V, 1.11V, 0.99V, 0.00V, 1.10V, 1.12V, -0.1V

[2] Power drain of AA cells in backpack not uniform; voltages were as follows: 1.35V, 1.36V, 1.36V, 1.36V, 1.36V, 1.35V -0.84V, 1.36V

Table A-11. Dissolved gas two-point calibration and membrane patency testing, July 7 and August 8, 2007.

Crew PG/TO

MS5 Serial No.	Site ID	Logger Clock Date/Time	GPS Data/Time	Time Correction (min)	TDG in Air Uncorrected (mmHg)	BP (mmHg)[1]	BP Box Canyon Forebay (mmHg)	TDG Correction (mmHg)[2]	TDG in Air Corrected (mmHg)	TDG +200 mmHG (mmHg)[3]	Sonde Temp in Water Bath (ºC)	Calibration Thermometer (ºC)	Old Membrane No.	Membrane Patent
045070	H1	7/7/07 12:40	7/7/07 12:34	0:06	705	706	705	0	705	909	15.98	15.9	1	y
045074	H2	7/7/07 15:40	7/7/07 15:33	0:07	703	705	704	0	703	902	17.20	17.0	13	y
045073	H3	7/7/07 13:35	7/7/07 13:28	0:07	705	705	705	0	705	905	16.41	16.3	3	y
045075	H4	7/7/07 14:30	7/7/07 14:22	0:08	705	705	704	0	705	906	16.75	16.5	4	n
045076	H5	7/7/07 14:48	7/7/07 14:40	0:08	705	705	704	0	705	905	16.70	16.7	17	y
045084	H6	7/7/07 15:08	7/7/07 15:01	0:07	709	705	704	-4	705	914	16.90	16.8	18	y
045085	H7	7/7/07 13:36	7/7/07 13:29	0:07	705	705	705	0	705	906	16.46	16.3	7	y
045088	H8	8/8/07 13:11	8/8/07 13:02	0:09	720	715	n/a	-5	715	921	20.31	20.2	8	n
045095	H9	7/7/07 12:40	7/7/07 12:36	0:04	705	706	705	0	705	908	15.95	15.9	9	y

[1] H1-H7 & H9 TDG (in air) was compared to concurrent DS4 barometric pressure; H8 TDG (in air) was compared to a recently calibrated barometer.
[2] TDG correction only performed if TDG difference was in excess of +/-2 mmHg.
[3] Two-point test conducted after 1-point calibration. Pressure gauge used was Ashcroft 2084 Precision Digital Test Gauge, Accuracy +/- 0.25% (+/- 0.5 mmHg).

Table A-12. Pre-Monitoring dissolved gas two-point TDG calibration and membrane patency testing, March 2008.

Location Field House in Ione, WA Crew PG/CK/HS on March 18-19; PG/CK on March 28

MS5 Serial No.	Site ID	Calibration Date	Calibration Start Time	Calibration End Time	Internal Battery (v)	TDG in Air Uncorrected (mmHg)	BP (mmHg)[1]	TDG Correction (mmHg)	TDG in Air Corrected (mmHg)	TDG +200 mmHG (mmHg)[4]	Silastic Membrane No.	Soda Max TDG (mmHg)	Membrane Patent	Sonde Temp in Water Bath (°C)	Cal Thermometer (°C)	MS5 Date/Time	GPS or Computer Date/Time	Locator Tag Code	Tag Active?	Air at Water Level (m)
045070	H1	3/18/08	17:30	18:30	12.0	706	707	1	707	910	1	1073	Y	14.0	13.8	3/18/08 18:18	3/18/08 18:18	22	Y	0.95
045074	H2	3/18/08	17:30	18:30	12.1	703	707	4	707	904	2	1009	Y	12.6	12.6	3/18/08 18:21	3/18/08 17:22	19	Y	0.95
045073	H3	3/18/08	20:48	21:55	12.1	706	707	1	707	908	3	915	Y	14.2	14.1	3/18/08 20:46	3/18/08 19:48	14	Y	0.95
045075	H4	3/18/08	20:48	21:55	12.1	706	707	1	707	908	5	956	Y	14.4	14.2	3/18/08 21:14	3/18/08 20:16	20	Y	1.02
045095	H5	3/19/08	10:00	10:35	12.1	710	710	0	710	912	9	953	Y	16.7	16.8	3/19/08 9:36	3/19/08 10:35	5	Y	1.02
045084	H6	3/18/08	21:55	22:34	12.1	708	708	0	708	915	10	903	Y	14.8	14.6	3/18/08 21:08	3/18/08 22:07	16	Y	1.05
045085	H7	3/18/08	21:55	22:34	12.1	707	708	1	708	911	7	917	Y	14.7	14.5	10/30/95 16:15	3/18/08 22:10	21	Y	0.95
045088	H8	3/19/08	10:05	10:35	12.1	710	710	0	710	915	8	923	Y	16.7	16.7	3/19/08 9:07	3/19/08 10:06	12	Y	1.11
045076	H9	3/28/08	14:15		11.8	704	704	0	704	904	13			n/a		3/28/08 13:15	3/28/08 14:12	15	Y	
	DS4a	3/28/08	14:15			704				901			n/a					n/a		

[1] H1-H7 TDG (in air) was compared to concurrent H8 TDG (in air).
[2] H9 TDG (in air) was compared to concurrent H3 TDG (in air).
[3] DS4a TDG (in air) was compared to concurrent H9 TDG (in air).
[4] Two-point test conducted after 1-point calibration. Pressure gauge used was a 300 mmHg sphygmomanometer (Ascroft) accuracy approx. +/- 0.5 mmHg.

Table A-13. TDG service logging status, 2008.

PULL/SET TIME LOG

MS5 Serial No.	Site ID	Pull/Set	Date	Time	Crew	Comments
45070	H1	Set	3/20/08	15:30	PG/HS/CK	
45070	H1	Pull	4/7/08	23:42	PG/CK/TM	4500 cfs
45070	H1	Set	4/8/08	5:36	PG/CK/TM	
45070	H1	Pull	4/28/08	22:39	PG/SW/TM	foam donuts degrading - need to be replaced
45070	H1	Set	4/29/08	15:27	PG/SW/TM	pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45070	H1	Pull	7/13/08	10:39	CK/FI/JM	pulled by BH/FI/DB
45074	H2	Set	3/20/08	15:44	PG/HS/CK	
45074	H2	Pull	4/7/08	23:48	PG/CK/TM	
45074	H2	Set	4/8/08	6:14	PG/CK/TM	cable got stuck, had to work loose, same problem last year
45074	H2	Pull	4/28/08	22:42	PG/SW/TM	foam donuts degrading - need to be replaced
45074	H2	Set	4/29/08	15:30	PG/SW/TM	pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45074	H2	Pull	7/24/08	15:20	CK/FI/JM	one strand of cable connecting housing to floats, rope going from housing to float
45073	H3	Set	3/20/08	15:39	PG/HS/CK	
45073	H3	Pull	4/7/08	23:55	PG/CK/TM	
45073	H3	Set	4/8/08	5:47	PG/CK/TM	
45073	H3	Pull	4/28/08	22:47	PG/SW/TM	Foam donuts degrading - need to be replaced
45073	H3	Set	4/29/08	15:31	PG/SW/TM	Pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45073	H3	Pull	7/13/08	10:44	CK/FI/JM	Pulled by BH/FI/DB
45075	H4	Set	3/20/08	15:35	PG/HS/CK	
45075	H4	Pull	4/8/08	0:00	PG/CK/TM	
45075	H4	Set	4/8/08	5:52	PG/CK/TM	
45075	H4	Pull	4/28/08	22:49	PG/SW/TM	Foam donuts degrading - need to be replaced
45075	H4	Set	4/29/08	15:37	PG/SW/TM	Pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45075	H4	Pull	7/13/08	10:48	CK/FI/JM	Pulled by BH/FI/DB
45095	H5	Set	3/20/08	15:50	PG/HS/CK	
45095	H5	Pull	4/8/08	0:08	PG/CK/TM	
45095	H5	Set	4/8/08	5:57	PG/CK/TM	
45095	H5	Pull	4/28/08	22:57	PG/SW/TM	Foam donuts degrading - need to be replaced
45095	H5	Set	4/29/08	15:40	PG/SW/TM	Pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45095	H5	Pull	7/13/08	11:17	CK/FI/JM	Pulled by BH/FI/DB
45084	H6	Set	3/20/08	14:44	PG/HS/CK	
45084	H6	Pull	4/8/08	0:14	PG/CK/TM	
45084	H6	Set	4/8/08	6:02	PG/CK/TM	
45084	H6	Pull	4/28/08	22:59	PG/SW/TM	Foam donuts degrading - need to be replaced
45084	H6	Set	4/29/08	15:45	PG/SW/TM	Pulled by hand at 32 kcfs, could pull with winch up to 40 kcfs
45084	H6	Pull	7/13/08	11:06	CK/FI/JM	Pulled by BH/FI/DB
45085	H7	Set	3/20/08	15:05	PG/HS/CK	
45085	H7	Pull	4/8/08	0:17	PG/CK/TM	
45085	H7	Set	4/8/08	6:05	PG/CK/TM	
45085	H7	Pull	4/28/08	23:00	PG/SW/TM	
45085	H7	Set	4/29/08		PG/SW/TM	Not deployed - sent for servicing
45088	H8	Set	3/24/08	12:06	PG/HS/CK	Same location as last year, seems deeper
45088	H8	Pull	4/21/08	13:00	CK/TM	Logging still (beeping)
45088	H8	Set	4/21/08	14:55	CK/TM	Logging still (beeping)
45088	H8	Pull	5/20/08	14:45	CK/TM	
45088	H8	Set	5/20/08	16:12	CK/TM	
45088	H8	Pull	6/12/08	10:53	PG/TM	Easy pull, some fine sediment in pipe, beeped - working & logging.
45088	H8	Set	6/12/08	12:41	PG/TM	Ok
45088	H8	Pull	7/13/08	12:30	CK/FI/JM	Pulled by BC/CC
45076	H9	Set	3/28/08	16:20	PG/HS/CK	Boundary forebay beside USGS station
45076	H9	Pull	4/8/08	7:17	PG/CK/TM	
45076	H9	Set	4/8/08	8:05	PG/CK/TM	
45076	H9	Pull	4/28/08	23:40	PG/SW/TM	Sent for servicing - not redeployed.
45085	**H9**	Set	5/23/08	13:45	CK/EL	**Deployed instrument that had been deployed at H7 earlier in season.**
45085	H9	Pull	7/7/08	17:02	CK/FI/PG	
45085	H9	Set	7/7/08	18:45	CK/FI/PG	
45085	H9	Pull	7/18/08		CK/FI/JM	

Table A-14. TDG data download and file confirmation, 2008.

DATA DOWNLOAD AND FILE CONTENT CONFIRMATION

				Old	New			Data Content Verified					
MS5 Serial No.	Site ID	Date	Crew	Battery Voltage (v)		Logging? (Y/N)	Download Ok? (Y/N)	Data Start Date	Data Start Time	Data End Date	Data End Time	Data File Name	Comments
45070	H1	4/8/08	PG/CK/TM	10.8	12.5	Y	Y	3/20/08	10:00	4/8/08	2:00	20Mar08 45070 H1	
45070	H1	4/29/08	PG/CK/TM	10.5	12.8	Y	Y	4/8/08	5:00	4/29/08	8:30	7Apr08 45070 H1	
45070	H1	7/24/08	CK/FI	dead	12.6	N	Y	4/29/08	9:45	5/4/08	12:15	29Apr08 45070 H1	
45074	H2	4/8/08	PG/CK/TM	0.7	12.5	Y	Y	3/20/08	10:00	4/8/08	2:45	20Mar08 45074 H2	
45074	H2	4/29/08	PG/CK/TM	10.9	12.5	Y	Y	4/8/08	4:00	4/29/08	11:45	7Apr08 45074 H2	
45074	H2	7/24/08	CK/FI	4.3	12.3	Y	Y	4/29/08	12:30	7/24/08	18:45	29APr08 45074 H2	
45073	H3	4/7/08	PG/CK/TM	10.7	12.5	Y	Y	3/20/08	10:00	4/8/08	3:00	20Mar08 45073 H3	
45073	H3	4/29/08	PG/CK/TM	10.9	12.7	Y	Y	4/8/08	4:00	4/29/08	11:00	7Apr08 45073 H3	
45073	H3	7/24/08	CK/FI	3.9	12.5	Y	Y	4/29/08	13:00	7/24/08	18:15	29Apr08 45073 H3	
45075	H4	4/8/08	PG/CK/TM	10.8	12.5	Y	Y	3/20/08	10:00	4/8/08	2:30	20Mar08 45075 H4	
45075	H4	4/29/08	PG/CK/TM	10.9		Y	Y	4/8/08	4:45	4/29/08	11:00	7Apr08 45075 H4	
45075	H4	7/24/08	CK/FI	dead	12.1	Y	Y	4/29/08	13:00	7/23/08	4:00	29Apr08 45075 H4	
45095	H5	4/8/08	PG/CK/TM	10.8	12.5	Y	Y	3/20/08	10:00	4/8/08	2:15	20Mar08 45095 H5	
45095	H5	4/29/08	PG/CK/TM	10.8	12.6	Y	Y	4/8/08	4:15	4/29/08	9:45	7Apr08 45095 H5	
45095	H5	7/24/08	CK/FI	dead	12.1	N	Y	4/29/08	11:00	7/23/08	7:45	29Apr08 45095 H5	
45084	H6	4/8/08	PG/CK/TM	10.6	12.5	Y	Y	3/20/08	10:00	4/8/08	1:30	20MAR08 45084 H6	
45084	H6	4/29/08	PG/CK/TM	11.1	12.6	Y	Y	4/8/08	4:45	4/29/08	11:45	7APR08 45084 H6	
45084	H6	7/24/08	CK/FI	DEAD	12.5	N	Y	4/29/08	12:45	7/10/08	12:30	29APR08 45084 H6	Downloaded twice - same start and end log dates & times.
45085	H7	4/8/08	PG/CK/TM	7.3	12.5	N	Y	3/20/08	10:00	3/23/08	13:30	20MAR08 45085	Not beeping - sudden power loss from 11.6 v.
45085	H7	4/29/08	PG/CK/TM	0.0	-	N	N	4/8/08	4:15	4/10/08	8:30		Not powered, stopped logging - all 0.87
45088	H8	4/21/08	CK/TM	10.2	12.6	Y	Y	3/24/08	11:45	4/21/08	13:15	21APR08 45088 H8	
45088	H8	5/20/08	CK/TM	12.5	10.6	Y	Y	4/21/08	14:30	5/20/08	14:45	21APR08 45088 H8	
45088	H8	6/12/08	PG/TM	10.7	12.6	Y	Y	5/20/08	16:00	6/12/08	11:15	20MAY08 45088	
45088	H8	7/24/08	CK/FI	10.3	N/A	Y	Y	6/12/08	12:15	7/18/08	13:00	12JUN08 45088 H8	
45076	H9	4/8/08	PG/CK/TM	7.2	12.5	N	Y	3/28/08	15:15	4/5/08	13:00	28MAR08 45076 H9	Stopped recording at 11.2 v for some reason.
45076	H9	4/29/08	PG/SW/TM	0.0	-	N	N	4/8/08	8:00	4/8/08	23:45		All new batteries, has internal short sent for repair
45085	H9	7/7/08	CK/FI/PG	10.2	12.7	Y	Y	5/23/08	13:45	7/7/08	17:15	H9 45085 23MAY08	Small amount of corrosion on pins - Rubber cap on tight.
45085	H9	7/24/08	CK/FI/PG	11.2	11.8	Y	Y	7/7/08	18:30	7/24/08	21:30	7JUL08 45085 H9	

Table A-15. TDG calibration service log, 2008.

CALIBRATION SERVICE LOG

MS5 Serial No.	Site ID	Crew	Calibration Date	Time	Old Silastic Membrane No.	Soda Max TDG (mmHg)	Old Membrane Patent (Y/N)	TDG In Air Uncorr. (mmHg)	TDG In Air new (mmHg)	TDG Correction (mmHg)	BP (portable)[1]	BP at USGS TR (FB) (mmHg)
45070	H1	PG/TM/CK	4/8/08	4:47	1	845	Y	718	718	0	718	716
45070	H1	PG/SW/TM	4/29/08	9:09	11	1031	Y	700	699	-1	699	707
45074	H2	PG/TM/CK	4/8/08	3:48	1	907	Y	719	718	-1	718	716
45074	H2	PG/SW/TM	4/29/08	12:13	14	871	Y	701	699	-2	699	707
45073	H3	PG/TM/CK	4/8/08	3:48	3?	913	Y	717	718	1	718	716
45073	H3	PG/SW/TM	4/29/08	12:40	1	821	Y	700	699	-1	699	707
45075	H4	PG/TM/CK	4/8/08	4:35	5	857	5	717	718	1	718	716
45075	H4	PG/SW/TM	4/29/08	12:40	19	870	Y	701	699	-2	699	707
45095	H5	PG/TM/CK	4/8/08	4:09	7	852	Y	717	718	1	718	716
45095	H5	PG/SW/TM	4/29/08	10:20	16	980	Y	700	699	-1	699	707
45084	H6	PG/TM/CK	4/8/08	4:40	10	896	Y	718	718	0	718	716
45084	H6	PG/SW/TM	4/29/08	12:28	8	863	Y	700	699	-1	699	707
45085	H7	PG/TM/CK	4/8/08	4:09	unknown	872	Y	717	718	1	718	716
45085	H7	PG/SW/TM	4/29/08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
45088	H8	TM/CK	4/21/08	13:49	unknown	1151	Y	714	714	0	n/a	717
45088	H8	CK/TM	5/20/08	15:26	?	n/a	Y	708	714	6	n/a	708
45088	H8	PG/TM	6/12/08	11:44	19	718 - 725	Y	714	714	0	n/a	718
45076	H9	PG/TM/CK	4/8/08	7:51	13	974	Y	709	710	1	710	708
45076	H9	PG/SW/TM	4/29/08	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
45085	H9	CK/FI/PG	7/7/08	18:06	14	1014	Y	709	709	0	709	709

		Patency Check New Membrane			Temperature Calibration			
MS5 Serial No.	Site ID	New Membrane No.	Soda Max TDG (mmHg)	New Membrane Patent (Y/N)	Sonde Temp in Water Bath (°C)	Cal Thermo (°C)	Depth Reading at Ambient (m)	Comments
45070	H1	11	937	Y	-	-	1.04	
45070	H1	2	1024	Y	n/a	n/a	0.87	ok
45074	H2	14	955	Y	-	-	1.07	
45074	H2	27	975	Y	-	-	0.88	ok
45073	H3	17	971	Y	n/a	n/a	0.94	
45073	H3	5	886	Y	n/a	n/a	0.85	ok
45075	H4	19	857	Y	-	-	1.14	
45075	H4	10	877	Y	n/a	n/a	0.92	ok
45095	H5	16	994	Y	-	-	1.07	
45095	H5	31	889	Y	n/a	n/a	0.87	ok
45084	H6	18	915	Y	-	-	1.16	#15 did not pressurize > 744 mmHg.
45084	H6	18	908	Y	n/a	n/a	0.94	ok
45085	H7	12	975	Y	-	-	1.10	Painted numbers wearing off membrane likely due to soda.
45085	H7	n/a	n/a	n/a	n/a	n/a	n/a	Sent for service.
45088	H8	12?	1038	Y	n/a	-	1.20	No # on new membrane, bottle & lid #12. Put old membrane in #12 bottle.
45088	H8	19	N/A	Y	-	-	1.08	Battery = 10.4 v; replaced (12.4 v) and then TDG of 708 mm in air taken.
45088	H8	10	780 - 782	Y	-	-	1.22	Batteries exchanged; BP/tdg in air 714 mmHg with new batteries.
45076	H9	unknown	924	Y	-	-	1.06	New
45076	H9	n/a	n/a	n/a	n/a	n/a	n/a	Sent for service
45085	H9	unknown	923	Y	-	-	-	

Table A-16. Re-Initialization and TDG log confirmation, 2008.

RE-INITIALIZATION AND LOG CONFIRMATION

MS5 Serial No.	Site ID	Crew	MS5 Date/Time	GPS or Computer Date/Time	Delay Log Start Date	Delay Log Start Time[1]	15 min Log Interval (Y/N)	2009 Log End Date (Y/N)	Log Start Confirmed	Comments
45070	H1	PG/CK/HS	3/19/08 21:53	3/19/08 21:53	3/20/08	10:00	Y	Y	Y	
45070	H1	PG/CK/TM	4/8/08 4:58	4/8/08 4:56	4/8/08	5:00	Y	Y	Y	
45070	H1	PG/SW/TM	4/29/08 9:19	4/29/08 9:19	4/29/08	9:30	Y	Y	Y	
45074	H2	PG/CK/HS	3/19/08 22:06	3/19/08 22:06	3/20/08	10:00	Y	Y	Y	
45074	H2	PG/CK/TM	4/8/08 3:48	4/8/08 3:46	4/8/08	4:00	Y	Y	Y	
45074	H2	PG/SW/TM	4/29/08 12:20	4/29/08 12:19	4/29/08	12:30	Y	Y	Y	
45073	H3	PG/CK/HS	3/19/08 21:36	3/19/08 21:36	3/20/08	10:00	Y	Y	Y	
45073	H3	PG/CK/TM	4/8/08 3:48	4/8/08 3:46	4/8/08	4:00	Y	Y	Y	
45073	H3	PG/SW/TM	4/29/08 12:37	4/29/08 12:38	4/29/08	13:00	Y	Y	Y	
45075	H4	PG/CK/HS	3/19/08 21:59	3/19/08 21:59	3/20/08	10:00	Y	Y	Y	
45075	H4	PG/CK/TM	4/8/08 4:35	4/8/08 4:37	4/8/08	4:45	Y	Y	Y	
45075	H4	PG/SW/TM	4/29/08 12:39	4/29/08 12:38	4/29/08	13:00	Y	Y	Y	
45095	H5	PG/CK/HS	3/19/08 21:17	3/19/08 21:17	3/20/08	10:00	Y	Y	Y	
45095	H5	PG/CK/TM	4/8/08 4:09	4/8/08 4:07	4/8/08	4:15	Y	Y	Y	
45095	H5	PG/SW/TM	4/29/08 10:16	4/29/08 10:15	4/29/08	9:45	Y	Y	Y	
45084	H6	PG/CK/HS	3/19/08 8:22	3/19/08 8:22	3/20/08	10:00	Y	Y	Y	
45084	H6	PG/CK/TM	4/8/08 4:40	4/8/08 4:42	4/8/08	4:45	Y	Y	Y	
45084	H6	PG/SW/TM	4/29/08 12:27	4/29/08 12:26	4/29/08	12:45	Y	Y	Y	
45085	H7	PG/CK/HS	3/19/08 22:15	3/19/08 22:15	3/20/08	10:00	Y	Y	Y	
45085	H7	PG/CK/TM	4/8/08 4:09	4/8/08 4:07	4/8/08	4:15	Y	Y	Y	
45085	H7	PG/SW/TM	4/29/08 0:00							Sent for service
45088	H8	PG/CK/HS	3/24/08 11:22	3/24/08 11:23	3/24/08	11:45	Y	Y	Y	
45088	H8	TM/CK	4/21/08 14:28	4/21/08 14:28	4/21/08	14:30	Y	Y	Y	
45088	H8	CK/TM	5/20/08 15:50	5/20/08 15:52	5/20/08	15:45	Y	Y	Y	New donuts and bolt needed for top (using ziptie right now).
45088	H8	PG/TM	6/12/08 12:03	6/12/08 12:03	6/12/08	12:15	Y	Y	Y	
45076	H9	PG/CK	3/28/08 14:58	3/28/08 14:58	3/28/08	14:15	Y	Y		MS5 went missing during shipping, which resulted in later deployment at H9 instead of H5.
45076	H9	PG/CK/TM	4/8/08 7:51	4/8/08 7:50	4/8/08	8:00	Y	Y	Y	
45076	H9	PG/SW/TM	4/29/08 0:00	N/A	N/A	N/A	N/A	N/A	N/A	Sent for service
45085	H9	CK/FI/PG	7/7/08 18:35	7/7/08 18:27	7/7/08	18:30	Y	Y	Y	Receiver set to PC/GPS time

[1] Start at 15-minute interval from top of hour (e.g., 15, 30, 45, or 60 minute positions)

Table A-17. Post-Monitoring dissolved gas two-point TDG calibration and membrane patency testing, July 25, 2008.

Location Field House in Ione, WA Crew CK/FI

MS5 Serial No.	Site ID	Calibration Date	Calibration Start Time	Calibration End Time	Internal Battery (v)	Pt in air uncorrected (mmHg)	BP (mmHg)[1]	TDG Correction (mmHg)	TDG in Air Corrected (mmHg)	TDG +200 mmHG (mmHg)[4]	Silastic Membrane No.	Soda Max TDG (mmHg)	Membrane Patent	Sonde Temp in Water Bath (°C)	Cal Thermometer (°C)	Depth in Air at Water Level (m)
045070	H1	7/25/08	9:00	12:30	12.0	708	707	0	708	912	2	800	Y	17.70	17.70	0.99
045074	H2	7/25/08	9:00	12:30	11.7	708	707	0	708	906	27	803	Y	17.70	17.70	0.99
045073	H3	7/25/08	9:00	12:30	11.8	707	707	0	707	908	5	771	Y	18.72	18.68	0.93
045075	H4	7/25/08	9:00	12:30	11.7	707	707	0	707	908	10	778	Y	18.72	18.68	1.02
045095	H5	7/25/08	9:00	12:30	11.8	707	707	0	707	907	31	770	Y	19.13	19.10	0.98
045084	H6	7/25/08	9:00	12:30	11.7	709	707	0	709	908	unknown	773	Y	19.12	19.10	1.06
045085	H9	7/25/08	9:00	12:30	11.8	706	707	0	706	903	unknown	776	Y	20.15	20.08	1.05
045088	H8	7/25/08	9:00	12:30	10.4	703	707	0	703	904	unknown	775	Y	20.10	20.08	1.07
045076	H7	7/25/08	MS5 not operable													
	DS4a	7/25/08	9:00	12:30	11.8	706	706	0	706	904		n/a	n/a	17.70	17.70	0.96

[1] H1-H7 TDG (in air) was compared to concurrent H8 TDG (in air).
[2] H9 TDG (in air) was compared to concurrent H3 TDG (in air).
[3] DS4a TDG (in air) was compared to concurrent H9 TDG (in air).
[4] Two-point test conducted after 1-point calibration. Pressure gauge used was a 300 mmHg sphygmomanometer (Ascroft) accuracy approx. +/- 0.5 mmHg.

Appendix 6: Figures of TDG Abatement Alternatives

[Note: Appendix 6 contains a series of project facility drawings. Per guidance from the Federal Energy Regulatory Commission, project facility drawings contain Critical Energy Infrastructure Information (CEII) and have therefore, been omitted from general distribution in the Updated Study Report (USR). This information has been filed with FERC with a CEII designation in Volume 6 of the USR submittal. Procedures for obtaining access to CEII may be found at 18 CFR § 388.113. Requests for access to CEII should be made to the Commission's CEII coordinator.]

Appendix 7: Engineer's Cost Opinion Tables

Table A.7-1. Sluice Gate Throttle (Option 1-3) One Gate.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$300,000.00	$300,000.00
Stainless Steel Plate				
Supply	6,500	lb	$5.00	$32,500.00
Install	900	Hrs	$100.00	$90,000.00
Anchors				
S.S. Bolts/Nuts	350	pcs	$1.10	$385.00
Cement Grout - Deflectors				
Supply and Install	1	L.S.	$10,000.00	$10,000.00
Concrete Anchors - Deflectors				
Anchors	1	L.S.	$20,000.00	$20,000.00
Steel Plate - Deflectors				
Supply and Install	5,000	lb	$30.00	$150,000.00
		Total Construction Costs		$452,885.00
Contingencies	150%	High	$1,507,212.50	
	50%	Low	$904,327.50	
	100%	Comparison	$1,205,770.00	$602,885.00
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$90,865.50
		Comparison Number Total		$1,296,635.50

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-2. Roughen Sluice Flow (Option 3-2) One Unit.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$350,000.00	$350,000.00
Steel Plate				
Supply and Install	141,600	lb	$10.00	$1,416,000.00
Concrete Anchors				
Dywidag Assemblies	4,000	ft	$60.00	$240,000.00
			Total Construction Costs	$1,806,000.00
Contingencies	150%	High	$5,015,000.00	
	50%	Low	$3,009,000.00	
	100%	Comparison	$4,012,000.00	$2,006,000.00
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$496,800.00
			Comparison Number Total	$4,508,800.00

Note:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-3. Spillway Modifications (Option 2-8) Air Induction Piping.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$200,000.00	$200,000.00
Demolition				
Slab Cut/Remove	1	L.S.	$50,000.00	$50,000.00
Walls Cut/Remove	1	L.S.	$15,000.00	$15,000.00
Concrete				
Hydraulic Jump	40	cubic yd	$1,000.00	$40,000.00
Reinforcing Steel				
Hydraulic Jump	6,068	lb	$1.74	$10,558.32
Common Excavation				
O/S spillway walls	170	cubic yd	$50.00	$8,500.00
Piping supply/Install	1	L.S.	$100,000.00	$100,000.00
Miscellaneous Metals				
Misc fastening Plates	750	lb	$9.00	$6,750.00
		Total Construction Costs		$430,808.32
Contingencies	150%	High	$1,077,020.80	
	50%	Low	$646,212.48	
	100%	Comparison	$861,616.64	$430,808.32
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$69,242.50
		Comparison Number Total		$930,859.14

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-4. Spillway Modifications (Option 2-8) Increase Turbulence of Spillway Gate.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$200,000.00	$200,000.00
Structural Steel				
Steel Roughening Elements	11,960	lbs	$9.00	$107,640.00
Installation	11,960	lbs	$5.00	$59,800.00
Structural Modifications	1	L.S.	$100,000.00	$100,000.00
Miscellaneous Metals				
Fasteners	1500	lb	$30.00	$45,000.00
		Total Construction Costs		$512,440.00
Contingencies	150%	High	$1,281,100.00	
	50%	Low	$768,660.00	
	100%	Comparison	$1,024,880.00	$512,440.00
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$93,732.00
		Comparison Number Total		$1,118,612.00

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-5. Spillway Modifications (Option 2-8) Deflector.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$200,000.00	$200,000.00
Cut Remove Slab Sections	1	L.S	$100,000.00	$100,000.00
Concrete				
Deflectors	65	cubic yd	$1,000.00	$65,000.00
Reinforcing Steel	10,813	lb	$1.74	$18,814.62
Anchor Bolts				
Rock Anchors to Substrate	360	lin. foot	$50.00	$18,000.00
		Total Construction Costs		$401,814.62
Contingencies	150%	High	$1,004,536.55	
	50%	Low	$602,721.93	
	100%	Comparison	$803,629.24	$401,814.62
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$60,544.39
		Comparison Number Total		$864,173.63

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-6. Right Abutment Tunnel (Option 4-7) 53,000 cfs.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$1,500,000.00	$1,500,000.00
Clearing	1	acre	$10,000.00	$10,000.00
Common Excavation				
Inlet	1,700	cubic yd	$25.00	$42,500.00
Outlet	62,500	cubic yd	$50.00	$3,125,000.00
Rock Excavation				
Inlet	15,000	cubic yd	$125.00	$1,875,000.00
Tunnel Horizontal	47,000	cubic yd	$135.00	$6,345,000.00
Tunnel Vertical	11,700	cubic yd	$175.00	$2,047,500.00
Expansion Chamber	15,200	cubic yd	$125.00	$1,900,000.00
Access Tunnel	900	cubic yd	$135.00	$121,500.00
Regulating Gate Chamber	1,000	cubic yd	$175.00	$175,000.00
Rock Anchors	115,100	lin. foot	$50.00	$5,755,000.00
Concrete				$0.00
Inlet Structure	6,300	cubic yd	$900.00	$5,670,000.00
Regulating Gate Chamber	6,200	cubic yd	$1,000.00	$6,200,000.00
Tunnel Liner	11,500	cubic yd	$1,000.00	$11,500,000.00
Expansion Chamber (silica fume)	2,400	cubic yd	$2,500.00	$6,000,000.00
Shotcrete				
Inlet	70	cubic yd	$278.00	$19,460.00
Outlet	90	cubic yd	$278.00	$25,020.00
Regulating Gate Chamber	5	cubic yd	$278.00	$1,390.00
Outlet	15	cubic yd	$278.00	$4,170.00
Reinforcing Steel				
Inlet Structure	955,710	lb	$1.74	$1,662,935.40
Tunnel Liner	2,944,572	lb	$1.74	$5,123,555.28
Expansion Chamber	399,264	lb	$1.74	$694,719.36
Grouting				
Outlet	1	L.S	$300,000.00	$300,000.00
Gates				
Intake Fixed Wheel	189,276	lb	$15.00	$2,839,140.00
Regulating	219,482	lb	$15.00	$3,292,230.00
Electrical Supply				
Temporary	1	L.S.	$80,000.00	$80,000.00
Permanent	1	L.S.	$40,000.00	$40,000.00

Table A.7-6, continued…

Description	Quantity	Unit	Unit Cost	Total
Ventilation Systems				
Temporary	1	L.S.	$100,000.00	$100,000.00
Access/Reg Chamber (perm)	1	L.S.	$60,000.00	$60,000.00
		Total Construction Costs		$66,449,120.04
Contingencies	150%	High	$166,122,800.10	
	50%	Low	$99,673,680.06	
	100%	Comparison	$132,898,240.08	$66,449,120.04
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$19,484,736.01
		Comparison Number Total		$152,382,976.09

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-7. Right Abutment Tunnel (Option 4-7) Unregulated 26,500 cfs.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$1,500,000.00	$1,500,000.00
Clearing	1	acre	$10,000.00	$10,000.00
Common Excavation				
Inlet	1,700	cubic yd	$25.00	$42,500.00
Outlet	46,700	cubic yd	$50.00	$2,335,000.00
Rock Excavation				
Inlet	15,000	cubic yd	$125.00	$1,875,000.00
Tunnel Horizontal	24,500	cubic yd	$135.00	$3,307,500.00
Tunnel Vertical	6,200	cubic yd	$175.00	$1,085,000.00
Expansion Chamber	6,000	cubic yd	$125.00	$750,000.00
Rock Anchors	66,600	lin. foot	$50.00	$3,330,000.00
Concrete				
Inlet Structure	6,300	cubic yd	$900.00	$5,670,000.00
Tunnel Liner	9,200	cubic yd	$1,000.00	$9,200,000.00
Expansion Chamber (silica fume)	1,630	cubic yd	$2,500.00	$4,075,000.00
Shotcrete				
Inlet	70	cubic yd	$278.00	$19,460.00
Outlet	15	cubic yd	$278.00	$4,170.00
Reinforcing Steel				
Inlet Structure	955,710	lb	$1.74	$1,662,935.40
Tunnel Liner	1,530,512	lb	$1.74	$2,663,090.88
Expansion Chamber	271,167	lb	$1.74	$471,830.58
Grouting				
Outlet	1	L.S	$300,000.00	$300,000.00
Gates				
Intake Fixed Wheel	222,877	lb	$15.00	$3,343,155.00
Electrical Supply				
Temporary	1	L.S.	$80,000.00	$80,000.00
Permanent	1	L.S.	$40,000.00	$40,000.00
Ventilation Systems				
Temporary	1	L.S.	$100,000.00	$100,000.00
		Total Construction Costs		$41,864,641.86
Contingencies	150%	High	$104,661,604.65	
	50%	Low	$62,796,962.79	
	100%	Comparison	$83,729,283.72	$41,864,641.86

Table A.7-7, continued…

Description	Quantity	Unit	Unit Cost	Total
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$12,109,392.56
		Comparison Number Total		$95,838,676.28

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-8. Left Abutment Tunnel (Option 4-8A).

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$1,500,000.00	$1,500,000.00
Construct Access				
Inlet	40,000	cubic yd	$100.00	$4,000,000.00
Steel Cofferdam-Sinking	673,000	lbs	$9.00	$6,057,000.00
Excavation to Bedrock	52,000	cubic yd	$50.00	$2,600,000.00
Dewatering	1	L.S.	$200,000.00	$200,000.00
Demolition				
Existing Tunnel Plugs	1	L.S	$125,000.00	$125,000.00
Rock Excavation				
Tunnel Vertical	13,500	cubic yd	$175.00	$2,362,500.00
Expansion Chamber	4,282	cubic yd	$125.00	$535,250.00
Access Tunnel	300	cubic yd	$125.00	$37,500.00
Regulating Gate Chamber	1,000	cubic yd	$175.00	$175,000.00
Rock Anchors	94,500	lin.. foot	$50.00	$4,725,000.00
Concrete				
Vertical Tunnel Liner	2,500	cubic yd	$1,000.00	$2,500,000.00
Regulating Gate	5,500	cubic yd	$1,000.00	$5,500,000.00
Horizontal Tunnel Liner	1,360	cubic yd	$1,000.00	$1,360,000.00
Expansion Chamber (silica fume)	2,450	cubic yd	$2,500.00	$6,125,000.00
New Tunnel Plug	7,697	cubic yd	$800.00	$6,157,600.00
Steel liner	908,453	lbs	$9.00	$8,176,077.00
Shotcrete				
Access Tunnel	29	cubic yd	$278.00	$8,062.00
Regulating Gate Chamber	5	cubic yd	$278.00	$1,390.00
Reinforcing Steel				
Tunnel Liner	1,557,130	lb	$1.74	$2,709,406.20
Regulating Gate	834,350	lb	$1.74	$1,451,769.00
Expansion Chamber	407,582	lb	$1.74	$709,192.68
Grouting				
Inlet	1	L.S	$200,000.00	$200,000.00
Gates				
Intake Floating	1	L.S.	$250,000.00	$250,000.00
Regulating	201,300	lb	$15.00	$3,019,500.00
Outlet Floating	1	L.S.	$250,000.00	$250,000.00

Table A.7-8, continued…

Description	Quantity	Unit	Unit Cost	Total
Electrical Supply				
Temporary	1	L.S.	$80,000.00	$80,000.00
Permanent	1	L.S.	$40,000.00	$40,000.00
Ventilation Systems				
Temporary	1	L.S.	$100,000.00	$100,000.00
Access/Reg Chamber (perm)	1	L.S.	$60,000.00	$60,000.00
		Total Construction Costs		$61,015,246.88
Contingencies	150%	High	$152,538,117.20	
	50%	Low	$91,522,870.32	
	100%	Comparison	$122,030,493.76	$61,015,246.88
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$17,854,574.06
		Comparison Number Total		$139,885,067.82

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-9. Penstock Draft Tube Bypass (Option 4-9) Steel Liner.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$2,000,000.00	$2,000,000.00
Rock Excavation				
Bypass Tunnel	1,100	cubic yd	$175.00	$192,500.00
Access Tunnel	150	cubic yd	$175.00	$26,250.00
Regulating Gate Chamber	300	cubic yd	$175.00	$52,500.00
Forebay Work				
Rock Excavation	2,000	cubic yd	$125.00	$250,000.00
Trashrack Upgrade	1	L.S.	$10,000,000.00	$10,000,000.00
Rock Anchors	22,030	lin. foot	$50.00	$1,101,500.00
Concrete				
Tunnel Liner Grout/Conc	310	cubic yd	$1,000.00	$310,000.00
Gate Structure	50	cubic yd	$1,000.00	$50,000.00
Steel Liner	155,000	lb	$9.00	$1,395,000.00
Shotcrete				
Access Tunnel	15	cubic yd	$278.00	$4,170.00
Regulating Gate Chamber	23	cubic yd	$278.00	$6,394.00
Reinforcing Steel				
Regulating Gate	8,318	lb	$1.74	$14,473.32
Grouting				
Outlet	1	L.S	$120,000.00	$120,000.00
Gate				
Regulating	64,959	lb	$15.00	$974,385.00
Electrical Supply				
Temporary	1	L.S.	$25,000.00	$25,000.00
Perminant	1	L.S.	$25,000.00	$25,000.00
Ventilation Systems				
Temporary	1	L.S.	$80,000.00	$80,000.00
Reg Gate Chamber (perm)	1	L.S.	$60,000.00	$60,000.00
Lost Generation				
Assumed lost generation during spill season	1	L.S.	$10,000,000.00	$10,000,000.00
		Total Construction Costs		$26,687,172.32
Contingencies	150%	High	$66,717,930.80	
	50%	Low	$40,030,758.48	
	100%	Comparison	$53,374,344.64	$26,687,172.32

Table A.7-9, continued…

Description	Quantity	Unit	Unit Cost	Total
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$7,406,151.70
		Comparison Number Total		$60,780,496.34

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-10. Left Abutment Tunnel (Option 4-10) Concrete Liner.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$1,500,000.00	$1,500,000.00
Clearing	1	acre	$10,000.00	$10,000.00
Forebay Work				
Rock Excavation	2,000	cubic yd	$125.00	$250,000.00
Trashrack Upgrade	1	L.S.	$10,000,000.00	$10,000,000.00
Common Excavation				
Inlet	1,900	cubic yd	$25.00	$47,500.00
Outlet	62,300	cubic yd	$50.00	$3,115,000.00
Rock Excavation				
Inlet	18,600	cubic yd	$125.00	$2,325,000.00
Tunnel Horizontal	43,000	cubic yd	$135.00	$5,805,000.00
Tunnel Vertical	11,700	cubic yd	$175.00	$2,047,500.00
Expansion Chamber	14,500	cubic yd	$135.00	$1,957,500.00
Regulating Gate Chamber	1,000	cubic yd	$175.00	$175,000.00
Rock Anchors	210,800	lin. foot	$50.00	$10,540,000.00
Concrete				
Inlet Structure	6,300	cubic yd	$900.00	$5,670,000.00
Regulating Gate Chamber	4,600	cubic yd	$1,000.00	$4,600,000.00
Tunnel Liner	10,700	cubic yd	$1,000.00	$10,700,000.00
Expansion Chamber (silica fume)	2,400	cubic yd	$2,500.00	$6,000,000.00
Shotcrete				
Inlet	70	cubic yd	$278.00	$19,460.00
Access Tunnel	0	cubic yd	$278.00	$0.00
Regulating Gate Chamber	5	cubic yd	$278.00	$1,390.00
Outlet	15	cubic yd	$278.00	$4,170.00
Reinforcing Steel				
Inlet Structure	955,710	lb	$1.74	$1,662,935.40
Tunnel Liner	2,545,308	lb	$1.74	$4,428,835.92
Expansion Chamber	399,264	lb	$1.74	$694,719.36
Grouting				
Outlet	1	L.S	$350,000.00	$350,000.00
Gates				
Intake bulkhead	184,609	lb	$15.00	$2,769,135.00
Regulating	219,482	lb	$15.00	$3,292,230.00

Table A.7-10, continued…

Description	Quantity	Unit	Unit Cost	Total
Electrical Supply				
Temporary	1	L.S.	$80,000.00	$80,000.00
Permanent	1	L.S.	$40,000.00	$40,000.00
Ventilation Systems				
Temporary	1	L.S.	$100,000.00	$100,000.00
Access/Reg Chamber (perm)	1	L.S.	$60,000.00	$60,000.00
		Total Construction Costs		$78,245,375.68
Contingencies	150%	High	$195,613,439.20	
	50%	Low	$117,368,063.52	
	100%	Comparison	$156,490,751.36	$78,245,375.68
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$23,023,612.70
		Comparison Number Total		$179,514,364.06

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

Table A.7-11. Left Abutment Tunnel (Option 4-10) Steel Liner.

Description	Quantity	Unit	Unit Cost	Total
Mobilization Demobilization	1	L.S.	$1,500,000.00	$1,500,000.00
Clearing	1	acre	$10,000.00	$10,000.00
Forebay Work				
Rock Excavation	2,000	cubic yd	$125.00	$250,000.00
Trashrack Upgrade	1	L.S.	$10,000,000.00	$10,000,000.00
Common Excavation				
Inlet	1,900	cubic yd	$25.00	$47,500.00
Outlet	62,300	cubic yd	$50.00	$3,115,000.00
Rock Excavation				
Inlet	18,600	cubic yd	$125.00	$2,325,000.00
Tunnel Horizontal	38,800	cubic yd	$135.00	$5,238,000.00
Tunnel Vertical	10,500	cubic yd	$175.00	$1,837,500.00
Expansion Chamber	14,500	cubic yd	$125.00	$1,812,500.00
Regulating Gate Chamber	1,000	cubic yd	$175.00	$175,000.00
Rock Anchors	210,800	Lin foot	$50.00	$10,540,000.00
Concrete				
Inlet Structure	6,300	cubic yd	$900.00	$5,670,000.00
Regulating Gate Chamber	4,600	cubic yd	$1,000.00	$4,600,000.00
Tunnel Liner Grout/Conc	5,200	cubic yd	$1,000.00	$5,200,000.00
Expansion Chamber (silica fume)	1,200	cubic yd	$2,500.00	$3,000,000.00
Steel Liner	2,084,400	lb	$9.00	$18,759,600.00
Shotcrete				
Inlet	70	cubic yd	$278.00	$19,460.00
Regulating Gate Chamber	5	cubic yd	$278.00	$1,390.00
Outlet	15	cubic yd	$278.00	$4,170.00
Reinforcing Steel				
Inlet Structure	955,710	lb	$1.74	$1,662,935.40
Tunnel Liner	1,630,328	lb	$1.74	$2,836,770.72
Expansion Chamber	199,632	lb	$1.74	$347,359.68
Grouting				
Outlet	1	L.S	$350,000.00	$350,000.00
Gates				
Intake bulkhead	184,609	lb	$15.00	$2,769,135.00
Regulating	219,482	lb	$15.00	$3,292,230.00

Table A.7-11, continued…

Description	Quantity	Unit	Unit Cost	Total
Electrical Supply				
Temporary	1	L.S.	$80,000.00	$80,000.00
Permanent	1	L.S.	$40,000.00	$40,000.00
Ventilation Systems				
Temporary	1	L.S.	$100,000.00	$100,000.00
Access/Reg Chamber (perm)	1	L.S.	$60,000.00	$60,000.00
		Total Construction Costs		$85,643,550.80
Contingencies	150%	High	$214,108,877.00	
	50%	Low	$128,465,326.20	
	100%	Comparison	$171,287,101.60	$85,643,550.80
Engineering & Management				
Engineering & Owners Costs	30%	Percentage		$25,243,065.24
		Comparison Number Total		$196,530,166.84

Notes:
Estimate used for alternative comparison only and basis for estimate is concept level without engineering design. The location for this work is remote and access conditions challenging for all projects. Actual construction costs may vary widely from these comparative costs.
L.S. – lump sum

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Appendix 8: Evaluation Matrix

Table A.8-1. TDG mitigation alternatives evaluation matrix.

			Criterion/Confidence Factor													
				TDG Performance			Technical Feasibility									
Alternative	**Description**	**Flow Capacity (cfs)**	**Biological Performance - Risk of Injury**	**Flow Capacity**	**Compatibility**	**Projected TDG Performance**	**Permitting**	**Schedule**	**Constructability**	**Dam Safety**	**Design and Construction Cost**	**Maintenance and Access**	**Impact on Operations**	**Ability to Prototype Test**	**Ability to Adjust on Basis of Performance**	**Weighted Total Criteria Score/Total Confidence Factor Score**
			Weighting Factor													
			4	**8**	**6**	**19**	**4**	**4**	**8**	**15**	**10**	**4**	**6**	**6**	**6**	
1-3	Throttle Sluice Gates (modify with seals for 4 ft opening)	12,000 to 18,000	4	2	5	4	5	5	5	5	4.86	3	5	5	5	444
			3	3	3	1	3	3	3	3	3	2	1	3	3	37
3-2	Throttle and Roughen Sluice Gate Discharge/Extend Lip	16,000 to 20,000	4	2	5	4	4	4	5	5	4.48	3	5	5	5	432
			3	2	3	1	3	3	3	3	3	2	1	3	3	36
2-8 (New)	Spillway Flow Splitter/Aerators	20,000 to 30,000	3	3	5	4	5	5	5	5	4.90	5	5	3	5	444
			2	2	3	1	3	3	3	3	3	3	3	3	3	38
4-7	New Right Abutment Tunnel with Submerged Discharge	26,500 to 53,000	3	4	5	3	1	1	2	3	0.76	3	5	0	1	256
			2	2	3	1	2	3	3	2	3	2	3	3	3	35
4-8A	New Left Abutment Tunnel Intercepts Diversion Tunnel	26,500 to 53,000	3	4	5	3	1	2	3	1	1.10	1	3	0	1	221
			2	2	3	1	2	3	2	3	3	3	3	3	3	36
4-9	Penstock/Draft Tube By-Pass	10,000 to 20,000	1	2	5	4	4	3	4	5	1.61	2	2	3	1	321
			3	1	3	1	3	2	3	3	2	2	1	3	2	32
4-10	New Short Left Abutment Tunnel Next to Unit # 51	26,500 to 53,000	3	4	5	1	1	2	2	1	0.00	3	1	0	1	160
			2	1	3	1	2	3	3	3	3	2	1	3	3	33

Appendix 9: Physical Model Drawings

[Note: Appendix 9 contains a series of drawings of the physical model of the project facility. Per guidance from the Federal Energy Regulatory Commission, project facility drawings contain Critical Energy Infrastructure Information (CEII) and have therefore, been omitted from general distribution in the Updated Study Report (USR). This information has been filed with FERC with a CEII designation in Volume 6 of the USR submittal. Procedures for obtaining access to CEII may be found at 18 CFR § 388.113. Requests for access to CEII should be made to the Commission's CEII coordinator.]