Lê, B. 2008. Total Dissolved Gas Abatement Plan. Wells Hydroelectric Project. Prepared by Public Utility District No. 1of Douglas County, East Wenatchee, WA. Prepared for Washington Department of Ecology, Yakima, WA, 98902-3452.

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2008 TOTAL DISSOLVED GAS ABATEMENT PLAN

WELLS HYDROELECTRIC PROJECT

February 2008

Prepared by:

Bao Le, Senior Aquatic Resource Biologist
Public Utility District No. 1 of Douglas County
East Wenatchee, WA 98802

Prepared for:

Washington Department of Ecology
Yakima, Washington 98902-3452

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1.0 INTRODUCTION

1.1 Total Dissolved Gas

Dissolved gasses in water occur from exchange of gas within the atmosphere and through biological activity such as photosynthesis or respiration. Optimal water quality conditions of dissolved gas for fish are considered to be close to the barometric pressure seen at the air-water interface. Dissolved gas may become a water quality issue when gasses supersaturate a river, lake or stream. Plunging water may cause an increase in total dissolved gas (TDG) of a body of water as air bubbles become entrained, pushed to depth and forced into solution due to increased pressure. This phenomenon occurs naturally at waterfalls and artificially at dams. Spill which can also increase the TDG concentrations of a body of water occurs when river flows exceed the hydraulic capacity of a dam due to limited generation capacity, a lack of demand for power, and for fish passage.

Despite the potential for higher levels of TDG, hydroelectric dams on the Columbia and Snake rivers provide safe passage routes for migrating juvenile salmonids through spill. Many variables contribute to dissolved gas supersaturation, including existing forebay gas concentrations, project operations, spill flow rates, tailwater bathymetry, air entrainment, spill plunge depths, entrainment flows, and temperature of the water.

1.1.1 Total Dissolved Gas and Impacts to Aquatic Life

Impacts to aquatic life from extended exposure to high levels of TDG have long been a concern in the Columbia River basin. High levels of TDG have been shown to cause air embolisms in fish that result in impaired health or even death. Gas Bubble Trauma (GBT) is a condition that affects aquatic animals residing in waters that are supersaturated with atmospheric gases. It occurs when dissolved gases in the blood come out of solution and form bubbles in various external and internal tissues (EPA 1976). Gas bubble trauma is a physically induced condition, caused by a pressure dis-equilibrium between the liquid and gas phases (Jensen et al. 1986). In juvenile salmonids, bubbles along the lateral line are one of the first and most frequent external signs of gas bubble trauma (Dawley et al. 1975, Weitkamp and Katz 1980).

Mortality can result from both acute and chronic symptoms of GBT. Acute mortality usually results from blockage of blood flow in the heart, gills, and other capillary beds, due to accumulation of emboli in the blood (Bouck 1980). Chronic mortality is associated with extravascular bubbles that reduce respiratory water flow (Jensen et al. 1986). Sublethal effects of GBT such as blindness, stress, and decreased lateral line sensitivity can indirectly lead to death from predation or other causes (Weitkamp and Katz 1980).

1.1.2 Washington State Water Quality Standards

The Water Quality Standards Chapter 173-201A of the Washington Administrative Code address standards for the surface waters of Washington State. The codes have been revised recently for consistency with the needs of fish (designated use for aquatic life) that may be found in those waters.

Based upon criteria developed by the Washington Department of Ecology (WDOE), TDG measurements shall not exceed 110 percent at any point of measurement in any state water body. WDOE acknowledges that an operator of a dam is not held to the TDG standards when the river flow exceeds the seven-day, 10-year-frequency flood (7Q10). The 7Q10 flow is the highest value of a running seven consecutive day average using the daily average flows that may be seen in a 10-year period. The 7Q10 total river flow for the Wells Project was computed using the hydrologic record from 1974 through 1998 and a statistical analysis to develop the number from 1930 through 1998. The United States Geological Survey (USGS) Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" was followed. The resulting 7Q10 flow at Wells Dam is 246,000 cfs (Pickett et. al. 2004).

In addition to allowances for natural flood flows, the TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a WDOE approved gas abatement plan. WDOE has approved on a per application basis, an interim waiver to the TDG standard (110 percent) to allow spill for juvenile fish passage on the Columbia and Snake rivers (WAC 173-201A-200(1)(f)(ii)). Dams in the Columbia and Snake rivers may be allowed a TDG exemption to the 110 percent TDG standard to allow for passage of juvenile fish downstream over the dams rather than through the turbines.

On the Columbia and Snake rivers there are three separate standards with regard to the TDG exemption. First, in the tailrace of a dam, TDG shall not exceed 125 percent as measured in any one-hour period. Further, TDG shall not exceed 120 percent in the tailrace of a dam and shall not exceed 115 percent in the forebay of the next dam downstream as measured as an average of the 12 highest consecutive hourly readings in any one day (24-hour period). The increased levels of spill resulting in elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. This TDG exemption provided by WDOE is based on a risk analysis study conducted by the National Marine Fisheries Service (NMFS) (NMFS 2000).

2.0 GOAL AND OBJECTIVES

The goal of the Wells Total Dissolved Gas Abatement Plan (Gas Abatement Plan) is to implement a long-term strategy to maintain compliance with the Washington state water quality standard for TDG in the Columbia River at the Wells Hydroelectric Project (Wells Project) while continuing to provide safe passage for downstream migrating juvenile salmonids. The Public Utility District No. 1 of Douglas County (Douglas PUD) which owns and operates the Wells Project is submitting this Gas Abatement Plan to WDOE for approval as required for receipt of a TDG exemption at Wells Dam.

In the past, WDOE has approved Wells Project Gas Abatement Plans and issued a TDG exemption at Wells Dam. Douglas PUD submitted a Gas Abatement Plan that was approved on March 27, 2003 for one year (Appendix A and B). In 2004, an extension was granted by WDOE (Appendix C). On March 31, 2005, WDOE approved Douglas PUD's 2005 Gas Abatement Plan allowing a TDG exemption in support of fish passage through February 2008 (Appendix D).

This Gas Abatement Plan summarizes the Wells Project, associated facilities and water management (Section 3.0), discusses Wells Project spill scenarios and defines the measures associated with Douglas PUD's monitoring program during spill operations in support of juvenile fish passage (Section 4.0), and provides a summary of past TDG activities and a future schedule of Wells Project TDG compliance activities (Section 5.0).

3.0 WELLS HYDROELECTRIC PROJECT

3.1 Project Overview

Wells Dam which is owned and operated by Douglas PUD is located at river mile (RM) 515.6 on the Columbia River in Washington State, approximately 30 river miles downstream of Chief Joseph Dam, which is owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream of Rocky Reach Dam, which is owned and operated by the Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town to Wells Dam is Pateros, Washington, located approximately 8 miles upstream of Wells Dam.

The Wells Project is the chief generating resource for Douglas PUD. It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The spillway is comprised of eleven spill gates that are capable of spilling a total of 1,180 kcfs. The crest of the spillways is approximately five and a half feet above normal tailwater elevation and two feet below tailwater elevation when plant discharge is 219 kcfs. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. The Wells Project is considered a "run-of-the-river" project due to its relatively limited storage capacity.

Adult fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a crest elevation of 795 feet in height. Juvenile fish passage facilities are located across the powerhouse of the dam. The system was developed by Douglas PUD and uses a barrier system to modify the intake velocities on all even numbered spillways (2, 4, 6, 8 and 10).

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The normal maximum surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre-feet at elevation of 781 feet MSL. At the Wells Project, the Columbia River forms the boundary between Douglas County and three other governmental jurisdictions: Okanogan County, Chelan County and the Colville Indian Reservation (Figure 3.1-1).

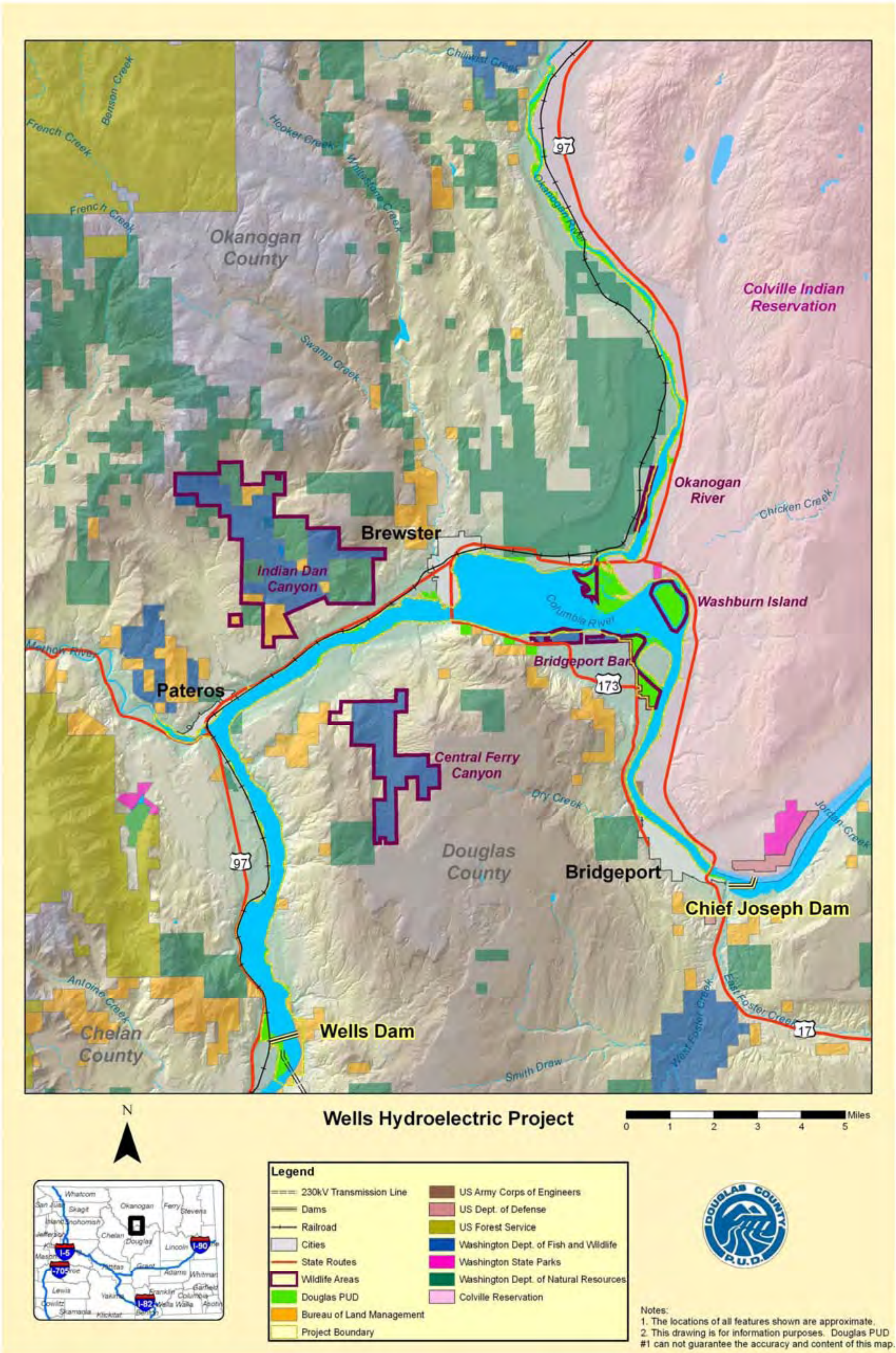

Figure 3.1-1 Map of the Wells Project area.

3.2 Runoff and Coordination

The Columbia Basin in eastern Oregon, Washington and British Columbia has climate that is best described as desert. Flow from the Columbia River originates in the headwaters of the Canadian Rockies and picks up snow melt from tributary streams such as the Methow, Wenatchee and Snake rivers as it travels over 1,243 miles before emptying into the Pacific Ocean. The natural hydrograph has low flows in November through January with high flows in May through July. Storage dams in the U.S. and Canada capture spring and summer high flows to hold for release in the winter months. There are 85,300 square miles of drainage area above Wells Dam. Table 3.2-1 presents information on Columbia River flow as measured at Wells Dam in 2007 and over the past 20 years.

Table 3.2-1 Columbia River Flows at Wells Dam (1978 – 2007) in kcfs.

	Monthly Average		**Monthly Minimum**	**Monthly Maximum**
	The Year 2007	From 1978 To 2007	From 1978 To 2007	From 1978 To 2007
MONTH				
January	114.5	112.7	75.7	159.2
February	85.3	111.8	69.9	180.7
March	120.3	106.6	56.0	193.9
April	154.7	113.4	51.9	177.4
May	159.2	141.2	55.2	251.9
June	152.0	149.7	84.5	300.3
July	133.0	122.0	53.4	182.8
August	113.1	101.9	63.9	152.1
September	60.0	75.4	57.2	106.0
October	64.4	77.6	56.0	108.9
November	80.1	90.6	70.9	110.0
December	86.8	105.7	75.1	149.0

In general, the hydropower system and reservoir operations in the Columbia River are coordinated through a set of complex agreements and policies to optimize the benefits and minimize the adverse effects of project operations. The Wells Project operates within the constraints of the Pacific Northwest Coordination Agreement, Canadian Treaty, Canadian Entitlement Agreement, Hourly Coordination Agreement, the Hanford Reach Fall Chinook Protection Program and the Federal Energy and Regulatory Commission (FERC) regulatory and license requirements.

Under the Hourly Coordination Agreement, power operations for the seven dams from Grand Coulee to Priest Rapids are coordinated to meet daily load requirements through the assignment of "coordinated generation" through Central Control at the Public Utility District No. 2 of Grant County (Grant PUD). Automatic control logic is used to maintain pre-set reservoir levels in order to meet load requirements and minimize involuntary spill. These pre-set reservoir levels are maintained at each project through management of a positive or negative "bias" which assigns a project more or less generation depending on whether the reservoir elevation should be increased or decreased in order to maximize system benefits and minimize involuntary spill.

4.0 HISTORY OF OPERATIONS AND COMPLIANCE

The passage and protection of migrating juvenile fish is provided at many dams with high levels of spill. This route is preferred for safe passage and research indicates that survival of migrating juvenile salmonids is greatly enhanced via spill passage routes (NMFS 2000). At Wells Dam, TDG monitoring during fish passage spill has occurred since 1998. A summary of the TDG monitoring at the Wells Project from 1998 – 2007 is shown in Table 4.0-1.

Table 4.0-1 Annual summaries of days with values greater than 110, 115, and 120 percent at the Wells Dam forebay, tailwater and the Rocky Reach forebay from 1998 to 2007 during the juvenile fish migration season (April-August).

YEAR	Wells FB	Wells TW	R Reach FB	Sampled
1998				
> 110%	42 days	72 days	45 days	153 days
> 115%	0 days	17 days	4 days	153 days
> 120%	0 days	4 days	0 days	153 days
1999				
> 110%	80 days	103 days	76 days	168 days
> 115%	0 days	21 days	2 days	168 days
> 120%	0 days	2 days	0 days	168 days
2000				
> 110%	60 days	99 days	27 days	168 days
> 115%	0 days	5 days	1 day	168 days
> 120%	0 days	1 day	0 days	168 days
2001				
> 110%	26 days	41 days	37 days	168 days
> 115%	0 days	0 days	0 days	168 days
> 120%	0 days	0 days	0 days	168 days
2002				
> 110%	77 days	111 days	88 days	168 days
> 115%	38 days	66 days	37 days	168 days
> 120%	0 days	31 days	11 days	168 days
2003				
> 110%	55 days	76 days	62 days	168 days
> 115%	0 days	8 days	2 days	168 days
> 120%	0 days	1 day	0 days	168 days
2004				
> 110%	38 days	69 days	67 days	168 days
> 115%	0 days	0 days	0 days	168 days
> 120%	0 days	0 days	0 days	168 days
2005				
> 110%	20 days	69 days	66 days	168 days
> 115%	0 days	1 day	2 days	168 days
> 120%	0 days	0 days	0 days	168 days
2006				
> 110%	70 days	108 days	96 days	168 days
> 115%	22 days	59 days	42 days	168 days
> 120%	0 days	29 days	19 days	168 days
2007				
> 110%	48 days	116 days	66 days	168 days
> 115%	0 days	11 day	1 day	168 days
> 120%	0 days	2 days	0 days	168 days

4.1 Wells Dam Operational Spill Plan

Wells Dam is a hydrocombine-designed dam where the spillway is situated directly above the powerhouse. Research at Wells in the mid-1980's showed that a modest amount of spill would effectively guide a high percentage of the downstream migrating juvenile salmonids through the Juvenile Bypass System (JBS). The operation of the Wells JBS utilizes the five even numbered spillways. These spillways have been modified with constricting barriers to improve the attraction flow while using modest levels of water. These spillways are used effectively pass downstream migrating juvenile salmonids from April through August. Normal operation of the JBS uses 2.2 kcfs per spillway. During periods of extreme high flow, one or more of the JBS barriers may be removed to provide adequate spill capacity to respond to a plant load rejection.

Typically, the JBS will use approximately 6 – 8 percent of the total river flow for fish guidance. The operation of the JBS adds a negligible level of TDG (0 – 2 percent) while meeting a very high level of fish guidance and protection. This high level of fish protection at Wells Dam has met the approval of the fisheries agencies and tribes and was vital to the recently approved Habitat Conservation Plan with NOAA Fisheries. The Wells Project fish bypass system is the most efficient system on the mainstem Columbia River. The bypass system on average collects and safely passes 92.0 percent of the spring migrating salmonids (yearling Chinook, steelhead and sockeye) and 96.2 percent of the summer migrating subyearling Chinook (Skalski et al., 1996).

The odd numbered spillways are available for all other forms of spill. Outside the juvenile salmonid migration season, all 11 spillways are available for spill. The high flow months in the Columbia River are May through July which is consistent with the time period when the five even numbered spillways are used for juvenile fish passage. At the Wells Project, five spill conditions may exist depending upon factors associated with river flows, fish bypass, plant operations and status, and demand for power (discussed in more detail in Section 4.2). In past years, various operational approaches have been implemented to address any spill that may occur at Wells Dam. Initially, spill operations beyond JBS spill at Wells Dam followed more traditional strategies used at other mainstem hydroelectric projects. These strategies consisted of spreading spill across the length of the dam to dissipate the amount of energy available to entrain atmospheric gases which reduces the levels of TDG. It has not been until more recently (beginning with assessments in 2006) that information collected during TDG studies at Wells Dam have indicated that non-traditional types of spill operations (concentrated spill shapes) may be more effective at reducing TDG production and may be at times, more appropriate in addressing TDG production for hydrocombine structures. The results of past Wells Project TDG production dynamics studies are presented in Section 5.1.

4.2 Spill Condition and Occurrence

The five main scenarios for spill at the Wells Project include:

- Fish Bypass System operation
- Flow in excess of hydraulic capacity of the turbines
- Flow in excess of power system needs

- Gas Abatement Spill
- Other spill

4.2.1 Fish Bypass System Operation

At Wells Dam, the JBS utilizes five of the eleven spillways equipped with constricting barriers to help guide juvenile migrating fish. This serves as an effective fish bypass. This configuration has demonstrated exceptionally high levels of protection while using 6 – 8 percent of the total discharge of the Columbia River on average annually. This system has helped meet the juvenile fish survival standard for passage set by the Wells Dam Habitat Conservation Plan (HCP). Douglas PUD has conducted three years of juvenile project survival studies at the Wells Project. These studies have shown an average survival rate of 96.2% for yearling Chinook and steelhead (Bickford et al., 2001).

The JBS is utilized for protection of downstream migrating juvenile salmonids. Fish Bypass operations at Wells Dam falls into two seasons, Spring Bypass and Summer Bypass. For 21 years, the status of the fish migration for both spring and summer periods was monitored by an array of hydroacoustic sensors placed in the forebay of Wells Dam. Starting in 2003, the operation of the juvenile bypass for the Wells HCP was set with fixed dates that were established based on 21 years of Hydroacoustic and Fyke Net data. The dates for bypass operation are from April 12 through August 26. These dates bracket greater than 95% of both the spring and summer migrants. Annually, there have been as many as ten million juvenile salmonids that have migrated past Wells Dam.

Between the years 1997 – 2004, the volume of water dedicated to the JBS has ranged from 1.5 to 3.2 million acre-feet. Operation of the JBS adds a negligible level of dissolved gas (0 – 2 percent) to the river while meeting a very high level of fish guidance and protection. WDOE has authorized an exemption to the total dissolved gas standard for fish protection on the Columbia and Snake rivers. Operation of the Wells Project JBS does not produce TDG at levels that exceed the WDOE TDG exemption.

4.2.2 Flow in Excess of Hydraulic Capacity of the Turbines

The Wells Project is a “run-of-the river” project with a relatively small storage capacity. River flows in excess of the hydraulic capacity of the ten turbines must be passed over the spillways.

The forebay elevation at Wells Dam is set between 781.0 and 771.0 MSL. The Wells Project has a hydraulic generating capacity of 219 kcfs (ASL, 2007) and a spillway capacity of 1,180 kcfs. Data for Columbia River flows for eighty-five years at Priest Rapids yields a peak daily average discharge of 690,000 on June 12, 1948 (USGS web page for historical flows at Priest Rapids on the Columbia River. http://waterdata.usgs.gov/wa/nwis/discharge/?site_no=12472800). The hydraulic capacity of Wells Dam is well within the range of recent historical flow data.

4.2.3 Flow in Excess of Power System Needs

Spill may occur at flows less than the Wells Project hydraulic capacity (219 kcfs) when the volume of water is greater than the amount required to meet electric power system loads. This may occur during temperate weather conditions when power demand is low or when non-power constraints on river control results in water being moved through the mid-Columbia at a different time of day than the power is required. Hourly coordination (Section 3.2) between hydroelectric projects on the river was established to minimize this situation for spill.

4.2.4 Gas Abatement Spill

Gas Abatement Spill is used to manage TDG levels throughout the Columbia River Basin. The Technical Management Team (including NMFS, U.S. Army Corps of Engineers, and Bonneville Power Administration) implements and manages this spill. Gas Abatement Spill is requested from dam operators from a section of the river where gas levels are high. A trade of power generation for spill is made between operators, providing power generation in the river with high TDG and trading an equivalent amount of spill from a project where TDG was low. Historically, the Wells Project has accommodated requests to provide Gas Abatement Spill. This spill, if excessive, may have a detrimental affect on gas levels in the Wells Dam tailrace. Wells Dam is low on the priority of Gas Abatement Spill requests because of the long distance to the de-gassing stretch of the Hanford Reach. To control TDG levels that may result from Gas Abatement Spill, Douglas PUD has adopted a policy not to participate in Gas Abatement Spill at Wells Dam.

4.2.5 Other Spill

Other spill includes spill as a result of maintenance or plant load rejection. A load rejection occurs when the generating plant is forced off line by an electrical fault, which trips breakers and shuts off the generation. At a hydroelectric dam, water used to spin turbines is shut off. At a run-of-the-river dam, the river flow that was producing power now must be spilled.

These events are extremely rare, and would account for approximately 10 minutes in every ten years. Maintenance spill is utilized for any activity that requires spill to assess the routine operation of individual spillways and turbine units. These activities include checking gate operation, and all other maintenance that would require spill. The FERC requires that all spillway gates be operated once per year. To control TDG levels associated with maintenance spill, Douglas PUD limits, to the extent practical, maintenance spill during the spill season.

4.3 Compliance Activities in 2006-2007

4.3.1 2006 Wells Project TDG Production Dynamics Study

Douglas PUD has continued to implement TDG assessments at the Wells Project to determine the best spillway configurations and project operations to minimize the production of TDG. In 2006, Douglas PUD hired a team of hydraulic and TDG experts from the Pacific Northwest to help design a monitoring program for a study that would examine various operational scenarios and their respective TDG production dynamics.

Thirteen sensors were placed along three transects in the tailrace; at 1,000, 2,500 and 15,000 feet below Wells Dam. There were also three sensors placed across the forebay, one being the fixed monitoring station midway across the face of the dam and two more a distance of 300 feet from the dam. The sensors were programmed to collect data in 15 minute increments for both TDG and water temperature. Each test required the operations of the dam to maintain static flows through the powerhouse and spillway for at least a three hour period. While there were 30 scheduled spill events, there were an additional 50 events where the power house and spillway conditions were held constant for a minimum three hour period. These "incidental" events provided an opportunity to collect additional TDG data on a variety of Project operations that met study criteria and are included in the results of the 2006 TDG Abatement Study. Spill amounts ranged from 5.2 to 52% of project flow and volume of spill and total flows ranged from 2.2 to 124.7 kcfs for spill and 16.4 to 254.0 kcfs for total discharge. There were six tests that were done at flows that exceeded the Wells Dam 7Q10 flows of 246 kcfs.

Results of the study indicated that two operational scenarios, spread spill and concentrated spill, produced the lowest levels of TDG and recommended continued testing of operational measures to ameliorate TDG production at Wells Dam (EES et al. 2007). The 2006 study also indicated that the current location of the tailwater TDG compliance monitoring station is appropriate in providing representative TDG production information both longitudinally and laterally downstream of Wells Dam.

4.3.2 2007 Wells Project TDG Playbook

In 2007, a spill playbook was developed to be used by operators at Wells Dam. The intent of the spill playbook was to guide Project operators in the configuration of spill operations (specifically the implementation of spread spill and concentrated spill) in a manner that further evaluated the results of the 2006 TDG study and that examined the spill playbook operating scenarios over a broader range of environmental conditions. There were no scheduled spill tests in 2007 and operators were instructed to utilize the playbook only during forced spill events (when river flows exceeded flows needed to meet load). Specific objectives of the 2007 assessment included:

1. Evaluate TDG production for full gate (concentrated) spills over a range of operational conditions.

2. Evaluate TDG production for spread spills over a range of operational conditions.

3. Evaluate indirect effects, operational, and logistical concerns for full gate spill that might limit their application for TDG management.

4. Collect additional TDG data in order to refine the relationships of spill momentum and submergence depth as they affect TDG production.

At the end of May 2007, it was determined that the logistics of operating gates 2 and 10 which require manual adjustments, made implementation of spread spills impractical. Douglas PUD decided to emphasize a concentrated spill strategy for the remainder of the assessment.

River flows in spring 2007 were 108.7% of the 20-year average. The peak total river discharge at Wells Dam (based on 15-minute average data) was 271 kcfs. The maximum spill flow was

155 kcfs. There were few spill events in excess of the fish bypass spill after May. Most of the spill events were of short duration, which did not meet the required 3-hour time period that is necessary to establish equilibrium conditions at the downstream TDG monitoring station (WELW); i.e., 3 hours provides for travel time and data collection time at the downstream monitoring station that is representative of the operational conditions at Wells Dam. Conclusions of the 2007 assessment are as follows:

1. 2007 was an above average water year. During the 2007 fish passage season (April 1-September 15) Wells Dam was able to maintain compliance with the TDG standards 97% of the time.

2. Maintaining a spread spill pattern at Wells Dam, utilizing spill gates 2 and 10, was not logistically feasible for low and moderate ranges of spill. As a result, future low and moderate spill testing should focus on collecting TDG response values for spill focused through full gate spillway patterns.

3. Spill in 2007 was not of a sufficient duration to adequately test the performance of a full gate spill pattern to minimize TDG below Wells Dam.

4. Although spill events that were in excess of JBS spill and of a steady state of at least 3 hours in duration were rare (6 total), data collected on Wells spill operations during 2007 were consistent with analytical results for the 2006 TDG Study (EES et al. 2007).

5.0 PROPOSED OPERATIONS AND ACTIVITIES

5.1 TDG Monitoring Program

As required by issuance of a TDG exemption for the Wells Project, Douglas PUD will continue to implement a physical and biological monitoring program at Wells Dam during the juvenile fish migration season. Activities include fisheries management activities, participation in Columbia River basin water quality forums, collection of total dissolved gas and temperature data during the migration season, and when necessary, collection of biological monitoring data.

5.1.1 Fisheries Management Activities

Douglas PUD shall continue to operate Wells Dam adult fishways and the juvenile bypass system in accordance with HCP operations criteria to protect aquatic life designated uses. Furthermore, all fish collection (hatchery broodstock and/or evaluation activities) or assessment activities that occur at Wells Dam will require approval by Douglas PUD and the HCP Coordinating Committee to ensure that such activities protect aquatic life designated uses.

Douglas PUD shall continue to operate the Wells Project in a coordinated manner toward reducing forebay fluctuations and maintaining relatively stable reservoir conditions that are beneficial to multiple designated uses (aquatic life, recreation, and aesthetics). Furthermore, coordinated operations reduce spill, thus reducing the potential for exceedances of the TDG numeric criteria and impacts to aquatic life associated with TDG.

5.1.2 Water Quality Meetings

Douglas PUD is currently involved in the Water Quality Team and the Adaptive Management Team meetings that are held monthly in Portland, Oregon. The purpose of the Water Quality Team meetings is to address regional water quality issues. This forum allows regional coordination for monitoring, measuring, and evaluating water quality in the Columbia Basin. The role of the Adaptive Management Team is to evaluate appropriate points of compliance for the TDG Total Maximum Daily Load (TMDL) implementation in the mid-Columbia River basin consistent with the 2004 mid-Columbia River TMDL (Picket et. al. 2004).

Douglas PUD will continue its involvement in both the Water Quality Team and Adaptive Management Team meetings for further coordination with other regional members.

Douglas PUD is also currently involved in the Transboundary Gas Group that meets semi-annually to coordinate and discuss cross border dissolved gas issues in Canada and the U.S. Douglas PUD will continue its involvement with the Transboundary Gas Group.

5.1.3 Physical Monitoring

5.1.3.1 Total Dissolved Gas Monitoring

TDG monitoring has been implemented in the Wells Dam forebay since 1984. Douglas PUD began monitoring TDG levels in the Wells Dam tailrace in 1997 by collecting data from a boat and drifting through the tailrace at four points across the width of the river. During transect monitoring, no “hot spots” were detected. The river appeared completely mixed horizontally. A fixed TDG monitoring station was established in 1998. The placement of the fixed monitoring station was determined based upon the 1997 work and was further verified as collecting data representative of river conditions during a 2006 TDG assessment at Wells Dam (EES et. al. 2007). Furthermore, locations of both forebay and tailrace sensor had to be protected to avoid sensor/data loss and damage and for safe accessibility during extreme high flows.

TDG monitoring at the Wells Project is scheduled to commence on April 1 and continue until September 15 annually. This monitoring period will encompass the operation of the Wells JBS as well as the time period river flows are at their highest and when a majority of forced spill occurs. Throughout this period, data from both forebay and tailrace sensors are transmitted by slave radio transmitters to a master radio at Wells Dam. This system is checked at the beginning of the season for communication between the probes and transmitters by technicians at Wells Dam. Total dissolved gas data are sent and logged at the Douglas PUD Headquarters’ building in 15-minute intervals. Information on barometric pressure, water temperature and river gas pressure is sent to the Corps of Engineers on the hour over the Internet. The four data points (15 minute) within an hour are used in compiling hourly TDG values, the 24 hour TDG average and twelve maximum hour TDG averages.

As part of the Douglas PUD’s Quality Assurance/Quality Control (QA/QC) program, a consultant will visit both TDG sensor sites monthly for maintenance and calibration of TDG instruments. Calibration follows criterion established by the COE, with the exception of monthly rather than bi-weekly calibration of sensors (Appendix E). A spare probe will be available and field-ready in the event that a probe needs to be removed from the field for repairs.

The consultant will inspect instruments during the monthly site visits and TDG data will be monitored weekly by Douglas PUD personnel. If, upon inspection of instruments or data, it is deemed that repairs are needed, they will be promptly made. Occasionally during the monthly sensor calibration, an error may develop with the data communication. These problems are handled immediately. Generally, the radio transmitters at each fixed station will run the entire season without any problems.

Douglas PUD intends to collect quality, usable data for each day over the 168-day (April 1 – September 15) monitoring season. As part of the quality assurance process, data anomalies will be removed. This would include data within a 2-hour window of probe calibration and any recording errors that result from communication problems. Data errors will prompt a site visit, inspection and instrument repair or replacement, if necessary.

5.1.3.2 Temperature Monitoring

Douglas PUD has been monitoring water temperatures throughout the Wells Reservoir and in the Wells Dam tailrace year round since 2005. Temperature monitoring locations are provided in the Table 4.3-1 below. Temperature monitoring through the reservoir and the inundated portions of tributary streams will be performed with Onset® Tidbit thermographs.

QA/QC measures will be accomplished through calibration of thermographs at the beginning and end of a period of sensor deployment. As part of the QA/QC process, data anomalies will be identified and removed from the data set. Sensors will be deemed unreliable if calibration against a Bureau of Standard accuracy thermometer shows a variance of ± 0.2°C. Thermographs will be swapped out quarterly (every three months) with recently tested sensors to avoid data loss.

Table 4.3-1 Wells Reservoir and tributary temperature monitoring stations. River mile is based upon United States Geological Survey (USGS) river mile.

River	Side/Mile	Location
Columbia	Left / 515.6	Wells Forebay*
Columbia	Left / 530	Near Brewster
Columbia	Left / 535.3	Brewster Flats
Columbia	Left / 544.5	Chief Joseph Tailrace
Columbia	Left/515.5	Wells Dam Tailrace
Columbia	Right/515.5	Wells Dam Tailrace
Methow	Right / 2.8	Near Pateros
Okanogan	Center / 10.5	Near Monse
Methow	Center/0.4	Mouth of Methow
Okanogan	Center/1.3	Mouth of Okanogan

*Station has sensors at multiple depths.

5.1.4 Biological Monitoring

Douglas PUD will work with the Washington Department of Fish and Wildlife hatchery programs to monitor the occurrence of GBT on adult broodstock collected for hatchery needs. Upon collection of brood, hatchery staff will inoculate each fish, place a marking identification tag on them and look for any fin markings or unusual injuries. NMFS has shown that GBT is low if the level of TDG can be managed under 120% (NMFS, 2000). They recommend that "the biological monitoring components will include smolt monitoring at selected smolt monitoring locations and daily data collection and reporting only when TDG exceeds 125% for an extended period of time." Thus, biological sampling at Wells Dam of adult broodstock will only occur when hourly TDG levels in the mid-Columbia exceed 125 percent.

At most hydroelectric projects on the Columbia River, a juvenile migrant sampling station is incorporated into the JBS. This allows for the external observation of fish for signs of GBT. The signs of GBT are bubbles under the skin of the fish along the fin rays and near the eye sockets. While juvenile migrants are the choice fish for sampling when inspecting for GBT, the JBS at Wells Dam does not have facilities incorporated to allow for juvenile fish sampling and observation. As in past years, if hourly TDG levels exceed 125 percent in the tailrace of Wells Dam, Douglas PUD will request biological sampling of migrating juveniles for symptoms of GBT at the juvenile sampling facility at Rocky Reach Dam.

5.2 Compliance Activities for 2008-2009

In response to the request from WDOE to identify near term solutions and to make continual improvements related to TDG at Wells Dam, the following actions are scheduled to be completed in 2008 and 2009.

5.2.1 Wells Project TDG Numeric Model Development

Douglas PUD has secured the services of the University of Iowa's Hydroscience and Engineering Department (IIHR) to develop a numerical model to investigate TDG production at Wells Dam. The development of a numerical model capable of predicting TDG in the Wells Dam tailrace will assist in evaluating the effectiveness of spill type and Project operations in reducing TDG production with the goal of achieving compliance with WA State Water Quality Standards. Model development, validation and testing will continue to expand upon the results of the 2006 and 2007 assessments. Final reporting will occur in 2008 and will provide the framework for field testing of model results in 2009. An outline of the 2008 proposed study can be found in Section 3.3. The 2008 IIHR study plan can be found in Appendix F.

5.2.2 Wells Project TDG Assessment

In 2009, Douglas PUD shall conduct a TDG field study at Wells Dam to evaluate and verify the results of the 2008 numerical model testing. It is expected that model results will further refine spread and full gate operations that have produced low levels of TDG during past studies. The 2009 field study will support Douglas PUD's goal of complying with the WA State Water Quality Standards for TDG.

5.3 Additional Requirements

Douglas PUD will operate the Wells Project in accordance with the following:

a. 7Q10. The 7Q10 for this project is 246 kcfs. The Project will not be expected to comply with state water quality standards for TDG for incoming flows exceeding this value.
b. Fish Spill. For purposes of compliance, the "fish spill" season is taken to occur from April 1 through August 31; and "non-fish spill" season occurs from September 1 to March 31, unless otherwise specified in writing by Ecology.
c. Compliance During Non-Fish Spill. During non-fish spill, the PUD will make every effort to remain in compliance with the 110% standards.
d. Compliance During Fish Spill. During fish spill, the PUD will make every effort not to exceed an average of 120% as measured in the tailrace of the dam. The Project also must not exceed an average of 115% as measured in the forebay of the next downstream dam. These averages are based on the twelve (12) highest consecutive hourly readings in any 24-hour period. In addition, there is a maximum one-hour average of 125%, relative to atmospheric pressure, during spillage for fish passage. Nothing in these special conditions allows an impact to existing and characteristic uses.
e. TDG Monitoring. The PUD will maintain two fixed monitoring stations at the dam to monitor TDG levels annually from April through August, one in the forebay and one in the tailrace at the approved monitoring sites. This information is available on a real time basis to all interested parties via the U.S. Army Corps of Engineers Columbia Basin Water Management Division website.
f. Reporting Spill for Fish and TDG Exceedances. The PUD will notify Ecology within 24 business hours of spill for fish and when TDG standards are exceeded. Reporting shall be electronically (by email) to the hydropower project manager in Ecology's CRO office.
g. General TDG Abatement Measures. The PUD will manage spill toward meeting water quality criteria for TDG during all flows below 7Q10 levels, but only to the extent consistent with meeting the passage and survival standards set forth in the HCP and Fish Management Plans, as follows:
    i. Minimize voluntary spill.
    ii. During fish passage, manage voluntary spill levels in real time in an effort to continue meeting TDG numeric criteria.
    iii. Minimize spill, to the extent practicable, by scheduling maintenance based on predicted flows.
h. Annual TDG Monitoring Report. The PUD shall submit an annual monitoring report. A draft monitoring report of the year's monitoring results shall be submitted to Ecology by October 31 of the monitoring year. The PUD will submit the final report, incorporating Ecology's suggested corrections, by December 31 of the same year. The contents of the report shall include, at a minimum:
    i. Flow and TDG levels, on a daily basis, with purpose of spill (e.g., fish spill, turbine down time).
    ii. Summary of exceedances and what was done to correct the exceedances.
    iii. Results of the fish passage efficiency (FPE) studies and survival per the HCP.

i. Revised Gas Abatement Plan (GAP). The PUD will revise the GAP annually, to reflect any changes and new or improved information and technologies. The PUD will submit a draft to Ecology for review and approval by February 28 of the year of implementation (e.g., February 28, 2009 for the 2009 spill season). The GAP shall be in the format of the PUD's 2008 GAP, unless modifications are requested by Ecology.
j. Ecology Contact. The PUD will direct its correspondence to:

   Hydropower Projects Manager
   Department of Ecology
   Central Region Office
   Water Quality Program
   200 W. Yakima Ave., Suite 200
   Yakima, WA 98908

6.0 REPORTING

Upon approval of the Wells Gas Abatement Plan and issuance of a Wells Project TDG exemption, Douglas PUD shall submit an annual report describing the results of all monitoring activities described within this Gas Abatement Plan. The report will be submitted to WDOE no later than December 31 of each year that the TDG exemption is active. The report will summarize all Gas Abatement Plan activities conducted for the year in which it is submitted as required by WDOE.

7.0 REFERENCES

ASL Environmental Sciences (ASL). 2007. Turbine Discharge Measurements by Acoustic Scintillation Flow Meter at Units 1 and 2, Wells Hydroelectric Project, Pateros, Washington, August 2006. Prepared by ASL Environmental Sciences Inc. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Bickford, S. A., J. R. Skalski, R. Townsend, S. McCutcheon, R. Richmond, R. Frith and R. Fechhelm. 2001. Project survival estimates for yearling summer steelhead migrating through the Wells Hydroelectric Facility, 2000.

Bouck, G. R. 1980. Etiology of gas bubble disease. Transactions of the American Fisheries Society 109:703-707.

Dawley, E., T. Blahm, G. Snyder, W. Ebel. 1975. Studies on effects of supersaturation of dissolved gases on fish. US Department of Commerce, National Marine Fisheries Service. Seattle, WA.

EES Consulting, Carroll, J., ENSR, and Parametrix. 2007. Total Dissolved Gas Production Dynamics Study. Wells Hydroelectric Project. FERC No. 2149. Prepared by EES Consulting, Joe Carroll, ENSR, and Parametrix. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Environmental Protection Agency (EPA). 1976. Quality Criteria for Water. PB-263943.

Jensen, J. O. T., J. Schnute, and D. F. Alderdice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose -- response model. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 43: 1694-1708.

National Marine Fisheries Service (NMFS). 2000. Endangered Species Act – Section 7 Consultation: Biological Opinion. Consultation on Remand for Operation of the Columbia River Power System and 19 Bureau of Reclamation Projects in the Columbia Basin. F/NWR/2004/00727. November 30, 2005. Pages 5-6, 5-7, 5-53, 10-9, and Appendix E: Risk Analysis.

Pickett, P., H. Rueda, M. Herold. 2004. Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt. Submittal Report. Washington Department of Ecology, Olympia, WA. U.S. Environmental Protection Agency, Portland, OR. June 2004. Publication No. 04-03-002.

Skalski, J. R, G. E. Johnson, C. M. Sullivan, E. Kudera and M. W. Erho. 1996. Statistical Evaluation of Turbine Bypass Efficiency at Wells Dam on the Columbia River, Washington. Canadian Journal of Fisheries and Aquatic Science. Volume 53, No. 10, 1996. Pages 2188-2198.

Weitkamp, D. E., and M. Katz. 1980. A review of dissolved gas supersaturation literature. Trans. Am. Fish Soc. 109: 659-702.

Appendix A

Letter from Megan White on Gas Abatement Plan for 2003
May 15, 2002

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
P.O. Box 47600 • Olympia, Washington 98504-7600
(360) 407-6000 • TDD Only (Hearing Impaired) (360) 407-6006

CERTIFIED MAIL

May 15, 2002

Mr. Bob Clubb
Douglas County Public Utility District
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Clubb:

Douglas County Public Utility District will need an approved gas abatement plan in order to spill water over Wells Dam for the purpose of passing juvenile salmonids down-river during the spring and summer migration season of 2003. Our data shows that Wells Dam does not contribute significantly to dissolved gas during most flows during most years. However, in most years the dam is occasionally out of compliance with the water quality standards for dissolved gas. Ecology's expectation is that you will investigate reduction of dissolved gas generated by the Wells Dam.

This requirement is described in Washington's water quality standards (Chapter 173-201A WAC, under *General Water Use and Criteria Classes (section 030)* and *General Considerations* (section 060)) for the purpose of passing juvenile salmonids. Several things will need to happen in order for you to move ahead with a gas abatement program and are described below.

Gas Abatement

Gas abatement planning is required by the water quality standards in order to demonstrate that all reasonable steps are being taken to reduce total dissolved gas associated with fish passage spills. This means investigating and where, appropriate, pursuing structural modifications and operational modifications to reduce gas generated by spill.

My staff plans to work with you, the fisheries agencies, and river management agencies in planning and prioritizing gas abatement options to pursue.

Expectations for the Coming Year:

1. Provide a Gas Abatement Plan that contains:

    a. A schedule for compliance toward taking all reasonable steps to reduce total dissolved gas associated with fish passage spills.

b. Steps to identify and reduce operational or uncontrolled spill (spill not associated with controlled spill to pass juvenile fish) in coordination with river-wide operational adjustments.

c. Steps to identify potential structural modifications to reduce gas generated by dam operation toward meeting water quality standards.

2. The real-time data from the fixed monitoring stations should continue to be made available for posting and publication to the TDG U.S. Army Corps of Engineers Monitoring Program Coordinator at a minimum beginning April 1 through August 31 of each year.

3. Continue to assess spatial variability of gas by conducting transect monitoring in the dam forebay and tailrace. The objective of this monitoring is to evaluate the representativeness of the fixed monitoring stations and to collect data to support the TDG TMDL. Provide assistance to Ecology staff who is conducting monitoring of TDG at Wells Dam. Cooperative monitoring of Wells Dam TDG by Douglas PUD (or its contractors) and Ecology will meet this condition and is encouraged.

Workgroup Participation

Staff from Douglas County will be expected to participate in the Columbia River Water Quality Team that meets in Portland either in person, through a consultant, or via conference call. Staff is also expected to continue to participate in the Transboundary Dissolved Gas Team that meets at various locations approximately twice a year.

Reports

Due August 31 of each year:

Any draft revisions to the gas abatement schedule for compliance with specific targets and dates for achieving gas abatement measures toward the goal of taking all reasonable steps to reduce total dissolved gas associated with fish passage spills. Include dates when reports will be submitted, predicted gas levels after each step, how and when decisions will be made on specific modifications to present structures and operations, and how funding or other mechanisms to carry out activities will be secured.

This report needs to include any revisions to:

- The forebay and tailrace monitoring plan.
- Draft QA/QC plan for the physical and biological monitoring that is to be done during the following season.
- Physical modeling plans.
- Structural and operational changes.
- Reductions in spill due to successes of alternative fish passage facilities.

Due by February 27 of each year:

1. Any final revisions to the schedule for compliance with specific targets and dates for achieving gas abatement measures toward the goal of achieving and maintaining water quality standards. This needs to include any revision to:

   - The forebay and tailrace monitoring plan.
   - Draft QA/QC plan for the physical and biological monitoring that is to be done during the following season.
   - Physical modeling plans.
   - A report on the progress of planning and achieving gas abatement through structural modifications.
   - A report on the operational gas abatement efforts including power trading and managing river levels on a system-wide basis as well as operational efforts being pursued at Wells Dam.
   - Reductions in spill due to successes of alternative fish passage.

3. A report of the results of physical and biological monitoring done in 2002. This is expected to be a similar report that was submitted by NMFS to the state of Oregon in 1999 entitled, *1998 Annual Report to the Oregon Department of Environmental Quality*. Please include in this report:

a. A description of water conditions for the year in terms of basin runoff conditions and flows as compared to average years.

b. Tables showing dates, times, and amounts (in percent saturation) of dissolved gas when water quality standards are exceeded. Explain reasons for exceedances. Discuss steps that were taken to fix each problem. Keep in mind that 110 percent dissolved gas is the standard. This amount can be raised to 120 percent only when expressly spilling water to pass juvenile salmonids.

c. Tables and graphs showing quantities (in kcfs) of voluntary spill (for fish passage) and involuntary spill at each dam. The data collected needs to include:

- Observed total river flow
- Project hydraulic capacity
- Total, real-time involuntary spill. Identify by each cause:
  - Lack of market
  - Lack of hydraulic capacity
  - Any other reason
- Voluntary spill to pass fish as per the intent to reach 95 percent fish passage survival
- Voluntary spill as systems-wide energy transfer spill between dams
- Total spill
- The percentage of total spill that was voluntary

Notification

The Department of Ecology must be notified of any exceedances of the adjusted dissolved gas standards due to spill to pass fish within seven days of exceedance. A weekly notification of violations for the previous seven days will satisfy this request. Include in this notice steps that have been taken to correct the problem. Call by telephone or send this notice to:

Chris Maynard
Water Quality Program
Department of Ecology
PO Box 47600
Olympia, WA 98504-7600.
Fax: (360) 407-6426. Phone: (360) 407-6484

As you are aware, the federal license for the Wells Hydroelectric Projects (FERC No.2149) expires in 2012. Before the Federal Energy Regulatory Commission may grant a new license for this project, the Department of Ecology must certify pursuant to the federal Clean Water Act that the project will meet applicable water quality requirements. The project's ability to meet total dissolved gas requirements through gas abatement planning will be a central issue of interest in Ecology's determination. Ecology's staff will be working with the Public Utility District during the licensing consultation process to ensure that appropriate studies, monitoring, and structural and operational abatement measures are undertaken in a manner that is consistent with ongoing efforts.

Please contact me at 360/407-6405 or Chris Maynard of my staff at 360/407-6484 if you have questions or comments regarding this approval.

Sincerely,

Megan White P.E., Manager
Water Quality Program

CM:ak
cc: Columbia Water Quality Team
Wells Coordinating Committee

Y:\...Chris\Dissolved Gas\Douglas PUD 2002 'Waiver'.doc

Appendix B

Letter of Approval for Wells Dam Gas Abatement Plan for 2003
March 27, 2003

CERTIFIED MAIL

March 27, 2003

Mr. Bob Clubb
Douglas County PUD
1151 Valley Mall Parkway
East Wenatchee, Washington 98802

Dear Mr. Clubb:

The state of Washington requires the operators of each dam on the Columbia River to obtain approval from the Washington Department of Ecology of a gas abatement plan in order to spill water over the dam to assist in the passage of juvenile salmonids downstream and thus potentially raise the total dissolved gas saturation level above 110 percent. This requirement is described in Washington's water quality standards (Chapter 173-201A WAC, under General Water Use and Criteria Classes, section 030; and General Considerations, section 060).

The Douglas County Public Utility District has provided us with information about gas abatement activities and monitoring being undertaken at Wells Dam on the Columbia River. This information meets our requirement. Therefore, **the gas abatement plan for the Wells Dam is approved for all activities related to fish passage for the period of one year.**

This means that Wells Dam may raise the dissolved gas levels above 110 percent saturation to aid fish passage but not to exceed 125 percent saturation as a one-hour average. Gas saturation may not exceed 120 percent in the tailrace and 115 percent in the forebay as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

Our water quality standards require gas abatement planning, monitoring, and reporting. This approval is further conditioned as follows:

Gas Abatement Planning

Continue to evaluate, refine, and implement gas abatement activities. If in following years, gas abatement efforts are determined by the agency to be sufficient for more than one year, the agency may approve the plan for up to five years. These plans must contain a schedule for taking all reasonable steps toward compliance by reducing total dissolved gas associated with spills:

a. Operational fish spills
b. Structural solutions
c. Uncontrolled spill

The Douglas County Public Utility District will be expected to participate in and provide information to regional groups that address system-wide dissolved gas problems.

Physical and Biological Monitoring

Programs for biological trauma monitoring for gas effects and physical monitoring at the fixed monitors shall remain the same as past years except where site-specific changes or additions are needed to obtain better information.

Reports

November 1, 2003. Any changes, modifications and additions to the October 2002 gas abatement plan will be reported to WDOE including:

- Compliance schedule changes regarding specific targets and dates for moving toward meeting water quality standards.
- Forebay and tailrace monitoring plans.
- Quality assurance plans.
- Physical modeling plans.
- Structural changes.
- Operational changes.
- Reduction in spill due to successes of alternative fish passage facilities.

By February 27, 2004, the PUD will submit:

1. Revised gas abatement plan. If this plan is approved by Ecology and is sufficient in moving toward achieving water quality standards in the longer-term, Ecology will approve the plan for up to five years.
2. Annual report of the physical and biological monitoring.:

- A description of the water year in terms of basin runoff conditions as compared to average years.
- Tables showing dates, times and amounts (in percent saturation) of dissolved gas when water quality standards are exceeded. Explain reasons for exceedances. Discuss steps taken to fix the problem. The higher gas standard

applies only when spilling water to aid fish passage, and managing system spill for improved fish conditions.

- A table or graph showing percentage of spill that was voluntary compared to the percentage that was due to other causes such as lack of electric demand, lack of hydraulic capacity, or any other reason.

Notification

The Department of Ecology must be notified of any exceedances of the adjusted dissolved gas standards due to spill to pass fish within seven days of the exceedance. A weekly notification for the previous seven days will satisfy this. Include in the notification steps that have been taken to correct the problem. Call by telephone, send by e-mail, or fax to:

Chris Maynard
Water Quality Program
Department of Ecology
PO Box 47600
Olympia, WA 98504-7600
Phone: (360) 407-6484
FAX: (360) 407-6426
E-mail: cmay461@ecy.wa.gov

Failure to abide by these conditions may result in administrative action if water quality standards are exceeded. The Department of Ecology is authorized to issue Administrative Orders requiring compliance whenever it determines that a person has exceeded or is about to exceed any provision of RCW 90.48.

Please contact me at (360) 407-6405 or Chris Maynard of my staff at (360)407-6484 if you have any questions or comments regarding this approval.

Sincerely,

Megan White, P.E., Manager
Water Quality Program

cc: Columbia River Water Quality Team
Mid Columbia Coordinating Council
Tom Tebb

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Appendix C

Letter Granting Extension of the Wells Dam Gas Abatement Plan to include 2004, February 27, 2004

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47600 • Olympia, WA 98504-7600 • 360-407-6000
TTY 711 or 800-833-6388 (For the Speech or Hearing Impaired)

CERTIFIED MAIL

February 27, 2004

Mr. Rick Klinge
Douglas County P.U.D.
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Klinge:

The Washington Department of Ecology requires the operators of each dam on the Columbia and Snake River to operate under a department-approved gas abatement plan in order to spill water over the dams on the Columbia and Snake Rivers during fish spills, thus potentially raising the total dissolved gas saturation level above the criteria of one hundred and ten per cent. This special fish passage exemption is described in Washington's water quality standards (WAC 173-201A-060 (4)(b), General Considerations).

This letter constitutes continued approval of the gas abatement plan that we currently have on file for your operation for all activities related to fish passage. This approval is for a period of one year. Please note that the department is in the process of determining how these plans will be incorporated into 401 certifications that are being developed and we will keep you informed as we move forward.

This approval means that the dissolved gas levels may be raised above 110 percent saturation to aid fish passage but not to exceed 125 percent saturation as a one-hour average. Gas saturation may not exceed 120 percent in the tailrace and 115 percent in the forebay of the next dam downstream as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

Please continue to evaluate, refine, implement, and report on gas abatement activities as needed.

This gas abatement plan approval does not limit the conditions placed in future permits, orders, and certifications issued by the department.

RECEIVED
MAR 0 2 2004
DOUGLAS PUD

Please contact me at (360) 407-6405 or Chris Maynard of my staff at (360) 407-6484 if you have any questions or comments regarding this approval.

Sincerely,

Richard K. Wallace, Manager
Water Quality Program

cc: Columbia River Water Quality Team
Mid-Columbia Coordinating Council
Columbia River Fisheries Program Office
US Army Corps of Engineers
Regional Ecology Section Managers

Appendix D

Letter from David Peeler on Gas Abatement Plan for 2005-2007
March 31, 2005

DOC NO. 91677

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47600 ∘ Olympia, WA 98504-7600 ∘ 360-407-6000
TTY 711 or 800-833-6388 (For the Speech or Hearing Impaired)

March 31, 2005

REGISTERED MAIL

Mr. Bob Clubb
Chief of Environmental and Regulatory Services
Douglas County PUD
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Clubb:

On March 21, 2005, the Douglas Public Utility District (Utility) requested approval to adjust the Total Dissolved Gas (TDG) criteria to spill water at Wells Dams on the Columbia River in Washington to assist downstream migration of juvenile salmonids. We require approval of gas abatement plans under Washington State Water Quality Standards WAC 173-201A-060(4)(b) in order to apply the adjusted TDG standards to the Columbia River.

The Utility submitted a gas abatement plan to Ecology. The submittal also included the following.

- TDG physical monitoring plans.
- Biological monitoring plans.

The Washington State Department of Ecology approves the gas abatement plan. This approval is based on the following findings.

1. Failure to act will result in more salmonid passage through the hydroelectric dam turbines. Estimated mortality from juvenile salmonids passing through turbines is several times greater than juvenile salmonid passage mortality over dam spillways.
2. Exposure to elevated TDG as a result of spill is harmful to fish. However, anadromous salmonids experience less harm when exposed to limited concentrations of TDG, than the harm experienced by passing through turbines. A risk analysis was performed by the United States National Oceanographic and Atmospheric Administrations Fisheries in 1996 and updated in 2002. Based on this risk analysis, Ecology water quality standards allow higher levels of TDG upon approval of gas abatement plans.
3. The Utility is investigating operational improvements.

This approval is subject to the following conditions.

1. This approval shall extend through February 2008, and apply to Wells Dam on the Columbia River in Washington State.

2. This approval means that spill may raise the dissolved gas levels above 110% saturation to aid fish passage, but not to exceed 125% saturation as a one-hour average. Gas saturation may not exceed 120% in the tailrace and 115% in the forebay of the next dam downstream as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

3. The Utility is expected to conduct the following activities.

    a. Investigate and pursue TDG reduction and monitoring improvements as new information becomes available.

    b. Investigate biological effects data gaps for TDG for all species in areas of concern. Plan for studies identified during this investigation. Provide yearly progress reports.

    c. Begin to investigate structural improvements in combination with operational improvements to reduce TDG. Provide yearly progress reports.

    d. Make reasonable attempts to reduce TDG entrainment during all flows during the spill season.

    e. Plan maintenance schedules and activities as much as possible to minimize TDG production resulting from spill to within water quality standards. Plan turbine outages as much as possible for outside the high flow season when this will not cause more harm to the environment or to the structural integrity of the dam.

    f. Notify Ecology within 48 hours of initiation of spring, summer, and other spills for fish. The notification may be electronic or written.

    g. Provide Ecology with an annual written report by December 31 of each year for the activities outlined in this letter and detailing the following:

        - Flow and runoff descriptions for the spill season.

        - Spill quantities and duration.

        - Quantities of water spilled for fish versus spill for other reasons for each project.

- Data from the physical and biological monitoring programs including a summary of exceedances for each dam and a description of what was done to correct the exceedance.

- Progress on TDG abatement implementation measures.

This gas abatement approval does not limit the conditions placed in future permits, orders, and certifications issued by this Department.

Please contact me at (360) 407-6405, or Chris Maynard of my staff at (360)407-6484, if you have any questions or comments regarding this approval.

Sincerely,

David C. Peeler
Water Quality Program Manager

cc: Tom Tebb
Pat Irle
Mike Schiewe, Chair, HCP Coordinating Committees
Columbia River Water Quality Team

Appendix E

Data Quality Criteria for Fixed Monitoring Stations

DATA QUALITY CRITERIA
FOR FIXED MONITORING STATIONS

INTRODUCTION:

The development of data quality criteria for fixed monitoring stations in the Pacific Northwest could be involved in meeting some of the requirements of RPA (Reasonable and Prudent Alternative) 131 and 198.

The NMFS 2000 Biological Opinion RPA 131 stipulates that the "Action Agencies shall monitor the effects of TDG." Further explanation of the RPA includes a discussion of Quality Control and Quality Assurance including redundant and backup monitoring, bi-weekly calibration, and spot-checking of monitoring equipment. In an effort to address these concerns the US Army Corps of Engineers has drafted Data Quality Criteria for the fixed monitoring stations at its projects. The Data Quality Criteria describe the accuracy, precision and completeness of the data needed at each station. The fixed monitoring stations will be assessed at the end of the monitoring season against these criteria and a performance report will be created. Adjustments will be made to the individual fixed monitoring stations that do not perform to the objectives described. The Data Quality Criteria approach is being recommended instead of the redundant and backup monitoring, and spot-checking approach described in the BiOp since it will provide greater flexibility with equipment and has less impact on program cost escalation.

The NMFS 2000 Biological Opinion RPA 198 stipulates "The Action Agencies, in coordination with NMFS, USFWS, and other Federal agencies, NWPPC, state, and Tribes, shall develop a common data management system for fish population, water quality, and habitat data." NWPPC's February 15, 2002 draft Data Management in Support of the Fish and Wildlife Program Summary encourages the development of regional data standards in support of a consistent and standardized database. The development of data quality criteria for TDG monitoring stations could be one of the regional standards towards the long-term goal of a consistent, standardized regional database.

The US Army Corps of Engineers, NW Division, is proposing the following Data Quality Criteria as an alternative to the redundant stations in RPA 131 and as a regional standard for TDG monitoring stations.

PROPOSED DATA QUALITY CRITERIA

The proposed data quality criteria for fixed monitoring station cover laboratory calibration, field instrument post-calibration; field performance check; and general criteria. The items are described as following:

1. Laboratory calibration:

There are four data quality criteria associated with laboratory calibration, including -calibration of the following: the secondary TDG standard ; the secondary barometric pressure standard; the field instrument TDG sensor ; and secondary standard thermistor. Each is described as follows:

<u>1. Calibration of Secondary TDG Standard</u>

Calibrate the TDG sensor at two points using the primary National Institute of Standards and Technology (NIST) standard. The TDG pressure must be +/- 2 mm Hg at both pressures;

otherwise the secondary standard is recalibrated. Pressures at which the sensor is calibrated must bracket the expected range of field measurements.

2. Calibration of Secondary Barometric Pressure Standard
Calibrate the secondary standard barometer at ambient barometric pressure to the NIST standard. The barometer must be +/- 1 mm Hg of the primary standard (NIST certified instrument) otherwise the secondary standard is recalibrated.

3. Calibration of Field Instrument TDG sensor
The two point TDG sensor calibration must agree within +/- 2 mmHg at both pressures, otherwise the sensor is recalibrated. Pressures at which the sensor is calibrated must bracket the expected range of field measurements.

4. Calibration of Secondary Standard Thermistor
The instrument's thermistor must agree within +/- 0.2°C with the primary NIST standard. This variance will be monitored and if the probe performs outside this range, it will be returned to the manufacturer for maintenance. A check or verification still constitutes a calibration and should be documented in records.

Field instrument post-calibration
There are three data quality criteria associated with field instrument post-calibration: two fixed points; two point TDG sensor calibration and suspected parameters. Each is described as follows:

1. Two Fixed Points: In order to reduce TDG calibration variability, two fixed points should be chosen and incorporated in the TDG calibration protocol. For example, calibrate the first point to ambient barometric pressure, and the second point to 200 mmHg over barometric pressure. The calibrated range for this example brackets 100-126 % TDG saturation. This ensures the same calibration curve is established each time for every instrument.

2. Two Point TDG Sensor Calibration: Following a two-week deployment, a two point TDG sensor calibration must agree within +/- 4 mmHg at both pressures. Pressures at which the sensor is calibrated must bracket the expected range of field measurements. If the pressure is not +/- 4 mmHg of the standard, the data will be reviewed and appropriately corrected. If, after data review, a correction cannot be applied, the data will be removed from the database. Sensor drift can be handled using a linearly prorated correction, but it is entirely possible for someone to enter incorrect calibration values, which would result in a shift affecting all readings equally.

3. Suspected Parameters: If any parameter is considered suspect following these calibration checks on return to the laboratory, the data collected for the previous time period will be reviewed and if applicable, corrections will be applied or the data will be removed from the database.

Field Performance check:
There are four data quality criteria associated with field performance check: TDG pressure compared to secondary standard; standby probes deployed; thermistor compared to secondary standard; and field barometer compared to secondary standard. Each is described as follows:

1. <u>TDG Pressure Compared to Secondary Standard:</u> After the deployment period, prior to removal of the field instrument, the TDG pressure will be compared to the secondary standard. The actual decision point regarding adjusting the data would be in the lab following the two point TDG sensor calibration described in field instrument post calibration. The field comparison actually involves sampling precision and should not be used as a decision point for shifting data.

2. <u>Standby Probe Deployed</u>: During initial deployment of a new instrument, after sufficient time for equilibration (up to one hour), the TDG pressure must be +/- 10 mmHg of the secondary standard otherwise another (standby) probe is deployed.

3. <u>Thermistor Compared to Secondary Standard:</u> During initial deployment of the new instrument, the thermistor will be +/- 0.4°C of the secondary standard, corrected for calibration, or the instrument will be replaced with a standby.

4. <u>Field Barometer Compared to Secondary Standard:</u> At each visit the field barometer reading should the same as the secondary standard or the field barometer will be calibrated.

General Criteria:

1. <u>Depth of Sensor:</u> The sensor must be deployed to a depth greater than the compensation depth; otherwise the TDG measurements may be underestimated. If the site does not accommodate maintaining the probe at greater than the compensation depth for more than 95% of the measurements, investigations will begin to re-locate the fixed monitoring station.

2. <u>Data Set Completeness:</u> As a goal, data collected at each site will be 95% of the data that could have been collected during the defined monitoring period. The calculation of data set completeness is based on temperature and percent TDG, encompassing barometric pressure and TDG pressure, not the completeness of each parameter measured.

Glossary - Definitions and Acronyms

NIST - National Institute of Standards and Technology

Primary Standard - NIST certified instrument

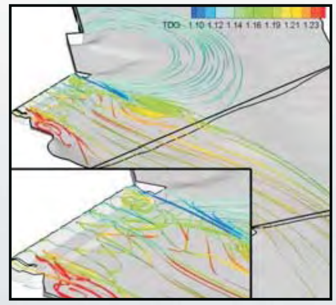
RPA - Reasonable and Prudent Alternative

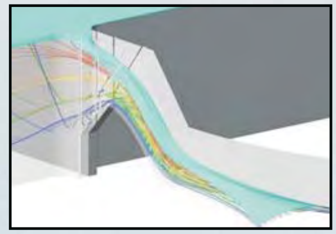
Secondary Standard - Instrument calibrated with a primary standard, often used for checking instrumentation in the field

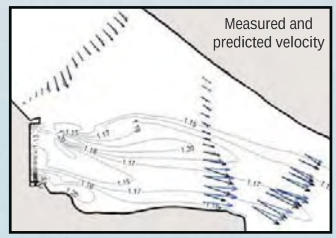
Appendix F

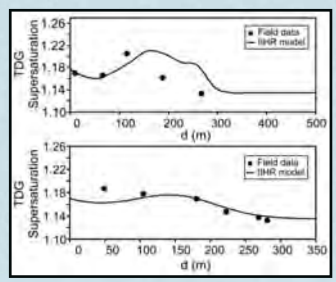
2008 Study Plan: Proposal for the TDG Modeling for the Tailrace of Wells Dam

Proposal for TDG Modeling for the Tailrace of Wells Dam









Submitted to:
Public Utility District No. 1 of Douglas County

Submitted by:
Dr. Larry Weber and
Dr. Marcela Politano

IIHR Hydroscience & Engineering

The University of Iowa

1. PURPOSE AND IDENTIFICATION OF THE PROPOSING ORGANIZATION

IIHR – Hydroscience & Engineering (IIHR), an educational institution of the University of Iowa, proposes numerical model studies to investigate total dissolved gas (TDG) production at Wells Dam. Wells Dam is owned and operated by Public Utility District No. 1 of Douglas County (Douglas PUD). Douglas PUD seeks to examine TDG production dynamics at the Wells Project to comply with state water quality standards as part of their federal relicensing process.

1.1 Brief Description of IIHR

IIHR (formerly Iowa Institute of Hydraulic Research) is one of the nation's premier and oldest fluids research and engineering laboratories. IIHR studies encompass a broad spectrum of fluid mechanics, environmental hydraulics, and hydrometeorology. Basic and applied engineering research projects are conducted at IIHR in nine modern, well-equipped laboratories with over 100,000 square feet of floor space.

For the past 30 years IIHR has been at the forefront of turbulence research, laboratory modeling, sediment transport, sediment-flow interactions, imaging analysis, and development of sensors for data acquisition of flow and climatic data. IIHR's rich history in theoretical and applied research, including ongoing multidisciplinary activities, is described at http://www.iihr.uiowa.edu/about/history/index.html. What perhaps makes IIHR unique among fluids research laboratories is its state-of-the-art, in-house capabilities for both computational and laboratory modeling and experimentation. This permits varying, yet complementary, approaches for investigation and solution of a wide variety of flow problems. Research facilities of IIHR include many hydraulics flumes, air- and water-flow units, and more routine experimental apparatus and instruments, newly acquired computer clusters that allow large scale, long term simulations, as well as several specialized sensors such as ADCPs, ADVs, Large Scale PIV for field operations, OBS, side scan sonar, and sediment tracers. For a detailed description of the facilities, please view the following site http://www.iihr.uiowa.edu/facilities/index.html. IIHR has a long-term partnership with the Office of Naval Research, USACE, and other Department of Defense agencies and has recently performed several field studies of mapping turbulence and sediment texture in the Upper Mississippi River, Columbia and Snake River systems in the Pacific Northwest, and the Tacoma Narrows and Elliot Bay in a collaborative research contract with the Pacific International Engineering.

1.2 Brief Description of the Wells Project

The spillway gates at Wells Dam are used to pass water when river flows exceed the powerhouse capacity of 195 kcfs (forced spill), to assist outmigration of juvenile salmonids (fish bypass spill), and to prevent flooding along the mainstem Columbia River (flood control spill). Douglas PUD is required to meet State standards for TDG levels in the tailrace for spill events up to 69.5 kcfs (corresponding to the 7Q10 flow). Currently, the State of Washington requires TDG levels to not exceed 110% at any point of measurement. Due to air entrainment in the plunge pool below the spillway, TDG levels sometimes exceed the State's limit during spill events. The exceptions to the State's standard when levels are allowed to be exceeded are (1) to pass flood flows at the Project and (2) to pass voluntary spill to assist out migrating juvenile salmonids.

Douglas PUD has recently completed a study which included an evaluation of past TDG data as well as a field monitoring program in 2006. The purpose of the study was to evaluate if the Project can be operated to successfully pass the 7Q10 river flow while remaining in compliance with State TDG requirements. The field study collected TDG data for 80 separate events. As a result of the study, operational spill scenarios were identified that move the project towards compliance.

As part of the ongoing effort to understand TDG at the Project, Douglas PUD is seeking to develop a numerical model capable of predicting TDG in the tailrace. The model would be employed to evaluate the effectiveness of spill type and plant operations in reducing TDG production with the goal of optimizing Project operations for minimized TDG downstream.

2. NUMERICAL MODELING CAPABILITIES

IIHR has a national and international reputation as a leader in computational fluid dynamics (CFD) model development and application. The blend of fundamental and applied numerical modeling at IIHR is unique and unmatched at any other organization. While most academic units focus primarily on code development and simulation of simple geometries and most architectural – engineering firms use commercially available software with inadequate knowledge of the core code limitations, IIHR's highly technical cadre of numerical modelers are all rooted in code development; have exceptional strength in fluid mechanics and turbulence modeling; and have a wealth of experience providing applied engineering simulations.

One of IIHR's codes, CFD Ship Iowa, is presently the only university-based CFD code supported and used by the Office of Naval Research for design of our nation's ships, submarines and various underwater projectiles. Using a similar approach beginning over ten years ago, IIHR has led the hydraulic engineering community into the era of CFD modeling with the development of U2RANS, the first CFD code developed specifically for use in river and lake applications. U2RANS has been successfully and cost-effectively used to provide engineering simulations for design of fish passage facilities and/or spillway flow deflectors at Wells Hydrocombine, Rocky Reach, Rock Island, Wanapum, Priest Rapids, McNary and The Dalles dams on the Columbia River and at Brownlee, Hells Canyon, Lower Granite and Ice Harbor dams on the Snake River. In addition, U2RANS has been used to simulate the Lake Washington Ship Canal and several other applications located outside of the Pacific Northwest.

IIHR's leadership in environmental hydraulics simulations has led to a recent partnership with Fluent Inc., the leading commercial CFD software company. IIHR's strength in laboratory experimentation, code development and understanding of emerging physical processes, such as total dissolved gas modeling, two-phase flows and density currents, to name a few, were very attractive to Fluent. IIHR researchers provide new mathematical models for inclusion in the core FLUENT code and subsequent technical transfer to the engineering community. In return for this expertise and code development, IIHR receives a 160 seat site license to use FLUENT for basic and applied research and mechanism to transfer technology developed at IIHR to its engineering partners. This win-win partnership provides our industrial clients with access to the latest research codes as well as the most advanced commercial software available without the burden of costly licensing fees.

IIHR provides cost-effective, research quality simulations to our industrial partners by using full-time, PhD-level engineering research staff to lead the numerical modeling projects. These professional researchers are supported by graduate students who conduct the time-intensive work of generating grids and developing plots and animations of the simulation results to demonstrate the processes being modeled. In addition, IIHR has provided training to a number of our clients in the use CFD modeling and/or post-processing software. Lastly, IIHR provides all the models and grids to the client at regular intervals during the project or at the completion of the project depending on the needs of the client.

2.1.1 Numerical Modeling Hardware and Software

Basic and applied research programs at IIHR are supported by a diverse set of computing resources and facilities. High-performance computing (HPC) at IIHR has recently moved from a pair of shared memory systems with attached storage (Silicon Graphics Power Challenge Arrays 16 MIPS R8000 processors and a Hewlett-Packard N-Class file server with dual attached HP AutoRAID storage units) toward a PC-based, distributed computing environment. This new architecture features PCs on each student and staff member's desk, network IP-based storage, and a cluster of Linux PCs with a Myrinet interconnect for high performance computing.

IIHR has recently commissioned a Sun Microsystems parallel, distributed memory compute cluster based on PC hardware (IA-32) running Linux, Sun GridEngine, OpenMP, MPI, and the Intel and GNU compiler and tool suites. This system features 128 processors running at 3.06 GHz, 256 GB memory, and 8 TB of temporary storage for computation. The distributed computing nodes feature a Myrinet-D interconnect for high-speed low latency messaging. Two head nodes provide access to the cluster for compiling and launching jobs. An additional 3 dual socket dual core Xeon Mac Pro systems are dedicated to Fluent jobs running under Windows-64.

HPC at IIHR is augmented by an Apple Xeon XServe hosted storage area network (SAN). This SAN features two load-balancing file servers with primary and secondary metadata servers, 10GB/s Ethernet for metadata and operational communications, and dual 2GB/s fibre attached XServe RAID storage units with 60 TB of storage. Tape archives are written to an Exabyte Magnum 448 LT03 tape library. Additional storage is provided by a pair of Hewlett-Packard MSA 1500 storage arrays with 20TB of disk space. These storage architectures provide both high-speed data access and data security via RAID and off-site archives. IIHR also operates dedicated project storage arrays based on Apple XServe/XServe RAID architecture with close to 15TB of additional storage.

Very large-scale computations are done at national and international computation centers accessed through longstanding IIHR-center relationships. In addition to the NSF and DOD/DOE centers, IIHR has developed a continuing collaboration with the National Center for High Performance Computing (NCHC) in Taiwan.

Supporting the local centralized facilities are a number of UNIX workstations, (10 Hewlett-Packard zx6000 wsystems with 6 GB RAM each and 2 j6000 systems with 2GB RAM), and over 240 individual PCs running MS Windows 2000/XP and/or Linux. There are 17 PC-based servers handling web, ftp, security, and specialized database services. In addition, a number of DVD-RAM mass-storage devices, publication-quality color printers, scanners, cameras, and other peripherals are in use.

This hardware is complemented by a carefully selected set of public domain, commercial, and proprietary software packages that include Tecplot, Gridgen, Fluent, FlowLab, Matlab, Origin, Rhino3D, ERDAS, ERMapper, ERSI, Skyview, and the core GNU utilities. Additionally, software such as AutoCAD, MS Windows, MS Office, OS X, Mathematica, IDL, SigmaPlot, and SAS, are used under University-wide site licenses.

IIHR is connected to the University campus via gigabit speed Ethernet over a redundant single-mode fiber-optic connection. The IIHR network segment is fully switched and capable of delivering 100-megabit speeds to the desktop. All IIHR on-campus buildings are interconnected using dedicated VLANs at Gigabit speeds. Our off-campus buildings are serviced by wireless networking provided by a local ISP.

Computer operations are under the direction of IIHR's Data Systems Coordinator with assistance from two full-time staff members (System Programmer, graphics/draftsman), and several student aides. Strategic support relationships exist with the Engineering Computer Network (CSS) and the Research Services group of the University’s Information Technology Services (ITS).

3. TDG MODELING AT IIHR

TDG abatement projects at IIHR include spillway flow deflectors, spill pattern optimization, topspill bulkheads, spillway gate modifications, and flow diversion through secondary spill paths. IIHR's experience with the mid-Columbia Public Utility Districts and Idaho Power Company has resulted in proven TDG abatement techniques. A list of recent reports and articles related to hydropower facilities is appended to this proposal as Section 8.

Physical models have been used at IIHR to design deflectors for TDG abatement at Wanapum, Rock Island, Hells Canyon, and Brownlee dams. In conjunction with physical models, computational models have been developed to predict TDG abatement potential downstream of each of the aforementioned dams. Free surface and temperature capabilities are now included to allow complex modeling of chutes, spillways, stratified reservoirs, complex flow mixing near turbine intakes, and many other applications relevant to TDG abatement.

IIHR has extensive experience in the use of coupled physical and numerical models. The coupling of both model types has allowed ongoing development and verification of new CFD codes and subroutines. These new developments continue to expand the capabilities of CFD for use independently of physical models. For example, over the past ten years IIHR has used physical models to develop a performance curve method for deflector design which has been successful at reducing field TDG levels by as much as twenty percent in prototype tests at Wanapum Dam. More recently, numerical models were used to replicate the tailrace hydrodynamics and predict flow regimes for a proposed fish bypass at Wanapum Dam. The numerical model predictions were validated with results from a 1:52 comprehensive tailrace model of Wanapum Dam and a 1:24 scale sectional model of the fish bypass which included a portion of the tailrace. The results of these studies are discussed further in Section 3.3.

3.1 Background of Hydrodynamics and TDG Prediction in Tailraces

Until recently, all TDG design projects have required multiple year schedules including: initial field data collection, two-dimensional laboratory modeling, three-dimensional laboratory modeling, field prototype testing and then possible refinement in the laboratory. The primary shortcoming for this approach is that the laboratory models cannot quantitatively predict the change in TDG from various design alternatives due to model scaling issues. The approach relies on qualitative performance curves that relate flow conditions with past field experiences. This has led to variable success in the projects, some being quite successful while others less successful. Obviously, this variable success imposes financial risk onto the dam owners.

Computational fluid dynamics (CFD) modeling offers a potentially powerful tool for TDG and hydrodynamics prediction. It can be used as a tool to help minimize risk to designers. The major issues regarding the prediction of the hydrodynamics and TDG are related with the gas distribution and the effect of spillway surface jets on the flow field. In the application to powerhouse/spillway flows the understanding of the underlying physics and the capability to model these highly three-dimensional physical phenomena is of paramount importance to perform reliable numerical studies.

Very recently, IIHR researchers have developed a numerical tool that accurately predicts the flow field and total dissolved gas concentration. The basis of the approach is the use of the general purpose CFD code, FLUENT, with the incorporation of fundamental physical equations that quantify gas transfer. The resulting model was calibrated against velocity and TDG data for Wanapum Dam and it is currently used to predict the flow field and TDG distribution in Little Goose Dam. The model allows designers to predict the level of TDG reduction for various design alternatives. Additionally, because the model is fully three-dimensional, the spatial variability in TDG is also predicted.

3.1.1 Role of Jet Hydrodynamics

It has been demonstrated that surface jets caused by spillway flows may cause a significant change of the flow pattern in the tailrace since they attract water toward the jet region, a phenomena called water entrainment (Liepmann 1990, Walker and Chen 1994, Walker 1997). Figure 1 illustrates the water entrainment from the powerhouse to the spillway region observed at Wanapum Dam. This entrainment leads to mixing, modifying the TDG field.

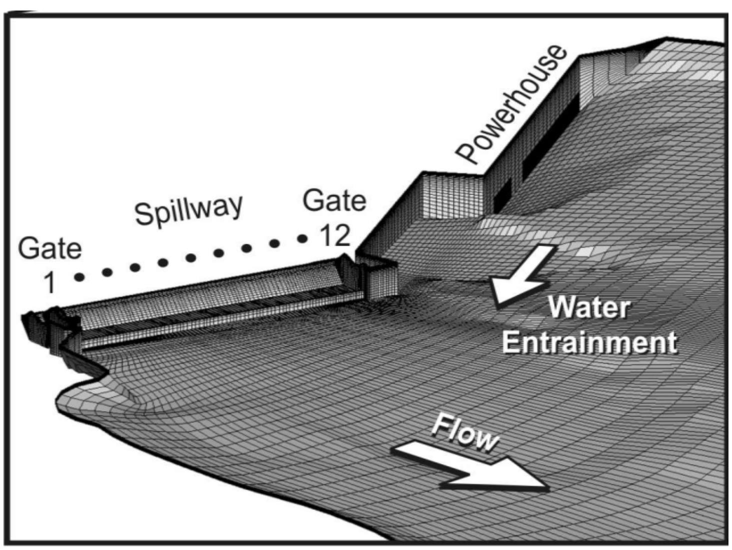


Figure 1. Water entrainment at Wanapum Dam

Figure 2 shows the contours of streamwise velocity and velocity vectors in a vertical plane through a superficial jet. Several mechanisms causing the water entrainment can be identified (Turan et al. 2007):

- Acceleration of the surrounding fluid as the jet decelerates: as stagnant liquid is accelerated by the jet it has to be replaced by surrounding fluid and causes entrainment.
- Surface currents: a vertically thin region of large transverse velocity develops adjacent to the surface. This phenomena can be explained by attenuation of the normal Reynolds stress near the free-surface and redistribution of kinetic energy.
- Coanda effect: jet migrates to a limiting boundary. In that boundary the pressure is smaller than in the surroundings, attracting flow and causing entrainment.

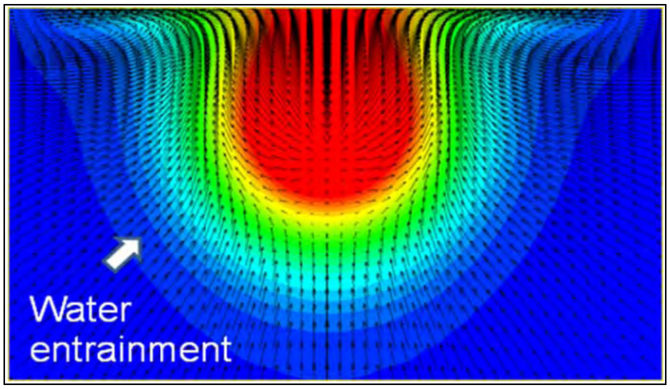


Figure 2. Streamwise velocity contours and vectors through a jet

As an additional complexity, the presence of bubbles has a strong effect on the hydrodynamics:

- The air-water mixture has an effective density smaller than the surrounding fluid: since most of the bubbles are generated by the impact of the spillway flow with the tailrace fluid, the maximum bubble volume fraction occurs within the jet. Due to buoyancy, this bubbly jet tends to rise and remain on the surface.
- The air-water mixture has a smaller effective shear stress: as the gas volume fraction increases, the shear stress decreases, contributing to maintain the jet.
- The turbulence is also affected by bubbles: work is done in providing buoyancy to the bubbles, energy is dissipated by lateral relative motion or rotation of the bubbles, and energy is absorbed by the bubbles.

3.1.2 Role of Bubbles

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 in the stilling basin and the mass transfer between bubbles and water.

The TDG distribution depends on extreme complex processes such as air entrainment in the spillway face, entrainment when the jet impacts the tailwater pool, breakup and coalescence of the bubbles entrained, dissolution of the entrained bubbles and degasification at the free surface. The complete process of air entrainment into the liquid flow for single jets has been studied previously by several researchers (Bin, 1993; Chanson, 1996; DeMoyer et al., 2003). The bubble breakup and coalescence processes can be considered negligible in the region downstream of the plunging jet where the gas volume fraction is relatively small.

Bubble dissolution

In the highly aerated flow below a spillway, the TDG concentration is mainly governed by the dissolution of the entrained bubbles. The mass transfer between the bubbles and the liquid column depends on the following parameters:

- Pressure: the elevated solubility of water under pressure results in supersaturation of the TDG concentration. The total pressure is composed of the atmospheric, hydrostatic and dynamic pressures. As an example, considering only hydrostatic pressure, gas solubility will double by moving from the water surface to a depth of about 10.3 m.
- Bubble size: the bubble size changes with the bubble dissolution and pressure.
  - At the same gas volume fraction, the bubble dissolution increases as the bubble size reduces due bigger interfacial area of small bubbles.
  - The bubble rise velocity increases with the bubble size, therefore larger bubbles are lost before the smaller bubbles, have a shorter residence time, and transfer less gas to the liquid.
- Turbulence: external turbulence could be important, mainly in regions of high shear near the walls and where the plunging jet impacts, enhancing the mass transfer.
- Interfacial tension: the dissolution of very small bubbles increases due to interfacial forces.
- Temperature: the dissolution decreases as the temperature of water is increased.

Degasification at the free surface

The mass transfer at the water surface drives to saturated TDG. The degasification at the free surface depends on the turbulence and surface waves that increase the air-water interfacial area.

3.1.3 Predictions with Reduced-Scale Models

Reduced-scale hydraulic models grossly under-predict the degree of entrainment observed in the field. Turbulent structures, air entrainment, and bubble size are not replicated to scale in a hydraulic model. As surface currents originated by superficial jets depend on the turbulence, the degree of entrainment in the hydraulic model is underestimated. Figures 3a and 3b show the simulated streamwise velocity at prototype and model scales. Note that the surface jets in the hydraulic model are weaker with less water entrainment.

Figures 3c and 3d show the gas volume fraction predicted at prototype and model scale assuming the same entrained volume fraction and bubble size in the spillway. In the reduced-scale model, bubbles rise to the surface faster and closer to the spillway with minor effect on the flow field. The effective density and shear stress in the reduced-scale model are larger, causing water entrainment to be underestimated. In addition, the suppression of turbulence due to bubbly flow is limited to a small region close to the spillway resulting in weaker jets.

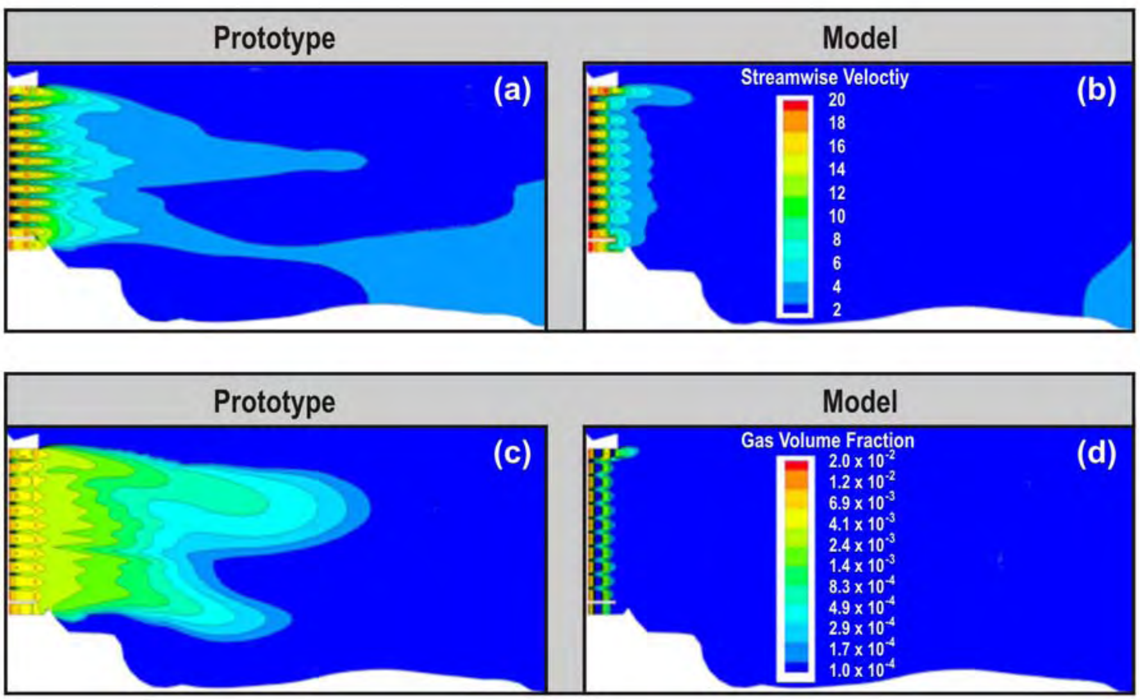


Figure 3. Simulated jets at prototype and model scales

3.1.4 Predictions with Standard CFD Models

Single-phase, isotropic RANS models grossly under-predict the degree of entrainment observed in the field. The presence of the free surface constrains the vertical motion of eddies. Since there are no restrictions on the tangential components of velocity, these turbulent components do not vary appreciably near the free surface. Therefore, the turbulent vertical velocity fluctuations are reduced and the horizontal velocity fluctuations are increased through a redistribution of the turbulent energy.

Most standard CFD models fails to predict the water entrainment because they do not consider the attenuation of the normal fluctuation at the free surface and therefore over-predict diffusion. Figure 4 shows streamwise velocity predicted with a standard isotropic model and a model considering the attenuation of the normal fluctuations at the free surface. If the normal fluctuations are not attenuated, the surface jet is weaker and the entrainment is under-predicted.

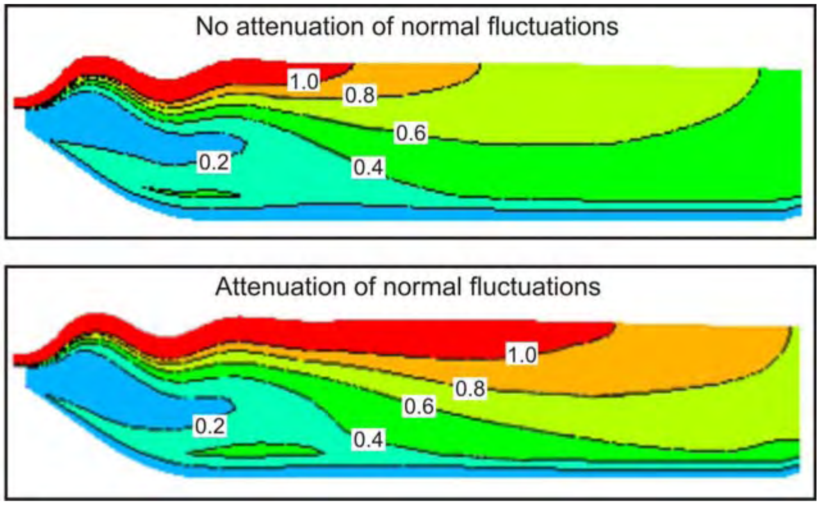


Figure 4. Streamwise velocity in simulated spillway jet with and without attenuation of normal fluctuations at the free surface

Single phase models do not consider the effect of the bubbles on the flow field. This results in weaker jets and under-prediction of the water entrainment.

3.2 Detailed Description of IIHR's TDG Model

A two-phase anisotropic turbulence model with attenuation of velocity fluctuations at the free surface was developed at IIHR to predict the water entrainment and TDG concentration in tailraces. The change in the density and shear stress in the mixture air-liquid is considering using a two-phase Eulerian model.

The Volume of Fluid (VOF) method is used to predict the flow regime and the free surface position. A rigid, non-flat lid approach, which utilizes the free surface shape obtained with the VOF method, is then used for the two phase flow model to obtain the hydrodynamics and TDG distribution.

The model assumes one variable bubble size, which may change due to local bubble/water mass transfer and pressure. The air entrainment (gas volume fraction and bubble size) is assumed a known inlet boundary condition. The model is intended for the region downstream of the jet impingement where the bubble breakup and coalescence process may be considered negligible. The bubble velocity for each size is calculated from a balance between gravity, pressure, drag and turbulent dispersion forces.

The model uses a Reynolds Stress Model (RSM) to provide anisotropic closure for the two-phase Reynolds-Averaged Navier-Stokes (RANS) equations. In order to capture the turbulence structures and water entrainment, a simple but effective boundary condition to enforce zero normal fluctuations at the free surface is implemented. A modified bubble-induced turbulence term is extended for the Reynolds stress components to account for suppression and production of turbulence by the bubbles.

The TDG is calculated with a two-phase transport equation in which the source is the bubble/liquid mass transfer. The effect of the pressure, gas volume fraction, bubble size, interfacial tension and turbulence on the mass transfer is considered in the model. The rate of mass transfer is computed considering that the air is soluble in water and obeys Henry's law and that the air molar composition is that of equilibrium at atmospheric pressure, which implies that the air is considered a unique gas with molar averaged properties.

It must be noted that the choice of bubble size and volume fraction at the spillway bays has an important effect on the level of entrainment. In general a bubble size distribution should be provided from experimental data. In the IIHR model a reasonable single-size bubble diameter and volume fraction are assumed. In order to match the observed hydrodynamics and TDG concentrations, the effect of the bubbles on the turbulence field is considered using a bubble turbulence constant $C_u = 0.5$. These three parameters are the only external parameters of the model.

The model was implemented into the commercial code FLUENT 6.2, which offers flexibility in the programming for specific physical models and boundary conditions.

3.2.1 Free Surface Modeling

The free surface can be modeled in FLUENT using the VOF method. The VOF method solves the RANS equations coupled to a surface-capturing algorithm. In the VOF model, the interface between fluids is calculated with a water volume fraction (α_w) equation. Mass conservation of the water phase requires that:

$$\frac{\partial \alpha_w}{\partial t} + \mathbf{v} \cdot \nabla \alpha_w = 0 \qquad (1)$$

Additionally, mass conservation required that cells can only be occupied by each fluid or a mixture of fluids, or numerically $\alpha_w + \alpha_a = 1$. Points in water have $\alpha_w = 1$, points in air have $\alpha_w = 0$, and points near the interface have $0 < \alpha_w < 1$. The jump conditions across the interface were embedded on the model by defining the fluid properties as: $\phi = \phi_w \alpha_w + \phi_a (1 - \alpha_w)$, where ϕ is either the density or the viscosity.

The VOF method works very well for flow regime predictions. However, the VOF method shows high numerical diffusion near the interface which destroys the surface jet and prevents prediction of the water entrainment, irrespective of the turbulence model used. The implementation of attenuation of normal fluctuations at the free surface in a VOF approach is complex in the framework of User Defined Functions (UDFs). Since the interface is not a boundary but is represented by an iso-surface ($\alpha = 0.5$), the enforcement of zero normal fluctuations requires body forces. This approach is more complex and it is expected to be significantly more expensive to perform the computations. In addition, the VOF model is not available with two-phase flow models in commercial codes; therefore the effect of bubbles cannot be easily simulated.

In order to predict the flow field and TDG entrainment, the VOF method is used to estimate the free surface position which is then fixed throughout the computation (rigid, non-flat lid approach) for the water entrainment and TDG predictions.

3.2.2 The algebraic slip mixture model

The algebraic slip mixture model available in FLUENT solves continuity and momentum equations for the mixture phase:

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_i}(\rho_m U_{m,i}) = 0 \tag{2}$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho_m U_{m,i}) + \frac{\partial}{\partial x_j}(\rho_m U_{m,i} U_{m,j}) = -\frac{\partial P}{\partial x_i} + \mu_m \frac{\partial^2 U_{m,i}}{\partial x_j^{\,2}} - \frac{\partial}{\partial x_j}\left(\rho_m \overline{u_{m,i} u_{m,j}}\right) + \\ \frac{\partial}{\partial x_i}\left(\alpha_g \rho_g \varepsilon_{ijk} U_{dr,g,j} U_{dr,g,k} + \alpha_l \rho_l \varepsilon_{ijk} U_{dr,l,j} U_{dr,l,k}\right) \end{aligned} \tag{3}$$

where P is the total pressure, ρ_m, μ_m and U_m are the mixture density, viscosity, and mass-averaged velocity defined as $\rho_m = \alpha_g \rho_g + \alpha_l \rho_l$, $\mu_m = \alpha_g \mu_g + \alpha_l \mu_l$ and $U_m = \frac{\alpha_g \rho_g U_g + \alpha_l \rho_l U_l}{\rho_m}$, with α_g the gas volume fraction. The subscripts *g* and *l* denote gas and liquid, respectively. $U_{dr,g}$ is the drift velocity defined as the velocity of the phase *g* relative to the mixture velocity.

The gas volume fraction is calculated from a continuity equation for the gas phase:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right)+\frac{\partial}{\partial x_i}\left(\alpha_g \rho_g U_{g,i}\right)=0 \tag{4}$$

The velocity of the phase g respect to phase l, U_{gl}, in most of the two phase models available commercial codes (Fluent, CFX, CFDLib, between others) assume a mean constant bubble size for the evaluation of the interfacial forces (Chen et al. 2005). In the IIHR model, an algebraic equation for the relative velocity $\vec{u}_r$ accounting for gravity, pressure, drag and turbulent dispersion forces for variable bubble size is used:

$$0=\alpha\frac{\partial P}{\partial x_i}+\rho_g\,\alpha\,g_i-\frac{3}{8}\alpha\,\rho_l\,\frac{C^D}{R}u_{r,i}\left|\vec{u}_r\right|-\frac{3}{8}\,\rho_l\,\frac{\nu_t}{Sc_b}\frac{C^D}{R}\left|\vec{u}_r\right|\frac{\partial\alpha}{\partial x_i} \tag{5}$$

where g is the gravity acceleration, R is the bubble radius, ν_t is the turbulent viscosity and $Sc_b=1$ is the bubble Schmidt number (Carrica et al. 1999). Note that this equation allows the bubbles to move at different velocities depending on their sizes. The standard drag coefficient is used (Ishii & Zuber, 1979, Moraga *et al.* 2003):

$$C^D=\begin{cases}\dfrac{24}{\mathrm{Re}_b} & if\ R<0.002\\ \dfrac{24\left(1+0.15\,\mathrm{Re}^{0.687}\right)}{\mathrm{Re}_b} & if\ 0.002<R<0.00222\\ 0.56 & if\ R>0.00222\end{cases} \tag{6}$$

where $\mathrm{Re}_b=2\rho_l\left|\vec{u}_r\right|R/\mu_l$ is the bubble Reynolds number.

3.2.3 <u>Bubble number density transport equation</u>

A transport equation for the bubble number density is implemented to predict the local bubble size. In flows downstream of the impingement region, the bubble size changes mainly due to mass transfer and pressure variations:

$$\frac{\partial N}{\partial t}+\frac{\partial u_{g,i}N}{\partial x_i}=0 \tag{7}$$

The bubble radius, which is needed to calculate interfacial forces in Eq. (5) and air-water mass transfer, is calculated from $R = [3\alpha/(4\pi N)]^{1/3}$.

3.2.4 Two-phase total dissolved gas transport equation

The TDG concentration in a given position is governed by a balance between the TDG transport due to the velocity field, air-water mass transfer and TDG transport due to concentration gradients.

A TDG transport equation is obtained using a mass balance of the gas dissolved in the liquid phase in a control volume. The resulting two-phase TDG transport equation is (Politano et al. 2007):

$$\frac{\partial \alpha_l C}{\partial t} + \frac{\partial u_{g,i} \alpha_l C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\nu_m + \frac{\nu_t}{Sc_C}\right)\alpha_l \frac{\partial C}{\partial x_i}\right) + S \qquad (8)$$

where C is the TDG concentration, ν_m the molecular viscosity and S the TDG source due to the air transfer from the bubbles to the liquid. The mass flux from gas to liquid can be expressed by (Deckert 1992, Politano et al. 2007):

$$S = 4\pi N R^2 k_l \left(\frac{P + \sigma/R}{He} - C\right) \qquad (9)$$

where σ is the interfacial tension and He is Henry's constant. The second term on the right hand side of Eq. (9) accounts for the effect of the interfacial tension on the equilibrium concentration. Takemura and Yabe (1998) proposed a correlation for the mass transfer coefficient of spherical rising bubbles, where the turbulence is generated by the bubble rising:

$$k_l^{rb} = \frac{D\,Pe^{0.5}}{R}\left(1 - \frac{2}{3\left(1 + 0.09\,\mathrm{Re}^{2/3}\right)^{0.75}}\right) \qquad (10)$$

where D is the molecular diffusivity and the Peclet number is $Pe = 2\left|\vec{u_r}\right| R/D$. In this case, the mass transfer coefficient can be calculated using the expression proposed by Lamont and Scott (1970):

$$k_l^t = 0.4\,Sc^{-1/2}(\nu\,\varepsilon)^{1/4} \qquad (11)$$

where $Sc = D/\nu$ and ε is the dissipation rate of turbulent kinetic energy. The maximum mass transfer coefficient between bubbles rising in stagnant liquid (k_l^{rb}) and bubbles in turbulent flow (k_l^t) is used: $k_l = \max\left(k_l^{rb}, k_l^t\right)$.

3.2.5 Turbulence closure

The Reynolds stresses , $\frac{\partial}{\partial x_j}\left(\rho_m \overline{u_{m,i}u_{m,j}}\right)$, in Eq. (3) need to be modelled to close the system of equations. The Reynolds Stress Model which solves transport equations for the six Reynolds stress components is given (Launder et al. 1975, Gibson and Launder 1978 and Launder 1989):

$$\frac{\partial}{\partial t}\left(\rho_m \overline{u_{m,i}\,u_{m,j}}\right)+\frac{\partial}{\partial x_k}\left(\rho_m U_{m,k}\,\overline{u_{m,i}\,u_{m,j}}\right)=\frac{\partial}{\partial x_k}\left[\left(\mu_m+\frac{\mu_m^t}{\sigma_R}\right)\frac{\partial \overline{u_{m,i}\,u_{m,j}}}{\partial x_k}\right]- \rho_m\left(\overline{u_{m,i}u_{m,k}}\,\frac{\partial U_{m,j}}{\partial x_k}+\overline{u_{m,j}u_{m,k}}\,\frac{\partial U_{m,i}}{\partial x_k}\right)+\phi_{ij}-\rho_m\,\varepsilon_{ij} \tag{12}$$

where $\sigma_R = 0.82$ and ϕ is the pressure-strain term that takes into account the redistribution of normal stresses near the wall. This term is calculated using the models proposed by Launder et al. (1975), Gibson and Launder (1978) and Launder (1989). The transport equations for the turbulent dissipation rate, ε , is given by (Launder and Spalding, 1972):

$$\frac{\partial}{\partial t}\left(\rho_m\,\varepsilon\right)+\frac{\partial}{\partial x_i}\left(\rho_m\,\varepsilon U_{m,i}\right)=\frac{\partial}{\partial x_j}\left[\left(\mu_m+\frac{\mu_m^t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}G_k-C_{\varepsilon 2}\,\rho_m\,\frac{\varepsilon^2}{k} \tag{13}$$

The turbulent viscosity is $\mu_m^t = C_\mu\,\kappa^2/\varepsilon$ with $C_\mu = 0.09$.

Effect of bubbles on the turbulence field

It was observed that turbulence is altered when bubbles are added to the flow (Wang *et al.* 1987, Serizawa and Kataoka 1990, Kataoka *et al.* 1993, Lopez de Bertodano *et al*. 1994). This phenomenon is explained by Serizawa (1974) considering the competition among the following effects: work done in providing buoyancy to the bubbles, energy dissipation associated with the lateral relative motion or rotation of the bubbles, and energy absorption by the bubbles. According to Wang *et al.* (1987) the last effect accounts for most of the reduction in the turbulence. A reduction in turbulence would cause a stronger superficial jet and more water entrainment.

The bubble induced turbulence S_b proposed by Kataoka *et al.* (1993) is programmed into FLUENT. As the anisotropy is hardly affected by bubbles (Wang *et al.* 1987), the source term for the transport equation of a shear stress component is assumed to be proportional to the contribution of the shear stress component to the kinetic turbulent energy:

$$S_{b-u_i} = C_u \left(\alpha \frac{\left(\sum_j u_j u_j \right)^{3/2}}{2R} + \alpha\, C^D \frac{\left| \overrightarrow{u_r} \right|^3}{2R} \right) \frac{u_i u_j}{\sum_j u_j u_j} \tag{14}$$

where u_i is the velocity fluctuation in the *i* direction and C_u is a model constant. Kataoka *et al.* (1993) used $C_u = 1$ to match the experimental data in pipes. The effect of bubbles in the turbulence dissipation rate is modeled following Solbakken and Hjertager (1998):

$$S_{b-\varepsilon} = C_{\varepsilon 1}\, S_{b-u_i} \frac{\varepsilon}{\sum_j u_j u_j} \tag{15}$$

where $C_{\varepsilon 1} = 1.44$ is a $k - \varepsilon$ model constant.

3.2.6 Boundary conditions

Walls and river bed

The sides and the river bed are considered impermeable walls with zero TDG flux. For the gas phase, no penetration across walls is assumed.

Outflow

The exit is defined as an outflow. A zero gradient condition is programmed for the TDG concentration and bubble number density.

Spillway and powerhouse

Uniform velocities with constant gas volume fraction of $\alpha = 0.1$ and bubble radius $R = 0.001$ *m* are used for the bays in the spillway region for all the simulations.

It is assumed that air is not entrained with the turbine flow and that the travel time in the spillway is short so that the exposure of water to air is limited. Therefore, the TDG concentration measured in the forebay is used as inlet condition at the spillway bays and powerhouse units.

Free surface

The free surface is usually modelled in FLUENT using a rigid lid approach using symmetry boundary condition or a wall with zero shear stress. The symmetry condition uses zero normal gradients for all of the turbulent quantities. Therefore, this condition fails to model the turbulence anisotropy caused by the free surface. On the other hand, a zero-shear wall boundary condition uses a linear pressure-strain model to redistribute the normal stresses near the wall. To overcome this limitation, the kinematic and dynamic boundary conditions, considering that the normal components of velocity fluctuations are zero at the free surface, were programmed through UDFs.

For the liquid phase, the rigid lid boundary must satisfy the kinematic and dynamic boundary conditions at the free surface. The gas can cross the free surface and thus is not subject to this condition. The kinematic boundary condition imposes zero mass flux across the free surface and the dynamic boundary condition enforces zero shear stresses in the tangential directions. These conditions are easily implemented in a surface-fitted coordinate system with one of the unit vectors normal to the free surface ($\boldsymbol{\eta}$) and the others tangent to it ($\boldsymbol{\zeta}$ and $\boldsymbol{\xi}$). The original system is defined by the coordinate system **x**,**y**,**z**. The new right handed Cartesian orthogonal system is given by the following conditions:

$$\begin{aligned} \boldsymbol{\eta}_i \, \boldsymbol{\xi}_i &= 0 \\ \boldsymbol{\eta}_i \, \boldsymbol{\zeta}_i &= 0 \\ \boldsymbol{\xi}_i \, \boldsymbol{\zeta}_i &= 0 \end{aligned} \tag{16}$$

with positive Jacobian. This system presents three degrees of freedom (DoF). The kinematic and dynamic boundary conditions in the new coordinate system are:

$$U_{k,i} \, \boldsymbol{\eta}_i = 0 \tag{17}$$

$$\begin{aligned} \frac{\partial}{\partial x_j}\left(U_{k,i} \, \boldsymbol{\xi}_i\right) \boldsymbol{\eta}_j &= 0 \\ \frac{\partial}{\partial x_j}\left(U_{k,i} \, \boldsymbol{\zeta}_i\right) \boldsymbol{\eta}_j &= 0 \end{aligned} \tag{18}$$

The presence of the free surface on the vertical motion of eddies can be modeled assuming that the normal fluctuations and the gradient of the tangential fluctuations in the normal direction are zero at the free surface. This approach assumes that the free surface elevation and resulting velocity fluctuations are small and can be neglected:

$$u_{m,i}\,\boldsymbol{\eta}_i = 0 \tag{19}$$

$$\begin{aligned}\frac{\partial}{\partial x_j}\left(u_{m,i}\,\boldsymbol{\xi}_i\right)\boldsymbol{\eta}_j &= 0\\ \frac{\partial}{\partial x_j}\left(u_{m,i}\,\boldsymbol{\zeta}_i\right)\boldsymbol{\eta}_j &= 0\end{aligned} \tag{20}$$

The gas phase is free to flow across the interface. Most of the studies found in the literature use a zero gradient condition for the gas velocity or assume terminal velocity at the free surface. This approaches resulted in bubble accumulation at the free surface. In the IIHR model, the normal component of the gas velocity at the free surface is calculated using a mass balance for the gas phase in each control volume contiguous to the interface and the resulting equation are implemented using UDFs.

For TDG, a Neumann boundary condition is used to represent the degasification at the free surface. The mass transfer coefficient at the free surface, from experimental data for tanks and bubble columns (DeMoyer et al. 2003), is $k_l = 0.0001$ m/s.

3.2.7 Numerical model

The mixture model equations are solved sequentially with the control volume technique used by FLUENT. The continuity condition is enforced using the SIMPLE algorithm. The pressure at the faces is obtained using the body force weighted scheme. The algebraic equation for the relative gas liquid velocity (Eqs. 5 and 6), the mass transfer from bubbles to liquid (Eqs. 9 to 11), the bubble-induced turbulence terms for the Reynolds Stress components and turbulent dissipation rate (Eqs. 15 and 16), free surface conditions (Eqs. 16 to 20) and specific boundary conditions for gas volume fraction and TDG are programmed using UDFs. Two two-phase scalar transport equations are used to calculate the TDG concentration and bubble number density.

3.3 Illustrations of Hydrodynamic Regime and TDG Predictions at Wanapum Dam

3.3.1 Prediction of flow regimes for Wanapum Tailrace

Numerical studies were performed to assist in the design of the future unit fish bypass (FUFB) structure for the downstream passage of juvenile salmonids through Wanapum Dam. The numerical model was used to investigate flowrate and free surface topology for different headwater elevations and gates settings. In order to obtain valid predicted stresses, the numerical model was constructed at prototype scale. Four different headwater elevations were considered. The numerical model was tested with free flow (ungated) and with gated flows. A vertical gate and one, two or three of the inclined gates were inserted within the gate slots for the gated flows. A detailed description of the physical and numerical studies related to this project is found in Lyons et al. (2005).

Grid design and operational conditions

Structured and unstructured hybrid grids accommodated the complex FUFB geometry, which included three gate slots, flow control gates, and an aeration slot. The grids were generated using GridgenV15.4. Hybrid grids, each containing around 1,000,000 nodes, were used for the various forebay and gate conditions. The grid quality was critical to achieve convergence. Historically, collocated methods had more problems of instabilities on the air-water interface region when using non-orthogonal grids and high aspect ratio. For this reason, nearly orthogonal structured grids with cell aspect ratio smaller than 10 and with expansion ratio no greater than 2 were used in the FUFB model wherever possible. Since the geometry was too complex to generate a fully structured grid with good quality (mainly when gates and gate slots are considered), complex geometry regions were generated using unstructured grids in one plane and structured on the third direction.

A view of a typical grid is shown in Figure 5. To resolve critical regions of interest, grids were refined at all no-slip (zero velocity) wall conditions, near the gates where large accelerations were found, and near the free-surface (critical to obtain good quality results). As a consequence, different grids were generated for each case in which the free surface location changed to properly fit the free surface region with a good quality structured grid.

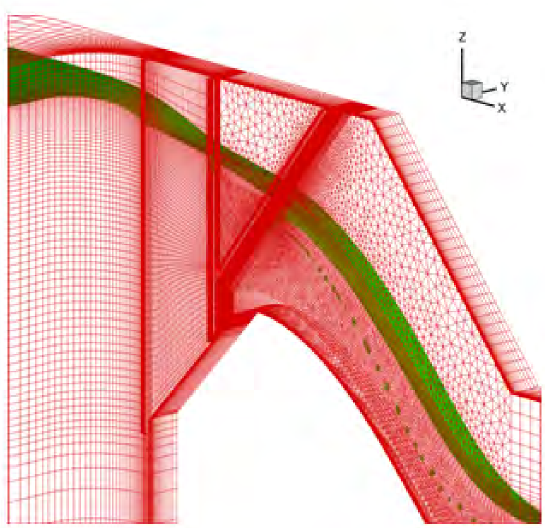


Figure 5. Grid for the FUFB free surface computations

Numerical Results

A typical solution is shown in Figure 6 in which the free surface is illustrated in light blue and streamline ribbons are depicted in red, yellow, green, and blue. The right wall is shown transparent to allow better flow visualization.

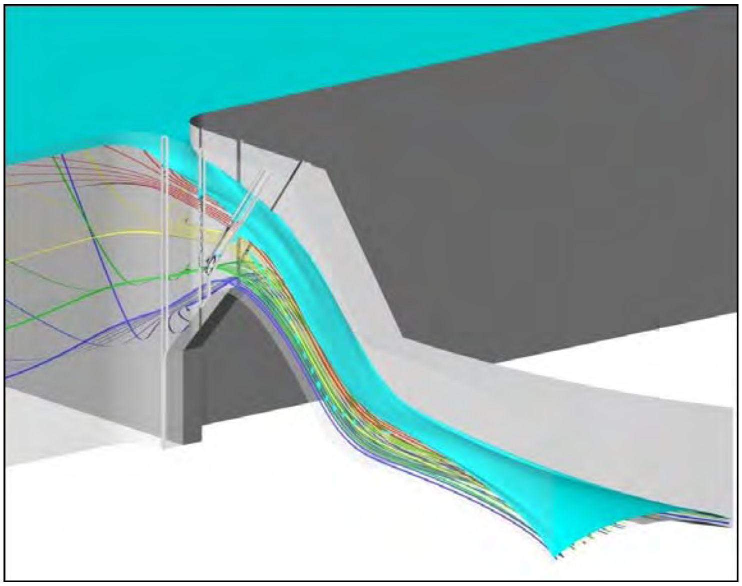


Figure 6. Numerical model graphic of streamlines and free surface for a typical solution

Free surface elevations, pressure at the ogee surface, and discharge rating curves were compared to experimental data taken on the 1:24 scale laboratory model for different forebay elevations and gate controls.

Figure 7 shows gate rating curves with flowrate comparison between the experimental data and the numerical data for regulated and unregulated flow conditions. The agreement between the measured 1:24 laboratory model and predicted numerical model discharges was favorable, with less than 2% difference for each point. Differences were likely due to approximations made on the numerical model, including the symmetry assumption, the extension of the inlet fairings to the bottom of the forebay, and to small errors in headwater elevation control caused by the spill region height at the inlet boundary. Differences could also be attributed to uncertainties in measuring flowrate, headwater, and gate invert elevation on the 1:24 model.

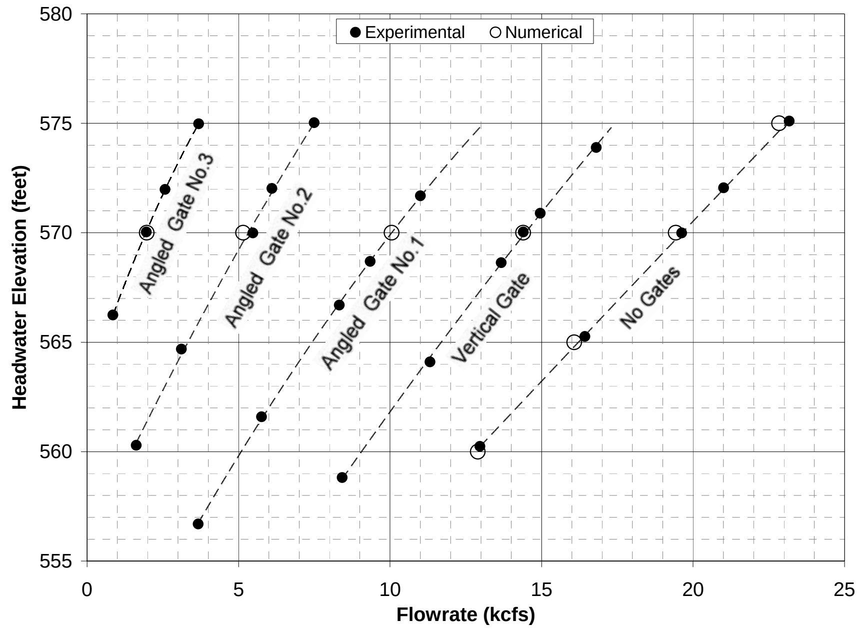


Figure 7. Experimental and numerical rating curves for gated and ungated conditions

Numerical gage pressure values at the ogee symmetry line for headwater elevations 570 and 575 feet are compared to the 1:24 model piezometric results in Figure 8. The 1:24 scale model and numerical model showed good agreement in predicting ogee pressures.

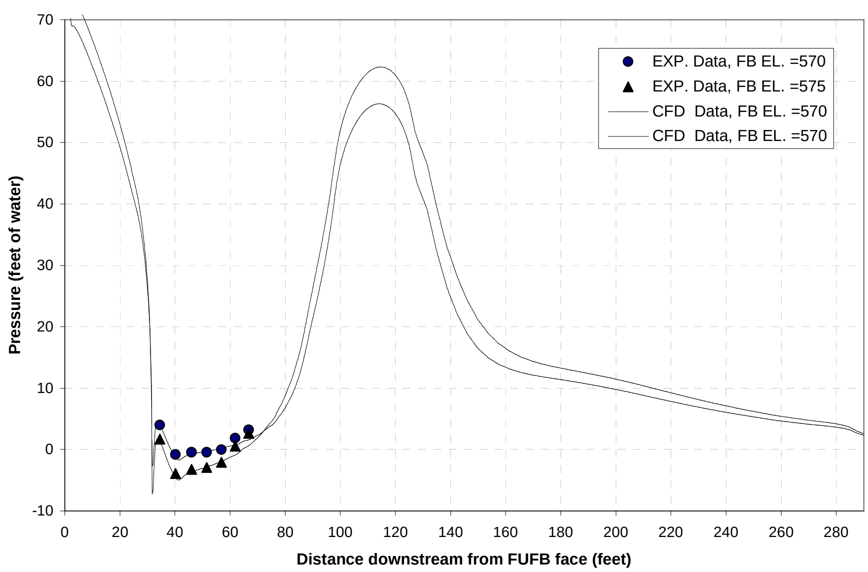


Figure 8. Experimental and numerical gage pressures along the ogee centerline

A complete performance curve was calculated with the numerical model. Figure 9 shows measured and predicted flow regimes. The numerical results presented herein demonstrate that the free surface model can be used to predict the flow regime in tailraces. Figure 10 shows numerically predicted flow regimes for tailwater elevations of 474.6 ft. (top), 479, 483.4, 487.7 and 492.1 ft. (bottom). The plots are colored with total velocity. Notice low tailrace water levels for the first two plots (plunging flow regime), while the flow is parallel to the free surface for the lower three plots (skimming flow regime).

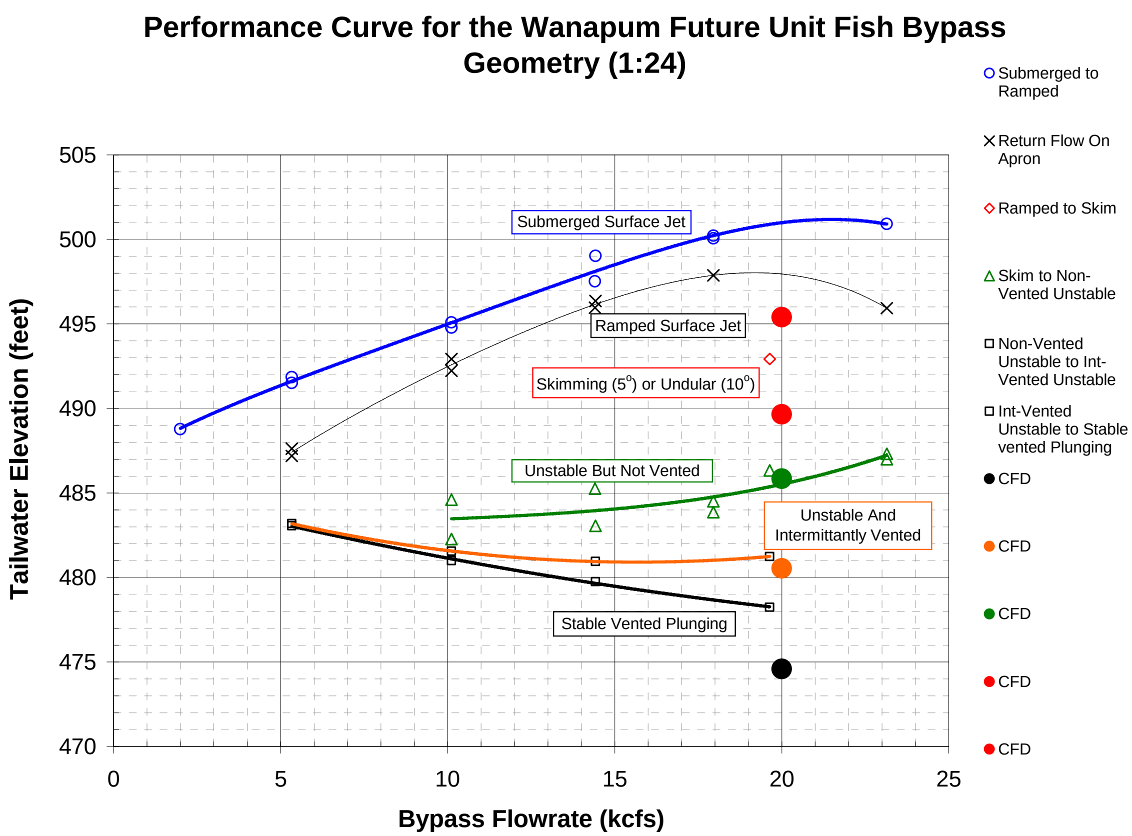


Figure 9. FUFB tailwater performance curve

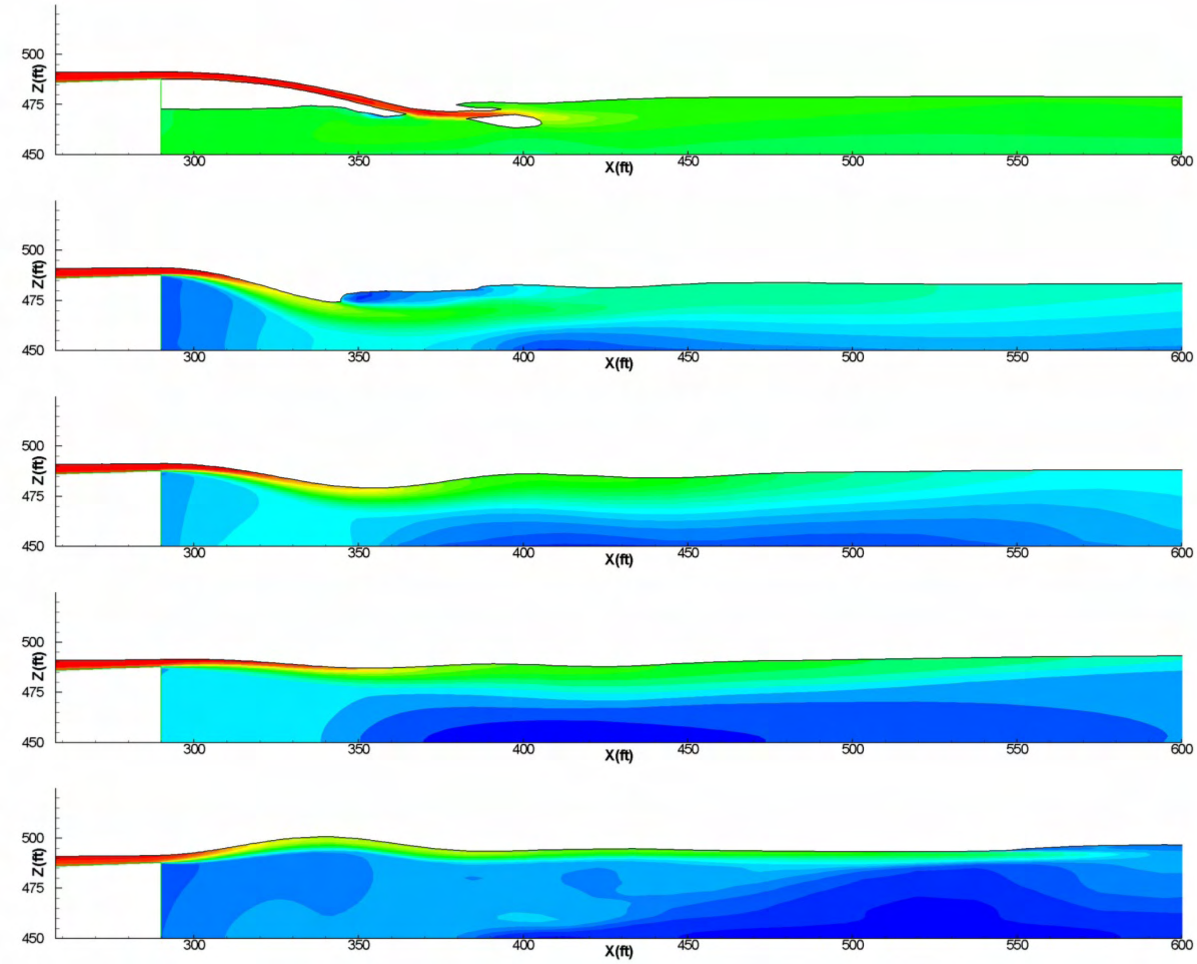


Figure 10. CFD predictions of tailrace flow regimes for the Wanapum Dam future unit fish bypass

3.3.2 <u>Prediction of the hydrodynamics and TDG in Wanapum tailrace</u>

The IIHR model was used to predict TDG in Wanapum tailrace. A contour map of th**e** solution domain is shown in Figure 11. TDG measurements were available for 30 stations along two transects: T1 at 244 m downstream of the spillway, and T2 at 640 m downstream of the spillway (black circles in Figure 11). In addition, instruments were incorporated in the forebay to monitor incoming TDG saturation. To complement this data, velocities were measured along three transects in the near field region of the dam (V1, V2 and V3 in Figure 11).

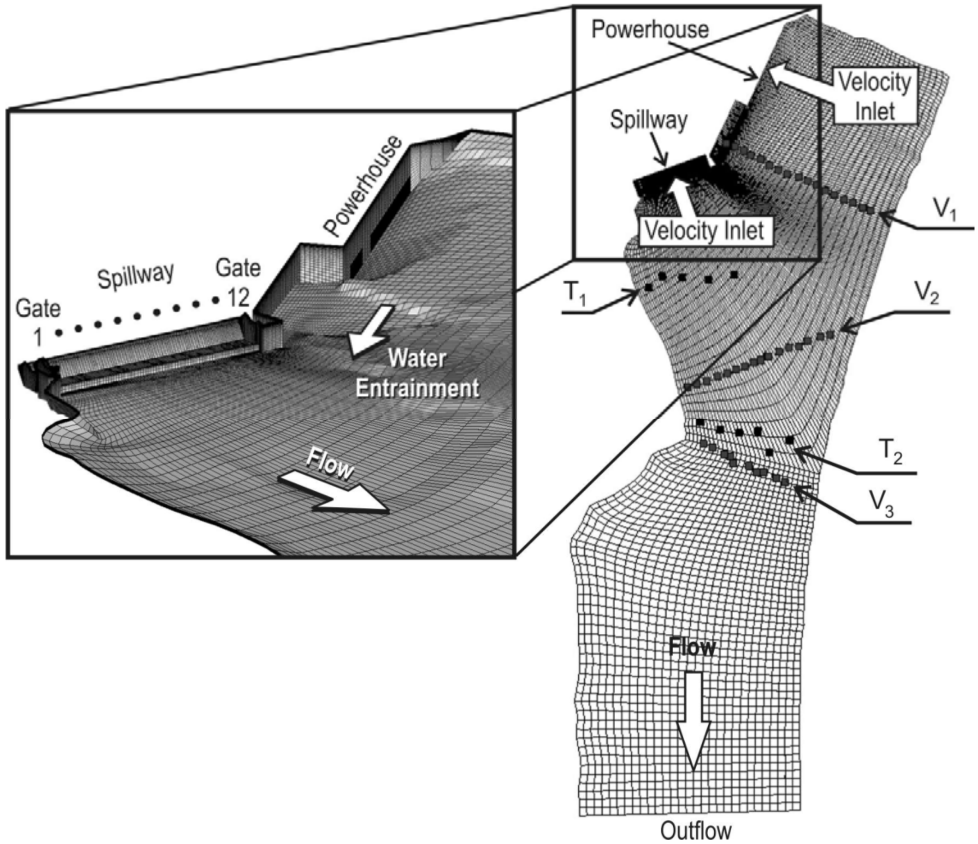


Figure 11. Illustration of the main structures at the Wanapum Dam tailrace, and grid

Grid design and operational conditions

The grid was generated using Gridgen V15. A multi-block structured grid was used to accommodate the complex geometry that includes flow deflectors on all twelve spillway bays, powerhouse units, sluice gate, fish ladders, and tailrace bathymetry. The grid consisted of about 350,000 nodes. Some of the grid and boundary conditions details are shown in Figure 11.

Two operational conditions were simulated to study the performance of the IIHR model. The three model parameters, gas volume fraction and bubble size at the spillway bays, and bubble turbulence constant, were determined using the data collected on May 2, 2000. On this day, the powerhouse and spillway flows were 125 kcfs and 75 kcfs, respectively and an appreciable water entrainment was measured.

The hydrodynamics and TDG distribution were also predicted for April 27, 2000. On this day, powerhouse and spillway flows were 124 kcfs and 140 kcfs, respectively. High spillway flows caused significant water entrainment and TDG concentration levels.

As mentioned in section 2.3.3., the water entrainment is under-predicted in reduced scale laboratory models. In order to evaluate the performance of the IIHR model at reduced scales, a simulation of the hydraulic model using the data recorded on May 2, 2000 was carried out. The predicted velocity data were compared against those obtained in the laboratory.

Validation Case: **Wanapum Tailrace on May 2, 2000**

Hydrodynamics

In Figure 12a the predicted depth averaged velocity is compared against prototype values for May 2, 2000. Black vectors represent the measured data at transects V1, V2, and V3. Green, blue and red vectors represent results obtained with the $k-\varepsilon$ model, RSM model without bubble turbulence production and suppression, and IIHR model (without TDG), respectively. Velocity vectors are compared at the three different transects. Note the entrainment close to the west bank in the first transect (V1). At this position both $k-\varepsilon$ model and the RSM model show similar results of under-predicting the entrainment. Significantly more entrainment is predicted when the bubble turbulence effect is included. In transect two (V2) more flow is observed near the west bank as a result of the water entrainment (note that the spillway flow is smaller than the powerhouse flow). This behavior is captured only by the IIHR model. The difference between the direction of the measured and predicted vectors close to the west bank is about 10 degrees, where the experimental data shows unphysical behavior toward the shore, and mass conservation forces the predicted vectors to move tangential to the boundary. This might be caused by uncertainties in the measured field velocity due to boat movements, inadequate measurement periods when compared with tailrace eddy periods or disagreement between field ADCP compass and boat gyrocompass readings (Haug and Weber, 2006). In the third transect (V3) the effect of the entrainment is diffused and all models show similar results.

Predicted and measured velocity vectors in model scale using the IIHR model are shown in Figure 12b. Note that for this case the water entrainment is considerably smaller than that observed in the prototype scale. Similar to laboratory observations, almost no water entrainment is predicted by the IIHR model.

Figure 12c shows TDG contours and velocity vectors with the IIHR model considering the bubble dissolution. Blue and black vectors represent the measured and predicted data. The inclusion of TDG in the model changes the gas volume fraction and bubble size distribution in the tailrace. The mean bubble size in the tailrace is smaller and the effect of the turbulence suppression by bubbles is stronger. Notice that this model performs best, a very good agreement is observed between predicted and measured velocity vectors in transect V1. This gives a strong indication that the flow field and in particular the water entrainment depends on calculating the Reynolds stresses with components normal to the free surface and the two-phase flow properly.

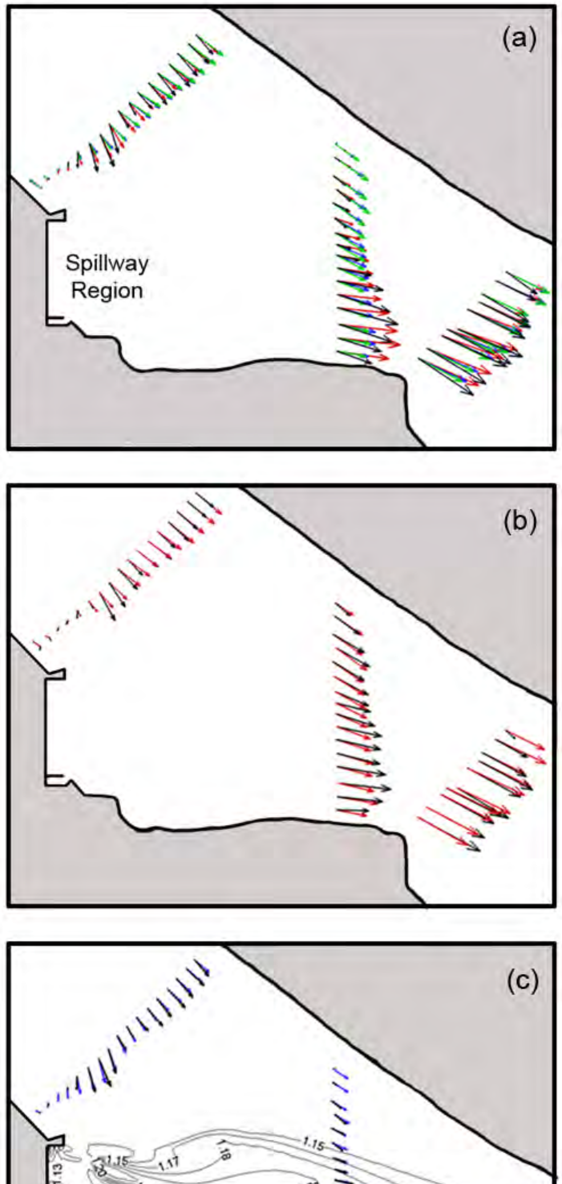


Figure 12. Measured and predicted velocity in Wanapum Dam on May 2, 2000. Black vectors: measured data. a) Prototype scale. Green, blue and red vectors: numerical results with the $k-\varepsilon$ model, RSM model and IIHR model without TDG, respectively, b) Model scale. Red vectors: numerical results with IIHR model, c) TDG contours at 1 m beneath the free surface. Blue vectors: numerical results with IIHR model with TDG.

Figures 13a and 13b show streamlines at the free surface predicted with the $k-\varepsilon$ model and the IIHR model. Note that for the $k-\varepsilon$ model some portion of the streamlines from the powerhouse turn towards to the spillway region. For the IIHR model, most of the flow from the powerhouses turns towards the spillway region instead of flowing towards the exit. This effect is more important when the bubble turbulence production and suppression is incorporated.

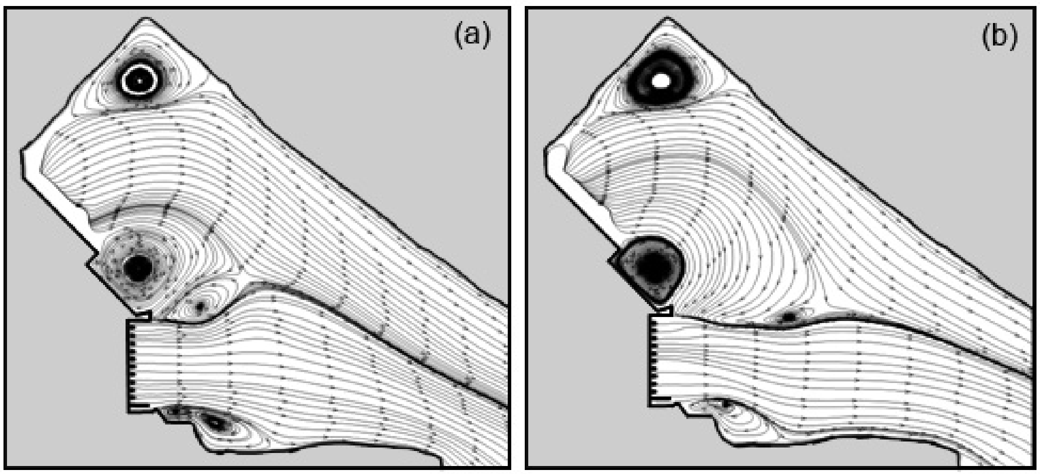


Figure 13. Streamlines at the free surface. a) $k-\varepsilon$ model and b) IIHR model.

TDG Predictions

Figure 14 shows the predicted and measured TDG as a function of the distance to the west shore at transects T1 and T2 (see Fig. 10). A good agreement between measured and predicted TDG concentration is observed. The highest value predicted at transect T1 is 1.21 and occurs close to the center of the spillway. The TDG at the east end of the transect T1 is diluted by powerhouse flow. In order to match the experimental observations it was necessary to include the effect of the bubbles on the turbulence field, considering a $C_u = 0.5$. The highest value at Transect T2 is found near the west side.

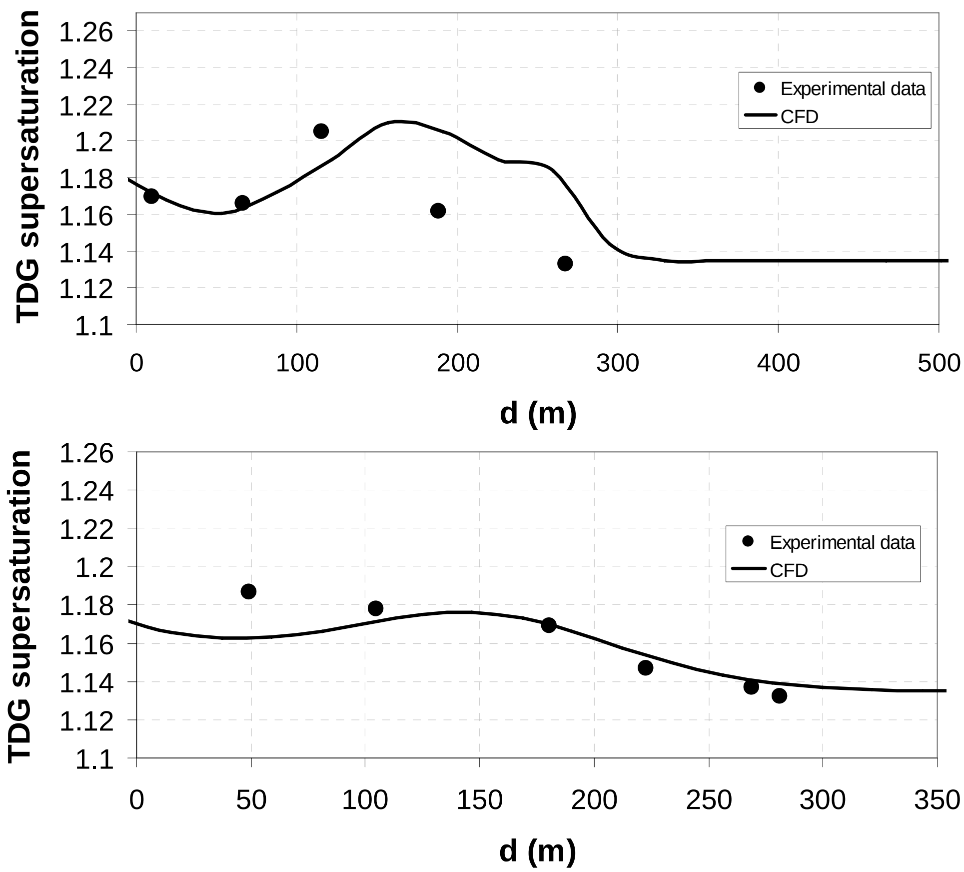


Figure 14. Measured and predicted TDG concentration in a) T1 and b) T2 on May 2, 2000.

In Figure 15 streamlines colored by TDG illustrate the water entrainment and TDG distribution in the tailrace. The two marked sections show the location of transects T1 and T2 were TDG measurements are available. When the effect of the bubbles on the flow field and the anisotropy at the free surface is included, the model is able to predict stronger spillway surface jets and a high portion of the powerhouse flow turns towards the spillway region. The inflow of water with low TDG from the powerhouse causes dilution and promotes mixing and redistribution of TDG. The highest TDG concentration is observed near the spillway endsill at the west region reaching 140%. At this position, the powerhouse inflow is a minimum and contains higher TDG concentration due to exposure to the aerated flow as it travels within the basin. Note the streamlines at the east side of the spillway near the free surface with low TDG concentration. At this location, the bubbles have moved up to regions of lower pressure with negative dissolution rate (absorption of air from the liquid to the bubbles) and strong degasification at the free surface.

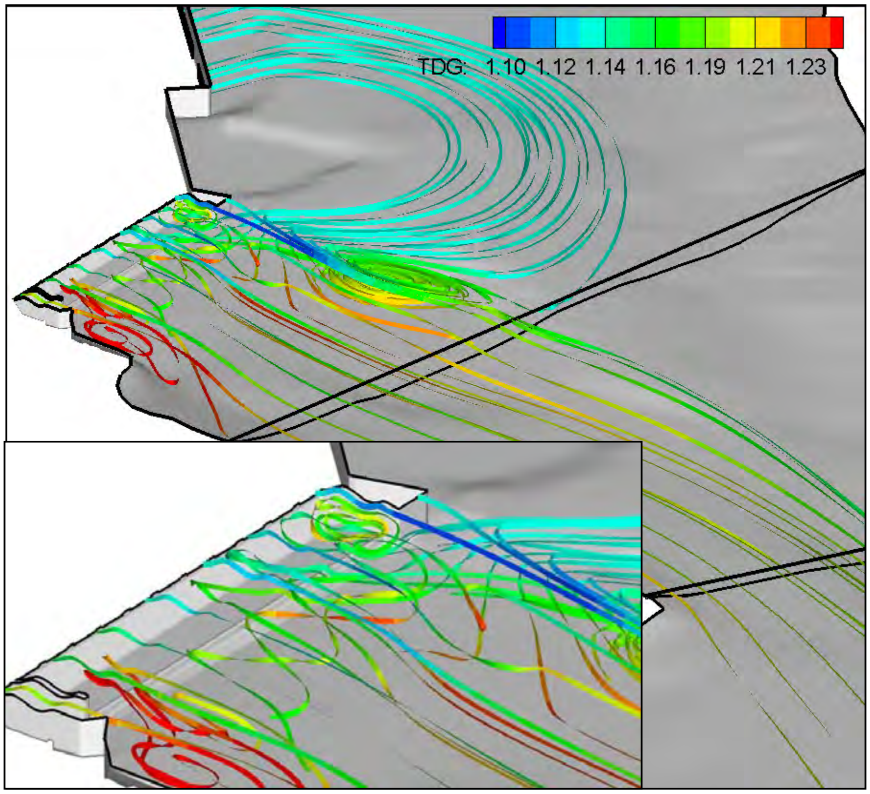


Figure 15. Streamlines colored by TDG concentration at the Wanapum tailrace on May 2, 2000

Figure 16 shows the spatial distribution of predicted TDG, gas volume fraction and bubble diameter contours. The gas dissolution region occurs within 50 to 100 m downstream of the spillway, after which the bubbles move up to regions of lower pressure and the dissolution rate decreases, with the possibility of becoming negative close to the free surface. Substantial desorption of TDG also takes place near the free surface downstream of the spillway (see Figs. 15 and 16a). Once the air bubbles are vented back into the atmosphere, the rate of mass exchange decreases significantly. The TDG concentration decreases downstream of the stilling basin and reaches a developed condition approximately 1 km from the spillway. As shown in Fig. 16b, surface jets are effective because they prevent bubbles from plunging deep, reducing thus the exposure of the bubbles to high pressure. However, a vertical circulation vortex generated beneath the surface jet transports some bubbles deep in the basin. Fig. 16c shows the bubble diameter. Near the bottom the bubbles shrink due to the air mass transfer and high pressure. The smaller the bubble size the stronger its tendency to dissolve. On the other side, near the free surface the bubbles grow due to the pressure drop.

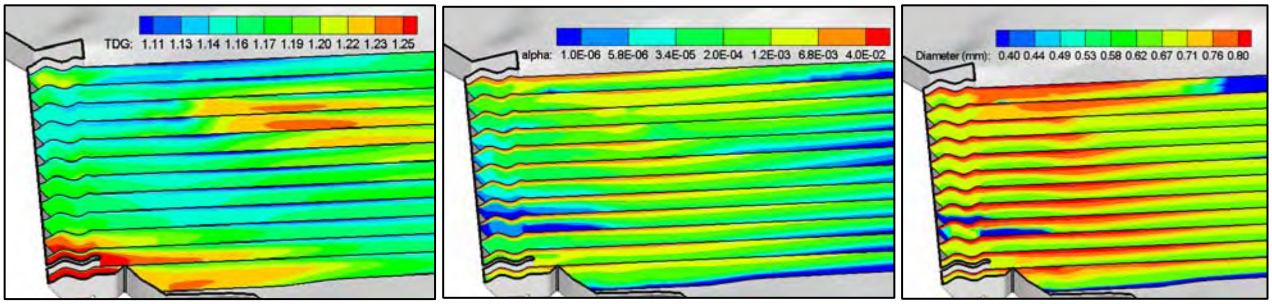


Figure 16. a) TDG, b) gas volume fraction and c) bubble diameter contours at slices passing through the spillway bays.

Validation Case: Wanapum tailrace on April 27, 2000

Hydrodynamics

Figure 17 shows the predicted depth averaged velocity for April 27, 2000. In this day 62.5% of the total river flow was spilled. During this high spillway discharge, the surface jets generated a strong water entrainment and most of the flow from the powerhouse is entrained into the spillway region instead of flowing toward the exit. A counterclockwise eddy is formed downstream of the spillway.

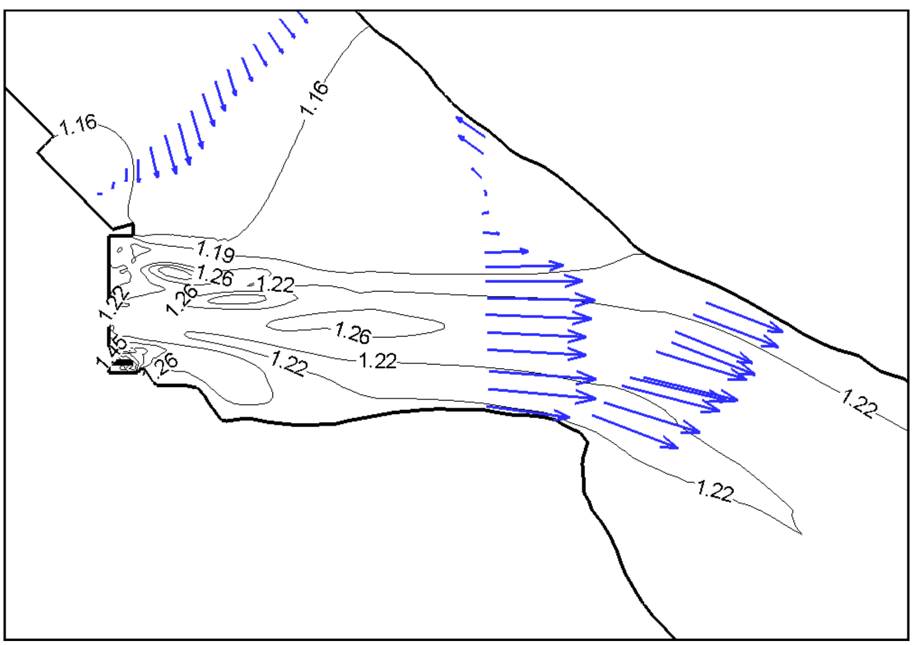


Figure 17. Predicted velocity and TDG contours in Wanapum Dam tailrace on April 27, 2000 with the IIHR model considering bubble dissolution

TDG Predictions

Figure 18 shows the predicted and measured TDG as a function of the distance to the west shore. The model compares well against the measured TDG concentration. Higher spillway flowrates caused more bubble entrainment and higher TDG concentrations in the stilling basin. TDG saturation as high as 1.36 was predicted at transect T1 close to the center of the spillway. Similar to observations on May 2, 2000, powerhouse flows entrained into the spillway region diluted the east end of the transect T1. The highest value at Transect T2 is also found near the west side for this case.

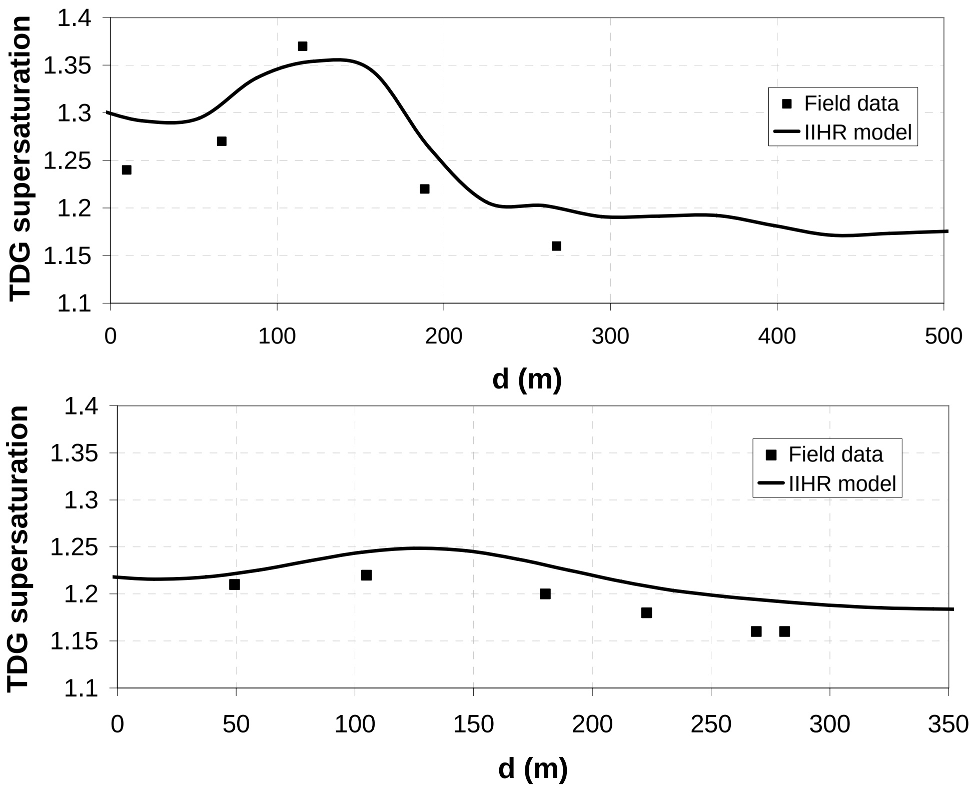


Figure 18. Measured and predicted TDG concentration in a) T1 and b) T2 on April 27, 2000.

Streamlines colored by TDG on April 27, 2000 are shown in Figure 19. Streamlines with low TDG concentration from the powerhouse region are entrained into the spillway region where they are exposed to aerated flow. On this day, high spillway flows caused more bubble entrainment and higher source of TDG. Due to the elevated bubble concentration, entrained powerhouse flow reached high TDG levels on the east side of the spillway region. Therefore, dilution by powerhouse flows is limited to a small region on the east region. Note the regions of low TDG at the free surface caused by absorption of air from the liquid to the bubbles and degasification.

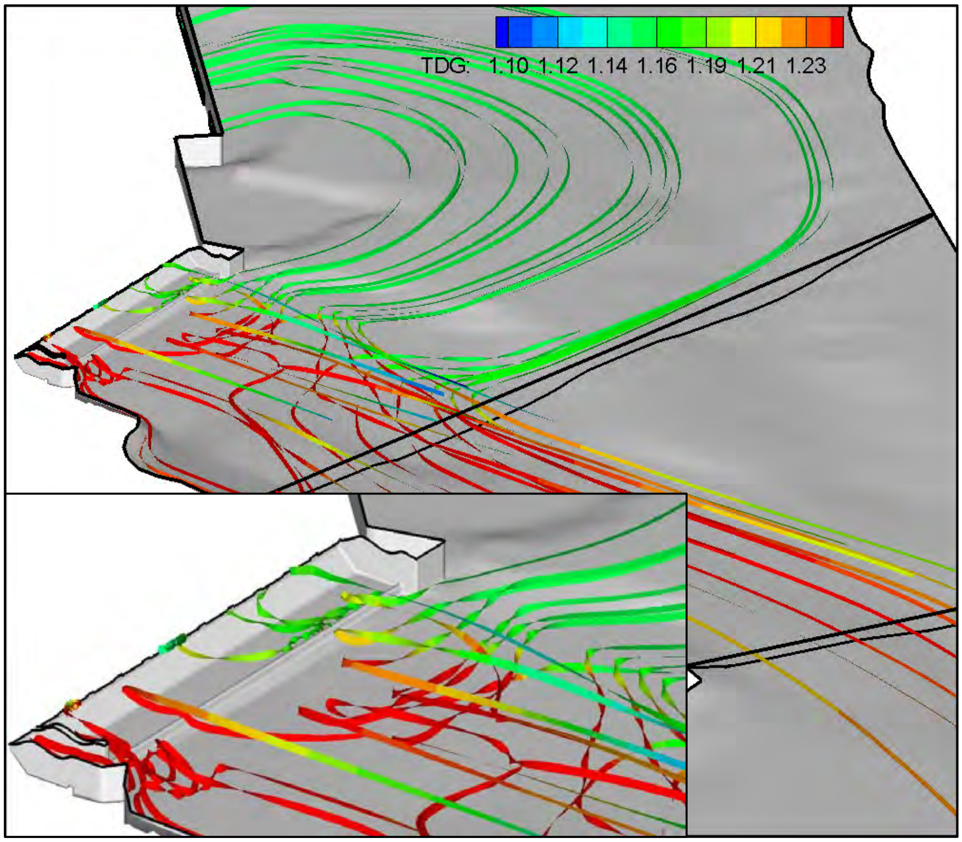


Figure 19. Streamlines colored by TDG concentration at the Wanapum tailrace on April 27, 2000.

3.4 Technical Papers and Publication Lists

Selected technical papers, articles, and reports are listed as Section 8 of this proposal. Should Douglas PUD desire to limit third-party access to the Wells Dam modeling program, IIHR reports can be issued with Limited Distribution Report (LDR) status. An LDR will not be distributed to any person or agency outside IIHR without Douglas PUD's consent.

4. WORK PLAN FOR THE WELLS PROJECT

4.1 Personnel

Drs. Larry Weber and Marcela Politano will direct the overall modeling project and provide expertise in the areas of numerical modeling, two-phase flow, air entrainment, TDG modeling, and general hydraulics. A post-doc and graduate student will assist with grid generation and post-processing. Dr. Politano will oversee the numerical simulations. Grid generation will be supervised by Dr. Weber and checked for quality assurance and quality control by Dr. Politano. Resumes for Drs. Weber and Politano are appended as Section 9. IIHR's organization chart is illustrated in Figure 20.

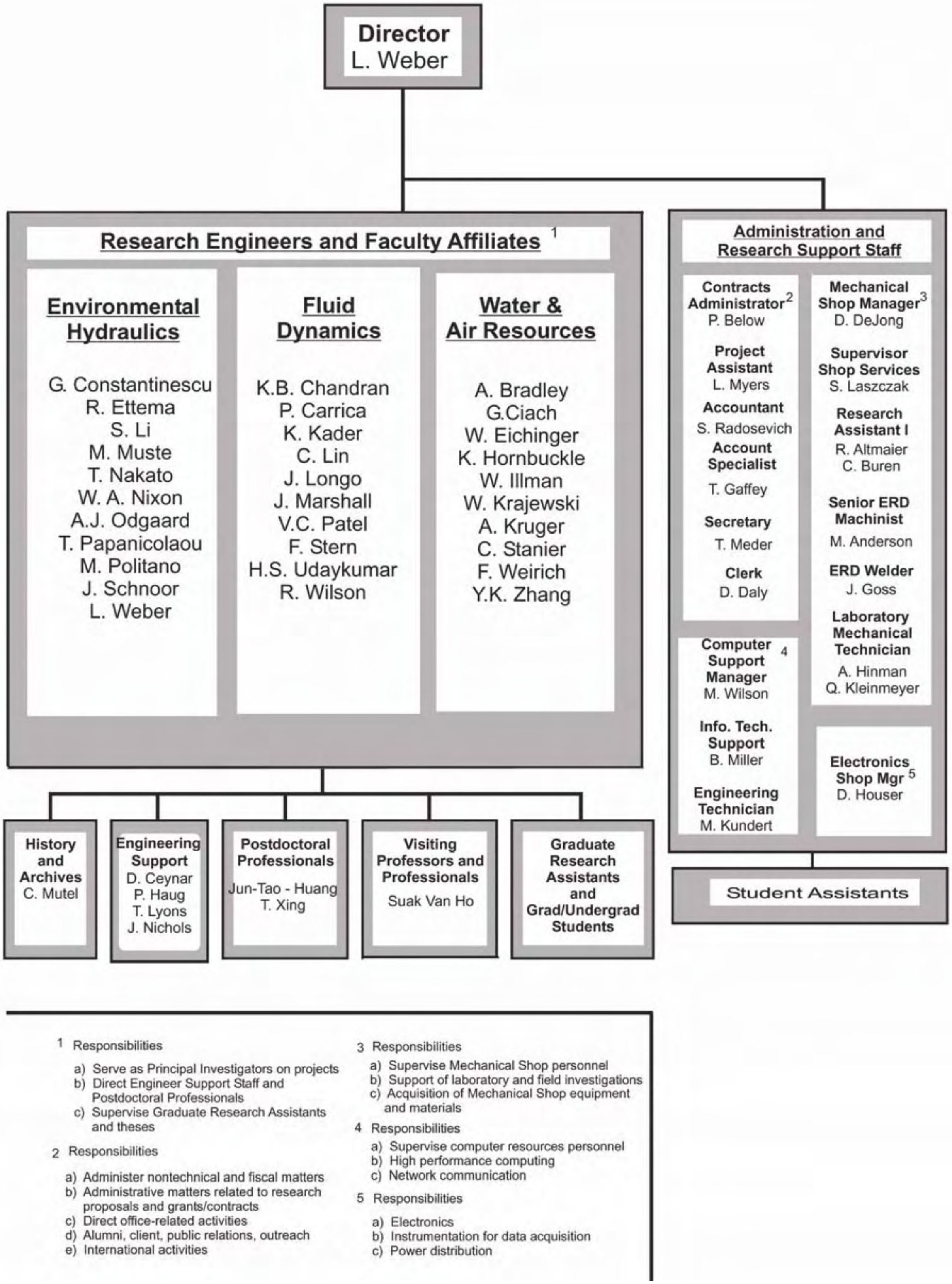


Figure 20. Organizational chart for IIHR

4.1.1 Lead Project Investigator Experience: Dr. Larry Weber

Dr. Weber has expertise in river hydraulics, hydraulic structures and fish passage facilities. As a project manager of fish passage projects on the Snake and Columbia Rivers during the past 12 years he has supervised a number of projects for industry using physical and numerical models for the design of hydraulic structures and juvenile fish passage facilities. Dr. Weber publishes regularly in peer-reviewed journals and conference proceedings; moderates fish passage sessions at national and international conferences; and is presently the committee chair of the ASCE Task Committee on Engineering for Fish Passage Enhancement. Some of the clients and design consultants for which Dr. Weber has worked include Idaho Power Corporation, Public Utility District No 1 of Chelan County, Public Utility District No. 2 of Grant County, U.S. Army Corps of Engineers Walla Walla District Office, ENSR Consulting, Jacobs Civil Inc, CH2M Hill, Hendrick Screen Company and Cook Screen Company.

As project manager of numerical modeling contracts Dr. Weber worked closely with computational fluid dynamics experts at IIHR and coordinated their involvement in numerous hydropower related projects.

Dr. Weber has been responsible for the development of a predictive three-dimensional model for quantifying total dissolved gas downstream from hydropower installations. This model will allow project engineers to quantify improvements to TDG resulting from spillway deflectors or other structural changes.

Dr. Weber has been the project manager for studies directed at reduction of total dissolved gas downstream of numerous hydroelectric installations. These projects investigated the effectiveness of using flow deflectors, energy dissipaters, flip buckets, spill gate modifications and large-scale tailrace modifications. These projects include Wanapum Dam spillway flow deflectors, Rock Island Dam spill gate modifications and flow deflectors and Hells Canyon and Brownlee Dam flow deflectors.

4.1.2 Project Investigator Experience: Dr. Marcela Politano

Dr. Politano has expertise in numerical modeling for hydraulic applications. During the past 4 years she has been involved in numerical models for Wanapum, Brownlee, McNary, Priest Rapids and Little Goose Dams, and the Mississippi River. She developed a mechanistic anisotropic multiphase flow model to compute the total dissolved gas (TDG) downstream of spillways. For McNary Dam she developed a transient three-dimensional thermal model. Dr. Politano publishes regularly in international journals, conference proceedings, and technical reports. Some of the clients and design consultants for which Dr. Politano has worked with include JDH Joint Venture, Grant County Utility District, and U.S. Army Corps of Engineers Walla Walla and St. Louis District Offices.

4.2 Schedule

Table1 lists estimated completion dates for each phase of the project. The completion dates are based on our understanding of the scope of work and can be adjusted as needed.

Activity or Milestone	Duration (Weeks)	Completion Date
Proposal Submittal	---	26-Oct
Laboratory Retained	---	1-Dec
Model Composition	8.0	26-Jan
Model Calibration and Validation	8.0	22-Mar
Phase 1 Tests	10.0	31-May
Interim Report	1.0	7-Jun
Phase 2 Tests	8.0	2-Aug
Performance Curve Development	2.0	16-Aug
Draft Report	2.0	1-Sep
Final Report	TBD	TBD

Table 1 Anticipated schedule for Wells Dam model studies

4.3 Brief Description of Project Activities

4.3.1 Model Development

It is anticipated that Douglas PUD will provide detailed construction drawings of the dam and civil structures with sufficient detail to model the powerhouse outlets, spillway gates and ogee profiles, and other structures that may exist within the study area. IIHR will incorporate bathymetry data supplied by Douglas PUD to generate the river bed downstream of the dam. A portion of the tailrace, approximately 5 km in length, will be modeled extending from Wells Dam downstream to transect TW3. Transect TW3 coincides with the TDG compliance monitoring station used in the 2006 field study. IIHR will provide 3D views of the model grid upon request.

4.3.2 Model Calibration and Validation

The model will be calibrated to available velocity and TDG data collected for two flow conditions during the 2006 field study (collected June 4-5). The two flow conditions represent total river flows of 172.4 and 222.3 kcfs. The velocity data was collected at stationary points along transects A, B, and C for both flow conditions. For the same flow conditions, TDG will be predicted at transects T1, T2, and T3 to compare with measured values available from the TDG sensors deployed continuously at those locations. If necessary, three coefficients can be adjusted during calibration. These coefficients are the bubble size and gas volume fraction at the spillway bay, and the bubble turbulence coefficient. The values for these coefficients will be set initially using reasonable values from experience at Wanapum Dam.

The free surface in the immediate area (300-400 ft) downstream of Wells Dam will be modeled using the Volume of Fluid (VOF) method. The VOF method provides an accurate representation of the water surface which is critical for replicating tailrace hydrodynamics. Further downstream the water surface will be modeled using a rigid lid. The slope of the rigid lid will be determined using the available water surface profiles collected on June 4-5 during the 2006 field study.

Once the model has been calibrated, a validation of TDG values will be executed for specific representative flows. IIHR recommends the validation runs include one case from the three targeted test spills. This would include one case each for spread spill, full gate spill, and crowned spill scenarios.

A brief letter report will be provided to Douglas PUD upon completion of model calibration and validation to summarize the results.

4.3.3 Phase 1 Testing

Based on our understanding of the project, IIHR plans to test three spill configurations for three flowrates, corresponding to nine runs. Additional runs can be added if necessary. Specific spillway and powerhouse flows for these runs will be determined at a later date.

4.3.4 Interim Report

IIHR will submit a brief report summarizing Phase 1 results. The report will include descriptions and details for each run. Color plots will be provided showing the results.

4.3.5 Phase 2 Testing

IIHR will complete additional runs for flow conditions to be determined by Douglas PUD. Due to the dependency of Phase 2 testing upon the results from Phase 1, we have intentionally left this phase open-ended. For cost-estimation sake, we assumed an additional nine runs would be necessary (Section 5).

4.3.6 Performance Curve Development

IIHR will develop performance curves to describe flow regimes for combinations of spillway flowrates and tailwater elevations. Depending on the spillway and tailwater values used for Phase 1 and 2 simulations, it may be necessary to perform additional runs to broaden the range of tailwaters and flowrates to adequately describe the performance curves. Additional runs could be performed with a smaller, more localized numerical model which would save computational time and reduce cost. It is not expected the cost to develop complete performance curves will exceed $9,800.

4.3.7 Project Report

IIHR will draft a report summarizing the complete modeling effort. The report will include details of model development, calibration, validation, and Phase 1 and 2 test results. IIHR will submit a draft report by September 1, 2008 for review by Douglas PUD's representatives. IIHR will issue the final report after responding to a consolidated set of review comments. An electronic copy of the report will be submitted upon finalizing the report. Ten hard copies of the report will follow within 2-3 weeks of the electronic copy. Additional copies will be made available upon request. The final report will be issued in IIHR's Limited Distribution Report series. The report will not be shared or distributed without the expressed consent of Douglas PUD.

5. BASIC OFFER

IIHR is committed to providing key resources and personnel necessary to this project's completion. Based on our understanding of the scope of work, completion of the numerical modeling test program will cost **$204,298**. This proposal and basic offer shall remain valid for acceptance for a period of sixty (60) days following the proposal date. Table 2 shows the cost breakdown for each modeling phase.

Cost Breakdown	**Other Direct Costs**	**Labor**
Model Composition	$ -	$ 35,568
Model Calibration and Validation	$ -	$ 28,278
Phase 1 Tests (9 runs)	$ -	$ 42,730
Phase 2 Tests (9 runs)	$ -	$ 42,730
Performance Curve Development	$ -	$ 9,800
Report	$ -	$ 19,980
Travel – 2 Trips for Dr. Weber	$ 1,760	$ 9,504
Travel – 2 Trips for Dr. Politano	$ 1,760	$ 6,688
Computing Resources	$ 5,500	$ -
Total	**$ 204,298**	

Table 2. Cost Breakdown for the Wells Dam Project

6. SUMMARY STATEMENT

IIHR has conducted a long-term research effort to develop a numerical tool to predict TDG downstream of spillways. The major issues regarding the prediction of TDG are concerned with the gas distribution and the effect of surface jets on the flow field. The most important source for the TDG is the gas transferred from the bubbles, therefore a proper model for TDG prediction in tailraces must account for the two-phase flow in the stilling basin and the mass transfer between bubbles and water. In addition, it has been demonstrated that surface jets may cause a significant change of the flow pattern since they entrain surrounding water into the jet region. This entrainment leads to mixing and subsequently modifys the TDG concentration field.

Standard isotropic CFD models and reduced-scale laboratory models fail to predict the water entrainment observed in the field. A two phase anisotropic model that accounts for the attenuation of the normal fluctuations at the free surface and bubble dissolution was developed at IIHR to capture the turbulence structure and water entrainment.

The IIHR model was validated against field data for TDG and velocities in the stilling basin of Wanapum Dam and it is currently being used to predict the flow field and TDG distribution in Little Goose Dam. Model results include three-dimensional fields of TDG, gas volume fraction, bubble sizes and velocities of the bubbles. Two interesting phenomena, important to evaluate the effectiveness of spill type and plant operation in reducing TDG, are capture by the model. The first is the distribution of TDG within the stilling basin and immediate tailrace region resulting from the dissolution of the bubbles. The other, even more important, is the entrainment of flow leaving the powerhouse that is strongly attracted by the spillway flow. Prediction of both effects requires the use of a multidimensional anisotropic multiphase flow model.

7. REFERENCES USED IN THIS PROPOSAL

Carrica P. M., D. Drew, F. Bonetto and R.T. Lahey Jr. (1999), "A Polydisperse model for bubbly two–phase flow around a surface ship," Int. J. Multiphase Flow, **25**, 257-305.

Chen, P., M.P. Dudukovic, and J. Sanyal (2005), "Three-dimensional simulation of bubble column flows with bubble coalescence and breakup," AIChE J., **51**(3), 696–712.

Deckert W. (1992). Bubble Column Reactors, John Wiley & Sons Ltd, England.

DeMoyer C.D., E.L. Schierholz, J.S. Gulliver & S.C.Wilhelms (2003), "Impact of Bubble and Free Surface Oxygen Transfer on Diffused Aeration Systems," Water Research, **37**(8), 1890-1904.

Gibson, M.M. and Launder, B.E., Ground effects on pressure fluctuations in the atmospheric boundary layer. Journal of Fluid Mechanics, 1978, **86**, 491-511.

Ishii M. and N. Zuber (1979), "Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows," AIChE J., **25**(5), 843-855.

Kataoka, I., A.Serizawa and D.C. Besnard, (1993), "Prediction of turbulence suppression and turbulence modeling in bubbly two-phase flow," Nuclear Eng. and Design, **141**, 145-158

Lamont J.C. and D.S. Scott (1970), "An eddy cell model of mass transfer into the surface of a turbulent liquid," AIChE J., **16**, 513-519.

Launder, B.E., Spalding, D.B., Lectures in Mathematical Models of Turbulence, 1972 (Academic Press: London).

Launder, B.E., Reece, G.J. and Rodi, W., Progress in the development of a Reynolds-Stress turbulence closure. Journal of Fluid Mechanics, 1975, **68**(3), 537-566.

Launder, B. E., Second-moment closure and its use in modeling turbulent industrial flows. International Journal for Numerical Methods in Fluids, 1989, **9**, 963-985.

Liepmann, D. (1990), The near-field dynamics and entrainment field of submerged and near surface jets, Ph.D. thesis, University of California, San Diego.

Lopez de Bertodano, M.L., R.T.Lahey Jr, and O.C. Jones (1994), "Development of a $k-\varepsilon$ model for bubbly two-phase flow," Journal of Fluids Eng., **116**, 128-134.

Moraga, F.J., A.E. Larreteguy, D.A. Drew, and R.T. Lahey Jr, (2003), "Assessment of turbulent dispersion models for bubbly flows in the low Stokes number limit," Int. J. Multiphase Flow, **29**, 655-673.

Politano M.S., P.M. Carrica, C. Turan, L. Weber (2007), "A multidimensional two-phase flow model for the total dissolved gas downstream of spillways",J. Hydraulic Res., **45**(2), 165-177.

Serizawa, A. (1974), "Fluid dynamics characteristics of two phase flow," Ph.D. thesis, Japan.

Serizawa, A. and I. Kataoka (1990), "Turbulence suppression in bubbly two-phase flow," Nuclear Eng. and Design, **122**, 1-16.

Solbakken, T. and B.H. Hjertager (1998), "A computational and experimental study of flowpattern in a pilot and a full scale bubble column," in Proceedings of the Third International Conference on Multiphase Flow, Lyon, France.

Takemura F. and A. Yabe (1998), "Gas Dissolution Process of Spherical Rising Gas Bubbles," Chem. Eng. Sc., **53**(15), 2691-2699.

Turan C., Politano M., Carrica P. M. and Weber L. 2007. Water Entrainment and Mixing due to Surface Jets. Computational Fluid Dynamics, 21, 3-4, 137-153.

Walker,D.T. (1997), "On the origin of the 'surface current' in turbulent free-surface flows," Journal of Fluid Mechanics, **339**, 275-285.

Walker,D.T. and C.Y. Chen (1994), "Evaluation of algebraic stress modelling in free-surface jet flows," Free Surface Turbulence, **181**,83-95, ASME.

Wang, S.K., S.J.Lee, O.C. Jones Jr, and R.T. Lahey Jr, (1987), 3-D turbulence structure and phase distribution measurements in bubbly two phase flow, Int. J. Multiphase Flow, 13(3),327-343.

8. SELECTED RELEVANT IIHR PUBLICATIONS

Allen, M, Elder, R.A., Hay, D., Odgaard, A.J., Weber, L.J. and Weitkamp, D., "Evaluation of Gatewell Flows for Fish Bypass at a Large Hydroelectric Plant", Proceedings of the First International Conference on Water Resources Engineering, San Antonio, Texas, Eds. W. Espey and P. Combs, 1995, pp. 534-538.

Allen, M.E., Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVII: Laboratory model Wanapum Dam Erosion Characteristics after Installation of Spillway Deflectors", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 286, 2000.

Blank, J.C. and Weber, L.J., "Numerical Simulations of Fish Passage Facilities at Lower Granite Lock and Dam", Work funded by US Army Corps of Engineers, Walla Walla District Office, Walla Walla, WA. IIHR Technical Report No. 412, 2000.

Cherian, M.P., Allen, M. and Weber, L.J., "Flow Through Vertical Barrier Screens - Numerical and Experimental Results", Proceedings of the North American Water and Environment Congress '96, Anaheim, California, 1996.

DeJong, D. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIV: Surface Collection Concepts for Wanapum Dam Forebay", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 269, 1998.

Den Bleyker, J.S., Weber, L.J. and Odgaard, A.J., "Development of a Flow Spreader for Fish Bypass Outfalls", North American Journal of Fisheries Management. Vol. 17, No. 3, August, 1997.

Den Bleyker, J., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part VIII: Identification of a Fish Bypass Outfall Location for Priest Rapids Tailrace", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . IIHR Limited Distribution Report No. 238, 1996.

Den Bleyker, J., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part X: Improvements to Outfall Plunge Characteristics", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 260, 1997.

Dierking, P. B. Hydraulic Modeling of Hells Canyon Dam for Spillway Deflector Design. University of Iowa Masters Thesis, 2001.

Goodwin, R.A., Nestler, J.M., Anderson, J.J. and Weber, L.J., "Forecast Simulations of 3-D Fish Response to Hydraulic Structures", Proceedings of 2004 EWRI Congress, Salt Lake City, UT, June 27 – July 1, 2004.

Goodwin, R.A., Nestler, J.M., Anderson, J.J. and Weber, L.J., "Virtual Fish to Evaluate Structures for Endangered Species", Proceedings of the 5th International Symposium on Ecohydraulics, Madrid, Spain, June 12 – 17, 2004.

Haug, P. E. Wanapum Dam Spillway Deflectors. University of Iowa Masters Thesis, 2000.

Haug, P.E., Li, S. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVIII: Summary of Hydraulic and CFD Models for Wanapum Dam", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 310, 2003.

Huang, H. Computational Model of Total Dissolved Gas Downstream of a Spillway. University of Iowa Doctoral Thesis, 2002.

Huang, J., Patel, V.C., Lai, L.G. and Weber, L.J., "Simulation Study of Flow Through a Reach of the Chattahoochee River," Journal of Hydraulic Research, IAHR, Vol. 42, No. 5, December 2004, 487-491.

Huang, J. and Weber, L.J., "Numerical Simulations of the Forebay of Lower Granite Lock and Dam", HydroVision 98, Reno, Nevada, July 28 – 31, 1998.

Huang, J., Weber, L.J. and Lai, Y.G., "Three-Dimensional Numerical Study of Flow in Open-Channel Junctions", Journal of Hydraulic Engineering, ASCE, Vol. 128, No. 3, March, 2002.

Lai, Y.G., Weber, L.J., and Patel, V.C., "A Non-hydrostatic Three-Dimensional Model for Hydraulic Flow Simulation – Part I: Formulation and Verification," Journal of Hydraulic Engineering, ASCE, accepted April 2002.

Lai, Y.G., Weber, L.J., and Patel, V.C., "A Non-hydrostatic Three-Dimensional Model for Hydraulic Flow Simulation – Part II: Validation and Application," Journal of Hydraulic Engineering, ASCE, accepted April 2002.

Li, S., Lai, Y.G., Weber, L.J., Silva, J.M. and Patel, V.C., "Validation of a Three-Dimensional Numerical Model for Water-Pump Intakes," Journal of Hydraulic Engineering, ASCE, submitted for review January 2002.

Lyons, T.C., Li, S. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIX: Summary of Hydraulic and CFD Models for Priest Rapids Dam", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 311, 2003.

Mannheim, C.O.M, and Weber, L.J., "A Unique Approach of Modeling Gas Supersaturation in a Laboratory model", Journal of Hydraulic Research, IAHR, Vol. 39, No. 1, 2001.

McCoy, A.W. and Weber, L.J., "Three-Dimensional Hydrodynamic and Total Dissolved Gas Simulations of Rock Island Dam Spillway", Contracted by Public Utility District No. 1 of Chelan County, Wenatchee, WA. IIHR Limited Distribution Report No. 314, September 2003.

Meselhe, E.A. and Weber, L.J., "Validation of a 3-Dimensional Numerical Model Using Field Measurement is a Large Scale River Reach", Proceedings of Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat, Theme B, Volume 2, , The 27th IAHR Congress, San Francisco, CA, Aug. 10 – 15, 1997, pp 827 – 832.

Morales, Y., Weber, L.J., Slaughter, C.W. and Haak, A., "Decision Support System of the Lake Amatitlan: Hydrodynamic and Sediment Transport Models," Proceedings of the 5th International Conference on Hydroinformatics, Cardiff, UK, August 2002.

Nielsen, K.D. and Weber, L.J., "Plunging Jet Measurement Improvements Using ADV", Proceedings of the 1998 International Water Resources Engineering Conference, Memphis, TN, Aug. 3 – 7, 1998.

Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 264, 1997.

Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XII: Laboratory model Study Data for Development of a Gas Concentration Computational Model", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . IIHR Limited Distribution Report No. 265, 1997.

Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIII: Laboratory model Study of the Top Spill Bulkhead", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 266, 1997.

Muste, M., Meselhe, E.A., Weber, L.J., and Bradley, A.A., "Coupled Physical-Numerical Analysis of Flows in Natural Waterways", Journal of Hydraulic Research, IAHR, Vol. 39, No. 1, 2001.

Meselhe, E.A., Weber, L.J., Odgaard, A.J., and Johnson, T., "Numerical Modeling for Fish Diversion Studies", Journal of Hydraulic Engineering, ASCE, Vol. 126, No. 5, May, 2000.

Nakato, T. and Cherian, M. P. Hydraulic Model Study of Union Electric's Keokuk Dam Ogee Spillways. IIHR Technical Report 390, 1997.

Nestler, J.M., Goodwin, R.A., Weber, L.J. and Lai, Y.G., "Theoretical and Computational Templates for Juvenile Salmon Swim Path Selection in the Complex Hydrodynamic Environments of Rivers and Designed Hydraulic Structures", US Army Corps of Engineers, ERCD/EL TR-00, November 2001.

Nielsen, K. D. Spillway Plunging Jets and Aeration: State-of-the-Art Assessment. University of Iowa Doctoral Thesis, 2001.

Nielsen, K. and Weber, L., "Headloss Analysis of Single and Tee Style Intake Screens", Contracted by Hendrick Screen Company, Owensboro, KY. IIHR Limited Distribution Report No. 254, 1997.

Nielsen, K. and Weber, L., "Lower Granite Dam Surface Bypass and Collection (SBC), Laboratory modeling of Behavioral Guidance Structure", Contracted by U.S. Army Corps of Engineers, Walla Walla District and CH2M Hill, Boise, Idaho. IIHR Technical Report No. 393, 1998.

Nielsen, K. and Weber, L., "Nursery Bridge Fishway and Marie Dorian Dam, Laboratory modeling of Nursery Bridge Drop Structure Stilling Basin", Contracted by U.S. Army Corps of Engineers, Walla Walla District and CH2M Hill, Boise, Idaho. IIHR Technical Report No. 409, 1999.

Nielsen, K. D. and L. J. Weber. Yelm Hydroelectric Project – Laboratory model Study of Stilling Basin for Spillway No. 3. IIHR Technical Report 400, 1998.

Nielsen, K.D., Weber, L.J. and Bennion, D.K., "Design Challenges of the Lower Granite Dam Behavioral Guidance Structure for Guiding Migrating Fish in the Powerhouse Forebay", HydroVision 98, Reno, Nevada, July 28 – 31, 1998.

Nielsen, K., Weber, L.J. and Haug, P., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVI: 1:32.5 scale sectional model of Wanapum Dam spillway deflectors", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 284, 2000.

Ouyang, H., Blank, J., Weber, L.J., and Odgaard, A.J., "Integration of Hydrodynamic Model and Monte-Carlo Simulation in Prediction of Fish Distribution", Proceedings of the 1999 International Water Resources Engineering Conference, Seattle, WA, Aug. 8 – 11, 1999.

Politano M., Turan C., Carrica P. and Weber L. 2007. A three Dimensional Anisotropic Model of the two-phase Flow and Total Dissolved Gas Downstream of Spillways. Proceedings of the Ninth International Symposium in Fluid Control, Measurements and Visualization, Flucome 2007. Tallahassee, Florida.

Politano M., Carrica P. M. and Weber L. 2005. Prediction of the Total Dissolved Gas Downstream of Spillways Using a Multidimensional two-phase flow model. Keynote Lecture at the *XX Computational Mechanics Conference.* Argentina.

Politano M., Carrica P. M. and Weber L. 2005. Prediction of Total Dissolved Gas Downstream of Spillways Using a Multiphase Flow Modeling. Presented at *2005 CFD Summit*. Dearborn, Michigan.

Politano M., Carrica P. M., Turan C. and Weber L. 2005. Multidimensional Simulations of the two-phase flow Downstream of Spillways for Total Dissolved Gas prediction. Proceedings of the World Water & Environmental Resources Congress. Alaska.

Politano M., Carrica P.M., Turan C. and Weber L. 2007. A Multidimensional two-phase Flow Model for the Total Dissolved Gas Downstream of Spillways. *J. Hydraulic Research*, 45, 2, 165-177.

Sinha, S.K., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part IX: Identification of a Fish Bypass Outfall Location for Wanapum Dam Tailrace", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 252, 1996.

Sinha, S.K., Weber, L.J. and Odgaard, A.J., "Numerical Model Studies for Fish Diversion at Priest Rapids /Priest Rapids Development, Part II: Flows Through Priest Rapids Dam Tailrace Reach", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 253, 1997.

Sinha, S.K., Weber, L.J. and Odgaard, A.J., “Using Computational Tools to Enhance Fish Bypass”, HydroReview, Vol. 18, No. 1, February, 1999.

Turan C., McDaniel B., Politano M., Carrica P. and Weber L. 2006. A Study of the Free Surface Flow on Brownlee Dam. Proceedings of the World Water & Environmental Resources Congress. Nebraska.

Turan C., Carrica P., Politano M. and Weber L. 2006. Water Entrainment and Mixing due to Spillways Discharges. Proceedings of the World Water & Environmental Resources Congress. Nebraska.

Turan C., Politano M., Carrica P. M. and Weber L. 2007. A Study of the Water Entrainment on Wanapum Dam. Proceedings of the 32nd IAHR Congress. Venice, Italy.

Turan C., Politano M., Carrica P. M. and Weber L. 2007. Water Entrainment and Mixing due to Surface Jets. *Computational Fluid Dynamics*, **21**, 3-4, 137-153.

Weber, L.J., Cherian, M.P., Allen, M.E. and Muste, M., “Headloss Characteristics for Perforated Plates and Flat Bar Screens”, IIHR Technical Report No. 411, 2000.

Weber, L.J. and Elder, R.A., "Laboratory model Studies of a Spillway Bulkhead for Passage of Downstream Migrating Juvenile Salmonids", Proceedings of Rivertech 96, 1st International Conference on New/Emerging Concepts for Rivers, Chicago, Illinois, 1996.

Weber, L.J., Huang, H., and Lai, Y., "Numerical Modeling of Dissolved Gas Supersaturation of a Spillway", Proceedings of The 29th IAHR Congress, Bejiing, China, September 17 -21, 2001, pp 785-792.

Weber, L.J., Huang, H., Lai, Y.G. and McCoy, A., "Modeling Total Dissolved Gas Production and Transport Downstream of Spillways - Three-Dimensional Model Development and Applications" Journal of River Basin Management, IAHR, Vol. 2, No. 3, December 2004.

Weber, L.J., Lai, Y.G., Blank, J.C. and Andrade, F., "Rocky Reach Dam: A Comprehensive Look at Calibration of a CFD Model Applied to Fish Passage", Proceedings of the 4th International Conference on Hydroinformatics, Cedar Rapids, IA, July 24-27, 2000.

Weber, L.J., and Lyons, T.C., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XXI: Construction and Calibration of the 1:64 Priest Rapids Dam Comprehensive Forebay Model", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 315, 2004.

Weber, L.J. and Mannheim, C.O., "A Unique Approach for Laboratory model Studies of Nitrogen Gas Supersaturation", Proceedings of Energy and Water: Sustainable Development, Theme D, Water for a Changing Global Community, The 27th IAHR Congress, San Francisco, CA, Aug. 10 – 15, 1997, pp 518 – 523.

Weber, L.J., Meselhe, E.A. and Odgaard, A.J., "Combining Hydrodynamic and Fish Tracking Information: The next approach to modeling fish passage facilities", Hydroinformatics 98, Copenhagen, Denmark, August 24 – 26, 1998.

Weber, L.J., Nielsen, K., and Haug, P.E., "Plunge Pool Solutions for the Rock Island Dam Notched Spillways", Proceedings of the 1999 International Water Resources Engineering Conference, Seattle, WA, Aug. 8 – 11, 1999.

Weber, L.J. and Odgaard, A.J., "Hydraulic Characteristics of Bar Screen Panels", Contracted by Cook Screen Technologies, Inc. IIHR Limited Distribution Report No. 215, 1993.

Weber, L.J., and Odgaard, A.J., "Laboratory model Studies of Dissolved Gas Supersaturation at Wanapum Dam", Proceedings of the North American Water and Environment Congress '96, Anaheim, California, 1996.

Weber, L.J., Odgaard, A.J. and Elder, R., "Study of the Effect of Withdrawal from a Vertical Slot Located Above a Turbine Intake on the Near Surface Velocities", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . IIHR Limited Distribution Report No. 221, 1994.

Weber, L.J., Shumate, E.D. and Mawer, “Experimental on Flow at a 90° Open-Channel Junction”, Journal of Hydraulic Engineering, ASCE, Vol. 127, No. 5, May, 2001.

Weber, L.J., Weitkamp, D., Hay, D., Odgaard, A.J. and Parameswar, C., "Development of a Juvenile Fish Outfall Structure", Water Power '95 Proceedings of International Conference on Hydropower, Ed. J. C Cassidy, 1995, pp 47- 56.

Weber, L.J., Young, N. and Haug, P., "Hydraulic Model Testing of ESBS Perforated Plate Vibrations", for U.S. Army Corps of Engineers, Walla Walla District Office. IIHR Limited Distribution Report No. 282, 2000.

9. RESUMES

LARRY J. WEBER

(ph 319-335-5597; fax –335-5238; e-mail larry-weber@uiowa.edu)

Higher Education

University	Degree (Field)	Date
University of Iowa, Iowa	B.S. (Civil & Environmental Engineering)	1989
University of Iowa, Iowa	M.S. (Civil & Environmental Engineering)	1990
University of Iowa, Iowa	Ph.D. (Civil & Environmental Engineering)	1993

Related Experience

Mary 2004 – present	Director, IIHR – Hydroscience and Engineering, U. of Iowa
July 2001 – present	Associate Professor, Dept. of Civil & Environmental Engineering, U. of Iowa
Aug. 1996 – June 2001	Assistant Professor, Dept. of Civil & Environmental Engineering, U. of Iowa
Jan. 1993 – Aug. 1996	Assistant Research Engineer, IIHR Hydroscience and Engineering, U. of Iowa

Active Research Areas

Dr. Weber has expertise in river hydraulics, hydraulic structures and fish passage facilities. As a project manager of fish passage projects on the Snake and Columbia Rivers during the past 12 years he has supervised a number of projects for industry using physical and numerical models for the design of hydraulic structures and juvenile fish passage facilities. Dr. Weber publishes regularly in peer-reviewed journals and conference proceedings; moderates fish passage sessions at national and international conferences; and is presently the committee chair of the ASCE Task Committee on Engineering for Fish Passage Enhancement. Some of the clients and design consultants for which Dr. Weber has worked include Idaho Power Corporation, Public Utility District No 1 of Chelan County, Public Utility District No. 2 of Grant County, U.S. Army Corps of Engineers Walla Walla District Office, ENSR Consulting, Jacobs Civil Inc, CH2M Hill, Hendrick Screen Company and Cook Screen Company.

Numerical Modeling

As project manager of numerical modeling contracts Dr. Weber worked closely with computational fluid dynamics experts at IIHR and has coordinated their involvement in numerous hydropower related projects.

Surface Collection Facilities: Dr. Weber has been responsible for coordination of numerical modeling for surface collections facilities at Wanapum Dam, Rocky Reach Dam and Lower Granite Lock and Dam. This work has focused on defining the hydrodynamic flow conditions in the immediate vicinity of the surface collection concepts. Data presented in these projects have not only included mean velocities but also higher order terms such as turbulence characteristics, velocity gradients, strain rate variables, accelerations and particle tracking. For many of these projects numerical model results have been linked directly with fish track data from the field to develop juvenile response parameters.

Total Dissolved Gas modeling: Dr. Weber has been responsible for the development of a predictive three-dimensional model for quantifying total dissolved gas downstream from hydropower installations. This model will allow project engineers to quantify improvements to TDG resulting from spillway deflectors or other structural changes.

Physical Modeling

As project manager of physical modeling contracts Dr. Weber has coordinated timely, cost-effective model studies for several hydroelectric utilities and consultants. His experience has included a broad range of physical model studies related to juvenile fish passage.

Surface Collection Facilities: Dr. Weber has been responsible for the hydraulic modeling of various surface collection concepts. These studies have focused on the approach flow condtions upstream of conceptual designs; impact of powerhouse collection facilities on turbine performance; impact of spillway facilities on gate performance and integrity and linkage of hydrodynamic data to fish tracking and response information. These projects include the Wanapum Dam surface attraction facility; the Wanapum Dam top spill bulkhead; enhanced spillway passage for Rock Island Dam; the Rock Island Dam guidance curtain; and headloss characteristics of the Lower Granite Lock and Dam behavioral guidance curtain.

Intake Screens Systems: Dr. Weber has been the project manager for numerous intake screen design studies. For these projects he has been responsible for hydraulic calculations and modeling of diversion screens; balancing of the flow through vertical barrier screens; determining loss coefficients and hydraulic computations for collection and conveyance systems; hydraulic design of extraction orifices and weirs from gatewells; vibration analysis of screen components and modeling of hydrodynamic trashracks. These projects include intake screen modeling for Wanapum Dam; Priest Rapids Dam; Rock Island Dam; the Rocky Reach Dam and McNary Dam.

Gas Abatement at Spillways: Dr. Weber been the project manager for studies directed at reduction of total dissolved gas downstream of numerous hydroelectric installations. These projects investigated the effectiveness of using flow deflectors, energy dissipaters, flip buckets, spill gate modifications and large-scale tailrace modifications. These projects include Wanapum Dam spillway flow deflectors, Rock Island Dam spill gate modifications and flow deflectors and Hells Canyon Dam flow deflectors.

Professional Service

American Society of Civil Engineers – Associate Member

Task Committee on Engineering for Fish Passage and Enhancement, *Chair* (*Jan.1999 ~ present*)
Session Convenor, 1999 ASCE Water Resources Conference, Fish Passage, Seattle, WA
Tour Group Leader, 35th Annual ASCE Environmental and Water Resources Conference, Iowa City, IA, April 3, 1997.
Task Committee Member: Migratory Juvenile Fish Bypass Systems, 1994 – 1998

International Association for Hydraulic Research – Member

Member, Local organizing committee, 4th International IAHR Conference on Hydroinformatics 2000, Cedar Rapids, IA, July 23-27, 2000.
Session Convener, Fish Passage Through Hydropower Installations Session, XXVII IAHR Congress, San Francisco, CA, 10-15 August 1997

Other

Steering Committee Member, HydroVision 2002, Portland Oregon, July 2002
Chair, Iowa Children's Museum Hydraulics Design Team, 1996 - 2000

Student Advising to Completion

- 4 PhD. Dissertations
- 16 MS Thesis Projects
- 22 Undergraduate Research Projects

Honors and Awards

1992 ASCE Collingwood Prize, Best Technical Paper by a Younger Member.

Relevant Journal Publications

1. Den Bleyker, J.S., Weber, L.J. and Odgaard, A.J., "Development of a Flow Spreader for Fish Bypass Outfalls", North American Journal of Fisheries Management. Vol. 17, No. 3, August, 1997.

2. Sinha, S.K., Weber, L.J. and Odgaard, A.J., "Using Computational Tools to Enhance Fish Bypass", HydroReview, Vol. 18, No. 1, February, 1999.

3. Meselhe, E.A., Weber, L.J., Odgaard, A.J., and Johnson, T., "Numerical Modeling for Fish Diversion Studies", Journal of Hydraulic Engineering, ASCE, Vol. 126, No. 5, May, 2000.

4. Muste, M., Meselhe, E.A., Weber, L.J., and Bradley, A.A., “Coupled Physical-Numerical Analysis of Flows in Natural Waterways”, Journal of Hydraulic Research, IAHR, Vol. 39, No. 1, 2001.

5. Mannheim, C.O.M, and Weber, L.J., “A Unique Approach of Modeling Gas Supersaturation in a Physical Model”, Journal of Hydraulic Research, IAHR, Vol. 39, No. 1, 2001.

6. Weber, L.J., Shumate, E.D. and Mawer, “Experimental on Flow at a 90° Open-Channel Junction ”, Journal of Hydraulic Engineering, ASCE, Vol. 127, No. 5, May, 2001.

7. Huang, J., Weber, L.J. and Lai, Y.G., “Three-Dimensional Numerical Study of Flow in Open-Channel Junctions”, Journal of Hydraulic Engineering, ASCE, Vol. 128, No. 3, March, 2002.

8. Lai, Y.G., Weber, L.J., and Patel, V.C., “A Non-hydrostatic Three-Dimensional Model for Hydraulic Flow Simulation – Part I: Formulation and Verification,” Journal of Hydraulic Engineering, ASCE, accepted April 2002.

9. Lai, Y.G., Weber, L.J., and Patel, V.C., “A Non-hydrostatic Three-Dimensional Model for Hydraulic Flow Simulation – Part II: Validation and Application,” Journal of Hydraulic Engineering, ASCE, accepted April 2002.

10. Li, S., Lai, Y.G., Weber, L.J., Silva, J.M. and Patel, V.C., “Validation of a Three-Dimensional Numerical Model for Water-Pump Intakes,” Journal of Hydraulic Engineering, ASCE, submitted for review January 2002.

11. Huang, J., Patel, V.C., Lai, L.G. and Weber, L.J., “Simulatioin Study of Flow Through a Reach of the Chattahoochee River,” Journal of Hydraulic Research, IAHR, Vol. 42, No. 5, December 2004, 487-491.

12. Weber, L.J., Huang, H., Lai, Y.G and McCoy, A., “Modeling Total Dissolved Gas Production and Transport Downstream of Spillways - Three-Dimensional Model Development and Applications” Journal of River Basin Management, IAHR, Vol. 2, No. 3, December 2004.

Relevant Conference Papers

1. Allen, M, Elder, R.A., Hay, D., Odgaard, A.J., Weber, L.J. and Weitkamp, D., "Evaluation of Gatewell Flows for Fish Bypass at a Large Hydroelectric Plant", Proceedings of the First International Conference on Water Resources Engineering, San Antonio, Texas, Eds. W. Espey and P. Combs, 1995, pp. 534-538.

2. Weber, L.J., Weitkamp, D., Hay, D., Odgaard, A.J. and Parameswar, C., "Development of a Juvenile Fish Outfall Structure", Water Power '95 Proceedings of International Conference on Hydropower, Ed. J. C Cassidy, 1995, pp 47- 56.

3. Cherian, M.P., Allen, M. and Weber, L.J., "Flow Through Vertical Barrier Screens - Numerical and Experimental Results", Proceedings of the North American Water and Environment Congress '96, Anaheim, California, 1996.

4. Weber, L.J., and Odgaard, A.J., "Physical Model Studies of Dissolved Gas Supersaturation at Wanapum Dam", Proceedings of the North American Water and Environment Congress '96, Anaheim, California, 1996.

5. Weber, L.J. and Elder, R.A., "Physical Model Studies of a Spillway Bulkhead for Passage of Downstream Migrating Juvenile Salmonids", Proceedings of Rivertech 96, 1st International Conference on New/Emerging Concepts for Rivers, Chicago, Illinois, 1996.

6. Weber, L.J. and Mannheim, C.O., "A Unique Approach for Physical Model Studies of Nitrogen Gas Supersaturations", Proceedings of Energy and Water: Sustainable Development, Theme D, Water for a Changing Global Community, The 27th IAHR Congress, San Francisco, CA, Aug. 10 – 15, 1997, pp 518 – 523.

7. Meselhe, E.A. and Weber, L.J., "Validation of a 3-Dimensional Numerical Model Using Field Measurement is a Large Scale River Reach", Proceedings of Environmental and Coastal Hydraulics: Protecting the Aquatic Habitat, Theme B, Volume 2, , The 27th IAHR Congress, San Francisco, CA, Aug. 10 – 15, 1997, pp 827 – 832.

8. Nielsen, K.D. and Weber, L.J., "Plunging Jet Measurement Improvements Using ADV", Proceedings of the 1998 International Water Resources Engineering Conference, Memphis, TN, Aug. 3 – 7, 1998.

9. Huang, J. and Weber, L.J., "Numerical Simulations of the Forebay of Lower Granite Lock and Dam", HydroVision 98, Reno, Nevada, July 28 – 31, 1998.

10. Nielsen, K.D., Weber, L.J. and Bennion, D.K., "Design Challenges of the Lower Granite Dam Behavioral Guidance Structure for Guiding Migrating Fish in the Powerhouse Forebay", HydroVision 98, Reno, Nevada, July 28 – 31, 1998.

11. Weber, L.J., Meselhe, E.A. and Odgaard, A.J., "Combining Hydrodynamic and Fish Tracking Information: The next approach to modeling fish passage facilities", Hydroinformatics 98, Copenhagen, Denmark, August 24 – 26, 1998.

12. Ouyang, H., Blank, J., Weber, L.J., and Odgaard, A.J., "Integration of Hydrodynamic Model and Monte-Carlo Simulation in Prediction of Fish Distribution", Proceedings of the 1999 International Water Resources Engineering Conference, Seattle, WA, Aug. 8 – 11, 1999.

13. Weber, L.J., Nielsen, K., and Haug, P.E., "Plunge Pool Solutions for the Rock Island Dam Notched Spillways", Proceedings of the 1999 International Water Resources Engineering Conference, Seattle, WA, Aug. 8 – 11, 1999.

14. Weber, L.J., Lai, Y.G., Blank, J.C. and Andrade, F., "Rocky Reach Dam: A Comprehensive Look at Calibration of a CFD Model Applied to Fish Passage", Proceedings of the 4th International Conference on Hydroinformatics, Cedar Rapids, IA, July 24-27, 2000.

15. Weber, L.J., Huang, H., and Lai, Y., "Numerical Modeling of Dissolved Gas Superstaturation of a Spillway", Proceedings of The 29th IAHR Congress, Bejiing, China, September 17 -21, 2001, pp 785-792.

16. Morales, Y., Weber, L.J., Slaughter, C.W. and Haak, A., "Decision Support System of the Lake Amatitlan: Hydrodynamic and Sediment Transport Models," Proceedings of the 5th International Conference on Hydroinformatics, Cardiff, UK, August 2002.

17. Morales, Y., Mynett, A., and Weber, L.J., "*An Individual Based Model for Freshwater Mussels of the Mississippi River*," Inland Waters: Research, Engineering and Management, Proc. IAHR Congress XXX, 24-29 August 2003, Thessaloniki, Greece, C, II, pp. 497-503 (Reprint 1630).

18. Young, N. Weber, L.J. and Nakato, T., "Hydrodynamic Characterization of Freshwater Mussel Habitats in the Upper Mississippi River," Inland Waters: Research, Engineering and Management, Proc. IAHR Congress XXX, 24-29 August 2003, Thessaloniki, Greece, C, II, pp. 497-503 (Reprint 1629).

19. Morales, Y., Weber, L.J. and Mynett, A.E., "Habitat Suitability Analysis for Mussels in the Mississippi River," Proc. Of the International Seminar in Hydroinformatics and Water Resources Management, AGUA, Cartagena, Columbia, pp. 39-48, September 2003.

20. Goodwin, R.A., Nestler, J.M., Anderson, J.J. and Weber, L.J., "Forescast Simulations of 3-D Fish Response to Hydraulic Structures", Proceedings of 2004 EWRI Congress, Salt Lake City, UT, June 27 – July 1, 2004.

21. Goodwin, R.A., Nestler, J.M., Anderson, J.J. and Weber, L.J., "Virtual Fish to Evaluate Structures for Endangered Species", Proceedings of the 5th International Symposium on Ecohydraulics, Madrid, Spain, June 12 – 17, 2004.

Other relevant technical publications

1. Weber, L.J. and Odgaard, A.J., "Hydraulic Characteristics of Bar Screen Panels", Contracted by Cook Screen Technologies, Inc. Iowa Institute of Hydraulic Research Limited Distribution Report No. 215, 1993.

2. Weber, L.J., Odgaard, A.J. and Elder, R., "Study of the Effect of Withdrawal from a Vertical Slot Located Above a Rurbine Intake on the Near Surface Velocities", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . Iowa Institute of Hydraulic Research Limited Distribution Report No. 221, 1994.

3. Den Bleyker, J., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part VIII: Indentification of a Fish Bypass Outfall Location for Priest Rapids Tailrace", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . Iowa Institute of Hydraulic Research Limited Distribution Report No. 238, 1996.

4. Sinha, S.K., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part IX: Indentification of a Fish Bypass Outfall Location for Wanapum Dam Tailrace", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 252, 1996.

5. Sinha, S.K., Weber, L.J. and Odgaard, A.J., "Numerical Model Studies for Fish Diversion at Priest Rapids /Priest Rapids Development, Part II: Flows Through Priest Rapids Dam Tailrace Reach", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 253, 1997.

6. Nielsen, K. and Weber, L., "Headloss Analysis of Single and Tee Style Intake Screens", Contracted by Hendrick Screen Company, Owensboro, KY. Iowa Institute of Hydraulic Research Limited Distribution Report No. 254, 1997.

7. Den Bleyker, J., Weber, L.J. and Odgaard, A.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part X: Improvements to Outfall Plunge Characteristics", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 260, 1997.

8. Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 264, 1997.

9. Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XII: Physical Model Study Data for Development of a Gas Concentration Computational Model", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. . Iowa Institute of Hydraulic Research Limited Distribution Report No. 265, 1997.

10. Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIII: Physical Model Study of the Top Spill Bulkhead", Contracted by

Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 266, 1997.

11. DeJong, D. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIV: Surface Collection Concepts for Wanapum Dam Forebay", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 269, 1998.

12. Nielsen, K. and Weber, L., "Lower Granite Dam Surface Bypass and Collection (SBC), Physical Modeling of Behavioral Guidance Structure", Contracted by U.S. Army Corps of Engineers, Walla Walla District and CH2M Hill, Boise, Idaho. Iowa Institute of Hydraulic Research Technical Report No. 393, 1998.

13. Nielsen, K. and Weber, L., "Nursery Bridge Fishway and Marie Dorian Dam, Physical Modeling of Nursery Bridge Drop Structure Stilling Basin", Contracted by U.S. Army Corps of Engineers, Walla Walla District and CH2M Hill, Boise, Idaho. Iowa Institute of Hydraulic Research Technical Report No. 409, 1999.

14. Weber, L.J., Cherian, M.P., Allen, M.E. and Muste, M., “Headloss Characteristics for Perforated Plates and Flat Bar Screens”, Iowa Institute of Hydraulic Research Technical Report No. 411, 2000.

15. Weber, L.J., Young, N. and Haug, P., "Hydraulic Model Testing of ESBS Perforated Plate Vibrations", for U.S. Army Corps of Engineers, Walla Walla District Office. Iowa Institute of Hydraulic Research Limited Distribution Report No. 282, 2000.

16. Nielsen, K., Weber, L.J. and Haug, P., “Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVI: 1:32.5 scale sectional model of Wanapum Dam spillway deflectors", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 284, 2000.

17. Allen, M.E., Mannheim, C.O.M. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVII: Physical Model Wanapum Dam Erosion Characteristics after Installation of Spillway Deflectors", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 286, 2000.

18. Blank, J.C. and Weber, L.J., “Numerical Simulations of Fish Passage Facilities at Lower Granite Lock and Dam”, Work funded by US Army Corps of Engineers, Walla Walla District Office, Walla Walla, WA. Iowa Institute of Hydraulic Research Technical Report No. 412, 2000.

19. Nestler, J.M., Goodwin, R.A., Weber, L.J. and Lai, Y.G., “Theoretical and Computational Templates for Juvenile Salmon Swim Path Selection in the Complex Hydrodynamic Environments of Rivers and Designed Hydraulic Structures”, US Army Corps of Engineers, ERCD/EL TR-00, November 2001.

20. Haug, P.E., Li, S. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XVIII: Summary of Hydraulic and CFD Models for Wanapum Dam", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 310, 2003.

21. Lyons, T.C., Li, S. and Weber, L.J., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XIX: Summary of Hydraulic and CFD Models for Priest Rapids Dam", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 311, 2003.

22. McCoy, A.W. and Weber, L.J., “Three-Dimensional Hydrodynamic and Total Dissolved Gas Simulations of Rock Island Dam Spillway”, Contracted by Public Utility District No. 1 of Chelan

County, Wenatchee, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 314, September 2003.

23. Weber, L.J., and Lyons, T.C., "Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XXI: Construction and Calibration of the 1:64 Priest Rapids Dam Comprehensive Forebay Model", Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. Iowa Institute of Hydraulic Research Limited Distribution Report No. 315, 2004.

POLITANO, MARCELA SUSANA

(ph 319-335-6393; email: marcela-politano@uiowa.edu)

Areas of Interest

Computational Fluid Dynamics, Multiphase Flow, Heat Transfer

Higher Education

Doctor in Engineering Science. 2001.
Instituto Balseiro. Argentina.
Thesis: Some Contributions to the Study of Polydisperse Multicomponent Flows.

Master in Chemical Engineering. 1996.
Universidad Nacional de Río Cuarto (UNRC). Argentina.
Thesis: Laser-induced Forces on Small Particles.

Chemical Engineer. 1993.
Universidad Nacional de Río Cuarto (UNRC). Argentina.
Thesis: Risk Analysis for the Bolivia-Brazil Gas Pipeline.

Research Experience

Assistant Research Engineer at IIHR – Hydroscience & Engineering, The University of Iowa (IIHR). October 2004 – present. Projects and working areas:

- Two-phase flow modeling for total dissolved gas concentration.
- CFD study of temperature dynamics at hydropower reservoirs.
- Anisotropic two-phase turbulence modeling.
- Numerical simulations of hydraulic structures and rivers.
- Free surface computations at complex fish bypass passages.

Postdoctoral Associate at IIHR. 2002-2004. Projects and working areas:

- Code development and numerical simulations of hydraulic transients for drainage systems.

Junior Researcher at the Department of Chemical Engineering at UNRC (Argentina). 1994-1998. Projects and working areas:

- Study of variability of characteristic parameters of liquid waste, analyzes of mechanisms of elimination of arsenic and fluorine using Hidroxiapatite, study of reduction of organic waste in Río Cuarto City, and study of disposal of hazardous waste Generated at UNRC.

Teaching Experience

Adjunct Assistant Professor at the Civil and Environmental Engineering Department, The University of Iowa. 2006 – present.

- 53:195 Contemporaneous Topics in Civil and Environmental Engineering: Applied CFD using commercial codes.
- Co-advising of three PhD thesis and two Master thesis.

Adjunct Assistant Professor at the College of Engineering, Universidad Argentina de la Empresa. 2001-2002. Course: Differential equations and Fourier series analysis.

Co-Instructor at the College of Engineering, UNRC. 1994-1998. Courses: Food technology, Chemical engineering process design. Advising of two degree thesis.

Teaching Assistant at the College of Engineering, UNRC. 1989-1993. Courses: Calculus, Vector calculus, Differential equations.

Industry Experience

Chemical Engineer. 1993.

Engevix-Engenharia, São Paulo, Brazil.
Projects and working areas: Risk Analysis of the Gas Pipeline Bolivia-Brasil (Petrobrás), Basic and Detailed Engineering for the Conversion of an Existing Plant into a Benzene, Toluene and Xilene distiller (Petrobrás) and Basic and Detailed Engineering for Storage and Transport of LPG (Monsanto).

Publications

International Journals (includes accepted papers)

1. Politano M., Haque MD. M. and Weber L. 2007. A Numerical Study of the Temperature Dynamics at McNary Dam. *J. Ecological Modelling. In press.*
2. Turan C., Politano M., Carrica P. M. and Weber L. 2007. Water Entrainment and Mixing due to Surface Jets. *Computational Fluid Dynamics*, 21, 3-4, 137-153.
3. Politano M., Odgaard J. and Klecan W. Case Study: Evaluation of Hydraulic Transients in a Drainage System by Numerical Modeling. *J. Hydraulic Engineering*, 133, 10, 1103-1110
4. Politano M., Carrica P.M., Turan C. and Weber L. 2007. A Multidimensional two-phase Flow Model for the Total Dissolved Gas Downstream of Spillways. *J. Hydraulic Research*, 45, 2, 165-177.
5. Politano M., Carrica P.M., Converti J. and Guido-Lavalle G. 2003. A Numerical Study of the Effect of the Bubble Size on the Gas/Liquid Distribution in a Vertical Channel. *Int. J. Heat and Technology*, 21, 1, 129-134.
6. Politano M., Carrica P.M. and Converti J. 2003. A Mathematical Model for Turbulent Polydisperse Two-Phase Flows in Vertical Channels. *Int. J. Multiphase Flow*, 29, 7, 1153-1182.
7. Politano M., Carrica P.M. and Baliño J. 2003. About Bubble Breakup Models to Predict Bubble Size Distributions in Homogeneous Systems. *Chemical Eng. Communications*, 190, 299-321.
8. Politano M., Carrica P.M. and Baliño J. 2001. A Polydisperse Model of the Two-Phase Flow in a Bubble Column. *Int. J. Heat and Technology*, 18, 2, 101-121.

International Journals (papers submitted)

1. Ferrari G., Politano M., and Weber L. 2007. 3D Numerical Simulations of Free Surface Flows on a Fish Bypass. *Submitted to Computers and Fluids*.

International Conferences

1. Ferrari G. Politano M. and Weber L. 2007. Numerical Simulations of Free Surface Flows on a Fish Bypass. Flucome 2007. Tallahassee, Florida.
2. Politano M., Turan C., Carrica P. and Weber L. 2007. A three Dimensional Anisotropic Model of the two-phase Flow and Total Dissolved Gas Downstream of Spillways. Flucome 2007. Tallahassee, Florida.
3. Troy L., Muste M., Weber L., Politano M., Carrica P., Hay D. 2007. Experimental and Numerical Model Study for the Design of Emergency Stoplogs Deployed in a Complex Flow Field. *Hydropower XV*. Chattanooga, Tennessee.
4. Politano M., Ferrari G., Carrica P. M. and Weber L. 2007. 3D Simulations of Free Surface Flows to Maximize Safe Fish Passage in Rocky Reach Dam. 6th International Symposium in EcoHydraulic. Christchurch, New Zealand.
5. Turan C., Politano M., Carrica P. M. and Weber L. 2007. A Study of the Water Entrainment on Wanapum Dam. *32nd IAHR Congress.* Venice, Italy.
6. Politano M., Sinha S., Haque MD H., Constantinescu G. and Weber L. 2006. Modeling the Potential Effect of Extreme Weather Condition on Water Temperature in McNary Dam. 7th International Conference in HydroInformatics. France.
7. Politano M., Haque MD H., Constantinescu G. and Weber L. 2006. A three-dimensional Thermal Model for McNary Dam. *World Water & Environmental Resources Congress.* Nebraska
8. Politano M., Carrica P., Turan C., Weber L. and Hay D. 2006. Model Study for the Design of Emergency Stoplogs Deployed in a Complex Flow Field – Part 2: Numerical Results. *World Water & Environmental Resources Congress.* Nebraska.
9. Turan C., McDaniel B., Politano M., Carrica P. and Weber L. 2006. A Study of the Free Surface Flow on Brownlee Dam. *World Water & Environmental Resources Congress.* Nebraska.
10. Turan C., Carrica P., Politano M. and Weber L. 2006. Water Entrainment and Mixing due to Spillways Discharges. *World Water & Environmental Resources Congress.* Nebraska.
11. Politano M., Odgaard J. and Klecan W. 2005. Numerical Simulation of Hydraulic Transients in Drainage Systems. *XX Computational Mechanics Conference.* Argentina.
12. Politano M., Carrica P. M. and Weber L. 2005. Prediction of the Total Dissolved Gas Downstream of Spillways Using a Multidimensional two-phase flow model. Keynote Lecture at the *XX Computational Mechanics Conference.* Argentina.
13. Politano M., Carrica P. M. and Weber L. 2005. Prediction of Total Dissolved Gas Downstream of Spillways Using a Multiphase Flow Modeling. Presented at *2005 CFD Summit*. Dearborn, Michigan.
14. Politano M., Carrica P. M., Turan C. and Weber L. 2005. Multidimensional Simulations of the two-phase flow Downstream of Spillways for Total Dissolved Gas prediction. *World Water & Environmental Resources Congress.* Alaska.
15. Politano M., Odgaard J., Jain S. and Klecan W. 2004. A Numerical Model for Hydraulic Transients in Drainage Systems. *World Water & Environmental Resources Congress.* Salt Lake City, Utah.
16. Politano M., Carrica P. M., Turan C. and Weber L. 2004. Prediction of the Total Dissolved Gas Downstream of Spillways using a two-phase Flow Model. *World Water & Environmental Resources Congress.* Salt Lake City, Utah.
17. Politano M., Carrica P. M. and Larreteguy A. 2001. Gas/Liquid Polydisperse Two-Phase Flow Modeling for Bubble Column Reactors. *ENPROMER. 3rd Mercosur Congress on Process Systems Eng. 1st Mercosur Congress on Chemical Eng*. Santa Fe. Argentina.

18. POLITANO M., CARRICA P. M., CONVERTI J. AND GUIDO-LAVALLE G. 2001. PHASE DISTRIBUTION IN A VERTICAL CHANNEL. THE EFFECT OF BUBBLE SIZE. *FLUIDOS-2001: VII INT. SEMINAR ON FLUIDS*. BUENOS AIRES. ARGENTINA.

19. Politano M., Carrica P. and Baliño J. 1999. A Preliminary Study of the Intrusivity of PIV Measurements. *2nd Int. Symposium on Two-Phase Flow Modeling and Experimentation. Pisa*. Italia.

IIHR Reports

1. Politano M., Ferrari G. and Weber L. 2006."Floating Islands in the Mississippi River – Computational Fluid Dynamics (CFD) Hydrodynamic Simulations. IIHR Limited Distribution Report N° 341.

2. Weber L., Constantinescu G., Politano M., Li S. and Wilson M. 2006. IIHR Fluent Activity Report. IIHR Limited Distribution Report N° 459.

3. Weber L., Politano M., Constantinescu G. and Haque Md. M. 2006. McNary Dam Forebay Temperature Improvements Computational Fluid Dynamics (CFD) Model. IIHR Limited Distribution Report N° 458.

4. Politano M. and Weber L. 2006. Rocky Reach Fish Passage CFD Hydrodynamic Simulations. IIHR Letter Report.

5. Politano M. and Odgaard J. 2004. Transient Flow Analyses for the West Area CSO Storage Tunnel, Atlanta, Georgia. IIHR Limited Distribution Report N° 318.

Fellowships, Awards and other Academic Merits

- NCSA **Award**, for the project: water entrainment and mixing in free surface jets. 2007.
- Performance **Award**, College of Engineering, The University of Iowa. 2006.
- **Fellowship Grant** by CONICET (Argentine Research Council) for graduate studies awarded in national competition, 1999-2001.
- **Fellowship Grant** by FOMEC (Fund for the Improvement of University Quality) for graduate studies awarded in national competition, 1997-1999.
- **Award** to the best grade average in the College of Engineering, UNRC. 1993.

Lê, B. and S. Kreiter. 2005. Aquatic Macrophyte Identification and Distribution Study. Wells Hydroelectric Project, FERC NO. 2149. Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

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AQUATIC MACROPHYTE IDENTIFICATION AND DISTRIBUTION STUDY

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

February, 2006

Prepared by:

B. Lê and S. Kreiter
Public Utility District No.1 of Douglas County
East Wenatchee, WA

Prepared for:

Public Utility District No. 1 of Douglas County
East Wenatchee, WA

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Relicensing
Attention: Mary Mayo
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509)884-7191, Ext. 2488
E-Mail: mmayo@dcpud.org

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ABSTRACT

In August and September of 2005, the Public Utility District No. 1 of Douglas County conducted a study to address the species composition, relative abundance and spatial distribution of macrophyte beds within the waters of the Wells Hydroelectric Project (Wells Project). Study methods consisted of an initial estimation of probable locations of macrophytes using detailed bathymetry and high resolution orthophotography. Macrophyte locations were estimated based upon water depth and based upon results from studies in nearby reservoirs. The estimated location of aquatic plant beds were then mapped using a Geographic Information System (GIS). The estimated locations were then field verified through a comprehensive survey of the Wells Reservoir to determine presence or absence of macrophyte beds in the estimated locations. During the field verification surveys, relative abundance and species composition data was collected and categorized into aquatic plant community types. Information collected was integrated into a final continuous macrophyte map layer in the GIS.

Sixty-one transects totaling 396 sample points were completed during the 2005 study. Depths of up to 30 feet were sampled and sampling points along transects were completed at intervals of 5 feet or less. A total of 9 aquatic plant species were documented. The two most dominant species in samples (samples in which the dominant species consisted of greater than 60% of the sample) collected were common waterweed (*Elodea canadensis*) and leafy pondweed (*Potamogeton foliosus*) at 24.7% and 16.7%, respectively. Both of these species are native to the Mid-Columbia River Basin. Non-native Eurasian watermilfoil (*Myriophyllum spicatum*) (EWM), which is an invasive species of concern, was dominant in only 6.3% of samples (25/396) collected. All of these samples were collected at depths between 4 and 15 feet. Samples in which no plants were identified (absent) consisted of 41.7% of all samples taken throughout the Wells Reservoir and supported the concept that macrophyte communities maintain a patchy distribution.

The study found that in general, macrophyte communities in the Wells Project were patchy and were distributed by depth. Water depth proved to be the most consistent variable in predicting the distribution of macrophyte communities in the Wells Reservoir. This observation was similar to the results from studies conducted in downstream reservoirs (Rocky Reach, Priest Rapids, Wanapum reservoirs).

In general, macrophyte communities did not recruit to depths of less than 4 feet in the Wells Project. Depths between 5 and 15 feet were characterized by a species composition where native species were dominant. In locations where Eurasian watermilfoil was present, this species was most often sub-dominant and present at relatively low densities (less than 10% milfoil). From depths of 15 to 24 feet, species composition consisted exclusively of native species. From 24 feet to 30 feet, macrophyte communities were absent most likely due to the limited availability of light at these depths. Overall, the study identified a total of 2,379 acres of macrophyte beds out of a total surface area of 9,740 acres.

1.0 INTRODUCTION

Aquatic plants are often an integral component of aquatic ecosystems and can be of ecological importance since they represent the major structural component of littoral habitats, acting as shelter, nesting, and feeding grounds for a wide variety of micro-organisms, fish and waterfowl (Hudon et al., 2000). The nature of these plant communities has been shown to affect light, temperature, turbulence, water and sediment chemistry, and the abundance and composition of other biotic assemblages from epiphytes to phytoplankton (Johnson and Ostrofsky, 2004). Within the Mid-Columbia River basin, native aquatic plant communities play an integral role in the success of both fish and wildlife communities. The abundance of native plant communities typically maintain a balance within the ecosystem encouraging the success of these communities as well as the success of other species of varying trophic levels that interact with it. These native aquatic plant communities create structural complexity resulting in high quality rearing habitat for juvenile fish, a stable prey base of forage fish for larger predatory fish, increased lower level trophic production (primary and secondary production), increased nutrient cycling and benefits to water quality.

Although aquatic plants are a natural component of aquatic habitat, their proliferation, especially non-native species, can result in a variety of detrimental impacts. Excessive proliferation of non-native species can displace diverse communities of native aquatic plants, affect trophic structure of fish assemblages, create over-populations of fish stunted in size, degrade water quality, and reduce the recreational and aesthetic enjoyment of a water body (Duke, 2001). The recent spread of invasive exotic macrophytes such as EWM into the Mid-Columbia River Basin is of particular concern. Like many invasive species, the spread of EWM can result in the displacement of diverse native plant communities and create a near monoculture of dense macrophytes (Olson et al., 1998) which in turn affect the entire aquatic ecosystem. The first documented occurrence of EWM in the State of Washington was in 1965. The source of introduction was most likely from sources in Canada and despite an effort to stop its spread, EWM infestations in Lake Osooyos, British Columbia spread down through the Okanogan Lakes and into the Okanogan River and Columbia River in 1974 (Duke, 2001).

Currently, some information exists on aquatic vegetation in the Mid-Columbia River system. Vegetation mapping in and around the Rocky Reach Reservoir (river miles 473.6 to 515.5) identified 979 acres of aquatic macrophyte habitat out of a total surface area of 8,167 acres (Duke, 2001). EWM percent biomass (oven dried weight) for plant communities in the Rocky Reach Reservoir represented 34 percent of all biomass samples taken (Duke, 2001). In the Priest Rapids and Wanapum reservoirs, the composition of EWM in the aquatic macrophyte community was higher at 42 percent of littoral plant biomass. Average macrophyte biomass in Wanapum and Priest Rapids reservoirs was 56.8 g/m^2 and 10 g/m^2, respectively (Normandeau et al., 2000). Various species such as EWM, a State-listed noxious weed, and several native species such as duckweed, sago pondweed, and waterweed, have been documented in aquatic macrophyte communities in the Wells Reservoir (NMFS, 2002). However, more detailed information is lacking on the location, size, habitat characteristics and species composition of macrophyte communities as well as the extent of EWM proliferation in the Wells Project. The primary goal of this study was to document, characterize and map the aquatic macrophyte communities present in the Wells Project.

2.0 STUDY GOALS

The goal of the study was to develop a better understanding of the aquatic macrophyte communities that are present within Wells Project waters. The specific study objectives were to:

1) Collect information on the location, size and relative species composition of aquatic macrophyte communities present in the Wells Project.

2) Produce a GIS map of the aquatic macrophyte communities using the information collected during the study.

3.0 STUDY AREA

Wells Dam is located at river mile (RM) 515.8 on the Columbia River in the State of Washington (Figure 3.0-1). It is located approximately 30 river miles downstream from Chief Joseph Dam which is owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from Rocky Reach Dam which is owned and operated by Chelan County PUD. The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from Wells Dam. Wells Dam impounds 29.5 miles of the Columbia River upstream to the tailrace of the Chief Joseph Hydroelectric Project at RM 545.1. The drainage area of the Columbia River Basin upstream of Wells Dam is approximately 85,300 square miles.

The Wells Reservoir has riverine characteristics in the upper 5-mile section downstream from the Chief Joseph Dam tailrace. The middle 10-mile section is more characteristic of a lacustrine environment. The lowermost 15-mile section is relatively narrow and fast flowing, compared to the middle section, but eventually slows and deepens as it nears the forebay of Wells Dam (Beak, 1999). The normal maximum surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at an elevation of 781. The normal maximum water surface elevation of the reservoir is 781 feet (Figure 3.0-1). The two major tributaries within the Wells Project are the Methow and Okanogan rivers.

The Methow River enters the Columbia River (RM 524) at the town of Pateros, Washington. The Wells Project impoundment affects 1.5 miles of the Methow River upstream from its confluence with the Wells Reservoir. The Okanogan River originates near Armstrong, British Columbia and flows south through a series of lakes to the Columbia River. It enters the Wells Reservoir at RM 534, approximately 18 miles upstream of Wells Dam. The Wells Project impoundment affects approximately 15.5 miles of the Okanogan River upstream from its confluence with the Columbia River.

The study area will include all water bodies within the Wells Project, including the Wells Reservoir and sections of the Methow and Okanogan rivers below the Wells Project Boundary. Field observations have found aquatic macrophytes to be non-existent in the Wells Dam tailrace. The absence of macrophytes is likely due to the incompatible habitat which consists of relatively deep water, high flows, and predominantly large substrate. Consequently, the absence of macrophytes in this area excluded it from the study area.

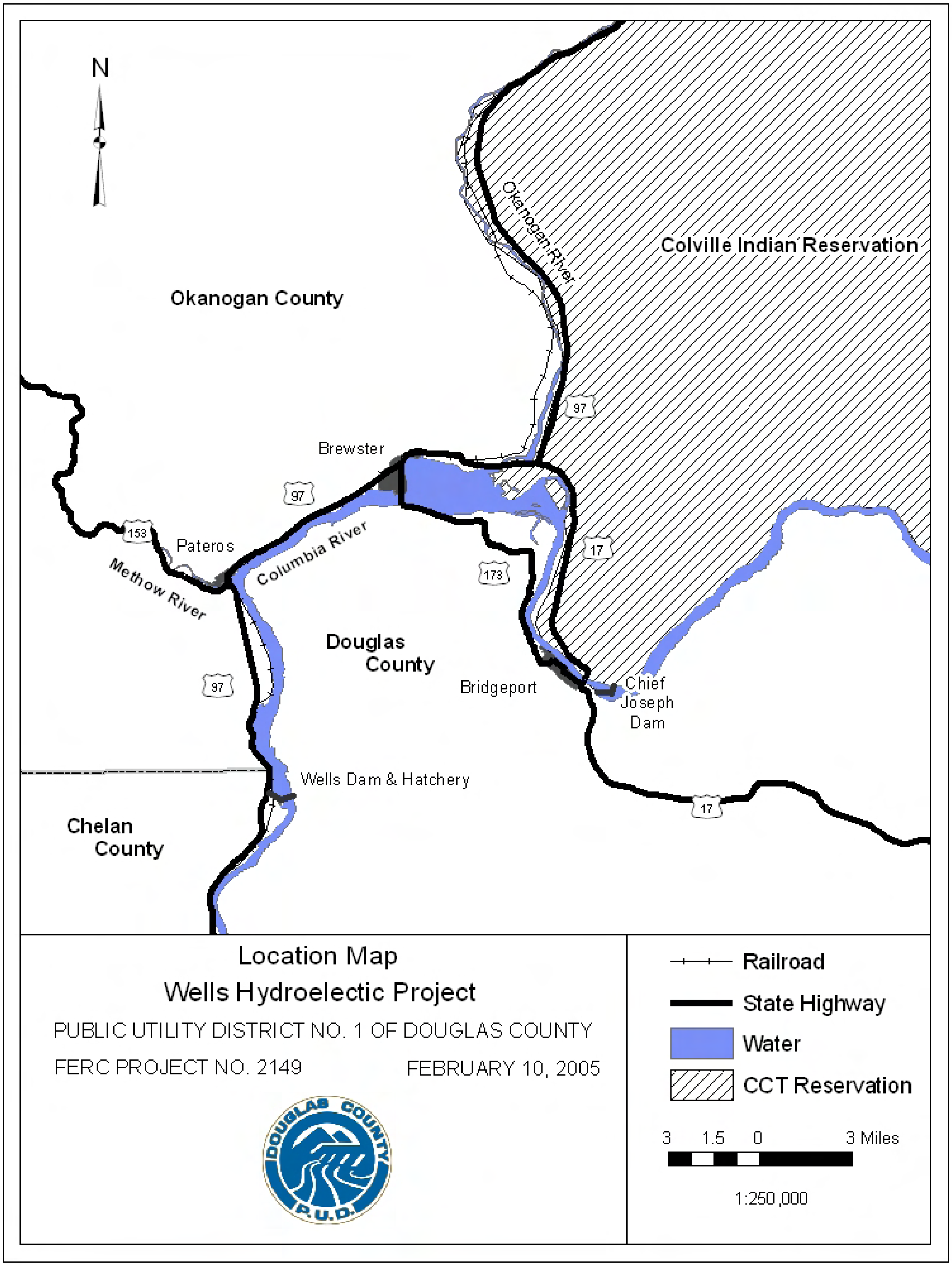

Figure 3.0-1 Location Map of the Wells Project

4.0 METHODS

The study methodology consisted of using high resolution orthophotography and detailed bathymetry to estimate probable locations of macrophyte beds throughout the reservoir. Estimates were made based on trends observed in similar studies at the Rocky Reach, Wanapum, and Priest Rapids reservoirs. These studies observed that depth gradients were a significant determinant in the distribution of aquatic macrophyte communities. Therefore, probable macrophyte locations in Wells Reservoir waters were estimated and mapped based on depth using a Geographic Information System (GIS). The presence or absence of macrophyte beds at these estimated locations were then field verified through a comprehensive survey of the reservoir.

Species composition of macrophyte beds were also field verified through a combination of randomized and non-randomized sampling. To increase the efficiency of data sampling and analysis, Wells Project waters were divided into six zones where distinct breaks were observed in habitat characteristics, macrophyte distribution, abundance and species composition (Table 4.0-1). Parameters such as river flow, bathymetry, and substrate type were considered during this exercise. Sampling was completed in each of the six designated zones in the Wells Project. At a minimum, sampling in each zone consisted of lateral transect surveys beginning at randomly selected points at 2 mile increments along the entire shoreline of all six zones. Lateral transects began near shore moving away from and perpendicular to shore. Sampling points along each transect were taken at a change in depth of every 4-5 feet until macrophytes were not present. Additionally, selected individual macrophyte beds that occurred at distinct habitat breaks were also surveyed using methods similar to the lateral transect sampling. Macrophyte sampling consisted of the deployment of a grappling hook at various depths along each transect. For each transect sampling point, the following information was collected:

- GPS beginning and end points, date and time for each transect;
- A measurement for water depth;
- Qualitative assessment of total plant density of the macrophyte bed;
- Aquatic macrophyte species present and their relative proportions using both visual surface assessment and sub-surface grab samples; and
- When necessary, GPS data points to assist in characterizing macrophyte bed surface size and shape.

Table 4.0-1 Wells Project zone designations for aquatic macrophyte identification and distribution study, 2005.

Zone	Description
1	Wells Dam tailrace (RM 515.8) to the upstream end of Pateros (RM 524)
2	Mouth of Methow River upstream to RM 1.5 of the Methow River
3	Pateros upstream to the Brewster Bridge (RM 530)
4	Brewster Bridge (RM 530) upstream to the north end of Park Island (RM 538.3)
5	Park Island upstream to Chief Joseph Dam (RM 545.1)
6	Mouth of the Okanogan River upstream to RM 15.5 of the Okanogan River

Qualitative information collected on the density and relative proportions of aquatic macrophyte species during the survey were used to categorize observations into pre-determined aquatic plant community types (Table 4.0-2). These (12) aquatic plant community types assisted in summarizing the information collected in the field into categories that can be integrated into the GIS. A final continuous macrophyte map layer was then generated in the GIS. The map layer shows the locations of all macrophyte beds and their respective plant community types as designated by species composition information observed in the field. Additional information that can be queried from the GIS includes the total area of community types and community type associations within the Wells Project boundary.

Table 4.0-2 Aquatic plant community types for the aquatic macrophyte identification and distribution study of the Wells Project, 2005. Community types are defined by two parameters at a particular site, species composition and plant density.

Aquatic Plant Community Type	
Species Composition	**Density**
Native (100% Native)	D, M, S[1]
Native Dominant (>60% Native)	D, M, S
EWM Dominant (>60% EWM)	D, M, S
EWM (100% EWM)	D, M, S
Absent	N/A

The proposed methodology for mapping macrophyte communities is consistent with professional practices used in previous aquatic habitat mapping studies (Duke, 2001, Normandeau et al., 2000) in the Mid-Columbia Basin. Field investigations on Wells Project waters were conducted in late summer (August and September) when macrophyte densities were at their peak and when water clarity was highest. All macrophyte samples were identified in the field using An Aquatic Plant Identification Manual for Washington's Freshwater Plants (WDOE, 2001). Samples for macrophyte species were also collected and verified by an independent reviewer for accuracy.

[1] D=Dense, M=Medium, S=Sparse

5.0 RESULTS

Field sampling for the study occurred between August 18 and September 8, 2005. Water temperatures during the study period ranged from 21.2°C in the Okanogan River to 19.4°C at the forebay of Wells Dam. With the exception of the Okanogan River, water clarity during the study was high with secchi disk readings (taken at Wells Dam) during the study period ranging from 12 to 15 feet.

In total, sixty-one transects totaling 369 sample points were completed during the study (Appendix A). The numbers of transects for zones 1 to 6 were 10, 2, 10, 15, 11, and 13, respectively. Average number of sample points per transect was 6.05. Depths ranging from 0.5 to 30 feet were sampled and sampling points along transects were completed at intervals of 5 feet or less.

A total of 9 aquatic plant species were documented (Table 5.0-1). Seven of these aquatic plant species are native to the Mid-Columbia River Basin whereas two of these species are considered non-native (Table 5.0-1). Table 5.0-1 presents the percentage of samples in which each of the identified aquatic species was categorized as the dominant species (consisting of >60% of the sample composition). The two most dominant species in samples collected were common waterweed (*Elodea canadensis*) and leafy pondweed (*Potamogeton foliosus*) at 24.7% and 16.7%, respectively. Both of these species are native and were present over the entire range of depths where macrophytes were present in samples. Non-native EWM was dominant in only 6.3% of samples taken (Table 5.0-1) and all of these samples were taken at depths between 4 and 15 feet. Samples in which no plants were collected (absent) consisted of 41.7% of all samples taken and support the concept that macrophyte communities maintain a patchy distribution (Table 5.0-1). Of the samples in which macrophytes were collected, 116 samples were qualitatively assessed as dense, 41 samples were identified as medium density and 74 samples were assessed as sparse or low density.

Table 5.0-1 Aquatic macrophyte species identified and the frequency at which each of the species was considered the dominant species (consisting of >60% of the total sample) in a given sample during the Wells Project Macrophyte Identification and Distribution Study, 2005.

Scientific Name	Common Name	Percentage of samples in which dominant	Native/Non-Native
Ceratophyllum demersum	Coontail	1.8% (7/396)	Native
Chara spp.	Muskgrass	.003% (1/396)	Native
Elodea canadensis	Common waterweed	24.7% (98/396)	Native
Myriophyllum spicatum	Eurasian watermilfoil	6.3% (25/396)	Non-native
Potamogeton crispus	Curly leaf pondweed	4.3% (17/396)	Non-native

Potamogeton foliosus	Leafy pondweed	16.7% (66/396)	Native
Potamogeton nodosus	American pondweed	1.3% (5/396)	Native
Potamogeton pectinatus	Sago pondweed	0.8% (3/396)	Native
Potamogeton zosteriformis	Flat-stemmed or eelgrass pondweed	2.3% (9/396)	Native
Absent		41.7% (165/396)	N/A

Results of the study found that in general, macrophyte communities in the Wells Project were distributed by various depth ranges. Table 5.0-2 presents the aquatic plant community types observed in each zone and how these community types shifted with changes in depth. In general, macrophyte communities did not recruit to depths of less than 4 feet in the Wells Project. Depths between 5 and 15 feet were characterized by a native dominant species composition (Table 5.0-2). If Eurasian watermilfoil were present at these depths, they were often sub-dominant or at low densities (less than 10% milfoil). From depths of 15 to 24 feet, species composition consisted of exclusively native species. From 24 feet to 30 feet, macrophyte communities were absent most likely due to the limited light at these depths. The maps in Appendix B graphically present the different aquatic plant community types observed in the Wells Project and the depth distributions at which they were observed. Table 5.0-3 presents total acreages for each of the aquatic plant community types observed in the Wells Project. Overall, 2,379 acres of macrophyte beds were identified out of a total surface area of 9,740 acres.

Table 5.0-2 Aquatic plant community types by Wells Reservoir zone designation and water depth, Wells Macrophyte Identification and Distribution Study 2005.

Zone Designation	Depth Range (ft)	Aquatic Plant Community Type	Density
1	0-4	Absent	N/A
	4.01-10	Native Dominant	Dense
	10.01-16	Native	Dense
	16.01-20	Native	Medium
	20.01-30	Absent	N/A
2	0-2	Absent	N/A
	2.01-9	Native Dominant	Dense
	9.01-15[2]	Absent	N/A
3	0-4	Absent	N/A
	4.01-15	Native Dominant	Dense
	15.01-18	Native	Dense
	18.01-24	Native	Medium

[2] Maximum depth along transect was 15 feet for all transects in Zone 2.

	24.01-30	Absent	N/A
4	0-4	Absent	N/A
	4.01-10	Native Dominant	Dense
	10.01-15	Native Dominant	Medium
	15.01-20	Native	Sparse
	20.01-30	Absent	N/A
5	0-5	Absent	N/A
	5.01-8	Native Dominant	Dense
	8.01-10	Native Dominant	Medium
	10.01-30	Absent	N/A
6	0-4	Absent	N/A
	4.01-6	Native Dominant	Dense
	6.01-8	Native	Sparse
	8.01-30	Absent	N/A

Table 5.0-3 GIS acreage estimates for the observed Aquatic Plant Community Types in the Wells Project. 2005 Wells Project Macrophyte Identification and Distribution Study.

Aquatic Plant Community Type	***Total Acreage***
Native Dense	201
Native Dominant Dense	995
Native Dominant Medium	433
Native Medium	348
Native Sparse	402
Total Acres	**2379**

6.0 DISCUSSION

The observation that depth may be a primary determinant of macrophyte distribution and species composition in Wells Project waters was consistent with the results of studies conducted in the Rocky Reach Reservoir (Duke, 2001) and the Priest and Wanapum reservoirs (Normandeau et al., 2000). Despite the general trend, there were some areas in which macrophyte presence was expected at appropriate water depths, but not observed.

In the Wells Project, macrophytes did not establish below 10 feet in Zone 5 (downstream of Chief Joseph Dam). The bathymetry in this zone is characterized by steep shoreline slopes and high water velocities due to the operations of Chief Joseph Dam. These characteristics created near shore environments similar to mid-channel environments downstream where high water velocities appeared to exclude macrophytes. In Zone 3 (Brewster Bridge to Park Island), depths below 20 feet were located in the middle of the Columbia River where it appears that river velocity was not conducive to macrophyte colonization. In Zone 6 (Okanogan River), limited light due to turbid conditions appeared to exclude macrophytes from depths greater than 8 feet (Table 5.0-2). These observations demonstrate that although depth may be a significant and effective parameter in determining macrophyte distribution and composition, macrophyte communities are complex and their colonization success is likely governed by multiple parameters.

Non-native EWM, although present in the Wells Project, was not observed at levels found in studies conducted in downstream Mid-Columbia River reservoirs. In the Rocky Reach Reservoir, EWM was found to be the most abundant species. Approximately one third of all the macrophyte bed acreage in the Project area was vegetated by dense EWM dominant growth (Duke, 2001). In the Priest Rapids and Wanapum reservoirs, EWM made up the highest percent composition over all samples at 41.7% (Normandeau et al., 2000). In the Wells Project, only 6.3% of samples collected were dominated by EWM. During the Wells Project study, EWM was often sub-dominant to several native species in samples collected. These contrasting observations between the Wells Reservoir and downstream reservoirs are not clearly understood. One would expect similar levels of EWM abundance in the Wells Project compared to that of the Rocky Reach Reservoir given their close proximity and connectivity. One possible explanation may be that EWM, which is a species that can proliferate from plant fragments (Ecology, 2001) has increased its ability to colonize due to potentially higher levels of disturbance in the Rocky Reach Reservoir as compared to the Wells Reservoir. The Rocky Reach Reservoir serves a larger population base, maintains an EWM removal program at recreational sites, and has higher levels of recreational use and development as compared to the Wells Reservoir. It is possible that these activities directly and indirectly re-mobilize EWM plant fragments and increase the potential for colonization in the Rocky Reach Reservoir as well as in downstream reservoirs.

7.0 LITERATURE CITED

Beak Consultants, Inc. and Rensel Associates. 1999. Assessment of Resident Fish in Lake Pateros, Washington. Final report. Prepared for Public Utility District No.1 of Douglas County. Beak Consultants, Inc. in cooperation with Rensel Associates. Arlington, Washington.

Duke (Duke Engineering & Services, Inc.). 2001. Aquatic Habitat Mapping Study Report. Report prepared for the Public Utility District No. 1 of Chelan County, Wenatchee, Washington.

WDOE (Washington State Department of Ecology). 2001. An Aquatic Plant Identification Manual for Washington's Freshwater Plants. Washington State Department of Ecology, June 2001, Publication 01-10-032.

Hudon C., Lalonde S., and P. Gagnon. 2000. Ranking the effects of site exposure, plant growth form, water depth, and transparency on aquatic plant biomass. Canadian Journal of Fisheries and Aquatic Sciences. **57**: 31-42.

Johnson, R.K. and M.L. Ostrofsky. 2004. Effects of sediment nutrients and depth on small-scale spatial heterogeneity of submersed macrophyte communities in Lake Pleasant, Pennsylvania. Canadian Journal of Fisheries and Aquatic Sciences. **61**: 1493-1502.

NMFS (National Marine Fisheries Service). 2002. Anadromous Fish Agreements and Habitat Conservation Plans Final Environmental Impact Statement for the Wells, Rocky Reach, and Rock Island Hydroelectric Projects. National Marine Fisheries Service, Northwest Region.

Normandeau Associates, Inc. 2000. An Evaluation of Water Quality and Limnology for the Priest Rapids Project Area. Report prepared for Public Utility District No. 2 of Grant County. Normandeau Associates, Inc. in cooperation with Washington State University and the Idaho Department of Fish and Wildlife.

Olson, M.H., Carpenter, S.R., Cunningham, P., Gafney, S., Herwig, B., Nibblelink, N., Pellet, T., Storlie C., Trebitz, A., and K. Wilson. 1998. Managing Macrophytes to Improve Fish Growth: A Multi-lake Experiment. Fisheries. **23**(2): 6-12.

Appendix A

2005 Wells Project Macrophyte Identification and Distribution Study Raw Data

Appendix A 2005 Wells Project Macrophyte Identification and Distribution Study Raw Data

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
8/18/2005	1	1	1	5	n/a	n/a	n/a	47 57.143	119 51.712
			2	8	<10 EWM	m	pc,ww,ewm		
			3	14	<10 EWM	l	ww,pc,ewm		
			4	20	<10 EWM	m	pc,ww,lp,ct		
			5	25	<10 EWM	l	ww,lp,pc		
			6	30	n/a	n/a	n/a		
8/18/2005	2	1	1	5	n/a	n/a	n/a	47 58.115	119 53.057
			2	6	30-60 EWM	d	pc/ww/ewm		
			3	8	30-60 EWM	d	pc/ww/ewm		
			4	8	30-60 EWM	d	pc/ewm		
			5	14	<10 EWM	s	ct/pc/ww		
			6	20	<10 EWM	s	ww/pc/ct		
			7	25		n/a	n/a		
			8	27		n/a	n/a		
8/18/2005	3	1	1	5	n/a	n/a	n/a	47 58.912	119 53.354
			2	8	<10 ewm	d	lp/ww/ct/ewm		
			3	5	n/a	n/a	n/a		
			4	8	>60 ewm	m	ewm/ww		
			5	10	<10 ewm	d	lp/ww/ewm/pc		
			6	13	<10 ewm	m	lp/pc/ww		
			7	18	<10 ewm	m	lp/pc/ww/ct		
			8	20	<10 ewm	s	ct		
			9	25	n/a	n/a	n/a		
8/19/2005	4	1	1	30	n/a	n/a	n/a	47 59.419	119 52.755
			2	26	<10 ewm	s	lp/pc/ct		
			3	21	<10 ewm	s	ww/lp/ewm/ct		
			4	16	<10 ewm	d	lp/ww/ct/pc		
			5	11	<10 ewm	s	lp/ww/ct/pc/ewm		
			6	11	<10 ewm	d	lp/pc/ww		
			7	6	<10 ewm	d	ww/ewm/pc		
			8	8	<10 ewm	d	lp/ww/ewm		
			9	9	<10 ewm	d	lp/ww/ewm		
			10	5	n/a	n/a	n/a		
								47 59.423	119 53.054

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
8/19/2005	5	1	1	26	n/a	n/a	n/a	47 58.527	119 52.789
			2	21	<10 ewm	s	lp/ww		
			3	16	<10 ewm	d	ww		
			4	11	<10 ewm	d	ww/pc/ct		
			5	8	<10 ewm	d	lp/ww/pc		
			6	5	<10 ewm	m	ww/lp/pc/ewm		
8/19/2005	6	1	1	26	<10 ewm	s	ww/lp	48 00.042	119 51.941
			2	21	<10 ewm	d	ww/lp/pc/ct		
			3	16	<10 ewm	d	lp/ww/ct		
			4	11	<10 ewm	d	ww/lp/ct		
			5	6	<10 ewm	d	ww/pc/ewm		
			6	5	n/a	n/a	n/a		
8/19/2005	7	1	1	26	n/a	n/a	n/a	48 01.199	119 52.536
			2	21	<10 ewm	s	lp/ww		
			3	16	<10 ewm	d	ww/lp/ct		
			4	11	<10 ewm	d	ww/pc		
			5	11	30-60 ewm	d	ewm/ww		
			6	6	30-60 ewm	d	ewm/ww		
			7	5	n/a	n/a	n/a		
8/19/2005	8	1	1	26	<10 ewm	s	ww/lp/ct	48 01.930	119 52.815
			2	26	<10 ewm	s	ww/ct		
			3	21	<10 ewm	d	ww/ct/lp		
			4	16	<10 ewm	d	ww/ct		
			5	10	30-60 ewm	d	ww/ewm/ct		
			6	6	n/a	n/a	n/a		
			7	5	n/a	n/a	n/a	48 01.938	119 52.787
8/19/2005	9	1	1	26	n/a	n/a	n/a	48 02.795	119 53.822
			2	21	<10 ewm	d	ww/lp		
			3	16	<10 ewm	d	lp/ct		
			4	13	<10 ewm	d	lp		
			5	11	<10 ewm	d	lp/pc/ct		
			6	10	<10 ewm	d	lp/ewm		
			7	6	<10 ewm	d	pc/ww		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			8	5	n/a	n/a	n/a	48 02.770	119 53.904
8/19/2005	10	1	1	26	n/a	n/a	n/a	48 02.838	119 53.515
			2	26	n/a	n/a	n/a		
			3	21	<10 ewm	d	ww/ct/pc		
			4	16	<10 ewm	d	ww/pc/ct		
			5	11	<10 ewm	d	ww/pc		
			6	6	<10 ewm	d	lp/pc/ww		
			7	5	n/a	n/a	n/a	48 02.861	119 53.475
8/19/2005	11	2	1	5	<10 ewm	dense	ww/pc/ewm	no GPS	
			2	5	n/a	n/a	n/a		
			3	16	n/a	n/a	n/a		
			4	11	n/a	n/a	n/a		
			5	12	n/a	n/a	n/a		
			6	16	n/a	n/a	n/a		
			7	6	<10 ewm	dense	ww/pc		
			8	5		n/a	n/a		
8/19/2005	12	2	1	9	<10 ewm	d	pc/lp/ww	no GPS	
			2	10.5	n/a	n/a	n/a		
			3	10	<10 ewm	m	pc		
			4	4	<10 ewm	m	lp		
			5	11	n/a	n/a	n/a		
8/24/2005	13	3	1	25	n/a	n/a	n/a	48 03.573	119 52.631
			2	20	<10 ewm	d	lp/ww/pc		
			3	15	<10 ewm	d	ww/lp/pc/ct		
			4	7	<10 ewm	d	ww/pc/ct		
			5	10	<10 ewm	d	lp/ww/ct/pc		
			6	5	<10 ewm	d	lp/pc		
8/23/2005	14	3	1	26	<10 ewm	sparse	ct/lp/ww	48 04.109	119 51.810
			2	21	<10 ewm	medium	lp/ww/ct		
			3	16	<10 ewm	dense	lp/pc/ww/ct		
			4	11	<10 ewm	dense	lp/ww/pc/ewm		
			5	7	<10 ewm	dense	ww/lp/pc		
			6	6	<10 ewm	dense	lp/pc		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			7	26	n/a	n/a	n/a		
			8	24	<10 ewm	sparse	lp		
8/24/2005	15	3	1	25	n/a	n/a	n/a	48 04.175	119 51.687
			2	20	n/a	n/a	n/a		
			3	15	<10 ewm	sparse	lp/pc/ewm		
			4	15	<10 ewm	medium	ww/lp/pc/ewm		
			5	10	>90 ewm	dense	ewm/ww		
			6	7	>90 ewm	dense	ewm/ww/ct		
			7	5	>90 ewm	dense	ewm/ww		
8/24/2005	16	3	1	26	n/a	n/a	n/a	48 04.943	119 49.375
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	<10 ewm	sparse	ewm		
			5	5	n/a	n/a	n/a		
8/23/2005	17	3	1	26	n/a	n/a	n/a	48 04.843	119 49.809
			2	21	<10 ewm	dense	ww/lp/pc/ct		
			3	16	<10 ewm	dense	pc/ww/lp/ct		
			4	11	>60 ewm	dense	ewm/ct/pc/ww		
			5	9	30-60 ewm	dense	ww/ewm/pc		
			6	8	30-60 ewm	dense	ww/ewm/pc		
			7	6	10-30 ewm	dense	ww/pc/ewm		
8/23/2005	18	3	1	26	n/a	n/a	n/a	48 05.304	119 47.535
			2	14	10-30 ewm	dense	ww/ewm/pc/lp		
			3	11	<10 ewm	dense	lp/ww/pc/ewm		
			4	12	<10 ewm	dense	ww/pc/lp/ewm		
			5	9	<10 ewm	dense	lp/ww/pc		
			6	11	<10 ewm	dense	lp/ww/ct		
			7	15	<10 ewm	dense	ww/pc/ct		
			8	19	<10 ewm	sparse	lp/ww		
			9	7	10-30 ewm	dense	lp/ww/ewm/pc		
			10	9	30-60 ewm	dense	ewm/pc/lp/ww		
8/24/2005	19	3	1	25	n/a	n/a	n/a	48 04.464	119 50.746

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			2	20	<10 ewm	medium	ww/lp/pc		
			3	15	<10 ewm	dense	pc/ww/lp		
			4	7	<10 ewm	dense	ww/lp/pc/ct		
			5	5	<10 ewm	dense	ww/lp		
8/24/2005	20	3	1	7	10-30 ewm	medium	lp/ww/ewm	48 04.940	119 48.799
			2	5	<10 ewm	sparse	ww/pc		
			3	7	<10 ewm	sparse	ww/pc/ewm		
			4	25	n/a	n/a	n/a		
			5	20	<10 ewm	sparse	lp		
			6	15	<10 ewm	medium	lp/ww/pc		
			7	10	<10 ewm	medium	ww/lp/pc		
			8	5	<10 ewm	dense	ww/lp/ewm		
8/24/2005	21	3	1	25	n/a	n/a	n/a	48 05.097	119 46.986
			2	15	>90 ewm	sparse	ewm		
			3	20	n/a	n/a	n/a		
			4	10	<10 ewm	sparse	ww/lp		
			5	5	n/a	n/a	n/a		
8/24/2005	22	3	1	25	n/a	n/a	n/a	48 04.335	119 51.019
			2	20	<10 ewm	dense	lp/ct/pc		
			3	13	10-30 ewm	dense	ewm/lp/ww		
			4	15	<10 ewm	dense	lp/ww/ct		
			5	11	10-30 ewm	dense	lp/ewm/ww		
			6	7	<10 ewm	dense	lp/pc/ww/ewm		
			7	8	<10 ewm	dense	lp/ww/ewm		
8/30/2005	23	4	1	25	n/a	n/a	n/a	48 06.050	119 46.580
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	<10 ewm	sparse	ww/ewm		
			5	8	<10 ewm	sparse	ct/ww/pc/ewm		
8/30/2005	24	4	1	25	n/a	n/a	n/a	48 06.079	119 46.125
			2	20	<10 ewm	sparse	ct/lp/ww		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			3	15	<10 ewm	sparse	ww/ct		
			4	10	<10 ewm	dense	lp/pc/ww/ct		
			5	5	<10 ewm	sparse	pc/ct/lp		
8/30/2005	25	4	1	25	<10 ewm	sparse	ct/ww/lp	48 06.360	119 45.958
			2	20	<10 ewm	sparse	lp/ww		
			3	20	<10 ewm	dense	ww/lp/pc		
			4	15	30-60 ewm	dense	ewm/ww/lp/ct		
			5	9	30-60 ewm	dense	ewm/ww/ct/lp		
			6	5	30-60 ewm	medium	ewm/pc/ww		
8/30/2005	26	4	1	25	n/a	n/a	n/a	48 06.019	119 44.236
			2	20	n/a	n/a	n/a		
			3	15	<10 ewm	sparse	ww/lp/ct		
			4	10	n/a	n/a	n/a		
			5	10	n/a	n/a	n/a		
8/30/2005	27	4	1	10	<10 ewm	dense	lp/pc/ww/ewm	48 05.128	119 45.445
			2	10	<10 ewm	dense	lp/pc/ww/ewm		
			3	10	<10 ewm	medium	lp/pc/ww/ewm		
			4	18	<10 ewm	sparse	ww/pc/lp		
			5	15	<10 ewm	dense	lp/pc/ww/ewm		
			6	23	<10 ewm	sparse	ww/pc		
			7	9	<10 ewm	dense	lp/pc		
			8	6	<10 ewm	medium	ww/pc/lp		
8/30/2005	28	4	1	7	<10 ewm	medium	ww/lp/pc	48 05.000	119 44.355
			2	13	n/a	n/a	n/a		
			3	13	n/a	n/a	n/a		
			4	10	<10 ewm	dense	ww/pc/lp		
			5	5	<10 ewm	medium	ww/pc/ewm/lp		
			6	15	<10 ewm	medium	pc/ww/lp		
			7	0-4	n/a	n/a	n/a		
			8	5	<10 ewm	dense	ww/lp/pc		
8/30/2005	29	4	1	25	n/a	n/a	n/a	48 04.860	119 42.890
			2	20	n/a	n/a	n/a		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			3	11	<10 ewm	very sparse	ww		
			4	5	n/a	n/a	n/a		
			5	10	<10 ewm	medium	ww/lp/pc		
8/30/2005	30	4	1	12	<10 ewm	sparse	lp/ww/pc	48 04.712	119 41.203
			2	14	<10 ewm	sparse	lp/pc/ww		
			3	6	<10 ewm	dense	lp/pc/ww/ewm		
			4	4	<10 ewm	sparse	ww/pc/ewm		
			5	5	<10 ewm	dense	ww/lp/pc/ewm		
			6	25	n/a	n/a	n/a		
			7	20	n/a	n/a	n/a		
			8	15	<10 ewm	very sparse	pc/lp		
			9	10	<10 ewm	very sparse	ww/lp		
			10	7	n/a	n/a	n/a		
			11	10	<10 ewm	sparse	ww/lp/pc		
			12	10	<10 ewm	dense	ww/lp/pc/ewm		
			13	7	<10 ewm	sparse	ww/lp/pc/ewm		
			14	6	<10 ewm	sparse	ww/pc/lp/ewm		
			15	<5	n/a	n/a	n/a		
8/31/2005	31	4	1	12	<10 ewm	sparse	lp/ww	48 05.576	119 43.249
			2	10	>60 ewm	dense	ewm/lp		
			3	15	<10 ewm	sparse	ww/lp/ewm		
			4	22	n/a	n/a	n/a		
			5	22	<10 ewm	sparse	ww/lp		
			6	10	30-60 ewm	medium	ewm/pc/ww/lp		
			7	8	30-60 ewm	sparse	ewm/pc/ct/lp		
			8	13	<10 ewm	dense	lp/ww/pc/ewm		
			9	6	<10 ewm	sparse	ww/pc/lp/ewm		
8/31/2005	32	4	1	12	n/a	n/a	n/a	48 05.319	119 42.906
			2	20	n/a	n/a	n/a		
			3	10	30-60 ewm	sparse	ewm/ww		
			4	7	<10 ewm	dense	ww/lp/pc/ewm		
			5	4	<10 ewm	dense	ww/lp/pc/ewm		
8/31/2005	33	4	1	25	n/a	n/a	n/a	48 05.362	119 41.602

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
8/31/2005	34	4	1	0-5	n/a	n/a	n/a	48 05.728	119 40.980
			2	7	<10 ewm	medium	ww/pc/ewm		
			3	10	30-60 ewm	sparse	ewm/ww		
			4	20	<10 ewm	sparse	lp		
			5	25	n/a	n/a	n/a		
			6	20	<10 ewm	medium	ww/lp		
			7	19	<10 ewm	sparse	lp/ww		
			8	15	10-30 ewm	dense	ww/lp/ewm		
			9	10	<10 ewm	dense	ww/lp/ewm/pc		
			10	6	30-60 ewm	sparse	ewm/pc/ww		
			11	0-5	n/a	n/a	n/a		
8/31/2005	35	4	1	22	n/a	n/a	n/a	48 05.310	119 41.138
			2	18	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	<10 ewm	sparse	ww/pc/ewm		
			5	12	n/a	n/a	n/a		
			6	13	<10 ewm	sparse	lp/ww/pc/ewm		
			7	6	<10 ewm	sparse	ww/pc/lp		
			8	3	n/a	n/a	n/a		
			9	8	n/a	n/a	n/a		
			10	25	<10 ewm	sparse	lp		
			11	10	<10 ewm	dense	lp/ww/pc		
			12	15	<10 ewm	medium	lp/ww/pc/ewm		
			13	0-8	n/a	n/a	n/a	48 04.899	119 41.324
8/31/2005	36	4	1	25	n/a	n/a	n/a	48 04.382	119 40.090
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
8/31/2005	37	4	1	6	n/a	n/a	n/a	48 04.869	119 40.180

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			2	8	<10 ewm	sparse	pc/ewm/lp/ww		
			3	10	30-60 ewm	dense	ww/ewm/lp/pc		
			4	13	<10 ewm	dense	ww/lp/ewm/pc		
			5	15	<10 ewm	medium	ww/lp/pc		
			6	20	<10 ewm	sparse	lp/ww		
			7	25	n/a	n/a	n/a		
			8	20	n/a	n/a	n/a		
			9	10	n/a	n/a	n/a		
			10	5	n/a	n/a	n/a	48 04.752	119 39.958
9/6/2005	38	5	1	25	n/a	n/a	n/a	48 04.219	119 40.350
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
9/6/2005	39	5	1	25	n/a	n/a	n/a	48 02.870	119 40.746
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	100 ewm	medium	ewm		
			5	8	30-60 ewm	dense	ewm/ww/ct		
			6	5	n/a	n/a	n/a		
9/6/2005	40	5	1	25	n/a	n/a	n/a	48 02.805	119 40.991
			2	19	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	3	<10 ewm	sparse	ww/lp/ewm		
9/6/2005	41	5	1	25	n/a	n/a	n/a	48 02.309	119 41.246
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
9/6/2005	42	5	1	25	n/a	n/a	n/a	48 01.854	119 41.721
			2	20	n/a	n/a	n/a		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	8	<10 ewm	sparse	ewm		
9/6/2005	43	5	1	25	n/a	n/a	n/a	48 01.308	119 41.400
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	10-30 ewm	medium	lp/ewm/pc/ww		
			5	5	10-30 ewm	dense	ww/ewm/lp		
9/6/2005	44	5	1	25	n/a	n/a	n/a	48 01.341	119 41.157
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
9/6/2005	45	5	1	25	n/a	n/a	n/a	48 00.881	119 40.636
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
9/6/2005	46	5	1	25	n/a	n/a	n/a	48 00.561	119 39.848
			2	20	n/a	n/a	n/a		
			3	15	<10 ewm	dense	ww/ct/ewm/pc		
			4	10	10-30 ewm	medium	ct/lp/ewm/ww		
			5	8	<10 ewm	dense	ww/ct/ewm		
			6	5	n/a	n/a	n/a		
9/6/2005	47	5	1	25	n/a	n/a	n/a	48 00.060	119 39.422
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	5	n/a	n/a	n/a		
9/6/2005	48	5	1	10	<10 ewm	sparse	ww/lp/pc	48 03.674	119 40.749

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			1	7	<10 wm	dense	ww/lp/pc/ewm	48 03.845	119 41.032
			1	7	<10 ewm	dense	ww/lp/ct	48 03.961	119 41.232
			1	5	<10 ewm	medium	muskgrass/ww	48 04.589	119 41.139
			2	10	<10 ewm	sparse	ww		
			3	10	<10 ewm	medium	lp/ww/pc		
			4	13	<10 ewm	sparse	lp/pc/muskgrass		
			5	10	<10 ewm	medium	lp/ww/pc/ewm		
			6	5	n/a	n/a	n/a	48 04.575	119 41.032
			1	4	<10 ewm	sparse	ww/muskgrass	48 04.322	119 41.349
			2	6	<10 ewm	medium	ww/lp/pc/ewm		
			3	9	<10 ewm	medium	ww/lp/pc		
			1	6	<10 ewm	dense	ww/lp	48 04.088	119 41.384
			2	10	<10 ewm	dense	ww/lp/ewm		
9/8/2005	49	6	1	30	n/a	n/a	n/a	48 06.079	119 42.600
			2	25	n/a	n/a	n/a		
			3	20	n/a	n/a	n/a		
			4	15	n/a	n/a	n/a		
			5	10	n/a	n/a	n/a		
			6	5	10-30 ewm	medium	ewm/ww/lp		
			7	5	<10 ewm	sparse	pc/ap		
9/8/2005	50	6	1	25	n/a	n/a	n/a	48 06.393	119 42.124
			2	20	n/a	n/a	n/a		
			3	15	n/a	n/a	n/a		
			4	10	n/a	n/a	n/a		
			5	6	<10 ewm	medium	ap/lp/ct/ewm		
			6	3	<10 ewm	sparse	ap/ct		
9/8/2005	51	6	1	15	n/a	n/a	n/a	48 06.978	119 41.007
			2	10	<10 ewm	sparse	eg		
			3	2	<10 ewm	dense	ww/eg/ap/pc		
			4	2	<10 ewm	medium	ww/ap		
			5	1	<10 ewm	sparse	ap/sp		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
9/8/2005	52	6	1	15	n/a	n/a	n/a	48 07.350	119 40.977
			2	10	n/a	n/a	n/a		
			3	8	<10 ewm	medium	ap/eg		
			4	5	<10 ewm	dense	ww/ap/pc/ct		
			5	1	<10 ewm	sparse	lp/ww/ap		
9/8/2005	53	6	1	10	n/a	n/a	n/a	48 08.811	119 40.172
			2	8	<10 ewm	dense	eg		
			3	1	<10 ewm	dense	ww/ap/sp		
			4	5	<10 ewm	dense	pc/eg/ap		
9/8/2005	54	6	1	15	n/a	n/a	n/a	48 09.160	119 39.924
			2	10	n/a	n/a	n/a		
			3	8	n/a	n/a	n/a		
			4	7	30-60 ewm	sparse	pc/ewm		
			5	4	30-60 ewm	medium	ewm/ct		
			6	2	<10 ewm	dense	ww/ewm/pc		
			7	1	<10 ewm	sparse	ap/lp		
9/8/2005	55	6	1	12	n/a	n/a	n/a	48 10.411	119 40.508
			2	10	<10 ewm	dense	eg		
			3	3 to 5	<10 ewm	dense	ww/pc/eg		
			4	<3	n/a	n/a	n/a		
9/8/2005	56	6	1	13	n/a	n/a	n/a	48 10.800	119 40.778
			2	9	<10 ewm	dense	eg		
			3	6	<10 ewm	dense	eg/pc		
9/8/2005	57	6	1	9	n/a	n/a	n/a	48 11.747	119 41.319
			2	8	n/a	n/a	n/a		
			3	6 to 8	<10 ewm	medium	ww		
9/8/2005	58	6	1	10	n/a	n/a	n/a	48 11.976	119 41.716
			2	8	n/a	n/a	n/a		
			3	8	<10 ewm	sparse	eg		

Appendix A (Continued)

Date	Transect	Zone	Sample	Depth (ft.)	Category	Density (D, M, S)	Species Comp	GPS (LAT)	GPS (LONG)
			4	6	< 10 ewm	dense	eg/pc/ww/ewm		
			5	5	<10 ewm	dense	eg/pc/ww		
9/8/2005	59	6	1	4	<10 ewm	dense	sp/pc/eg	48 12.796	119 43.163
			2	3	n/a	n/a	n/a		
			3	2	n/a	n/a	n/a		
			4	1	n/a	n/a	n/a		
9/8/2005	60	6	1	6	n/a	n/a	n/a	48 12.433	119 42.469
			2	5	n/a	n/a	n/a		
			3	4	<10 ewm	sparse	eg/sp/ww		
9/8/2005	61	6	1	7	n/a	n/a	n/a	48 12.406	119 42.328
			2	6	<10 ewm	dense	sp		
			3	3	<10 ewm	medium	sp/ww/eg		
			4	<2	n/a	n/a	n/a		

Appendix B

GIS Maps of Macrophyte Beds in the Wells Project

MAPS AVAILABLE UPON REQUEST

OR CAN BE FOUND AT THE FOLLOWING WEBSITE:

http://relicensing.douglaspud.org/documents/pud_relicensing_documents/downloads/SR/MacrophyteIdentificationandDistributionStudyMAPS.pdf

Lê, B. and J. Murauskas. 2009. Total Dissolved Gas Abatement Plan. Wells Hydroelectric Project, FERC No. 2149. Public Utility District No. 1 of Douglas County. Prepared for Washington Department of Ecology, Yakima, Washington.

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2009 TOTAL DISSOLVED GAS ABATEMENT PLAN

WELLS HYDROELECTRIC PROJECT

April 2009

Prepared by:

Bao Le
Long View Associates
Portland, Oregon

And

Joshua Murauskas
Public Utilities District No. 1 of Douglas County
East Wenatchee, Washington

Prepared for:

Washington Department of Ecology
Yakima, Washington 98902-3452

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1.0 INTRODUCTION

1.1 Total Dissolved Gas

Dissolved gasses in water occur from exchange of gas within the atmosphere and through biological activity such as photosynthesis or respiration. Optimal water quality conditions of dissolved gas for fish are considered to be close to the barometric pressure seen at the air-water interface. Dissolved gas may become a water quality issue when gasses supersaturate a river, lake or stream. Plunging water may cause an increase in total dissolved gas (TDG) of a body of water as air bubbles become entrained, pushed to depth and forced into solution due to increased pressure. This phenomenon occurs naturally at waterfalls and artificially at dams. Spill which can also increase the TDG concentrations of a body of water occurs when river flows exceed the hydraulic capacity of a dam due to limited generation capacity, a lack of demand for power, and for fish passage.

Despite the potential for higher levels of TDG, hydroelectric dams on the Columbia and Snake rivers provide safe passage routes for migrating juvenile salmonids through spill. Many variables contribute to dissolved gas supersaturation, project operations, spill flow rates, tailwater bathymetry, air entrainment, spill plunge depths, entrainment flows, wind and temperature of the water.

1.1.1 Total Dissolved Gas and Impacts to Aquatic Life

Impacts to aquatic life from extended exposure to high levels of TDG have long been a concern in the Columbia River basin. High levels of TDG have been shown to cause air embolisms in fish that result in impaired health or even death. Gas Bubble Trauma (GBT) is a condition that affects aquatic animals residing in waters that are supersaturated with atmospheric gases. It occurs when dissolved gases in the blood come out of solution and form bubbles in various external and internal tissues (EPA 1976). Gas bubble trauma is a physically induced condition, caused by pressure dis-equilibrium between the liquid and gas phases (Jensen et al. 1986). In juvenile salmonids, bubbles along the lateral line are one of the first and most frequent external signs of gas bubble trauma (Dawley et al. 1975, Weitkamp and Katz 1980).

Mortality can result from both acute and chronic symptoms of GBT. Acute mortality usually results from blockage of blood flow in the heart, gills, and other capillary beds, due to accumulation of emboli in the blood (Bouck 1980). Chronic mortality is associated with extravascular bubbles that reduce respiratory water flow (Jensen et al. 1986). Sublethal effects of GBT such as blindness, stress, and decreased lateral line sensitivity can indirectly lead to death from predation or other causes (Weitkamp and Katz 1980).

1.1.2 Washington State Water Quality Standards

The Water Quality Standards Chapter 173-201A of the Washington Administrative Code address standards for the surface waters of Washington State. The codes have been revised recently for consistency with the needs of fish (designated use for aquatic life) that may be found in those waters.

Based upon criteria developed by the Washington Department of Ecology (Ecology), TDG measurements shall not exceed 110 percent at any point of measurement in any state water body. Ecology acknowledges that an operator of a dam is not held to the TDG standards when the river flow exceeds the seven-day, 10-year-frequency flood (7Q10). The 7Q10 flow is the highest value of a running seven consecutive day average using the daily average flows that may be seen in a 10-year period. The 7Q10 total river flow for the Wells Project was computed using the hydrologic record from 1974 through 1998 and a statistical analysis to develop the number from 1930 through 1998. The USGS Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" was followed. The resulting 7Q10 flow at Wells Dam is 246,000 cfs (Pickett et. al. 2004).

In addition to allowances for natural flood flows, the TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with an Ecology approved gas abatement plan. Ecology has approved on a per application basis, an interim waiver to the TDG standard (110 percent) to allow spill for juvenile fish passage on the Columbia and Snake rivers (WAC 173-201A-200(1)(f)(ii)). Dams in the Columbia and Snake rivers may be allowed a TDG exemption to the 110 percent TDG standard to allow for passage of juvenile fish downstream over the dams rather than through the turbines.

On the Columbia and Snake rivers there are three separate standards with regard to the TDG exemption. First, in the tailrace of a dam, TDG shall not exceed 125 percent as measured in any one-hour period. Further, TDG shall not exceed 120 percent in the tailrace of a dam and shall not exceed 115 percent in the forebay of the next dam downstream as measured as an average of the 12 highest consecutive hourly readings in any one day (24-hour period). The increased levels of spill resulting in elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. This TDG exemption provided by Ecology is based on a risk analysis study conducted by the National Marine Fisheries Service (NMFS) (NMFS 2000).

2.0 GOAL AND OBJECTIVES

The goal of the Wells Total Dissolved Gas Abatement Plan (Gas Abatement Plan) is to implement a long-term strategy to maintain compliance with the Washington state water quality standard for TDG in the Columbia River at the Wells Hydroelectric Project (Wells Project) while continuing to provide safe passage for downstream migrating juvenile salmonids. The Public Utility District No. 1 of Douglas County (Douglas PUD) which owns and operates the Wells Hydroelectric Project is submitting this Gas Abatement Plan to Ecology for approval as required for receipt of a TDG exemption at Wells Dam.

In the past, Ecology has approved Wells Project Gas Abatement Plans and issued a TDG exemption at Wells Dam. Douglas PUD submitted a Gas Abatement Plan that was approved on March 27, 2003 for one year (Appendix A and B). In 2004, an extension was granted by Ecology (Appendix C). On March 31, 2005, Ecology approved Douglas PUD's 2005 Gas Abatement Plan allowing a TDG exemption in support of fish passage through February 2008 (Appendix D). In 2008, Douglas PUD again submitted a Gas Abatement Plan for the fish passage season that was approved by Ecology.

This Gas Abatement Plan summarizes the Wells Project, associated facilities and water management (Section 3.0), discusses Wells Project spill scenarios and defines the measures associated with Douglas PUD's monitoring program during spill operations in support of juvenile fish passage (Section 4.0), and provides a summary of past TDG activities and a future schedule of Wells Project TDG compliance activities (Section 5.0).

3.0 WELLS HYDROELECTRIC PROJECT

3.1 Project Overview

The Wells Project is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 3.1-1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE); and 42 miles upstream from the Rocky Reach Hydroelectric Project owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Douglas PUD. It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The spillway is comprised of eleven spill gates that are capable of spilling a total of 1,180 kcfs. The crest of the spillways is approximately five and a half feet above normal tailwater elevation and two feet below tailwater elevation when plant discharge is 219 kcfs. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a top of dam elevation of 795 feet above mean sea level (msl). The system was developed by Douglas PUD and uses a barrier system to modify the intake velocities on all even numbered spillways (2, 4, 6, 8 and 10). The Wells Project is considered a "run-of-the-river" project due to its relatively limited storage capacity.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 feet (Figure 3.1-1).

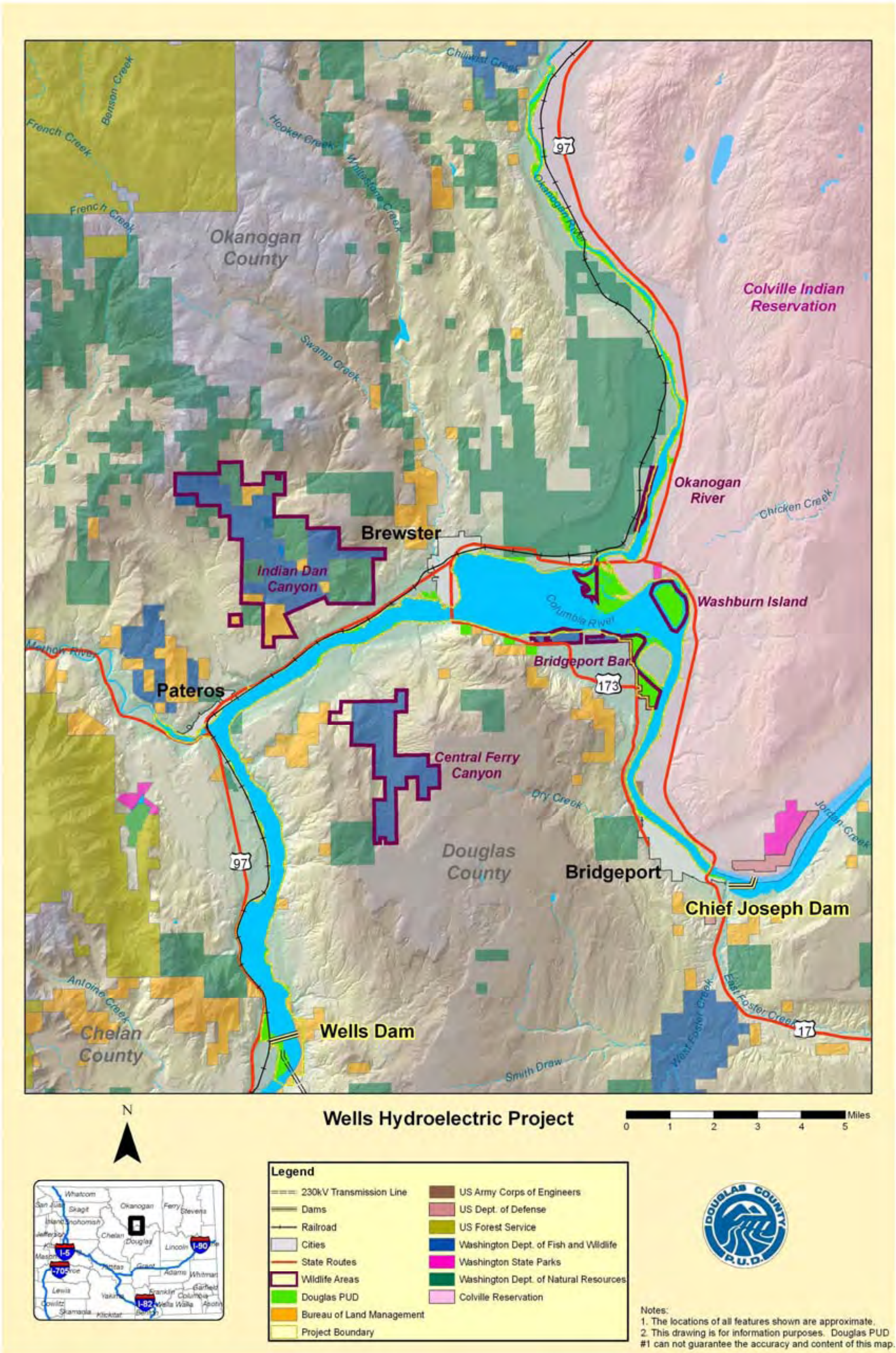

Figure 3.1-1 Map of the Wells Project area.

3.2 Runoff and Coordination

The Columbia Basin in eastern Oregon, Washington and British Columbia has climate that is best described as desert. Flow from the Columbia River originates in the headwaters of the Canadian Rockies and picks up snow melt from tributary streams as it travels over 1,243 miles before emptying into the Pacific Ocean. The natural hydrograph has low flows in November through January with high flows in May through July. Storage dams in the U.S. and Canada capture spring and summer high flows to hold for release in the fall and winter months. There are 85,300 square miles of drainage area above Wells Dam. Table 3.2-1 presents information on Columbia River flow as measured at Wells Dam in 2008 and over the past 20 years.

Table 3.2-1 Columbia River Flows at Wells Dam (1989 to 2008) in kcfs.

	Monthly Average		Minimum	Maximum
Month	2008	1989-2008	1989-2008	1989-2008
January	104.0	111.7	75.7	159.2
February	88.6	109.5	69.9	180.7
March	82.4	101.9	56.0	169.7
April	90.3	113.0	51.9	177.4
May	158.7	145.5	55.2	251.9
June	206.8	161.7	84.5	300.3
July	135.3	125.5	53.4	182.8
August	86.5	103.9	68.7	152.1
September	60.7	74.1	57.2	106.0
October	63.0	75.8	56.0	108.9
November	75.1	89.6	70.9	109.6
December	94.2	106.1	79.1	149.0

In general, the hydropower system and reservoir operations in the Columbia River are coordinated through a set of complex agreements and policies to optimize the benefits and minimize the adverse effects of project operations. The Wells Project operates within the constraints of the Pacific Northwest Coordination Agreement, Canadian Treaty, Canadian Entitlement Agreement, Hourly Coordination Agreement, the Hanford Reach Fall Chinook Protection Program and the Federal Energy and Regulatory Commission (FERC) regulatory and license requirements.

Under the Hourly Coordination Agreement, power operations for the seven dams from Grand Coulee to Priest Rapids are coordinated to meet daily load requirements through the assignment of "coordinated generation" through Central Control hosted at the Public Utility District No. 2 of Grant County (Grant PUD). Automatic control logic is used to maintain pre-set reservoir levels in order to meet load requirements and minimize involuntary spill. These pre-set reservoir levels are maintained at each project through management of a positive or negative "bias" which assigns a project more or less generation depending on whether the reservoir elevation should be increased or decreased in order to maximize system benefits and minimize involuntary spill.

4.0 HISTORY OF OPERATIONS AND TDG COMPLIANCE MONITORING

The passage and protection of migrating juvenile fish is provided at many dams with high levels of spill. This route is preferred relative to turbine passage and research has consistently indicated that survival of migrating juvenile salmonids is greatly enhanced via spill passage routes (NMFS 2000). At Wells Dam, TDG monitoring during fish bypass spill has occurred since 1998. A summary of the TDG monitoring at the Wells Project from 1998 – 2008 is shown in Table 4.0-1.

Table 4.0-1 Annual summaries of days with values greater than 110, 115, and 120 percent at the Wells Dam forebay, tailwater and the Rocky Reach forebay from 1998 to 2008 during the juvenile fish migration season (April-August).

Year		Wells FB	Wells TW	R. Reach FB	Sampled
1998	> 110%	42 days	72 days	45 days	153 days
	> 115%	0 days	17 days	4 days	153 days
	> 120%	0 days	4 days	0 days	153 days
1999	> 110%	80 days	103 days	76 days	168 days
	> 115%	0 days	21 days	2 days	168 days
	> 120%	0 days	2 days	0 days	168 days
2000	> 110%	60 days	99 days	27 days	168 days
	> 115%	0 days	5 days	1 day	168 days
	> 120%	0 days	1 day	0 days	168 days
2001	> 110%	26 days	41 days	37 days	168 days
	> 115%	0 days	0 days	0 days	168 days
	> 120%	0 days	0 days	0 days	168 days
2002	> 110%	77 days	111 days	88 days	168 days
	> 115%	38 days	66 days	37 days	168 days
	> 120%	0 days	31 days	11 days	168 days
2003	> 110%	55 days	76 days	62 days	168 days
	> 115%	0 days	8 days	2 days	168 days
	> 120%	0 days	1 day	0 days	168 days
2004	> 110%	38 days	69 days	67 days	168 days
	> 115%	0 days	0 days	0 days	168 days
	> 120%	0 days	0 days	0 days	168 days
2005	> 110%	20 days	69 days	66 days	168 days
	> 115%	0 days	1 day	2 days	168 days
	> 120%	0 days	0 days	0 days	168 days
2006	> 110%	70 days	108 days	96 days	168 days
	> 115%	22 days	59 days	42 days	168 days
	> 120%	0 days	29 days	19 days	168 days
2007	> 110%	48 days	116 days	66 days	168 days
	> 115%	0 days	11 day	1 day	168 days
	> 120%	0 days	2 days	0 days	168 days
2008	> 110%	86 days	94 days	80 days	168 days
	> 115%	40 days	73 days	58 days	168 days
	> 120%	0 days	28 days	8 days	168 days

4.1 Wells Dam Operational Spill Plan

Wells Dam is a hydrocombine-designed dam where the spillway is situated directly above the powerhouse. Research at Wells in the mid-1980s showed that a modest amount of spill would effectively guide a high percentage of the downstream migrating juvenile salmonids through the (JBS). The operation of the Wells JBS utilizes the five even numbered spillways. These spillways have been modified with constricting barriers to improve the attraction flow while using modest levels of water. These spillways are used effectively to pass downstream migrating juvenile salmonids from April through August. Normal operation of the JBS uses 2.2 kcfs per spillway. During periods of extreme high flow, one or more of the JBS barriers may be removed to provide adequate spill capacity to respond to a plant load rejection.

Typically, the JBS will use approximately 6 to 8 percent of the total river flow for fish guidance. The operation of the JBS adds a negligible level of TDG (0 – 2 percent) while meeting a very high level of fish guidance and protection. This high level of fish protection at Wells Dam has met the approval of the fisheries agencies and tribes and is vital to meeting the survival performance standards contained within the FERC approved Habitat Conservation Plan (HCP) with National Oceanic and Atmospheric Administration Fisheries (NOAA). The Wells Project fish bypass system is the most efficient system on the mainstem Columbia River. The bypass system on average collects and safely passes 92.0 percent of the spring migrating salmonids (yearling Chinook, steelhead and sockeye) and 96.2 percent of the summer migrating subyearling Chinook (Skalski et al. 1996).

The odd numbered spillways are available for all other forms of spill. Outside the juvenile salmonid migration season, all 11 spillways are available for spill. The high flow months in the Columbia River are May through July which is consistent with the time period when the five even numbered spillways are used for juvenile fish passage. At the Wells Project, five spill conditions may exist depending upon factors associated with river flows, fish bypass, plant operations and status, and demand for power (discussed in more detail in Section 4.2). In past years, various operational approaches have been implemented to address any spill that may occur at Wells Dam. Initially, spill operations beyond JBS spill at Wells Dam followed more traditional strategies used at other mainstem hydroelectric projects. These strategies consisted of spreading spill across the length of the dam to dissipate the amount of energy available to entrain atmospheric gases which reduces the levels of TDG. It has not been until more recently (beginning with assessments in 2006) that information collected during TDG studies at Wells Dam have indicated that non-traditional types of spill operations (concentrated spill shapes) may be more effective at reducing TDG production and may be at times, more appropriate in addressing TDG production for hydrocombine structures. The results of past Wells Project TDG production dynamics studies are presented in Section 5.1.

4.2 Spill Condition and Occurrence

The five main scenarios for spill at the Wells Project include:

- Fish Bypass System operation
- Flow in excess of hydraulic capacity of the turbines
- Flow in excess of power system needs
- Gas Abatement Spill
- Other spill

4.2.1 Fish Bypass System Operation

At Wells Dam, the JBS utilizes five of the eleven spillways equipped with constricting barriers to help guide juvenile migrating fish. This serves as an effective fish bypass. This configuration has demonstrated exceptionally high levels of protection while using 6 to 8 percent of the total discharge of the Columbia River on average annually. This system has helped meet the juvenile fish survival standard for passage set by the Wells Dam HCP. Douglas PUD has conducted three years of juvenile project survival studies at the Wells Project. These studies have shown an average survival rate of 96.2% for yearling Chinook and steelhead (Bickford et al., 2001).

The JBS is utilized for protection of downstream migrating juvenile salmonids. Fish Bypass operations at Wells Dam falls into two seasons, Spring Bypass and Summer Bypass. For 21 years, the status of the fish migration for both spring and summer periods was monitored by an array of hydroacoustic sensors placed in the forebay of Wells Dam. Starting in 2003, the operation of the juvenile bypass for the Wells HCP was set with fixed dates that were established based on 21 years of Hydroacoustic and Fyke Net data. The dates for bypass operation are from April 12 through August 26. These dates bracket greater than 95% of both the spring and summer migrants. Annually, there have been as many as ten million juvenile salmonids that have migrated past Wells Dam.

Between the years 1997 and 2004, the volume of water dedicated to the JBS has ranged from 1.5 to 3.2 million acre-feet. Operation of the JBS adds a negligible level of dissolved gas (0 to 2 percent) to the river while meeting a very high level of fish guidance and protection. Ecology has authorized an exemption to the total dissolved gas standard for fish protection on the Columbia and Snake rivers. Operation of the Wells Project JBS does not produce TDG at levels that exceed the Ecology TDG exemption.

4.2.2 Flow in Excess of Hydraulic Capacity of the Turbines

The Wells Project is a “run-of-the river” project with a relatively small storage capacity. River flows in excess of the hydraulic capacity of the ten turbines must be passed over the spillways.

The forebay elevation at Wells Dam is set between 781.0 and 771.0 msl. The Wells Project has a hydraulic generating capacity of approximately 220 kcfs (ASL, 2007) and a spillway capacity of 1,180 kcfs. Data for Columbia River flows for eighty-five years at Priest Rapids yielded a peak daily average discharge of 690,000 on June 12, 1948 (United States Geological Survey (USGS) web page for historical flows at Priest Rapids on the Columbia River. http://waterdata.usgs.gov/wa/nwis/discharge/?site_no=12472800). The hydraulic capacity of Wells Dam is well within the range of recent historical flow data.

4.2.3 Flow in Excess of Power System Needs

Spill may occur at flows less than the Wells Project hydraulic capacity when the volume of water is greater than the amount required to meet electric power system loads. This may occur during temperate weather conditions when power demand is low or when non-power constraints on river control results in water being moved through the mid-Columbia at a different time of day than the power is required. Hourly coordination (Section 3.2) between hydroelectric projects on the river was established to minimize this situation for spill.

4.2.4 Gas Abatement Spill

Gas Abatement Spill is used to manage TDG levels throughout the Columbia River Basin. The Technical Management Team (including NMFS, U.S. Army Corps of Engineers, and Bonneville Power Administration) implements and manages this spill. Gas Abatement Spill is requested from dam operators from a section of the river where gas levels are high. A trade of power generation for spill is made between operators, providing power generation in the river with high TDG and trading an equivalent amount of spill from a project where TDG was low. Historically, the Wells Project has accommodated requests to provide Gas Abatement Spill. In an effort to limit TDG generated at the Wells Project, Douglas PUD has adopted a policy of not accepting in Gas Abatement Spill at Wells Dam.

4.2.5 Other Spill

Other spill includes spill as a result of maintenance or plant load rejection. A load rejection occurs when the generating plant is forced off line by an electrical fault, which trips breakers and shuts off the generation. At a run-of-the-river hydroelectric dam, if water cannot flow through operating turbines, then the river flow that was producing power has to be spilled until turbine operation can be restored.

These events are extremely rare, and would account for approximately 10 minutes in every ten years. Maintenance spill is utilized for any activity that requires spill to assess the routine operation of individual spillways and turbine units. These activities include checking gate operation, and all other maintenance that would require spill. The FERC requires that all spillway gates be operated once per year. To control TDG levels associated with maintenance spill, Douglas PUD limits, to the extent practical, maintenance spill during the spill season.

4.3 Compliance Activities from 2006-2008

4.3.1 2006 Wells Project TDG Production Dynamics Study

Douglas PUD has continued to implement TDG assessments at the Wells Project to determine the best spillway configurations and project operations to minimize the production of TDG. In

2006, Douglas PUD hired a team of hydraulic and TDG experts from the Pacific Northwest to help design a monitoring program for a study that would examine various operational scenarios and their respective TDG production dynamics.

Thirteen sensors were placed along three transects in the tailrace; at 1,000, 2,500 and 15,000 feet below Wells Dam. There were also three sensors placed across the forebay, one being the fixed monitoring station midway across the face of the dam and two more a distance of 300 feet from the dam. The sensors were programmed to collect data in 15 minute increments for both TDG and water temperature. Each test required the operations of the dam to maintain static flows through the powerhouse and spillway for at least a three hour period. While there were 30 scheduled spill events, there were an additional 50 events where the powerhouse and spillway conditions were held constant for a minimum three hour period. These "incidental" events provided an opportunity to collect additional TDG data on a variety of Project operations that met study criteria and are included in the results of the 2006 TDG Abatement Study. Spill amounts ranged from 5.2 to 52 percent of project flow and volume of spill and total flows ranged from 2.2 to 124.7 kcfs for spill and 16.4 to 254.0 kcfs for total discharge. There were six tests that were done at flows that exceeded the Wells Dam 7Q10 flows of 246 kcfs.

Results of the study indicated that two operational scenarios, spread spill and concentrated spill, produced the lowest levels of TDG and recommended continued testing of operational measures to ameliorate TDG production at Wells Dam (EES et al. 2007). The 2006 study also indicated that the current location of the tailwater TDG compliance monitoring station is appropriate in providing representative TDG production information both longitudinally and laterally downstream of Wells Dam.

4.3.2 2007 Wells Project TDG Operations Playbook

In 2007, a spill playbook was developed to be used by operators at Wells Dam. The intent of the spill playbook was to guide Project operators in the configuration of spill operations (specifically the implementation of spread spill and concentrated spill) in a manner that further evaluated the results of the 2006 TDG study and that examined the spill playbook operating scenarios over a broader range of environmental conditions. There were no scheduled spill tests in 2007 and operators were instructed to utilize the playbook only during forced spill events (when river flows exceeded flows needed to meet load). Specific objectives of the 2007 assessment included:

1. Evaluate TDG production for full gate (concentrated) spills over a range of operational conditions.

2. Evaluate TDG production for spread spills over a range of operational conditions.

3. Evaluate indirect effects, operational, and logistical concerns for full gate spill that might limit their application for TDG management.

4. Collect additional TDG data in order to refine the relationships of spill momentum and submergence depth as they affect TDG production.

At the end of May 2007, it was determined that the logistics of operating gates 2 and 10 which require manual adjustments, made implementation of spread spills impractical. During the remainder of the study, Douglas PUD emphasized testing the concentrated spill strategy.

River flows in spring 2007 were 108.7 percent of the 20-year average. The peak total river discharge at Wells Dam (based on daily averages) was 238 kcfs. The maximum daily spill flow was 127 kcfs. There were few spill events in excess of the fish bypass spill after May. Most of the spill events were of short duration, which did not meet the required 3-hour time period that is necessary to establish equilibrium conditions at the downstream TDG monitoring station (WELW);

Conclusions of the 2007 assessment are as follows:

1. 2007 was an above average water year. During the 2007 fish passage season (April 1-September 15) Wells Dam was able to maintain compliance with the TDG standards 97 percent of the time.

2. Maintaining a spread spill pattern at Wells Dam, utilizing spill gates 2 and 10, was not logistically feasible for low and moderate ranges of spill.

3. Spill in 2007 was not of a sufficient duration to adequately test the performance of a full gate spill pattern to minimize TDG below Wells Dam.

4. Although spill events that were in excess of JBS spill and of a steady state of at least 3 hours in duration were rare (6 total), the data collected on Wells spill operations during 2007 were consistent with analytical results for the 2006 TDG Study (EES et al. 2007).

4.3.3 2008 Wells Project TDG Operations Playbook

The study objective for the 2008 Wells Project playbook was to further evaluate the effectiveness of the concentrated spill type that the 2006 TDG study identified as producing relatively lower TDG production dependent upon total spill and tailwater elevation and the 2007 TDG study identified as operationally feasible to implement.

Specific objectives include:

1. Evaluate TDG production for full gate spills over a range of operational conditions.

2. Evaluate indirect effects, operational, and logistical concerns for full gate spill that might limit their application for TDG management.

3. Collect additional TDG data in order to refine the relationships of spill momentum and submergence depth as they affect TDG production.

River flows in spring 2008 were 104.3 percent of the 20-year average. The peak total river discharge at Wells Dam (based on daily averages) was 270 kcfs. The maximum daily spill flow was 145 kcfs. Spill events that met the required 3-hour time period occurred from May to July;

Conclusions of the 2008 assessment are as follows:

1. There were 20 spill events that met the required 3-hour time period to establish equilibrium conditions at the WELW.

2. During these 20 events, total Q ranged from 22.7 to 260.8 kcfs. Total spill Q ranged from 6.6 to 98.0 kcfs. WEL TDG ranged from 106 percent to 116 percent. WELW TDG ranged from 113 percent to 127 percent.

3. 2008 was an above average water year, with up to 128% of average river flows (June) and high TDG levels resulting from spill at Chief Joseph Dam (Wells forebay exceeded 115% TDG 23.8% of days monitored).

4. There were six spill events that exceeded the 246 kcfs 7Q10 flood flow at Wells Dam. These events occurred in May and June.

4.3.4 2008 Wells Project TDG Numerical Model Development

In 2008, Douglas PUD secured the services of the IIHR-Hydroscience and Engineering Laboratory of the University of Iowa (IIHR) to develop an unsteady three-dimensional (3D) two-phase flow computational fluid dynamics (CFD) tool to predict the hydrodynamics and TDG distribution within the Wells tailrace. Two models were used in the study; a volume of fluid (VOF) model and a rigid-lid two-phase flow model.

The VOF model predicts the flow regime and the free-surface characteristics, recognizing that a spillway jet may plunge to depth in the tailrace or remain closer to the surface depending upon the geometry of the outlet and the tailwater elevation.

The rigid-lid model included 16,500 ft of the Wells tailrace, from Wells Dam downstream to the TDG compliance monitoring station. This two-phase flow model characterizes the hydrodynamics and three-dimensional distribution of gas volume fraction, bubble size and TDG in the Wells tailrace. The upstream velocity profiles derived from the VOF model were input to the rigid-lid model. The gas volume fraction and bubble diameter at the spillbays are the external parameters of the model.

The model was calibrated and validated using field data collected in 2006 during a TDG production dynamics study (EES et al. 2007). The model was then calibrated using data collected during spill tests conducted on June 4 and June 5, 2006. The spillway flow was spread across spillbays on June 4 and concentrated through a single spillbay on June 5. Agreement was attained between the depth-averaged velocity data collected in the field and those generated by the model. A gas volume fraction of 3 percent and bubble diameter of 0.5 mm in the spillbays produced TDG values that bracketed the 2006 field observations.

Once calibrated, the predictive ability of the model was validated by running the model for three different operational conditions tested in 2006. The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The numerical results demonstrate that the model provides a reliable predictor of tailrace TDG and therefore can be used as a tool to identify Project operations that can minimize TDG concentrations downstream of Wells Dam.

5.0 PROPOSED OPERATIONS AND ACTIVITIES

5.1 TDG Monitoring Program

As required by issuance of a TDG exemption for the Wells Project, Douglas PUD will continue to implement a physical and biological monitoring program at Wells Dam during the juvenile fish migration season. Activities include fisheries management activities, participation in Columbia River basin water quality forums, collection of total dissolved gas and temperature data during the migration season, and when necessary, collection of biological monitoring data.

5.1.1 Fisheries Management Activities

Douglas PUD shall continue to operate Wells Dam adult fishways and the juvenile bypass system in accordance with HCP operations criteria to protect aquatic life designated uses. Furthermore, all fish collection (hatchery broodstock and/or evaluation activities) or assessment activities that occur at Wells Dam will require approval by Douglas PUD and the HCP Coordinating Committee to ensure that such activities protect aquatic life designated uses.

Douglas PUD shall continue to operate the Wells Project in a coordinated manner toward reducing forebay fluctuations and maintaining relatively stable reservoir conditions that are beneficial to multiple designated uses (aquatic life, recreation, and aesthetics). Furthermore, coordinated operations reduce spill, thus reducing the potential for exceedances of the TDG numeric criteria and impacts to aquatic life associated with TDG.

5.1.2 Water Quality Meetings

Douglas PUD is currently involved in the Water Quality Team meetings held in Portland, Oregon. The purpose of the Water Quality Team meetings is to address regional water quality issues. This forum allows regional coordination for monitoring, measuring, and evaluating water quality in the Columbia Basin.

Douglas PUD will continue its involvement in the Water Quality Team meetings for further coordination with other regional members.

Douglas PUD is also currently involved in the Transboundary Gas Group that meets annually to coordinate and discuss cross border dissolved gas issues in Canada and the U.S. Douglas PUD will continue its involvement with the Transboundary Gas Group.

5.1.3 Physical Monitoring

5.1.3.1 Total Dissolved Gas Monitoring

TDG monitoring has been implemented in the Wells Dam forebay since 1984. Douglas PUD began monitoring TDG levels in the Wells Dam tailrace in 1997 by collecting data from a boat and drifting through the tailrace at four points across the width of the river. During transect monitoring at the WEL location, no "hot spots" were detected. The river appeared completely mixed horizontally. A fixed TDG monitoring station was established in 1998. The placement of the fixed monitoring station was determined based upon the 1997 work and was further verified as collecting data representative of river conditions during a 2006 TDG assessment at Wells Dam (EES et. al. 2007). Results of the 2008-2009 TDG numerical modeling activities being conducted by IIHR have also confirmed that the tailrace monitoring station is located at a site representative of the river, particularly during higher flows. Furthermore, locations of both forebay and tailrace sensor had to be protected to avoid sensor/data loss and damage and for safe accessibility during extreme high flows. The current locations of both the forebay and tailrace monitors took these criteria into consideration.

TDG monitoring at the Wells Project commenced on April 1 and will continue until September 15 annually. This monitoring period will encompass the operation of the Wells JBS as well as the time period river flows are at their highest and when a majority of forced spill occurs. Throughout this period, data from both forebay and tailrace sensors are transmitted by slave radio transmitters to a master radio at Wells Dam. This system is checked at the beginning of the season for communication between the probes and transmitters by technicians at Wells Dam. Total dissolved gas data are sent and logged at the Douglas PUD Headquarters' building in 15-minute intervals. Information on barometric pressure, water temperature and river gas pressure is sent to the U.S. Corps of Engineers on the hour over the Internet. The four data points (15 minute) within an hour are used in compiling hourly TDG values, the 24 hour TDG average and twelve maximum hour TDG averages.

As part of the Douglas PUD's Quality Assurance/Quality Control (QA/QC) program, Douglas PUD's water quality consultant will visit both TDG sensor sites monthly for maintenance and calibration of TDG instruments. Calibration follows criterion established by the COE, with the exception of monthly rather than bi-weekly calibration of sensors (Appendix E). A spare probe will be available and field-ready in the event that a probe needs to be removed from the field for repairs.

The consultant will inspect instruments during the monthly site visits and TDG data will be monitored weekly by Douglas PUD personnel. If, upon inspection of instruments or data, it is deemed that repairs are needed, they will be promptly made. Occasionally during the monthly sensor calibration, an error may develop with the data communication. These problems are handled immediately. Generally, the radio transmitters at each fixed station will run the entire season without any problems.

Douglas PUD intends to collect quality, usable data for each day over the 168-day (April 1 – September 15) monitoring season. As part of the quality assurance process, data anomalies will be removed. This would include data within a 2-hour window of probe calibration and any recording errors that result from communication problems. Data errors will prompt a technician or water quality specialist site visit, to inspect the instrument and repair or replacement, if necessary.

5.1.3.2 Temperature Monitoring

Douglas PUD has been monitoring water temperatures throughout the Wells Reservoir and in the Wells Dam tailrace year round since 2005. Temperature monitoring locations are provided in the Table 4.3-1 below. Temperature monitoring through the reservoir and the inundated portions of tributary streams will be performed with Onset® Tidbit thermographs.

QA/QC measures will be accomplished through calibration of thermographs at the beginning and end of a period of sensor deployment. As part of the QA/QC process, data anomalies will be identified and removed from the data set. Sensors will be deemed unreliable if calibration against a Bureau of Standard accuracy thermometer shows a variance of ± 0.2°C. Thermographs will be swapped out quarterly (every three months) with recently tested sensors to avoid data loss.

Table 4.3-1 Wells Reservoir and tributary temperature monitoring stations. River mile is based upon United States Geological Survey river mile.

River	Side/Mile	Location
Columbia	Left / 515.6	Wells Forebay*
Columbia	Left / 530	Near Brewster
Columbia	Left / 535.3	Brewster Flats
Columbia	Left / 544.5	Chief Joseph Tailrace
Columbia	Left/515.5	Wells Dam Tailrace
Columbia	Right/515.5	Wells Dam Tailrace
Methow	Right / 2.8	Near Pateros
Okanogan	Center / 10.5	Near Monse
Methow	Center/0.4	Mouth of Methow
Okanogan	Center/1.3	Mouth of Okanogan

*Station has sensors at multiple depths.

5.1.4 Biological Monitoring

Douglas PUD will work with the Washington Department of Fish and Wildlife hatchery programs to monitor the occurrence of GBT on adult broodstock collected for hatchery needs. Upon collection of brood, hatchery staff will inoculate each fish, place a marking identification tag on them and look for any fin markings or unusual injuries. NMFS has shown that GBT is low if the level of TDG can be managed to below 120 percent (NMFS 2000). They recommend that "the biological monitoring components will include smolt monitoring at selected smolt monitoring locations and daily data collection and reporting only when TDG exceeds 125 percent for an extended period of time." Thus, biological sampling at Wells Dam of adult broodstock will only occur when hourly TDG levels in the mid-Columbia exceed 125 percent.

At most hydroelectric projects on the Columbia River, a juvenile migrant sampling station is incorporated into the JBS. This allows for the external observation of fish for signs of GBT. The signs of GBT are bubbles under the skin of the fish along the fin rays and near the eye sockets. While juvenile migrants are the choice fish for sampling when inspecting for GBT, the JBS at Wells Dam does not have facilities incorporated to allow for juvenile fish sampling and observation. As in past years, if hourly TDG levels exceed 125 percent in the tailrace of Wells Dam, Douglas PUD will request biological sampling of migrating juveniles for symptoms of GBT at the juvenile sampling facility at Rocky Reach Dam.

5.2 Compliance Activities for 2009

In response to the request from Ecology to identify near term solutions and to make continual improvements related to TDG at Wells Dam, the following actions are scheduled to be completed in 2009.

5.2.1 Wells Project TDG Numeric Model Development

As discussed in Section 4.3.4, Douglas PUD secured the services of the IIHR to develop a numerical model to investigate TDG production at Wells Dam. The numeric model is an unsteady three-dimensional (3D) two-phase flow computational fluid dynamics (CFD) tool to predict the hydrodynamics and TDG distribution within the Wells tailrace. Two models were used in the study; a volume of fluid (VOF) model and a rigid-lid two-phase flow model.

In April 2009, the model demonstrated that Wells Dam can be operated to meet the TDG tailrace standard of 120% up to flows of 246 kcfs (7Q10 flow at Wells). Compliance was achieved through the use of a concentrated spill pattern through gate No. 7 and using higher than normal flows through JBS gates No. 6 and No. 8. Although the model was able to prove compliance up to 7Q10 flows, Douglas PUD is planning on continuing to utilize the TDG model toward possibly identifying additional spillway operations that can further reduce TDG in the Wells tailrace. Results from these additional model scenarios are expected to be available during the later part of 2009. Should a better operating condition be identified, then an updated TDG report will be prepared and filed with Ecology.

5.2.2 2009 Wells Project Playbook

Based upon the new preferred operating condition, Douglas PUD plans to implement a revised spill playbook during the 2009 spill season. Objectives of the 2009 playbook are similar to those identified in 2008 (Section 4.3.3). Similar to past years, additional TDG production dynamics data will be collected opportunistically at the Wells Project. These additional data combined with the results of past assessments will assist in refining the relationship of operations and tailwater elevation with TDG production to support the identification of the most effective operational approach for minimizing TDG production at Wells Dam.

5.3 Additional Requirements

Douglas PUD will operate the Wells Project in accordance with the following:

a. 7Q10. The 7Q10 for this project is 246 kcfs. The Project will not be expected to comply with state water quality standards for TDG for incoming flows exceeding this value.

b. Fish Spill. For purposes of compliance, the "fish spill" season is taken to occur from April 1 through August 31; and "non-fish spill" season occurs from September 1 to March 31, unless otherwise specified in writing by Ecology.
c. Compliance During Non-Fish Spill. During non-fish spill, the PUD will make every effort to remain in compliance with the 110 percent standards.
d. Compliance During Fish Spill. During fish spill, the PUD will make every effort not to exceed an average of 120 percent as measured in the tailrace of the dam. The Project also must not exceed an average of 115 percent as measured in the forebay of the next downstream dam. These averages are based on the twelve (12) highest consecutive hourly readings in any 24-hour period. In addition, there is a maximum one-hour average of 125 percent, relative to atmospheric pressure, during spillage for fish passage. Nothing in these special conditions allows an impact to existing and characteristic uses.
e. TDG Monitoring. The PUD will maintain two fixed monitoring stations at the dam to monitor TDG levels annually from April through August, one in the forebay and one in the tailrace at the approved monitoring sites. This information is available on a real time basis to all interested parties via the U.S. Army Corps of Engineers Columbia Basin Water Management Division website.
f. Reporting Spill for Fish and TDG Exceedances. The PUD will notify Ecology within 24 business hours of spill for fish and when TDG standards are exceeded. Reporting shall be electronically (by email) to the Hydropower Projects Manager (Pat Irle) in Ecology's CRO office.
g. General TDG Abatement Measures. The PUD will manage spill toward meeting water quality criteria for TDG during all flows below 7Q10 levels, consistent with meeting the passage and survival standards set forth in the HCP and Fish Management Plans, as follows:
    i. Minimize voluntary spill.
    ii. During fish passage, manage voluntary spill levels in real time in an effort to continue meeting TDG numeric criteria.
    iii. Minimize spill, to the extent practicable, by scheduling maintenance based on predicted flows.
h. Annual TDG Monitoring Report. The PUD shall submit an annual monitoring report. A draft monitoring report of the year's monitoring results shall be submitted to Ecology by October 31 of the monitoring year. The PUD will submit the final report, incorporating Ecology's suggested corrections, by December 31 of the same year. The contents of the report shall include, at a minimum:
    i. Flow and TDG levels, on a daily basis, with purpose of spill (e.g., fish spill, turbine down time).
    ii. Summary of exceedances and what was done to correct the exceedances.
    iii. Results of any applicable fish passage efficiency (FPE) studies and survival studies conducted per the HCP.
i. Revised Gas Abatement Plan (GAP). The PUD will revise the GAP annually, to reflect any changes and new or improved information and technologies. The PUD will submit a draft to Ecology for review and approval by February 28 of the year of implementation (e.g., February 28, 2009 for the 2009 spill season). The GAP shall be in the format of the PUD's 2008 GAP, unless modifications are requested by Ecology.
j. Ecology Contact. The PUD will direct its correspondence to:

Hydropower Projects Manager
Department of Ecology
Central Region Office
Water Quality Program
200 W. Yakima Ave., Suite 200
Yakima, WA 98908

6.0 REPORTING

Upon approval of the Wells Gas Abatement Plan and issuance of a Wells Project TDG exemption, Douglas PUD shall submit an annual report describing the results of all monitoring activities described within this Gas Abatement Plan. The report will be submitted to Ecology no later than December 31 of each year that the TDG exemption is active. The report will summarize all Gas Abatement Plan activities conducted for the year in which it is submitted as required by Ecology.

7.0 REFERENCES

ASL Environmental Sciences (ASL). 2007. Turbine Discharge Measurements by Acoustic Scintillation Flow Meter at Units 1 and 2, Wells Hydroelectric Project, Pateros, Washington, August 2006. Prepared by ASL Environmental Sciences Inc. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Bickford, S. A., J. R. Skalski, R. Townsend, S. McCutcheon, R. Richmond, R. Frith and R. Fechhelm. 2001. Project survival estimates for yearling summer steelhead migrating through the Wells Hydroelectric Facility, 2000.

Bouck, G. R. 1980. Etiology of gas bubble disease. *Transactions of the AmericanFisheries Society* 109:703-707.

Dawley, E., T. Blahm, G. Snyder, W. Ebel. 1975. Studies on effects of supersaturation ofdissolved gases on fish. US Department of Commerce, National Marine Fisheries Service. Seattle, WA.

EES Consulting, Carroll, J., ENSR, and Parametrix. 2007. Total Dissolved Gas Production Dynamics Study. Wells Hydroelectric Project. FERC No. 2149. Prepared by EES Consulting, Joe Carroll, ENSR, and Parametrix. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Environmental Protection Agency (EPA). 1976. Quality Criteria for Water. PB-263943.

Jensen, J. O. T., J. Schnute, and D. F. Alderdice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose -- response model. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 43: 1694-1708.

National Marine Fisheries Service (NMFS). 2000. Endangered Species Act – Section 7 Consultation: Biological Opinion. Consultation on Remand for Operation of the Columbia River Power System and 19 Bureau of Reclamation Projects in the Columbia Basin. F/NWR/2004/00727. November 30, 2005. Pages 5-6, 5-7, 5-53, 10-9, and Appendix E: Risk Analysis.

Pickett, P., H. Rueda, M. Herold. 2004. Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt. Submittal Report. Washington Department of Ecology, Olympia, WA. U.S. Environmental Protection Agency, Portland, OR. June 2004. Publication No. 04-03-002.

Skalski, J. R, G. E. Johnson, C. M. Sullivan, E. Kudera and M. W. Erho. 1996. Statistical Evaluation of Turbine Bypass Efficiency at Wells Dam on the Columbia River, Washington. *Canadian Journal of Fisheries and Aquatic Science*. Volume 53, No. 10, 1996. Pages 2188-2198.

Weitkamp, D. E., and M. Katz. 1980. A review of dissolved gas supersaturation literature. *Trans. Am. Fish Soc.* 109: 659-702.

Appendix A

Letter from Megan White on Gas Abatement Plan for 2003, May 15, 2002

STATE OF WASHINGTON

DEPARTMENT OF ECOLOGY

P.O. Box 47600 • Olympia, Washington 98504-7600
(360) 407-6000 • TDD Only (Hearing Impaired) (360) 407-6006

CERTIFIED MAIL

May 15, 2002

Mr. Bob Clubb
Douglas County Public Utility District
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Clubb:

Douglas County Public Utility District will need an approved gas abatement plan in order to spill water over Wells Dam for the purpose of passing juvenile salmonids down-river during the spring and summer migration season of 2003. Our data shows that Wells Dam does not contribute significantly to dissolved gas during most flows during most years. However, in most years the dam is occasionally out of compliance with the water quality standards for dissolved gas. Ecology's expectation is that you will investigate reduction of dissolved gas generated by the Wells Dam.

This requirement is described in Washington's water quality standards (Chapter 173-201A WAC, under *General Water Use and Criteria Classes (section 030)* and *General Considerations* (section 060)) for the purpose of passing juvenile salmonids. Several things will need to happen in order for you to move ahead with a gas abatement program and are described below.

Gas Abatement

Gas abatement planning is required by the water quality standards in order to demonstrate that all reasonable steps are being taken to reduce total dissolved gas associated with fish passage spills. This means investigating and where, appropriate, pursuing structural modifications and operational modifications to reduce gas generated by spill.

My staff plans to work with you, the fisheries agencies, and river management agencies in planning and prioritizing gas abatement options to pursue.

Expectations for the Coming Year:

1. Provide a Gas Abatement Plan that contains:

    a. A schedule for compliance toward taking all reasonable steps to reduce total dissolved gas associated with fish passage spills.

b. Steps to identify and reduce operational or uncontrolled spill (spill not associated with controlled spill to pass juvenile fish) in coordination with river-wide operational adjustments.

c. Steps to identify potential structural modifications to reduce gas generated by dam operation toward meeting water quality standards.

2. The real-time data from the fixed monitoring stations should continue to be made available for posting and publication to the TDG U.S. Army Corps of Engineers Monitoring Program Coordinator at a minimum beginning April 1 through August 31 of each year.

3. Continue to assess spatial variability of gas by conducting transect monitoring in the dam forebay and tailrace. The objective of this monitoring is to evaluate the representativeness of the fixed monitoring stations and to collect data to support the TDG TMDL. Provide assistance to Ecology staff who is conducting monitoring of TDG at Wells Dam. Cooperative monitoring of Wells Dam TDG by Douglas PUD (or its contractors) and Ecology will meet this condition and is encouraged.

Workgroup Participation

Staff from Douglas County will be expected to participate in the Columbia River Water Quality Team that meets in Portland either in person, through a consultant, or via conference call. Staff is also expected to continue to participate in the Transboundary Dissolved Gas Team that meets at various locations approximately twice a year.

Reports

Due August 31 of each year:

Any draft revisions to the gas abatement schedule for compliance with specific targets and dates for achieving gas abatement measures toward the goal of taking all reasonable steps to reduce total dissolved gas associated with fish passage spills. Include dates when reports will be submitted, predicted gas levels after each step, how and when decisions will be made on specific modifications to present structures and operations, and how funding or other mechanisms to carry out activities will be secured.

This report needs to include any revisions to:

- The forebay and tailrace monitoring plan.
- Draft QA/QC plan for the physical and biological monitoring that is to be done during the following season.
- Physical modeling plans.
- Structural and operational changes.
- Reductions in spill due to successes of alternative fish passage facilities.

Due by February 27 of each year:

1. Any final revisions to the schedule for compliance with specific targets and dates for achieving gas abatement measures toward the goal of achieving and maintaining water quality standards. This needs to include any revision to:

   - The forebay and tailrace monitoring plan.
   - Draft QA/QC plan for the physical and biological monitoring that is to be done during the following season.
   - Physical modeling plans.
   - A report on the progress of planning and achieving gas abatement through structural modifications.
   - A report on the operational gas abatement efforts including power trading and managing river levels on a system-wide basis as well as operational efforts being pursued at Wells Dam.
   - Reductions in spill due to successes of alternative fish passage.

3. A report of the results of physical and biological monitoring done in 2002. This is expected to be a similar report that was submitted by NMFS to the state of Oregon in 1999 entitled, *1998 Annual Report to the Oregon Department of Environmental Quality*. Please include in this report:

a. A description of water conditions for the year in terms of basin runoff conditions and flows as compared to average years.

b. Tables showing dates, times, and amounts (in percent saturation) of dissolved gas when water quality standards are exceeded. Explain reasons for exceedances. Discuss steps that were taken to fix each problem. Keep in mind that 110 percent dissolved gas is the standard. This amount can be raised to 120 percent only when expressly spilling water to pass juvenile salmonids.

c. Tables and graphs showing quantities (in kcfs) of voluntary spill (for fish passage) and involuntary spill at each dam. The data collected needs to include:

- Observed total river flow
- Project hydraulic capacity
- Total, real-time involuntary spill. Identify by each cause:
  Lack of market
  Lack of hydraulic capacity
  Any other reason
- Voluntary spill to pass fish as per the intent to reach 95 percent fish passage survival
- Voluntary spill as systems-wide energy transfer spill between dams
- Total spill
- The percentage of total spill that was voluntary

Notification

The Department of Ecology must be notified of any exceedances of the adjusted dissolved gas standards due to spill to pass fish within seven days of exceedance. A weekly notification of violations for the previous seven days will satisfy this request. Include in this notice steps that have been taken to correct the problem. Call by telephone or send this notice to:

Chris Maynard
Water Quality Program
Department of Ecology
PO Box 47600
Olympia, WA 98504-7600.
Fax: (360) 407-6426. Phone: (360) 407-6484

As you are aware, the federal license for the Wells Hydroelectric Projects (FERC No.2149) expires in 2012. Before the Federal Energy Regulatory Commission may grant a new license for this project, the Department of Ecology must certify pursuant to the federal Clean Water Act that the project will meet applicable water quality requirements. The project's ability to meet total dissolved gas requirements through gas abatement planning will be a central issue of interest in Ecology's determination. Ecology's staff will be working with the Public Utility District during the licensing consultation process to ensure that appropriate studies, monitoring, and structural and operational abatement measures are undertaken in a manner that is consistent with ongoing efforts.

Please contact me at 360/407-6405 or Chris Maynard of my staff at 360/407-6484 if you have questions or comments regarding this approval.

Sincerely,

Megan White P.E., Manager
Water Quality Program

CM:ak
cc: Columbia Water Quality Team
Wells Coordinating Committee

Y:\...Chris\Dissolved Gas\Douglas PUD 2002 'Waiver'.doc

Appendix B

Letter of Approval for Wells Dam Gas Abatement Plan for 2003, March 27, 2003

KK file

CERTIFIED MAIL

March 27, 2003

Mr. Bob Clubb
Douglas County PUD
1151 Valley Mall Parkway
East Wenatchee, Washington 98802

Dear Mr. Clubb:

The state of Washington requires the operators of each dam on the Columbia River to obtain approval from the Washington Department of Ecology of a gas abatement plan in order to spill water over the dam to assist in the passage of juvenile salmonids downstream and thus potentially raise the total dissolved gas saturation level above 110 percent. This requirement is described in Washington's water quality standards (Chapter 173-201A WAC, under General Water Use and Criteria Classes, section 030; and General Considerations, section 060).

The Douglas County Public Utility District has provided us with information about gas abatement activities and monitoring being undertaken at Wells Dam on the Columbia River. This information meets our requirement. Therefore, **the gas abatement plan for the Wells Dam is approved for all activities related to fish passage for the period of one year.**

This means that Wells Dam may raise the dissolved gas levels above 110 percent saturation to aid fish passage but not to exceed 125 percent saturation as a one-hour average. Gas saturation may not exceed 120 percent in the tailrace and 115 percent in the forebay as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

Our water quality standards require gas abatement planning, monitoring, and reporting. This approval is further conditioned as follows:

Gas Abatement Planning

Continue to evaluate, refine, and implement gas abatement activities. If in following years, gas abatement efforts are determined by the agency to be sufficient for more than one year, the agency may approve the plan for up to five years. These plans must contain a schedule for taking all reasonable steps toward compliance by reducing total dissolved gas associated with spills:

a. Operational fish spills
b. Structural solutions
c. Uncontrolled spill

The Douglas County Public Utility District will be expected to participate in and provide information to regional groups that address system-wide dissolved gas problems.

Physical and Biological Monitoring

Programs for biological trauma monitoring for gas effects and physical monitoring at the fixed monitors shall remain the same as past years except where site-specific changes or additions are needed to obtain better information.

Reports

November 1, 2003. Any changes, modifications and additions to the October 2002 gas abatement plan will be reported to WDOE including:

- Compliance schedule changes regarding specific targets and dates for moving toward meeting water quality standards.
- Forebay and tailrace monitoring plans.
- Quality assurance plans.
- Physical modeling plans.
- Structural changes.
- Operational changes.
- Reduction in spill due to successes of alternative fish passage facilities.

By February 27, 2004, the PUD will submit:

1. Revised gas abatement plan. If this plan is approved by Ecology and is sufficient in moving toward achieving water quality standards in the longer-term, Ecology will approve the plan for up to five years.
2. Annual report of the physical and biological monitoring.:
- A description of the water year in terms of basin runoff conditions as compared to average years.
- Tables showing dates, times and amounts (in percent saturation) of dissolved gas when water quality standards are exceeded. Explain reasons for exceedances. Discuss steps taken to fix the problem. The higher gas standard

applies only when spilling water to aid fish passage, and managing system spill for improved fish conditions.

- A table or graph showing percentage of spill that was voluntary compared to the percentage that was due to other causes such as lack of electric demand, lack of hydraulic capacity, or any other reason.

Notification

The Department of Ecology must be notified of any exceedances of the adjusted dissolved gas standards due to spill to pass fish within seven days of the exceedance. A weekly notification for the previous seven days will satisfy this. Include in the notification steps that have been taken to correct the problem. Call by telephone, send by e-mail, or fax to:

Chris Maynard
Water Quality Program
Department of Ecology
PO Box 47600
Olympia, WA 98504-7600
Phone: (360) 407-6484
FAX: (360) 407-6426
E-mail: cmay461@ecy.wa.gov

Failure to abide by these conditions may result in administrative action if water quality standards are exceeded. The Department of Ecology is authorized to issue Administrative Orders requiring compliance whenever it determines that a person has exceeded or is about to exceed any provision of RCW 90.48.

Please contact me at (360) 407-6405 or Chris Maynard of my staff at (360)407-6484 if you have any questions or comments regarding this approval.

Sincerely,

Megan White, P.E., Manager
Water Quality Program

cc: Columbia River Water Quality Team
Mid Columbia Coordinating Council
Tom Tebb

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Appendix C

Letter Granting Extension of the Wells Dam Gas Abatement Plan to include 2004, February 27, 2004

STATE OF WASHINGTON

DEPARTMENT OF ECOLOGY

PO Box 47600 • Olympia, WA 98504-7600 • 360-407-6000
TTY 711 or 800-833-6388 (For the Speech or Hearing Impaired)

CERTIFIED MAIL

February 27, 2004

Mr. Rick Klinge
Douglas County P.U.D.
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Klinge:

The Washington Department of Ecology requires the operators of each dam on the Columbia and Snake River to operate under a department-approved gas abatement plan in order to spill water over the dams on the Columbia and Snake Rivers during fish spills, thus potentially raising the total dissolved gas saturation level above the criteria of one hundred and ten per cent. This special fish passage exemption is described in Washington's water quality standards (WAC 173-201A-060 (4)(b), General Considerations).

This letter constitutes continued approval of the gas abatement plan that we currently have on file for your operation for all activities related to fish passage. This approval is for a period of one year. Please note that the department is in the process of determining how these plans will be incorporated into 401 certifications that are being developed and we will keep you informed as we move forward.

This approval means that the dissolved gas levels may be raised above 110 percent saturation to aid fish passage but not to exceed 125 percent saturation as a one-hour average. Gas saturation may not exceed 120 percent in the tailrace and 115 percent in the forebay of the next dam downstream as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

Please continue to evaluate, refine, implement, and report on gas abatement activities as needed.

This gas abatement plan approval does not limit the conditions placed in future permits, orders, and certifications issued by the department.

RECEIVED
MAR 0 1 2004
DOUGLAS PUD

Please contact me at (360) 407-6405 or Chris Maynard of my staff at (360) 407-6484 if you have any questions or comments regarding this approval.

Sincerely,

Richard K. Wallace, Manager
Water Quality Program

cc: Columbia River Water Quality Team
Mid-Columbia Coordinating Council
Columbia River Fisheries Program Office
US Army Corps of Engineers
Regional Ecology Section Managers

Appendix D

Letter from David Peeler on Gas Abatement Plan for 2005-2007, March 31, 2005

DOC NO. 91677

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47600 ◦ Olympia, WA 98504-7600 ◦ 360-407-6000
TTY 711 or 800-833-6388 (For the Speech or Hearing Impaired)

March 31, 2005

REGISTERED MAIL

Mr. Bob Clubb
Chief of Environmental and Regulatory Services
Douglas County PUD
1151 Valley Mall Parkway
East Wenatchee, WA 98802

Dear Mr. Clubb:

On March 21, 2005, the Douglas Public Utility District (Utility) requested approval to adjust the Total Dissolved Gas (TDG) criteria to spill water at Wells Dams on the Columbia River in Washington to assist downstream migration of juvenile salmonids. We require approval of gas abatement plans under Washington State Water Quality Standards WAC 173-201A-060(4)(b) in order to apply the adjusted TDG standards to the Columbia River.

The Utility submitted a gas abatement plan to Ecology. The submittal also included the following.

- TDG physical monitoring plans.
- Biological monitoring plans.

The Washington State Department of Ecology approves the gas abatement plan. This approval is based on the following findings.

1. Failure to act will result in more salmonid passage through the hydroelectric dam turbines. Estimated mortality from juvenile salmonids passing through turbines is several times greater than juvenile salmonid passage mortality over dam spillways.
2. Exposure to elevated TDG as a result of spill is harmful to fish. However, anadromous salmonids experience less harm when exposed to limited concentrations of TDG, than the harm experienced by passing through turbines. A risk analysis was performed by the United States National Oceanographic and Atmospheric Administrations Fisheries in 1996 and updated in 2002. Based on this risk analysis, Ecology water quality standards allow higher levels of TDG upon approval of gas abatement plans.
3. The Utility is investigating operational improvements.

This approval is subject to the following conditions.

1. This approval shall extend through February 2008, and apply to Wells Dam on the Columbia River in Washington State.

2. This approval means that spill may raise the dissolved gas levels above 110% saturation to aid fish passage, but not to exceed 125% saturation as a one-hour average. Gas saturation may not exceed 120% in the tailrace and 115% in the forebay of the next dam downstream as measured at the fixed monitoring stations as an average of the twelve highest readings in any one day.

3. The Utility is expected to conduct the following activities.

    a. Investigate and pursue TDG reduction and monitoring improvements as new information becomes available.

    b. Investigate biological effects data gaps for TDG for all species in areas of concern. Plan for studies identified during this investigation. Provide yearly progress reports.

    c. Begin to investigate structural improvements in combination with operational improvements to reduce TDG. Provide yearly progress reports.

    d. Make reasonable attempts to reduce TDG entrainment during all flows during the spill season.

    e. Plan maintenance schedules and activities as much as possible to minimize TDG production resulting from spill to within water quality standards. Plan turbine outages as much as possible for outside the high flow season when this will not cause more harm to the environment or to the structural integrity of the dam.

    f. Notify Ecology within 48 hours of initiation of spring, summer, and other spills for fish. The notification may be electronic or written.

    g. Provide Ecology with an annual written report by December 31 of each year for the activities outlined in this letter and detailing the following:

        - Flow and runoff descriptions for the spill season.

        - Spill quantities and duration.

        - Quantities of water spilled for fish versus spill for other reasons for each project.

- Data from the physical and biological monitoring programs including a summary of exceedances for each dam and a description of what was done to correct the exceedance.

- Progress on TDG abatement implementation measures.

This gas abatement approval does not limit the conditions placed in future permits, orders, and certifications issued by this Department.

Please contact me at (360) 407-6405, or Chris Maynard of my staff at (360)407-6484, if you have any questions or comments regarding this approval.

Sincerely,

David C. Peeler
Water Quality Program Manager

cc: Tom Tebb
Pat Irle
Mike Schiewe, Chair, HCP Coordinating Committees
Columbia River Water Quality Team

Appendix E

Letter from Pat Irle regarding 2008 Gas Abatement Plan March 38, 2008

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
15 W Yakima Ave, Ste 200 • Yakima, WA 98902-3452 • (509) 575-2490

March 28, 2008

CERTIFIED MAIL
7007 2560 0001 7692 2574

Douglas County Public Utility District No. 1
1151 Valley Mall Parkway
East Wenatchee, WA 98802

RE: **Wells Hydroelectric Project No. 2149**
2008 TDG Gas Abatement Plan

Dear Bao Le,

Thanks for the 2008 Gas Abatement Plan (GAP) for the Wells Hydropower project, submitted in accordance with WAC 173-201A-200(1)(f)(ii)). **This plan is approved for the 2008 spill season**. This approval does not limit the conditions placed in future approvals, permits, orders or certifications issued by this department.

In future GAPs, we ask that you include the following language from the Washington State water quality standards (WAC 173-201A-200(1)(f)(ii)), which describes the content of the GAP:

"The approved gas abatement plan must be accompanied by fisheries management and physical and biological monitoring plans."

Under the new standards, the downstream forebay measurements are made on the basis of 12 *consecutive* hours. We suggest that when reporting the results of your TDG measurements you consider the following:

a) The 12 consecutive hours be represented by the first of the 12 measurements (e.g., 1 a.m. represents the value at 1 a.m., plus the values of the previous 11 hours);
b) The first 12-hour average starting at 1 a.m. be the first measurement for the reporting date; and
c) The highest value in the 24 hours of the reporting date is the compliance value.

A reminder that you will need to submit an updated GAP for the 2009 spill season.

NOTED
MAR 31 2008
MEMO

Thank you for the quality of your product. If you have any questions or would like to meet to discuss the content or format of future GAPs, please feel free to call me at (509) 454-7864.

Sincerely,

Patricia S. Irle
Hydropower Projects Manager

Cc: Jon Merz, Ecology CRO WQ
Chris Maynard, Ecology HQ WQ
Marcie Mangold, Ecology ERO WQ

Lê, B. and B. Patterson. 2010. Total Dissolved Gas Abatement Plan. Wells Hydroelectric Project, FERC No. 2149. Public Utility District No. 1 of Douglas County. Prepared for Washington Department of Ecology, Yakima, Washington.

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2010 TOTAL DISSOLVED GAS ABATEMENT PLAN

WELLS HYDROELECTRIC PROJECT

Prepared by:

Bao Le
Long View Associates
Portland, Oregon

And

Beau Patterson
Public Utilities District No. 1 of Douglas County
East Wenatchee, Washington

Prepared for:

Pat Irle
Hydropower Projects Manager
Washington Department of Ecology
Yakima, Washington 98902-3452

April 2010

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Executive Summary

Under the Water Quality Standards (WQS) Chapter 173-201A of the Washington Administrative Code (WAC) criteria developed by Ecology, Total Dissolved Gas (TDG) measurements shall not exceed 110 percent at any point of measurement in any state water body. The standards state that an operator of a dam is not held to the TDG standards when the river flow exceeds the seven-day, 10-year-frequency flood (7Q10). In addition to allowances for natural flood flows, the TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with an Ecology-approved gas abatement plan. Ecology has approved, on a per-application basis, an interim waiver to the TDG standard (110 percent) to allow spill for juvenile fish passage on the Columbia and Snake rivers (WAC 173-201A-200(1)(f)(ii)).

On the Columbia and Snake rivers there are three separate standards with regard to the TDG exemption. First, in the tailrace of a dam, TDG shall not exceed 125 percent as measured in any one-hour period. Further, TDG shall not exceed 120 percent in the tailrace of a dam and shall not exceed 115 percent in the forebay of the next dam downstream as measured as an average of the 12 highest consecutive hourly readings in any one day (24-hour period). The increased levels of spill resulting in elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. This TDG exemption provided by Ecology is based on a risk analysis study conducted by the National Marine Fisheries Service (NMFS) (NMFS 2000).

The goal of the Wells Total Dissolved Gas Abatement Plan (Gas Abatement Plan) is to implement a long-term strategy to achieve compliance with the Washington state water quality standard for TDG in the Columbia River at the Wells Hydroelectric Project (Wells Project) while continuing to provide safe passage for downstream migrating juvenile salmonids. Douglas PUD, which owns and operates the Wells Project, is submitting this Gas Abatement Plan to Washington Department of Ecology (Ecology) for approval as required for receipt of a TDG exemption at Wells Dam.

This Gas Abatement Plan summarizes the background information related to regulatory and project specific TDG information at the Wells Project (Section 1.0), discusses proposed Wells Project operations and activities related to TDG management (Section 2.0 and 3.0), and provides a summary of compliance and physical monitoring plans, the development of Quality Assurance Project Plans (QAPP), and reporting (Section 4.0).

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1.0 Introduction and Background

The Wells Hydroelectric Project Gas Abatement Plan (Gas Abatement Plan) provides details on operation and structural measures to be implemented in 2010 by Public Utility District No. 1 of Douglas County, Washington (Douglas PUD) at Wells Dam under FERC license for Project No. 2149. These measures are intended to result in compliance with the modified Washington State water quality standards (WQS) for total dissolved gas (TDG) allowed under the TDG exemption.

The goal of the Gas Abatement Plan is to implement a long-term strategy to achieve compliance with the Washington state water quality standard for TDG in the Columbia River at the Wells Hydroelectric Project (Wells Project) while continuing to provide safe passage for downstream migrating juvenile salmonids. Douglas PUD, which owns and operates the Wells Project, is submitting this Gas Abatement Plan to Washington Department of Ecology (Ecology) for approval as required for receipt of a TDG exemption at Wells Dam.

In the past, Ecology has approved Gas Abatement Plans and issued a TDG exemption at Wells Dam. Douglas PUD submitted a Gas Abatement Plan that was approved on March 27, 2003 for one year. In 2004, an extension was granted by Ecology. On March 31, 2005, Ecology approved Douglas PUD's 2005 Gas Abatement Plan allowing a TDG exemption in support of fish passage through February 2008. In 2008 and 2009, Douglas PUD again submitted Gas Abatement Plans for the fish passage seasons which were approved by Ecology (Appendix 1).

This Gas Abatement Plan summarizes the background information related to regulatory and project specific TDG information at the Wells Project (Section 1.0), discusses proposed Wells Project operations and activities related to TDG management (Section 2.0 and 3.0), and provides a summary of compliance and physical monitoring plans, the development of Quality Assurance Project Plans (QAPP), and reporting (Section 4.0).

1.1 Project Description

The Wells Project is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (USACE); and 42 miles upstream from the Rocky Reach Hydroelectric Project owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Douglas PUD. It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The spillway is comprised of eleven spill gates that are capable of spilling a total of 1,180 kcfs. The crest of the spillways is approximately five and a half feet above normal tailwater elevation and two feet below tailwater elevation when plant discharge is 219 kcfs. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a top of dam elevation of 795 feet above mean sea level (msl). The system was developed by Douglas PUD and uses a barrier system to modify the intake velocities on all even numbered spillways (2, 4, 6, 8 and 10). The Wells Project is considered a "run-of-the-river" project due to its relatively limited storage capacity.

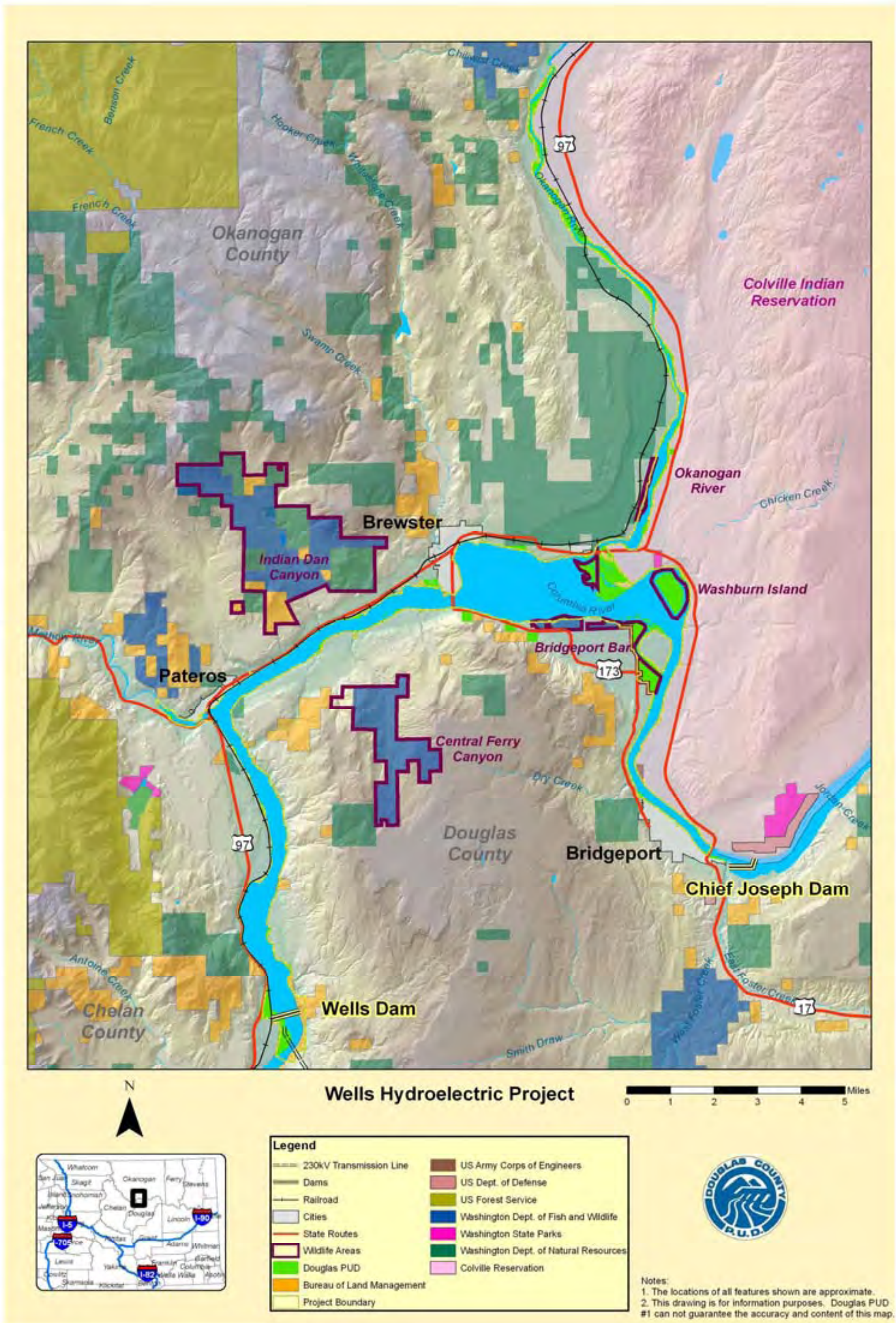

Figure 1. Map of the Wells Hydroelectric Project in Central Washington.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre-feet at the normal maximum water surface elevation of 781 feet.

1.2 Regulatory Framework

The WQS of the Washington Administrative Code address standards for the surface waters of Washington State.

Under the WQS, TDG shall not exceed 110 percent at any point of measurement in any state water body. The standards allow that an operator of a dam is not held to the TDG standards when the river flow exceeds the seven-day, 10-year-frequency flood (7Q10). The 7Q10 flow is the highest value of a running seven consecutive day average using the daily average flows that may be seen in a 10-year period. The 7Q10 total river flow for the Wells Project was computed using the hydrologic record from 1974 through 1998 and a statistical analysis to develop the number from 1930 through 1998. The United States Geological Survey (USGS) Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" was followed. The resulting 7Q10 flow at Wells Dam is 246,000 cfs (Pickett et. al. 2004).

In addition to allowances for natural flood flows, the TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with an Ecology-approved gas abatement plan. This plan must be accompanied by fisheries management and physical and biological monitoring plans. Ecology may approve, on a per application basis, an interim waiver to the TDG standard (110 percent) to allow spill for juvenile fish passage on the Columbia and Snake rivers (WAC 173-201A-200(1)(f)(ii)). On the Columbia and Snake rivers there are three separate standards with regard to the TDG exemption. First, in the tailrace of a dam, TDG shall not exceed 125 percent as measured in any one-hour period. Further, TDG shall not exceed 120 percent in the tailrace of a dam and shall not exceed 115 percent in the forebay of the next dam downstream as measured as an average of the 12 highest consecutive hourly readings in any one day (24-hour period). The increased levels of spill resulting in elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. This TDG exemption provided by Ecology is based on a risk analysis study conducted by the National Marine Fisheries Service (NMFS) (NMFS 2000).

1.2.1 7Q10

The 7Q10 for this project is 246 kcfs. The Project will not be expected to comply with state water quality standards for TDG for incoming flows exceeding this value.

1.2.2 Fish Spill Season

At this time, for purposes of compliance with the WQS for TDG, the "fish spill" season is assumed to occur from April 1 through August 31; and "non-fish spill" season occurs from September 1 to March 31. During non-fish spill, the PUD will make every effort to remain in compliance with the 110 percent standards. During fish spill, the PUD will make every effort not to exceed an average of 120 percent as measured in the tailrace of the dam. The Project also must not exceed an average of 115 percent as measured in the forebay of the next downstream dam. These averages are based on the twelve (12) highest consecutive hourly readings in any 24-hour period. In addition, there is a maximum one-hour average of 125 percent, relative to atmospheric pressure, during spillage for fish passage. Nothing in these special conditions allows an impact to existing and characteristic uses.

1.2.3 Incoming TDG Levels

Per the TDG exemption criteria, TDG shall not exceed 115 percent in the forebay of the next dam downstream dam as measured as an average of the 12 highest consecutive hourly readings in any one day (24-hour period). During the juvenile fish passage season, TDG concentrations in the Wells Project forebay are primarily determined by the upstream water management activities of Chief Joseph Dam. In June 2000, the USACE recommended installation of flow deflectors at Chief Joseph Dam combined with the "joint operation" of Chief Joseph Dam with Grand Coulee Dam in order to provide the greatest benefit of TDG reduction in the Mid-Columbia River. Since the completion of spill deflectors at Chief Joseph Dam in 2008 and a disproportionate amount of spill from the project resulting from joint operations, relatively higher TDG concentrations are expected in the forebay of Wells Dam.

1.2.4 TMDL

In June 2004, a total maximum daily load (TMDL) report was submitted for the Mid-Columbia River and Lake Roosevelt based on a listing of the area by Washington State on its federal Clean Water Act 303(d) list due to TDG levels exceeding state water quality standards. A summary implementation strategy prepared by Ecology and the Spokane Tribe describe proposed measures that could be used to reduce TDG levels in the Columbia River. Short-term actions primarily focus on meeting Endangered Species Act (ESA) requirements, while long-term goals address both ESA and TMDL requirements (Pickett et. al., 2004). Many of the actions recommended by the TMDL are currently being addressed by Douglas PUD through the implementation of Habitat Conservation Plan activities for anadromous salmon, the Bull Trout Monitoring and Management Plan resulting from consultation with the U.S. Fish and Wildlife Service, and requirements described in current and past Gas Abatement Plans. A status review of the TDG TMDL is planned for 2010. Due to an increase in interest in the TDG requirements, an advisory group consisting of representatives from tribes, federal and state agencies and others, have been convened to evaluate appropriate points of compliance for this TMDL. This group is called the Adaptive Management Team (AMT).

1.3 History of Operations and Compliance

1.3.1 Flows

The Columbia Basin in eastern Oregon, Washington and British Columbia has climate that is best described as desert. Flow from the Columbia River originates in the headwaters of the Canadian Rockies and picks up snow melt from tributary streams as it travels over 1,243 miles before emptying into the Pacific Ocean. The natural hydrograph had low flows in November through January with high flows in May through July. Storage dams in the U.S. and Canada on the Columbia River and its tributaries upstream of the Wells project capture spring and summer high flows to hold for release in the fall and winter months. There are 85,300 square miles of drainage area above Wells Dam. Table 1 presents information on Columbia River flow as measured at Wells Dam in 2009 and over the past 10 years and shows the current hydrograph of the Columbia River as controlled by upstream storage and release regimes. Because the Wells Project operates in run-of-river mode with very limited active storage, juvenile anadromous salmonid migration occurs within a regime of reduced flows during the spring migration period.

In general, the hydropower system and reservoir operations in the Columbia River are coordinated through a set of complex agreements and policies to optimize the benefits and minimize the adverse effects of project operations. The Wells Project operates within the constraints of the Pacific Northwest Coordination Agreement, Canadian Treaty, Canadian Entitlement Agreement, Hourly Coordination Agreement, the Hanford Reach Fall Chinook Protection Program and the Federal Energy Regulatory Commission (FERC) regulatory and license requirements.

Table 1. Average monthly flows (kcfs) at Wells Dam, by month (2000-2009).

						Month						
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2000	145.5	116.0	101.3	146.0	149.7	121.0	118.6	109.1	83.1	73.9	93.1	104.4
2001	96.5	88.2	73.8	62.9	55.2	84.5	53.4	70.3	62.5	56.1	70.9	79.1
2002	91.0	91.9	66.1	116.9	135.0	205.6	176.5	115.1	73.9	79.4	96.7	93.3
2003	75.7	69.9	82.2	106.7	130.7	137.6	106.2	96.4	64.0	74.6	87.7	105.5
2004	96.2	80.5	70.0	87.3	114.2	132.3	101.5	95.7	75.7	79.3	90.9	112.0
2005	102.0	104.4	94.9	85.4	122.1	130.8	136.8	107.9	67.6	78.5	90.9	91.8
2006	101.2	104.5	87.3	148.4	165.3	195.1	127.9	103.9	66.3	66.3	77.1	90.8
2007	114.5	85.3	120.3	154.7	159.2	152.0	133.0	113.1	60.0	64.4	80.2	86.8
2008	104.0	88.6	82.4	90.3	158.7	206.8	135.3	86.5	60.7	63.0	75.2	94.2
2009	107.8	80.2	71.5	111.0	122.7	146.6	103.1	74.5	53.5	58.1	80.1	101.8
All	110.1	104.7	99.5	116.8	145.6	166.7	130.4	106.9	74.3	75.8	88.2	106.9

1.3.2 Spill Operations

1.3.2.1 General Operation

Under the Hourly Coordination Agreement, power operations for the seven dams from Grand Coulee to Priest Rapids are coordinated to meet daily load requirements through the assignment of "coordinated generation" through Central Control hosted at the Public Utility District No. 2 of Grant County (Grant PUD). Automatic control logic is used to maintain pre-set reservoir levels in order to meet load requirements and minimize involuntary spill. These pre-set reservoir levels are maintained at each project through management of a positive or negative "bias" which assigns a project more or less generation depending on whether the reservoir elevation should be increased or decreased in order to maximize system benefits and minimize involuntary spill.

1.3.2.2 Spill for Fish

Wells Dam is a hydrocombine-designed dam where the spillway is situated directly above the powerhouse. Research at Wells Dam in the mid-1980s showed that a modest amount of spill would effectively guide a high percentage of the downstream migrating juvenile salmonids through the Juvenile Bypass System (JBS). The operation of the Wells JBS utilizes the five even numbered spillways. These spillways have been modified with constricting barriers to improve the attraction flow while using modest levels of water. These spillways are used to provide a non-turbine passage route for downstream migrating juvenile salmonids from April through August. Normal operation of the JBS uses 2.2 kcfs per spillway. During periods of extreme high flow, one or more of the JBS barriers may be removed to provide adequate spill capacity to respond to a plant load rejection.

Typically, the JBS will use approximately 6 to 8 percent of the total river flow for fish guidance. The operation of the JBS adds a negligible level of TDG (0 – 2 percent) while meeting a very high level of fish guidance and protection. This high level of fish protection at Wells Dam has met the approval of the fisheries agencies and tribes and is vital to meeting the survival performance standards contained within the FERC approved Habitat Conservation Plan (HCP) with NMFS. The Wells Project fish bypass system is the most efficient system on the mainstem Columbia River. The bypass system on average collects and safely passes 92.0 percent of the spring migrating salmonids (yearling Chinook, steelhead and sockeye) and 96.2 percent of the summer migrating subyearling Chinook (Skalski et al. 1996) (Table 2).

Table 2. Wells Hydroelectric Project Juvenile Bypass Efficiency.

Species	% JBS Passage
Yearling (spring) Chinook	92.0
Steelhead	92.0
Sockeye	92.0
Subyearling (summer/fall) Chinook	96.2

The JBS is utilized for protection of downstream migrating juvenile salmonids. Fish bypass operations at Wells Dam falls into two seasons, Spring Bypass and Summer Bypass. For 21 years, the status of the fish migration for both spring and summer periods was monitored by an array of hydroacoustic sensors placed in the forebay of Wells Dam. Starting in 2003, the operation of the juvenile bypass for the Wells HCP was set with fixed dates that were established based on 21 years of hydroacoustic and fyke net data. The dates for bypass operation are from April 12 through August 26. These dates bracket greater than 95% of both the spring and summer migrants. Annually, there have been as many as ten million juvenile salmonids that have migrated past Wells Dam.

Between the years 1997 and 2004, the volume of water dedicated to the JBS has ranged from 1.5 to 3.2 million acre-feet. Operation of the JBS adds a small amount of dissolved gas (0 to 2 percent) to the river while meeting a very high level of fish guidance and protection. Ecology has authorized an exemption to the total dissolved gas standard for fish protection on the Columbia and Snake rivers. Operation of the Wells Project JBS does not produce TDG at levels that exceed the Ecology TDG exemption.

1.3.2.3 Flows in Excess of Hydraulic Capacity

The Wells Project is a “run-of-the river” project with a relatively small storage capacity. River flows in excess of the hydraulic capacity of the ten turbines must be passed over the spillways.

The forebay elevation at Wells Dam is set between 781.0 and 771.0 msl. The Wells Project has a hydraulic generating capacity of approximately 220 kcfs (ASL, 2007) and a spillway capacity of 1,180 kcfs. Data for Columbia River flows for eighty-five years at Priest Rapids yielded a peak daily average discharge of 690,000 on June 12, 1948 (USGS web page for historical flows at Priest Rapids on the Columbia River, http://waterdata.usgs.gov/wa/nwis/dv/?site_no=12472800). The hydraulic capacity of Wells Dam is well within the range of recent historical flow data.

1.3.2.4 Flow in Excess of Power Demand

Spill may occur at flows less than the Wells Project hydraulic capacity when the volume of water is greater than the amount required to meet electric power system loads. This may occur during temperate weather conditions when power demand is low or when non-power constraints on river control results in water being moved through the mid-Columbia at a different time of day than the power is required. Hourly coordination (Section 3.2) between hydroelectric projects on the river was established to minimize this situation for spill.

1.3.2.5 Gas Abatement Spill

Gas Abatement Spill is used to manage TDG levels throughout the Columbia River Basin. The Technical Management Team (including NMFS, U.S. Army Corps of Engineers, and Bonneville Power Administration) implements and manages this spill. Gas Abatement Spill is requested from dam operators from a section of the river where gas levels are high. A trade of power generation for spill is made between operators, providing power generation in the river with high TDG and trading an equivalent amount of spill from a project where TDG was low. Historically, the Wells Project has accommodated requests to provide Gas Abatement Spill. In an effort to limit TDG generated at the Wells Project, Douglas PUD has adopted a policy of not accepting Gas Abatement Spill at Wells Dam.

1.3.2.6 Other Spill

Other spill includes spill as a result of maintenance or plant load rejection. A load rejection occurs when the generating plant is forced off-line by an electrical fault, which trips breakers and shuts off the generation. At a run-of-the-river hydroelectric dam, if water cannot flow through operating turbines, then the river flow that was producing power has to be spilled until turbine operation can be restored.

These events are extremely rare, and would account for approximately 10 minutes in every ten years. Maintenance spill is utilized for any activity that requires spill to assess the routine operation of individual spillways and turbine units. These activities include checking gate operation, and all other maintenance that would require spill. The FERC requires that all spillway gates be operated once per year. To control TDG levels associated with maintenance spill, Douglas PUD limits, to the extent practical, maintenance spill during the spill season.

1.3.3 Compliance Activities in Previous Year

1.3.3.1 Operational

The Wells Project is a "run-of-the river" project with a relatively small storage capacity. River flows in excess of the hydraulic capacity of the ten turbines must be passed over the spillways. Outside of system coordination and gas abatement spill (Douglas PUD has adopted a policy of not accepting the latter), minimization of involuntary spill has primarily focused on minimizing TDG production dynamics of water spilled based upon a reconfiguration of spillway operations. The Wells Project 2009 Gas Abatement Plan (Le and Murauskas, 2009) introduced the latest numerical model developed by the University of Iowa's IIHR-Hydroscience and Engineering Hydraulic Research Laboratories. The two-phase flow computational fluid dynamics tool was used to predict hydrodynamics of TDG distribution within the tailrace of Wells Dam and further identify operational configurations that would minimize TDG production at the project. In an April 2009 report, the model demonstrated that Wells Dam can be operated to meet the TDG fish spill waiver standards during the passage season with flows up to 7Q-10 levels (246,000 cfs; Pickett et. al. 2004). Compliance was achieved through the use of a concentrated spill pattern through Spillbay No. 7 and surplus flow volume through other spillbays in a defined pattern. These preferred operating conditions create surface-oriented flows by engaging submerged spillway lips below the ogee, thus increasing degasification at the tailrace surface, decreasing supersaturation at depth, and preventing high-TDG waters from bank attachment. These principles were the basis of the 2009 Wells Project Spill Playbook and were fully implemented for the first time during the 2009 fish passage (spill) season.

River flows in 2009 were below average compared to the trailing 10-year average at the Wells Project (Table 3). Flow in 2009 was most similar to 2003-2005, and 2008. These low flow years typically begin with average flows around 100 kcfs in April, gradually increasing to 130-150 kcfs in May and June, and tapering off to below 70 kcfs in September. TDG values for low flow years are slightly lower than, but generally indistinguishable from, the 10-year average. These below average river flow years with available TDG measurements will be used comparatively in discussion, given their similarities to the 2009 monitoring season (Table 4).

From a compliance perspective, two differences are noticeable between current and past low flow years: (1) the higher frequency of out of compliance days at the Wells Forebay, resulting from operations at Chief Joseph Dam; and, (2) the evident improvement of TDG management in the Wells Tailrace through implementation of the 2009 Wells Project Spill Playbook.

Exceedances of TDG numeric criteria of water leaving Chief Joseph Dam increased from 0.2 percent in 2003, 2004, and 2005 (1 of 549 days) to 15.1 percent in 2008 and 2009 (48 of 318 days). This represents a greater than 7,500 percent increase in the frequency of exceedances in the forebay at Wells Dam during low flow years, caused by recent changes in spill and generation management at the upstream

Chief Joseph and Grand Coulee dams. Extensive spill testing, installation of tailrace flow deflectors, and the exchange of spill for generation with Grand Coulee Dam are all likely contributing factors in this dramatic increase in TDG exceedances for water entering the Wells Project (personal communication, K. Easthouse, USACE).

Despite the lack of fish passing Chief Joseph Dam, the USACE has obtained TDG waivers for fish passage in recent years. Unlike typical TDG waivers, operators at Chief Joseph Dam have been allowed a year-round exemption from WQS for TDG (personal communication, R. Turner, USACE). This has allowed increased spill at Chief Joseph Dam and waters with increased TDG levels entering the Wells Project, resulting in TDG exceedances in the forebays of both Wells and Rocky Reach dams.

Despite the additional complicating factor of incoming waters with higher concentrations of TDG in recent years, operations at the Wells Project have improved the management of TDG at downstream compliance stations. During 2009, zero exceedances occurred in the tailrace of Wells Dam (0 of 183 days). During the last four low flow years (2003-2005, and 2008), 97.5 percent of days were in compliance (18 of 714 days). The reduction of exceedances to 0 percent in the tailrace of Wells Dam was likely a result of environmental circumstances in combination with improved operations in the Wells Project. Similarly, compliance in the downstream forebay of Rocky Reach Dam was achieved 100 percent of the time during the 2009 monitoring season. During the last four low flow years, only 93.6 percent of days were in compliance (47 of 685).

Table 3. 2009 river flows compared to 10-yr average flows (in kcfs). Spring is defined as April 12 – June 30. Summer is defined as July 1 – August 26.

Season	10 Year (2000-2009)Average Flows (kcfs)	2009 Average Flows	% of 10 Year Average (%)
Spring	131.2	127.0	96.8
Summer	108.2	89.0	82.3

Table 4. Average hourly flow (kcfs) and TDG (percent saturation) during the fish spill season at the Wells Project (including tailrace and forebay) 2000-2009, by month. Years of similar river flow volume to 2009 are shaded for comparison.

	April		May		June		July		August		All	
YR	Flow	TDG	Flow	TDG	Flow	TDG	Flow	TDG	Flow	TDG	Flow	TDG
2000	146	108	150	110	121	112	119	111	109	110	121	109
2001	63	107	55	109	85	107	53	110	70	107	65	107
2002	117	108	135	110	206	119	177	119	115	112	137	112
2003	107	106	131	109	138	112	106	112	96	108	107	109
2004	87	108	114	109	132	109	101	111	96	109	101	109
2005	85	107	122	109	131	111	137	111	108	108	109	108
2006	148	108	165	115	195	120	128	115	104	109	134	113
2007	155	109	159	112	152	112	133	112	113	108	129	110
2008	90	106	159	111	207	119	135	113	86	111	123	111
2009	111	107	123	110	147	113	103	114	75	110	102	110
All	117	107	146	110	167	114	130	113	107	109	124	110

1.3.3.2 Structural

No structural modifications were proposed or conducted in the 2009 monitoring season.

1.3.4 Compliance Success in Previous Year (2009)

1.3.4.1 TDG

No hourly TDG measurements were recorded above 125 percent saturation, and the 12C-High daily values did not surpass 120 percent on any given day in the tailrace of Wells Dam. The 12C-High values at the forebay of Rocky Reach Dam did not surpass 115 percent on any given day when incoming waters from Chief Joseph Dam were in compliance (12C-High < 115 percent in the forebay of Wells Dam) (Table 5). Although 2009 was a relatively low flow year compared to the past 10 years, management of TDG levels in the Wells Project showed substantial improvements over similar years of river flow. The improvement of TDG management, despite an increasing frequency of TDG exceedances in water entering the Wells Project, is confirmation that the newly implemented 2009 Wells Project Spill Playbook is providing a useful means to meet WQS within the Wells Project.

Table 5. Summary of Spill and TDG Compliance in 2009. Spring is defined as April 12 – June 30. Summer is defined as July 1 – August 26.

Season	Average Daily % Spill	Average Daily Spill Volume (kcfs)	Wells Tailrace TDG Compliance (%)	Rocky Reach Forebay TDG Compliance (%)
Spring	6.8	134.4	100	100
Summer	7.8	90.6	100	100

2.0 Proposed Operations and Activities

2.1 Operational Spill

2.1.1 Minimizing Involuntary Spill

Based on the success of last year's operations associated with implementation of the Wells Project Spill Playbook, those operations will be followed again this year. The 2009 playbook is attached as Appendix 2.

2.2 Implementation

2.2.1 Fisheries Management Plans

Juvenile salmon and steelhead survival studies conducted at the Wells Project in accordance with the HCP have shown that the operation of the Wells Project, of which the JBS is an integral part, provides an effective means for outmigrating salmon and steelhead to pass through the Wells Project with a high rate of survival (Bickford et al. 2001)(Table 6). The Wells Anadromous Fish Agreement and Habitat Conservation Plan (Douglas PUD 2002) is the Wells Project's fisheries management plan for anadromous salmonids, and directs operations of the Wells JBS in order to achieve the NNI standard for HCP Plan Species. The Wells JBS is the most efficient juvenile fish bypass system on the mainstem Columbia River (Skalski et al. 1996).

Table 6. 1998 -2000 Wells Hydroelectric Project Juvenile Survival Study Results.

Species	% Project Survival
Yearling (spring) Chinook	96.2
Steelhead	96.2

The HCP requires juvenile project survival studies to be repeated at Wells Dam in 2010. Final results of those studies may suggest the use of additional passage tools including the use of voluntary spill if necessary to reach survival goals of the HCP. The current phase designations (status of salmon and steelhead species reaching final survival determination) for the HCP Plan species are summarized in Table 7. Specific details regarding survival study design, implementation, analysis, and reporting are available in annual summary reports prepared and approved by the Wells HCP Coordinating Committee.

Table 7. Wells Hydroelectric Project Habitat Conservation Plan Species Phase Designations.

Species	Phase Designation
Yearling (spring) Chinook	Phase III[1] – Standards Achieved (22-Feb-05)
Steelhead	Phase III – Standards Achieved (22-Feb-05)
Sockeye	Phase III – Additional Juvenile Studies (22-Feb-05)
Subyearling (summer/fall) Chinook	Phase III – Additional Juvenile Studies (22-Feb-05)
Coho	Phase III – Additional Juvenile Studies (27-Dec-06)

In 2010, Douglas PUD shall continue to operate Wells Dam adult fishways and the JBS in accordance with HCP operations criteria to protect aquatic life designated uses. Furthermore, all fish collection (hatchery broodstock and/or evaluation activities) or assessment activities that occur at Wells Dam will require approval by Douglas PUD and the HCP Coordinating Committee to ensure that such activities protect aquatic life designated uses.

Douglas PUD shall continue to operate the Wells Project in a coordinated manner toward reducing forebay fluctuations and maintaining relatively stable reservoir conditions that are beneficial to multiple designated uses (aquatic life, recreation, and aesthetics). Coordinated operations reduce spill, thus reducing the potentials for exceedances of the TDG numeric criteria and impacts to aquatic life associated with TDG.

2.2.2 Biological Monitoring

Douglas PUD will work with the Washington Department of Fish and Wildlife hatchery programs to monitor the occurrence of Gas Bubble Trauma (GBT) on adult broodstock collected for hatchery needs. Upon collection of brood, hatchery staff will inoculate each fish, place a marking identification tag on them and look for any fin markings or unusual injuries. NMFS has shown that GBT is low if the level of TDG can be managed to below 120 percent (NMFS 2000). They recommend that "the biological monitoring components will include smolt monitoring at selected smolt monitoring locations and daily data collection and reporting only when TDG exceeds 125 percent for an extended period of time." Thus, biological sampling at Wells Dam of adult broodstock will only occur when hourly TDG levels in the mid-Columbia exceed 125 percent.

At most hydroelectric projects on the Columbia River, a juvenile migrant sampling station is incorporated into the JBS. This allows for the external observation of fish for signs of GBT. The signs of GBT are bubbles under the skin of the fish along the fin rays and near the eye sockets. While juvenile migrants are the choice fish for sampling when inspecting for GBT, the JBS at Wells Dam does not have facilities incorporated to allow for juvenile fish sampling and observation. As in past years, if hourly TDG levels exceed 125 percent in the tailrace of Wells Dam, Douglas PUD will request biological sampling of migrating juveniles for symptoms of GBT at the juvenile sampling facility at Rocky Reach Dam.

[1] Phase III = Dam survival >95% or project survival >93% or combined juvenile and adult survival >91% (Standard Achieved).

2.2.3 Water Quality Forums

Douglas PUD is currently involved in the Water Quality Team meetings held in Portland, Oregon. The purpose of the Water Quality Team meetings is to address regional water quality issues. This forum allows regional coordination for monitoring, measuring, and evaluating water quality in the Columbia Basin.

Douglas PUD will continue its involvement in the Water Quality Team meetings for further coordination with other regional members.

Douglas PUD is also currently involved in the Transboundary Gas Group that meets annually to coordinate and discuss cross border dissolved gas issues in Canada and the U.S. Douglas PUD will continue its involvement with the Transboundary Gas Group.

In 2009, Douglas PUD actively participated in regional water quality forums with Ecology, Washington Department of Fish and Wildlife, Tribal Agencies, the U.S. Fish and Wildlife Service, the USACE, and other Mid-Columbia PUDs (i.e., Grant and Chelan counties). These meetings, ranging from the Trans-boundary Gas Group to Columbia Basin meetings with the USACE, allow for regional coordination for monitoring, measuring, and evaluating water quality in the Columbia Basin. Douglas PUD will continue its involvement in such forums to further improve coordination with other regional water quality managers as detailed in section 5.1.2.

3.0 Structural Activities

No structural modifications related to spill are scheduled to occur at the Wells Project in 2010.

4.0 Compliance and Physical Monitoring

4.1 Monitoring Locations

4.1.1 TDG

TDG monitoring has been implemented in the Wells Dam forebay since 1984. Douglas PUD began monitoring TDG levels in the Wells Dam tailrace in 1997 by collecting data from a boat and drifting through the tailrace at four points across the width of the river. During the transect monitoring, no TDG "hot spots" were detected; the river appeared completely mixed horizontally. A fixed TDG monitoring station was established in 1998. The placement of the fixed monitoring station was determined based upon the 1997 work and was further verified as collecting data representative of river conditions during a 2006 TDG assessment at Wells Dam (EES et. al. 2007). Results of the 2008-2009 TDG numerical modeling activities being conducted by University of Iowa/IIHR have also confirmed that the tailrace monitoring station is located at a site representative of the river, particularly during higher flows. Furthermore, locations of both forebay and tailrace sensors had to be protected to avoid sensor/data loss and damage and for safe accessibility during extreme high flows. The current locations of both the forebay and tailrace monitors took these criteria into consideration.

TDG monitoring at the Wells Project commenced on April 1 and will continue until September 15 annually. This monitoring period will encompass the operation of the Wells JBS as well as the time period river flows are at their highest and when a majority of forced spill occurs. Throughout this period, data from both forebay and tailrace sensors are transmitted by slave radio transmitters to a master radio at Wells Dam. This system is checked at the beginning of the season for communication between the probes and transmitters by technicians at Wells Dam. Total dissolved gas data are sent and logged at the Douglas PUD Headquarters' building in 15-minute intervals. Information on barometric pressure, water temperature and river gas pressure is sent to the U.S. Army Corps of Engineers on the hour over the Internet. The four data points (15 minute) within an hour are used in compiling hourly TDG values, the 24 hour TDG average and twelve maximum hour TDG averages.

4.1.2 Water Temperature

Douglas PUD has been monitoring water temperatures throughout the Wells Reservoir and in the Wells Dam tailrace year round since 2005. Temperature monitoring locations are provided in Table 8. Temperature monitoring through the reservoir and the inundated portions of tributary streams will be performed with Onset� Tidbit thermographs.

Table 8. List of Wells Reservoir and tributary temperature monitoring stations.

River	Side/Mile	Location
Columbia	Left / 515.6	Wells Forebay*
Columbia	Left / 530	Near Brewster
Columbia	Left / 535.3	Brewster Flats
Columbia	Left / 544.5	Chief Joseph Tailrace
Columbia	Left/515.5	Wells Dam Tailrace
Columbia	Right/515.5	Wells Dam Tailrace
Methow	Right / 2.8	Near Pateros
Okanogan	Center / 10.5	Near Monse
Methow	Center/0.4	Mouth of Methow
Okanogan	Center/1.3	Mouth of Okanogan

4.2 Quality Assurance

4.2.1 TDG

As part of the Douglas PUD's Quality Assurance/Quality Control (QA/QC) program, Douglas PUD's water quality consultant will visit both TDG sensor sites monthly for maintenance and calibration of TDG instruments. Calibration follows criteria established by the USACE, with the exception of monthly rather than bi-weekly calibration of sensors. A spare probe will be available and field-ready in the event that a probe needs to be removed from the field for repairs.

The consultant will inspect instruments during the monthly site visits and TDG data will be monitored weekly by Douglas PUD personnel. If, upon inspection of instruments or data, it is deemed that repairs are needed, they will be promptly made. Occasionally during the monthly sensor calibration, an error may develop with the data communication. These problems are handled immediately. Generally, the radio transmitters at each fixed station will run the entire season without any problems.

Douglas PUD intends to collect quality, usable data for each day over the 168-day (April 1 – September 15) monitoring season. As part of the quality assurance process, data anomalies will be removed. This would include data within a 2-hour window of probe calibration and any recording errors that result from communication problems. Data errors will prompt a technician or water quality specialist site visit, to inspect the instrument and repair or replace if necessary.

4.2.2 Water Temperature

QA/QC measures will be accomplished through calibration of thermographs at the beginning and end of a period of sensor deployment. As part of the QA/QC process, data anomalies will be identified and removed from the data set. Sensors will be deemed unreliable if calibration against a Bureau of Standard accuracy thermometer shows a variance of ± 0.2°C. Thermographs will be swapped out quarterly (every three months) with recently tested sensors to avoid data loss.

4.3 Reporting

Upon approval of the Wells Gas Abatement Plan and issuance of a Wells Project TDG exemption, Douglas PUD shall submit an annual report describing the results of all monitoring activities described within this Gas Abatement Plan. The report will be submitted to Ecology no later than December 31 of each year that the TDG exemption is active. The report will summarize all Gas Abatement Plan activities conducted for the year in which it is submitted as required by Ecology.

5.0 Conclusions

Pending approval by Ecology, implementation of the measures identified within the 2010 Gas Abatement Plan are intended to serve as a long-term strategy to maintain compliance with the Washington state water quality standard for TDG in the Columbia River at the Wells Project while continuing to provide safe passage for downstream migrating juvenile salmonids.

6.0 Literature Cited

ASL Environmental Sciences (ASL). 2007. Turbine Discharge Measurements by Acoustic Scintillation Flow Meter at Units 1 and 2, Wells Hydroelectric Project, Pateros, Washington, August 2006. Prepared by ASL Environmental Sciences Inc. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Bickford, S. A., J. R. Skalski, R. Townsend, S. McCutcheon, R. Richmond, R. Frith and R. Fechhelm. 2001. Project survival estimates for yearling summer steelhead migrating through the Wells Hydroelectric Facility, 2000.

EES Consulting, Carroll, J., ENSR, and Parametrix. 2007. Total Dissolved Gas Production Dynamics Study. Wells Hydroelectric Project. FERC No. 2149. Prepared by EES Consulting, Joe Carroll, ENSR, and Parametrix. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Le, B and J. Murauskas. 2009. Total Dissolved Gas Abatement Plan. Wells Hydroelectric Project. April 2009. Prepared for Washington Department of Ecology, Yakima, Washington, 98902-3452.

National Marine Fisheries Service (NMFS). 2000. Endangered Species Act – Section 7 Consultation: Biological Opinion. Consultation on Remand for Operation of the Columbia River Power System and 19 Bureau of Reclamation Projects in the Columbia Basin. F/NWR/2004/00727. November 30, 2005. Pages 5-6, 5-7, 5-53, 10-9, and Appendix E: Risk Analysis.

Pickett, P., H. Rueda, M. Herold. 2004. Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt. Submittal Report. Washington Department of Ecology, Olympia, WA. U.S. Environmental Protection Agency, Portland, OR. June 2004. Publication No. 04-03-002.

Skalski, J. R, G. E. Johnson, C. M. Sullivan, E. Kudera and M. W. Erho. 1996. Statistical Evaluation of Turbine Bypass Efficiency at Wells Dam on the Columbia River, Washington. Canadian Journal of Fisheries and Aquatic Science. Volume 53, No. 10, 1996. Pages 2188-2198.

7.0 Appendices

Appendix 1. Letter from Pat Irle on Gas Abatement Plan for 2009.

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
15 W Yakima Ave, Ste 200 • Yakima, WA 98902-3452 • (509) 575-2490

June 4, 2009

Josh Murauskas
Douglas County PUD No. 1
1151 Valley Mall Boulevard
East Wenatchee, WA 98802

RE: Wells Hydropower Project No. 2149
2008 Annual Gas Abatement Report and
2009 Gas Abatement Plan

Dear Josh Murauskas:

The 2009 Gas Abatement Plan for the Wells Dam is hereby approved for the 2009 fish spill season.

The results presented in the 2008 Gas Abatement Report and in other studies Douglas Public Utility District (PUD) has done over the recent months as part of the re-licensing effort are truly appreciated.

As we discussed recently, it would be helpful if the mid-Columbia PUDs could meet with Ecology to coordinate on format and content of the Gas Abatement Plans (GAPs) and Gas Abatement reports.

Following are comments on the 2008 ("annual") Gas Abatement Report. We expect these problems will be addressed in the draft and final Gas Abatement reports for the 2009 fish spill season. We would like to meet with the PUD to discuss the content of the draft report shortly after we receive it.

I. General Comments

We really appreciate the inclusion of the "2009 Playbook" as part of the GAP. This provides very useful information.

NOTED
JUN 05 2009
MEM

The 2008 GAP required that the following be included in the (annual) Gas Abatement Report (see Section 5.3 h):

- i. Flow and TDG levels, on a daily basis, *with purpose of spill* (e.g., fish spill, turbine down time.)
- ii. Summary of exceedances and what was done to correct the exceedances.
- iii. Results of the fish passage efficiency (FPE) studies and survival per the Habitat Conservation Plan (HCP).

It is very important that this information be included in the next (2009) Annual Gas Abatement Report. Note that the purpose of spill is to be provided for each day.

II. More Specific

1) Table 4.0-1 could be made more useful to help determine: a) compliance with state water quality standards; b) impacts of incoming flows on compliance; and/or c) impacts of operation on compliance.
2) Section 4.2.4, last sentence, says the PUD "has adopted a policy of not accepting in [sic] Gas Abatement Spill at Wells Dam". What does this mean? Did you mean "not any"? Or something else?
3) Please describe the locations of "WELW" (page 13) and "WEL" (page 15).
4) Need section in Chapter 4 that describes the 2008 fish management activities and any results or comments provided by the PUD at the water quality meetings.
5) It seems more appropriate to put the discussion of the historical TDG monitoring in the forebay (page 15, first paragraph) in Section 4, "History of Operations and TDG Compliance Monitoring".
6) Where are the adult broodstock collected (page 16)?

Please let me know if you have any questions or suggestions.

Sincerely,

Pat Irle
Hydropower Projects Manager
Water Quality Program

Appendix 2. Wells Hydroelectric Project Spill Playbook, 2010.

Memorandum

To: Ken Pflueger, Mike Bruno, Dub Simmons, Arlen Simon, Hank Lubean
From: Joshua Murauskas, Shane Bickford, Duncan Hay (Oakwood Consultants)
Date: April 21, 2009
Subject: Wells Dam Spill Playbook, 2009

Douglas PUD has conducted several modeling assessments aimed at gaining a better understanding of the effect of spill operations on the production, transport and mixing of TDG in the Wells Dam tailrace.

Results indicate that:

1. Concentrated spill operations (as opposed to spread) reduce TDG production and increase degasification at the tailwater surface.

2. Discharge from spillbays (denoted *S* hereafter) located near the middle of the dam (e.g., *S7*) prevent water with high TDG from attaching to the shoreline.

3. Forced spill exceeding Juvenile Bypass System (JBS) flows of 2.2 kcfs must be increased to ≥ 15 kcfs to ensure that the submerged spillway lip below the ogee is engaged. The resulting force will create flows that are surface oriented, ultimately promoting degasification at the tailwater surface.

The attached Spill Strategy is based on these principles and the preferred operating conditions will help achieve compliance with the Washington State water quality standards. Further details are provided in the *Wells Hydroelectric Project Updated Study Report* Document submitted to the FERC on April 15th, 2009.

I. No Forced Spill

The Wells Dam JBS (even numbered spillbays, 10.0 kcfs total) should be operated continuously throughout the juvenile salmon outmigration (normally April 12 to August 26). The Wells JBS is normally operated with 1.7 kcfs passed through *S2* and *S10*, and 2.2 kcfs through *S4*, *S6*, and *S8* (Figure 1).

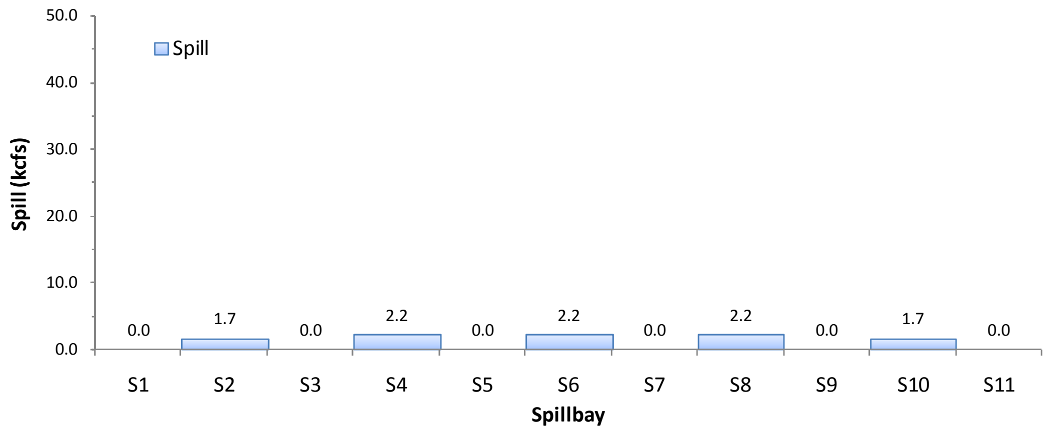

Figure 1. Operational configuration under no forced spill (JBS only).

II. Forced Spill (≤ 53.0 kcfs)

As forced spill increases, Project Operators should allocate all spill through *S7* until the maximum capacity is reached through that spillbay (~43.0 kcfs). This, along with the already established JBS spill (10.0 kcfs) would equal 53.0 kcfs (Figure 2). Over 90% of the spill events over the past decade could have been handled under this configuration.

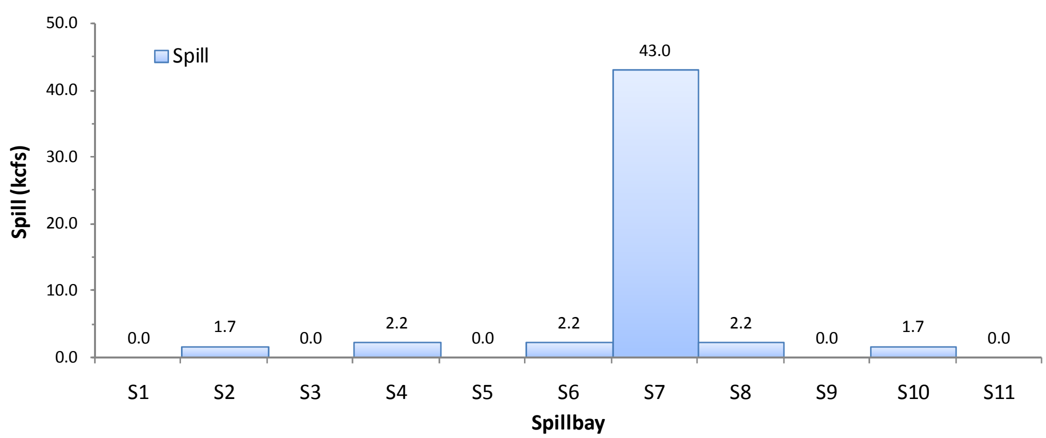

Figure 2. Operational configuration under spill ≤ 53.0 kcfs (including JBS).

III. Forced Spill (> 53.0 kcfs)

After *S7* reaches 43.0 kcfs, spill should be allocated to *S5*. Since a minimum of 15.0 kcfs is needed to fully engage the submerged spillway lip below the ogee, spill through *S7* must be relocated to *S5* (Figure 3). As flow increases, spill should continually increase through *S5* until paired with *S7* (e.g., 28.0 kcfs through *S5* and *S7*). After this point (66.0 kcfs), both *S5* and *S7* can be increased until both spillbays have reached 43.0 kcfs (96.0 kcfs, Figure 4).

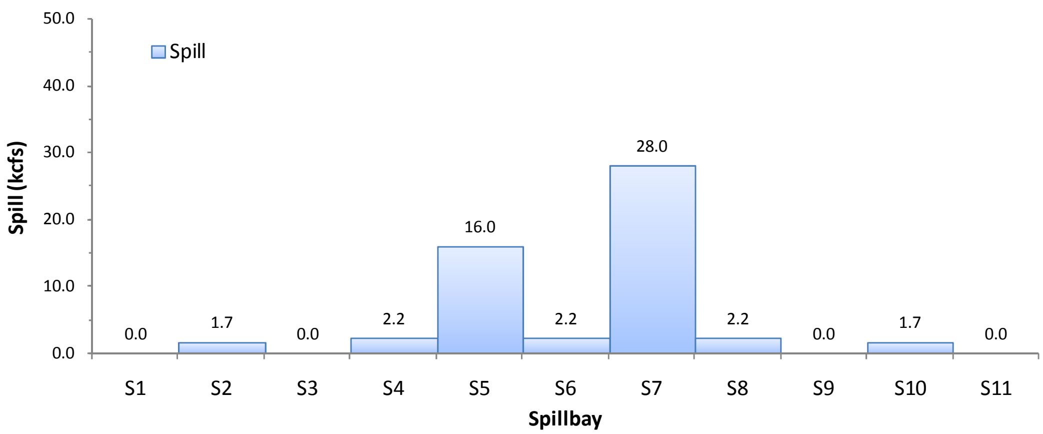

Figure 3. Operational configuration under forced spill > 53.0 kcfs (including JBS). In this instance (54.0 kcfs of total spill), 16.0 kcfs is allocated through *S5* in order to engage the submerged spillway lip.

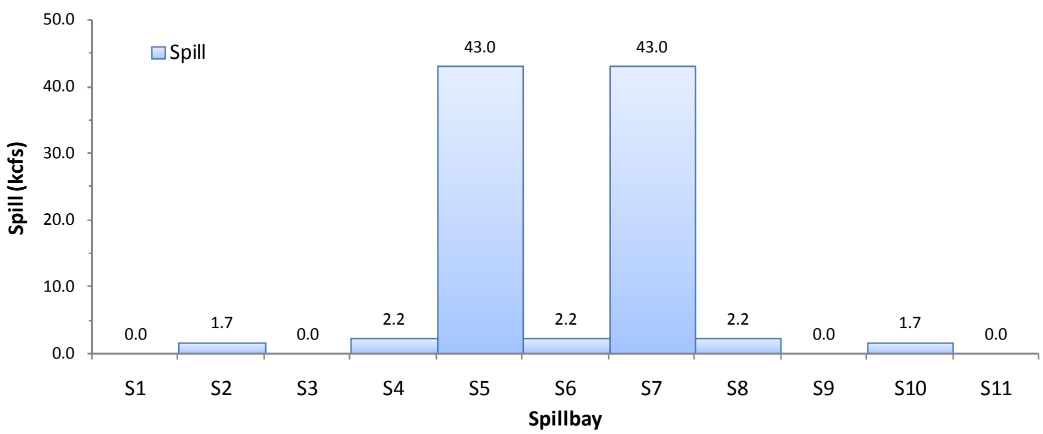

Figure 4. Operational configuration under forced spill > 53.0 kcfs (including JBS). In this instance (96.0 kcfs of spill), 43.0 kcfs is allocated through both *S5* and *S7*.

IV. Forced Spill (> 96.0 kcfs)

After both *S5* and *S7* reach 43.0 kcfs, spill should be allocated to *S9*. Since a minimum of 15.0 kcfs is needed to fully engage the submerged spillway lip below the ogee, spill through *S5* should be relocated to *S9* (Figure 5). As flow increases, spill can be continually increased through *S5* until paired with *S9* (28.0 kcfs through *S5* and *S9*, while *S7* continues at 43.0 kcfs). After this point, both *S5* and *S7* can be increased until both spillbays have reached 43.0 kcfs, equal to discharge through *S7* (139.0 kcfs, Figure 6).

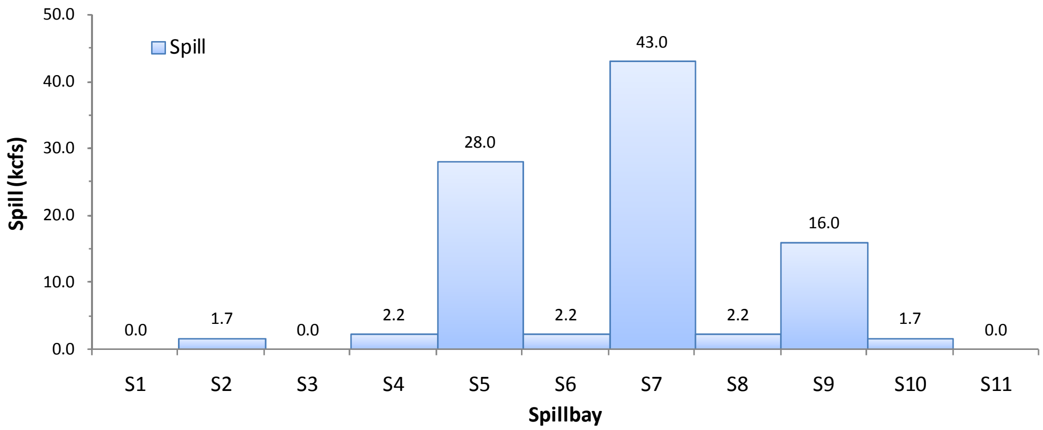

Figure 5. Operational configuration under forced spill > 96.0 kcfs (including JBS). In this instance (97.0 kcfs of total spill), 16.0 kcfs is allocated through *S9* in order to engage the submerged spillway lip.

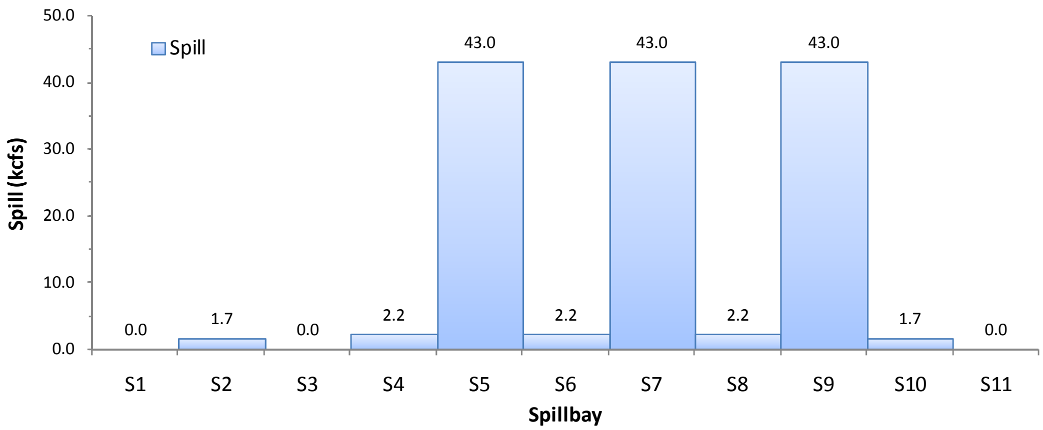

Figure 6. Operational configuration under forced spill > 96.0 kcfs (including JBS). In this instance (139.0 kcfs of total spill), 43.0 kcfs is allocated through *S5*, *S7*, and *S9*.

V. Forced Spill (> 96.0 kcfs) and JBS Barriers in *S6* Removed

After both *S5* and *S7* reach 43.0 kcfs, spill can also be allocated to *S6*, provide the JBS barrier has been removed. Since a minimum of 15.0 kcfs is needed to fully engage the submerged spillway lip below the ogee, spill through *S5* (or *S9* if scenario IV is in play) should be relocated to *S6* (Figure 7). As flow increases, spill can be continually increased through *S5* until paired with *S6* (30.0 kcfs through S5 and S6, while S7 continues at 43.0 kcfs). After this point, both *S5* and *S6* can be increased until all three spillbays have reached 43.0 kcfs(136.8 kcfs of spill, Figure 8).

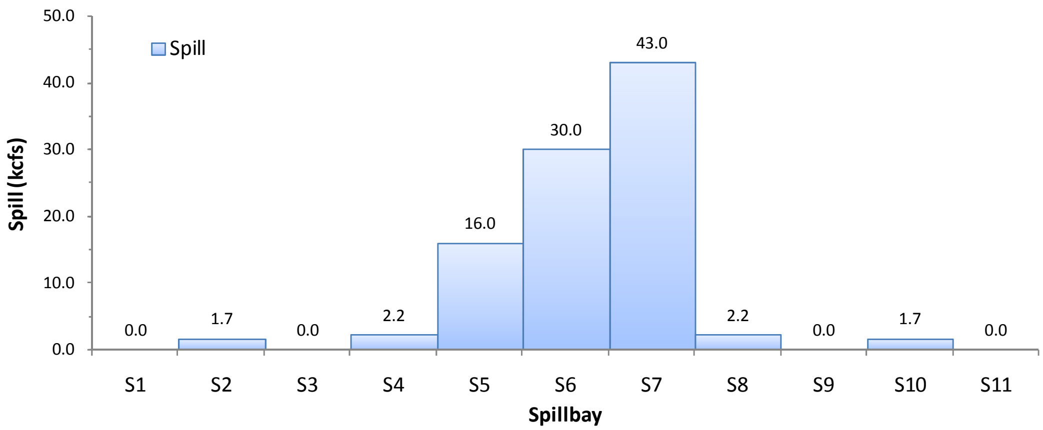

Figure 7. Operational configuration under forced spill > 96.0 kcfs (with removal of JBS barriers in *S6*). In this instance (96.8 kcfs of total spill), spill from *S5* is relocated to *S6* to maintain concentrated flow with *S7*. A spill of 16.0 kcfs is maintained in *S5* as to engage the spillway lip below the ogee.

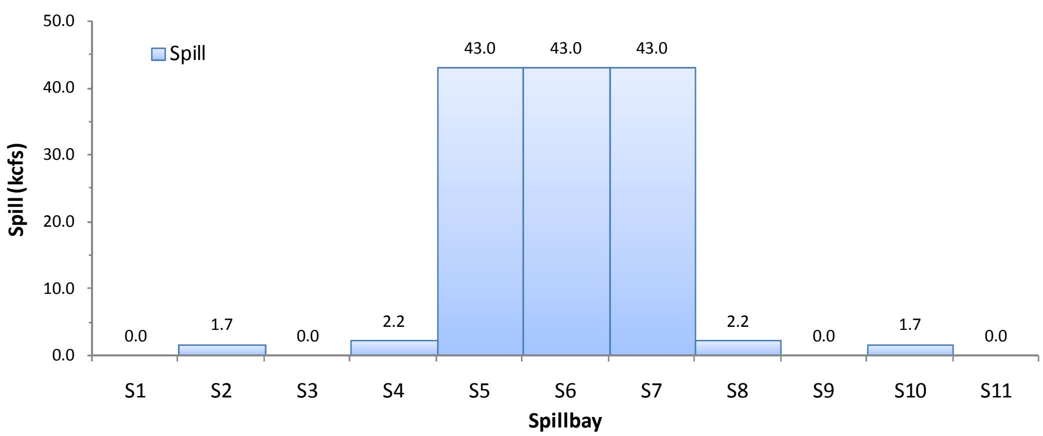

Figure 8. Operational configuration under forced spill > 96.0 kcfs (with removal of JBS barriers in *S6*). In this instance (136.8 kcfs of total spill), 43.0 kcfs is allocated through *S5*, *S7*, and *S9*.

VI. Forced Spill (> 139.0 kcfs)

Forced spill exceeding 139.0 kcfs rarely occurs (less than 0.5%). If these conditions arise and total river flow exceeds 246.0 kcfs, then 7Q-10 conditions are occurring and Wells Dam is exempt from the TDG standards. Under this situation, Project Operators may perform any combination of operations to ensure that flood waters are safely passed. Also, at this point, JBS barriers will likely be removed allowing additional flexibity to spill up to 43 kcfs through *S2*, *S4*, *S6*, and *S8*. Project Operators may pass spill through *S3* in a similar fashion to operations mentioned above (starting at a minimum of 15.0 kcfs to ensure that spillway lips are engaged).

I. Spill Lookup Table

Operation	Total Spill	Spillbay Number *S1* -	*S2* *JBS*	***S3***	*S4* *JBS*	***S5***	*S6* *JBS*	***S7***	*S8* *JBS*	***S9***	*S10* *JBS*	*S11* -
I. No Forced Spill	10.0	0.0	1.7	0.0	2.2	0.0	2.2	0.0	2.2	0.0	1.7	0.0
II. Spill (≤ 53.0 kcfs), min.	20.0	0.0	1.7	0.0	2.2	0.0	2.2	10.0	2.2	0.0	1.7	0.0
II. Spill (≤ 53.0 kcfs), max.	53.0	0.0	1.7	0.0	2.2	0.0	2.2	43.0	2.2	0.0	1.7	0.0
III. Spill (> 53.0 kcfs), min.	54.0	0.0	1.7	0.0	2.2	16.0	2.2	28.0	2.2	0.0	1.7	0.0
III. Spill (> 53.0 kcfs), max.	96.0	0.0	1.7	0.0	2.2	43.0	2.2	43.0	2.2	0.0	1.7	0.0
IV. Spill (> 96.0 kcfs), min.	97.0	0.0	1.7	0.0	2.2	28.0	2.2	43.0	2.2	16.0	1.7	0.0
IV. Spill (> 96.0 kcfs), max.	139.0	0.0	1.7	0.0	2.2	43.0	2.2	43.0	2.2	43.0	1.7	0.0
V. Spill (> 96.0 kcfs, *S6* JBS out), min.	96.8	0.0	1.7	0.0	2.2	16.0	30.0	43.0	2.2	0.0	1.7	0.0
V. Spill (> 96.0 kcfs, *S6* JBS out), max.	136.8	0.0	1.7	0.0	2.2	43.0	43.0	43.0	2.2	0.0	1.7	0.0
V. Spill (>139.0 kcfs), min.	140.0	0.0	1.7	16.0	2.2	43.0	2.2	43.0	2.2	28.0	1.7	0.0
V. Spill (>139.0 kcfs), max.	-	*Operators may adjust as needed.* *TDG exemption in place when total river flows exceed 246.0 kcfs.*										

Notes: (1) No spill through *S1* and *S11* as to minimize interference with fish ladders. (2) Even-numbered spillbays are designated as the Juvenile Bypass System (JBS). (3) Primary spillbays for forced spill are *S7*, *S5*, *S9*, and *S3* (in that order).

LGL (LGL Limited) and Douglas PUD. 2007. Wells Bull Trout Monitoring and Management Plan, 2006 Annual Report. Wells Hydroelectric Project FERC No. 2149.

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WELLS BULL TROUT MONITORING AND MANAGEMENT PLAN 2006 ANNUAL REPORT

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

March 30, 2007

Prepared by:
LGL Limited Environmental Research Associates
9768 Second Street
Sidney, BC CANADA V8L 3Y8

and

Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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ABSTRACT

The goal of the Wells Bull Trout Monitoring and Management Plan (WBTMMP) is to monitor and evaluate bull trout (*Salvelinus confluentus*) presence in the Wells Project and to quantify potential project-related impacts on bull trout. The plan has four main objectives.

The first objective of the plan is to "identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and implement appropriate measures to monitor any incidental take of bull trout." In order to meet the first objective of the WBTMMP, the Public Utility District No.1 of Douglas County (Douglas PUD) implemented a bull trout telemetry program to monitor upstream and downstream passage, and implemented an experimental off-season bull trout counting program during the winter. In 2006, 10 adult bull trout were trapped in the Wells Dam fishway, radio-tagged, and released upstream of the dam. Also in 2006, the US Fish and Wildlife Service (USFWS) radio-tagged and released 13 bull trout in the Methow; and the Public Utility District No. 1 of Chelan County (Chelan PUD) released 29 radio-tagged bull trout at Rock Island and Rocky Reach dams. In total, 13 downstream passage events and 8 upstream passage events were recorded, and there were no conclusive instances of bull trout mortality resulting from these passage events. Based on video monitoring data, upstream passage events were observed from 16 May to 12 July, with a peak on 31 May. In general, upstream passage events were more likely to take place between 11 AM and 8 PM and typically coincided with periods of highest total discharge. Off-season video monitoring of the Wells Dam fishways for the 2005-2006 winter period (November 16, 2005 to April 30, 2006) found no adult bull trout utilizing the fishway.

The second objective is to assess project-related impacts on upstream and downstream passage of sub-adult bull trout. To this end, sub-adult bull trout were PIT tagged opportunistically when encountered during standard fish sampling operations at the Project or during tributary smolt trapping activities. In 2006, no sub-adult bull trout were observed at the Project, but 20 sub-adults were opportunistically PIT-tagged during tributary smolt trapping operations. Off-season video monitoring of the Wells Dam fishways for the 2005-2006 winter period (November 16, 2005 to April 30, 2006) found no sub-adult bull trout utilizing the fishway.

The third objective is to investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of the Wells Reservoir. In 2006, this objective was addressed through a field survey of potential bull trout stranding sites conducted during a period of low reservoir elevation associated with the Methow River flood control program. High resolution bathymetric information in combination with Project information (reservoir elevations, backwater curves, inflow patterns) were used to identify potential stranding sites for the survey. No stranded bull trout (sub-adult or adult) were found during the 2006 field survey.

The fourth objective is to identify the Core Areas and Local Populations of those bull trout that utilize the Wells Project. In 2006, 10 genetic samples were collected from adult bull trout during radio-tagging operations at Wells Dam. Additionally, Douglas PUD also provides funding for genetic sampling (including PIT tagging) of adult and sub-adult bull trout captured from smolt trapping operations at locations outside of the Wells Project Boundary on the Twisp and Methow rivers (up to 10 genetic samples per location). Ten genetic samples were collected from these

off-Project operations in 2006. These samples will be analyzed and compared to genetic baseline data by the USFWS. Currently, such a genetic baseline has not yet been developed, and more work is required by the USFWS to generate useful information from the collected genetic data. However, for the 10 bull trout radio-tagged at Wells Dam in 2006, spawning stock information may be inferred, since all 10 were detected in spawning tributaries during spawning-season mobile surveys. Based on these mobile radio-telemetry surveys, the bull trout sampled at the Wells Dam fishways in 2006 appear to be 70% associated with the Methow River Core Area, and 30% associated with the Entiat River Core Area.

The WBTMMP is a multi-year plan for which tagging is scheduled each year from 2005 to 2007, and for which tracking will continue until 2008. This report represents the results of activities conducted in 2006.

1.0 INTRODUCTION

In August 1993, Douglas, Chelan, and Grant Public Utility Districts (collectively, "Mid-Columbia PUDs") initiated discussions to develop a long-term, comprehensive program for managing fish and wildlife that inhabit the mid-Columbia River basin (the portion of the Columbia River from the tailrace of Chief Joseph Dam to the confluence of the Yakima and Columbia rivers).

These discussions first explored the possibility of developing an ecosystem-based plan for managing fish and wildlife resources inhabiting the mid-Columbia River basin. Due to the immense breadth of this type of plan, the negotiating parties decided to focus on an agreement for aquatic species inhabiting the mid-Columbia River basin including fish, plants and animals. After extensive review, the negotiating parties further concluded, given the likelihood that certain species of salmon and steelhead would be listed in the near future under the Endangered Species Act (ESA) and given the lack of information regarding the other aquatic species, that the best basin-wide approach would be to develop an agreement for anadromous salmonids, specifically: spring, summer/fall Chinook salmon (*Oncorhynchus tshawytsha*); sockeye salmon (*O. nerka*); coho salmon (*O. kisutch*); and steelhead (*O. mykiss*) (collectively, "Plan Species") which are under the jurisdiction of the National Marine Fisheries Service (NMFS).

On July 30, 1998, the Public Utility District No. 1 of Douglas County (Douglas PUD), which operates the Wells Hydroelectric Project (Wells Project), submitted an unexecuted form of an Application for Approval of the Wells Anadromous Fish Agreement and Habitat Conservation Plan (the "HCP Agreement") to the Federal Energy and Regulatory Commission (FERC) and to NMFS. Furthermore, to expedite the ability of FERC to complete formal consultation, Douglas PUD prepared a biological evaluation of the effects of implementing the Habitat Conservation Plan (HCP) on listed species under the jurisdiction of the US Fish and Wildlife Service (USFWS).

In a letter to FERC, the USFWS requested consultation under Section 7 of the ESA regarding the effects of hydroelectric project operations on bull trout (*Salvelinus confluentus*) in the Columbia River (letter from M. Miller, USFWS, to M. Robinson, FERC, dated January 10, 2000). The request for consultation was based on observations of bull trout in the study area. In its reply to the USFWS, FERC noted that there was virtually no information on bull trout in the mainstem Columbia River.

On November 24, 2003, Douglas PUD filed an application for approval of the executed Wells HCP. The 2004 application for approval replaced the 1998 application with the executed form of the Wells HCP.

On December 10, 2003, the USFWS received a request from FERC for formal consultation to determine whether the proposed incorporation of the HCP Agreement into the FERC license for operation of the Wells Hydroelectric Project was likely to jeopardize the continued existence of the Columbia River distinct population segment (DPS) of ESA-listed bull trout, or destroy or adversely modify proposed bull trout critical habitat. In response to the FERC request, the USFWS submitted a Biological Opinion (BO) and issued an Incidental Take Permit (ITP) to

Douglas PUD. On June 21, 2004, FERC issued an order incorporating the HCP Agreement and the bull trout BO into the FERC license for the Wells Project. As requested by the new license article, Douglas PUD, in concert with the USFWS, developed and began to implement the Wells Bull Trout Monitoring and Management Plan (WBTMMP).

2.0 STUDY GOAL

The goal of the WBTMMP is to monitor and evaluate bull trout presence in the Wells Project and quantify and address, to the extent feasible, potential project-related impacts on bull trout from Project operations and facilities. The plan is designed specifically to (1) address ongoing project-related impacts through the life of the existing operating license; (2) provide consistency with recovery actions as outlined in the USFWS's draft bull trout recovery plan; and (3) monitor and minimize the extent of any incidental take of bull trout consistent with Section 7 of the Endangered Species Act.

The WBTMMP has four main objectives, specifically to (1) identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and implement appropriate measures to monitor any incidental take of bull trout; (2) assess similar impacts on sub-adult bull trout; (3) investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of Wells Reservoir; and (4) identify which Core Areas and Local Populations of bull trout utilize the Wells Project.

This report is divided into four parts. The first part consists of background information outlining the Plan's origin (Section 1.0 and Section 2.0). The second part provides a brief description of bull trout biology, life history, and their status under the Endangered Species Act (Section 3.0). The third part provides a description of the Wells Project study site including background regarding previous bull trout studies at Wells Dam (Section 4.0). The fourth part describes the strategies used by Douglas PUD to address the four objectives of the plan, the methods used, the results observed to 31 Jan 2007, and a brief discussion of ongoing and future work (Section 5.0 and 6.0).

3.0 BULL TROUT BIOLOGY AND STATUS

Bull trout are native to northwestern North America, historically occupying a large geographic range extending from California north into the Yukon and Northwest Territories of Canada, and east to western Montana and Alberta (Cavender 1978). They are generally found in interior drainages, but also occur on the Pacific Coast in Puget Sound and in the large drainages of British Columbia.

Bull trout currently occur in lakes, rivers and tributaries in Washington, Montana, Idaho, Oregon (including the Klamath River basin), Nevada, two Canadian Provinces (British Columbia and Alberta), and several cross-boundary drainages in extreme southeast Alaska. East of the Continental Divide, bull trout are found in the headwaters of the Saskatchewan River in Alberta, and the McKenzie River system in Alberta and British Columbia (Cavender 1978; McPhail and Baxter 1996; Brewin and Brewin 1997). The remaining distribution of bull trout is highly fragmented.

Bull trout are members of the char group within the family Salmonidae. Bull trout closely resemble Dolly Varden (*Salvelinus malma*), a related species. However, genetic analyses indicate that bull trout are more closely related to an Asian char (*S. leucomaenis*) than to Dolly Varden (Pleyte et al. 1992). Bull trout are sympatric with Dolly Varden over part of their range, most notably in British Columbia and the Coastal-Puget Sound region of Washington State.

Bull trout are believed to have more specific habitat requirements than other salmonids (Rieman and McIntyre 1993). Growth, survival, and long-term persistence are dependent upon habitat characteristics such as cold water, complex instream habitat, a stable substrate with a low percentage of fine sediments, high channel stability, and stream/population connectivity. Stream temperature and substrate type, in particular, are critical factors for the sustained long-term persistence of bull trout. Spawning is often associated with the coldest, cleanest, and most complex stream reaches within basins. However, bull trout may exhibit a patchy distribution, even in pristine habitats (Rieman and McIntyre 1995), and should not be expected to occupy all available habitats at the same time (Rieman et al. 1997).

Bull trout exhibit four distinct life history types: resident, fluvial, adfluvial, and anadromous. The resident, fluvial and adfluvial forms exist throughout the range of the bull trout (Rieman and McIntyre 1993). These forms spend their entire life in freshwater. The anadromous life history form is currently known only to occur in the Coastal-Puget Sound region within the coterminous United States (Volk 2000; Mongillo 1993). Multiple life history types may be expressed in the same population, and this diversity of life history types is considered important to the stability and viability of bull trout populations (Rieman and McIntyre 1993).

The majority of growth and maturation for anadromous bull trout occurs in estuarine and marine waters, adfluvial bull trout in lakes or reservoirs, and fluvial bull trout in large river systems. Resident bull trout populations are generally found in small headwater streams where fish remain their entire lives.

For migratory life history types, juveniles tend to rear in tributary streams for 1 to 4 years before migrating downstream into a larger river, lake, or estuary and/or nearshore marine area to mature (Rieman and McIntyre 1993). In some lake systems, age 0+ fish (less than 1 year old) may migrate directly to lakes (Riehle et al. 1997). Juvenile and adult bull trout in streams frequently inhabit side channels, stream margins and pools with suitable cover (Sexauer and James 1993) and areas with cold hyporheic zones or groundwater upwellings (Baxter and Hauer 2000).

3.1 Bull Trout Status

On June 10, 1998, the USFWS listed bull trout within the Columbia River basin as threatened under the Endangered Species Act (FR 63(111)). Later (November 1, 1999), the USFWS listed bull trout within the coterminous United States as threatened under the ESA (FR 63(111)). The USFWS identified habitat degradation, fragmentation and alterations associated with dewatering, road construction and maintenance, mining, and grazing; blockage of migratory corridors by dams or other diversion structures; poor water quality; incidental angler harvest; entrainment into diversion channels; and introduced non-native species as major factors affecting the distribution and abundance of bull trout. They noted that dams (and natural barriers) have isolated population segments resulting in a loss of genetic exchange among these segments (FR 63(111)). The USFWS believes many populations are now isolated and disjunct.

In October 2002, the USFWS completed the first draft of a bull trout recovery plan intended to provide information and guidance to lead to recovery of the species, including its habitat. Threatened bull trout population segments are widely distributed over a large area and because population segments were subject to listing at different times, the USFWS adopted a two-tiered approach to develop the draft recovery plan for bull trout (USFWS 2002).

The first tier addressed broad aspects of bull trout recovery that apply at the level of Distinct Population Segments. The USFWS, identified the Columbia River, Coastal-Puget Sound, St. Mary-Belly River, Jarbidge River, and the Klamath River as Distinct Population Segments. The second tier addressed bull trout recovery in smaller areas, such as specific river basins or collections of river basins within population segments, termed "recovery units." There are 22 recovery units in the Columbia River, 1 in the Klamath River, 1 in the Jarbidge River, 1 in the St. Mary-Belly River, and 2 in the Coastal-Puget Distinct Population Segment (USFWS 2002).

The State of Washington contains the Coastal-Puget Sound Distinct Population Segment and is a part of the larger Columbia River Distinct Population Segment. In total, there are 9 recovery units within the state; the Olympic Peninsula, Puget Sound, Lower Columbia River, Middle Columbia River, Upper Columbia River, Northeast Washington, and portions of the Snake River, Umatilla-Walla Walla River and Clark Fork River Recovery Unit.

The Wells Project is situated within the Upper Columbia River Recovery Unit and the USFWS has identified the Wenatchee, Entiat, and Methow rivers as its core areas. A core area represents the closest approximation of a biologically functioning unit for bull trout. Within a core area, many local populations may exist. A local population is assumed to be the smallest group of fish that is known to represent an interacting reproductive unit. Nineteen Local Populations were identified in the Wenatchee (7), Entiat (2) and Methow (10) Core Areas (Judy DelaVergne, Pers. Comm.).

4.0 STUDY AREA

The Wells Hydroelectric Project is located on the mainstem Columbia River at RM 515.6. The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from Wells Dam. The dam spans 4,460 feet, with the hydro-combine structure (spillway, turbine and fishways combined into one structure) comprising 1,130 feet. Wells Dam is a 185 foot high concrete gravity dam completed in 1967. The reservoir formed by the Project extends upstream 29.5 miles past the cities of Pateros, Brewster and Bridgeport and up to the Army Corps of Engineer's Chief Joseph Dam, totaling 331,200 acre feet of water, and having a surface area of 9,740 acres at the normal maximum reservoir elevation of 781 feet above msl.

The Project includes a spillway, powerhouse, an earthen embankment section, a juvenile bypass system and two adult fishways. The spillway consists of 11 spillway gates with a combined capacity of 1,180 kcfs. The powerhouse has 10 Kaplan turbine units, equipped with minimum gap turbine runners to increase protection for juvenile salmonids during turbine passage, with a combined hydraulic capacity of 205 kcfs and a peak generating capacity of 840,000 kW of electricity. The two adult fishways are mirror image left and right bank fishway facilities. Each of the two fishways contains a single main entrance, a collection gallery, a fish ladder, adult count station, trapping facilities and an exit in the forebay. The juvenile bypass system utilizes five of the existing spill bays and consists of five evenly spaced surface collector entrances that guide fish into and through the juvenile bypass system and into the tailrace of the dam.

4.1 Previous Bull Trout Study at Wells Dam

Columbia River bull trout have been observed and counted at Wells Dam since 1998. In 2000 the USFWS requested that the mid-Columbia PUDs evaluate the status of bull trout in their respective project areas. This request was due to the potential for operations at the mid-Columbia PUD dams to affect the movement and survival of bull trout. At that time, little was known about the life-history characteristics (e.g., movements, distribution, habitat use, etc.) of bull trout in the mid-Columbia River. Therefore, in order to assess the operational effects of hydroelectric projects on bull trout within the mid-Columbia, a three PUD (Grant, Chelan and Douglas PUDs) radio-telemetry study was implemented beginning in 2001 (BioAnalysts 2004). The goal of the study was to monitor the movements and migration patterns of adult bull trout in the mid-Columbia River. The number of bull trout collected and tagged at each dam (Rock Island, Rocky Reach, and Wells) was based on the proportion of fish that migrated past those dams in 2000. Radio tags were applied to bull trout during their upstream migrations in 2001 and 2002.

Bull trout at Wells Dam were trapped at the brood-stock collection facility located within the left bank fish ladder. Bull trout > 40 cm were anesthetized, weighed, measured and radio tags were inserted into the peritoneal cavity using surgical procedures similar to those described in Summerfelt and Smith (1990). After recovery from sedation, the fish were released. In order to increase the sample size of fish ascending the ladder system, half of the radio-tagged fish were released downstream of the dam. The remaining radio-tagged fish were released upstream from the dam, as close to the dam as possible, yet outside of the influence of the forebay hydraulics (including spill and bypass entrainment flows). A combination of aerial and underwater antennas were deployed in order to document the presence of bull trout at the Project, identify passage times and determine their direction of travel (upstream/downstream). Additional telemetry systems were deployed to monitor behavior in the fish ladders. All possible access points to the adult fish ladders and the exits were monitored individually in 2001, 2002 and 2003, allowing the route of passage to be determined as well as the exact time of entrance and exit from the ladder system. English et al. (1998, 2001) provided a detailed description of the telemetry systems at each of the dams and within the tributaries. To assess bull trout movements into and out of the Wells Reservoir, fixed-station telemetry monitoring sites were established at the mouth of the Methow and Okanogan rivers and periodic aerial surveys were conducted on the reservoir and throughout both watersheds (see English et al. 1998, 2001).

The key findings of these previous studies (BioAnalysts 2004) were:

- Total upstream fishway counts (May 1st to November 15th) at Wells Dam from 2000 to 2003 were 90, 107, 76, and 53 bull trout, respectively. Bull trout migrating upstream through Wells Dam in 2001 were 5 year old (n=2, mean fork length=55.6cm) and 6 year old (n=6, mean fork length= 54.6cm) fish as determined by scales.

- Adult bull trout made migrations upstream through Wells Dam from May through November. Peak movement occurred in May and June with 94, 95, 92, and 89 percent of adult bull trout being detected during these months at Wells Dam for years 2000-2003, respectively.
- Tagged migratory adult bull trout successfully moved both upstream and downstream past the Project. Five radio-tagged bull trout passed downstream through Wells Dam, four through Rocky Reach, and eight through Rock Island from 2001 to 2003. None of the downstream passage events resulted in mortality to bull trout.
- Median Wells tailrace occupancy times in 2001-2003 were 1.53, 7.84, and 1.00 days, respectively. Median Wells fishway passage times in 2001-2003 were 8.87, 7.60, and 1.16 days, respectively. Median Wells ladder passage times in 2001-2003 were 5.70, 0.23, and 0.16 days, respectively.
- Adult bull trout migrating upstream of Wells Dam were destined for the Methow River. Between 2001-2003, no bull trout selected the Okanogan system (one trout moved into the Okanogan, but left shortly thereafter and moved into the Methow system).
- Median travel time from Wells Dam (ladder exit) to the Methow River in 2001-2003 was 0.40, 2.78, and 1.09 days, respectively.
- All 28 tributary entrance events occurred before June 27. Bull trout in the Methow system selected two primary areas, the mainstem Methow River and the Twisp River.
- 30% of bull trout that entered the Methow River have been detected leaving the system. Tributary exit dates were recorded for 78% of these emigrating bull trout and 86% of these left the Methow River system between Oct-Dec.
- It appears that no radio tagged bull trout were injured at the dams or in the reservoirs due to project effects during telemetry monitoring in 2001, 2002, and 2003.
- 92% and 53% of tagged bull trout detected in the vicinity of Wells Dam entered the Wells Hatchery Outfall in 2001 and 2002, respectively, possibly in search of prey near the hatchery outfall.

5.0 WELLS BULL TROUT MONITORING AND MANAGEMENT PLAN

The goal of the WBTMMP is to identify, develop, and implement measures to monitor and address potential project-related impacts on bull trout from Wells Project operations and facilities. This plan is intended to be an adaptive approach, where strategies for meeting the goals and objectives may be negotiated under a collaborative effort with the USFWS based on new information and ongoing monitoring results.

Through monitoring and implementation of WBTMMP measures, this plan's goals are designed specifically to: (1) address ongoing project-related impacts through the life of the existing operating license; (2) provide consistency with recovery actions as outlined in the USFWS's draft bull trout recovery plan; and (3) monitor and minimize the extent of any incidental take of bull trout consistent with Section 7 of the Endangered Species Act.

Douglas PUD has committed to use the management strategies outlined in this section to meet the protection, monitoring, and evaluation (PME) measures outlined in the 2004 BO for bull trout; and will simultaneously address potential project-related impacts on bull trout for the duration of the existing license as required by license articles 61, 62 & 63. The PME measures will also be consistent with the USFWS's overall bull trout recovery plan and with Section 7 of the Endangered Species Act.

The WBTMMP has four main objectives. Specifically, these are to: (1) identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and implement appropriate measures to monitor any incidental take of bull trout; (2) assess similar impacts on sub-adult bull trout; (3) investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of the Wells Reservoir; and (4) identify which Core Areas and Local Populations of bull trout utilize the Project area. Each of these four objectives is treated separately below.

5.1 Objective 1

The first objective was to identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and implement appropriate measures to monitor any incidental take of bull trout. This objective was addressed using four strategies: (1) an adult bull trout telemetry program was implemented to monitor adult upstream and downstream passage in the Wells Project and to monitor any incidental take of bull trout; (2) passage results and operational data were analyzed to determine if correlations exist between passage times and passage events and project operations; (3) video monitoring was used to determine off-season adult bull trout passage through the adult fishways at Wells Dam; and (4) should upstream or downstream passage problems be identified, to assess the feasibility of options to modify upstream passage facilities or operations that reduce the impact to bull trout passage.

5.1.1 Strategy 1-1: Adult bull trout telemetry program

The adult bull trout telemetry program has several main goals. First, the program would allow monitoring of bull trout movements in the Wells Project, including the timing and frequency of upstream and downstream passage events (and associated survival rates). Second, the program allowed for monitoring of any incidental take. Finally, the program also supported several of the other objectives of the WBTMMP. For example, the program provided genetic samples of the radio-tagged bull trout (in support of strategy 4-1), and provided data on the timing and frequency of movements into and out of spawning tributaries (in support of strategy 4-2). In brief, the program involves the capture and radio-tagging of 10 adult bull trout each year for three years (May 2005 through July 2007), and tracking until 2008. Details of methodology and results are presented below.

5.1.1.1 Tagging

Bull trout at Wells Dam were trapped using the brood-stock collection facilities located within the East and West fishways. Trapping operations occurred during the peak of the bull trout passage period. The majority of the trapping occurred in the East fishway, though the West fishway trap was used periodically in both 2005 (LGL and Douglas PUD 2006) and 2006 (Table 1).

In 2006, trapping occurred in the East fishway for 6 days per week, and for 8 hours per day. In addition, the Washington Department of Fish and Wildlife (WDFW) operated the West ladder trap one 24 hour period of every three day period for Chinook brood-stock collection. Bull trout were tagged opportunistically from the West ladder (Table 1). The brood-stock collection facilities were located at pool 40 approximately half way up each fish ladder. The traps were operated by placing a barrier fence across the entire width of the pool. When a trap was in operation, all fish attempting to ascend the ladder were forced to ascend a steep-pass denil into an upwell enclosure, and then down a sorting chute. When a bull trout was observed in the sorting chute, it was redirected into a holding facility; whereas non-target species were shunted back to the ladder upstream of the trapping barrier. When a bull trout was observed in the West ladder sorting chute, a technician activated a pneumatic gate diverting the fish into the Wells Hatchery brood stock collection pond. In the East ladder, bull trout were pneumatically diverted into a 1236 L holding tank. The fish ladder supplied the East ladder holding tank with freshwater at a rate of 24 L/min to maintain adequate dissolved oxygen and temperature levels. For details of the 2005 tagging efforts, see the 2005 WBTMMP Annual Report (LGL and Douglas PUD 2006).

Bull trout collected in the East ladder were tagged immediately after capture. Those collected in the West ladder were tagged at the end of the 24 hour trapping session when the hatchery pond was processed for fish. Bull trout captured on the West ladder were subsequently transported over to the East ladder tagging facility. The collected bull trout were netted from the holding tank and transferred to an anesthetic vessel containing an 90 mg/L solution of tricaine methanesulfonate (MS-222) and a few drops of Stress Coat (Aquarium Pharmaceuticals, Inc. Chalfont, PA). After 1.5 to 2 minutes, the fish lost equilibrium and was considered to be adequately anesthetized. The fish was then removed from the solution, weighed, measured, and placed in a wet V-shaped trough (coated with Stress Coat to minimize scale loss and maintain the exterior mucous coat) for further processing. A tube was placed in the fish's mouth, supplying cool river water and MS-222 (45 mg/L), flushing the gills, and maintaining unconsciousness during the procedure. A small (1 cm^2) clip was taken from the upper lobe of the caudal fin, and placed in non-denatured alcohol to be sent to the USFWS for genetic analyses. Four to five scales were removed from the area above the lateral line (adjacent to the "line" between the end of the dorsal fin and the start of the anal fin), and placed in a scale book to be sent to the WDFW for aging analyses. For sub-adults, (bull trout smaller than 40 cm), a Passive Integrated Transponder (PIT) tag was injected into the dorsal musculature, and the fish was released back into the fish ladder (upstream of the trapping barrier). Larger fish were PIT and radio-tagged as described below.

Surgical procedures were similar to those described in Adams et al. (1998), Martinelli et al. (1998), and Summerfelt and Smith (1990). A 3-4 cm incision was made 2 cm away from and parallel to the mid-ventral line starting approximately 3 cm anterior to the pelvic girdle (and only deep enough to penetrate the peritoneum). A PIT tag was placed into the body cavity. A shielded-needle catheter was then inserted through the incision, posteriorly between the pelvic girdle and viscera, to a point 5-10 cm off-center from the mid-ventral line and posterior to the origin of the pelvic fins. The catheter was then pulled back onto the needle shaft, exposing the point of the needle. Pressure was then applied until both the needle and catheter pierced the skin of the fish. The needle was pulled back out of the incision, leaving the catheter in position to guide the transmitter antenna through the body wall of the fish.

Table 1. Timing of trap operations and catch of bull trout at Wells Dam, 2006.

EAST LADDER

Day	Date	Open	Close	Duration (h)	Catch
Sunday	14 May	10:00 AM	6:00 PM	8.0	
Monday	15 May	10:00 AM	6:00 PM	8.0	
Tuesday	16 May	10:00 AM	6:00 PM	8.0	
Wednesday	17 May	10:00 AM	6:00 PM	8.0	
Thursday	18 May	10:00 AM	6:00 PM	8.0	1
Friday	19 May	10:00 AM	6:00 PM	8.0	1
Saturday	20 May			0.0	
Sunday	21 May	9:00 AM	5:00 PM	8.0	1
Monday	22 May	9:00 AM	5:00 PM	8.0	
Tuesday	23 May	9:00 AM	5:00 PM	8.0	
Wednesday	24 May	9:00 AM	1:50 PM	4.8	4
	TOTAL CATCH				**7 Bull Trout**
	Total Op Time				**76.83 h**

WEST LADDER

Day	Date	Open	Close	Duration (h)	Catch
Sunday	14 May			0.0	
Monday	15 May	11:00 AM	12:00 AM	13.0	
Tuesday	16 May	12:00 AM	8:00 AM	8.0	2
Wednesday	17 May			0.0	
Thursday	18 May	8:15 AM	12:00 AM	15.8	
Friday	19 May	12:00 AM	8:15 AM	8.3	1
Saturday	20 May			0.0	
Sunday	21 May	8:00 AM	12:00 AM	16.0	
Monday	22 May	12:00 AM	8:00 AM	8.0	
Tuesday	23 May			0.0	
Wednesday	24 May			0.0	
	TOTAL CATCH				**3 Bull Trout**
	Total Op Time				**69.00 h**

The radio transmitter was implanted by first threading the antenna through the incision end of the catheter. Both the antenna and catheter were then gently pulled posteriorly while the transmitter was inserted into the body cavity through the incision. The position of the transmitter inside the fish was adjusted by gently pulling on the antenna until the transmitter was resting horizontally in the body cavity directly under the incision. An intraperitoneal antibiotic was pipetted (50 μL) into the incision to prevent infection. The incision was closed with four to five interrupted, absorbable sutures (3-0 braided Coated Vicryl and taper RB-1 needle, Ethicon Corp.) evenly spaced across the incision. The antenna was then attached to the side of the fish with a single suture approximately 1 cm posterior to the antenna exit site. The incision site was cleaned, and a small amount of a cyanoadhesive compound (Vetbond) was applied to the incision and antenna exit site to secure the sutures in place. The fish was then transferred to a recovery tank (a cooler, supplied with flow-through river-water, and supplied with oxygen through an air stone) located on the back of a pickup truck. Note that approximately one minute before the procedure was complete, the MS-222 was removed from the water flushing over the gills to begin the recovery process. Surgical equipment was disinfected with a diluted germicidal solution before and after each fish.

After the surgical procedure was complete, the flow-though water was detached from the recovery tank, and the fish was quickly transported to the release site. At the release site, the air stone was removed and the recovery tank was placed into the river. The tank was gently rolled onto its side and the lid was opened allowing the fish to swim free of the vessel. The swimming behavior of the fish was observed and any abnormalities were noted. All fish were released at the Starr Boat Ramp, which was as close to the dam as possible, while still outside of the influence of the forebay hydraulics (including spill and bypass entrainment flows). All tagged fish, released upstream of Wells Dam, were counted as a successful adult fishway passage event for the year it was tagged.

The goal was to tag and release 10 adult bull trout each year from 2005-2007. This number represents approximately 13% of the average annual ladder counts from May to July, 2000 to 2003. To increase sample size, it was decided to monitor the radio-tagged bull trout that were released by the USFWS in the Methow in 2006 (n=13), and those that were released by the Public Utility District No. 1 of Chelan County (Chelan PUD) at Rock Island and Rocky Reach dams in 2005 (n=38) and 2006 (n=29).

A variety of tag types were used to track bull trout in the mid-Columbia during the study period. Chelan PUD tagged bull trout using coded transmitters manufactured by Lotek. In 2005, Douglas PUD tagged bull trout using similar tags, but from a different manufacturer (Grant Systems Engineering). In 2006, Douglas PUD and the USFWS both used motion-sensor coded transmitters manufactured by Lotek. These transmitters changed their broadcast code if the tag remained motionless for 24 hours. For this study, the “motionless” signal was assumed to indicate the death of the fish or the expulsion of the tag. Tags were programmed to have mid-range motion sensitivity, which was shown during Lotek field tests (Lotek, unpublished data) to be most suitable to detect the death of fish.

Battery life for all tags was approximately two-years, but because of variable tag retention times in individual fish, and inherent inconsistencies in transmitter battery life, take levels were calculated using data from only the first year (365 days) of tag life for each tagged fish. Tag detections occurring outside of this period were not used for take monitoring, but were compiled (through July 2008) to assist the USFWS with characterizing movements of bull trout in the mainstem (Douglas PUD, 2004).

5.1.1.2 Telemetric monitoring

A combination of aerial and underwater antennas were used to document the presence of bull trout at the Project, identify passage times and determine their direction of travel (upstream/downstream). Three aerial antennas monitored the mainstem Columbia River 3 miles downstream of the dam to detect any movements of bull trout out of the study area. Two aerial stations, located immediately downstream of the dam on each side of the river, monitored movements within the Wells tailrace. Five combined aerial antennas monitored movements in the Wells forebay. Underwater dipole arrays were deployed into each of five spillbays (2, 4, 6, 8, and 10) where spring/summer bypass spill is typically released. In each spillbay, a dipole antenna was mounted on each of the left and right bulkhead tracks at approximately 10 ft off the bottom of the spill intake floor. In addition, on gates 2 and 10, paired dipole antennas were deployed approximately 10 ft below the water surface to monitor spill water passing via the sluice gates. Finally, nine underwater antennas were deployed within each fishway to monitor bull trout approach, ascent, and exit timing. To assess bull trout movements into and out of the Wells Reservoir, fixed-telemetry monitoring sites were established at the mouth of the Methow and Okanogan rivers. For each tributary, a pair of antennas were deployed, one facing upstream and one facing downstream, in order to determine the direction of fish movements within the tributary. English et al. (1998, 2001) provided a description of the typical telemetry systems setup for Wells Dam and at the mouths of tributaries.

Radio-tagged bull trout were tracked while in the Wells Project (dam and reservoir) until a tributary entrance was observed, and after reservoir re-entry. Fixed-station receiver sites were operated to detect any upstream and downstream movement at tributary entrances. Periodic mobile tracking methods were also used to confirm the presence of bull trout within tributaries and to track fish within the reservoirs (Table 2 - Table 4). Mobile methods included aircraft, boat, vehicle and/or foot surveys.

Tracking data were compiled continuously throughout the year to determine fish locations, tag status, and the need to deploy tag recovery operations in the Wells Project. Douglas PUD sponsored tracks in the Wells Dam reservoir and surrounding areas (Table 2). The USFWS conducted several mobile surveys of the Methow River Core Area (Table 3), and provided Douglas PUD with the location and date of any records of bull trout detections. Similarly, Chelan PUD monitored Douglas PUD bull trout frequencies during several of their mobile tracks in the Entiat and the Wenatchee systems (Table 4).

Table 2. Dates and locations of Douglas PUD sponsored mobile tracks of the Wells Dam reservoir and surrounding areas, 2006.

Date	Survey Type	Location	Tags Detected
9 May 2006	Truck	Wells forebay, Methow to old hatchery	none
23 May 2006	Boat	Wells tailrace to gateway	none
23 May 2006	Truck	Wells forebay, Methow to old hatchery	11,12,13,15,16
19 Sep 2006	Boat	Wells Tailrace	one non-DCPUD tag
21 Dec 2006	Boat	Wells tailrace to Beebe Bridge	11,20, one non-DCPUD tag

Table 3. Mobile tracks performed by the U.S. Fish and Wildlife Service (USFWS) for which Douglas PUD bull trout tags were detected in 2006. Survey types are not known by date, but the USFWS performed a total of 60 truck and foot surveys.

Date	Locations	DPUD Tags Detected
20 Apr 2006	Columbia	3
11 May 2006	Columbia	2
1 Jun 2006	Columbia	14
5 Jun 2006	Columbia, Methow	2,11,12,15,16,17,18,20
6 Jul 2006	Methow	20
7 Jul 2006	Entiat	13,17,19
12 Jul 2006	Goat Creek	16
13 Jul 2006	Twisp	2,11,12,14,15,18
21 Jul 2006	Entiat	13,17,19
11 Oct 2006	Methow, Twisp	2,11,12,14,15,16,18,20
19 Oct 2006	Methow	11,12

Table 4. Dates and locations of Chelan PUD mobile tracks that monitored the Douglas PUD bull trout tag frequencies in 2006.

Date	Survey Type	Locations	DPUD Tags Detected
19 Sep 2006	Aerial	Columbia, Wenatchee, Entiat (a), Methow (b)	a: 13, 19; b: 12, 20
30 Nov 2006	Boat	RR reservoir (RR Dam to Beebe Bridge); 1/2 of RI reservoir.	none
1 Dec 2006	Boat	Rest of RI reservoir; WAN reservoir (Crescent Bar to RI Dam)	none
20 Dec 2006	Aerial	Columbia, Wenatchee, Entiat, Mad	none
10 Jan 2007	Boat	Columbia mainstem (RI to Wells)	none
11 Jan 2007	Boat	Columbia mainstem (RI to Cresent Bar)	none
24 Jan 2007	Aerial	Columbia, Wenatchee, Entiat, Mad	none

Aerial surveys typically included the Columbia River (from Rock Island Dam to Wells Dam), the Wenatchee River (from the confluence to the lake), the Entiat River (from the confluence to Entiat Falls), and the Mad River (from Maverick Saddle to the confluence), but were dependent upon weather conditions. Boat surveys typically surveyed both Rocky Reach and Rock Island reservoirs in their entirety, but were dependent upon weather conditions and time constraints.

5.1.1.3 Data processing

Fish detection data were downloaded from the Lotek receivers a minimum of two times per month, and more often if receiver memory began to exceed capacity prior to the scheduled downloads. In addition, telemetry systems (i.e., antennas, amplifiers, power inserters and receivers) were tested periodically during the study period to ensure they were operational and functioning correctly.

Data logged by the Lotek receivers were downloaded to a laptop computer as hex-encoded files, which were converted to standard ASCII format using software developed by LGL Limited. This software assessed several diagnostics, including the number of invalid records. If the number of invalid records was large, the receiver was downloaded a second time. The program also displayed the distribution of antenna noise by power level, so that problems with specific antennas could be isolated, and the appropriate troubleshooting measures could be taken. Data files were then uploaded to the LGL FTP site and subsequently downloaded by staff at the LGL Limited office.

Data processing throughout the study period were performed using Telemetry Manager Version 3.0, and other computer programs developed in Visual FoxPro by LGL Limited. The Telemetry Manager imported raw ASCII data files downloaded from the Lotek SRX receivers, and constructed an initial database containing records for each logged data transmission from the tagged fish. The Telemetry Manager then edited the database to remove records that did not meet the criteria identified for valid data records. Examples of invalid data included background noise at the Project, records with a signal strength that is below a set threshold, single records for a given frequency-code-location combination, and records that were recorded before the official release time and date. The Telemetry Manager then constructed an operational database that summarized the time of arrival and departure from each zone of interest. Queries of the operational database specified subsets of tagged fish for use in specific comparisons and analyses.

5.1.1.4 Data analyses

At the end of the present study, upstream and downstream passage results will be included to calculate a long-term average incidental take level for the Project. The long-term average take will be calculated by averaging the annual observed take levels for two bull trout studies (i.e., the present study will be combined with data collected from 2001 to 2003 (BioAnalysts 2004)). Total Project effect will be calculated for each passage route where feasible, by dividing the number of tagged fish “taken” via that route, by the total number of radio tagged fish. Data from each of the Douglas PUD bull trout studies will be evaluated in this manner, and at the conclusion of the present study (2008), the results from all of the previous years of monitoring will be averaged to determine the Project’s take level.

The incidental take for each passage route (if any and if feasible) is to be estimated by the number of observed mortalities to tagged fish that are attributable to that passage route divided by the total number of tagged fish known to have passed through that route. If the passage route was unknown, the route determination would default to downstream passage through the dam. If any take occurred, a statistical analysis would be used to detect if the level of incidental take for each passage route (and for the total project) exceeds the anticipated incidental take level as documented in the applicable USFWS biological opinion. The statistical analysis would be a one-tailed test of the hypothesis that the anticipated incidental take level is not exceeded.

If Project effects were shown to be negligible as measured by incidental take monitoring, then the monitoring program will be repeated on a ten year interval, as described in the WBTMMP.

5.1.1.5 Douglas PUD 2006 Tagging Results

Trapping efforts to target bull trout began on 14 May 2006, and continued for six days a week (8 hours per day) until the tenth bull trout was tagged on 24 May (Table 1). In total, 145.8 trap-hours of effort were expended, including 76.8 and 69 hours at the East and West ladders, respectively.

The radio-tagged bull trout ranged from 43 to 70 cm in fork length, and from 1.0 to 5.2 kg in weight. For the first and eighth fish, 1.0 h elapsed between the start of surgery and release, but for all other fish, the procedure took less than 35 minutes (avg. 29 minutes).

The detection histories of the 10 radio-tagged bull trout (Table 5) were as follows:

- Fish 1-56 was released on 16 May at 2:10 PM. This fish was detected between Lion Rock and the mouth of the Methow at 4:12 PM during a mobile survey on 23 May. On May 27, Fish 1-56 was detected moving upstream past the receiver in the mouth of the Methow River. It was detected on the downstream-facing antennas from 2:39 to 2:44 PM, and on the upstream-facing antenna from 2:53 PM until 3:12 PM. The fish was seen during a USFWS mobile track on 5 June at Methow River Mile 3, and again 13 July in the Twisp downstream of Reynolds Creek. Fish 1-56 moved from the Twisp into the Methow, where it was detected on 11 Oct about 5 miles downstream of Twisp. The fish was detected in the lower Methow (river mile 32) during a USFWS mobile survey on 19 Oct, 9 Nov, and 16 Nov. On 17 Nov, the fish passed the Methow fixed station moving downstream. On 18 Nov, it was detected in the Wells forebay from 12:18 to 3:36 PM. Its next detections were on 19 Nov (7 AM – 8 PM) at the Wells gateway station. Therefore, the downstream passage event occurred on 18 or 19 Nov. Since there was no spill at the time of passage, the fish must have passed via a turbine. Fish 11 was next detected on 21 Dec 2006 near Beebe Bridge, and again on 24 Jan 2007. These data show that Fish 1-56 survived passage downstream through Wells Dam.
- Fish 1-52 was released on 16 May at 2:12 PM. This fish was detected between Lion Rock and the mouth of the Methow at 4:12 PM during a mobile survey on 23 May. Fish 1-52 was detected moving upstream past the receiver in the mouth of the Methow River. It was detected at the mouth of the Methow from 31 May to 4 June. The fish was detected during a USFWS mobile track on 5 June near US 97 Bridge. Subsequently, the fish moved back to the mouth from 6 June at midnight until 7 June at 1 AM. On 13 July, it was detected between War Creek and Mystery Campground during a USFWS mobile survey of the Twisp River. Fish 1-52 moved from the Twisp to the Methow River, and was detected on 19 Sept just north of the town of Carlton, and on 11 Oct near the town of Methow. On 1 Nov, this fish was detected moving downstream past the Methow fixed station.

- Fish 1-68 was released on 18 May at 2:55 PM. Fish 1-68 was detected at 5 PM on 21 May in the Wells forebay; and a few minutes later, it was in the Wells tailrace. Therefore, the downstream passage event occurred on 21 May. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. This fish was detected downstream of the United States Geological Survey (USGS) Gauging Station (just downstream of the Wells tailrace) during a 23 May mobile survey. On 24 May, this fish was detected in the Wells tailrace between 4:20 and 7:24. It was then detected in the gateway area downstream of Wells from May 24 (8 PM) until May 25 (noon). By 5 PM on 25 May, the fish was back in the tailrace, where it moved into the right fish ladder up to the first weir. By 26 May at 5 PM, it was back in the tailrace, and by 11 PM on 27 May, it was back in the gateway area. At noon on 28 May, it was again in the tailrace area, where it explored both fishways as far as the first wall. By May 31 at 3 PM, it was back in the tailrace again. The fish was detected from 11:30 PM until midnight in the gateway area. On 25 June, this fish was detected at the USFWS fixed-station at the junction of the Entiat and Mad Rivers. On 7 July, this fish was detected at mile 29 of the Entiat River during a mobile survey conducted by the USFWS. It was detected again in the Entiat on 21 July, 19 September, 19 October, and near the mouth on 2 Nov. Fish 1-68 was next detected outside of the Entiat. It was detected on three separate mobile surveys (30 Nov 2006, 10 Jan 2007, and 24 Jan 2007) in the Columbia near the Desert Canyon Golf Course. These data show that Fish 13 survived passage downstream through Wells Dam.
- Fish 1-64 was released on 19 May at 11:22 AM. Fish 1-64 was first detected in the Wells tailrace on 24 May at 5 PM. Therefore, it was not detected on the Wells forebay aerial array or the underwater spillway array, and the passage event must have occurred between 19 and 24 May. The precise passage route for this fish is unknown. It explored the right fishway up to the first wall, and was also detected at the entrance of the left fishway. It departed the tailrace on 2 June at noon. From 8:30 AM on 3 June until noon, this fish was detected in the gateway area. By 4 PM it was back in the tailrace, and entered the left fishway as far as the beginning of the fish ladder. However, the fish returned to the tailrace. The fish continued in the Wells tailrace, and successfully ascended the left ladder on 13 June (detected at the entrance at 6:55 AM and at the exit at 7 PM). The fish remained near the exit until 14 June at 10 AM. By 5 PM, the fish was detected at the upstream-facing receiver at the mouth of the Methow. On 13 July, a USFWS mobile survey relocated the fish in Twisp River upstream of Poorman Creek. Fish 1-64 moved from the Twisp into Reynolds Creek (a tributary to the Twisp), where its tag was recovered on 11 Oct. The tag was located in a pool downstream of the road culvert, near the edge in shallow water, broadcasting its "motionless" signal. It was laying on the bottom underneath some fallen tree limbs and brush. There were no carcasses in the area. These data show that Fish 1-64 survived both downstream and upstream passage through Wells Dam.

- Fish 1-58 was released on 19 May at 3:12 PM. This fish was detected at the Highway 97 bridge on the Methow at 4:11 PM during a mobile survey on 23 May. It passed the receiver station at the mouth of the Methow. It was first detected on the downstream-facing antennas at noon on 24 May. It was last seen on the upstream-facing antennas at 6:30 PM on 25 May. The fish was seen during a USFWS mobile track on 5 June near the pump station at the mouth of the Methow (just upstream from the fixed-station receiver). On 13 July, it was detected again in Twisp River downstream of War Creek. On 11 Oct, it was again detected in the Twisp. Fish 1-58 moved out of the Twisp, and was detected during a mobile track in the Methow (mile 39) on 16 Nov. Fish 1-58 next was detected in the Methow on 20 Dec 2006 near the junction of highways 20 and 153.
- Fish 1-60 was released on 21 May at 4:17 PM. This fish passed the receiver station at the mouth of the Methow. On 23 May, it was first detected on the downstream-facing antennas at 1:30 PM; its last detections on that receiver were on the upstream-facing antennas at 1:57 PM. This fish was detected downstream of Libby Creek on the Methow River at 4:03 PM during a mobile survey on 23 May. The fish was seen during a USFWS mobile track on 5 June upstream of Black Canyon Creek, and on 12 July in Goat Creek near Long Creek. It was detected again in Goat Creek on 11 Oct. On 18 October and 9 November, the tag was detected in Goat Creek broadcasting its "motionless" signal.
- Fish 1-66 was released on 24 May at 11:10 AM. Fish 1-66 was detected for about 3 minutes around 5 AM on 28 May in the Wells Forebay. Starting at 4 PM on 29 May, this fish was detected in the gateway area. Therefore, the downstream passage event occurred between 28 and 29 May. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. It was also not detected on the tailrace array. The fish was detected at 8 PM on 30 May in the gateway area, and was seen during a USFWS mobile track on 5 June at the mouth of the Entiat. The fish was detected in the gateway area on 15 June from 8:30 to 9:30 AM. By 5:50 PM, it was in the Wells tailrace, where it remained until 18 June at 6 PM. The fish moved out of the tailrace, and was detected at the gateway site on 19 June from 3:28 PM to 3:36 PM. On 4 July, this fish was detected at the USFWS fixed-station at the junction of the Entiat and Mad Rivers. It was detected within the Entiat on 7 July, 21 July, and 8 October. It was detected near the mouth of the Entiat on 14 Nov. It was next detected in the Columbia, near the mouth of the Entiat on 20 Dec 2006. These data show that Fish 1-66 survived passage downstream through Wells Dam.
- Fish 1-50 was released on 24 May at 1:09 PM. This fish passed the receiver station at the mouth of the Methow. It was first detected at 9:30 AM on 26 May, on the downstream-facing antennas. Its last detections were on the upstream-facing antennas at 6:45 PM on 30 May. It was seen during a USFWS mobile track on 5 June near the pump station. This fish was detected during a 13 July USFWS mobile survey in the Twisp River upstream of South Creek. Fish 1-50 was again detected in the Twisp on 11 and 13 Oct. On 15 November, the tag was detected in the Twisp, near the Poplar Flat campground, broadcasting its "motionless" signal.

- Fish 1-54 was released on 24 May at 1:11 PM. Fish 1-54 was detected at 6:45 PM on 24 May in the Wells forebay. About an hour later, it was detected in the Wells tailrace, where it was observed until 8 PM on 24 May. Therefore, the downstream passage event occurred on 24 May. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. It was then detected in the gateway area downstream of Wells Dam from May 30 (9:45 AM) until May 31 (3 AM). By 8 AM on 31 May, the fish was back in the tailrace, where it remained until 8 June at noon. It was detected in the gateway area from 11 PM on 8 June until 11 PM on 9 June. By 4 AM on 10 June, the fish was back in the tailrace. The fish moved between the tailrace and the gateway area, where it was detected until 30 June at 6 AM. On 7 July, this fish was detected at mile 10 of the Entiat River during a mobile survey conducted by the USFWS. It was detected in the Entiat River on 8 July, 21 July, 19 September, and again on 25 September. It was detected near the mouth of the Entiat on 2 Nov. These data show that Fish 1-54 survived passage downstream through Wells Dam.
- Fish 1-62 was released on 24 May at 2:12 PM. This fish passed the receiver station at the mouth of the Methow. It was first detected at 2:45 AM on 25 May, on the downstream-facing antennas and on the upstream-facing antennas at 6:15 AM on 25 May. It was seen during a USFWS mobile track on 5 June downstream of the town of Methow, and on 6 July in the Methow River at Lost Confluence. Fish 1-62 moved within the Upper Methow from the Lost River confluence to the West Fork where it was detected on 19 Sept and 11 Oct. Fish 1-62 was detected during a 12 Nov mobile survey in the Methow (at mile 6.7). Next, the fish was detected in the Wells forebay from 15 to 16 Nov. Fish 1-62 was then detected at the gateway array (30 Nov 2006). Therefore, the downstream passage event occurred between 16 and 30 Nov. Since there was no spill at the time of passage, the fish must have passed via the turbines. Subsequently, it was detected in four separate mobile tracks in the Columbia, in the Beebe Bridge / Chelan Falls area (1 Dec, 20 Dec, 21 Dec 2006; and 24 Jan 2007). These data show that Fish 1-62 survived passage downstream through Wells Dam.

Of the fish radio-tagged by Douglas PUD in 2006, there were six downstream and one upstream passage events (Table 5). All bull trout that passed through Wells Dam, either upstream or downstream, survived. All fish that passed downstream through Wells Dam during the spring (May/June) of 2006 were subsequently detected in a spawning tributary – three were detected in the Entiat, whereas one re-ascended through Wells Dam and entered the Methow. In the fall (November), two bull trout left the Methow and passed downstream through Wells Dam. Both were detected moving out of the study area at the gateway array (upper Rocky Reach Pool). Both were subsequently detected near Beebe Bridge in the mainstem Columbia River.

Travel times from release to entry into the Methow ranged from 9.8 hours to 25.5 days. The slowest bull trout was the one that descended and re-ascended through Wells Dam. For the remaining bull trout, maximum travel time to the Methow was 14.4 days (median 2.4 days).

Travel times to the Entiat could not be measured precisely because there was no fixed-station receiver operating at the mouth of the Entiat River. The first detection of all three Douglas PUD bull trout that entered the Entiat was made during a 7 July mobile survey, but the exact date of entry is unknown. For these three fish, downstream passage through Wells Dam occurred between 0 and 4 days after release. The time between downstream passage and the last detection at the gateway array ranged from 10 to 37 days.

5.1.1.6 Douglas PUD 2005 Tagging Results

Douglas PUD released 6 radio-tagged bull trout between 26 May and 26 June 2005 (LGL and Douglas PUD 2006). Four of these bull trout were detected in the study area between 1 Feb 2006 and 31 Jan 2007. The complete detection histories for the bull trout tagged in 2005 (Table 6) are as follows:

- Fish 1-2 was released on 26 May 2005, entered the Methow River 7 hours later, was detected on 1 Sep in the West Fork of the upper Methow River, and was still in that location when it was last detected on 27 Sep 2005. The tag from this fish was recovered by USFWS staff in the West Fork Methow River on Oct 13 2005. The associated fish was not found; it is not clear what happened to it.
- Fish 1-4 was released on 2 June 2005, entered the Methow River 21 hours later, and was detected on 31 Aug 2005 in the Twisp River above the confluence of Buttermilk Creek. It has since been detected in the Wells forebay (3 Feb – 6 March 2006), and then twice at Beebe Bridge (11 May and 5 June 2006). Therefore, the downstream passage event occurred between 6 March and 11 May 2006. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. By 12 June 2006 the fish returned to the tailrace, and ascended the dam through the left fish-ladder (17 June 2006). It was then detected in the Twisp River during three mobile tracks (13 July-11 Oct 2006). These data show that Fish 1-4 survived both downstream and upstream passage events through Wells Dam. The upstream passage event occurred more than 1 year after release, and as a result will not be included in incidental take calculations.
- Fish 1-6 was released on 3 June 2005, and entered the Methow River 4 days later. It was detected on 31 Aug 2005 in the Twisp River above the confluence of Buttermilk Creek. It then moved down river and was detected on 10 Nov 2005 on the receiver at the mouth of the Methow River. This fish was subsequently detected near the town of Pateros in the Columbia River on 20 Apr 2006.
- Fish 1-8 was released on 7 June 2005, and entered the Methow River approximately 12 hours later. On 12 June 2005, the fish was detected in the Wells tailrace. It was not detected in the forebay, hence the downstream passage event was assumed to have occurred on 12 June 2005. It was not detected on the underwater spillway array so it likely passed via the turbines. The fish left the study area when it passed the gateway array on 28 Nov 2005, where it was not detected again until 10 Jan 2006. Since then, this fish was detected in the tailrace and at the gateway from 16 Feb to 12 May 2006. This movement within the tailrace indicated that Fish 1-8 survived a downstream passage event through Wells Dam in 2005.
- Fish 1-10 was released on 7 June 2005, and entered the Methow River approximately 12 days later. It was detected on 27 September 2005 in the Lost River gorge, and was last detected on 13 October 2005 in Lost River near Lost River Road bridge.

- Fish 1-12 was released on 28 June 2005, and 3 hours later was detected in the Wells forebay, where it remained for under an hour. The fish entered the Methow River without being detected, but was detected 2 months later (on 31 Aug 2005) in the Twisp River above the confluence of Buttermilk Creek. Since then, the fish has been detected at the mouth of the Methow (10 April 2006), in the Wells forebay (28 April – 13 May 2006), and in the tailrace of Wells Dam (17 May – 6 June 2006). Therefore, the downstream passage event occurred between 13 and 17 May 2006. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. This fish was observed moving about in the tailrace, thus it was considered to have survived dam passage. It has not been detected on any array since 6 June 2006. These data show that Fish 1-12 survived a downstream passage events through Wells Dam in 2006. This passage event occurred less than 1 year after release, and as a result will be included in incidental take calculations.

All of the bull trout radio-tagged by Douglas PUD in 2005 entered the Methow River system. Travel time between release and Methow River entry ranged from 7 hours to 12 days. Subsequently, there were four passage events at Wells Dam (3 downstream and 1 upstream; Table 6). All bull trout that passed through Wells Dam, either upstream or downstream, survived. One fish passed downstream and then re-ascended past wells and moved into the Twisp – the upstream passage event occurred more than 1 year after the fish was released, thus it will not be included in the incidental take calculations (Table 7). The other 2 downstream passage events were followed by detections indicating movement within the tailrace. Both were last detected alive in the Wells tailrace.

Table 5. **Release date, tributary entry and exit dates, last locations and the upstream and downstream Wells passage events for the 10 bull trout that were radio-tagged and released at Wells Dam in 2006. The columns are laid out in an order that corresponds to the sequence of detections for the fish: release, spring passage events, tributary entry, tributary exit, fall passage events, and final detection locations.**

Fish	Release Date	Spring Passage Event Date: Downstream	Spring Passage Event Date: Upstream	First Detection in Spawning Tributary	Spawning Tributary	Tributary Exit	Fall Downstream Passage Event Date	Last Location
1-56	16 May 2006	-	-	27 May	Methow	17 Nov	18-19 Nov	Columbia R. near Beebe Bridge
1-52	16 May 2006	-	-	31 May	Methow	1 Nov ?		Methow R. near mouth
1-68	18 May 2006	21 May	-	25 June [a]	Entiat	30 Nov		Columbia R. near Desert Canyon
1-64	19 May 2006	19-24 May	13 June	14 June	Methow	-		Recovered 10/11/06; Twisp River
1-58	19 May 2006	-	-	23 May	Methow	-		Methow River
1-60	21 May 2006	-	-	23 May	Methow	-		Goat Creek
1-66	24 May 2006	28-29 May	-	4 July [a]	Entiat	20 Dec		Columbia R. near Entiat mouth
1-50	24 May 2006	-	-	26 May	Methow	-		Twisp River
1-54	24 May 2006	24 May	-	7 July [a]	Entiat	-		Entiat R. near Columbia Junction
1-62	24 May 2006	-	-	25 May	Methow	15 Nov	16-30 Nov	Columbia R. near Beebe Bridge

[a] Exact tributary entry date unknown as no fixed station was deployed at the mouth.

Table 6. Date of release, upstream and downstream passage events, and site of last detection for bull trout detected in the Wells study area.

	Tag Info		Passage Event Date		
Tag Group	Channel-Code	Release Date	Downstream	Upstream	Last Location
DPUD 2005	1-2	26 May 2005			Recovered 10/13/05 West Fork Methow
DPUD 2005	1-4	2 Jun 2005	Mar/May 2006	17 Jun 2006*	Twisp River
DPUD 2005	1-6	3 Jun 2005			Pateros
DPUD 2005	1-8	7 Jun 2005	12 Jun 2005		Wells tailrace 05/12/06
DPUD 2005	1-10	7 Jun 2005			Lost River
DPUD 2005	1-12	28 Jun 2005	13-17 May 2006		Wells tailrace 06/06/06
USFWS 2006	1-74	12 Apr 2006	19 Jul 2006		Recovered 9/19/06 Wells tailrace
USFWS 2006	1-76	18 Jul 2006			Dead. Pateros
Chelan 2005	14-3	30 May 2005		14 Jun 2005	Methow
Chelan 2005	14-30	31 May 2005			Wells Gateway
Chelan 2005	14-31	31 May 2005	May/June 2006	25 Jun 2005	Columbia near Wenatchee
Chelan 2005	14-34	6 Jun 2005			Beebe Bridge
Chelan 2005	14-36	7 Jun 2005			Recovered 10/28/05 Entiat
Chelan 2005	14-41	16 Jun 2005			Columbia near Wenatchee
Chelan 2005	14-42	16 Jun 2005			Wenatchee
Chelan 2005	14-44	27 Jun 2005	16 Nov 2006*	23 May 2006	Entiat
Chelan 2005	14-46	30 Jun 2005			Wells Gateway
Chelan 2006	14-171	25 May 2006	10-17 Dec 2006	3 Jun 2006	Wells Gateway
Chelan 2006	14-174	26 May 2006	14 Nov 2006	4 Jun 2006	Columbia below Entiat
Chelan 2006	14-177	30 May 2006		7-23 June 2006	Methow?
Chelan 2006	14-180	31 May 2006		4 Jun 2006	Wells Forebay
Chelan 2006	14-181	1 Jun 2006			Columbia near Wenatchee
Chelan 2006	14-182	2 Jun 2006			Columbia near Wenatchee
Chelan 2006	14-184	5 Jun 2006		19 Jun 2006	Methow near mouth
Chelan 2006	14-186	14 Jun 2006			Beebe Bridge
Chelan 2006	14-188	22 Jun 2006	Oct/Dec 2006	30 Jun 2006	Crescent Bar
Chelan 2006	14-190	29 Jun 2006			Columbia near Orondo

* passage event occurred more than 1 year after release, and will not be included in incidental take calculations

5.1.1.7 USFWS 2006 Tagging Results

Of the 13 radio-tagged bull trout released by the USFWS, two were detected in the study area between 1 Feb 2006 and 31 Jan 2007 (Table 6). The complete detection histories for these radio-tagged bull trout are as follows:

- Fish 1-74 was released in the Methow River. It was detected at the mouth of the Methow (on 17 July 2006 from 2 to 5 AM), in the Wells forebay (19 July 2006 at 3 PM), and subsequently in the Wells tailrace (19 July 2006 at 7 PM). Therefore, the downstream passage event occurred on 19 July 2006. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. It was detected repeatedly in the right tailrace until 25 July 2006, when it moved into the left tailrace. This movement within the tailrace indicated that the fish survived downstream passage through Wells Dam. From 11 Aug until noon on 17 Sept 2006, the tag was broadcasting its "motionless" signal, suggesting that the tag had been expelled or the fish had died. On 19 Sept 2006, the tag was recovered from the shore in the tailrace. The tag was found in a very active fishing location indicating a potential harvest. No carcass was found.

- Fish 1-76 was released in the Methow River. It was detected in the Methow on 19, 26 and 29 Sept 2006, and at the mouth of the Methow (fixed station) from 28 Sept until 1 Oct 2006. Most recently, the tag was detected on 15 Nov and again on 20 Dec 2006 (broadcasting its motionless signal on both occasions) in the Columbia mainstem near the town of Pateros.

One bull trout tagged by the USFWS in 2006 (Fish 1-74) passed downstream through Wells Dam (Table 6). The tag was later recovered from the shore of the tailrace. As required by the WBTMMP, Douglas PUD notified the USFWS within 48 hours of tag recovery (Douglas PUD, 2004). Since the detection history for this fish showed movement within the tailrace for 2 weeks, it was assumed to have survived passage and was not considered an incidental take event due to Wells Project operations.

5.1.1.8 Chelan PUD 2005 Tagging Results

In 2005, Chelan PUD released 38 radio-tagged bull trout, of which nine were detected in the Douglas PUD study area (Table 6). The complete detection histories for these radio-tagged bull trout are as follows:

- Fish 14-3 was not detected passing the gateway area. On 12 June 2005, the fish was first seen in the right tailrace area. It milled around the tailrace until 14 June 2005, when it entered the left fishway, passed the trap and the area of the video recorder, backed down to below the trap, and re- ascended. The fish exited into the forebay on 16 June 2005. On 29 June 2005, the fish was detected entering the Methow system. On 19 Oct, 2006, the fish was detected during a mobile survey of the lower Methow. From 26-28 Oct 2006, the fish was detected in the Wells forebay. By 16 Nov 2006, the fish had returned to the Methow, as it was detected at mile 3.2. These data show that Fish 14-3 survived upstream passage through Wells Dam.
- Fish 14-30 was detected at gateway site and in the Wells tailrace in 2005. The fish was last detected at 3 AM on 21 August 2005 at the gateway zone.
- Fish 14-31 was first detected at the right fishway entrance on 3 June, 2005. The fish made repeated movements between the gateway and the tailrace area, where it milled about and ventured into fishways, but always moved back out. On 22 June, the fish left the gateway area, and moved into the Wells tailrace. It milled around in the tailrace until 25 June 2005, when it entered the right fishway. It passed the trap and the video station, and was detected at the fishway exit at 11 PM. It remained in the area of the exit until 26 June 2005. By 27 June 2005, the fish was detected entering the Methow system. In 2006, this fish was again detected at the mouth of the Methow, from 24 to 29 May, but was last seen on the upstream-facing antenna. On 29 June 2006, it was detected downstream of the dam. Therefore, the downstream passage event occurred between 29 May and 29 June 2006. The precise passage route is unknown, but the fish was not detected on the underwater spillway array. On 2 Nov 2006, it was detected during a mobile track of the Wenatchee. On 30 Nov 2006, it was detected in the Columbia near the Wenatchee Golf Course. On 11 Jan, 2007, it was detected in the Columbia upstream of Rock Island Dam. These data show that Fish 14-31 survived both upstream and downstream passage through Wells Dam.

- Fish 14-34 was first detected at the gateway site on 11 June 2005. It left the gateway area on 16 July 2005, and milled around in the Wells tailrace until 22 July 2005 when it moved into the left fishway. It passed the 1st wall, and was detected at the "fishway beginning" zone, but later moved back into the tailrace. The fish was detected on 22 July 2005 in the Wells tailrace. It was detected in the upper Entiat on 8 July 2005. Since then, it has been detected at Beebe Bridge on 5 separate mobile surveys in 2005: 3 Aug, 1 Sep, 8 Sep, 7 Oct and 19 Oct.
- Fish 14-36 was detected at the gateway site and in the Wells tailrace in 2005. From 11 to 20 June 2005, the fish was detected moving among the gateway and tailrace zones. At Wells Dam, the fish was last detected on 20 June 2005 at the right-side tailrace aerial zone. Between 8 July and 28 October 2005, it was detected during 5 separate mobile tracks in the Entiat River. The tag has since been recovered in the Entiat.
- Fish 14-41 was detected at the gateway site and in the Wells tailrace in 2005. From 20 June to 16 Sept 2005, the fish was detected moving among the gateway and tailrace zones. At Wells Dam, the fish was last detected on 16 September 2005 at the gateway zone. This fish was later detected on 21 July 2006 in the Wenatchee, and on 30 Nov 2006 in the Columbia near the mouth of the Wenatchee.
- Fish 14-42 was detected at the gateway site and in the Wells tailrace in 2005. From 26 June to 21 Aug 2005, the fish was detected moving among the gateway and tailrace zones. At Wells Dam, the fish was last detected on 21 August 2005 at the right-side tailrace aerial zone. This fish was later detected on 2 Nov 2006 in the Wenatchee.
- Fish 14-44 was detected at the gateway site and in the Wells tailrace in 2005. From 29 June to 25 Oct 2005, the fish was detected moving among the gateway and tailrace zones. In 2006, the fish was detected passing the gateway area on 5 May. By 21 May 2006 the fish was first seen in the tailrace area. It entered the right fishway on 23 May 2006, passed the trap and the video area, and exited into the forebay. On 24 May 2006, the fish was detected entering the Methow system. On 9 Nov 2006, the fish was detected on the downstream antenna at the Methow mouth. From 12 -15 Nov, the fish was detected on the Wells forebay aerial antennas, and on the underwater antennas near spill-gate 10. On 15 Nov 2006, the fish was detected during a mobile track downstream of the Starr Boat Ramp. On 16 Nov 2006, the fish was again detected in the forebay, and then in the tailrace. At Wells Dam, the fish was last seen at the gateway array, where it was detected from 16-18 Nov 2006. Therefore, the downstream passage event occurred on 16 Nov 2006. Since there was no spill at the time of passage, the fish must have passed via the turbines. On 20 Dec 2006 and 24 Jan 2007, the fish was detected in the Entiat near the mouth. These data show that the fish survived both upstream and downstream passage through Wells Dam.
- Fish 14-46 was detected at the gateway site and in the Wells tailrace in 2005. From 1-30 July 2005, the fish was detected moving among the gateway and tailrace zones. On one occasion (14 July 2005), the fish moved into the right fishway as far as the 1st wall, but later moved back out into the tailrace. The fish was last detected on 30 July 2005 at the gateway zone.

Three of the bull trout that were tagged by Chelan PUD in 2005 passed Wells Dam, recording three upstream passage events, and two downstream events (Table 6). All bull trout that passed through Wells Dam, either upstream or downstream, survived. All three of the fish that passed upstream through Wells moved into the Methow during the spawning season. Two of these fish later returned downstream past Wells Dam. One fish was subsequently detected near the mouth of the Wenatchee. The other fish was detected in the Entiat (the downstream passage event for this fish occurred more than 1 year after it was released, thus it will not be included in the incidental take calculations; Table 7).

5.1.1.9 Chelan PUD 2006 Tagging Results

In 2006, Chelan PUD released 29 radio-tagged bull trout: four were released at Rock Island, and 25 at Rocky Reach. Of the 29 tagged bull trout, 11 were detected in the Douglas PUD study area (Table 6). The complete detection histories for these radio-tagged bull trout are as follows:

- Fish 14-171 moved between the gateway area and the Wells tailrace from 27 May to 3 June 2006. On 3 June, it moved through the left tailrace, and began its ascent of the left fishway (10:19 AM). It passed the trap at 1:45 PM, and exited into the forebay at 4 PM. The fish was detected on 16 Nov 2006 in the Methow. These data show a successful upstream passage through Wells Dam. Subsequently, this fish was detected on the upstream-facing antenna at the mouth of the Methow on 10 Dec 2006, and then at the Wells gateway array on 17 Dec, 2006. These data show a downstream passage event (between 13 and 17 Dec 2006) through Wells Dam. Since there was no spill at the time of passage, the fish must have passed via a turbine. Although the fish was not detected in the tailrace, it was assumed to have survived downstream passage, given that it was detected at the gateway array.
- Fish 14-174 moved between the gateway area and the Wells tailrace from 29 May to 4 June 2006. On 4 June 2006, it moved through the right tailrace, and started its ascent of the right fishway at 8:27 AM. It passed the trap at 10 AM on 5 June. The fish was not detected at the fishway exit. At 11:55 PM on 7 June 2006, Fish 14-174 was detected entering the Methow system. Subsequently, this fish was detected in the Methow during a 19 Oct 2006 mobile track. Detections from 9-13 Nov 2006 show the fish moving downstream past the fixed station at the Methow mouth. The fish was detected in the Wells forebay from 6-8 AM on 14 Nov 2006, and then in the tailrace at 1 PM. Therefore, the downstream passage event occurred on 14 Nov 2006. Since there was no spill at the time of passage, the fish must have passed via the turbines. From 21-22 Nov 2006, the fish was detected at the gateway array. On 20 Dec 2006, the fish was detected in the Columbia downstream of the mouth of the Entiat. These data show that the fish survived both upstream and downstream passage through Wells Dam.
- Fish 14-177 was detected at the gateway site at noon on 1 June 2006. From 2-7 June 2006, the fish was detected in the tailrace. This fish was subsequently in the Methow on 9 and 23 June 2006. These data show that Fish 14-177 survived an upstream passage event through Wells Dam, and that passage occurred sometime between 7 and 23 June 2006 without the fish being detected. The USFWS believes this tag to be malfunctioning (Mark Nelson, pers. comm.).
- Fish 14-180 passed the gateway area on 2 June 2006. By 3 June 2006, it had been detected in the Wells tailrace. On 4 June 2006, it began its ascent of the left fishway. It passed the trap at noon, and was detected at the fishway exit at 3:45 PM. On 7 June 2006, it was detected entering the Methow system. On 15 Nov 2006, this fish was detected in the Columbia near Pateros. On 28 Nov 2006, the fish was detected in the

Wells forebay. This fish is potentially still in the Wells reservoir. These data show that the fish survived upstream passage through Wells Dam.

- Fish 14-181 was detected at the gateway site on 4 June 2006. It was subsequently detected (2 Nov 2006) in the Entiat. The fish was detected on 20 Dec 2006 in the Columbia at the mouth of the Wenatchee.
- Fish 14-182 moved past the gateway site on 8 June 2006. It moved into and out of the tailrace until 10 Aug 2006, and made several excursions into the left and right fishways up to the 1st wall. The fish was detected near the Wenatchee on 14 Aug 2006.
- Fish 14-184 passed the gateway area on 10 June 2006. It milled in the tailrace, ascending both fishways to the 1st wall. On 19 June 2006, the fish entered the left fishway, passed the trap at noon, and was detected at the fishway exit at 2:19 PM. It was detected in the Wells forebay until 3 PM. By 8:46 PM, the fish was detected entering the Methow system. It was subsequently detected (16 Nov 2006) in the Methow near Gold Creek. From 9-11 Dec 2006, this fish was detected on the downstream facing antenna at the mouth of the Methow. This fish may have moved into the Wells reservoir. These data show that the fish survived upstream passage through Wells Dam.
- Fish 14-186 passed the gateway site on 18 June 2006. It milled within the Wells tailrace, entered the left fishway to the 1st wall twice (20 and 21 June 2006), and moved back to the gateway site, where it was detected until 23 June 2006. It was subsequently detected near Beebe Bridge on 16 Nov, 30 Nov, 20 Dec, and 21 Dec 2006.
- Fish 14-188 was not detected at the gateway area, but was first seen in the Wells tailrace on 26 June 2006. The fish milled within the tailrace, and at one point (28 June 2006) entered the left fishway up to the 1st weir. On 30 June 2006, the fish entered the right fishway, passed the trap at 6 AM on 1 July 2006, and was detected at the fishway exit at 8:38 AM. The fish was detected entering the Methow system on 2 July 2006. The fish was detected at the USFWS fixed-station at Methow river mile 6.7 on 24 Oct 2006. Then, it was detected on the downstream-facing receiver at the Methow mouth on 31 Oct 2006. This fish was subsequently detected passing through Rocky Reach, and Rock Island dams, and was detected on 20 Dec 2006 in the Columbia near Crescent Bar. Therefore, the downstream passage event occurred sometime between October and December 2006. Since there was no spill at the time of passage, the fish must have passed via the turbines. These data show that the fish survived both upstream and downstream passage through Wells Dam.
- Fish 14-190 passed the gateway area on 1 July 2006. On 11 July 2006, the fish entered the right fishway, it passed the trap at 7 PM, and entered the video area at 8 PM. The fish moved back down to the trap area, where it remained until 5 AM on 12 July 2006. It then moved back out to the tailrace, and then to the gateway area (15 July 2006). From 23 July 2006 to 24 Sept 2006, Fish 14-190 was detected moving about the tailrace area. On 14 Nov 2006, the fish was detected in the Columbia downstream of the junction with the Entiat. On 24 Jan 2007, the fish was detected in the Columbia near Orondo.

Six of the bull trout that were tagged by Chelan PUD in 2006 passed Wells Dam, recording six upstream passage events, and three downstream events (Table 6). All bull trout that passed upstream through Wells Dam survived, and moved into the Methow during spawning season. Two of these remained in the Methow, and one was last detected in the Wells forebay. The other three fish returned downstream through Wells Dam. All three of these fish survived during downstream passage through Wells Dam. Two of these fish were detected downstream of the Entiat, and one was last detected at the Wells gateway array. This last fish was not detected in the Wells forebay or tailrace. Given that there were no detections at Wells Dam, the status on this fish is inconclusive (Table 7).

Table 7. Upstream and downstream passage of radio-tagged bull trout at Wells Dam in 2006. Passage events were included if they occurred within one year of the release date.

	Downstream Passage			Upstream Passage		
Tag Group	Events	Survived	Died [a]	Events	Survived	Died [b]
USFWS 2006	1	1	0	0	0	0
Chelan 2005	1	1	0	1	1	0
Chelan 2006	3	3	0	6	6	0
Douglas PUD 2005	2	2	0	0	0	0
Douglas PUD 2006	6	6	0	1	1	0
Total	13	13	0	8	8	0
Survival Rate		100%			100%	

a) prolonged detection of the tag in one place within the tailrace (i.e., no evidence of movement within tailrace).
b) last detected in forebay

5.1.1.10 Incidental Take Calculation

The 2005 and 2006 radio-tagging of adult bull trout was implemented to identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and to monitor any incidental take of bull trout. In 2006, 23 passage events were recorded for 17 radio-tagged bull trout. Two of these occurred more than 1 year after the fish had been released. Of the remaining 21 passage events (Table 7), there were 13 downstream and 8 upstream passage events. There were no conclusive instances of bull trout mortality resulting from these passage events. All passage events resulted in the survival of the bull trout as indicated either by movement out of the tailrace, or by movement among the tailrace detection zones. As such, the rate of incidental take in 2006 is estimated to be 0%.

5.1.2 Strategy 1-2: Correlations between passage events and Project operations

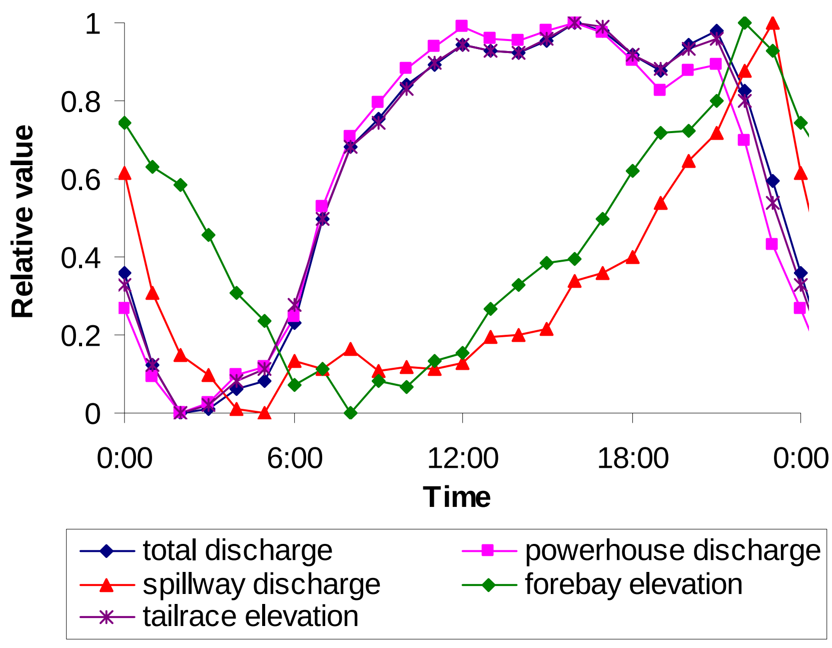
In order to assess potential impacts of Project operations on the passage of adult bull trout, correlations were generated between passage events and a suite of metrics of Project operations. These included flow through spillways and turbines, and reservoir elevations.

The upstream passage event data, as collected for radio-tagged bull trout, were compared against the video counts in 2006. Of the eight radio-tagged bull trout for which upstream passage data exist (i.e., excluding Fish 14-177; see above), six had a corresponding video-count observation in the correct ladder, on the correct date, and at approximately the correct time. The two missed radio-tagged fish were added to the video-count data, bringing the total number of observed bull trout upstream passage events in 2006 to 100. These 100 upstream passage-timing data points were used in subsequent analyses of effects of Project operations on passage.

Of the 15 downstream passage events recorded for radio-tagged bull trout in 2006, six had detections in both the forebay and tailrace, and hence were of precisely known timing. Two others were known with ±1 day. Because of uncertainty in their passage timing, the other seven bull trout were excluded from analyses of Project operation effects on downstream passage.

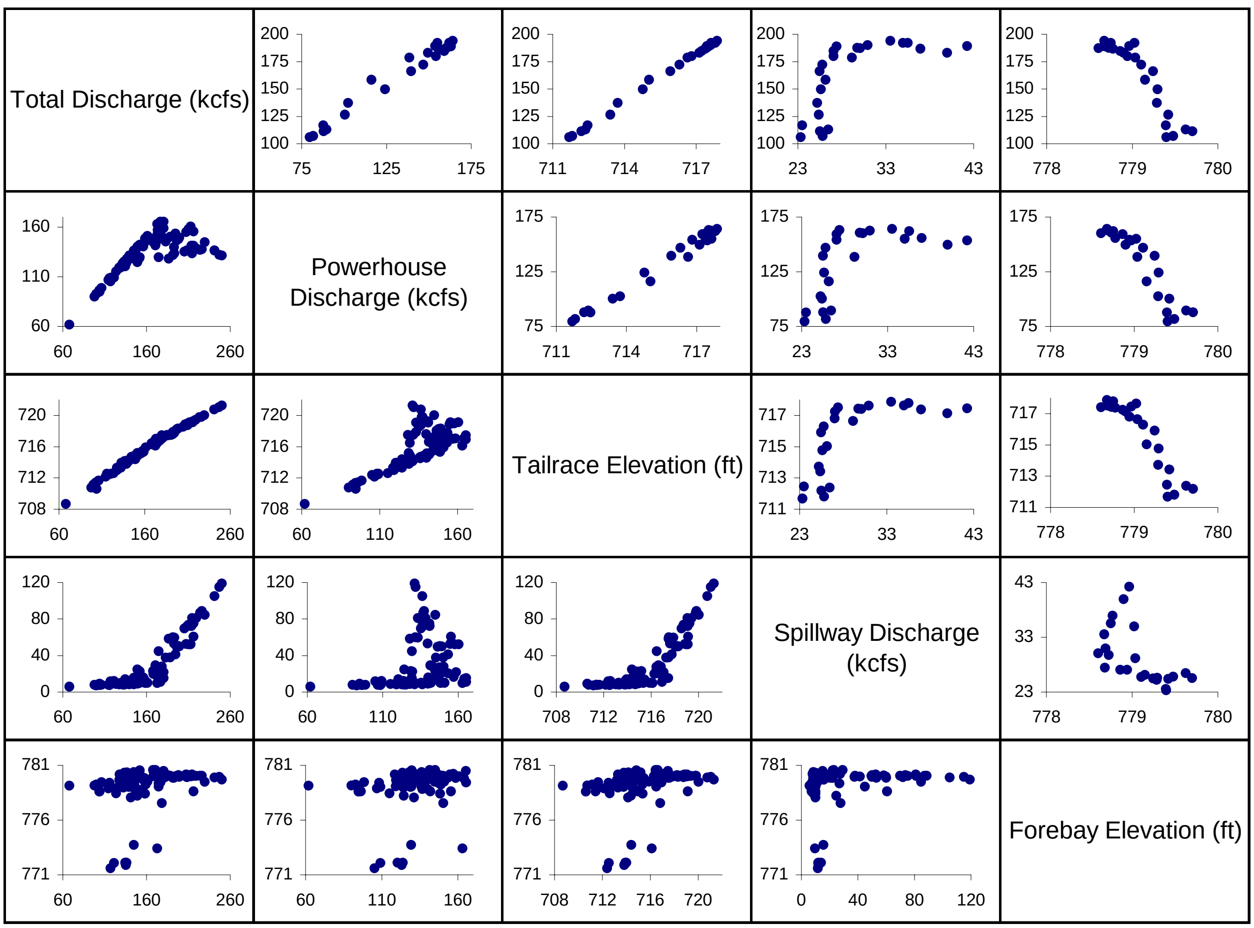
The five available metrics of Project operations were total, powerhouse and spillway discharge; and forebay and tailrace elevations. Hourly data (from 1 May to 31 July 2006) were averaged across days to calculate hourly means (Figure 1). Lag times of -8 to +8 hours were considered for each variable to find the strongest correlations (note that a strong *negative* correlation was expected between forebay elevation and discharge). Total discharge, powerhouse discharge and tailrace elevation tracked each other, whereas spillway discharge was offset by -3 hours, and forebay elevation by +6 hours (Figure 1).

Figure 1. **Diurnal trends in Wells Project operations data, averaged from 1 May to 31 July, 2006. For comparison, the five Project operation metrics have been standardized (each observation is shown as a proportion of the range between the minimum and maximum observed values for that metric).**



Using the lagged raw operations data, hourly means were calculated for each metric. There were very strong correlations among total discharge, powerhouse discharge and tailrace elevation (r = 0.99; $P < 0.0001$; Figure 2). These three metrics were strongly and negatively correlated with the lagged forebay elevation (r = -0.92; $P < 0.0001$; Figure 2). Lagged spillway discharge was correlated with all four other metrics, though the relationships were weaker (lagged forebay elevation r = -0.57; other three r = 0.61 to 0.66; P = 0.0004 to 0.0035; Figure 2). Due to the significant colinearity of these five metrics, only one was considered (total discharge) during subsequent analyses of diurnal trends.

Figure 2. Correlation matrix for Wells Project operations data, 1 May to 31 July, 2006. Graphs above the diagonal show correlations among average hourly metrics (note spillway discharge is lagged by -3 h; and forebay elevation by +6 h); those below the diagonal show correlations among average daily metrics (no lags).



Daily mean values showed a very strong correlation between total discharge and tailrace elevation (r = 0.99; $P < 0.0001$; Figure 2). Spillway discharge was also correlated with these two metrics (r = 0.85 to 0.88; $P < 0.0001$), as was powerhouse discharge (r = 0.70 to 0.74; $P < 0.0001$; Figure 2). The remaining pair-wise correlations, including all relationships with forebay elevation, were weaker (r = 0.23 to 0.31) but nonetheless statistically significant (P = 0.0023 to 0.027; Figure 2). Due to the significant colinearity of the three discharge metric and the tailrace elevation, only one of these four metrics (total discharge) was included in subsequent analyses of seasonal trends. The forebay elevation metric (which was only weakly correlated with the other four metrics) was also included in subsequent seasonal analyses.

Diurnal trends in total discharge were correlated with upstream bull trout passage (r = 0.55; P = 0.0058; Figure 3a). Both metrics followed a strong diurnal pattern, showing little activity in the hours before dawn, and the majority of activity in the afternoon. Bull trout upstream passage events decreased quickly in the afternoon, whereas discharge stayed high until about 10 PM and then dropped off precipitously. In general, upstream movements were less likely during periods of low discharge (Figure 3b). Note that this correlation may be coincidental (i.e., not causal), because power use (and hence Project operations) declines at night, and because fish migrations might be inhibited during darkness (i.e., not because of reduced discharge).

Figure 3. Relationship between diurnal trends in total discharge and bull trout passage at Wells Dam, 1 May to 31 July, 2006. a) Average values, plotted as time series, were standardized for ease of comparison (each observation is shown as a proportion of the range between the minimum and maximum observed values for that metric); b) Scatter-plot of bull trout passage as a function of average hourly total discharge.

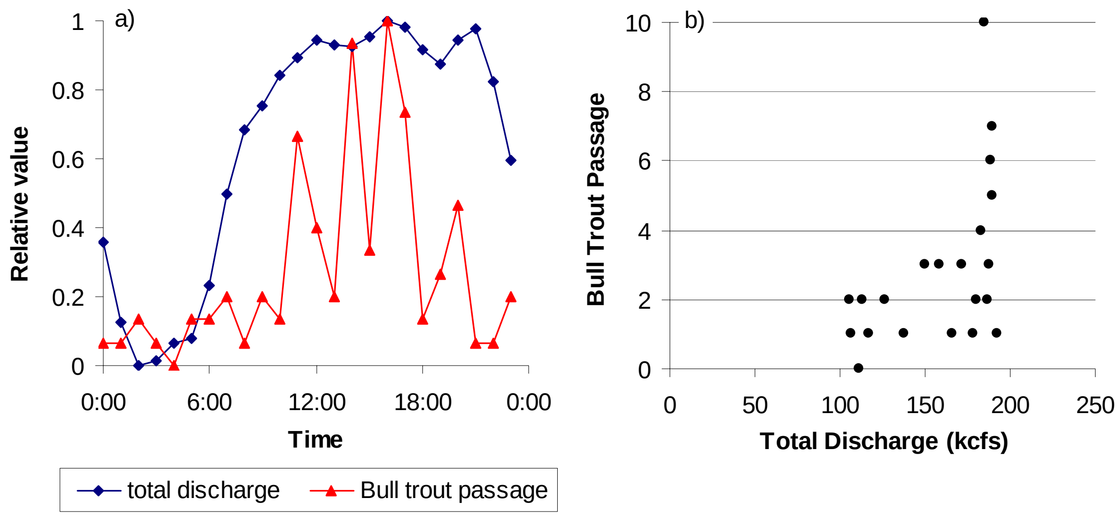
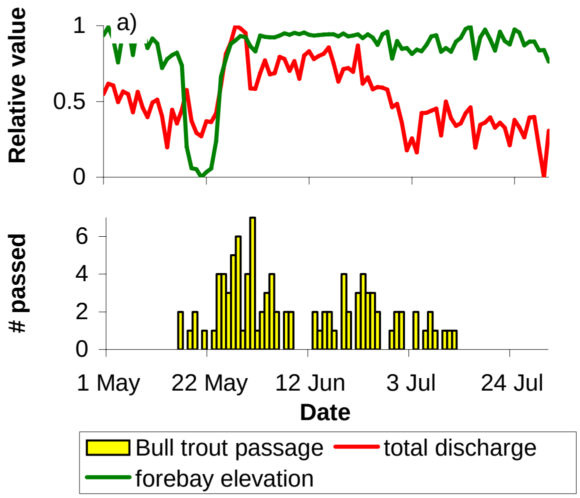
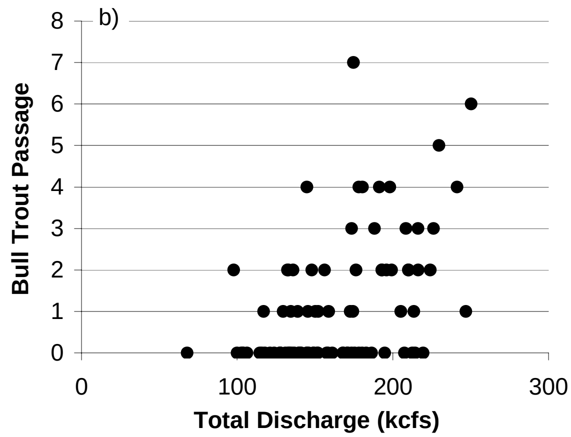


Figure 4. **Seasonal time series of bull trout passage events, average daily total discharge, and forebay elevation at Wells Dam, 1 May to 31 July, 2006. a) Average values, plotted as time series, were standardized for ease of comparison (each observation is shown as a proportion of the range between the minimum and maximum observed values for that metric); b) Scatter-plot of bull trout passage as a function of average daily total discharge.**





Seasonal trends in bull trout passage were significantly correlated with daily average total discharge (r = 0.48; $P < 0.0001$; Figure 4a), but not with forebay elevation (r = 0.03; $P = 0.80$; Figure 4a). A large increase in flows in late May were accompanied by an increase in upstream bull trout passage events. In general, upstream movements were less likely during periods of low discharge (Figure 4b). At daily average total discharge levels below 150 kcfs, the number of upstream bull trout passage never exceed 2 fish.

Too few radio-tagged bull trout moved downstream past Wells in 2006 to draw any conclusions about Project operations. Passage dates were clustered in May (mostly fish that were tagged in 2006, released above Wells, and that moved downstream to spawn in the Entiat) and in November (post spawning movements out of the Methow to reaches areas downstream of Wells Dam).

5.1.3 Strategy 1-3: Off-season fishway passage of adult bull trout

Off-season video monitoring of both Wells Dam fishways for the 2005-2006 winter period began on November 16, 2005 and continued until April 30, 2006. During this period no adult bull trout were observed utilizing the fishways.

5.1.4 Strategy 1-4: Modifications to passage facilities or operations

To date, there have been no problems identified as impacting upstream or downstream passage of adult bull trout. As such, there is no need for Douglas PUD to develop modifications to current passage facilities or operations.

5.2 Objective 2

The second objective was to assess project-related impacts on upstream and downstream passage of sub-adult bull trout. Because of an inability to collect a sufficient sample size of sub-adult bull trout, it is currently not feasible to assess sub-adult passage at Wells Dam. As such, the second objective was addressed using two strategies: (1) sub-adult bull trout were PIT tagged opportunistically when encountered at the Project, or in smolt tributary traps; and (2) video monitoring was used to determine off-season sub-adult bull trout passage through the adult fishways at Wells during the 2005-2006 winter period.

5.2.1 Strategy 2-1: Sub-adult PIT tagging program

Due to the inability to collect a sufficient sample size of sub-adult bull trout and because sub-adult bull trout are not large enough to be radio-tagged, it is not currently feasible to assess effects of Wells Dam on sub-adult bull trout passage. However, Douglas PUD has agreed to indirectly monitor take for sub-adult bull trout through PIT-tagging. This effort includes providing PIT-tags, equipment and facilitated training to enable PIT-tagging of sub-adult bull trout when these fish are incidentally encountered during certain fish sampling operations. Fish sampling operations that could have incidental captures of sub-adult bull trout included the Wells adult fishway, Methow brood stock traps, and juvenile salmonid trapping activities on the Methow and Twisp rivers. Different entities conduct these fish sampling operations, thus the provision of tags, equipment and methodology have been standardized.

Douglas PUD passively collected information from all PIT-tagged fish, including bull trout, as they passed through the fishways at Wells Dam. Douglas PUD also scanned all bull trout incidentally captured at the screw traps and adult brood collection facilities. The information collected at the dam and in the tributaries were posted on the PTAGIS website, which is operated and maintained by the Pacific States Marine Fisheries Commission.

To date (2005 and 2006 activities), no sub-adult bull trout have been PIT-tagged during tagging operations at Wells Dam. As previously mentioned, Douglas PUD provides support for PIT-tagging of bull trout collected at several off-site smolt collection facilities (Twisp and Methow rivers). In 2006, these operations PIT-tagged 20 sub-adult bull trout (all at the Twisp weir). A query of the PTAGIS database shows that none of these PIT-tagged bull trout have since been detected.

5.2.2 Strategy 2-2: Off-season fishway passage of sub-adult bull trout

Off-season video monitoring of both Wells Dam fishways for the 2005-2006 winter period began on November 16, 2005 and continued until April 30, 2006. During this period no sub-adult bull trout were observed utilizing the fishways.

5.3 Objective 3

The third objective was to investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of the Wells Reservoir. This objective was addressed by evaluating Wells inflow patterns, reservoir elevations, and backwater curves to determine the extent of stranding or entrapment of sub-adult bull trout (if any).

5.3.1 Strategy 3-1: Inflow patterns, reservoir elevations, and backwater curves

From 17 May 11:00 PM to 18 May 8:00 AM, 2006 the elevation of the Wells Reservoir was reduced to an elevation of 772 mean sea level (msl) as part of the Methow River flood control program in order to accommodate flood flows in the Methow River. Douglas PUD conducted a field survey on 18 May from 10:00 AM to 4:00 PM towards gathering information on the potential for sub-adult bull trout stranding. Detailed bathymetric maps produced in 2005 combined with Wells Reservoir hydraulic information identified several locations where stranding of sub-adult bull trout could potentially occur. In total, 5 potential stranding locations were identified. These locations were the Methow River mouth, the Okanogan River mouth, the Kirk Islands, the shallow water habitat in the Columbia River directly across from the mouth of the Okanogan River, and the off-channel areas of the Bridgeport Bar Islands. Boat and foot surveys were conducted and included a combination of shoreline transects and inspection of isolated sanctuary pools. No bull trout, sub-adult or adult, were observed during the survey which suggests that in the event of a Wells reservoir drawdown, bull trout are able to avoid stranding and entrapment areas.

5.4 Objective 4

The fourth objective was to identify the Core Areas and Local Populations, as defined in the USFWS's Draft Bull Trout Recovery Plan, of those bull trout that utilize the Project area. This objective was addressed using 2 strategies: (1) genetic samples were gathered from radio tagged and PIT tagged fish for comparison to baseline genetic samples from Local Populations and Core Areas; and (2) in cooperation with other agencies, the locations of radio-tagged fish outside the Project area were recorded, and related to the distribution of local populations.

5.4.1 Strategy 4-1: Genetic sampling program

Douglas PUD provided the equipment and facilitated training to enable genetic sampling of bull trout during bull trout radio-tagging operations and when bull trout were incidentally collected during other fish sampling operations (on-site and off-site). Fish sampling operations that could have incidental captures of bull trout included the Wells adult fishway and juvenile and sub-adult salmonid trapping activities on the Methow and Twisp rivers. Since different entities conduct these fish sampling operations, provision of equipment and methodology were standardized. Ideally these genetic samples will be compared, by the USFWS, to genetic baseline samples when those baselines become available.

In 2006, ten genetic samples were collected from adult bull trout during radio-tagging operations at Wells Dam. Additionally, 10 genetic samples were collected from smolt trapping operations conducted by the WDFW on the Twisp and Methow rivers. All samples were sent to the USFWS's Abernathy Fish Technology Center for storage and future analysis. Currently, a genetic baseline for mid-Columbia River basin bull trout populations has not yet been developed by the USFWS. More work is required to generate useful information from the collected genetic data.

5.4.2 Strategy 4-2: Destination locations of Wells Dam bull trout

The destinations of Wells Dam bull trout were evaluated from the results of the adult radio-tagging program (see Strategy 1-1). In brief, the program involves the capture and radio-tagging of 10 adult bull trout each year from 2005 to 2007, and tracking until 2008. These fish were tracked in the Wells Reservoir, and into tributary rivers. Since other agencies were performing mobile tracking in areas outside of the Wells Reservoir, Douglas PUD worked cooperatively with these agencies to obtain more detailed locations of the radio-tagged fish.

Of the 10 bull trout tagged in 2006, seven were tracked into the Methow River. The remaining three bull trout returned downstream through Wells Dam and entered the Entiat drainage. The results of the radio-telemetry tracking suggest that 70% of bull trout tagged at Wells Dam in 2006 were associated with the Methow core area and 30% of the Wells bull trout tagged in 2006 were associated with the Entiat Core Area.

6.0 CONCLUSIONS AND RECOMMENDATIONS

As part of the first objective, 10 adult bull trout were radio-tagged at Wells Dam in 2006. Of these, 6 traveled to the Methow River, with a median travel time of 2.4 days (range 9.8 hours to 14.4 days). A seventh fish descended through Wells Dam, re-ascended through the east fishway, and reached the Methow 25.5 days after release. The remaining three bull trout tagged in 2006 passed downstream through Wells Dam, and moved into the Entiat River sometime before a 7 July mobile survey. Tracking of bull trout released by Douglas PUD, Chelan PUD and the USFWS, resulted in the detection of 13 downstream passage events and 8 upstream passage events. Based on these passage events, all of which resulted in the survival of the fish, it was estimated that the rate of incidental take in 2006 was 0%.

The second objective was to assess project-related impacts on upstream and downstream passage of sub-adult bull trout. To this end, opportunistic PIT tagging of sub-adults was successfully completed in 2006. Although no sub-adult bull trout were observed or captured at Wells Dam, 20 sub-adults were PIT-tagged during tributary trapping operations in 2006. Opportunistic PIT tagging of sub-adults should be continued in order to increase the probability of gaining useful data on migrations in the future.

The third objective was to investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of Wells Reservoir. In 2006, this objective was addressed through a field survey of potential bull trout stranding sites conducted during a period of low reservoir elevation associated with the Methow River flood control program. High resolution bathymetric information in combination with Project information (reservoir elevations, backwater curves, inflow patterns) were used to identify potential stranding sites for the survey. No stranded bull trout (sub-adult or adult) were found during the 2006 field survey.

The fourth objective was to identify the Core Areas and Local Populations of those bull trout that utilize the Project area. In 2006, a total of 10 genetic samples have been collected from bull trout during radio-tagging operations at Wells Dam and off-site HCP related fish sampling activities. Genetic samples collected from various sites will be used to develop a genetic baseline against which the data from which bull trout passing Wells Dam may eventually be compared. These samples were provided to the USFWS for analysis. Genetic samples will again be collected from adult and sub-adult bull trout during the 2007 field season.

The 2006 radio-telemetry data indicate that the Core Areas associated with 70% of the radio-tagged bull trout was the Methow River. The Core Area associated with the remaining 30% of the radio-tagged fish was the Entiat River.

7.0 REFERENCES

Adams, N. S., Rondorf, D. W., Evans, S. D., and Kelly, J. E. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behaviour of juvenile Chinook salmon. Transactions of the American Fisheries Society. 127: 128-136.

Baxter, C. V., and F. R. Hauer. 2000. Geomorphology, hyporheic exchange, and the selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Aquatic Science. 57:1470-1481.

BioAnalysts. 2004. Movement of bull trout within the Mid-Columbia River and tributaries, 2001-2004. Report prepared by BioAnalysts for Public Utility District No.1 of Chelan County, Public Utility District No.1 of Douglas County, and Public Utility District No.2 of Grant County.

Brewin P. A. and M. K. Brewin. 1997. Distribution maps for bull trout in Alberta. Pages 206-216 in: Mackay, W.C., M. D. Brewin and M. Monita, editors. Friends of the Bull Trout Conference Proceedings. Bull Trout Task Force (Alberta), c/o Trout Unlimited Calgary, Alberta, Canada

Cavender, T. M. 1978. Taxonomy and distribution of the bull trout, *Salvelinus confluentus* (Suckley) from the American Northwest. California Fish and Game 64:139-174.

Douglas PUD (Public Utility District No. 1 of Douglas County). 2004. Wells Hydroelectric Project Bull Trout Monitoring and Management Plan, 2004-2008. Prepared by Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

English, K. K., T. C. Nelson, C. Sliwinski, and J. R. Stevenson. 1998. Assessment of passage facilities for adult sockeye, Chinook, and steelhead at Rock Island and Rocky Reach dams on the mid-Columbia River in 1997. Report to Public Utility District No. 1 of Chelan County, Wenatchee, WA.

English, K. K., C. Sliwinski, B. Nass, and J. R. Stevenson. 2001. Assessment of passage facilities for adult steelhead at Priest Rapids, Wanapum, Rock Island, Rocky Reach, and Wells dams on the mid-Columbia River in 1999. Report to Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Judy Delavergne, USFWS. Personal Communication. Email to Bao Le, Douglas PUD, on March 2, 2007.

LGL and Douglas PUD. 2006. Wells bull trout monitoring and management plan: 2005 annual report. Report to Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Mark Nelson, USFWS. Personal Communication. Discussion with Bryan Nass and David Robichaud, LGL Limited.

Martinelli, T. L., Hansel, H. C., and Shively, R. S. 1998. Growth and physiological responses to surgical and gastric radio transmitter implantation techniques in subyearling Chinook salmon (*Oncorhynchus tshawytscha*). Hydrobiologia. 371/372: 79-87.

McPhail, J. D. and J. S. Baxter. 1996. A review of bull trout (*Salvelinus confluentus*) life history and habitat use in relation to compensation and improvement opportunities. Fisheries management report no. 104. University of British Columbia. Vancouver, B.C.

Mongillo, P. E. 1993. The distribution and status of bull trout/Dolly Varden in Washington State. Washington Department of Wildlife. Fisheries Management Division, Report 93- 22. Olympia, Washington. 45 pp.

Pleyte, Kay A., S. D. Duncan, and R. B. Phillips. 1992. Evolutionary relationships of the fish genus *Salvelinus* inferred from DNA sequences of the first internal transcribed spacer (ITS 1) of ribosomal DNA. Molecular Phylogenetics and Evolution, 1(3): 223-230.

Riehle, M. W. Weber, A. M. Stuart, S. L. Thiesfeld and D. E. Ratliff. 1997 Progress report of the multi-agency study of bull trout in the Metolius River system, Oregon. In Friends of the Bull Trout Conference Proceedings. Bull Trout Task Force. Calgary, (Alberta). Pages 137-144.

Rieman, B. E., and J. D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. U.S. Forest Service, Intermountain Research Station. General Technical Report INT-302.

Rieman, B. E., and J. D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varied size. Transactions of American Fisheries Society. Vol. 124 (3): 285-296.

Rieman, B. E., D. C. Lee and R. F. Thurow. 1997. Distribution, status and likely future trends of bull trout within the Columbia River and Klamath Basins. North American Journal of Fisheries Management. 17(4): 1111-1125.

Sexauer, H. M. and P. W. James. 1993. A survey of the habitat use by juvenile and prespawning adult bull trout, *Salvelinus confluentus*, in four streams in the Wenatchee National Forest. Ellensburg, WA, Central Washington University.

Summerfelt, R. C. and L. S. Smith. 1990. Anesthesia, surgery and related techniques. Pages 213-272 In: C. B. Shreck and P. B. Moyle, editors. Methods of fish biology. American Fisheries Society Symposium 7, Bethesda, Maryland.

U.S. Fish and Wildlife Service. 2002. Chapter 22, Upper Columbia Recovery Unit, Washington. 113 p. In: U.S. Fish and Wildlife Service. Bull Trout (*Salvelinus confluentus*) Draft Recovery Plan. Portland, Oregon.

Volk, E. C. 2000. Using otolith strontium to infer migratory histories of bull trout and Dolly Varden from several Washington State rivers. Submitted to Olympic National Park in fulfillment of Contract #2550041. Washington Department of Fish and Wildlife, Olympia.

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LGL and Douglas PUD. 2008a. Adult Pacific Lamprey Passage Evaluation. Wells Hydroelectric Project. No. 2149. Prepared by LGL Limited, Ellensburg, WA. Prepared for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

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ADULT PACIFIC LAMPREY PASSAGE AND BEHAVIOR STUDY AQUATIC ISSUE 6.2.1.3

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

February 2008

Prepared by:
LGL Limited Environmental Research Associates
Ellensburg, Washington

and

Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509) 884-7191
E-Mail: relicensing@dcpud.org

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ABSTRACT

An adult Pacific lamprey (*Lampetra tridentata*) passage and behavior study was conducted at Wells Dam in 2007 in accordance with the Integrated Licensing Process (ILP) as promulgated by FERC regulations. The goal of this study is to evaluate the effect of the Wells Project and its operations on adult Pacific lamprey upstream migration and behavior as it relates to fishway passage, timing, and downstream passage events (drop back) through the dam. This information will be used to help identify potential areas of passage impediment within the Wells fishways. Specific objectives of the study include: 1) Conduct a literature review of existing adult Pacific lamprey passage studies at Columbia and Snake river dams; 2) identify methods for capturing adult Pacific lamprey at Wells Dam; 3) document the timing and abundance of radio-tagged lamprey passage through Wells Dam; 4) determine whether adult lamprey are bypassing the adult counting windows at Wells Dam; 5) where sample size is adequate, estimate passage metrics including fishway passage times and efficiencies, residence time between detection zones, and downstream passage events (drop back); and 6) if necessary, identify potential areas of improvement to existing upstream fish passage facilities for the protection and enhancement of adult lamprey at the Wells Project.

A review of past adult lamprey passage studies indicated commonalities among lamprey behavior at hydroelectric projects and trapping methodologies were developed to capture adult lamprey at Wells Dam. During the 2007 study, 21 lamprey were captured, surgically radio-tagged, and released. Of these fish, 10 were released into the tailrace and 11 were released into the fishway between mid-August and early October. One tailrace-released fish was recaptured and re-released into the fishway, bringing total ladder releases to twelve. Ten of the twelve (83%) lamprey released into the middle fishway successfully ascended, with a median upper fishway passage time of 7.9 hours. Seven of the ten (70%) lamprey released into the tailrace were detected at the outside of a fishway entrance. Only one of these seven (14%) lamprey entered into the collection gallery and ascended the fishway with a lower fishway passage time of 6.1 hours and upper fishway passage time of 5.9 hours. This fish, along with at least one mid-ladder release, traveled through some portion of the auxiliary water supply (AWS) chamber. Including one tailrace-released fish, 6 of 11 (55%) tagged-lamprey that ascended the upper fishway were detected inside the video bypass area. Three of the eleven (27%) fish that exited the ladder passed through the upper fish ladder without being observed at the counting window. No drop backs were detected by fish that exited the fishway. These results suggest that: 1) lamprey are having difficulty negotiating the fishway entrance; 2) lamprey are passing the upper fishway at high rates, in a reasonable amount of time, and with negligible drop back within the ladder; and 3) some lamprey are bypassing the adult counting windows.

1.0 INTRODUCTION

1.1 General Description of the Wells Hydroelectric Project

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington. Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from the Rocky Reach Hydroelectric Project owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Public Utility District No. 1 of Douglas County (Douglas PUD). It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides the hydrocombine, which is 1,130 feet long, 168 feet wide, with a crest elevation of 795 feet in height.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The normal maximum surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at elevation of 781. The normal maximum water surface elevation of the reservoir is 781 feet (Figure 1.1-1).

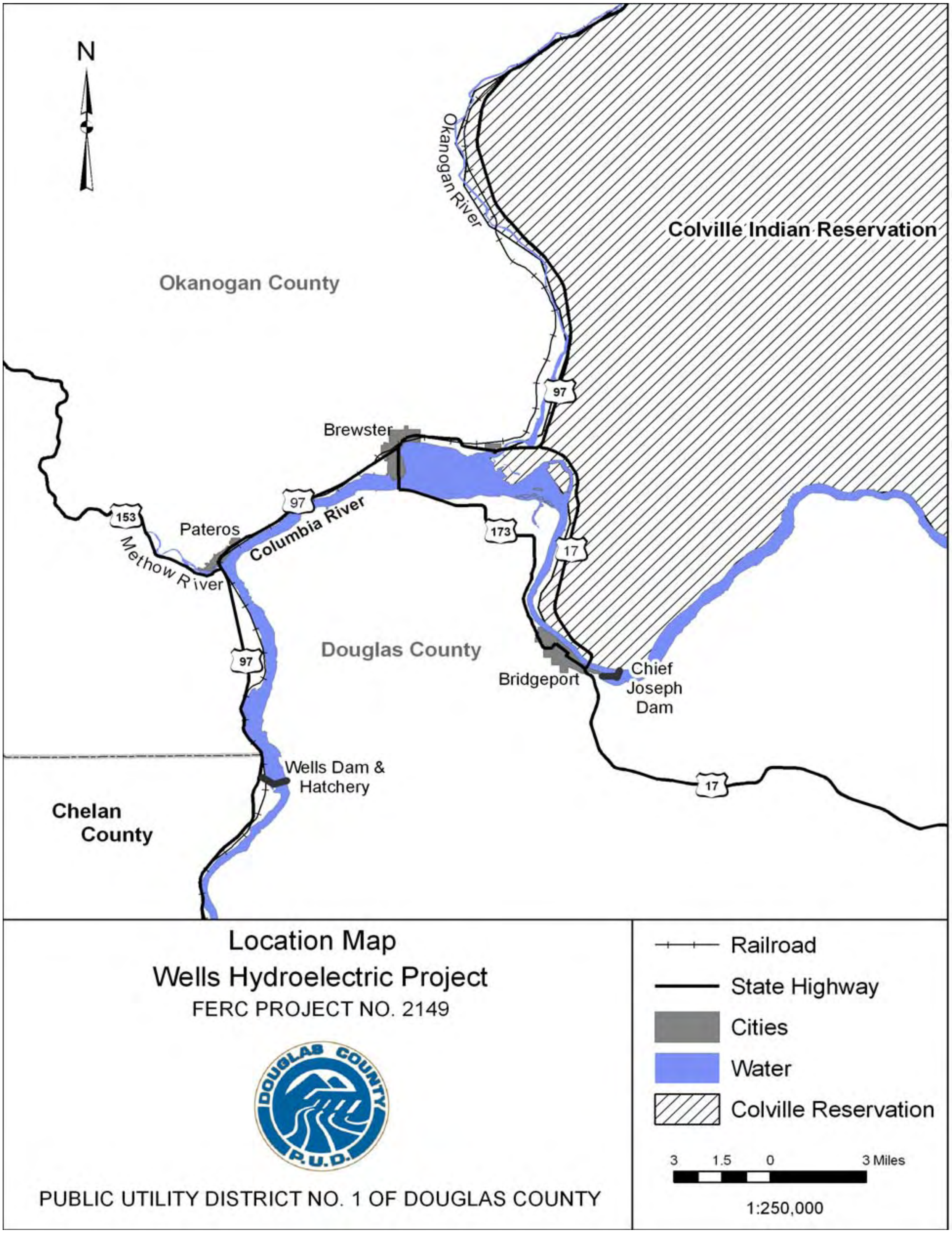


Figure 1.1-1 Location map of the Wells Project

1.2 Relicensing Process

The current Wells Project license will expire on May 31, 2012. Douglas PUD is using the Integrated Licensing Process (ILP) as promulgated by FERC regulations issued July 23, 2003 (18 CFR Part 5). Various state and federal agencies, tribes, local governments, non-governmental organizations and the general public will participate in the Wells Project ILP. During the ILP, information needs related to the relicensing of the Wells Project will be identified. All study plans intended to meet these information needs will be prepared in a manner that addresses each of the required seven FERC criteria described in 18 CFR § 5.9(b).

18 CFR § 5.9(b) Content of study request. Any information or study request must:

(1) Describe the goals and objectives of each study and the information to be obtained;
(2) If applicable, explain the relevant resource management goals of the agencies or Indian tribes with jurisdiction over the resource to be studied;
(3) If the requester is not a resource agency, explain any relevant public interest considerations in regard to the proposed study;
(4) Describe existing information concerning the subject of the study proposal, and the need for additional information;
(5) Explain any nexus between project operation and effects (direct, indirect, and/or cumulative) on the resource to be studied, and how the study results would inform the development of license requirements;
(6) Explain how any proposed study methodology is consistent with generally accepted practices in the scientific community or, as appropriate, considers relevant tribal values and knowledge. This includes any preferred data collection and analysis techniques, or objectively quantified information, and a schedule including appropriate field season(s) and the duration;
(7) Describe considerations of level of effort and cost, as applicable, and why any proposed alternative studies would not be sufficient to meet the stated information needs.

All study plans submitted to FERC will be reviewed by Douglas PUD and the applicable Resource Work Group(s) to determine if studies proposed will fill the information needs related to the Wells Project Relicensing. Any dispute over alternative study methods, that cannot be reconciled with stakeholders, will be decided by FERC.

2.0 GOALS AND OBJECTIVES

The goal of this study is to evaluate the effect of the Wells Project and its operations on adult Pacific lamprey upstream migration and behavior as it relates to fishway passage, timing, and downstream passage events (drop back) through the dam. This information will be used to help identify potential areas of passage impediment within the Wells fishways.

Specific objectives of the study include:

- Conduct a literature review of existing adult Pacific lamprey passage studies at Columbia and Snake river dams;
- Identify methods for capturing adult Pacific lamprey at Wells Dam;

- Document the timing and abundance of radio-tagged lamprey passage through Wells Dam;
- Determine whether adult lamprey are bypassing the adult counting windows at Wells Dam;
- Where sample size is adequate, estimate passage metrics including fishway passage times and efficiencies, residence time between detection zones, and downstream passage events (drop back); and
- If necessary, identify potential areas of improvement to existing upstream fish passage facilities for the protection and enhancement of adult lamprey at the Wells Project.

3.0 STUDY AREA

The study area includes Wells Dam, the Wells Dam tailrace, and the Wells Dam forebay (Figure 1.1-1).

4.0 BACKGROUND AND EXISTING INFORMATION

Pacific lampreys are present in most tributaries of the Columbia River and in the mainstem Columbia River during their migration stages. They have cultural, utilitarian and ecological significance in the basin since Native Americans have historically harvested them for subsistence, ceremonial and medicinal purposes (Close et al., 2002). As an anadromous species, they also contribute marine-derived nutrients to the basin. Little specific information is available on the life history or status of lamprey in the mid-Columbia River watersheds. They are known to occur in the Methow, Wenatchee and Entiat rivers (NMFS, 2002) and recently have been captured during juvenile trapping operations in the Okanogan River.

In general, adults are parasitic on fish in the Pacific Ocean while ammocoetes (larvae) are filter feeders that inhabit the fine silt deposits in backwaters and quiet eddies of streams (Wydoski and Whitney, 2003). Adults generally spawn in low-gradient stream reaches in the tail areas of pools and in riffles, over gravel substrates (Jackson et al., 1997). Adults die after spawning. After hatching, the ammocoetes burrow into soft substrate for an extended larval period filtering particulate matter from the water column (Meeuwig et al., 2002). The ammocoetes undergo a metamorphosis, between 3 and 7 years after hatching, and migrate from their parent streams to the ocean from October to April (Close et al., 2002). Adults typically spend 1-4 years in the ocean before returning to freshwater tributaries to spawn.

Pacific lamprey populations of the Columbia River have declined in abundance over the last 40 years according to counts at dams on the lower Columbia and Snake rivers (Close et al., 2002). Starke and Dalen (1995) reported that adult lamprey counts at Bonneville Dam that regularly exceeded 100,000 fish in the 1960's and more recently have ranged between 20,000 and 120,000 for the period 2000-2004 (DART- www.cqs.washington.edu/dart/adult.html).

Close et al. (2002) identified several factors that may account for the decline in lamprey counts in the Columbia River Basin. This includes reduction in suitable spawning and rearing habitat from flow regulation and channelization, pollution and chemical eradication, reductions of prey in the ocean, and juvenile and adult passage problems at dams (Nass et al., 2005).

Returning adult Pacific lamprey have been counted at Wells Dam since 1998. Between the years of 1998 and 2007, the numbers of lamprey passing Wells Dam annually has averaged 350 fish and ranged from 21 fish in 2006 to 1,410 fish in 2003 (Table 4.0-1). The relatively small number of adult lamprey observed at Wells Dam can be attributed to fact that the Wells Project is the last passable dam on the mainstem Columbia River and the fact that the Wells Project is over 500 miles upstream from the Pacific Ocean. Pacific lamprey counts for Columbia and Snake river dams are presented in Table 4.0-1 and 4.0-2.

Table 4.0-1 Pacific lamprey counts at Columbia River mainstem dams, by dam and year, 1997-2007.

Year	Bonneville	The Dalles	John Day	McNary	Priest Rapids	Rock Island	Rocky Reach	Wells
1997	20,891	6,066	9,237	.	.	.	.	.
1998	.	.	.	.	.	.	.	343
1999	.	.	.	.	.	.	.	73
2000	19,002	8,050	5,844	1,281	.	822	767	155
2001	27,947	9,061	4,005	2,539	1,624	1,460	805	262
2002	100,476	23,417	26,821	11,282	4,007	4,878	1,842	342
2003	117,035	28,995	20,922	13,325	4,340	5,000	2,521	1,410
2004	61,780	14,873	11,663	5,888	2,647	2,362	1,043	647
2005	26,667	8,361	8,312	4,158	2,598	2,267	404	214
2006	38,941	6,894	9,600	2,459	4,383	1,326	370	21
2007	19,304	6,083	5,753	3,454	6,593	1,300	696	35
Total	432,043	111,800	102,157	44,386	26,192	19,415	8,448	3,502
Min	19,002	6,066	4,005	1,281	1,624	822	370	21
Max	117,035	28,995	26,821	13,325	6,593	5,000	2,521	1,410
Average	48,005	12,422	11,351	5,548	3,742	2,427	1,056	350
SD	37,162	8,364	7,611	4,417	1,631	1,632	750	416

Table 4.0-2 Pacific lamprey counts at Snake River mainstem dams, by dam and year, 1996-2007.

Year	Ice Harbor	Lower Monumental	Little Goose	Lower Granite
1996	737	.	.	490
1997	668	.	.	1,122
1998	.	.	.	.
1999	.	.	.	.
2000	315	94	71	28
2001	203	59	104	27
2002	1,127	284	365	138
2003	1,702	476	660	282
2004	805	194	243	122
2005	461	222	213	42
2006	277	175	125	35
2007	290	138	72	34
Total	6,585	1,642	1,853	2,320
Min	203	59	71	27
Max	1,702	476	660	1,122
Average	659	205	232	232
SD	469	130	200	346

Lamprey pass Wells Dam from early July until late November with peak passage times between mid-August and late October (Figure 4.0-1). In all years since counting was initiated, Pacific lamprey counts at the east fish ladder are greater than at the west fish ladder. It is important to note that historically, counting protocols were designed to assess adult salmonids and did not necessarily conform to lamprey migration behavior (Moser and Close 2003). Traditional counting times for salmon did not coincide with lamprey passage activity which occurs primarily at night; the erratic swimming behavior of adult lamprey also makes them inherently difficult to count (Moser and Close, 2003). Furthermore, Beamish (1980) noted that lamprey overwinter in freshwater for one year prior to spawning. Consequently, lamprey counted in one year may actually have entered the system in the previous year (Moser and Close, 2003) which confounds annual returns back into the Columbia River Basin. It is unknown to what degree these concerns are reflected in Columbia River lamprey passage data. However, it is important to consider such caveats when examining historic lamprey count data at Columbia River dams including Wells Dam.

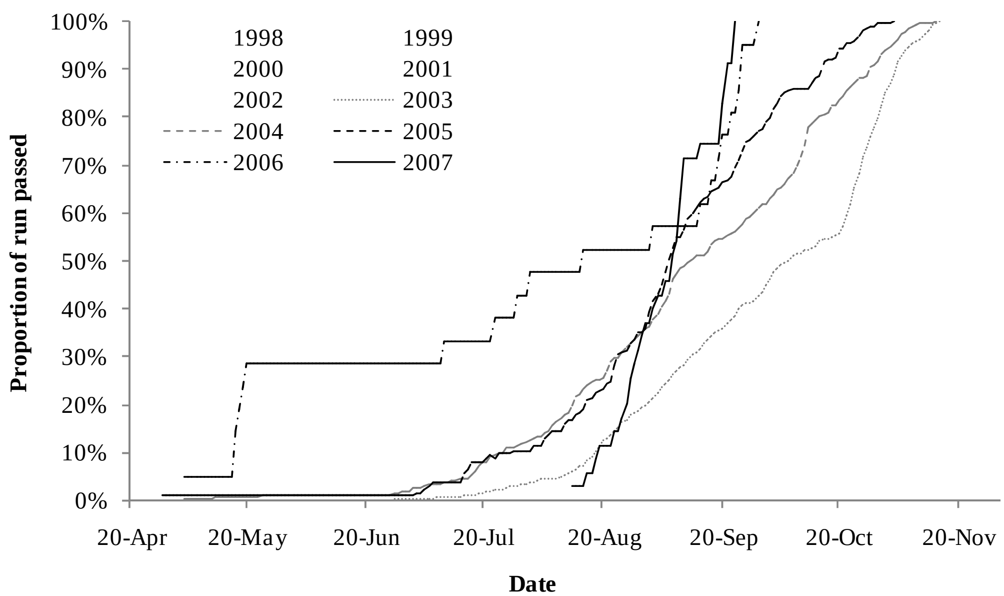


Figure 4.0-1 **Run timing of Pacific lamprey at Wells Dam by year, 1998-2007. Years 1998-2002 are lightened to allow better view of past five years (in grayscale).**

Until recently, relatively little information was available on Pacific lamprey in the mid-Columbia River Basin. However, with increased interest in the species coupled with a petition for listing under the ESA, the mid-Columbia PUDs have started to initiate studies to address Pacific lamprey passage and migratory behavior in their respective project areas.

The study of adult Pacific lamprey migration patterns past dams and through reservoirs in the lower Columbia River has provided the first data sets on lamprey passage timing, travel times, and passage success at hydroelectric projects (Vella et al., 2001; Ocker et al., 2001; Moser et al., 2002a; Moser et al., 2002b). These studies have shown that approximately 90% of the radio-tagged lamprey released downstream of Bonneville Dam, migrated back to the tailrace below

Bonneville Dam; however, less than 50% of the lamprey which encountered a fishway entrance actually passed through the ladder exit at the dam (Nass et al., 2005).

Similar collection and passage efficiency results were observed at Rocky Reach, Wanapum and Priest Rapids dams during tagging studies conducted at those projects (Nass et al., 2003; Stevenson et al., 2005).

Of the 125 radio-tagged lampreys released approximately 7 kilometers downstream of Rocky Reach Dam, 93.6% were detected at the project, and of those fish, 94.0% entered the fishway. Of the fish that entered the Rocky Reach fishway, 55.5% exited the ladder.

During studies at Wanapum and Priest Rapids dams in 2001 and 2002, a total of 51 and 74 lamprey were radio-tagged and released downstream of Priest Rapid Dam, respectively. Over the two years of study, the proportion of fish that approached the fishway that exited the ladders was 30% and 70% at Priest Rapids and 100% and 51% at Wanapum Dam in 2001 and 2002, respectively.

Two recent reviews of Pacific lamprey (Hillman and Miller 2000; Golder Associates Ltd. 2003) in the mid-Columbia River have indicated that little specific information is known on their status (Stevenson et. al., 2005).

In 2004, Douglas PUD contracted with LGL Limited to conduct a lamprey radio-telemetry study at Wells Dam in coordination with the Chelan PUD who was conducting a similar study at Rocky Reach Dam. A total of 150 lamprey were radio-tagged and released at or below Rocky Reach Dam. The radio-tags used in this study had an expected operational life of 45 days (Nass et al., 2005). It is important to note that because of the release site of the fish was over 50 miles downstream of Wells Dam the value of the study was limited by the relatively small numbers of tagged fish observed at Wells (n=18) and the fact that many of the radio-tags detected at Wells Dam were within days of exceeding their expected battery life.

With that stated, the 2004 study at Wells was implemented through a combination of fixed-station monitoring at Wells Dam and fixed-stations at tributary mouths. Collectively, these monitoring sites were used to determine migration and passage characteristics of lamprey entering the Wells Project area. Of the 150 adult lamprey released at or below Rocky Reach in 2004, 18 (12% of 150) were detected in the Wells Dam tailrace, and ten (56% of 18) of these were observed at an entrance to the fishways at Wells Dam. Two of the 10 lamprey approached both fishways to produce 12 total entry events. A total of 3 radio-tagged lamprey passed Wells Dam prior to expiration of the tags, resulting in a Fishway Efficiency estimate of 30% (3 of 10) for the study period. A single lamprey was detected upstream of Wells Dam at the mouth of the Methow River (Nass et al., 2005).

For lamprey that passed the dam, the majority (92%) of Project Passage time was spent in the tailrace. Median time required to pass through the fishway was 0.3 d and accounted for 8% of the Project Passage time (Nass et al., 2005).

Although the 2004 study at Wells provided preliminary passage and behavioral information for migrating adult lamprey, the limited observations due to the small sample size (n=18) is insufficient in addressing the objectives set forth in Section 2.0 with statistical confidence.

4.1 Aquatic Resource Work Group

As part of the preparation for the relicensing of the Wells Project, Douglas PUD established an Aquatic Resource Work Group (RWG) which began meeting informally in November, 2005. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to collaboratively identify potential resource issues related to Project operations and relevant to relicensing, and to develop preliminary study plans to be included in the Wells Pre-Application Document (PAD).

Through a series of meetings, the Aquatic RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed Upon Study Plans. An Issue Statement is an agreed upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWGs' efforts to review the existing project information and to determine whether an issue matches with FERC's seven criteria and would be useful in making future relicensing decisions. Agreed Upon Study Plans are the finished products of the informal RWG process.

Based upon these meeting and discussions, the Aquatic RWG is proposing to include a study into the Wells PAD that would include a radio-telemetry study to assess lamprey behavior as it relates to passage, timing, drop back and upstream migration. The need for this study was agreed to by all of the members of the Aquatic RWG, including Douglas PUD. This study will help to inform future relicensing decisions and will fill data gaps that have been identified by the Aquatic RWG.

4.1.1 Issue Statement (6.2.1.3)

The Wells Project may affect adult Pacific lamprey behavior related to ladder passage, timing, drop back and upstream migration.

4.1.2 Issue Determination Statement (6.2.1.3)

Work group members have determined that this issue has a tie to the Project as it relates to lamprey migration through Wells Dam. Preliminary passage information has been collected at Wells Dam; however, the sample size of the study was limited and additional information is needed. A radio-telemetry study would be feasible to address passage, timing, drop back and upstream migration. The results of an adult lamprey passage study would be useful during the development of Protection, Mitigation and Enhancement (PME) measures.

The resource work group agrees that a radio-telemetry study to assess lamprey behavior as it relates to passage, timing, drop back and upstream migration should be conducted at Wells Dam during the two-year ILP study period.

4.2 Project Nexus

The Wells Project may affect adult Pacific lamprey behavior related to ladder passage, timing, drop back and upstream migration. This issue has a tie to the Project as it relates to lamprey migration through Wells Dam. Potential problems facing successful passage of adult Pacific lamprey at dams may be related to their unique method of movement and specific areas within fishways. Specifically, adult Pacific lamprey at other projects have experienced difficulty passing over diffusion gratings and through areas of high velocity, bright light and through orifices with squared, un-rounded edges. Typically, lamprey move through an adult fishway in a repeated series of motions consisting of attaching to the ladder floor with their mouths, surging forward, and re-attaching. The physiological response of adult Pacific lamprey to exhaustive exercise may be immediate, sometimes severe, but short-lived (Mesa el al. 2003). This may suggest that lamprey have difficulty negotiating fishways with high current velocities.

Two recent reviews of Pacific lamprey (Hillman and Miller, 2000; Golder Associates Ltd. 2003) in the mid-Columbia River have indicated that little specific information is known on their status. The 2004 study at Wells Dam provided preliminary information into the migration characteristics of adult Pacific lamprey through Wells Dam. However, it is important to note that the study was compromised by the relatively small numbers of tagged fish observed at the Project (n=18) and the fact that many of the radio-tags detected at Wells Dam were within days of exceeding their expected battery life. Combined, these factors suggest that additional lamprey passage information is needed at Wells Dam.

The proposed lamprey radio-telemetry study will assist in providing the information needed as identified by the Aquatic RWG and will inform the development of future license requirements.

5.0 METHODOLOGY

5.1 Literature Review

The literature review consisted of a search of all existing information currently available on adult Pacific lamprey passage studies at Columbia and Snake river dams. This search examined the availability of information from peer-reviewed journals, federal and state publications, academia, private industry, and grey literature. References cited from the initial literature search that are of relevance to the subject matter were also collected and added to literature database.

5.2 Telemetry Study Period

Adult Pacific lamprey were collected, sampled and tagged at Wells Dam during the 2007 peak migration period of August and September. To address lamprey passage characteristics, fixed station telemetry monitoring in the Wells Project took place from August through November 2007.

5.3 Capture, Tagging, and Release of Lamprey

5.3.1 Trapping

Adult lamprey traps were designed by Douglas PUD and LGL biologists and hydromechanics in the spring of 2007 (Appendix A). Lamprey traps used at Rocky Reach Dam were used as a base template, though modifications were made to better suit fishways at Wells Dam. The 0.6×0.4×0.6 m aluminum holding box sits along the fishway wall on the upstream side of an overflow weir. The trap passively captures fish that travel over the weir through an overflow slot adjacent to the fishway's outer wall. The trap's funnel guides lamprey from the wall and weir sill into a chute that leads to a holding box. The entire trap is affixed to the fishway wall by a track that allows operators to raise the unit out of the fishway for fish removal and cleaning (Figure 5.3-1). Traps are located between pools #39 and #40 in both fishways. The traps are numbered in ascending order, from the west most (Trap 1) to the east most (Trap 4) trap.

Figure 5.3-1 Douglas PUD adult lamprey trap, 2007. Views (clockwise from top left) from the side (at installation), front (at installation), front (active), and top (active) in the east fishway of Wells Dam.

Expected trap efficiency was based on the following assumptions: 1) only a small portion of lamprey will utilize the weir orifice to pass between fishway pools; 2) lamprey will be attracted to the reduced flow and ease of travel along the fishway wall; 3) trap escapement will be negligible; and 4) lamprey will not drop back upon encountering the trap. These assumptions were based on flow measurements, documented swimming capabilities of adult lamprey (see literature cited), and observed behavior at fishways of other hydroelectric projects (Chris Peery, University of Idaho, pers. comm.).

Trapping was initiated following the first observed lamprey at the Wells fish counting stations (12 August) and continued over a ten week period from the weeks ending on 19 August through 21 October, 2007. Traps were fished five or six days per week and checked twice daily during the morning (6:00-10:00 hrs) and evening (15:00-17:00 hrs). All fish were identified, enumerated, and bycatch was released into the fishway upstream of the trapping location. Lamprey were immediately transferred by covered buckets to insulated 1.0×0.5×0.5 m, 113 L holding tanks (Igloo MaxCold 120©) with flow-through river water (± 2°C fishway temperature, 9-12 mg/L dissolved oxygen). The maximum capacity for each tank was set at eight lamprey (roughly 30 grams of fish per liter of water), and maximum holding time prior to tagging was set at 36 hours (M. Moser, NOAA, pers. comm.; Molly Haddock, WDFW, pers. comm.).

During the latter half of the project and following discussions with the Aquatic RWG, additional lamprey were supplied to the study from trapping efforts at Rocky Reach Dam (42 miles downstream). The supplementation was in response to the low numbers of lamprey observed at Wells Dam and the desire to meet the proposed sample size target of the study (n=40). Lamprey captured at Rocky Reach Dam from 19 September to 2 October were moved to holding tanks by Chelan or Douglas PUD employees. LGL biologists visited the Rocky Reach Dam three days a week to transport fish to Wells Dam for tagging (with the 36 h maximum holding time still in place). Fish were transported by truck in a 113 L cooler filled with river water. An air tank and air stones were used to maintain proper oxygen levels. The 42-mile trip generally took an hour and lamprey were tagged as soon as possible (20-60 minutes after arrival at Wells Dam).

5.3.2 Tagging and Release

Model NTC-4-2L Nano Tags (Lotek® Newmarket, Ontario) with an 87 day battery life were used for all lamprey. The tags were set up in 5.0 second burst rates on a frequency of 148.320 MHz (channel 1), codes 100-119 and 130-149. Tag dimensions were 18.3 mm (length) by 8.3 mm (diameter), with a dry weight of 2.1 grams – less than 0.8% of total body weight for all lamprey. Research has shown that tagged and un-tagged lamprey perform similarly with radio-tags at 7.4 g or less provided adequate recovery time (Close et al., 2003). Tags were sequenced, activated, and tested prior to each surgery.

Surgical tagging methods were based on techniques described by Moser et al. (2002a), Close et al. (2003), and Stevenson et al. (2005), in combination with LGL Limited guidelines for surgical tag implantation. The tagging area was prepared with a tub containing a heavy sedation mixture and two surgery buckets, one containing a light sedation mixture and the other river water. Clove oil was used as an anesthetic, with the heavy sedation mixture prepared at 1.2 mL to 20 L of river water, and the light sedation at 1.2 mL to 10 L of river water. A few drops of Stress Coat (Aquarium Pharmaceuticals, Inc. Chalfont, PA) were added to all containers and the surgery trough to minimize effects of handling. The surgery trough was made of sectioned PVC tubing, angled to allow pooling near the head and gills of the lamprey. Tubing from the surgery buckets to the trough allowed controlled flow of either the light sedation mixture or water over the gills of the lamprey (Figure 5.3-2). Surgery tools were placed alongside the surgery trough and the radio-tag was activated and tested.

Lamprey were transferred to the heavy sedation tub prior to surgery. Fish would generally lose equilibrium after a few minutes and were usually adequately anesthetized within eight minutes. The lamprey was then removed from the solution, weighed to the nearest gram, measured to the nearest 0.5 cm (length and girth), and placed into the surgery trough. The light sedation bucket was activated to maintain unconsciousness during the procedure. A 1.5-2.0 cm incision was made approximately 1 cm above the ventral midline with the posterior end of the cut ending in line with the anterior insertion of the first dorsal fin. The catheter was inserted and pushed through the outside wall of the stomach cavity, approximately 3 cm posterior to the incision (Figure 5.3-3). The radio-tag antenna was threaded through the catheter and the tag was inserted into the stomach cavity. Liquimycin was applied to the stomach cavity and 2-3 sutures were used to close the incision. A 19-mm needle was used, with 3-0 absorbable surgical sutures. A light coat of Polysporin ointment was applied to the closed incision and the fish was subsequently moved to the recovery tank.

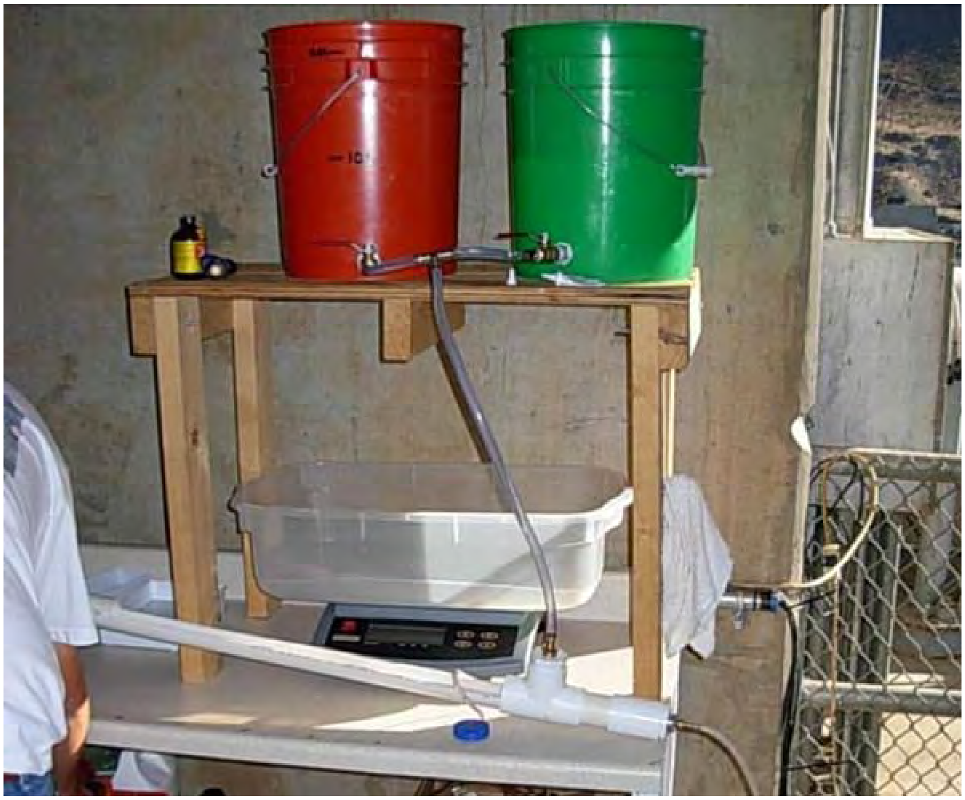


Figure 5.3-2 Lamprey tagging trough, surgery buckets, scale, and platform.

Figure 5.3-3 Radio-tag and data form (left) and incision and catheter prior to tag insertion during the surgery process.

Fish were transferred to the release container following roughly one hour in the recovery tank. A 19 L bucket was used for fishway releases. The bucket was placed into the recovery tank and the lamprey was collected (i.e., scooped) with 8-10 L of water. The covered bucket was lowered by rope into Pool #43 (between the above trap and below trap antennas), the lid was removed, and the lamprey was allowed volitional release from the container into the fishway. A 6” PVC tube approximately 1.2 meters long was used for tailrace releases. The container was closed at the bottom end to retain water and had attachment rings at both ends. The tube was filled with approximately 15 L of river water and a tagged lamprey was inserted head-first into the container. The tube was then lowered upright by a pulley system into the tailrace. The “head” or downward side of the tube was then lifted as to allow the fish to back out of the container into the tailrace. Both release methods typically took less than 10 minutes.

5.4 Telemetry Array

5.4.1 Fixed Stations

The movement and passage of radio-tagged lamprey was documented by combining detection data collected using underwater and aerial antenna arrays (dipoles and yagi antennas) at Wells Dam (Figure 5.4-1). The arrays were designed to monitor movements of radio-tagged lamprey from the Columbia River into the fishway entrances and through the exits at Wells Dam, and were also designed to detect downstream passage movements. Aerial antennas were used in the tailrace, at remote stations on tributary mouths, and during mobile tracking. Underwater antennas were used in the fishways. A total of 8 Lotek telemetry receivers, monitoring multiple arrays (6 at Wells Dam, 1 at Methow River, and 1 at Okanogan River) were used during the study.

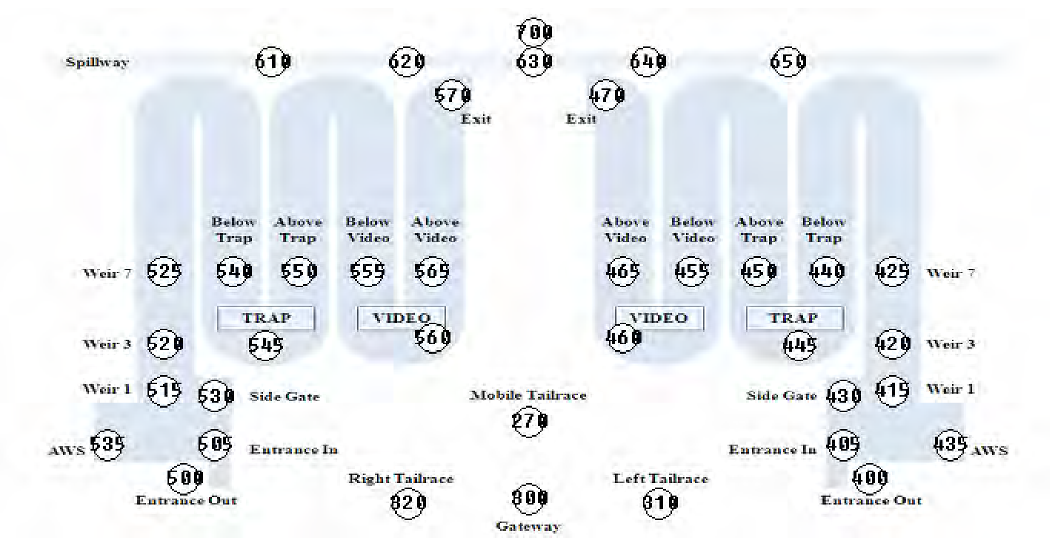


Figure 5.4-1 Radio-telemetry array at Wells Dam by station number, 2007. Underwater arrays were added to the video bypass (stations 560 and 460) to determine use by tagged lamprey.

5.4.2 Mobile Tracking

Mobile tracking was conducted by boat in a 2 km reach of the river below Wells Dam. Tracking was recorded using Global Positioning System (GPS) with a built-in data logger. Twin three-element aerial antennas were mounted to a post and secured in the boat. Surveys were conducted by transects running upstream and downstream in the river with the aerials pointed in opposite directions, and usually at each bank.

5.4.3 Data Analyses

The data collected was analyzed using Telemetry Manager, Ascent and other computer programs developed in Visual FoxPro by LGL Limited. In order to differentiate detection locations and streamline analyses, individual antennas were grouped into "zones" that define pivotal areas of interest, such as individual fishway entrances and exits (Nass et al., 2005).

Telemetry Manager imports raw ASCII data files downloaded from the Lotek SRX receivers. After importing the raw files, Telemetry Manager constructs an initial database containing records for each logged data transmission from the tagged fish. Telemetry Manager then edits the database to remove records that do not meet the criteria identified for valid data records. Examples of invalid data include background noise at the Project, records with a signal strength that are below a given threshold, single records for a given fish-location combination, and records that were recorded before the official release time and date. After filtering the invalid records, Telemetry Manager constructs an operational database that summarizes the time of arrival and departure from each zone of interest ("benchmark times").

5.4.4 Definition of Passage and Residence Times

Strategic deployment of receivers and antennas made it possible to determine the amount of time that each lamprey spent in the tailrace, fishway entrances, and fishways. Passage times were calculated from benchmark dates and times corresponding to the first and last detection of a given radio-tagged lamprey at specific locations. At Wells Dam, the benchmark times for lamprey that pass the Project were:

1. first detection in the tailrace,
2. first detection at the fishway entrance of passage,
3. last detection at the fishway entrance of passage, and
4. last detection at the fishway exit.

From these benchmark times, passage times were calculated for the following passage segments:

Segment	Time	Name
A)	1 to 2	Tailrace Passage time
B)	2 to 3	Entrance Passage time
C)	3 to 4	Fishway Passage time
D)	1 to 4	Project Passage time

From the benchmark times at each of the monitored locations, the passage times and passage efficiencies (proportions) were calculated for each radio-tagged lamprey where,

Passage Efficiency for a section of the fishway = No. tags at a fishway detection zone (above)/ No. tags at the fishway zone (below), or No. tags at a fishway detection zone / No. tags at an entrance.

It then follows that:

Fishway Efficiency = No. of tags at an exit / No. of tags at an entrance.

In addition to the above standard passage segments, a detailed analyses of the time lamprey spent in and between detection zones (i.e., residence time) in the Wells Dam fishways were conducted.

The primary residence time analyses include:

- Entrance – at the entrance (first to last detection),
- Between the Entrance and Upper Collection Gallery (last detection to first detection),
- Upper Collection Gallery - the first vertical wall in the fishway (first to last detection),
- Between Upper Collection Gallery and Fishway Transition (last detection to first detection),
- Fishway Transition – first section of orifice weirs which are usually inundated with water depending on the water elevation in the tailrace (first to last detection),
- Between Fishway Transition and Below Trap (last detection to first detection),
- Below Trap - just downstream of the adult trapping facility (first to last detection),
- Between Below Trap and Above Trap (last detection to first detection),
- Above Trap – mid-point in series of orifice weirs between the trap and the video station (first to last detection),
- Between Above Trap and Below Video (last detection to first detection),
- Below Video – just downstream of the video station (first to last detection),
- Between Below Video and Above Video (last detection to first detection),
- Above Video – just upstream of the video station (first to last detection),
- Between Above Video and Exit (last detection to first detection), and
- Exit- fishway exit to forebay (first to last detection).

The residence and passage times for each radio-tagged lamprey will be determined by working backwards through a sequence of detections. The fishway of ultimate passage and the respective passage time is determined by identifying a sequence of detections in the ascent of a fishway, starting with detections in a fishway exit zone.

5.4.5 Definition of Downstream Passage Events and Drop Back

For the purpose of analysis, a downstream passage event is defined as a tag that is detected at a fishway exit and subsequently detected in the tailrace or a fishway entrance without any detections at antennas monitoring the inside fishway zones. Drop back is defined as those tags in a fishway detection zone that are subsequently detected in zones directly downstream in the fishway.

6.0 RESULTS

6.1 Literature Review

6.1.1 Lower-Columbia River Dams

Millions of dollars and dozens of projects have been dedicated to Pacific lamprey research and restoration since 1994 when the Bonneville Power Administration (BPA) funded studies on the Umatilla Indian Reservation (Stone, 2004). Since then, a majority of this research has been conducted by federal, state, and academic institutions on the lower-Columbia River (e.g., Close et al., 1995; Jackson et al., 1997; Close et al., 2002). Radio-telemetry work to examine adult lamprey interactions with lower Columbia River dams began in 1997, ultimately leading to several peer-reviewed publications on entrance efficiency (Moser et al., 2002a), passage efficiency (Moser et al., 2002b), migration rates (Moser et al., 2005), and population status (Moser and Close 2003). This is the most substantial body of work regarding Pacific lamprey and their migratory behavior in the Pacific Northwest. The resulting publications detailed the following information for the first time:

- Most (~90%) lamprey re-approach hydroelectric projects after being radio-tagged and released downstream.
- Entrance efficiency (successful entrants divided by the number that approach) of adult lamprey is around 50% at lower Columbia River dams. Approaches are more frequent during the night (22:00-01:00) and lamprey typically make multiple entrance attempts.
- Entrance type and configuration has a significant effect on entrance efficiency, and increased attachment surface may be more important than decreased water velocity.
- Passage success through fishways is generally lowest in collection galleries and transition zones, often in areas with inadequate attachment surfaces (e.g., diffuser grating, 90° corners). Passage through fish counting areas is also low in some cases, likely due to the bright lights, confusing currents, and narrowing channels with relatively higher water velocities.
- Counts at hydroelectric dams are often unreliable and can be misleading, regularly underestimating losses between dams and exaggerating time to pass through reservoirs
- Overall passage efficiency (number that ascended the fishway divided by the number that approach) of lamprey is 38-47% at Bonneville Dam, 50-82% at The Dalles Dam, and generally less than 40% at John Day Dam. The median passage time from first detection at an entrance to fishway exit ranges from 2.0 to 5.7 days at these dams. Little to no drop back occurs once lamprey have successfully ascended a fishway and passed a dam.
- Travel times between Bonneville, The Dalles, and John Day dams (i.e., time to migrate through the reservoirs between each dam) are generally on the order of 3-4 days between projects.
- On average, only 3% of lamprey tagged below Bonneville were detected upstream from John Day on the Columbia River, largely due to low passage efficiency and the movement of some fish into Columbia River tributaries (e.g. Deschutes River).

These findings have led to more detailed research to identify obstacles, develop passage improvements, and to better understand physiological performance of lamprey while migrating through Columbia River dams (Mesa et al., 2001; Close et al., 2003; Mesa and Moser 2004).

6.1.2 Mid-Columbia River Dams

Radio-telemetry studies have been completed at four of the five passable mid-Columbia dams (Priest Rapids, Wanapum, Rocky Reach, and Wells (discussed earlier) dams) to evaluate adult Pacific lamprey passage (Figure 6.1-1). Study results from Priest Rapids and Wanapum dams (2001-2002) indicated that entrance efficiency averaged over 50% at both dams (Nass et al. 2003). Overall passage efficiency was 30-70% at Priest Rapids Dam and over 50% at Wanapum Dam. Decreased passage rates were noticed at count stations in both dams, and in the lower fishway at Priest Rapids Dam, presumably due to similar conditions identified by Moser et al. in lower Columbia River dams (2002a; 2002b). Median total fishway passage times (first detection at fishway entrance to exit) at Priest Rapids and Wanapum dams ranged from 1.1 to 1.8 days. Overall, these data suggest that passage through these two projects is comparable to lower Columbia River dams, though overall passage efficiency and median total passage times are considerably lower.

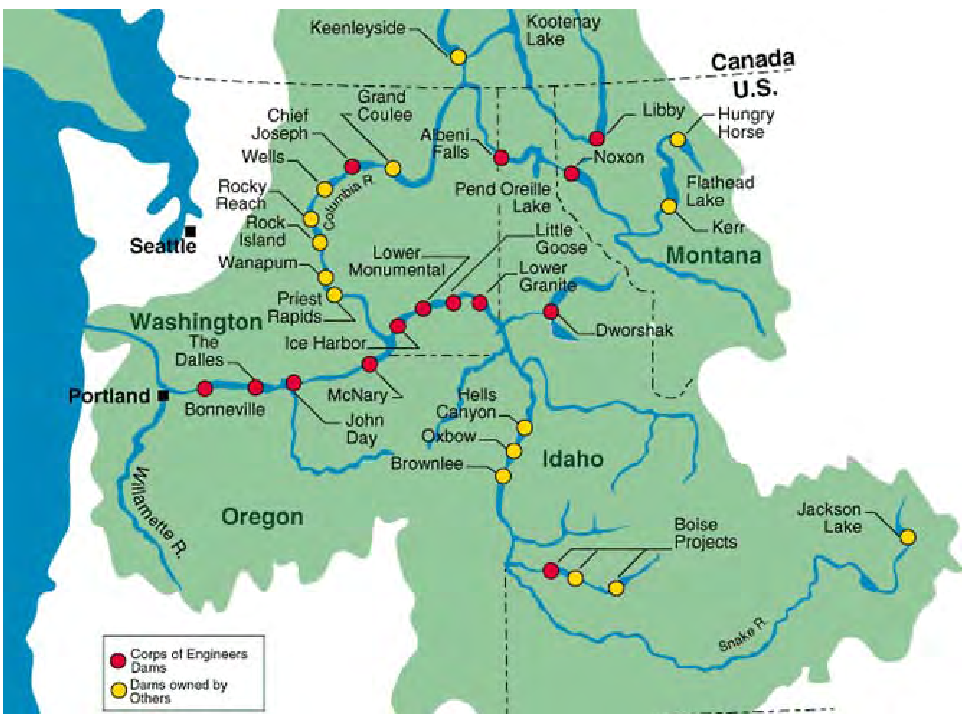


Figure 6.1-1 Columbia River system dams (from www.nwd-wc.usace.army.mil/report/colmap.htm).

Radio-telemetry work conducted at Rocky Reach Dam in 2004 indicated that fishway passage efficiency of tagged adult lamprey was over 50% (Stevenson et al. 2005). Radio-tagged adult lamprey at Rocky Reach Dam had the highest entrance efficiency (94%) and drop back rate

(22%) of all the previously studied mainstem dams. To account for fish that re-ascended, a "Net Ladder Passage Efficiency" (NLPE) was calculated to provide a comparative measure of the number of tagged lamprey detected in the tailrace to the number that ultimately ascended the fishway. The NLPE was greater at Rocky Reach (47%) than observed at other mainstem dams, except for Wanapum Dam (48.9%). However, this metric may be slightly misleading by negating the energetic costs of re-ascent and potential consequences to survival and reproduction (Mesa et al. 2001). Exclusion of these fish equals an overall passage efficiency of 42%. Results also indicated that a portion (>15%) of tagged lamprey that did not successfully pass the dam were last detected in the fishway, with some of those fish likely entering into the attraction water system. Median migration rates of tagged lamprey through the Rocky Reach fishway were reported at 1.0 m/min from the base of the lower fishway to the flow regulation diffuser (~60 m downstream of the exit), and less than 0.1 m/min from the diffuser to the fishway exit. The slowest median rates were observed through the upper section of the fishway. This observation may be attributed to the diffuser, Pickett barrier, public viewing windows, and fish counting station located in the upper fishway. Median total fishway passage time at Rocky Reach Dam was less than 1.0 day (Stevenson et al. 2005). Aside from the substantially greater entrance efficiency and drop back rate, these data suggest that overall passage efficiency through Rocky Reach Dam is comparable to other Columbia River dams.

6.1.3 Snake River Dams

Radio-telemetry work to assess Pacific lamprey behavior at the four passable lower Snake River dams (Figure 6.1-1) began in 2005 (Peery et al., 2006). The ongoing research is intended to collect baseline information on potential obstacles and passage success of migrating adult lamprey. Fish counts at these dams suggest that few lamprey that pass McNary Dam are observed at Ice Harbor Dam (12% on average), and an average of roughly 650 adult lamprey ultimately pass the project annually since 2000 (range 290-1,702; DART 2008). Researchers have reported an entrance efficiency of less than 50% for Ice Harbor Dam, although this is based on a small sample size from preliminary work (Peery et al., 2006). Further research is planned to obtain more detailed information and determine what set of conditions are associated with the decision made by adult lamprey to enter the Snake River or continue up the Columbia River (Peery et al., 2006).

6.2 Capture, Tagging, and Release of Lamprey

6.2.1 Trapping

The four adult lamprey traps were checked 112 times each over the 10-week trapping period (56 days of effort per trap). Trapping was extended past the original end date of 30 September in hopes of catching more lamprey, but ended unsuccessfully after three additional weeks in October. Four hundred ninety-nine (499) fish were caught, including 21 jack Chinook salmon (*Oncorhynchus tshawytscha*), 388 chub/suckers (peamouth *Mylocheilus caurinus,* chiselmouth *Acrocheilus alutaceus*, and suckers (Catostomids)), 6 Pacific lamprey, 9 rainbow trout/steelhead (*O. Mykiss*), 68 pikeminnow (*Ptychocheilus oregonensis*), and 7 jack sockeye salmon (*O. nerka*) (Table 6.2-1). A majority of the total catch was composed of chubs, suckers, and pikeminnow (91%), and numbers were greatest during the third week of trapping (week ending 2 September,

Table 6.2-2). Over 60% of the total catch and 100% of all lamprey were removed during the morning checks (i.e., fish were captured overnight and early morning), leaving only bycatch observed during daytime trapping effort (37% of the total trapped).

Table 6.2-1 Total fish captured by species and trap number (traps labeled west to east), 2007.

Species	Trap 1	Trap 2	Trap 3	Trap 4	Total	Percent
Chinook salmon	4	3	1	13	21	4.2%
Chub/Sucker	78	51	55	204	388	77.8%
Pacific Lamprey	2	2	1	1	6	1.2%
O. Mykiss	.	3	.	6	9	1.8%
Pikeminnow	10	8	18	32	68	13.6%
Sockeye salmon	.	2	4	1	7	1.4%
Total	94	69	79	257	499	100%

Table 6.2-2 Total fish captured by species and week of trapping, 2007.

	Week of trapping (weeks ending 08/19 through 10/21)										
Species	1	2	3	4	5	6	7	8	9	10	Total
Chinook salmon	1	.	1	15	3	1	.	.	.	.	21
Chub/Sucker	26	16	337	6	.	3	.	.	.	.	388
Pacific Lamprey	4	.	.	1	1	.	.	.	.	.	6
O. Mykiss	4	.	1	.	4	.	.	.	.	.	9
Pikeminnow	3	4	21	27	12	1	.	.	.	.	68
Sockeye salmon	6	1	.	.	.	.	.	.	.	.	7
Total	44	21	360	49	20	5	0	0	0	0	499

Six lamprey were caught, four of which were caught in the first week of trapping. All fish were in excellent condition at the time of capture. Four lamprey were caught in Trap 1 and Trap 2 (the west fishway traps), and two lamprey were caught in Trap 3 and Trap 4 (the east fishway traps). Trapping efficiency was much lower than expected as indicated by counts at the video count station located upstream of the traps. Out of the 35 lamprey observed by fish enumerators, only 12 were handled by LGL/Douglas PUD biologists, indicating that at least 23 lamprey bypassed the trap. Considering that some portion of lamprey that ascend Wells Dam fishways were bypassing the count station (discussed later), it is reasonable to believe that trapping efficiency in 2007 was less than 25%.

Traps appeared to operate well, except Trap 3 where upwelling sometimes created a gap between the trap entrance and the weir sill (first noticed on 6 September). Weight was added to the trap beginning 8 September to help maintain its position. To test escapement, an adult lamprey that did not meet size criteria for tagging was placed in Trap 3 during an evening check on 21 September. The fish was gone the following morning indicating that trap escapement was also a potential issue. This was not recognized until the end of the lamprey migration and no modifications were made to the traps.

Fifteen lamprey were transferred from Rocky Reach Dam on 6 occasions between 20 September and 3 October. Though additional handling occurred with these fish, there were no indications of problems with the transport, and fish behaved similarly to lamprey captured at Wells Dam. Lamprey captured at Rocky Reach Dam were slightly larger than fish from Wells (1% longer, 9% heavier, and 3% thicker on average), though this difference was not significant.

6.2.2 Tagging and Release

Twenty-one (21) lamprey were tagged between 14 August and 2 October (Appendix B). These fish averaged 66 cm in total length (54-73 cm) and 0.42 kg in weight (0.27-0.53 kg). The girth of these fish averaged 10.4 cm, ranging from 9.0 to 11.5 cm. Two fish were identified as females when oocytes were noticed during surgery. Sex was not determined in any other lamprey. Total surgery time averaged 13.7 minutes (9.5-21.5 min), including an average 7.9 minutes (5.3-16.8 min) of heavy sedation and 5.8 minutes (4.1-10.5 min) of light sedation/surgery. Recovery time averaged 1.5 hours (0.8-2.6 hrs) excluding one fish that was held overnight (16 hrs) to ensure adequate recovery after irregular bleeding during surgery. Fish generally showed immediate signs of recovery and appeared to be in good to excellent shape prior to release.

6.3 Telemetry Array

Fixed stations were downloaded bi-weekly throughout the study period. No problems occurred with receivers or antenna arrays. Two mobile tracking surveys also were completed. The first survey was conducted on 18 September to search for tagged lamprey below the dam. Several transects were completed across the tailrace with no detections. One tag (later considered to be a shed or mortality) was detected in the alcove area of the east tailrace. A snorkel survey of this area was conducted to look for the fish, tag, or any evidence. The substrate was mostly covered by large riprap and most of the crevasses could not be examined. No lamprey were observed and the tag was not recovered. Another mobile tracking survey was conducted on the evening of 23 October to search for 9 tagged lamprey below the dam. The survey was scheduled for the evening (sundown to past midnight) in hopes of increased activity and detection ability of the nocturnal fish. Five of the nine missing tags were detected, three of which were found using a deep-water (10-25 m) antenna in the tailrace.

The DIDSON was deployed during the mobile survey conducted on 18 September to assess the value for imaging lamprey on or near structures along the face of the dam. The DIDSON was deployed from a pole mount and aimed either downward or laterally at variable depths, and imaging data were collected as the boat moved slowly along the dam face. Areas surveyed included spillway structures at turbine units 1, 2, 9 and 10, guidance walls and entrances to fishways, and riprap areas at the east and west ends of the dam. No lamprey were observed, though numerous images resembling adult salmonids were collected. Given the high resolution images of structure and individual fish that were acquired, the DIDSON would have likely captured images of lamprey had they been present during the survey.

Thirty-five (35) lamprey were observed by fish enumerators between 12 August and 23 September. Water temperatures averaged 19.7 °C (range 18.3-20.4 °C) during lamprey observations and fish were equally distributed between ladders (± 3%). Similar to observations at other dams on the Columbia River, lamprey movement in Wells Dam fishways occurs almost exclusively at night. The earliest (in relation to midnight) observation in 2007 occurred at 15:56

and the latest occurred at 10:46, though a few of these outliers may be fish that were recently tagged and released above the trapping area. The average time for all observations was 2:53 (± 4:41 SD), and roughly 90% of lamprey were observed between 8:00 PM and 8:00 AM (Figure 6.3-1).

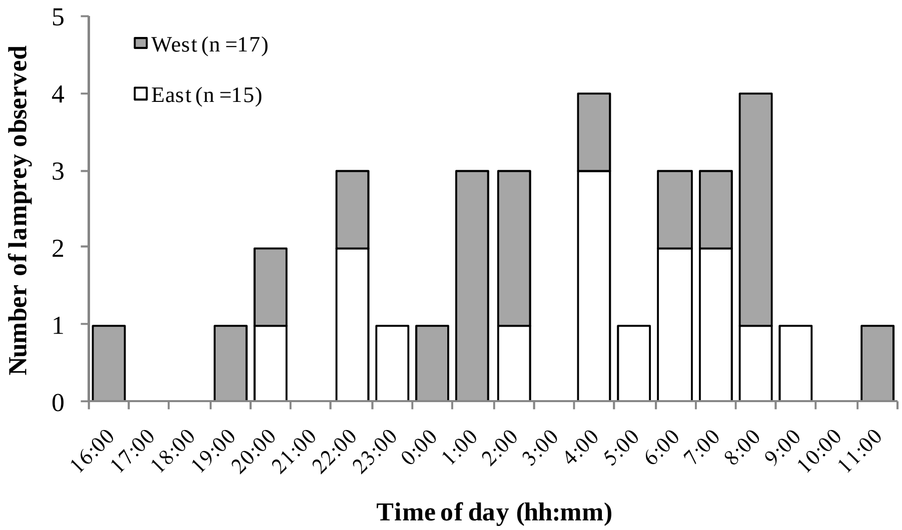


Figure 6.3-1 Number of lamprey observations at Wells fish counting stations by ladder and time, 2007.

6.3.1 Data Analyses

6.3.1.1 Detections

Nineteen (19) of the 21 tagged lamprey were detected at some point subsequent to their release. One fish (Fish 101) was never detected following release into the west tailrace, and another (Fish 100) shed the tag or died near the release site. The remaining 19 fish were detected a total of 179 (including 19 detections at release) separate times at fixed and mobile stations. The number of hits at each station ranged from a few hits over a couple seconds to as many as 1,661 hits over a 68 hour period, when Fish 130 remained in the east tailrace detection zone between early 22 August and late 24 August. The earliest fixed station detection occurred on 14 August and the last occurred 3 October near midnight outside the east fishway entrance. The period of detections likely coincides with migratory activity of lamprey in the immediate area (lamprey observations at the fish counting window ranged from 12 August to 23 September).

The number of post-release detections ranged from 0 (Fish 101) to 31 (Fish 102), with an average of 7.6 individual detections per fish. By excluding the lamprey released into the fishways and a fish that sat in between the west and east tailrace detection zones (Fish 118, 16 sequences on 14 August), the average number of individual detections per fish drops to 1.8 (range 0-7). This suggests that the ability to detect tagged lamprey outside the fishways and below the dam is extremely low, likely due to the depth limitations of aerial arrays and limited number of underwater antennas (only located at the outside of each fishway entrance).

The duration of detections (i.e., sequential hits) in all zones ranged from less than one minute to over 68 hours (average 1.82 hours) (Table 6.3-1). Zones where detections averaged over one hour include both tailrace aerial arrays, outside both fishway entrances, both trapping areas (below trap antenna), and both fishway exits. Detections at the west video bypass also averaged over one hour (1:47), though two of the ten detections there exceeded eight hours. Zones where detections averaged less than one hour (often on the order of minutes) included the above trap, below video, and above video zones in both fishways. The average detection length at the east video bypass (0:02) and inside the east fishway entrance (0:17) were also short, though no detections occurred inside the west fishway entrance and data from the west video bypass were skewed by two outliers.

Table 6.3-1 Time spent within detection zones in the WPA by tagged lamprey by zone, 2007 (zone descriptions in Figure 5.4-1). Zones where detections averaged over one hour are in bold.

Zone	Statistics		Zone	Statistics		Zone	Statistics	
310	Min	0:00	**440**	Min	11:08	**540**	Min	0:01
(n=11)	Max	68:20	(n=2)	Max	20:10	(n=3)	Max	2:54
	Average	6:18		Average	15:39		Average	1:54
320	Min	0:00	445	Min	0:01	550	Min	0:09
(n=10)	Max	6:16	(n=6)	Max	0:19	(n=5)	Max	0:21
	Average	1:40		Average	0:10		Average	0:13
400	Min	0:00	450	Min	0:06	555	Min	0:00
(n=13)	Max	38:06	(n=6)	Max	0:15	(n=10)	Max	5:07
	Average	2:57		Average	0:10		Average	0:42
405	Min	0:04	455	Min	0:01	560	Min	0:03
(n=7)	Max	1:00	(n=9)	Max	0:14	(n=11)	Max	1:39
	Average	0:17		Average	0:07		Average	0:26
415	Min	0:00	460	Min	0:02	**565**	Min	0:01
(n=3)	Max	0:00	(n=9)	Max	0:30	(n=10)	Max	8:15
	Average	0:00		Average	0:10		Average	1:47
420	Min	0:00	465	Min	0:00	**570**	Min	1:22
(n=1)	Max	0:00	(n=5)	Max	0:05	(n=5)	Max	2:38
	Average	0:00		Average	0:02		Average	2:03
425	Min	0:21	**470**	Min	0:17	871	Min	0:01
(n=1)	Max	0:21	(n=6)	Max	4:01	(n=1)	Max	0:01
	Average	0:21		Average	1:24		Average	0:01
435	Min	0:11	**500**	Min	0:00	872	Min	0:02
(n=2)	Max	0:43	(n=4)	Max	22:17	(n=1)	Max	0:02
	Average	0:27		Average	9:12		Average	0:02

6.3.1.2 Movements

The 19 tagged lamprey made a total of 138 directional movements between detection zones subsequent to the first detection after release, averaging 7 moves per fish (range 1-30). The most frequent moves were between the west and east tailrace arrays (though detections may overlap in some instances), between the below video, the video bypass, and above the video antennas, and between the inside and outside entrance antennas in the east fishway (Table 6.3-2). Interaction to, from, and within the video area of both fishways accounted for the largest majority of movements (73 movements, or 52% of total). These movements fell into 17 different direction classifications of only 11 lamprey indicating substantial interactions with the bypass and window chute. The duration of movements between zones (i.e., difference between the first observation at the current zone and first observation at the previous zone) averaged over 18 hours in the tailrace and 3 hours in the fishway (average excludes movements to mobile tailrace, Methow River, time in trapping area, and release to first detection). Movements in the tailrace ranged from less than 30 seconds between the inside and outside entrance antennas, to nearly 200 hours between the east and west fishway entrances. Movements in the fishways ranged from roughly one minute between Weirs 1 and 3, to over 17 hours between the video bypass and above video antennas (Table 6.3-2). No drop backs occurred throughout the monitoring period. That is, none of the tagged lamprey that exited the fishway were subsequently detected below the dam. Two of the radio-tagged lamprey that exited the Wells Dam fishways were later detected entering the Methow River.

Table 6.3-2 Movements made by tagged lamprey at Wells Dam by frequency of occurrence, 2007.

From (detection zone) → to (detection zone)	Count	Min	Max	Average
West Tailrace → East Tailrace	8	0:07	6:16	2:03
West Below Video → West Above Video	8	0:01	5:11	0:52
East Tailrace → West Tailrace	7	0:01	0:22	0:04
West Above Video → West Video Bypass	7	0:00	1:40	0:27
East Entrance Out → East Entrance In	6	0:00	0:12	0:03
East Entrance In → East Entrance Out	6	0:00	0:16	0:07
East Trap → East Above Trap	6	0:16	2:18	0:45
East Above Trap → East Below Video	6	1:34	7:59	3:30
East Below Video → East Above Video	6	0:01	16:56	2:55
East Above Video → East Exit	6	0:25	1:20	0:57
West Above Trap → West Below Video	5	2:22	6:22	3:59
West Video Bypass → West Above Video	5	0:08	17:25	3:43
East Below Video → East Video Bypass	4	0:05	0:15	0:10
West Below Video → West Video Bypass	4	0:02	0:21	0:13
West Video Bypass → West Below Video	4	0:00	8:17	2:16
East Tailrace → East Entrance Out	3	47:57	110:54	75:56
East Video Bypass → East Below Video	3	0:00	0:15	0:05
East Video Bypass → East Above Video	3	0:07	0:17	0:12
West Below Trap → West Above Trap	3	0:31	3:41	2:06
West Above Video → West Below Video	3	0:10	1:15	0:38
West Above Video → West Exit	3	0:47	1:41	1:12
West Tailrace → East Trap	2	0:53	4:38	2:46
East Entrance Out → Mobile Tailrace	2	671:12	1560:01	1115:36
East Entrance Out → West Entrance Out	2	118:18	194:58	156:38
East Entrance In → East AWS	2	0:09	0:55	0:32
East AWS → East Weir 1	2	0:11	0:44	0:27
East Below Trap → East Trap	2	11:24	20:25	15:55
East Above Video → East Video Bypass	2	0:10	0:21	0:16
West Video Bypass → West Exit	2	0:17	0:50	0:34
East Tailrace → Mobile Tailrace	1	694:51	694:51	694:51
East Entrance In → East Weir 1	1	1:03	1:03	1:03
East Weir 1 → East Entrance In	1	0:00	0:00	0:00
East Weir 1 → East Weir 3	1	0:00	0:00	0:00
East Weir 1 → East AWS	1	0:00	0:00	0:00
East Weir 3 → East Weir 7	1	0:09	0:09	0:09
East Weir 7 → East Trap	1	1:20	1:20	1:20
East AWS → East Entrance In	1	0:01	0:01	0:01
East Trap → East Below Trap	1	3:30	3:30	3:30
East Above Video → East Below Video	1	0:11	0:11	0:11
East Exit → Methow A1	1	92:12	92:12	92:12
East Exit → Methow A2	1	50:11	50:11	50:11
West Entrance Out → Mobile Tailrace	1	41:31	41:31	41:31
West Entrance Out → East Tailrace	1	3:34	3:34	3:34
West Entrance Out → West Tailrace	1	105:32	105:32	105:32
West Entrance Out → East Entrance Out	1	0:57	0:57	0:57

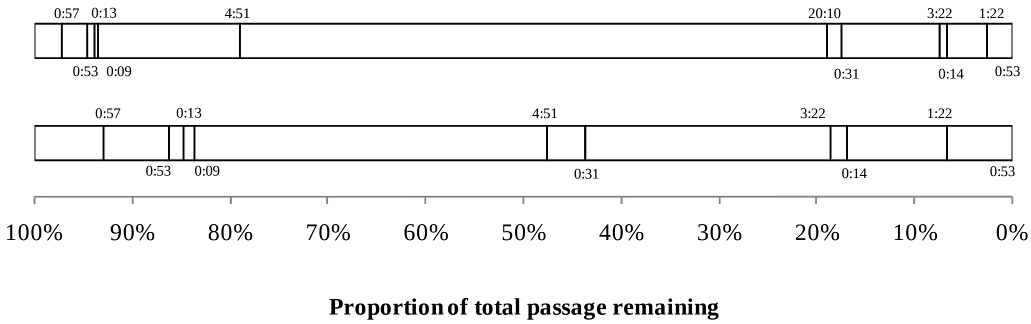
6.3.1.3 Fishway Passage Metrics

Entrance and Passage Efficiency

Excluding the tag that was likely a shed or mortality, 78% (7 of 9) of tagged lamprey released into the tailrace approached either fishway entrance. These fish made 17 separate approaches to the west (n = 4) and east (n =13) fishways. Only one lamprey successfully entered the collection gallery, indicated by detections on the antenna located on the inside of the fishway entrance. This results in an overall entrance efficiency of 14% (1 successful entrant out of 7 lamprey that approached). The low sample size prohibits the ability to make any conclusions about the difference in success between the west and east fishways (0/3 versus 1/4, respectively). The one lamprey that made it past the entrance and into the lower fishway successfully ascended Wells Dam. This results in a lower fishway efficiency of 100%, though little can be determined by one fish. Over 80% (10 of 12) of the tagged lamprey released into the fishway successfully ascended the fish ladder. The two that did not pass through the ladder prior to their tag expiring included one that rejected the fishway by traveling through the Auxiliary Water Supply (AWS) to the collection gallery and another that disappeared in between detection zones.

Project Passage

Only one tagged lamprey made a complete ascent through a fishway at Wells Dam in 2007. Fish 102 was released into the east tailrace on 6 September and began ascent in the east fishway two days later following nearly one hour of detections on the inside and outside entrance antennas. Within minutes of entering the collection gallery, Fish 102 was detected in the AWS chamber until reaching Weir 1 53 minutes later. Travel times from Weir 1 to Weir 3 and Weir 7 were relatively fast at only 23 minutes (less than 5 minutes per pool) (Figure 6.3-2). Travel from Weir 7 to the first detection at the below trap antenna took nearly 5 hours at roughly 9 minutes per pool (33 pools). Fish 102 then spent just over 20 hours in the detection zone of the below trap antenna. Data is not available to suggest whether the fish was interacting with the lamprey trap or another obstacle, resting, stopped migrating during the day (the pause occurred from 4:36 to past midnight), or a combination of these factors; although, the trap was not engaged until ~15:00 to 17:00 that day. The fish then made it to the above trap antenna in 31 minutes. This was the quickest rate observed in 2007 at less than 4 minutes per pool. The remaining segments of the ascent were all within the distribution observed for other upper fishway ascents of fishway-released lamprey. Altogether, the total fishway passage time for Fish 102 was 32:41, including a 6:07 lower fishway passage, a 5:53 upper fishway passage, 20:10 at the below trap antenna, and 0:31 below the above trap antenna. Rates of ascent were faster in the lower fishway (about 10 minutes per pool) than the upper fishway (about 15 minutes per pool), though pools #1-56 are 1.2 m (4 feet) shorter than the 4.9 m (16 feet) pools from #57 to #73.



Detection benchmark	Date/Time	Time difference	Running total
First approach to entrance	9/8/07 21:31	0:00	0:00:00
First detection at inside entrance	9/8/07 22:28	0:57	0:57:00
First detection at Weir 1	9/8/07 23:22	0:53	1:50:39
First detection at Weir 3	9/8/07 23:35	0:13	2:03:46
First diction at Weir 7	9/8/07 23:44	0:09	2:12:53
First detection at below trap	9/9/07 4:36	4:51	7:04:16
Last detection at below trap	9/10/07 0:46	20:10	27:14:25
First detection at above trap	9/10/07 1:17	0:31	27:45:55
First detection at below video	9/10/07 4:40	3:22	31:08:12
First detection at above video	9/10/07 4:54	0:14	31:22:45
First detection at ext	9/10/07 6:16	1:22	32:45:07
Last detection at exit	9/10/07 7:10	0:53	33:38:55

Figure 6.3-2 Graphical and tabular timeline of the only complete fishway ascent by a tagged lamprey (Fish 102), 2007. The topmost timeline (total passage = 32:42 + approach) includes the 20+ hours spent at the below trap detection zone. The bottom timeline (total passage = 12:31 + approach) excludes the duration spent in the below trap detection zone.

Upper Fishway Passage and Video Bypass

A total of 11 tagged lamprey successfully ascended the upper fishway at Wells Dam between 6 and 23 September. This includes 9 of the 11 fishway-released lamprey, the additional fishway release of a recaptured fish (Fish 130), and one of the lamprey released into the tailrace (Fish 102). Upper fishway passage times in both ladders ranged from 2.8 to 29.1 hours, with median and average times slightly shorter in the east fishway (Table 6.3-3). This difference is not significant and removing the unusually quick fish (Fish 110) and the three unusually slow fish (Fish 106, 111, and 112) brings the difference in average upper fishway passage between ladders within 3% of each other.

Table 6.3-3 Descriptive statistics of upper fishway passage times of tagged lamprey at Wells Dam by fishway, 2007.

Statistic	Fishway East	Fishway West	Fishway All
Minimum	2:48:38	5:11:07	2:48:38
Maximum	24:16:15	29:05:13	29:05:13
Median	6:53:03	9:44:29	7:53:06
Average	9:11:26	15:07:51	11:53:26
Standard deviation	7:45:01	11:03:20	9:24:36

The three unusually slow lamprey had numerous and extended detections on the video area antennas (below video the count window, the video bypass, and above the video count window) and similar passage times (Table 6.3-4). The radio-telemetry data show that these three fish all spent several hours in the video area during daylight hours, presumably resting. Fish 106 spent roughly 5 hours (7-12:00) in the detection zone of the below video antenna, and moved into the video bypass for 8 hours (12-20:00) before continuing ascent. Likewise, Fish 111 spent about 8 hours (6-14:00) in the west video bypass, and Fish 112 spent 17 hours -(4-21:00) between the below video and above video detection zones before continuing ascent. The travel times of these fish were also similar, reaching the above trap antenna around 23:00 and completing ascent just over 24 hours later. The starting times of the upper fishway ascent for these fish also were the three latest for all lamprey released into the fishway. Had the three slower fish continued ascent, their passage times would have been similar to fish that ascended without stopping (Table 6.3-5).

Table 6.3-4 Upper fishway passage times of tagged lamprey at Wells Dam by fishway, 2007. Fish that spent extended time in the video area are highlighted with red font.

Fish number	Fishway	First observation at above trap antenna	Last observation at fishway exit antenna	Upper fishway passage time
102	East	9/10/08 1:17	9/10/08 7:10	5:53:00
108	East	9/20/08 20:16	9/21/08 1:03	4:46:43
109	East	9/20/08 20:32	9/21/08 4:25	7:53:06
110	East	9/20/08 21:50	9/21/08 0:38	2:48:38
112	East	9/22/08 23:38	9/23/08 23:54	24:16:15
130	East	9/6/08 13:46	9/6/08 23:17	9:30:54
103	West	9/13/08 14:59	9/14/08 0:43	9:44:29
104	West	9/20/08 20:48	9/21/08 1:59	5:11:07
105	West	9/20/08 20:41	9/21/08 3:25	6:43:51
106	West	9/20/08 22:53	9/21/08 23:47	24:54:33
111	West	9/21/08 22:55	9/23/08 4:00	29:05:13

Table 6.3-5 Descriptive statistics of upper fishway passage times of tagged lamprey at Wells Dam by grouping (short or long), 2007. The "long" group included three lamprey that spent extended time in the video bypass area.

	Grouping		
Statistic	Short (n = 8)	Long (n = 3)	All
Minimum	2:48	24:16	2:48
Maximum	9:44	29:05	29:05
Median	6:18	24:54	7:53
Average	6:33	26:05	11:53
Standard deviation	2:23	2:36	9:24

The remaining tagged lamprey (i.e., those that did not spend extended time in the video area) had upper fishway passage times ranging from just under 3 hours (Fish 110) to nearly 10 hours (Fish 103). These median and average upper fishway passage times (6:18 and 6:34, respectively) for these fish are 75% lower than those of the longer group and likely representative of the time it takes a lamprey to travel from the above trap area to the exit of either fishway (Table 6.3-5). Water flow from the above trap antenna (Pool #47) to Pool #56 are maintained at a constant 48 cfs, with each pool containing overflow weirs and two 18×15" orifices. Water flow in the remaining portion of the fishway (pools #57-73) ranges from 31-44 cfs, depending on reservoir elevation, with pools containing two 30×16.5" orifices and no overflow weirs. Based on observed upper fishway passage times in 2007 (excluding the three fish that spent extended time in the video area), lamprey successfully ascend this portion of the fishway at an average rate of nearly 15 minutes per pool, ± 5 minutes standard deviation. This equates to an ascent rate of over 0.3 m/min.

The upper fishway passage time can be divided into four segments: 1) the first detection at the above trap antenna to the first detection at the below video count window antenna; 2) the first detection at the below video count window antenna to the first detection at the above video count window antenna; 3) the first detection at the above video count window antenna to the first detection at the exit; and, 4) the first detection at the exit to the last detection at the exit. Over half of upper fishway passage was usually spent traveling between the above trap and below video count window antennas. This portion of the fishway includes 17 of the 27 pools (63%) in the metric, and typically accounted for over 50% of the total time (Table 6.3-6). Average passage time through this segment was slightly below (faster) the average rate of 15 minutes per pool. The time spent between the first detection at the below and above video count window antennas (Pool #64) accounted for less than 5% of the upper fishway passage time for all fish. Average passage time through this segment (one pool) was nearly equal to the average rate of 15 minutes per pool. Time spent between the first detection at the above video count window antenna and the first detection at the exit (8 pools) usually accounted for 15% of the total time, though three fish spent over 18 hours there. Otherwise, passage through this segment was substantially below (nearly 50% faster) the average rate of 15 minutes per pool. Time spent within the detection zone of the fishway exit antenna usually accounted for 25% of the upper fishway passage time. Only four of the eleven fish that exited the fishway passed this pool in under one hour, with average passage through this segment substantially above the average rate of 15 minutes per pool, though this detection zone is much larger than those in other pools. A summary of tagged lamprey passage metrics is shown in Table 6.3-6.

Table 6.3-6 Descriptive statistics of segmented upper fishway passage times of tagged lamprey at Wells Dam, 2007. The first detection at the above trap antenna is considered the start of upper fishway passage (i.e., 0:00).

	Segment	Time elapsed from previous zone: 1st detection Below video	1st detection Above video	1st detection at Exit	Last detect. at Exit	Total
All fish	Min	1:34	0:03	0:20	0:17	2:48
	Max	7:59	0:46	21:10	4:01	29:05
	Median	2:51	0:14	1:20	1:32	7:53
	Average	3:43	0:18	6:10	1:42	11:53
	SD	2:07	0:12	8:53	1:07	9:24
Excluding resting fish	Min	1:34	0:03	0:20	0:17	2:48
	Max	7:59	0:29	1:54	4:01	9:44
	Median	2:41	0:14	1:06	1:36	6:18
	Average	3:36	0:16	1:00	1:42	6:33
	SD	2:16	0:08	0:33	1:20	2:23

Table 6.3-7 Summary of tagged lamprey release, passage times, and location last detected.

Fish	Release date	Release location	Passage times: Upper	Lower	Total	Bypass	Last location	Notes*
130	9/6	East fishway	9:30	.	.	Yes	Exit	Second release
107	9/20	East fishway	.	.	.	.	East tailrace	Fishway reject, AWS
108	9/20	East fishway	4:46	.	.	No	Exit	.
109	9/20	East fishway	7:53	.	.	Yes	Exit	.
110	9/20	East fishway	2:48	.	.	Yes	Exit	.
112	9/22	East fishway	24:16	.	.	Yes	Exit	Long at video bypass
103	9/13	West fishway	9:44	.	.	No	Exit	.
104	9/20	West fishway	5:11	.	.	Yes**	Exit	.
105	9/20	West fishway	6:43	.	.	Yes	Exit	.
106	9/20	West fishway	24:54	.	.	Yes	Exit	Long at video bypass
111	9/21	West fishway	29:05	.	.	Yes	Exit	Long at video bypass
114	9/22	West fishway	.	.	.	.	Below trap	Probable AWS exit
118	8/14	East tailrace	.	.	.	.	East tailrace	.
102	9/6	East tailrace	5:53	6:07	32:42	Yes	Exit	Only complete ascent
113	9/22	East tailrace	.	.	.	.	East entrance	.
119	10/3	East tailrace	.	.	.	.	East entrance	.
130	8/14	West tailrace	.	.	.	.	Recaptured	Released in fishway
100	8/16	West tailrace	.	.	.	.	West tailrace	Tag shed/mortality
101	8/16	West tailrace	.	.	.	.	Release site	.
115	9/22	West tailrace	.	.	.	.	East tailrace	.
116	9/25	West tailrace	.	.	.	.	East entrance	.
117	9/28	West tailrace	.	.	.	.	West entrance	.

7.0 DISCUSSION

7.1 Conduct a Literature Review of Existing Adult Pacific Lamprey Passage Studies at Columbia and Snake River Dams

The literature reviewed confirmed methodologies used in the Wells Dam study and provides insight to commonalities among adult Pacific lamprey behavior and interactions with hydroelectric dams throughout the Columbia and Snake rivers. Mainly, researchers have confirmed that fishway entrance efficiency is generally low (≤ 50%) among all hydroelectric projects. Further, project passage times are comparatively slow throughout the basin. Much of this may be accredited to entrance difficulties and problematic areas within fishways (e.g., diffuser grating, 90° corners).

7.2 Identify Methods for Capturing Adult Pacific Lamprey at Wells Dam

Results of the 2007 study suggest that the current method of trapping adult Pacific lamprey in Wells Dam fishways is less efficient than anticipated. This conclusion is based on evidence indicating that only a small portion of lamprey utilized the weir orifice to pass between fishway pools; and the fact that adult lamprey were able to escape out of the traps in between trap inspections. The fact that at least half of the lamprey passed the trapping area in both fishways suggests that they are traveling through the orifice or traveling above the overflow weir away from the wall. Since the latter seems unlikely, it is reasonable to believe that a majority of lamprey traveled through the orifice. This was expected, though not to this extent (≥80%). It is possible that the fish are unable to detect the flow reduction offered by the trap once they are committed to travelling along the bottom of the fishway. Lamprey have been observed regularly passing through orifices using burst and attach movements at other dams on the Columbia River (C. Peery, University of Idaho, pers. comm.). Results also suggest that the assumption regarding escapement is invalid. This was confirmed by the untagged fish leaving Trap 3, indicating that escapement is, at the very least, possible. The detection history of Fish 102 (the only complete fishway ascent) added to this suspicion when over 20 hours of detections were recorded at the below trap antenna. Interestingly, the detections occurred on a Sunday and the fish was present for at least 10 hours before the trap was lowered. The period of inactivity also occurred during the period of day when lamprey are generally inactive. However, the fish did not leave the detection zone until past midnight indicating that interaction with the trap and escapement remains a possibility.

Since fewer lamprey were observed than the target sample size, modifications should be made to increase trapping efficiency and decrease escapement. A mechanism to limit orifice passage is recommended to increase trapping efficiency. This could be achieved by installing a perforated plate on the fishway floor roughly 0.5 m downstream, upstream, and through the orifice. This would prevent lamprey from passing through the orifice by the typical burst and attach movements since suction to perforated surfaces is unlikely. Lamprey are usually unable to pass through weir orifices by free-swimming only and often search other passage routes throughout the water column after failing orifice passage. This has been observed by video monitoring at other projects on the Columbia River and orifice exclusion has shown to increase trapping efficiency (C. Peery, University of Idaho, pers. comm.). The use of a floor plate also eliminates the potential to influence orifice passage of other species, especially salmonids. Lastly, a funneled flap constructed of plastic mesh on the chute leading into the holding box is recommended to decrease trap escapement. Similar designs are used at Bonneville Dam to ensure one-way travel through lamprey passage systems (Jonathan Rerecich, US Army Corps of Engineers, pers. comm.), and flexible funnels are used in most fish traps (fyke nets, minnow traps, eel pots, etc.). This trap modification should make escapement more difficult by promoting one-way movement into the holding box.

7.3 Document the Timing and Abundance of Radio-Tagged Lamprey Passage through Wells Dam

The use of the radio-telemetry data from the 2007 study to document timing and abundance of lamprey passage at Wells Dam is not practical due to the small number of fish captured in Wells fishways (n = 6) and complete fishway ascents (n =1). Therefore, data retrieved from DART (2008) were used to make reasonable conclusions about migratory length, timing, and abundance. Although lamprey enumeration at dams lack total precision, counts are likely highly correlated to absolute numbers and therefore can provide insight to the timing, length, and size of migrations.

On average, lamprey observations at Wells Dam begin 12 June, though these data are highly variable among years (SD ± 36 days). Counts start as early as 28 April (2005) or as late as 12 August (2007). Based on what is known about Pacific lamprey life history, earlier observations are likely fish that overwintered in the system (Close et al., 2002; Moser and Close 2003). Migration reaches mid-point by 8 September on average, with considerable reliability (SD ± 13 days). Likewise, 75% of the run will pass by 24 September on average (SD ± 15 days). The last lamprey to pass Wells Dam will do so by 22 October, on average (SD ± 21 days), ranging from 23 September (2007) to 15 November (2003). Based on this information (shown by year with descriptive statistics in Table 7.3-1), the bulk of the Pacific lamprey migration will occur between the last calendar week in August and the third week in September (Figure 4.0-1).

Table 7.3-1 Run timing of Pacific lamprey at Wells Dam, by year, distribution of run, total lamprey observed, length of migration, and fish per day, 1998-2007. Descriptive statistics are listed at bottom of table.

Year	Start date	25%	50%	75%	Finish date	Total lamprey	Length of run	Average fish/day
1998	30-Jun	27-Aug	5-Sep	14-Sep	30-Sep	343	92	3.7
1999	31-May	1-Sep	9-Sep	12-Sep	11-Oct	73	133	0.5
2000	22-Jul	25-Aug	2-Sep	16-Sep	20-Oct	155	90	1.7
2001	4-Jul	26-Aug	16-Sep	24-Sep	11-Nov	262	130	2.0
2002	31-May	2-Sep	9-Sep	19-Sep	8-Nov	342	161	2.1
2003	27-Jun	6-Sep	7-Oct	28-Oct	15-Nov	1,410	141	10.0
2004	4-May	19-Aug	12-Sep	11-Oct	14-Nov	647	194	3.3
2005	28-Apr	22-Aug	6-Sep	27-Sep	3-Nov	214	189	1.1
2006	4-May	19-May	15-Aug	20-Sep	29-Sep	21	148	0.1
2007	12-Aug	27-Aug	7-Sep	14-Sep	23-Sep	35	42	0.8
Min	28-Apr	19-May	15-Aug	12-Sep	23-Sep	21	42	0.1
Max	12-Aug	6-Sep	7-Oct	28-Oct	15-Nov	1,410	194	10.0
Median	13-Jun	26-Aug	8-Sep	19-Sep	27-Oct	238	137	1.9
Average	12-Jun	17-Aug	8-Sep	24-Sep	22-Oct	350	132	2.6
Stand Dev.	36	32	13	15	21	416	47	2.9

The length of the adult lamprey migration at Wells Dam (i.e., time between the first and last observations) averages approximately 19 weeks (> 4 months), with considerable variation among years (SD ± 47 days). Observations will span well over 5 months some years (e.g., 2004), and last only 3 months in others (1998, 2000). For unknown reasons, the 2007 migration was the shortest yet, lasting only 42 days. This may have been shorter if lamprey were not transferred from Rocky Reach Dam in late September. Regardless, the variability in migration length among years is largely influenced by observations of few lamprey during the spring months. Half of the recorded years have had few lamprey observations in April and May. Despite these differences, the majority of the adult Pacific lamprey migration through Wells Dam will occur over a three to four week period (Table 7.3-1). The length of migration also has somewhat of a positive linear correlation with migration size, with larger migrations spanning over a greater time span (R2 = 0.27, when excluding 2003).

Total adult lamprey counts at Wells Dam average 350 fish, also with significant variation among years (SD ± 416 lamprey). This is largely due to three outliers, including one abnormally large run (1,410 lamprey in 2003), and two unusually small runs (56 combined lamprey observations between 2006 and 2007). Only one other year had a substantially low (75% below average) run. In 1999 only 73 lamprey were observed passing Wells Dam. Likewise, only one other year had a substantially high (75% above average) run – 647 lamprey were observed in 2004 following the record high in 2003. Although the total observed adult lamprey at Wells Dam have declined in recent years, similar trends have been noticed downstream at Rocky Reach and Rock Island dams (Figure 7.3-1).

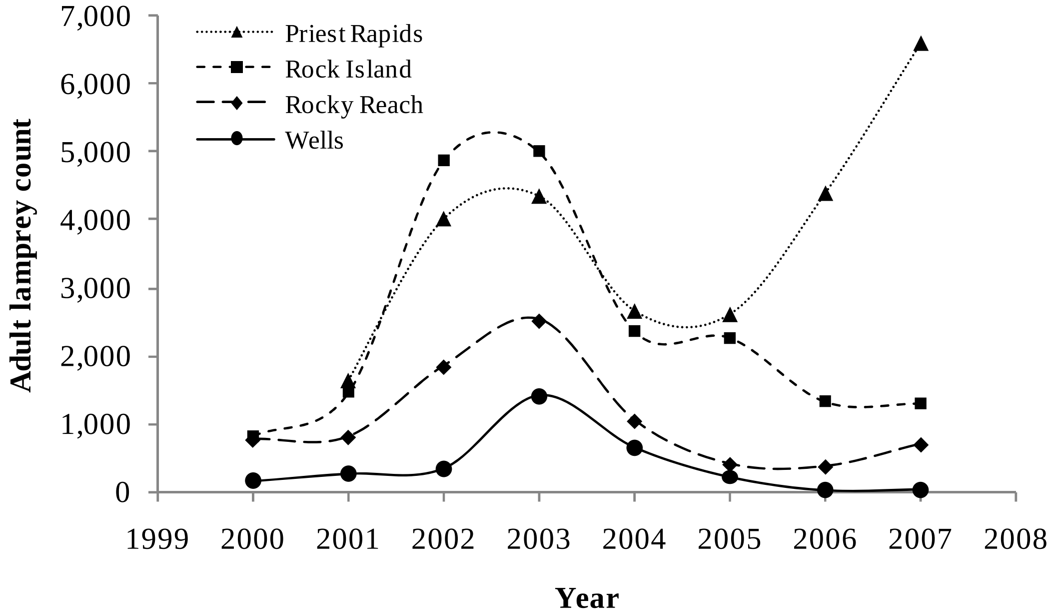


Figure 7.3-1 Lamprey counts at mid-Columbia River dams, 2000-2007, by project.

7.4 Determine Whether Adult Lamprey are Bypassing the Adult Counting Windows at Wells Dam

Eleven tagged lamprey passed the fish counting facilities in both fishways with detections on at least two of the three antennas at each video station. Nine of these fish were detected by the video bypass antenna, although three fish were detected for less than 20 seconds and probably did not completely enter the bypass. Eight of these lamprey were not counted at the video window, and two fish had zero detections on the above video antenna. These results indicate that radio-telemetry detection efficiency of tagged lamprey at the counting facilities is 100%, and, though a few detections may be spurious, a majority of tagged lamprey are interacting with the video bypass system at some point during ascent. Further, visual detections at the count windows could be significantly lower (e.g., under estimating by 73% according to these data) than the actual total number of lamprey passing the fish counting facilities.

Based on these conclusions and the results of segmented upper fishway passage metrics, it appears that the use of the video bypass is an enumeration issue, rather than a passage concern. Aside from the three fish that spent extensive time in the video area presumably resting, tagged lamprey generally move through this portion of the fishway efficiently and at above average speeds. Structural modifications to encourage passage by the video window are not recommended at this time. However, further consideration should be given regarding effective monitoring of lamprey passage through the video bypass depending on the importance of accurate counts at the project.

7.5 Where Sample Size is Adequate, Estimate Passage Metrics Including Fishway Passage Times and Efficiencies, Residence Time Between Detection Zones, and Downstream Passage Events

Passage of lamprey through Wells Dam consists of several segments, including approach, lower fishway passage, and upper fishway passage. A majority of tagged lamprey released into the tailrace approached an entrance more than twice on average. However, successful approaches were low (6%), as was overall entrance efficiency (1 out of 7, or 14%). These results suggest that tagged lamprey are able to approach the entrance, but most are unable to negotiate entry. The only lamprey that entered the collection gallery successfully ascended the lower fishway, and 83% of fish that were at or above Pool #40 successfully ascended the upper fishway. Of the two fish that did not ascend the upper fishway prior to tag expiration, one rejected the fishway and the other was never detected subsequent to release. The first fish was detected at the below trap antenna, followed by detections in the AWS chamber and a descending sequence through the collection gallery and to the entrance. This sequence, particularly the lack of detections at three in-ladder antennas between the two zones, suggests that this fish travelled through some portion of the AWS beneath the fish ladder. The second fish was never detected subsequent to the in-ladder release. Considering that the detection efficiency of fishway antennas is near 100%, it is probable that the fish entered the AWS through diffuser grating in the fishway floor below Pool #22. All of the tagged lamprey that reached the count station completed their ascent. This suggests that lamprey are capable of negotiating the upper fishway with a high level of success, although a portion of fish will interact with the AWS with some of those ultimately failing to ascend the fishway. Since only one tagged lamprey made a complete fishway ascent in 2007, data for approach and lower fishway passage times are limited to one observation. For this fish, approach was 49.0 hours, including 1.0 hours (2% or approach) of negotiating the entrance, and the lower fishway passage time was 6.1 hours. Median upper fishway passage time was 7.9 hours (n = 11), or 6.3 hours when excluding the three outliers. These passage times are within acceptable levels compared to studies at other Columbia Basin dams, suggesting that once inside and committed to the fishway, adult lamprey are able to negotiate the Wells Dam in reasonable time. Since no tagged lamprey dropped back through the Wells Dam subsequent to exiting the fishway (n = 11), drop back appears to be little or no concern at this point.

Altogether, these results suggest that: 1) lamprey have difficulty negotiating the entrances to Wells fishways; 2) some lamprey interact with the AWS; and 3) lamprey have high passage efficiency in reasonable time once inside the fishway. However, these statements are based on a limited amount of data (only 13 tagged lamprey were detected inside the fishway) and therefore lack the ability to conclude questions surrounding passage of Wells Dam. The first recommendation to improve the ability to estimate fishway passage metrics and efficiency is to increase the number of tagged fish released at Wells Dam. This can be accomplished by increasing trap efficiency and decreasing escapement (discussed earlier), and supplementing catch with lamprey from Rocky Reach Dam to ensure sample size targets are met. Based on the detection histories of lamprey obtained from Rocky Reach Dam in 2007, there is no evidence to suggest that their behavior is different from those captured at Wells Dam. This is further supported by the observation that none of the radio-tagged lamprey that were obtained from Rocky Reach Dam and released at Wells Dam were later detected leaving the Wells Project, at

Rocky Reach Dam, or at the Entiat River. An increased sample size would ultimately increase precision of estimates and help clarify conclusions made from the 2007 data.

The second recommendation to improve the ability to estimate fishway passage metrics and efficiency is to decrease the number of tagged lamprey released in the trapping area (i.e., mid-fishway releases), increase releases into the tailrace, and add a release location within the collection gallery near the side gate entrance. Since upper fishway passage data suggests that lamprey passage through this portion of Wells Dam is both timely and efficient, there would be little benefit to continue mid-fishway releases aside from further investigation of interactions with the AWS and video bypass area. Although, the video bypass is not a passage issue, but rather a monitoring issue (discussed earlier), increased tailrace releases would provide more data regarding entrance efficiency since a majority of tagged lamprey will approach either fishway entrance (based on 2007 results and Nass et al., 2005). This should be a priority considering the small number of successful entrants in 2007 (one lamprey) and indication that this may be the most difficult area for lamprey to negotiate. Releasing tagged lamprey into the collection gallery of both fishways would provide better insight to the ability of lamprey to negotiate the collection gallery after entrance into the fishway, the transition zone into the fishway ladder, and the lower fishway.

The last recommendation to improve the ability to estimate fishway passage metrics and efficiency is to reconsider fixed and mobile radio-telemetry monitoring throughout Wells Dam. Aside from the recently installed antennas in the video bypass and outside both fishway entrances, monitoring at Wells Dam has been generally designed for detecting movements of adult salmonids. This layout has proved to be inadequate in two general areas: the tailrace and the AWS system. Results from the 2007 study indicate that tagged lamprey regularly travel lower in the water column and at slower rates than salmonids, equating to fewer detections on the tailrace aerial arrays. Further, the smaller radio-tags implanted in lamprey have a smaller detection range and shorter tag life than tags typically used in salmonid studies (J. Murauskas, LGL Northwest, unpublished data). Additional deep-water mobile surveys at night (previously described) during the peak of the lamprey migration are recommended to better understand movements below the dam. The 2007 data also indicate that some lamprey interact with the AWS system, particularly in the collection gallery and below the fishway ladder downstream of Pool #22. Since access to this area is limited to fishes smaller than adult salmonids, monitoring in the AWS has been limited to one antenna in each fishway (Figure 5.4-1). Consideration of adjusting this antenna and possibly adding detection zones near the fishway transition zone and below the lower ladder is recommended to better understand movements through and use of the AWS system by migrating lamprey.

7.6 Identify Potential Areas of Improvement to Existing Upstream Fish Passage Facilities for the Protection and Enhancement of Adult Lamprey at the Wells Project

Based on the limited data collected in 2007, we were not able to identify area for potential fishway improvement.

8.0 ACKNOWLEDGMENTS

We thank the many Douglas PUD employees at Wells Dam for their support throughout the study. Mike Bruno and Frank Taylor are thanked for their support in project implementation. Steve Nieuwenhuis, Ray Harter, and other Douglas PUD Hydromechanics were instrumental in the design, fabrication, and installation of adult lamprey traps in Wells fishways, as well as insight to lamprey behavior within the hydrocombine. Wayne Marsh, Dick Weinstein, and Scott Kreiter are thanked for the numerous trap checks, data recording, and fish handling throughout the project. Douglas PUD Fish Enumerators Tanya Gibson, Sylvia Robertson, and Betty Walters, along with Douglas PUD Fish Biologist Rick Klinge, were supportive in providing detailed accounts of lamprey passage. Lynda Andrews (LGL Northwest) was responsible for data downloads and maintenance of monitoring stations throughout the project. Mary Mayo, Bao Le, and Shane Bickford made significant editorial contributions throughout the reporting process.

9.0 REFERENCES

Beamish, R.J. 1980. Adult biology of the river lamprey (Lampetra ayresi) and the Pacific lamprey (Lampetra tridentata) from the Pacific coast of Canada. Canadian Journal of Fisheries and Aquatic Sciences 37: 1906-1923.

Beamish, R.J. and C.D. Levings. 1991. Abundance and freshwater migrations of the anadromous parasitic lamprey, Lampetra tridentata, in a tributary of the Fraser River, British Columbia. Canadian Journal of Fisheries and Aquatic Science. 48: 1250-1263.

BioAnalysts. 2000. Status of Pacific lamprey in the mid-Columbia region. Rocky Reach Hydroelectric Project, FERC No. 2145. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

CBFWA. 2004. Columbia River Basin Lamprey Technical Workgroup. Statement of Purpose, 3/10/2004. Retrieved 1/29/2008 from www.fws.gov/columbiariver/lampreywg/docs.htm (last accessed February 2008)

Close, D., M. Fitzpatrick, H. Li, B. Parker, D. Hatch, and G. James. 1995. Status report of the Pacific Lamprey (Lampetra tridentata) in the Columbia River basin. Project No. 94-026, Contract No. 95BI39067. Report to the US Department of Energy, Bonneville Power Administration, Portland Oregon. USA.

Close, D., M. Fitzpatrick, and H. Li. 2002. The ecological and cultural importance of a species at risk of extinction, Pacific Lamprey. North American Journal of Fisheries Management 27(7):19-25.

Close, D.A., M.S. Fitzpatrick, C.M. Lorion, H.W. Li, and C.B. Schreck. 2003. Effects of intraperitoneally implanted radio transmitters on the swimming performance and physiology of Pacific lamprey. North American Journal of Fisheries Management 23:1184-1192.

Dauble, D.D., R.A. Moursund, and M.D. Bleich. 2006. Swimming behaviour of juvenile Pacific lamprey, Lampetra tridentata. Environmental Biology of Fishes 75:167-171.

DART. 2008. Columbia River Data Access in Real Time. Retrieved 15 January from www.cbr.washington.edu/dart/. (last accessed February 2008) University of Washington.

Golder Associates. 2003. Review of Pacific lamprey in the Rocky Reach Project Area. Internal Draft. Report to Chelan County Public Utility District, Wenatchee, WA.

Hillman, T. and M. Miller. 2000. Status of Pacific lamprey in the mid-Columbia region. BioAnalysts, Inc. Report to Chelan County Public Utility District, Wenatchee, WA.

Jackson, A.D., D.R. Hatch, B.L. Parker, M.S. Fitzpatrick, D.A. Close, and H. Li. 1997. Pacific lamprey research and restoration: Annual report, 1997. Prepared for the Bonneville Power Administration, Division of Fish and Wildlife. Project Number 1994-026.

Mesa, M.G., J.M. Bayer, J.G. Seelye, and L.K. Weiland. 2001. Swimming performance and exhaustive stress in Pacific lampreys (Lampetra tridentata): implications for upstream migrations past dams. Draft Annual Report to U.S. Army Corps of Engineers, Portland District, Portland, OR.

Mesa, M.G., J.M. Bayer and J.G. Seelye. 2003. Swimming performance and physiological responses to exhaustive exercise in radio-tagged and untagged Pacific lampreys. Transactions of the American Fisheries Society 132: 483 - 492.

Mesa, M.G. and Moser, M. 2004. Passage considerations for Pacific lamprey. Prepared by the Columbia River Basin Lamprey Technical Workgroup, September 2004. Endorsed by the Columbia Basin Fish and Wildlife Authority, October 2005.

Moser, M.L., A.L. Matter, L.C. Stuehrenberg, and T.C. Bjornn. 2002a. Use of an extensive radio receiver network to document Pacific Lamprey (Lampetra tridentata) entrance efficiency at fishways in the Lower Columbia River, USA. Hydrobiologia 483:45-53.

Moser, M.L., P.A. Ocker, L.C. Stuehrenberg, and T.C. Bjornn. 2002b. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA. Transactions of the American Fisheries Society 131:956-965.

Moser, M. and D. Close. 2003. Assessing Pacific lamprey status in the Columbia River Basin. Northwest Science 77(2):116-125.

Moser, M.L., D.A. Ogden, and C.A. Peery. 2005. Migration behavior of adult Pacific lamprey in the lower Columbia River and evaluation of Bonneville Dam modifications to improve passage, 2002. Technical report submitted to U.S. Army Corps of Engineers, Portland, OR.

Moser, M.L., R.W. Zabel, B.J. Burke, L.C. Stuehrenberg, and T.C. Bjornn. 2005. Factors affecting adult Pacific lamprey passage rates at hydropower dams: using “time to event” analysis of radio telemetry data. Pages 61-70 in M.T. Spedicato, G. Lembo, and G. Marmulla, editors. Aquatic telemetry: advances and applications. Proceedings of the Fifth Conference on Fish Telemetry held in Ustica, Italy 9-13 June 2003.

Nass, B.L., C. Sliwinski, K.K. English, L. Porto, and L. Hildebrand. 2003. Assessment of adult lamprey migratory behavior at Wanapum and Priest Rapids Dams using radio-telemetry techniques, 2001-2002. Report prepared by LGL Limited, Sidney, BC, Canada, for Public Utility District No. 2 of Grant County, Ephrata, WA.

Nass, B.L., C. Sliwinski, D. Robichaud. 2005. Assessment of Adult Pacific Lamprey Migratory Behavior at Wells Dam Using Radio-telemetry Techniques, 2004. Report prepared by LGL Limited, Sidney, B.C. Canada, for Public Utility District No. 1 of Douglas County, WA.

Page, L.M. and B.M Burr. 1991. Peterson Field Guides: Freshwater Fishes. Houghton Mifflin Company, New York, NY.

Peery, C.A., M.L. Moser, and N. Adams. 2006. Research Pre-Proposal: Evaluation of adult Pacific lamprey passage success at McNary and lower Snake River dams – 2007. Study Code: ADS-P-00-8. Submitted to U.S. Army Corps of Engineers, Walla Walla District.

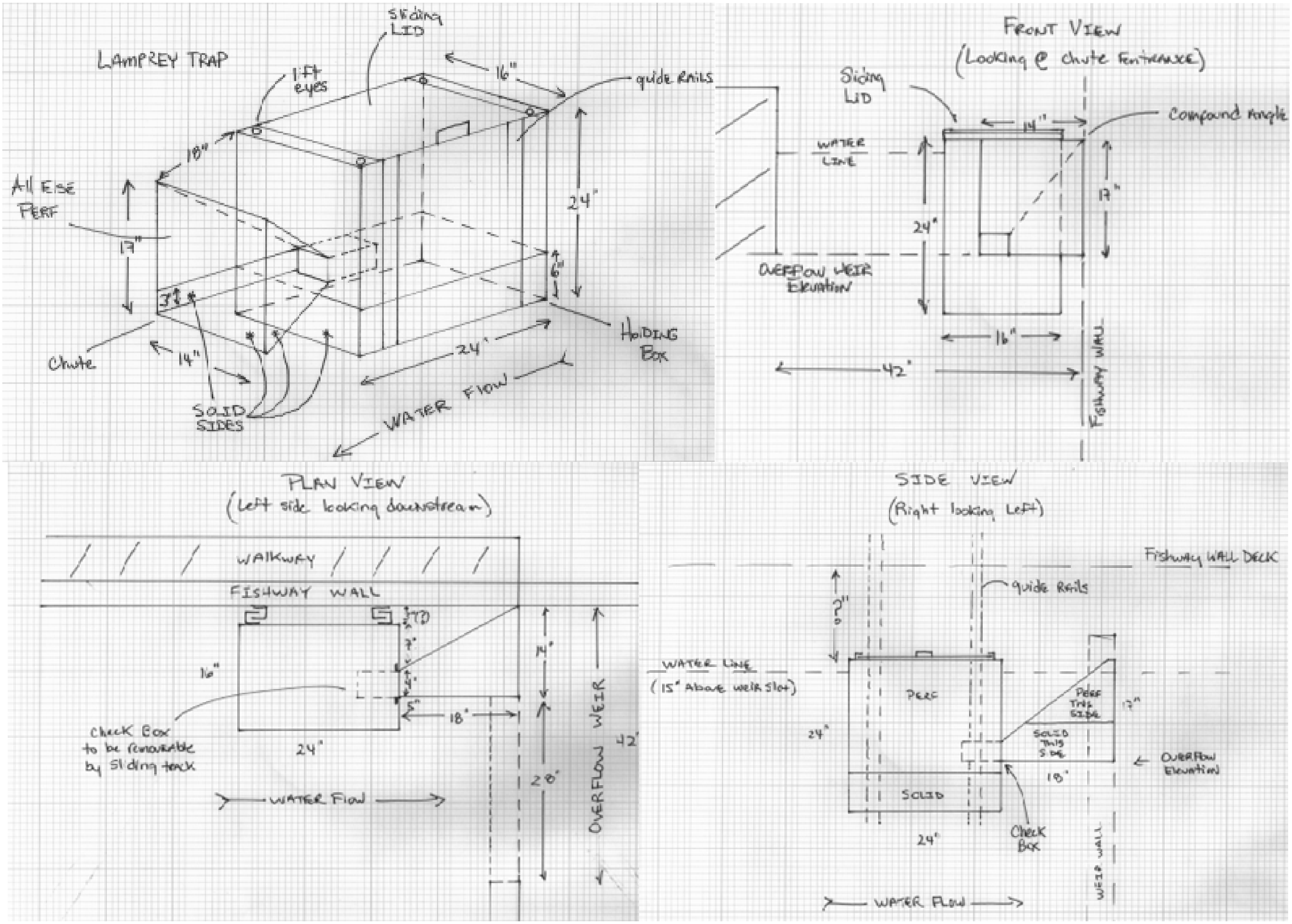
Starke, G. and J. Dalen. 1995. Pacific Lamprey (Lampetra tridentata) passage patterns past Bonneville Dam and incidental observations of lamprey at the Portland District Columbia River dams in 1993. U.S. Army Corps of Engineers, Cascade Locks, Oregon. USA.

Stevenson, J.R., P. Westhagen, D. Snyder, J. Skalski, and A. Giorgi. 2005. Evaluation of Adult Pacific Lamprey Passage at Rocky Reach Dam Using Radio-telemetry Techniques, 2004. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Stone, J. 2004. Update to the Columbia River Lamprey Program Summary; Prepared by the Columbia River Basin Lamprey Technical Workgroup, July 2004.

Appendix A

Wells Dam Adult Lamprey Trap Draft Schematics, 2007


LAMPREY TRAP
Sliding LID
lift eyes
16"
guide Rails
18"
All Else PERF
24"
17"
6"
Chute
14"
24"
Holding Box
SOLID SIDES
WATER FLOW
FRONT VIEW
(Looking @ chute Entrance)
Sliding LID
14"
Compound Angle
WATER LINE
24"
17"
OVERFLOW WEIR Elevation
16"
42"
FISHWAY WALL
PLAN VIEW
(Left side looking downstream)
WALKWAY
FISHWAY WALL
16"
7"
4"
5"
14"
18"
24"
Check Box to be removable by sliding track
WATER FLOW
28"
OVERFLOW WEIR
42"
SIDE VIEW
(Right looking Left)
Fishway WALL DECK
guide Rails
WATER LINE
(15" Above weir slot)
PERF
PERF THIS SIDE
SOLID THIS SIDE
17"
24"
SOLID
18"
OVERFLOW Elevation
Check Box
24"
WEIR WALL
WATER FLOW

Appendix B

Tagged Lamprey at Wells Dam, 2007

Date	Trap	Capture location	Code (Ch 1)	Length (cm)	Weight (kg)	Girth (cm)	Heavy Anesth.	Start Surgery	Start Recovery	Release Time	Release Location
14-Aug	Trap 3	East fishway	118	65.0	0.445	11.0	15:14:30	15:20:30	15:31:00	8:06:00	East Alcove
14-Aug	Trap 2	West fishway	130	64.0	0.404	10.5	16:14:00	16:22:00	16:28:00	17:50:00	West Alcove
16-Aug	Trap 1	West fishway	100	60.0	0.310	9.0	9:20:30	9:27:00	9:33:00	12:09:00	West Alcove
16-Aug	Trap 1	West fishway	101	67.0	0.400		10:04:00	10:11:00	10:17:00	12:15:00	West Alcove
6-Sep	Trap 4	East fishway	102	68.6	0.370	10.0	11:28:00	11:37:55	11:42:59	13:50:00	East Alcove
13-Sep	Trap 2	West fishway	103	66.0	0.446	10.7	12:46:48	12:54:22	13:00:27	14:27:00	West In-ladder
20-Sep		Rocky Reach	104	67.0	0.506	11.5	13:59:33	14:06:33	14:11:20	16:15:00	West In-ladder
20-Sep		Rocky Reach	105	68.0	0.438	10.5	14:14:40	14:19:59	14:25:00	16:15:00	West In-ladder
20-Sep		Rocky Reach	106	64.0	0.484	11.5	14:19:30	14:36:16	14:40:57	16:15:00	West In-ladder
20-Sep		Rocky Reach	107	69.0	0.494	11.0	14:54:50	15:00:15	15:04:20	16:49:00	East In-ladder
20-Sep		Rocky Reach	108	69.0	0.430	10.0	15:08:00	15:15:50	15:20:10	16:42:00	East In-ladder
20-Sep		Rocky Reach	109	63.0	0.408	10.3	15:23:50	15:29:30	15:34:00	16:50:00	East In-ladder
20-Sep		Rocky Reach	110	62.0	0.360	10.0	15:39:00	15:46:30	15:51:00	16:40:00	East In-ladder
21-Sep		Rocky Reach	111	54.0	0.270	9.0	13:31:10	13:37:42	13:46:00	15:06:00	West In-ladder
22-Sep		Rocky Reach	112	61.0	0.356	10.0	10:18:07	10:26:15	10:31:00	11:46:00	East In-ladder
22-Sep		Rocky Reach	113	68.0	0.484	11.0	10:33:40	10:43:20	10:48:00	11:52:00	East Alcove
22-Sep		Rocky Reach	114	69.0	.	11.0	10:44:00	10:53:00	11:00:00	12:31:00	West In-ladder
22-Sep		Rocky Reach	115	73.0	0.528	11.0	11:06:00	11:13:00	11:18:00	12:20:00	West Alcove
25-Sep		Rocky Reach	116	64.0	0.384	10.0	10:05:08	10:12:09	10:17:30	11:20:00	West Alcove
28-Sep		Rocky Reach	117	64.0	0.404	10.0	11:12:00	11:19:30	11:25:00	12:30:00	West Alcove
3-Oct		Rocky Reach	119	71.0	0.502	11.0	10:06:43	10:17:50	10:26:20	11:34:00	East Alcove

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LGL and Douglas PUD. 2008b. Bull Trout Monitoring and Management Plan, 2005-2008 Final Report. Wells Hydroelectric Project FERC No. 21. 49. Prepared for Public Utilities District No. 1 of Douglas County. East Wenatchee, Washington.

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BULL TROUT MONITORING AND MANAGEMENT PLAN
2005-2008 FINAL REPORT

WELLS HYDROELECTRIC PROJECT

FERC PROJECT NO. 2149

December 2008

Prepared by:
LGL Environmental Research Associates
Ellensburg, Washington
and
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509) 884-7191
E-Mail: relicensing@dcpud.org

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EXECUTIVE SUMMARY

The goal of the Wells Hydroelectric Project (Wells Project) Bull Trout Monitoring and Management Plan (Bull Trout Plan) is to identify, develop, and implement measures to monitor and address potential project-related impacts on bull trout (*Salvelinus confluentus*) associated with the operations of the Wells Project and associated facilities (Douglas PUD 2004). The Bull Trout Plan was prepared and implemented to meet monitoring requirements stipulated in a U.S. Fish and Wildlife Service (USFWS) Biological Opinion (USFWS 2004) regarding implementation of the Wells Project Anadromous Fish Agreement and Habitat Conservation Plan. The USFWS Biological Opinion monitoring requirements were also incorporated by the Federal Energy Regulatory Commission (FERC) into the existing Wells Project license in 2004. The Bull Trout Plan was developed in collaboration with the USFWS, National Marine Fisheries Service (NMFS), Washington Department of Fish and Wildlife (WDFW), the Colville Confederated Tribes, and the Yakama Nation, and was approved by the FERC. The Bull Trout Plan has four objectives, addressed by implementing various field study components from 2004 to 2008 at the Wells Project. This document is the final report summarizing the results of all study activities required by the Bull Trout Plan.

The first objective was to identify potential project-related impacts on upstream and downstream passage of adult bull trout (fish ≥ 400 mm in length) through Wells Dam and reservoir, and implement appropriate measures to monitor any incidental take of adult bull trout. To meet the first objective, radio telemetry was used to monitor upstream and downstream passage, and off-season video counting was done in the Wells Project fishways during the winter. Between 2005 and 2008, 26 adult bull trout were trapped at Wells Dam and radio-tagged. Concurrent with the implementation of the Bull Trout Plan, the USFWS and Public Utility District No. 1 of Chelan County (Chelan PUD) radio-tagged and released 136 adult bull trout at other mid-Columbia River basin locations including the Methow River, and Rock Island and Rocky Reach dams (50 USFWS tags 2006-2008, 86 Chelan PUD tags 2005-2007).

From 2005 to 2008, 25 downstream passage events and 52 upstream passage events by 40 individual bull trout were recorded at Wells Dam. Of these, 17 downstream and 41 upstream passage events occurred within one year of tagging and release. Of all tags released from 2001 to 2004, there were 2 downstream passage events and 41 upstream passage events. Of these, 2 downstream and 38 upstream passage events occurred within one year of release. The take estimates for the Wells Project were based upon the number of unique upstream and downstream passage events that took place within one year each bull trout being tagged and release. During the six year study and eight years of monitoring, 19 downstream and 79 upstream passage events took place at Wells Dam by radio-tagged bull trout within one year of release. Taking into account all observed passage events a total of 27 downstream and 93 upstream passage events took place at Wells Dam Radio-tagged bull trout passed downstream through the turbines or spillways as no downstream passage events were recorded via the fishways. Out of the 19 downstream passage events that occurred within one year of tagging, zero bull trout injury or mortality was observed at the Wells Project. Out of the 79 upstream passage events that occurred within one year of tagging, zero bull trout injury or mortality was observed at the Wells Project.

Upstream passage of adult bull trout through the fish ladders at Wells Dam has historically occurred between early May and late October, with peak passage typically occurring in May and June. During the 2005 and 2008 study, 214 adult bull trout were counted passing upstream through Wells Dam. The proportion of the bull trout population at Wells Dam that was radio-tagged was 24% (52/214 = 0.24).

Project operations did not appear to influence the movements of adult bull trout. Instead, adult bull trout passage events appeared to be more closely associated with water temperature, photoperiod and time of year with rather predictable patterns of upstream and downstream movement. Because no take (injury or mortality) was observed during the study, there was no need to investigate how Project operations affected take at Wells Dam.

During the 2005-2008 monitoring period, no adult bull trout were counted during the 24-hour off-season fishway counting period (November 16 to April 30).

No upstream or downstream passage problems were identified during this study. Passage times upstream through the fishway appeared reasonable relative to the species migration and spawn timing. Because no passage problems were identified during the study, there was no need to develop recommendations to change or modify the fishway operations at Wells Dam.

The second objective was to assess project-related impacts on upstream and downstream passage of sub-adult bull trout (fish <400 mm in length). During the development of the Bull Trout Plan, stakeholders agreed that because of the inability to collect a sufficient sample size of sub-adult bull trout at Wells Dam, it was not feasible to assess sub-adult passage. However, when encountered at Wells Dam, or in tributary traps, sub-adult bull trout would be PIT tagged. Douglas PUD provided funding, equipment, training, and coordination for the sub-adult bull trout PIT tag program. From 2004 to 2008, 67 sub-adult bull trout were PIT tagged in the Methow River sub-basin during standard tributary smolt trapping operations. Douglas PUD operated PIT tag detection systems year-round within the Wells Dam fishways during the study period (2005 to 2008) and no PIT tagged sub-adult bull trout were detected. Additionally, sub-adult bull trout were to be PIT tagged opportunistically when encountered at the Wells Project; however, no sub-adult bull trout were encountered at Wells Dam during the study period.

Off-season (November 16 to April 30) video monitoring of the Wells Dam fishways for sub-adult bull trout was conducted during each of the years of this study including the winter of 2004 and 2005 as required by the Bull Trout Plan. Additional off-season counting took place during the winters of 2006 and 2007. To date, no sub-adult bull trout have been observed utilizing the fishways at Wells Dam.

The third objective was to investigate the potential for sub-adult entrapment or stranding in off-channel or backwater areas of Wells Reservoir. Field surveys were conducted at potential bull trout stranding sites during a period of low reservoir elevation. High resolution bathymetric information, reservoir elevations, backwater curves, and inflow patterns were used to identify potential stranding sites for the survey. No stranded or entrapped bull trout of any size were found during the field surveys conducted in 2006 and 2008. No surveys were conducted during 2005 or 2007 because river operations were not low enough to warrant a survey.

The fourth objective was to identify the core areas and local populations of bull trout that utilize the Wells Project. Data from radio-tagged bull trout tracked during the 2005 to 2008 study period were analyzed with data from the 2001 to 2004 study. Bull trout that pass Wells Dam (either upstream or downstream) migrated into the Methow, Entiat, and Wenatchee rivers during the spawning period. Observed tributary entrances of bull trout detected at Wells Dam from 2005 to 2008 were 86% Methow River, 10% Entiat River, and 2% Wenatchee River. Genetic samples of all fish tagged at Wells Dam were submitted to the USFWS for analysis. The USFWS is responsible for analyzing the genetic samples and providing those results. To further support this objective (Strategy 4-2: Work cooperatively with other agencies to obtain locations of radio-tagged fish outside the project area), Douglas PUD regularly coordinated bull trout data and monitoring activities with other agencies including the USFWS, and CCPUD).

In summary, no mortality or injury was observed for bull trout (adult and sub-adult) passing through or interacting with the operations of the Wells Project during the take monitoring studies conducted between 2001 and 2008. No incidental take of bull trout was observed at the Wells Project, and the Wells Project is presumed to be within the incidental take levels authorized by the USFWS Biological Opinion Incidental Take Statement (USFWS 2004).

1.0 INTRODUCTION

In August 1993, Douglas, Chelan, and Grant Public Utility Districts (collectively, "mid-Columbia PUDs") initiated discussions to develop a long-term, comprehensive program for managing fish and wildlife that inhabit the mid-Columbia River basin (the portion of the Columbia River from the tailrace of Chief Joseph Dam to the confluence of the Yakima and Columbia rivers). These discussions first explored the possibility of developing an ecosystem-based plan for managing fish and wildlife resources inhabiting the mid-Columbia River basin. Due to the scope and scale of this conceptual plan, the negotiating parties decided to focus on an agreement for aquatic species inhabiting the mid-Columbia River basin including fish, plants, and animals. After extensive review, the negotiating parties determined that the best basin-wide approach would be to develop an agreement for anadromous salmonids, specifically: spring and summer/fall Chinook salmon (*Oncorhynchus tshawytscha*); sockeye salmon (*O. nerka*); coho salmon (*O. kisutch*); and steelhead (*O. mykiss*) (collectively, "Plan Species") which are under the jurisdiction of National Marine Fisheries Service (NMFS).

On July 30, 1998, Public Utility District No. 1 of Douglas County (Douglas PUD), which operates the Wells Hydroelectric Project (Wells Project), submitted an unexecuted form of an Application for Approval of the Wells Anadromous Fish Agreement and Habitat Conservation Plan (the "HCP Agreement") to Federal Energy Regulatory Commission (FERC) and NMFS. To expedite the ability of FERC to complete formal consultation, Douglas PUD prepared a biological evaluation of the effects of implementing the Habitat Conservation Plan (HCP) on listed species under the jurisdiction of the U.S. Fish and Wildlife Service (USFWS).

In a letter to FERC, the USFWS requested consultation under Section 7 of the ESA regarding the effects of hydroelectric project operations on bull trout (*Salvelinus confluentus*) in the Columbia River (letter from M. Miller, USFWS, to M. Robinson, FERC, dated January 10, 2000). The request for consultation was based on observations of bull trout in the study area. In its reply to the USFWS, FERC noted that there was virtually no information on bull trout in the mainstem Columbia River. To begin to address this information gap, an initial radio telemetry study of bull trout in the mid-Columbia basin was requested by USFWS in 2000 and implemented from 2001 to 2004 by Douglas, Chelan, and Grant PUDs (BioAnalysts, Inc. 2004).

On November 24, 2003, Douglas PUD filed an application with FERC for approval of the executed Wells HCP. The 2003 application for approval replaced the 1998 application with the executed form of the Wells HCP. On December 10, 2003, the USFWS received a request from FERC for formal Section 7 ESA consultation to determine whether the proposed incorporation of the HCP Agreement into the FERC license for operation of the Wells Project was likely to jeopardize the continued existence of the Columbia River distinct population segment (DPS) of ESA-listed bull trout, or destroy or adversely modify proposed bull trout critical habitat. In response to the FERC request, the USFWS issued a Biological Opinion (BO) pursuant to Section 7 of the ESA to assess the effects of the HCP on ESA listed bull trout and other listed species under the jurisdiction of the USFWS. The BO included an Incidental Take Statement outlining reasonable and prudent measures (RPMs) and associated terms and conditions to monitor and limit bull trout take at the Wells Project. On June 21, 2004, FERC issued orders amending the license for the Wells Project to implement the terms of the Wells HCP. FERC incorporated the

USFWS bull trout RPMs and terms and conditions into the existing Wells Project license, which are represented as license articles 61, 62, and 63.

Article 61 of the license required Douglas PUD to file with FERC a Bull Trout Plan for implementing the USFWS bull trout RPMs and terms and conditions, which were designed to monitor and limit bull trout take associated with Wells Project operations. Article 61 further required that Douglas PUD prepare the Bull Trout Plan in consultation with the USFWS, National Marine Fisheries Service (NMFS), WDFW, and interested Indian Tribes (Colville Confederated Tribes and the Yakama Nation). Following consultation with these stakeholders, on February 28, 2005, Douglas PUD filed with FERC the "*Wells Hydroelectric Project Bull Trout Monitoring and Management Plan, 2004-2008"* (Douglas PUD 2004), which is referred to as the "Bull Trout Plan" in this document. The Bull Trout Plan was approved by FERC on April 19, 2005.

Article 62 of the license requires Douglas PUD to prepare and file with FERC an annual report describing the activities required by the Bull Trout Plan. On March 26, 2008, Douglas PUD with approval from USFWS filed a request for an extension of time to submit the 2007 annual bull trout monitoring report and to consolidate the 2007 annual report with the final bull trout monitoring report, required to be filed with FERC by December 31, 2008. On April 16, 2008, FERC issued an order granting this request. This document summarizes all data collected to meet the Bull Trout Plan objectives over the required monitoring period from 2005 to 2008 and represents the final monitoring report. This final monitoring report completes all monitoring objectives outlined in the USFWS bull trout RPMs and terms and conditions, and the Wells Project license articles 61 and 62.

Article 63 was a reservation of authority by FERC to require the licensee to carry out specified measures for the purpose of participating in the development and implementation of a bull trout recovery plan. The USFWS has only recently reactivated the bull trout recovery planning process following a multi-year hiatus. In response to compliance with article 63 of the Wells Project license, Douglas PUD has and will continue to participate in the development of future recovery planning documents for bull trout.

2.0 GOALS AND OBJECTIVES

The goal of the Bull Trout Plan is to identify, develop, and implement measures to monitor and address potential project-related impacts on bull trout from Wells Project operations and facilities. The Bull Trout Plan was intended to be an adaptive approach, where strategies for meeting the goals and objectives may be negotiated under a collaborative effort with stakeholders based on new information and ongoing monitoring results. The plan was designed specifically to: (1) address ongoing project-related impacts through the life of the existing operating license; (2) provide consistency with recovery actions as outlined in the USFWS Draft Bull Trout Recovery Plan; and (3) monitor and minimize the extent of any incidental take of bull trout consistent with Section 7 of the ESA.

The Bull Trout Plan has four main objectives including: (1) identify potential project-related impacts on upstream and downstream passage of adult bull trout through the Wells Dam and reservoir and implement appropriate measures to monitor any incidental take of bull trout; (2) assess project-related impacts on upstream and downstream passage of sub-adult bull trout; (3) investigate the potential for bull trout entrapment or stranding in off-channel or backwater areas of Wells Reservoir; and (4) identify the core areas and local populations, as defined in the USFWS Draft Bull Trout Recovery Plan, of the bull trout that utilize the Wells Project Area. The overall strategy framework to implement each objective is summarized below from the Bull Trout Plan[1]. A more detailed activity description is given in the methods section of this report.

2.1 Objective 1 - Adult Bull Trout Passage Monitoring

Strategy 1-1: Implement an adult bull trout telemetry program to monitor adult upstream and downstream passage in the Wells Project Area and implement appropriate measures to monitor any incidental take of bull trout.

- Radio-tag 10 bull trout per year for three years from May 2005 to July 2007. Release tagged fish upstream of Wells Dam. Each fish will be counted as one successful adult fishway passage event for the year it is tagged.
- Install and maintain receiver arrays necessary to adequately monitor upstream and downstream passage through Wells Dam from 2005 to 2008.
- Track and monitor monthly movement of tagged fish from May 2005 to July 2008 until a tributary entrance is observed. Continue tracking all fish that re-enter the reservoir. Fixed receiver sites will be operated to detect any upstream and downstream movement at the dam and tributary entrances.
- Evaluate upstream and downstream tag detection data of each individual and conduct tag recovery operations in the Wells Project Area when warranted.
- Use data from the 2001 to 2004 study and from the 2005 to 2008 study to calculate a Wells Project 6-year-average take of bull trout by passage route where feasible, and statistically compare the level of take anticipated by the USFWS BO Incidental Take Statement (USFWS 2004) using a one-tailed test of the hypothesis that the anticipated incidental take level is not exceeded.
- If project effects are shown to be negligible as measured by incidental take monitoring, then the monitoring program will be repeated on a ten year interval to re-evaluate bull trout take.
- Douglas PUD will engage in cost share funding with the USFWS for analysis of genetic samples from fluvial bull trout sampled during the 2005 radio telemetry study.

Strategy 1-2: Analyze passage results and operational data to determine if correlations exist between passage times and passage events and project operations.

- Compile and characterize Project (spill, turbines, reservoir elevations, TDG) and ladder operations data during times of downstream passage for active tagged fish.

[1] Please see the Bull Trout Plan for detailed strategy language.

Strategy 1-3: Determine off-season adult bull trout passage through the adult fishway (numbers and times of year) at Wells for an experimental period 2004-2005.

- Implement off-season fishway video counts at Wells Dam during the winter of 2004 through 2005, to record dates and times of adult bull trout passage.
- Evaluate results to determine if passage trends exist and when ladder maintenance should occur during the off-season during low bull trout usage periods (where reasonable and feasible).

Strategy 1-4: Should upstream or downstream passage problems be identified, pursue the feasibility of options to modify upstream passage facilities or operations that reduce the impact to bull trout passage.

- Douglas PUD will work with stakeholders to develop a collaborative plan to address adult passage problems, if warranted.

2.2 Objective 2 - Sub-adult Bull Trout Passage Monitoring

Strategy 2-1: The stakeholders agree at this time[2] that because of the inability to collect a sufficient sample size of sub-adult bull trout, it is not feasible to assess sub-adult passage at Wells. However, when encountered at the Wells Project, or in tributary traps, sub-adult bull trout will be PIT tagged.

- Douglas PUD will provide PIT tags, equipment, standardized methods, training and coordination to enable tagging of sub-adult bull trout when these fish are incidentally encountered during operations at the Wells fishway, Methow brood-stock trap, and juvenile fish trapping in the Methow, Twisp, and Chewuch rivers.
- Douglas PUD will participate in efforts to explore new methods to monitor sub-adult bull trout movements in the Columbia River and evaluate, in conjunction with the USFWS, and implement new appropriate methods at the Wells Project.
- Douglas PUD will collect information from all PIT-tagged bull trout as they pass through the fishways at Wells Dam, screw traps and brood-stock collection facilities, and post PIT tag information to the PTAGIS website.

Strategy 2-2: Determine off-season sub-adult bull trout passage through the adult fishway (numbers and times of year) at Wells for an experimental period from 2004 to 2005.

- Implement off-season fishway video counts at Wells Dam during the entire winter of 2004 and 2005 to record dates and times of sub-adult bull trout passage.
- Evaluate results to determine if passage trends exist and when ladder maintenance should occur during the off-season during low bull trout usage periods (where reasonable and feasible).

[2] At the time that the Bull Trout Plan was prepared in 2004.

2.3 Objective 3 - Bull Trout Entrapment and Stranding Evaluation

Strategy 3-1: Evaluate Wells inflow patterns, reservoir elevations, and backwater curves to determine if stranding or entrapment of bull trout may occur.

- Review Wells forebay elevations, backwater curves, and historical discharges (daily, hourly) from Chief Joseph to determine Wells Reservoir surface water elevations during low flow periods.
- Determine if backwater locations exist that could pose stranding or entrapment hazards to bull trout during low flow hours, assess operational scenarios that could result in these hazards, and implement an appropriate study to determine bull trout use of such locations during low flow hours.
- Douglas PUD will work with stakeholders to address take resulting from entrapment or stranding (if identified).

2.4 Objective 4 - Identification of Core Area and Local Populations of Bull Trout that Utilize the Wells Project Area

Strategy 4-1: Gather genetic samples from radio-tagged and PIT-tagged bull trout for comparison to baseline genetic samples from local populations and core areas.

- Douglas PUD will provide genetic sampling equipment, standardized methods, training, and coordination to enable collection of bull trout genetic samples during the radio telemetry study, and when fish are incidentally encountered during operations at the Wells fishway, and fish trapping in the Methow, Twisp, and Chewuch rivers.
- Douglas PUD will provide funding for the analysis of the genetic samples.

Strategy 4-2: Work cooperatively with other agencies to obtain locations of radio-tagged fish outside the Project area.

- Douglas PUD will participate in information exchanges and regional efforts to coordinate radio-tag frequencies for bull trout monitoring.
- If radio-tag frequencies deployed by Douglas PUD are not compatible with other monitoring efforts, the PUD will (when feasible) allow the use of their portable telemetry equipment for periodic aerial telemetry efforts.

3.0 STUDY AREA

3.1 Wells Bull Trout Plan Study Area

The study area for this report included all waters within the Wells Project, including the lower Okanogan and Methow rivers, the Wells Reservoir, Wells Dam, and Wells Tailrace, downstream to the "Gateway" location set at approximately 3 miles downstream from Wells Dam. Additional monitoring also took place at downstream hydroelectric projects and other accessible reaches of the mid-Columbia Basin including the Methow, Wenatchee, Entiat, Wenatchee and Okanogan rivers. PIT tagging activities also occurred in the Methow and Twisp rivers.

3.2 General Description of the Wells Hydroelectric Project Area

The Wells Project is located at river mile (RM) 515.6 on the Columbia River in the State of Washington. Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from the Rocky Reach Hydroelectric Project owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Douglas PUD. It includes 10 generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a crest elevation of 795 feet mean sea level (msl) in height.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The normal maximum surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre-feet at elevation of 781 feet msl. The normal maximum water surface elevation of the reservoir is 781 feet msl (Figure 3.2-1).

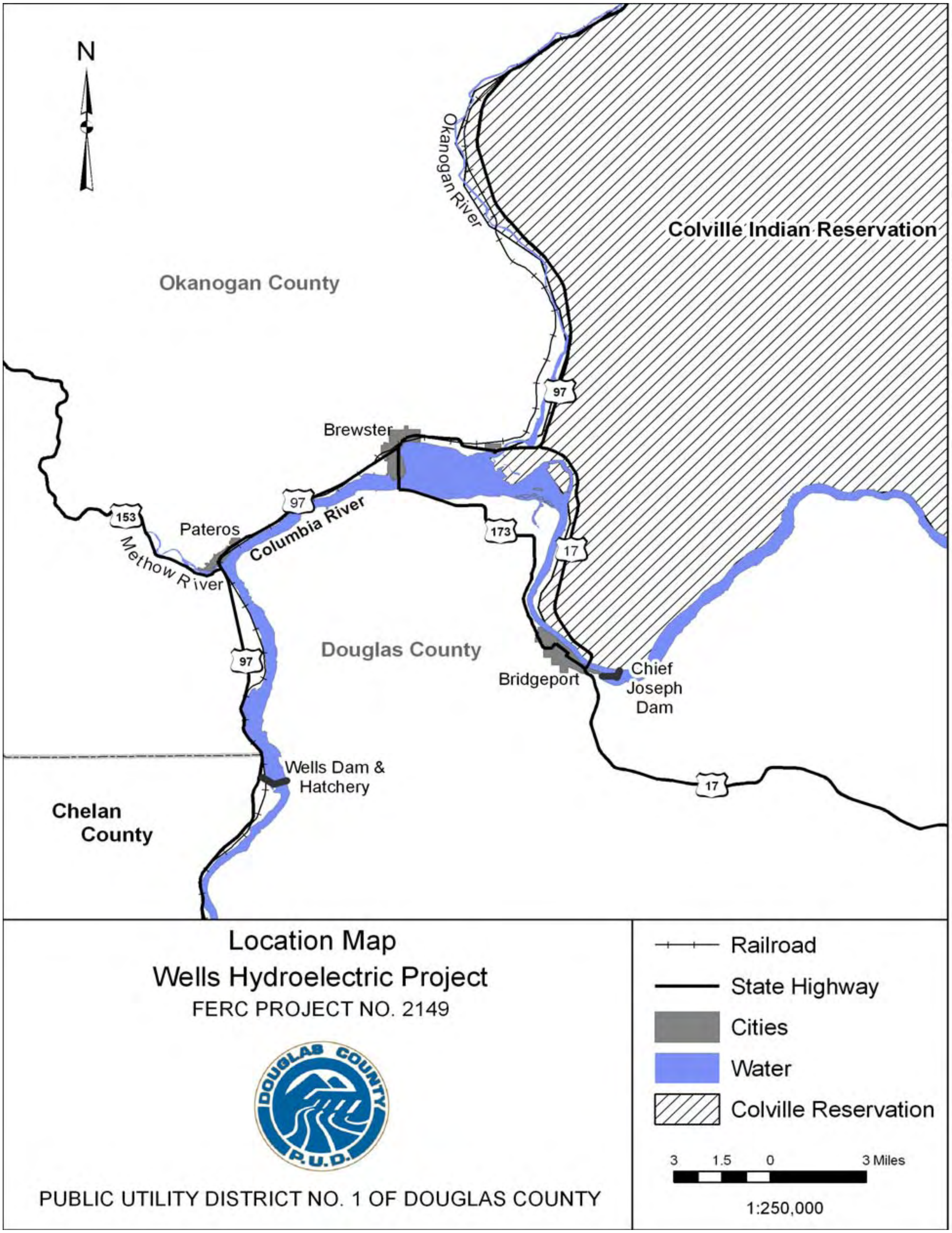

Figure 3.2-1 Location map of the Wells Project.

4.0 BACKGROUND AND EXISTING INFORMATION

4.1 Bull Trout Biology

Bull trout are native to northwestern North America, historically occupying a large geographic range extending from California north into the Yukon and Northwest Territories of Canada, and East to Western Montana and Alberta (Cavender 1978). They are generally found in interior drainages, but also occur on the Pacific Coast in Puget Sound and in the large drainages of British Columbia.

Bull trout currently occur in lakes, rivers and tributaries in Washington, Montana, Idaho, Oregon (including the Klamath River basin), Nevada, two Canadian Provinces (British Columbia and Alberta), and several cross-boundary drainages in extreme southeast Alaska. East of the Continental Divide, bull trout are found in the headwaters of the Saskatchewan River in Alberta, and the Mackenzie River system in Alberta and British Columbia (Cavender 1978; McPhail and Baxter 1996; Brewin and Brewin 1997). The remaining distribution of bull trout is highly fragmented.

Bull trout are a member of the char group within the family Salmonidae. Bull trout closely resemble Dolly Varden (*Salvelinus malma*), a related species. Genetic analyses indicate, however, that bull trout are more closely related to an Asian char (*Salvelinus leucomaenis*) than to Dolly Varden (Pleyte et al. 1992). Bull trout are sympatric with Dolly Varden over part of their range, most notably in British Columbia and a small portion of the Coastal-Puget Sound region of Washington State.

Bull trout are believed to have more specific habitat requirements than other salmonids (Rieman and McIntyre 1993). Growth, survival, and long-term persistence are dependent upon habitat characteristics such as clean, cold, connected, and complex instream habitat (USFWS et al. 2000), and stream/population connectivity. Stream temperature and substrate type, in particular, are critical factors for the sustained long-term persistence of bull trout. Spawning is often associated with the coldest, cleanest, and most complex stream reaches within basins. However, bull trout may exhibit a patchy distribution, even in pristine habitats (Rieman and McIntyre 1995), and should not be expected to occupy all available habitats at the same time (Rieman et al. 1997).

Bull trout exhibit four distinct life history types: resident, fluvial, adfluvial, and anadromous. The fluvial, adfluvial, and resident forms exist throughout the range of the bull trout (Rieman and McIntyre 1993), although each form is not present everywhere. The anadromous life history form is currently known only to occur in the Coastal-Puget Sound region within the coterminous United States (Volk 2000; Kraemer 1994; Mongillo 1993). Multiple life history types may be expressed in the same population, and this diversity of life history types is considered important to the stability and viability of bull trout populations (Rieman and McIntyre 1993).

The majority of growth and maturation for anadromous bull trout occurs in estuarine and marine waters, adfluvial bull trout in lakes or reservoirs, and fluvial bull trout in large river systems.

Resident bull trout populations are generally found in small headwater streams where fish remain their entire lives.

For migratory life history types, juveniles tend to rear in tributary streams for 1 to 4 years before migrating downstream into a larger river, lake, or estuary and/or nearshore marine area to mature (Rieman and McIntyre 1993). In some lake systems, age 0+ fish (less than 1 year old) may migrate directly to lakes, but it is unknown if this emigration is a result of density dependent effects from limited stream rearing habitat, or if these young-of-the-year actually survive in the lake environment (Riehle et al. 1997). Juvenile bull trout in streams frequently inhabit side channels, stream margins and pools with suitable cover (Sexauer and James 1993) with maximum summer water temperatures generally less than 16ºC (Dunham et al. 2003) and areas with cold hyporheic zones or groundwater upwellings (Baxter and Hauer 2000).

4.2 Status

On June 10, 1998, the USFWS listed bull trout within the Columbia River basin as threatened under the ESA (FR 63(111)). Later (November 1, 1999), the USFWS listed bull trout within the coterminous United States as threatened under the ESA (FR 64(210)). The USFWS identified habitat degradation, fragmentation, and alterations associated with dewatering, road construction and maintenance, mining, and grazing; blockage of migratory corridors by dams or other diversion structures; poor water quality; incidental angler harvest; entrainment into diversion channels; and introduced non-native species as major factors affecting the distribution and abundance of bull trout. They noted that dams (and natural barriers) have isolated population segments resulting in a loss of genetic exchange among these segments (FR 63(111)). The USFWS believes many populations are now isolated and disjunct. In October 2002, the USFWS completed the first draft of a bull trout recovery plan intended to provide information and guidance that will lead to recovery of the species, including its habitat (USFWS 2002). Threatened bull trout population segments are widely distributed over a large area and because population segments were subject to listing at different times, the USFWS adopted a two-tiered approach to develop the draft recovery plan for bull trout (USFWS 2002). In November 2002, the USFWS published in the federal register a proposed rule for the designation of critical habitat for the Klamath River and Columbia River distinct population segments of bull trout (67 FR 71235). In October 2004, the USFWS published a final rule in the Federal Register designating critical habitat for the Klamath River and Columbia River populations of bull trout (69 FR 59995).

In April 2008, the USFWS completed the 5-year status review for Columbia River bull trout with two recommendations: maintain “threatened” status for the species, and determine if multiple distinct population segments exist within the Columbia River that merit protection under the ESA. The recommendations intend to facilitate analysis of project effects over more specific and biologically appropriate areas, ultimately allowing a greater focus of regulatory protection and recovery resources (USFWS 2008a). The review also identified specific issues that limit the overall ability to accurately and quantitatively evaluate the current status of bull trout. Seven recommendations were made to improve future evaluation and management decisions, all of which are largely based on improvement and standardization of monitoring and evaluation techniques, better delineation and agreement of core areas and Recovery Units, and multi-agency cooperation and management (USFWS 2008b).

The Wells Project is situated within the Upper Columbia River Recovery Unit[3] and the USFWS has identified the Wenatchee, Entiat, and Methow rivers as its core areas. A core area represents the closest approximation of a biologically functioning unit for bull trout. A core area may function as a metapopulation for bull trout. Not all core areas are equal and each has specific functions that are unique. For example, the Entiat Core Area depends heavily on the mainstem Columbia River to provide overwintering, migration, and foraging habitats. The Wenatchee Core Area has populations using lake and riverine habitat (both the Wenatchee and Columbia rivers) for overwintering, migration, and foraging. Within a core area, many local populations may exist. A local population is assumed to be the smallest group of fish that is known to represent a regularly interacting reproductive unit. Nineteen local populations have been identified in the Wenatchee (7), Entiat (2), and Methow (10) core areas (USFWS 2002).

4.3 2001-2004 Mid-Columbia Bull Trout Radio Telemetry Study

Listed Columbia River bull trout have been counted at Wells Dam since 1998. In 2000, due to the potential for operations at mid-Columbia dams to affect the movement and survival of bull trout, the USFWS requested that the three mid-Columbia PUDs evaluate the movement and status of bull trout in their respective project areas. At that time, little was known about the life-history characteristics (e.g., movements, distribution, habitat use, etc.) of bull trout in the mid-Columbia River. Therefore, in order to assess the operational effects of hydroelectric projects on bull trout within the mid-Columbia, a three PUD coordinated radio telemetry study was implemented beginning in 2001. The goal of the study was to monitor the movements and migration patterns of adult bull trout in the mid-Columbia River using radio telemetry (Figure 4.3-1). The number of bull trout to be collected and tagged at each dam (Rock Island, Rocky Reach, and Wells) was based on the proportion of fish that migrated past those dams in 2000.

From 2001 to 2003, bull trout were collected from the Wells, Rocky Reach, and Rock Island dams, radio-tagged, and monitored through 2004. Multiple-telemetry techniques were used to assess the movement of tagged bull trout within the study area. At Wells Dam, a combination of aerial and underwater antennas was deployed. The primary purpose for this system was to document the presence of bull trout at the project, identify passage times and determine their direction of travel (i.e., upstream/downstream). In addition to these systems, a number of additional telemetry systems were deployed to address specific questions posed by the USFWS and Douglas PUD. At Wells Dam, several additional systems were installed to identify whether tagged bull trout could enter, ascend, and exit specific gates and fish ladders. All possible access points to the adult fish ladders and the exits were monitored individually during the study period from 2001-2004, allowing the route of passage to be determined as well as the ability to establish the exact time of entrance and exit from the ladder system.

[3] Note that while the USFWS refers to the area encompassing the Wells Project as the Upper Columbia Recovery Unit for bull trout, the section of the Columbia River from Chief Joseph Dam to the confluence of the Yakima and Columbia rivers is generally termed the "mid-Columbia" for other watershed and salmon and steelhead recovery planning, and is the term used in this document when referring to the reach.

To assess bull trout movements into and out of the Wells Reservoir, fixed-telemetry monitoring sites were established at the mouth of the Methow and Okanogan rivers and periodic aerial surveys were conducted on the reservoir and throughout both watersheds (English et al. 1998, 2001). English et al. (1998, 2001) provide a detailed description of the telemetry systems at each of the dams and within the tributaries.

Overall, successful bull trout upstream and downstream passage was observed at the Wells Project. No bull trout injury or mortality was observed associated with the Wells Project. Radio-tagged bull trout that migrated upstream past Wells Dam utilized the Methow River subbasin during the bull trout spawning period. Key findings of the 2001 to 2004 study are used in this document to assess the 6-year average take analysis as stipulated in the Bull Trout Plan (Objective 1, Strategy 1-1) and are summarized in the results section of this document.

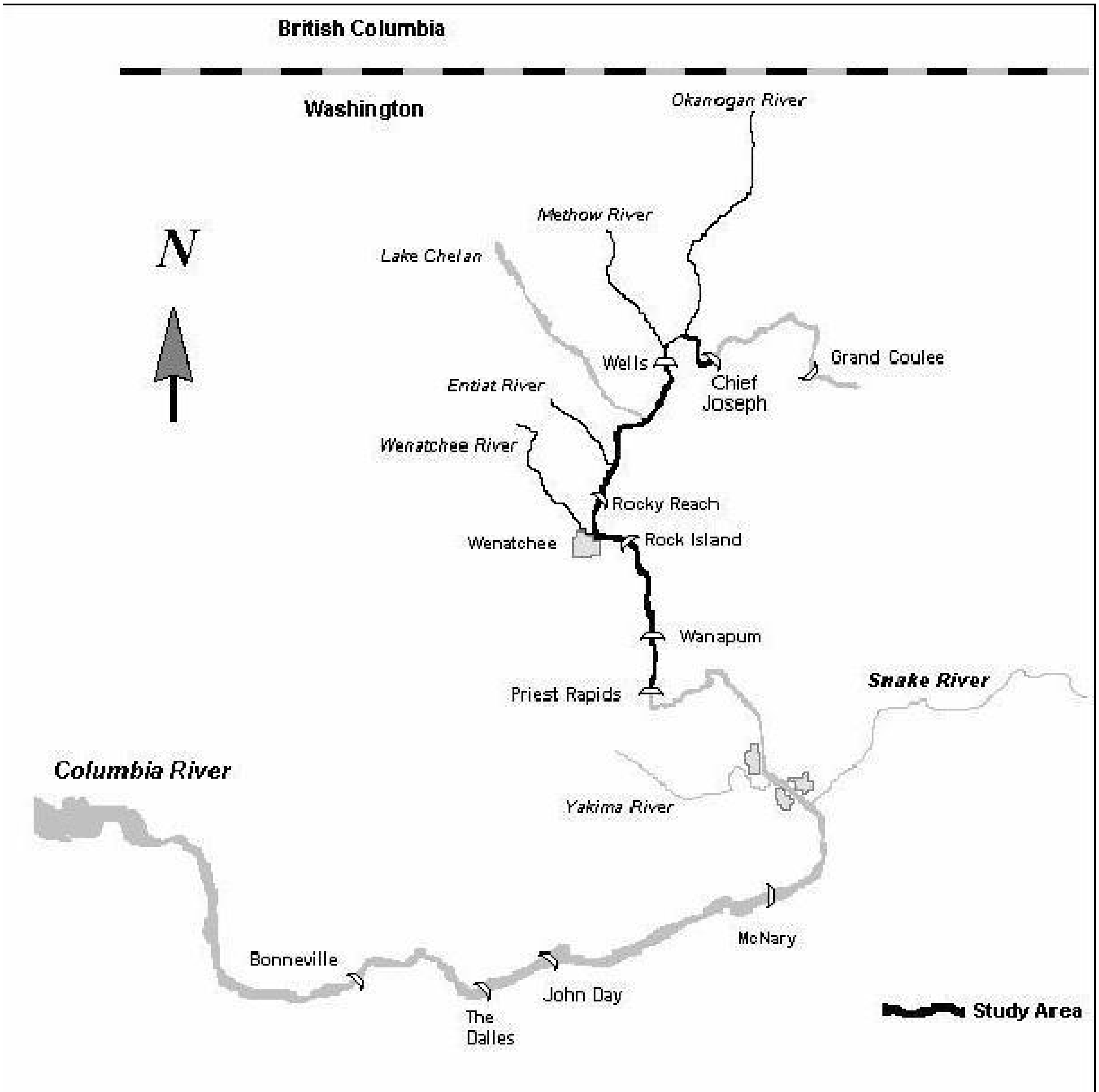

Figure 4.3-1 Study area for assessing migration patterns of bull trout in the mid-Columbia River (2001-2004).

5.0 METHODOLOGY

A detailed description of the methodology to implement each Bull Trout Plan objective-strategy is presented below by individual strategy point.

5.1 Strategy 1-1: Adult bull trout telemetry program

The adult bull trout telemetry program allowed monitoring of bull trout movements in the Wells Project, including the timing and frequency of upstream and downstream passage events, passage routes, and associated survival rates and quantification of take. The telemetry program also supported several of the other objectives of the Bull Trout Plan. For example, the telemetry program provided genetic samples of the radio-tagged adult bull trout in support of Strategy 4-1, and provided data on the timing and frequency of movements into and out of tributaries in support of Strategy 4-2. The telemetry program goal was to capture and radio-tag 10 adult bull trout each year for three years at Wells Dam (May 2005 through July 2007), with associated tracking through July 2008 as required by the Bull Trout Plan. Specific methods are presented below.

5.1.1 Tagging

In 2005, bull trout at Wells Dam were surgically implanted with Model Pisces coded radio tags manufactured by Grant Systems Engineering. Based on recommended tag weight to fish weight ratios, and bull trout length to weight relationships, only bull trout greater than 400 mm in length were selected for tagging. Also for the purposes of this study, "adult" bull trout were defined as fish $\geq$ 400 mm in length. In 2006 and 2007, Model MCFT-3A motion-sensor (i.e., mortality sensor) radio tags manufactured by Lotek were used. The motion-sensor tags changed their broadcast code if the tag remained motionless for 24 hours. For this study, the “motionless” signal was assumed to indicate fish mortality or expulsion of the tag. Tags were programmed to have mid-range motion sensitivity, which was shown during Lotek field tests (Lotek, unpublished data) to be most suitable to detect fish mortality.

Bull trout at Wells Dam were trapped using the brood-stock collection facilities located within the East and West fishways. Trapping operations occurred during the peak of the bull trout passage period as determined by the 2001-2004 study. The majority of the trapping occurred in the East fishway, though the west fishway trap was used periodically in all three tagging years.

The brood-stock collection facilities were located at pool 40 approximately half way up each fish ladder. The traps were operated by placing a barrier fence across the entire width of the pool. When a trap was in operation, all fish attempting to ascend the ladder were forced to ascend a steep-pass denil ladder into an upwell enclosure, and then down a sorting chute. When a bull trout was observed in the sorting chute, a technician redirected the fish via a pneumatic diversion gate into a holding facility. Fish captured in the West fishway were directed to a hatchery brood-stock collection pond, while in the East fishway captured fish were directed to a 1,236 L holding tank.

Bull trout collected in the East fishway were tagged immediately after capture. Those collected in the West fishway were tagged at the end of the 24 hour trapping session when the hatchery pond was processed for fish. Bull trout captured in the West fishway were subsequently transported over to the East fishway tagging facility. The collected bull trout were netted from the holding tank and transferred to an anesthetic tank containing a 90 mg/L solution of tricaine methanesulfonate (MS-222) and a few drops of Stress Coat (Aquarium Pharmaceuticals, Inc. Chalfont, PA). After 1.5 to 2.0 minutes, the fish lost equilibrium and was considered to be adequately anesthetized for surgical radio tag implantation. The fish was then removed from the solution, weighed, measured, and placed in a wet V-shaped trough for tagging (coated with Stress Coat to minimize scale loss and maintain the exterior mucous coat). A tube was placed in the fish's mouth, supplying cool river water and MS-222 (45 mg/L), aerating the gills and maintaining anesthesia during the tagging procedure. A small (1 cm^2) clip was taken from the upper lobe of the caudal fin, placed in non-denatured alcohol, and sent to the USFWS for genetic analyses. Four to five scales were removed and placed in a scale book, which was sent to WDFW for fish age analyses.

Radio tag surgical implantation methods were similar to those described in Adams et al. (1998) and Summerfelt and Smith (1990), using the "shielded needle" surgical implantation technique. In addition, intraperitoneal antibiotic was pipetted (50 μL) into the incision to prevent infection. A PIT tag was also inserted into the body cavity during radio-tag implantation. The incision was closed with four to five interrupted, absorbable sutures (3-0 braided Coated Vicryl, Ethicon Corp.) evenly spaced across the incision. The antenna was then attached to the side of the fish with a single suture approximately 1 cm posterior to the antenna exit site. The incision site was cleaned, and a small amount of a cyanoadhesive compound (Vetbond) was applied to the incision and antenna exit site to secure the sutures in place. The fish was then transferred to a recovery tank (a cooler, supplied with flow-through river-water, and supplied with oxygen through an air stone) located on the back of a pickup truck. Approximately one minute before the procedure was complete the MS-222 was removed from the water flushing over the gills to begin the recovery process. Surgical equipment was disinfected with a diluted germicidal solution between each fish tagged.

After the surgery was complete, the flow-though water was detached from the recovery tank, and the fish was quickly transported to the release site. At the release site, the air stone was removed and the recovery tank was placed into the river. The tank was gently rolled onto its side and the lid was opened allowing the fish to swim free of the tank. The swimming behavior of the fish was observed and any abnormalities were noted. All fish were released at the Starr Boat Launch, which was chosen as a release site because it was the closest possible release point to the dam accessible by vehicle, but that was also outside of the influence of forebay hydraulics (including spill and bypass entrainment flows) to reduce the potential for fall back of newly tagged fish.

5.1.2 Telemetry monitoring

A combination of aerial and underwater antennas was used to detect tagged bull trout at the Wells Project, to identify passage routes and times and determine direction of travel (upstream/downstream). Three aerial antennas monitored the mainstem Columbia River, 3 miles downstream of the dam, to detect any movements of bull trout out of the study area. Two aerial stations, located immediately downstream of the dam on each side of the river, monitored movements within the Wells tailrace. Five combined aerial antennas monitored movements in the Wells forebay. Underwater dipole antennae arrays were deployed into each of five spillbays (2, 4, 6, 8, and 10) where spring/summer bypass spill is typically released. In each spillbay, a dipole antenna was mounted on each of the left and right bulkhead tracks at approximately 10 ft above the bottom of the spillbay intake floor. In addition, on gates 2 and 10, paired dipole antennas were deployed approximately 10 ft below the water surface to monitor spill water passing via the sluice gates. Nine underwater antennas were deployed within each fishway to monitor bull trout approach, ascent, and exit timing.

To assess bull trout movements into and out of the Wells Reservoir, fixed-telemetry monitoring sites were established at the mouths of the Methow and Okanogan rivers. Two antennas were deployed for each tributary to determine the direction of fish movements. Other researchers were conducting radio telemetry studies on bull trout in the mid-Columbia reach concurrent with the Douglas PUD study, and fixed telemetry arrays were present at Rock Island and Rocky Reach dams, and at the mouths of the Wenatchee and Entiat rivers located downstream of the Wells Project. Bull trout tagged by the USFWS and Chelan PUD were monitored at the Wells Project and observations within Project boundaries are included in this document where applicable to the Wells Project Bull Trout Plan objectives.

Radio-tagged bull trout were mobile tracked while in the Wells Project Area. Periodic mobile tracking was also used to confirm the presence of bull trout within tributaries and to track fish within the reservoirs. Mobile tracking methods included aircraft, boat, vehicle, and foot surveys. Tracking data were compiled continuously throughout the year to determine fish locations, tag status, and the need to deploy tag recovery operations in the Wells Project Area. Douglas PUD conducted tracking in the Wells Reservoir and surrounding areas. The USFWS conducted several mobile surveys of the Methow River subbasin as part of their concurrent study, and provided Douglas PUD with the location and date for Wells Dam radio-tagged bull trout detections. Similarly, Chelan PUD monitored Wells Dam radio-tagged bull trout frequencies during several of their mobile tracking surveys in the Entiat and the Wenatchee river subbasins.

5.1.2.1 Data processing

Fish detection data were downloaded from the Lotek receivers at the fixed telemetry arrays a minimum of twice per month, and more often if receiver memory began to exceed capacity prior to the scheduled downloads. Telemetry array systems (i.e., antennas, amplifiers, power inverters, and receivers) were tested periodically during the study to ensure correct operation and function.

Data stored by Lotek receivers were downloaded to a laptop computer as hex-encoded files and converted to standard ASCII format using software developed by LGL Limited. This software assessed several diagnostics, including the number of invalid records; if the number of invalid records was large, the receiver was downloaded a second time. The software also recorded the distribution of antenna noise by power level, allowing identification and correction of individual antenna issues. Data files were uploaded to the LGL FTP site and subsequently downloaded at the LGL Limited office.

Telemetry Manager Version 3.0 software was used for data processing, as well as programs developed in Visual FoxPro by LGL Limited. Invalid data were censored, including background noise at the Project, records with a signal strength that was below a set threshold, single records for a given frequency-code-location combination, and records prior to the fish release time and date. An operational database summarized arrival and departure times from each detection zone.

5.2 Strategy 1-1: Calculation of Incidental Take for Adult Bull Trout

The Wells Project incidental take analysis stipulates specific statistical analyses for determining the 6-year average annual observed take of bull trout during two separate study periods. The incidental take observed under this study period (2005-2008) was averaged with take observed during the 2001 to 2004 telemetry study period to calculate total Project take. Total take was partitioned by upstream and downstream passage events. Take levels were calculated using data from only the first year (365 days) of tag life for each tagged fish; that is, tag detections occurring outside of this period were not used. Further, capture of each bull trout at Wells Dam for tagging was considered a successful upstream passage event and is included in the take calculations.

Project take was calculated by dividing the number of tagged fish "taken" by the total number of radio-tagged fish detected passing either upstream or downstream through Wells Dam (Douglas PUD 2004). The total number of radio-tagged bull trout detected in the WPA included all fish tagged by Douglas PUD, as well as bull trout tagged by Chelan PUD and the USFWS that were detected moving through Wells Dam.

Take associated with turbine and spillway passage was not calculated for the 19 downstream passage events that occurred within one year of tagging because zero take was observed.

5.3 Strategy 1-2: Correlations between adult bull trout passage events and Project operations

As stipulated in the Bull Trout Plan (Douglas PUD 2004), data were compiled for Project (spill, turbines, reservoir elevations) and ladder operations during times of downstream passage for active tagged fish. Daily average Project operations data were extracted for each date on which a downstream passage event occurred and plotted for each day of the study period to provide context for the data. Although the absence of mortalities associated with Project operations prohibited examination of "take" and potential correlates, passage events were compared to operation variables. The Multivariate Platform in JMP® 7 was used to further explore how Project operations were related to downstream passage. A scatterplot matrix of date, total discharge, turbine discharge, total spill, in flow, forebay elevation, TDG (%), water temperature, and downstream passage events of radio-tagged bull trout from 2005-2008 was used to visualize correlations with 95% bivariate normal density ellipses. Further, a pairwise correlations table was used to document the Pearson product-moment correlations for each pair of the *Y* variables, using all available values. The table also provides significance probabilities and compares the correlations with a bar chart.

5.4 Strategy 1-3: Off-season fishway passage of adult bull trout

The Bull Trout Plan required off-season video counts of fishways at Wells Dam during the entire winter of 2004-2005 to record dates and times of adult bull trout passage and to investigate passage trends in relation to ladder maintenance needs. Off-season video monitoring of both Wells Dam fishways for the 2004-2005 winter period began on November 16, 2004 and continued until April 30, 2005. In addition to the requirements of the Bull Trout Plan, Douglas PUD, in consultation with the USFWS, has continued the off-season video monitoring every year since the winter of 2005 including the winters of 2005-2006, 2006-2007 and 2007-2008.

5.5 Strategy 1-4: Develop plan to address adult bull trout passage problems if identified

No adult bull trout passage problems have been identified that require a corrective plan.

5.6 Strategy 2-1: Sub-adult bull trout PIT tagging program

Sub-adult bull trout were defined as fish < 400 mm in length. Douglas PUD provided WDFW with PIT tags and tagging equipment to mark sub-adult bull trout incidentally encountered during certain fish sampling operations, including the WDFW smolt-trapping programs in the Methow and Twisp rivers. In addition to providing PIT tag equipment and training, Douglas PUD facilitated an annual pre-season coordination meeting. WDFW tagged sub-adult bull trout caught during their trapping operations using standard PIT tagging protocols developed and distributed by the Pacific States Marine Fisheries Commission. PIT tag data for all bull trout encountered and tagged were uploaded by WDFW to the PITAGIS database.

Douglas PUD passively monitored Wells Dam fishways for PIT tagged bull trout using a fixed PIT tag detection system developed for salmon and steelhead monitoring. The PIT tag detection system operated year-round during the study period (2005 to 2008). Based on previous testing, the PIT tag detection efficiency was estimated at 99.98% for PIT tagged run of the river steelhead and salmon. The PITAGIS database was queried in an effort to determine whether sub-adult bull trout tagged in the Methow are utilizing the Wells Project.

5.7 Strategy 2-2: Off-season fishway passage of sub-adult bull trout

The monitoring effort described for Strategy 1-3 (adult bull trout off-season video monitoring) also was used to monitor sub-adult bull trout fishway passage. No sub-adult bull trout were detected during the off-season fishway counting periods. Because no sub-adult fish were counted, an analysis of sub-adult passage trends was not completed and no recommendations for modifying the adult fish ladder maintenance schedule were developed.

5.8 Strategy 3-1: Evaluate bull trout stranding and entrapment

Douglas PUD contracted with GeoEngineers in March 2005 to develop detailed bathymetric maps of the Wells Project. The maps were produced at a 1-foot contour interval and were combined with Wells Dam operational data to assess potential areas of bull trout entrapment or stranding. The analysis identified several locations where stranding or entrapment of bull trout could potentially occur, including the Methow River mouth, the Okanogan River mouth, the Kirk Islands, the shallow water habitat in the Columbia River directly across from the mouth of the Okanogan River, Schluneger Flats, and the off-channel areas of the Bridgeport Bar Islands.

On May 18, 2006, Douglas PUD field crews surveys 5 reservoir sites during operational and environmental conditions that could potentially result in bull trout stranding or entrapment. From 11:00 PM May 17 to 8:00 AM May 18, 2006 the Wells Reservoir elevation was reduced to 772 feet msl. Douglas PUD conducted field surveys on May 18 from 10:00 AM to 4:00 PM for bull trout stranding or entrapment. Boat and foot surveys were conducted and included a combination of shoreline transects and inspection of isolated sanctuary pools at all sites to visually identify entrapped or stranded bull trout.

On November 5, 2008 an additional stranding survey was conducted at three of the five sites and one new site identified as having the highest probability of stranding during the 2006 study (Methow River mouth, Okanogan River mouth, Columbia River across from the Okanogan River and Sloniger Flats). The Wells Reservoir elevation during this survey was 772.5 msl. The field survey was conducted from 9:30 AM to 3:00 PM. Foot surveys were conducted and included inspection of sanctuary pools and shoreline areas.

5.9 Strategy 4-1: Genetic sampling program

Douglas PUD provided sampling equipment and facilitated standardized training to collect genetic samples from bull trout incidentally collected as part of several on-going projects. Genetic samples were collected from bull trout captured for this study at Wells Dam. Genetic samples were also taken from bull trout incidentally encountered during other fish sampling operations, including juvenile and sub-adult salmonid trapping activities on the Methow and Twisp rivers. All genetic samples were sent to the USFWS Abernathy Fish Technology Center for storage and future analysis.

5.10 Strategy 4-2: Determine locations of Wells Dam bull trout outside the Project Area

Radio-tagged bull trout detected at Wells Dam were tracked to determine movements after leaving the Wells Project Area. As previously discussed, Douglas PUD worked cooperatively with these agencies to obtain more detailed locations of bull trout that interacted with the Wells Project. Coordination between all research projects included tag frequency coordination and sharing of radio telemetry data sets from fixed antenna arrays and mobile tracking.

Core areas (tributaries) used by radio-tagged bull trout captured or detected at Wells Dam were determined for each fish in each year that a tributary entrance was detected. Each observation of an entry in a given year was used as an independent data point. A unique fish could have more than one tributary selection or none at all. Proportional use of each tributary by all radio-tagged bull trout was determined.

6.0 RESULTS

6.1 Strategy 1-1: Adult bull trout telemetry program

6.1.1 Bull trout tagged by Douglas PUD

The telemetry program goal was to capture and radio-tag 10 adult bull trout at Wells Dam each year for three years. Total bull trout released with tags were 6, 10, and 10 for 2005, 2006, and 2007, respectively. Trapping effort and catch for each year of operation are presented below in the respective sections.

6.1.1.1 Results from Fish Tagged in 2007

Ten adult bull trout were captured and tagged between May 19 and June 5, 2007 (Table 6.1-1). Fish were actively collected on the East and West fishway brood-stock collection facilities by WDFW employees. Trapping was conducted on the East fishway from 15 May to 5 June for 20 days and a total of 164 hours. Trapping was conducted on the West fishway from 16 May to 31 May for 6 days and a total of 56 hours. Total trapping effort was 220 hours.

Three mobile tracking surveys were conducted between 15 Aug and 13 Dec, 2007 in the Wells Project Area. Only one tag was detected; #29 on the third and last survey.

There were a total of 22 passage events through Wells Dam in 2007[4] for bull trout tagged by Douglas PUD from 2005 to 2007, including 6 downstream and 16 upstream events (Table 6.1-2). Of these, 2 downstream and 10 upstream events occurred within one year of release.

Detection summaries for each bull trout radio-tagged by Douglas PUD in 2007 are included as Appendix A.

[4] Note that there were no upstream or downstream passage events of DCPUD-tagged bull trout through the monitoring period in 2008 (ending in July). Only two passage events occurred in 2008 – a CCPUD bull trout tagged in 2006 successfully made both an upstream and downstream passage (Table 6.1-2)

Table 6.1-1 Radio-tagged bull trout released by Douglas PUD, 2005-2007.

Tagging Year	Fish No.	Ch-Cd	Release	Tributary Use Name	Tributary Use Entrance	Tributary Use Exit	Last Location
2005							
	1	1-2	May-26	Methow	May-26	none	Tag recovered in Methow R. Oct 13 2005
	2	1-4	Jun-02	Methow	Jun-03	May-11-06	Methow R. confluence Sep 2 2007
	3	1-6	Jun-03	Methow	Jun-07	Nov-10-05	Columbia R. at gateway Aug 24 2007
	4	1-8	Jun-07	Methow	Jun-08	Jun-12-05	Columbia R. at Wells Dam tailrace May 12 2006
	5	1-10	Jun-07	Methow	Jun-19	none	Methow R. Oct 13 2005
	6	1-12	Jun-28	Methow	< 31 Aug	Apr-10-06	Columbia R. below WPA Jun 6 2006
2006							
	11	1-56	May-16	Methow	May-27	Nov-17-06	Columbia R. at gateway Jun 30 2007
	12	1-52	May-16	Methow	May-31	Nov-1-06	Methow R. confluence Oct 3 2007
	13	1-68	May-18	Entiat	Jun-25	Nov-30-06	Entiat R. Sep 5 2007
	14	1-64	May-19	Methow	Jun-14	none	Tag recovered in Methow R. Nov 10 2006
	15	1-58	May-19	Methow	May-24	none	Methow R. confluence Jul 8 2008
	16	1-60	May-21	Methow	May-23	none	Methow R. Oct 11 2006
	17	1-66	May-24	Entiat	Jul-04	unk	Methow R. confluence Jul 6 2008
	18	1-50	May-24	Methow	May-26	none	Tag motionless in Methow R. Jul 18 2007
	19	1-54	May-24	Entiat	Jul-07	unk	Methow R. confluence May 14 2008
	20	1-62	May-24	Methow	May-25	Nov-15-06	Columbia R. below Wells Dam Jul 3 2008
2007							
	21	1-69	May-19	Methow	May-21	Jul-8-08	Columbia R. at Wells Dam forebay Jul 8 2008
	22	1-67	May-20	Methow	May-20	none	Methow R. Nov 27 2007
	23	1-65	May-25	Methow	May-26	Jun-11-07	Tag recovered in Methow R. Jul 20 2007
	24	1-63	May-29	Methow	May-31	none	Tag motionless in Methow R. Jul 20 2007
	25	1-61	Jun-02	Methow	Jun-02	none	Tag recovered in Methow R. Jul 26 2007
	26	1-59	Jun-04	Methow	Jun-07	Apr-10-08	Columbia R. at gateway Apr 11 2008
	27	1-57	Jun-04	Methow	Jun-06	none	Methow R. confluence Jun 25 2007
	28	1-55	Jun-04	Methow	Jun-07	none	Tag recovered in Methow R. Jul 18 2007
	29	1-53	Jun-04	Methow	Jun-07	Nov-17-07	Tag motionless in Columbia R. 1.5 mi above Wells Dam Dec 13 2007
	30	1-51	Jun-05	Methow	Jun-07	none	Methow R. Sep 17 2007

Table 6.1-2 Radio-tagged bull trout that passed downstream or upstream through Wells Dam, 2005-2008.

Tag Group	Fish No.	Ch-Cd	Release	Downstream Passage Event 2005	Downstream 2006	Downstream 2007	Downstream 2008	Upstream Passage Event [a] 2005	Upstream 2006	Upstream 2007	Upstream 2008
DCPUD 2005											
	1	1-2	May-26					May-26			
	2	1-4	Jun-02		May-11			Jun-2	Jun-17		
	3	1-6	Jun-03			Aug-24		Jun-3			
	4	1-8	Jun-07	Jun-12				Jun-7			
	5	1-10	Jun-07					Jun-7			
	6	1-12	Jun-28		May-13			Jun-28			
DCPUD 2006											
	11	1-56	May-16		Nov-19	Jun-30			May-16	Jun-18	
	12	1-52	May-16			Apr-19			May-16	May-19	
	13	1-68	May-18		May-21				May-18		
	14	1-64	May-19		May-24				May-19, Jun-14		
	15	1-58	May-19						May-19		
	16	1-60	May-21						May-21		
	17	1-66	May-24		May-29				May-24	May-29	
	18	1-50	May-24						May-24		
	19	1-54	May-24		May-24				May-24	May-31	
	20	1-62	May-24		Nov-30	Jun-5, Oct-22			May-24	Jun-3, Jun-22	
DCPUD 2007											
	21	1-69	May-19							May-19	
	22	1-67	May-20							May-20	
	23	1-65	May-25							May-25	
	24	1-63	May-29							May-29	
	25	1-61	Jun-02							Jun-2	
	26	1-59	Jun-04			Apr-11				Jun-4	
	27	1-57	Jun-04							Jun-4	
	28	1-55	Jun-04							Jun-4	
	29	1-53	Jun-04							Jun-4	
	30	1-51	Jun-05							Jun-5	
CCPUD 2005											
	531	14-31	May-31		Jun-29			Jun-25			
	544	14-44	Jun-27		Nov-16				May-23		
	503	14-3	May-30					Jun-17			
CCPUD 2006											
	409	14-171	May-25		Dec-17				Jun-3	May-14	
	412	14-174	May-26		Nov-14				Jun-5	Jun-30	
	418	14-180	May-31			Mar-13			Jun-4	Jun-18	
	422	14-184	Jun-05			Jul-3	May-16		Jun-19	Jul-18	May-27
	426	14-188	Jun-22		Dec-20				Jul-1	Jun-19	
	428	14-190	Jun-29							Jun-10	
CCPUD 2007											
	1034	14-111	May-16							Jun-2	
	1038	14-115	May-24							May-30	
	1039	14-116	May-29							Jun-15	
USFWS 2006											
	204	1-74	Apr-12		Jul-19						
USFWS 2007											
	300	1-83	Jun-20			Jul-5					
USFWS 2008											
	none										
			Yearly Count	1	14	9	1	8	18	25	1
			Total Count				25				52

Shading indicates event occurred greater than 1 year after release.

[a] one successful passage event for each bull trout tagged by DPUD is included, as per the BTMP.

6.1.1.2 Results from Fish Tagged in 2006

Ten adult bull trout were captured and tagged from May 16 to May 24, 2006 (Table 6.1-1). Fish were actively collected on the East and West fishway brood-stock collection facilities by WDFW employees. Trapping was conducted on the East fishway from May 14 to May 24 for 10 days and a total of 77 hours. Trapping was conducted on the West fishway from May 14 to May 24 for 6 days and a total of 69 hours. Total trapping effort was 146 hours.

Five mobile tracking surveys were conducted between May 19 and Dec 21, 2006 in the WPA (Table 6.1-3).

There were a total of 20 passage events through Wells Dam in 2006 of bull trout tagged by Douglas PUD from 2005 to 2006, including 8 downstream and 12 upstream events (Table 6.1-2). Of these, 8 downstream and 11 upstream events occurred within one year of release.

Table 6.1-3 Mobile tracking surveys conducted by Douglas PUD, 2006.

Date	Survey Type	Location	Tag numbers detected
19 May 2006	Truck	Wells forebay to Methow confluence	none
23 May 2006	Boat	Wells tailrace to gateway station	none
23 May 2006	Truck	Wells forebay to Methow confluence	11, 12, 13, 15, 16
19 Sep 2006	Boat	Wells tailrace	one non-DCPUD
21 Dec 2006	Boat	Wells tailrace to Chelan Falls	11, 20, one non-DCPUD

6.1.1.3 Results from Fish Tagged in 2005

Six adult bull trout were captured and tagged between May 26 and June 21, 2005 (Table 6.1-1). Fish were actively collected on the East and West fishway brood-stock collection facilities by WDFW employees. Trapping was conducted on the East fishway from May 26 to June 21 for 15 days and a total of 208 hours. Trapping was conducted on the West fishway from June 19 to June 21 for 3 days and a total of 24 hours. Total trapping effort was 232 hours.

Five mobile tracking surveys were conducted between July 20 and December 23, 2005 in the Wells Project. No tagged bull trout were detected on any of these surveys.

There were a total of 7 passage events through Wells Dam in 2005 of bull trout tagged by Douglas PUD in 2005, including 1 downstream and 6 upstream events (Table 6.1-2). Of these, 1 downstream and 6 upstream events occurred within one year of release.

6.1.2 Bull trout tagged by Chelan PUD

Twenty-four bull trout tagged by Chelan PUD have been detected in the WPA, including eleven fish tagged in 2005, nine fish tagged in 2006, and four fish tagged in 2007.

There were a total of 2 passage events through Wells Dam in 2008 of bull trout tagged by Chelan PUD from 2005 to 2007, including 1 downstream and 1 upstream event (Table 6.1-2). Of these, 0 downstream and 0 upstream events occurred within one year of release.

There were a total of 10 passage events through Wells Dam in 2007 of bull trout tagged by Chelan PUD from 2005 to 2007, including 2 downstream and 8 upstream events (Table 6.1-2). Of these, 1 downstream and 5 upstream events occurred within one year of release.

There were a total of 11 passage events through Wells Dam in 2006 of bull trout tagged by Chelan PUD from 2005 to 2006, including 5 downstream and 6 upstream events (Table 6.1-2). Of these, 3 downstream and 6 upstream events occurred within one year of release.

There were a total of 2 passage events through Wells Dam in 2005 of bull trout tagged by Chelan PUD in 2005, including 0 downstream and 2 upstream events (Table 6.1-2). Of these, 0 downstream and 2 upstream events occurred within one year of release.

6.1.3 Bull trout tagged by US Fish and Wildlife Service

Two bull trout tagged by USFWS were detected making movements through the Wells Project, including one fish tagged in 2006 (Ch 1, codes 74 and 76) and one fish tagged in 2007 (Ch 1, code 83).

There was a total of 1 passage event through Wells Dam in 2007 of bull trout tagged by the USFWS from 2005 to 2007, including 1 downstream and 0 upstream events (Table 6.1-2). Of these, 1 downstream and 0 upstream events occurred within one year of release.

There was a total of 1 passage event through Wells Dam in 2006 of bull trout tagged by the USFWS from 2005 to 2006, including 1 downstream and 0 upstream events (Table 6.1-2). Of these, 1 downstream and 0 upstream events occurred within one year of release.

There were no passage events through Wells Dam in 2005 of bull trout tagged by the USFWS in 2005 (Table 6.1-2).

6.1.4 Results from 2001 to 2004 bull trout telemetry project (BioAnalysts, Inc. 2004)

Tagged migratory adult bull trout successfully move both upstream and downstream past the Project. From the 79 bull trout radio-tagged in 2001 and 2002 at Rock Island, Rocky Reach, and Wells dams, five bull trout passed downstream through Wells Dam with no documented mortality. Two of these events occurred within 1 year of release.

Between 2001 and 2003, a total of 10 (2 tagged at Rock Island, 4 Rocky Reach, 4 Wells), 11 (5 Rocky Reach, 4 Wells, 2 from 2001), and 1 (1 Wells) tagged bull trout were detected moving upstream of the project, respectively. Nineteen of these events occurred within 1 year of release.

Adult bull trout migrating upstream of Wells Dam appear to be destined for the Methow River. Between 2001 and 2003, no bull trout selected the Okanogan system (one bull trout moved into the Okanogan, but left shortly thereafter and moved into the Methow system).

6.1.5 Wells Project 6-year-average Incidental take calculation (2000 to 2004 and 2005 to 2008 monitoring years combined)

Of all tags released from 2005 to 2007 by Douglas PUD, Chelan PUD, and the USFWS, there were 25 downstream passage events and 52 upstream passage events by radio-tagged bull trout recorded at Wells Dam (n=40 individuals) (Table 6.1-2). Of these, 17 downstream and 41 upstream passage events occurred within one year of release (Table 6.1-4). Of all tags released from 2001 to 2004, there were 2 downstream passage events and 41 upstream passage events by radio-tagged bull trout recorded or tagged at Wells Dam (BioAnalysts, 2004). Of these, 2 downstream and 38 upstream passage events occurred within one year of release (Table 6.1-4). There were 27 downstream and 93 upstream total passage events at Wells Dam by radio-tagged bull trout, and 19 downstream and 79 upstream passage events at Wells Dam by radio-tagged bull trout within one year of release over the six years of tagging and eight years of monitoring (Table 6.1-4). Radio-tagged bull trout passed downstream through the turbines or spillways as no downstream passage events were recorded via the fishways. No bull trout injury or mortality was observed at the Wells Project during either study period, by fish passing within one year of release or by fish passing greater than 1 year, as indicated by subsequent movement and detections. Therefore, in-depth take calculations and analysis are not necessary as the observed take over eight years of monitoring was zero out of 98 passage events occurring within one year of tagging.

Table 6.1-4 Summary of downstream and upstream passage events of radio-tagged bull trout within one year of release through Wells Dam, 2001-2007.

Tag Group	Downstream Passage Event Total	Downstream Passage Event Survived	Downstream Passage Event Died	Upstream Passage Event [a] Total	Upstream Passage Event [a] Survived	Upstream Passage Event [a] Died
DCPUD 2005	3	3	0	6	6	0
DCPUD 2006	7	7	0	11	11	0
DCPUD 2007	1	1	0	10	10	0
CCPUD 2005	0	0	0	3	3	0
CCPUD 2006	4	4	0	8	8	0
CCPUD 2007	0	0	0	3	3	0
USFWS 2005	0	0	0	0	0	0
USFWS 2006	1	1	0	0	0	0
USFWS 2007	1	1	0	0	0	0
USFWS 2008	0	0	0	0	0	0
subtotal (2005-2008)	17	17	0	41	41	0
CCPUD 2001 [b]	0	0	0	20	20	0
CCPUD 2002 [b]	2	2	0	18	18	0
subtotal (2001-2004)	2	2	0	38	38	0
Totals	19	19	0	79	79	0

[a] one successful passage event for each bull trout tagged by DPUD is included, as per the BTMP.
[b] BioAnalysts, Inc. 2004

6.2 Strategy 1-2: Correlations between passage events and Project operations

Data were compiled for Project (spill, turbines, and reservoir elevations) and ladder operations for dates of downstream passage events of radio-tagged fish (Table 6.2-1). Mean daily discharge was 124 kcfs, and ranged from 49 kcfs to 247 kcfs for the dates on which a radio-tagged bull trout passed downstream through Wells Dam. Discharge via spill was typically below 16 kcfs and often zero during downstream passage events. Mean daily forebay elevation and ladder operations varied very little by day, month, or seasonal basis during the study and as a result did not appear to have a relationship to downstream passage events at Wells Dam. Similarly, downstream passage events occurred over a large range of discharge conditions and turbine/spill operations that were consistent with the normal range of conditions at Wells Dam on a seasonal basis (Figure 6.2-1). These data indicate that there was no apparent direct relationship between the timing of downstream events and discharge/operational conditions at Wells Dam.

Further review of multivariate analyses supports the observations that no direct relationship exists between downstream passage events and Project operations. A scatterplot matrix of associated variables (e.g., total spill) and downstream passage events show that downstream passage events had no apparent relationship to any variables related to Project operations (Figure 6.1-2). No correlation values were considered to be large (0.5 to 1.0 or -0.5 to -1.0), and none were of statistical significance (Table 6.2-1).

The monthly timing of downstream passage events does however exhibit a seasonal trend (Figure 6.2-3) that appears to be more related to their biological life history of moving into and out of spawning tributaries. On a monthly basis, downstream passage events demonstrated a bimodal pattern of occurrence at Wells Dam with the peak number of events occurring in May and November.

Table 6.2-1 Project operations data for dates on which a bull trout passed downstream through Wells Dam, 2005-2008.

Downstream Date	Total Discharge	Turbine Discharge	Spill Discharge	Forebay Elevation	Total Inflow
Jun-12-05	87.5	80.5	7.0	777.7	74.2
May-11-06	157.7	144.1	13.6	780.7	157.6
May-13-06	141.2	131.2	10.0	779.5	140.1
May-21-06	117.0	105.2	11.8	772.2	117.3
May-24-06	144.9	129.2	15.7	776.3	158.4
May-24-06	144.9	129.2	15.7	776.3	158.4
May-29-06	246.9	131.8	115.1	780.4	250.0
Jun-29-06	152.0	141.9	10.1	779.9	148.6
Jul-19-06	139.7	129.8	9.9	779.4	131.1
Nov-14-06	96.8	96.7	0.1	780.5	100.9
Nov-16-06	80.0	80.0	0.0	778.6	74.0
Nov-19-06	48.6	48.6	0.0	779.5	50.7
Nov-30-06	89.4	89.4	0.0	778.7	88.4
Dec-17-06	91.0	91.0	0.0	780.5	99.9
Dec-20-06	109.6	109.6	0.0	780.8	114.2
Mar-13-07	85.4	85.4	0.0	778.9	79.1
Apr-11-07	151.7	138.5	13.2	780.8	155.1
Apr-19-07	162.3	146.5	15.8	780.8	161.9
Jun-5-07	157.0	140.7	16.3	780.4	157.2
Jun-30-07	118.4	110.4	8.1	780.5	121.9
Jul-3-07	115.7	107.5	8.2	780.7	132.8
Jul-5-07	146.8	130.8	16.0	780.9	148.7
Aug-24-07	116.0	108.2	7.8	779.9	117.2
Oct-22-07	68.3	64.2	4.1	779.7	80.7
May-16-08	139.4	129.4	10.0	780.2	145.6
Mean	124.3	112.0	12.3	779.4	126.6
Median	118.4	110.4	9.9	779.9	131.1
Max	246.9	146.5	115.1	780.9	250.0
Min	48.6	48.6	0.0	772.2	50.7

Table 6.2-2 Project operations data for dates on which a bull trout passed downstream through Wells Dam, 2005-2008.

Variable	by Variable	Correlation	Count	Signif Prob	Plot Correlation
Downstream Passage	Date	-0.2027	23	0.3535	
Downstream Passage	Total Discharge	0.1148	23	0.6019	
Downstream Passage	Turbine Discharge	0.1486	23	0.4987	
Downstream Passage	Total Spill	0.0319	23	0.8853	
Downstream Passage	In Flow	0.1738	23	0.4276	
Downstream Passage	Forebay Elevation	-0.3484	23	0.1032	
Downstream Passage	TDG (%)	0.0009	14	0.9976	
Downstream Passage	Temp (Scroll Case)	-0.1610	14	0.5823	

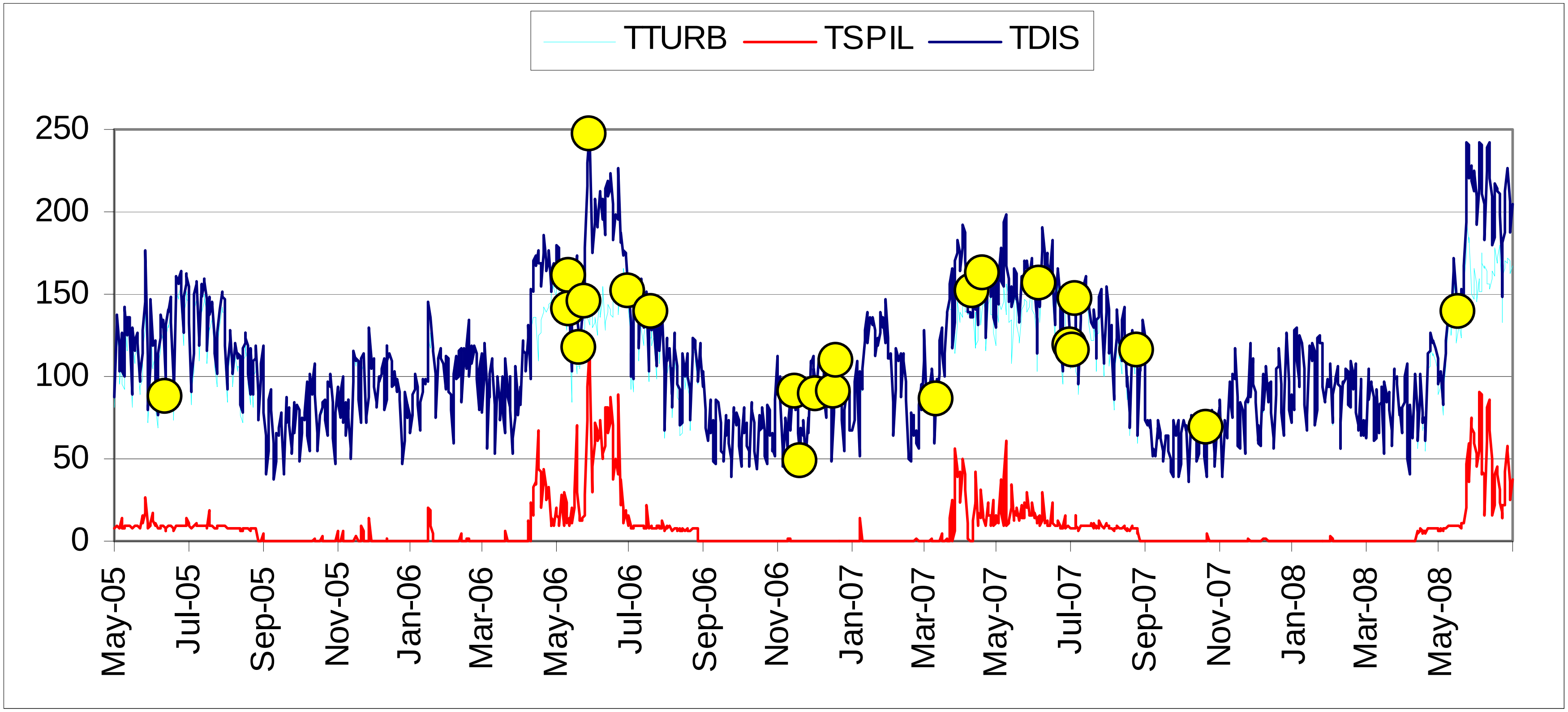

Figure 6.2-1 **Mean daily values for turbine, spill, and combined discharge at Wells Dam during bull trout monitoring at Wells Dam. Circles indicate downstream passage events of bull trout.**

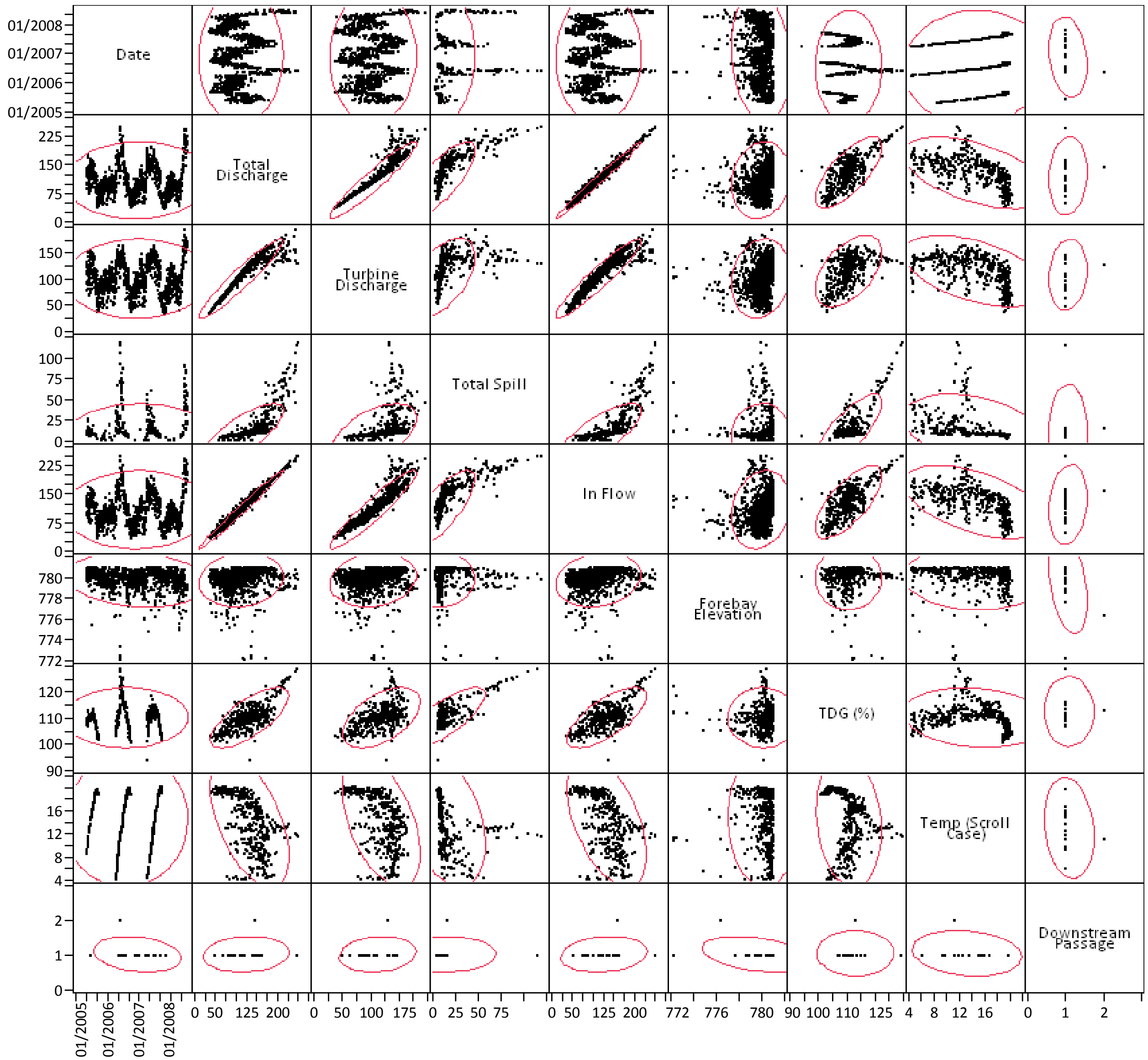

Figure 6.2-2 **Scatterplot matrix of Project operation variables and downstream passage events of radio-tagged bull trout at Wells Dam, 2005-2008.**

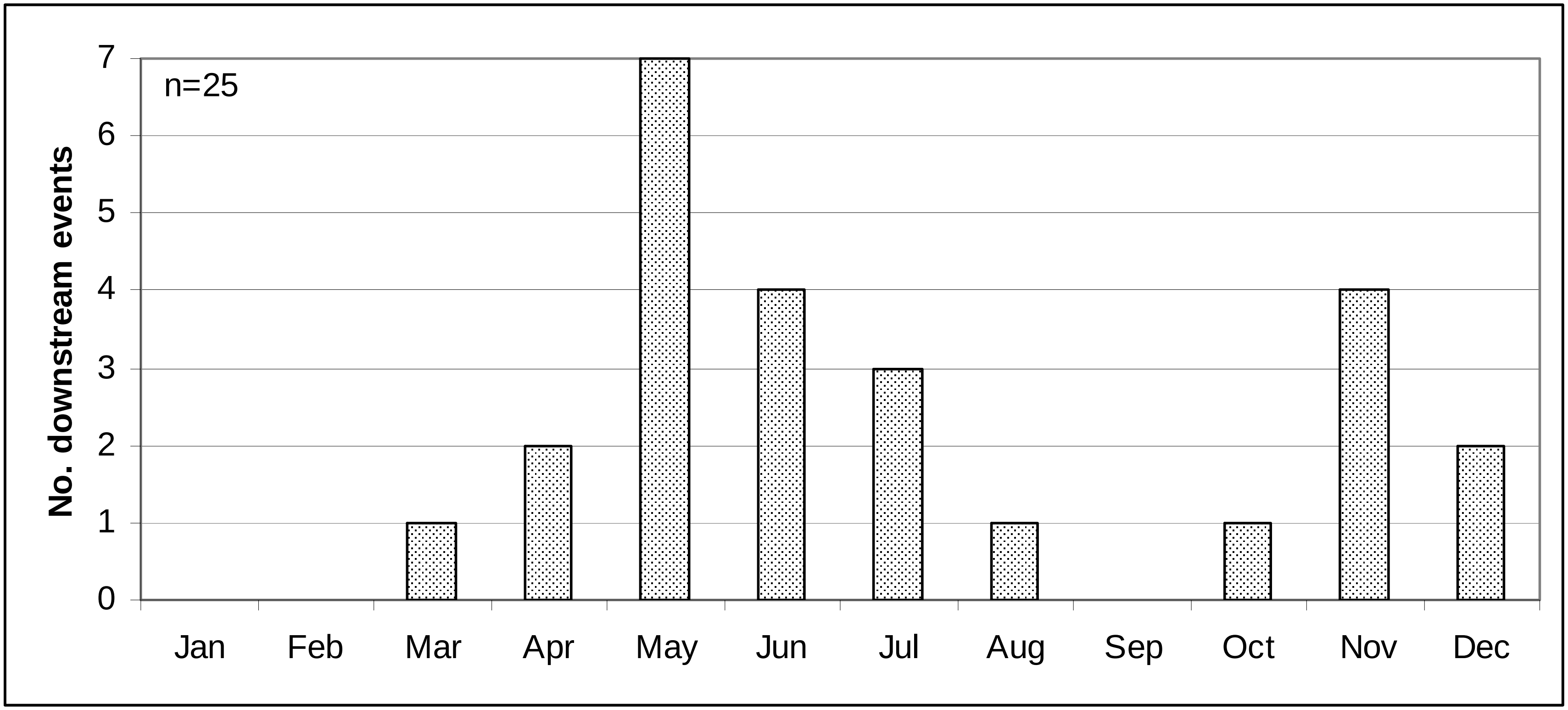

Figure 6.2-3 Distribution of downstream passage events of bull trout passing through Wells Dam by month.

6.3 Strategy 1-3: Off-season fishway passage of adult bull trout

In addition to regular season monitoring, off-season video monitoring of both Wells Dam fishways was conducted continuously for the 2005-2006, 2006-2007, and 2007-2008 winter periods (November 16 - April 30). During these continuously monitored periods, no adult bull trout were observed utilizing the fishways (Figure 6.3-1). Further, all fishway outages for annual service occurred within the off-season period and therefore did not overlap in timing with any upstream passage events (Table 6.3-1).

Table 6.3-1 Fishway outage periods at Wells Dam, 2005-2007.

Year	East	West
2005	-	1 to 31 Dec
2006	1 to 10 Jan, 20 to 31 Dec	16 Jan to 23 Feb
2007	1 Jan to 8 Mar, 1 to 31 Dec	12 to 30 Mar

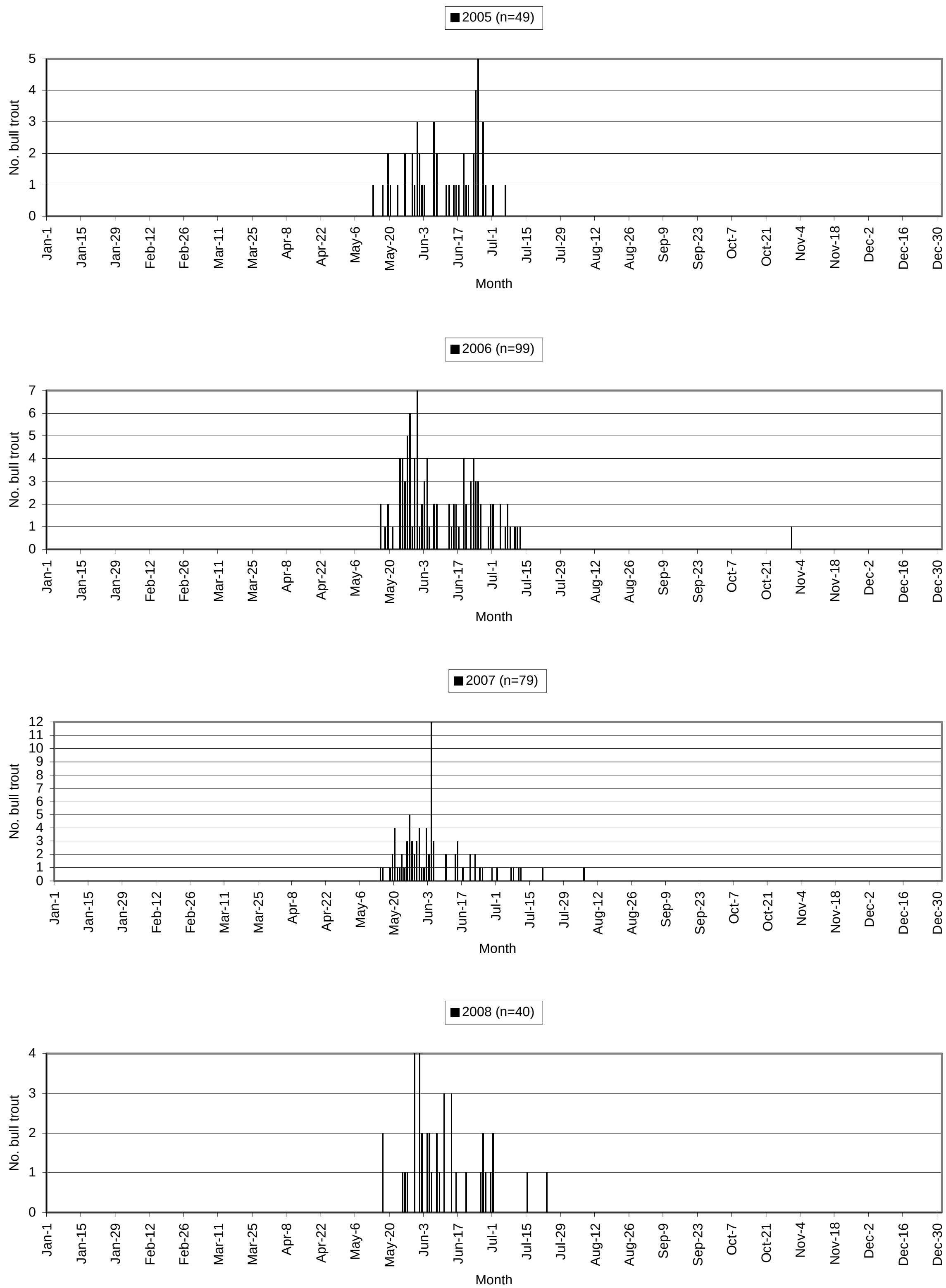

Figure 6.3-1 Daily count of bull trout passing upstream through Wells Dam, 2005-2008. Bull trout captured for tagging are included.

6.4 Strategy 1-4: Modifications to passage facilities or operations

There has been no passage issues identified that limit upstream or downstream passage of adult bull trout at Wells Dam. Therefore, there is no need for modifications to current passage facilities or operations.

6.5 Strategy 2-1: Sub-adult PIT tagging program

Douglas PUD passively collected information from all PIT tagged fish, including bull trout, as they passed through the fishways at Wells Dam. Douglas PUD also scanned all bull trout incidentally captured at rotary screw traps and adult brood collection facilities. The information collected at the dam and in the tributaries was posted on the PTAGIS website, which is operated and maintained by the Pacific States Marine Fisheries Commission.

No sub-adult bull trout were observed or captured during the 2005 to 2007 study period at Wells Dam. Douglas PUD provided support to WDFW for PIT tagging bull trout collected at two off-site smolt collection facilities (Table 6.5-1). During the three years of study 67 sub-adult bull trout were PIT tagged at two Methow River basin trap sites. The PTAGIS database shows that none of these PIT tagged bull trout have since been detected, either at Wells Dam or any other location where monitoring takes place throughout the Columbia Basin.

Table 6.5-1 Sub-adult bull trout PIT tagged in the Methow Basin, 2005-2008 (data from C. Snow, WDFW).

Year	Collection/tag site	# PIT tagged	# DNA sampled
2007	Methow River trap	4	4
2008	Methow River trap	1	1
2005	Twisp River trap	16	16
2006	Twisp River trap	20	10
2007	Twisp River trap	10	10
2008	Twisp River trap	16	10

6.6 Strategy 2-2: Off-season fishway passage of sub-adult bull trout

In addition to regular season monitoring (May 1 – November 15), off-season video monitoring of both Wells Dam fishways was conducted for the 2005-2006, 2006-2007, and 2007-2008 winter periods (November 16 - April 30). No sub-adult bull trout were observed utilizing the fishways during off-season video monitoring.

6.7 Strategy 3-1: Inflow patterns, reservoir elevations, and backwater curves

On May 18, 2006 and again on November 5, 2008, Douglas PUD conducted stranding surveys intended to document whether or not bull trout are becoming stranding in the Wells Reservoir during deeper than normal reservoir operations. The survey locations were selected based upon an analysis of detailed bathymetric maps produced in 2005 combined with Wells Reservoir hydraulic information. This effort identified several locations where stranding of sub-adult bull trout could potentially occur. Six total potential stranding locations were identified. These locations were the Methow River mouth, the Okanogan River mouth, the Kirk Islands, the shallow water habitat in the Columbia River directly across from the mouth of the Okanogan River, Schluneger Flats and the off-channel areas of the Bridgeport Bar Islands. Boat and foot surveys were conducted and included a combination of shoreline transects and inspection of isolated sanctuary pools. No bull trout were observed during either of the two surveys which suggests that bull trout are able to avoid stranding and entrapment areas in the event of a Wells reservoir drawdown.

6.8 Strategy 4-1: Genetic sampling program

From 2005 to 2007, 26 genetic samples were collected from adult bull trout during radio-tagging operations at Wells Dam. Additional genetic samples (n=61) were collected from sub-adult bull trout captured during smolt trapping operations conducted by the WDFW on the Twisp and Methow rivers (data provided by C. Snow, WDFW). All samples were sent to the USFWS Abernathy Fish Technology Center for analysis. Genetic analysis results are not yet available.

6.9 Strategy 4-2: Destination locations of Wells Dam bull trout

All six bull trout tagged in 2005 by Douglas PUD entered the Methow River (Table 6.1-1). One fish (#4) exited after five days and moved downstream of Wells Dam. One fish (#2) was detected moving into the Methow River again in 2006 (Table 6.9-1).

Seven of the 10 bull trout tagged in 2006 by DPUD entered the Methow River, and three entered the Entiat River during the year tagged (Table 6.1-1). Six of these fish were also detected entering a tributary in 2007 and one in 2008, however two fish entered a different tributary than previously selected (Table 6.9-1).

All 10 bull trout tagged in 2007 by DPUD entered the Methow River during the year tagged (Table 6.1-1).

In total, 26 bull trout tagged by DPUD made 34 tributary entries over the study period (Table 6.9-1). Of these, 30 (88% of 34) chose the Methow River and four (12% of 34) the Entiat River.

There were 25 tributary entries detected over the study period for the 12 bull trout tagged by CPUD from 2005 to 2008 that were detected at Wells Dam (Table 6.9-1). Of these, 21 (84% of 25) chose the Methow River, 2 (8%) the Entiat River, and 2 (8%) the Wenatchee River. Three of these fish entered a different tributary than previously selected.

For the 2 bull trout tagged by USFWS from 2006 to 2007 that were detected at Well Dam, there were no subsequent observations of tributary entry after being captured and tagged in the Methow River.

There were 59 tributary entries detected over the study period with 51 (86.4%) in the Methow River, 6 (10.2%) in the Entiat River, and 2 (3.4%) in the Wenatchee River. Of 38 bull trout tracked with tributary entries, 6 chose a different tributary than previously selected.

Table 6.9-1 Tributary use of radio-tagged bull trout detected at Wells Dam, 2005-2008.

Tag Group	Fish No.	Ch-Cd	Tributary Use [a] 2005	2006	2007	2008
DCPUD 2005						
	1	1-2	Methow			
	2	1-4	Methow	Methow		
	3	1-6	Methow			
	4	1-8	Methow			
	5	1-10	Methow			
	6	1-12	Methow			
DCPUD 2006						
	11	1-56		Methow	Methow	
	12	1-52		Methow	Methow	
	13	1-68		Entiat	Entiat	
	14	1-64		Methow		
	15	1-58		Methow		
	16	1-60		Methow		
	17	1-66		Entiat	Methow	
	18	1-50		Methow		
	19	1-54		Entiat	Methow	Methow
	20	1-62		Methow	Methow	
DCPUD 2007						
	21	1-69			Methow	
	22	1-67			Methow	
	23	1-65			Methow	
	24	1-63			Methow	
	25	1-61			Methow	
	26	1-59			Methow	
	27	1-57			Methow	
	28	1-55			Methow	
	29	1-53			Methow	
	30	1-51			Methow	
CCPUD 2005						
	531	14-31	Methow	Wenatchee	Wenatchee	
	544	14-44		Methow	Entiat	
	503	14-3	Methow	Methow	Methow	Methow
CCPUD 2006						
	409	14-171		Methow	Methow	
	412	14-174		Methow	Entiat	Methow
	418	14-180		Methow	Methow	
	422	14-184		Methow	Methow	Methow
	426	14-188		Methow	Methow	
	428	14-190			Methow	
CCPUD 2007						
	1034	14-111			Methow	
	1038	14-115			Methow	
	1039	14-116			Methow	
USFWS 2006						
	204	1-74		Methow		
USFWS 2007						
	300	1-83		Methow		
USFWS 2008						
	none					

7.0 CONCLUSIONS

Through the implementation of the strategies outlined in the Bull Trout Plan, six years of tagging, and eight years of monitoring, Douglas PUD has not identified any project-related impacts to adult or sub-adult bull trout from passage through the Wells Project, nor by stranding/entrapment due to lowering of the reservoir elevation. Douglas PUD has also determined there are no apparent correlations between project operations and downstream passage events, and that there is no upstream movement of adult bull trout through the Wells Dam fishways during the off-season period of November 16 through April 30. Bull trout captured and tagged at Wells Dam were radio-tracked to the Methow and Entiat Core Areas during spawning periods, and have also demonstrated movement between these systems by successfully passing upstream or downstream through Wells Dam.

Currently, Douglas PUD is working with the USFWS on a package of bull trout monitoring and management measures that can be incorporated into the new operating license for the Wells Project. The USFWS will be assessing the effect of relicensing the Project on bull trout within the context of ESA section 7. These proposed measures are intended to be consistent with the Bull Trout recovery plan being developed by the USFWS.

8.0 ACKNOWLEDGMENTS

Douglas PUD Fish Enumerators Tanya Gibson, Sylvia Robertson, and Betty Walters were supportive in providing detailed accounts of bull trout passage throughout the study. Radio-tagging was conducted by Dave Robichaud, Megan Mathews, and Josh Murauskas in the years 2005, 2006, and 2007, respectively. Lynda Andrew conducted radio telemetry station downloads over the entire study. Mary Mayo, Bao Le, and Shane Bickford made significant editorial contributions throughout the reporting process.

9.0 REFERENCES

Adams, N. S., Rondorf, D. W., Evans, S. D., and Kelly, J. E. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behaviour of juvenile Chinook salmon. Transactions of the American Fisheries Society. 127: 128-136.

Baxter, C. V., and F. R. Hauer. 2000. Geomorphology, hyporheic exchange, and the selection of spawning habitat by bull trout (Salvelinus confluentus). Canadian Journal of Aquatic Science. 57:1470-1481.

BioAnalysts. 2004. Movement of bull trout within the Mid-Columbia River and tributaries, 2001-2004. Report prepared by BioAnalysts for Public Utility District No.1 of Chelan County, Public Utility District No.1 of Douglas County, and Public Utility District No.2 of Grant County.

Brewin P. A. and M. K. Brewin. 1997. Distribution maps for bull trout in Alberta. Pages 206-216 in: Mackay, W.C., M. D. Brewin and M. Monita, editors. Friends of the Bull Trout Conference Proceedings. Bull Trout Task Force (Alberta), c/o Trout Unlimited Calgary, Alberta, Canada.

Cavender, T. M. 1978. Taxonomy and distribution of the bull trout, Salvelinus confluentus (Suckley) from the American Northwest. California Fish and Game 64:139-174.

Delavergne, J. USFWS. Personal Communication. Email to Bao Le, Douglas PUD, on March 2, 2007.

Douglas PUD (Public Utility District No. 1 of Douglas County). 2004. Wells Hydroelectric Project Bull Trout Monitoring and Management Plan, 2004-2008. Prepared by Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Dunham, J., B. Rieman, G. Chandler. 2003. Influences of temperature and environmental variables on the distribution of bull trout within streams at the southern margin of its range. North American Journal of Fisheries Management, 23:894–904.

English, K. K., T. C. Nelson, C. Sliwinski, and J. R. Stevenson. 1998. Assessment of passage facilities for adult sockeye, Chinook, and steelhead at Rock Island and Rocky Reach dams on the mid-Columbia River in 1997. Report to Public Utility District No. 1 of Chelan County, Wenatchee, WA.

English, K. K., C. Sliwinski, B. Nass, and J. R. Stevenson. 2001. Assessment of passage facilities for adult steelhead at Priest Rapids, Wanapum, Rock Island, Rocky Reach, and Wells dams on the mid-Columbia River in 1999. Report to Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Kraemer, C. 1994. Some observations on the life history and behavior of the native char, Dolly Varden (Salvelinus malma) and bull trout (Salvelinus confluentus) of the North Puget Sound Region. Washington Department of Wildlife. Draft.

LGL and Douglas PUD. 2006. Wells bull trout monitoring and management plan: 2005 annual report. Report to Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

McPhail, J. D. and J. S. Baxter. 1996. A review of bull trout (Salvelinus confluentus) life history and habitat use in relation to compensation and improvement opportunities. Fisheries management report no. 104. University of British Columbia. Vancouver, B.C.

Mongillo, P. E. 1993. The distribution and status of bull trout/Dolly Varden in Washington State. Washington Department of Wildlife. Fisheries Management Division, Report 93- 22. Olympia, Washington. 45 pp.

Nelson, Mark. USFWS. Personal Communication. Discussion with Bryan Nass and David Robichaud, LGL Limited.

Pleyte, Kay A., S. D. Duncan, and R. B. Phillips. 1992. Evolutionary relationships of the fish genus Salvelinus inferred from DNA sequences of the first internal transcribed spacer (ITS 1) of ribosomal DNA. Molecular Phylogenetics and Evolution, 1(3): 223-230.

Riehle, M. W. Weber, A. M. Stuart, S. L. Thiesfeld and D. E. Ratliff. 1997. Progress report of the multi-agency study of bull trout in the Metolius River system, Oregon. In Friends of the Bull Trout Conference Proceedings. Bull Trout Task Force. Calgary, (Alberta). Pages 137-144.

Rieman, B. E., and J. D. McIntyre. 1993. Demographic and habitat requirements for conservation of bull trout. U.S. Forest Service, Intermountain Research Station. General Technical Report INT-302.

Rieman, B. E., and J. D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varied size. Transactions of American Fisheries Society. Vol. 124 (3): 285-296.

Rieman, B. E., D. C. Lee and R. F. Thurow. 1997. Distribution, status and likely future trends of bull trout within the Columbia River and Klamath Basins. North American Journal of Fisheries Management. 17(4): 1111-1125.

Sexauer, H. M. and P. W. James. 1993. A survey of the habitat use by juvenile and prespawning adult bull trout, Salvelinus confluentus, in four streams in the Wenatchee National Forest. Ellensburg, WA, Central Washington University.

Summerfelt, R. C. and L. S. Smith. 1990. Anesthesia, surgery and related techniques. Pages 213-272 In: C. B. Shreck and P. B. Moyle, editors. Methods of fish biology. American Fisheries Society Symposium 7, Bethesda, Maryland.

U.S. Fish and Wildlife Service, National Marine Fisheries Service, Plum Creek Timber Company, Inc., and CH2M Hill. 2000. Final Environmental Impact Statement and Native Fish Habitat Conservation Plan – Proposed Permit for Taking of Federally Listed Native Fish Species on Plum Creek Timber Company, Inc. Lands. September, 2000.

U.S. Fish and Wildlife Service. 2002. Chapter 22, Upper Columbia Recovery Unit, Washington. 113 p. In: U.S. Fish and Wildlife Service. Bull Trout (Salvelinus confluentus) Draft Recovery Plan. Portland, Oregon.

U.S. Fish and Wildlife Service. 2004. Biological Opinion and Conference Opinion for the License Amendment to incorporate the Rocky Reach, Rock Island and Wells Anadromous Fish Agreement and Habitat Conservation Plans. Federal Energy Regulatory Commission (FERC). FWS Reference Number: 04-W0203. U.S. Fish and Wildlife Service, Central Washington Field Office, Wenatchee.

U.S. Fish and Wildlife Service. 2008a. News Release: Status Review of Bull Trout Completed. Contacts T. Koch and J. Jewett. Portland, OR.

U.S. Fish and Wildlife Service. 2008b. Bull Trout (Salvelinus confluentus). 5-Year Review: Summary and Evaluation. Portland, OR.

Volk, E. C. 2000. Using otolith strontium to infer migratory histories of bull trout and Dolly Varden from several Washington State rivers. Submitted to Olympic National Park in fulfillment of Contract #2550041. Washington Department of Fish and Wildlife, Olympia.

Appendix A

Detection History Summaries for each Bull Trout Detected in the Wells Project Area

The summary of detection histories for each bull trout tagged by Douglas PUD in 2007 is as follows:

Fish 21 (Code 69)

Released in Columbia R. 19 May 2007. Entered Methow R. 21 May 2007, and exited 8 Jul 2008. Last detected in the Wells Dam forebay 8 Jul 2008. Fish 21 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 22 (Code 67)

Released in Columbia R. 20 May 2007. Entered Methow R. 20 May 2007. Last detected in the Twisp R. 27 Nov 2007. Fish 22 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 23 (Code 65)

Released in Columbia R. 25 May 2007. Entered Methow R. 26 May, and exited 11 Jun 2007. Detected at mouth of Okanogan R. 12 Jun 2007. Re-entered Methow R. between 13 and 16 Jun 2007. Tag recovered in Twisp R. 20 Jul 2007. Fish 23 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 24 (Code 63)

Released in Columbia R. 29 May 2007. Entered Methow R. prior to 31 May 2007. Last detected motionless in Twisp R. 20 Jul 2007. Fish 24 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 25 (Code 61)

Released in Columbia R. 2 Jun 2007. Entered Methow R. 2 Jun 2007. Tag recovered in West Fork Methow R. 26 Jul 2007. Fish 25 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 26 (Code 59)

Released in Columbia R. 4 Jun 2007. Entered Methow R. 7 Jun 2007, and exited 10 Apr 2008. Passed downstream through Wells Dam on 11 Apr 2008. Last detected leaving the WPA at the gateway station on 11 Apr 2008. Fish 26 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 27 (Code 57)

Released in Columbia R. 4 Jun 2007. Entered Methow R. 6 Jun 2007. Last detected at mouth of Methow R. 25 Jun 2007. Fish 27 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 28 (Code 55)

Released in Columbia R. 4 Jun 2007. Entered Methow R. 7 Jun 2007. Tag recovered in Twisp R. 18 Jul 2007. Fish 28 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 29 (Code 53)

Released in Columbia R. 4 Jun 2007. Entered Methow R. 7 Jun and exited 17 Nov 2007. Last detected motionless in Columbia R. 1.7 miles upstream of Wells Dam 13 Dec 2007. Fish 29 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 30 (Code 51)

Released in Columbia R. 5 Jun 2007. Entered Methow R. 7 Jun. Last detected in Twisp R. 17 Sep 2007. Fish 30 successfully made ***one upstream*** passage at Wells Dam during its detection history.

The summary of detection histories for each bull trout tagged by Douglas PUD in 2006 is as follows:

Fish 11 (Code 56)

Released in Columbia R. 16 May 2006. Entered Methow R. 27 May, and exited on 17 Nov 2006. Passed downstream through Wells Dam between 18 and 19 Nov and exited the WPA at the gateway station on 19 Nov 2006. Approached Wells Dam 22 May 2007 and completed an upstream passage through Wells Dam 18 Jun 2007. Entered Methow R. 19 Jun and exited on 29 Jun 2007. Completed a downstream passage through Wells Dam on 30 Jun and last detected leaving the WPA at the gateway station on 30 Jun 2007. Fish 11 successfully made ***two upstream*** and ***two downstream*** passages through Wells Dam during its detection history.

Fish 12 (Code 52)

Released in Columbia R. 16 May 2006. Entered Methow R. 31 May, and exited 1 Nov 2006. Passed downstream through Wells Dam before 19 Apr 2007. Began ascent through fishway and diverted from West fishway trapping facilities to hatchery pond on 19 May 2007. Re-released in Columbia R. 21 May 2007. Entered Methow R. 25 May, and last detected 3 Oct 2007 on upstream antenna at mouth of Methow R. Fish 12 successfully made ***two upstream*** and ***one downstream*** passages through Wells Dam during its detection history.

Fish 13 (Code 68)

Released in Columbia R. 18 May 2006. Passed downstream through Wells Dam on 21 May 2006. Detected in Entiat R. between 25 Jun and 2 Nov 2006, and near the confluence between 30 Nov 2006 and 3 Apr 2007. Re-detected in Entiat R. between 7 Jun and 5 Sep (last detection)

2007. Fish 13 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 14 (Code 64)

Released in Columbia R. 19 May 2006. Passed downstream through Wells Dam between 19 and 24 May 2006. Passed upstream through Wells Dam on 14 Jun 2006. Entered Methow R. on 14 Jun. Tag recovered in tributary to Twisp R. on 11 Oct 2006. Fish 14 successfully made ***two upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 15 (Code 58)

Released in Columbia R. 19 May 2006. Entered Methow R. 24 May 2006. Last detected at confluence 8 Jul 2008. Fish 15 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 16 (Code 60)

Released in Columbia R. 21 May 2006. Entered Methow R. on 23 May 2006. Last detected in Methow R. on 11 Oct 2006. Fish 16 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 17 (Code 66)

Released in Columbia R. 24 May 2006. Passed downstream through Wells Dam between 28 and 29 May, and exited the WPA on 19 Jun 2006. Detected in Entiat R. on 4 Jul 2006. Re-entered the WPA at the gateway station and approached Wells Dam on 28 May 2007. Passed upstream through Wells Dam on 29 May 2007. Entered Okanogan River 9 Jun, and exited on 17 Jun. Entered the Methow R. on 17 Jun 2007, and exited on 25 May 2008. Last detected at Methow confluence on 6 Jul 2008. Fish 17 successfully made ***two upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 18 (Code 50)

Released in Columbia R. 24 May 2006. Entered Methow R. 26 May 2006. Tag detected motionless in Twisp R. on 18 Jul 2007. Fish 18 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 19 (Code 54)

Released in Columbia R. 24 May 2006. Passed downstream through Well Dam on 24 May 2006. Remained downstream of Wells Dam until leaving the WPA at the gateway station on 30 Jun 2006. Detected in the Entiat R. between 7 Jul and 25 Nov 2006. Entered the WPA 4 May 2007, and passed upstream through Wells Dam on 31 May 2007. Entered Methow R. on 31 May, 2007, and exited on 24 Nov 2007. Re-detected at Methow confluence on 5 May 2008, and last seen moving upstream on 14 May. Fish 19 successfully made ***two upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 20 (Code 62)</u>

Released in Columbia R. 24 May 2006. Entered Methow R. 25 May 2006, and exited between 12 and 15 Nov 2006. Passed downstream through Wells Dam between 16 and 30 Nov 2006. Remained downstream of Wells Project Area from 30 Nov 2006 to 24 May 2007. Approached Wells Dam 29 May 2007, and captured in the West fishway trapping facilities on 3 Jun 2007. Re-released above Wells Dam in Columbia R. 4 Jun. Passed downstream through Wells Dam on or before 5 Jun 2007. Passed upstream through Wells Dam 22 Jun 2007. Entered Methow R. 23 Jun, and exited 19 Oct 2007. Passed downstream through Wells Dam on 22 Oct 2007. Detected downstream of the WPA through 4 Apr 2008. Re-entered the WPA on 28 May 2008 and approached Wells Dam on 29 May 2008. Last detected in below Wells Dam in the WPA 3 Jul 2008. Fish 20 successfully made ***three upstream*** and ***three downstream*** passages through Wells Dam during its detection history.

The summary of detection histories for each bull trout tagged by Douglas PUD in 2005 is as follows:

<u>Fish 1 (Code 2)</u>

Released in Columbia R. 26 May 2005. Entered Methow R. 26 May 2005. Tag recovered in Methow R. on 13 Oct 2005. Fish 1 successfully made ***one upstream*** passage at Wells Dam during its detection history.

<u>Fish 2 (Code 4)</u>

Released in Columbia R. 2 Jun 2005. Entered Methow R. on 3 Jun 2005. Exited Methow R. between 6 Mar and 11 May 2006 when it passed downstream through Wells Dam. Passed upstream through Wells Dam on 17 Jun 2006. Re-entered Methow R. 13 Jul 2006. Last detected at mouth of Methow R. on 2 Sep 2007. Fish 2 successfully made ***two upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 3 (Code 6)</u>

Released in Columbia R. 3 Jun 2005. Entered Methow R. on 7 Jun, and exited on 10 Nov 2005. Detected in Columbia R. near Pateros on 20 Apr 2006, and last detected 24 Aug 2007 exiting the WPA at the gateway station (passed downstream through Wells Dam undetected). Fish 3 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 4 (Code 8)

Released in Columbia R. 7 Jun 2005. Entered Methow R. on 8 Jun, and then passed downstream through Wells Dam between 8 and 12 Jun 2005. Exited and entered the WPA at the gateway station two times between 24 Oct 2005 and 10 Jan 2006. Last detected in tailrace of Wells Dam on 12 May 2006. Fish 4 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 5 (Code 10)

Released in Columbia R. 7 Jun 2005. Entered Methow R. 19 Jun 2005, and last detected in Methow R. on 13 Oct 2005. Fish 5 successfully made ***one upstream*** passage at Wells Dam during its detection history.

Fish 6 (Code 12)

Released in Columbia R. 28 Jun 2005. Entered Twisp R. by 31 Aug 2005 (not detected at the confluence). Exited Methow R. 10 Apr 2006, and passed downstream through Wells Dam on 13 May 2006. Last detected in Columbia R. downstream of WPA on 6 Jun 2006. Fish 6 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

The summary of detection histories for bull trout tagged by Chelan PUD that made up- or down-stream passages through Wells Dam are as follows:

Fish 1034 (code 14-111)

Released 16 May 2007 in Columbia R. at Rocky Reach Dam. Entered the WPA at the gateway station on 18 May, and approached Wells Dam on 19 May 2007. Passed upstream through Wells Dam on 2 Jun 2007, and entered the Methow R. on 3 Jun 2007. Tag recovered in Methow R. 26 Jul 2007. Fish 1034 successfully made ***one upstream*** passage through Wells Dam during its detection history.

Fish 1038 (code 14-115)

Released 24 May 2007 in Columbia R. at Rocky Reach Dam. Entered the WPA and approached Wells Dam on 26 May 2007. Passed upstream through Wells Dam on 30 May, and entered the Methow R. on 31 May. Last detected in the Twisp R. 24 Oct 2007. Fish 1038 successfully made ***one upstream*** passage through Wells Dam during its detection history.

Fish 1039 (code 14-116)

Released 29 May 2007 in Columbia R. at Rocky Reach Dam. Entered the WPA at the gateway station on 31 May, and approached Wells Dam on 2 Jun 2007. Passed upstream through Wells Dam on 15 Jun 2007. Detected in Twisp R. between 11 and 18 Jul 2007 (not detected at confluence). Tag recovered in Methow R. 2 Aug 2007. Fish 1039 successfully made ***one upstream*** passage through Wells Dam during its detection history.

<u>Fish 409 (code 14-171)</u>

Released 25 May 2006 in Columbia R. at Rocky Reach Dam. Entered the WPA at gateway station and approached Wells Dam on 27 May 2006. Passed upstream through Wells Dam on 3 Jun 2006. Detected in Methow R. on 16 Nov, and exited on 10 Dec 2006. Passed downstream through Wells Dam before 17 Dec 2006. Approached Wells Dam 9 May 2007 and passed upstream through Wells Dam on 14 May 2007. Entered Methow R. 19 May 2007. Last detected in Methow R. on 8 Nov 2007. Fish 409 successfully made ***two upstream*** passages and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 412 (code 14-174)</u>

Released 26 May 2006 in Columbia R. at Rocky Reach Dam. Entered the WPA and approached Wells Dam on 29 May 2006. Began ascent of Wells Dam, recaptured at the adult trap, and released upstream on 5 Jun 2006. Entered Methow R. on 7 Jun, and exited on 13 Nov 2006. Passed downstream through Wells Dam 14 Nov 2006 and exited the WPA at the gateway station on 21 Nov 2006. Detected in Entiat R. 20 Jul 2007. Approached Wells Dam 2 Sep 2007, but returned to Entiat R. on 11 Sep 2007. Re-entered WPA on 19 Jun 2008, and approached Wells Dam on 20 Jun 2008. Passed upstream through Wells Dam on 30 Jun 2008. Entered the Methow R. on 1 Jul 2008. Fish 412 successfully made ***two upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 418 (code 14-180)</u>

Released 31 May 2006 in Columbia R. at Rocky Reach Dam. Entered the WPA at the gateway station on 2 Jun, and approached Wells Dam on 3 Jun 2006. Passed upstream through Wells Dam on 4 Jun 2006. Entered Methow R. 7 Jun, and exited after 15 Nov 2006. Passed downstream through Wells Dam undetected between 18 Feb and 13 Mar 2007, and exited the WPA at the gateway station between 22 Mar and 1 Apr 2007. Re-entered the WPA on 3 Jun, and approached Wells Dam 4 Jun 2007. Began ascent of Wells Dam, recaptured at the adult trap, and released upstream on 18 Jun 2007. Entered the Methow R. on 20 Jun, and exited on 29 Jun. Last detected in Wells Dam Forebay 29 Jun 2007. Fish 418 successfully made ***two upstream*** passages and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 422 (code 14-184)</u>

Released 5 Jun 2006 in Columbia R. at Rocky Reach Dam. Entered the WPA and approached Wells Dam on 10 Jun 2006. Passed upstream through Wells Dam on 19 Jun 2006. Entered Methow R. 19 Jun, and exited on 11 Dec 2006. Passed downstream through Wells Dam before 3 Jul 2007. Passed upstream through Wells Dam on 8 Jul 2007. Entered Methow R. 9 Jul; exited the Methow R. 2 Nov 2007 and remained in the vicinity through 29 Mar 2008. Passed downstream through Wells Dam on 16 May 2008. Passed upstream through Wells Dam on 27

May 2008. Entered the Methow R. on 28 May 2008, and last seen at the same. Fish 422 successfully made ***three upstream*** passages and ***two downstream*** passages through Wells Dam during its detection history.

<u>Fish 426 (code 14-188)</u>

Released 22 Jun 2006 in Columbia R. at Rocky Reach Dam. Approached Wells Dam on 26 Jun, and passed upstream through Wells Dam on 1 Jul 2006. Entered Methow R. on 2 Jul, and exited on 31 Oct 2006. Passed downstream through Wells Dam between 31 Oct and 20 Dec 2006 and moved downstream of the WPA near the Entiat R. Re-entered the WPA at the gateway station on 13 Jun, and approached Wells Dam 14 Jun 2007. Passed upstream through Wells Dam on 19 Jun 2007. Entered Methow R. 19 Jun, and last detected in Methow R. on 20 Nov 2007. Fish 426 successfully made ***two upstream*** passages and ***one downstream*** passage through Wells Dam during its detection history.

<u>Fish 428 (code 14-190)</u>

Released 29 Jun 2006 in Columbia R. at Rocky Reach Dam. Entered the WPA at the gateway station on 1 Jul, and approached Wells Dam on 2 Jul. Moved downstream of the WPA near the Entiat R. after 24 Sep 2006. Re-entered the WPA at the gateway station on 9 Jun 2007. Passed upstream through Wells Dam on 10 Jun 2007. Entered the Okanogan R. several times between 11 and 15 Jun 2007. Entered Methow R. on 16 Jun, and later detected in Twisp R. between 11 Jul and 1 Nov 2007 (last detection). Fish 428 successfully made ***one upstream*** passage through Wells Dam during its detection history.

<u>Fish 503 (code 14-3)</u>

Released 30 May 2005 in Columbia R. at Rocky Reach Dam. Approached Wells Dam on 12 Jun. Passed upstream through Wells Dam on 17 Jun 2005. Entered Methow R. on 29 Jun 2005, and exited after 19 Oct 2006. Detected in Wells forebay on 26 Oct 2006, and re-entered Methow R. before 16 Nov 2006. Detected in Methow R. through 1 Oct 2007 and last seen in Methow R. on 10 Apr 2008. Fish 503 successfully made ***one upstream*** passage through Wells Dam during its detection history.

<u>Fish 531 (code 14-31)</u>

Released 31 May 2005 in Columbia R. at Rocky Reach Dam. Approached Wells Dam on 5 Jun 2005. Passed upstream through Wells Dam on 25 Jun 2005. Entered Methow R. 27 Jun 2005, and exited on 29 May 2006. Passed downstream through Wells Dam undetected between 29 May and 29 Jun 2006 when it was detected in the Columbia R. downstream of the WPA. Detected in the Wenatchee R. between 19 Sep 2006 and 2 Nov 2007, and in the Columbia R. below the Entiat R. confluence 30 Nov 2006 through 11 Jan 2007. Detected again in the Wenatchee R. 9 Jul 2007. Tag recovered downstream of the WPA 5 Sep 2007. Fish 531 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

Fish 544 (code 14-44)

Released 27 Jun 2005 in Columbia R. at Rocky Reach Dam. Entered the WPA at gateway station on 29 Jun, and approached Wells Dam on 30 Jun 2005. Remained in the vicinity through 25 Oct 2005 when it exited the WPA. Re-entered the WPA 5 May 2006 and passed upstream through Wells Dam on 23 May 2006. Entered the Methow R. 24 May 2006. Exited Methow R. 9 Nov 2006. Passed downstream through Wells Dam 16 Nov 2006. Exited the WPA on 18 Nov 2006 and later detected in the Entiat R. between 20 Dec 2006 and 3 Apr 2007. Last detected at Wells Gateway Station 25 Aug 2007. Fish 544 successfully made ***one upstream*** and ***one downstream*** passage through Wells Dam during its detection history.

The summary of detection histories for bull trout tagged by USFWS that made up- or down-stream passages through Wells Dam are as follows:

Fish 204 (code 1-74)

Released 12 Apr 2006 in Methow R. Exited the Methow R. 17 Jul 2006. Passed downstream through Wells Dam 19 Jul 2006, and detected moving around the tailrace through 14 Aug 2006. For a period of approximately one week, it was detected in the right tailrace (possibly the Wells hatchery outfall where bull trout have been observed before). It was then detected in the left tailrace from 25 Jul to 26 Jul before disappearing from detection for 3 days, and then reappearing on 29 Jul. This pattern of detection/no detection/detection occurred 3 more times from 30 Jul to 2 Aug, 2 Aug to 9 Aug, and 14 Aug to 18 Aug and suggests that the fish was moving in and out of detection zones. On 18 Aug, the tag began emitting the mortality signal consistently with a stable maximum power. Given the tag detection history, the immense fishing pressure that was occurring in the Wells Dam tailrace, and the condition of the recovered tag (without any trace of fish), the most likely scenario is that this bull trout was caught by anglers and the tag thrown into the nearshore area. The tag was recovered 19 Sep 2006 on the right bank approximately 1 mile downstream of Wells Dam. The tag was clean and found in large cobble substrate in what is likely several feet of water when the Rocky Reach pool is up. Documented in an email from Bao Le to Steve Lewis, 19 Sep 2006. Fish 204 successfully made ***one downstream*** passage through Wells Dam during its detection history.

Fish 300 (code 1-83)

Released 20 Jun 2007 in Chewuch River. Exited the Methow R. and passed downstream through Wells Dam 5 Jul 2007. Last detected on 6 Jul 2007 downstream of the WPA. Fish 300 successfully made ***one downstream*** passage through Wells Dam during its detection history.

Appendix B

Comments from U.S. Fish and Wildlife Service
Mid-Columbia Relicensing Coordinator

RESPONSE FROM DOUGLAS PUD TO THE USFWS REGARDING THE USFWS' COMMENTS ON THE BULL TROUT MONITORING REPORT

-----Original Message-----
From: Josh Murauskas
Sent: Tuesday, December 23, 2008 9:18 AM
To: 'Stephen_Lewis@fws.gov'
Cc: Shane Bickford
Subject: RE: Draft Wells Bull Trout Management Plan (USFWS Comments)

Steve -

I just wanted to touch base again and let you know that Shane and I have discussed your comments and they'll be addressed in our final report to FERC.

Travel safely and enjoy the holiday!

Josh

Joshua Murauskas, Sr. Aquatic Resource Biologist Public Utility District No. 1 of Douglas County
1151 Valley Mall Parkway East Wenatchee, WA 98802
509.881.2323 (v) 509.884.0553 (f)

COMMENTS FROM THE USFWS REGARDING DOUGLAS PUD'S DRAFT BULL TROUT MONITORING REPORT

-----Original Message-----
From: Stephen_Lewis@fws.gov [mailto:Stephen_Lewis@fws.gov]
Sent: Monday, December 22, 2008 5:50 PM
To: Josh Murauskas
Cc: Shane Bickford
Subject: Draft Wells Bull Trout Management Plan (USFWS Comments)

Josh/Shane-

Thanks for sharing this draft with us. I do have a few comments for your consideration:

Executive Summary: Based upon my quick tally, I ended up with 41 events as well. Plus, I would frame the context of the entire study for eight years depending on how you divide the monitoring versus tagging components

The report would benefit from a breakdown of how downstream adult/sub-adult passage events are characterized. For example, is there a specific affinity for individuals to pass through specific slots?? This would greatly assist in the section 7 process.

With regard to the conclusions, I agree that the data appears to suggest minimal effect to tagged individuals. However, as you know, USFWS will be assessing the effects of relicensing the Wells Project in the context of ESA Section 7 where the assessment of effects is finer-scale in nature. I suggest you include the following sentence at the end of the conclusions section: "The Service will be assessing the effect of relicensing the project on bull trout within the context of ESA section 7 analysis."

Thanks for divulging the multivariate analysis, interesting stuff, a bit surprising to a find a lack of correlation(s)...

S-

Stephen T. Lewis
Mid-Columbia Relicensing Coordinator
U.S. Fish and Wildlife Service
Central Washington Field Office
215 Melody Lane, Suite 119
Wenatchee, WA 98801
phone: (509) 665-3508 Ext. 14
fax: (509) 665-3523
e-mail: Stephen_Lewis@fws.gov

REQUEST FROM DOUGLAS PUD TO USFWS TO REVIEW THE DRAFT BULL TROUT MONITORING REPORT

"Josh Murauskas" joshm@dcpud.org
To <Stephen_Lewis@fws.gov>
12/15/2008 03:48 PM
cc "Shane Bickford" <ShaneB@dcpud.org>

Steve –

Please find the attached 3-year report for bull trout at the Wells Project for your review.

Please contact us should you have any questions.

Thanks,

Josh

Joshua Murauskas, Sr. Aquatic Resource Biologist Public Utility District No. 1 of Douglas County
1151 Valley Mall Parkway East Wenatchee, WA 98802
509.881.2323 (v) 509.884.0553 (f)
(See attached file: Wells BT 2005-2008 Draft Report.doc)

McGee, J. A. 1979. Fisheries Survey of Wells Reservoir. Public Utility District of Douglas County, East Wenatchee, Washington.

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DOC # 33971

DOC NO. 33971

FISHERIES SURVEY OF WELLS RESERVOIR

1979

J.A. McGee

Douglas County PUD

1151 Valley Mall Parkway

East Wenatchee, WA 98801

INTRODUCTION

A fisheries abundance and distribution survey was conducted by Public Utility District No. 1 of Douglas County in the Wells Project Reservoir (RM 515.6 to RM 538.0) Columbia River, Washington (Figure 1). This information is intended to provide additional knowledge of the fisheries resource within the Wells pool.

The study began 12 September and extended through 22 October 1979. During this time an effort was made to obtain as much information as possible utilizing portable trap nets and beach seining. This information is augmented by angling in the project area from 30 July through 10 October 1979.

METHODS AND PROCEDURES

Materials and Equipment

To collect as many resident and migratory fish as possible three types of fish collection gear were used.

Two New York Trap Nets were used during the majority of the study. These nets were used because they are relatively easy to set and relocate. General information on trap design, construction details and trap dimensions are given in Figure 2.

A 150-foot by 15-foot beach seine was used during the last four days of the study. The seine tapered to three feet at the ends. The ends were 30 feet long by 3/4 inch mesh. The bag was constructed of 1/4 inch woven mesh.

Approximately 56.5 man hours were spent from 30 June to 10 October angling in several locations for game fish. Spinning gear was used exclusively during this period.

A 16-foot Boston Whaler with 85 HP outboard was used during the entire study.

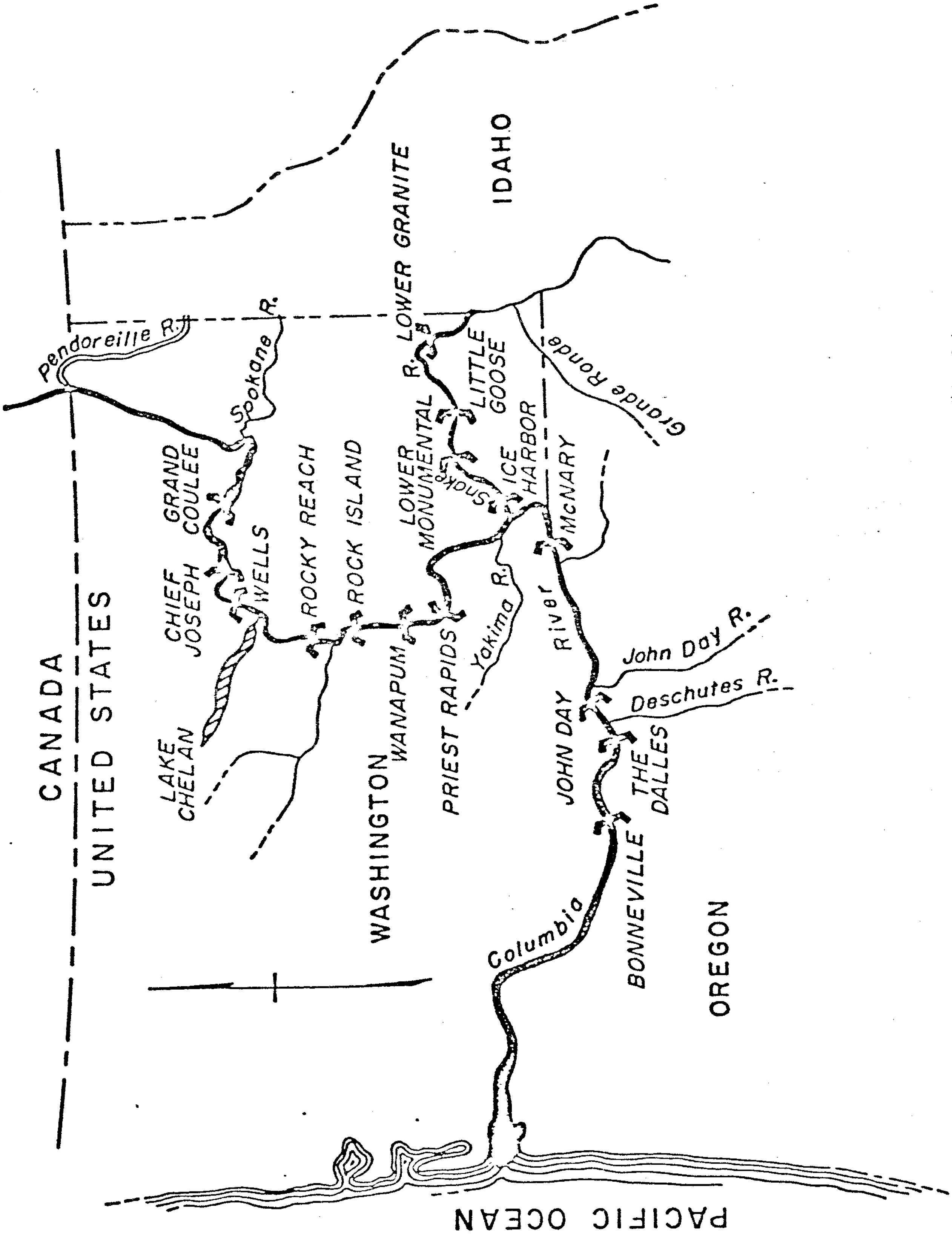

Figure 1. Map of Dams on Main Stem of the Columbia River

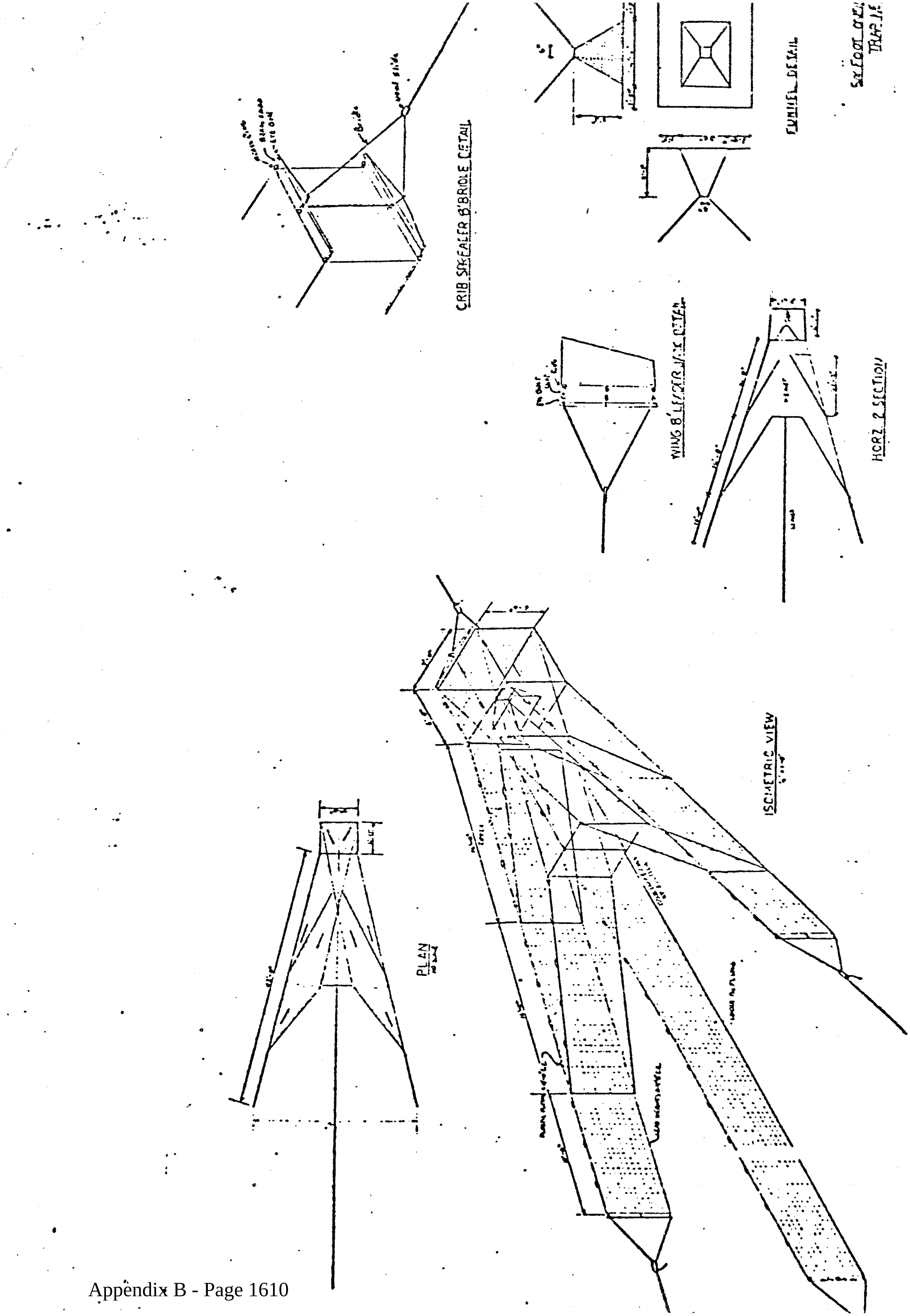

Figure 2 – New York Trap Net

Procedure

The New York Trap nets were set at one location for a 23 to 24.5 hour period then moved to a new location. No fish remained in the trap for more than 24.5 hours. Two sets were made above the mouth of the Methow River in the first pool. To prevent possible conflict with local steelhead fishermen, the sets were made during daylight hours (5 and 5.5 hours) and watched to prevent vandalism.

Past experience by other researchers (Steve Hayes, Chelan County P.U.D., Pers. Comm.) has determined that the best fishing results are obtained when the trap is set in shallow water six feet in depth with a gentle slope to shore. The trap was set with the floor resting on the bottom and the heart hood just below the surface. The central lead ran to shore or shallow water less than one-foot in depth.

Most sets were made in locations where travel lanes existed between deeper areas in an attempt to increase the catch. Only fish moving in the zero to six-foot contour were collected.

The beach seine was set by the usual methods. Care was taken to prevent the lead line from losing contact with the bottom. Fish in the zero to fifteen foot contour were collected.

Both the beach seine and New York Traps are shore oriented. Random sampling could not be used since shallow shoreline and backwater areas were not available throughout the pool. Except for angling, no fish were taken in areas with a strong current or at a depth greater than 15-feet.

Fish collected were anesthetized with MS222 (tricane methanesulfonate) before handling and were allowed to recover before release. All fish were released alive. Game fish and a subsample of non-game fish were measured to the nearest .5 cm (Fork Length). Each fish was superficially examined for wounds, parasites and identifying marks.

Live trap and beach seine sites and angling locations are indicated on the reservoir map (Figure 3). All three types of gear were used in various locations in the pool.

RESULTS

Fish Catch

The total catch of resident and migratory fish included 20 of the 27 known species previously trapped in the mid-Columbia Reservoirs. Table 1 gives the known species captured in the mid-Columbia Reservoirs (Dell, M. B., et al 1975). Suckers, dace and sculpins will be identified by family in this report. A total of 2,480 fish were collected during the study period, including angling. Salmonids and game fish totaled 459 including pumpkinseed, rainbow trout, steelhead, black crappie, bullhead, smallmouth bass, mountain whitefish, yellow perch and juvenile chinook. Non-game fish totaled 2,021 including chiselmouth, carp, peamouth, squawfish, dace, shiners, tench, suckers, and sculpins. Table 2 gives the percentage of each species caught.

The trap net catch totaled 1,909 fish for 406.5 hours fishes. Beach seining for 10 hours caught 522 fish. Angling produced a total of 49 fish for 54.5 hours fishes.

Beach seining was the most efficient method used to catch fish with 52.0 fish per hour, and 59 percent game fish in the catch. The trap net was second in efficiency with 4.71 fish per hour but with a game fish catch of only 6.47 percent. Angling though more selective for game fish (53.1%) was the least efficient use of time with .89 fish per hour.

Location of Catch

Salmonids

The distribution of rainbow trout in the catch was confined to areas trapped below the mouth of the Okanogan River, except for one trout caught on hook and

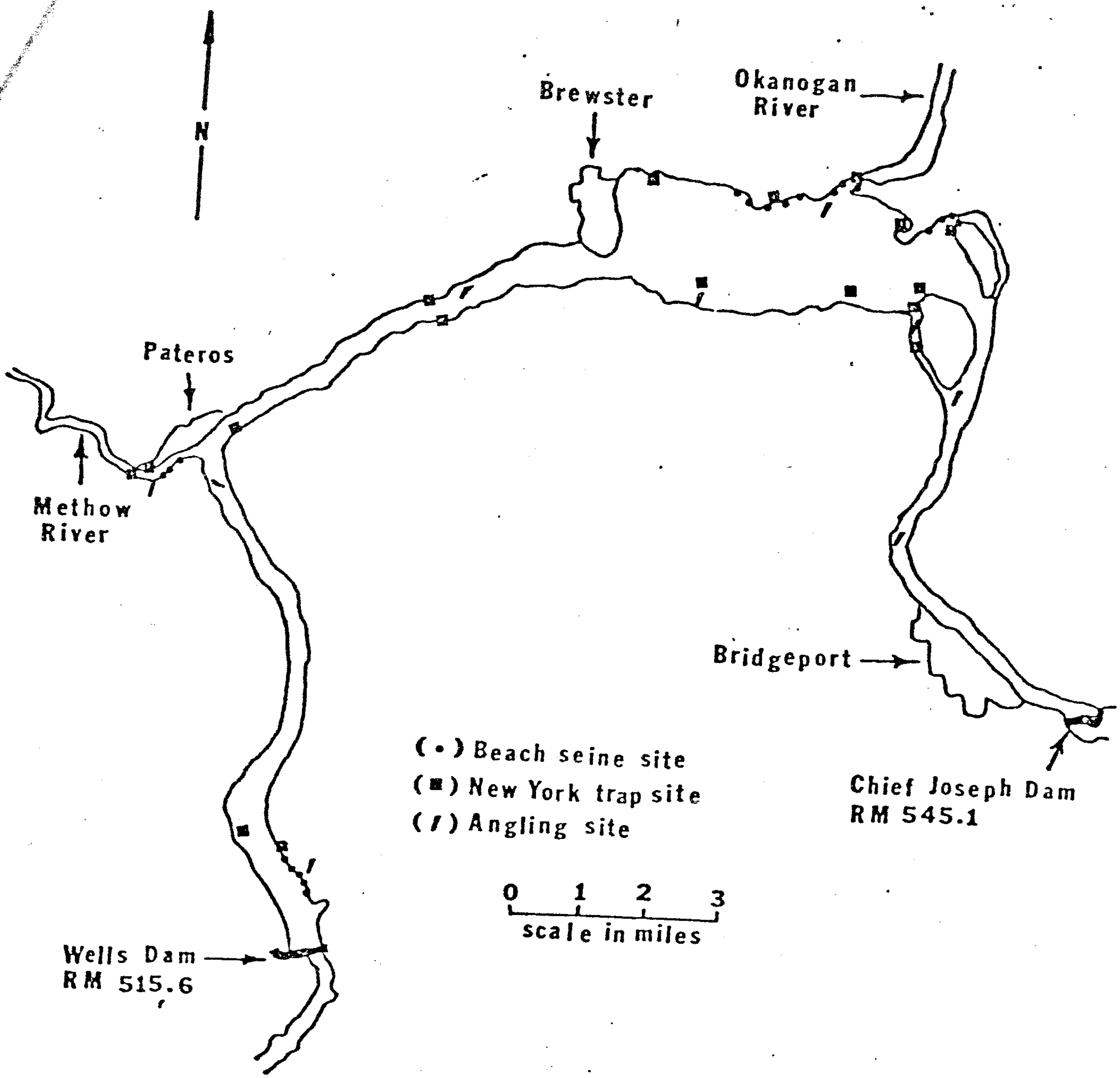

Figure 3. Sampling sites on Wells Reservoir.

Table 1. Names of fish species collected from the main stem of the Columbia River (River Miles 397.1 to 545.1) May-August 1974. (Dell, M B, et. al., 1975)

Family and Common Name	Scientific Name
Petromyzontidae:	
Pacific lamprey	Entosphenus tridentatus
Salmonidae:	
Coho salmon	Oncorhynchus kisutch
Chinook salmon*	O. tshawytscha
Mountain whitefish*	Prosopium willamsoni
Rainbow trout (steelhead)*	Salmo gairdneri
Rainbow trout (resident)*	S. gairdneri
Dolly Varden	Salvelinus malma
Cyprinidae:	
Chiselmouth*	Acrocheilus alutaceus
Carp*	Cyrpinus carpio
Peamouth*	Mylocheilus caurinus
Northern squawfish*	Ptychocheilus oregonensis
Dace*	Rhinichthys spp.
Redsided shiner*	Richardsonius balteatus
Tench*	Tinca tinca
Catostomidae:	
Bridgelip sucker(Finescale)*	Catostomus columbianus
Largescale sucker*	C. macrocheilus
Ictaluridae:	
Black bullhead*	Ictalurus melas
Brown bullhead*	I. nebulosus
Percopsidae:	
Sand roller (Trout Perch)	Percopsis transmontana
Centrarchidae:	
Pumpkinseed*	Lepomis gibbosus
Bluegill	L. macrochirus
Smallmouth bass*	Micropterus dolomieui
Largemouth bass	M. salmoides
Black crappie*	Pomoxis nigromaculatus
Percidae:	
Yellow perch*	Perca flavescens
Walleye	Stizostedion vitreum
Cottidae:	
Sculpins*	Cottus spp.
Gasterosteidae:	
Threespine stickleback	Gasterosteus aculeatus

* Fish species collected in Wells Reservoir between RM 515.6 and 538.0 (1979).

	Trap Net N=1909		Beach Seine N= 522		Total Catch N=2431	
	Number Caught	Percent	Number Caught	Percent	Number Caught	Percent
GAME FISH						
Salmonidae						
Chinook	1	0.05	0	0.0	1	0.04
Steelhead	3	0.16	0	0.0	3	0.12
Rainbow Trout	8	0.42	0	0.0	8	0.33
Mt. Whitefish	1	0.05	6	1.15	7	0.29
Centrarchidae						
Pumpkinseed	34	1.77	287	55.19	321	13.17
Smallmouth Bass	4	0.20	8	1.54	12	0.49
Black Crappie	21	1.10	4	0.76	25	1.03
Percidae						
Yellow Perch	3	0.16	0	0.0	3	0.12
Ictaluridae						
Black Bullhead	19	0.99	4	0.76	23	0.94
Brown Bullhead	8	0.42	0	0.0	8	0.33
Game Fish Sub-Total	124	6.47	309	59.42	433	17.77
NON-GAME FISH						
Cyprinidae						
Chiselmouth	1045	54.51	1	0.19	1046	42.92
Carp	13	0.68	2	0.38	15	0.62
Peamouth	60	3.13	12	2.31	72	2.95
Squawfish	193	10.07	2	0.38	195	8.00
Dace	11	0.57	0	0.0	11	0.45
Redsided Shiner	159	8.29	155	29.81	314	12.88
Tench	11	0.57	1	0.19	12	0.49
Catostomidae						
Bridgelip Sucker	2	0.10	0	0.0	2	0.08
Largescale Sucker	287	14.97	24	4.61	311	12.76
Cottidae						
Sculpins	4	0.20	16	3.07	19	0.91
Non-Game Fish Sub-Total	1785	93.11	213	40.96	1998	81.98

Table 2. Total number and percentage of each species caught by trap net and beach seine.

line at the upstream end of Park Island. The trout fishery in the upper pool is spotty at best. All of the trout were collected in areas where the bottom dropped off sharply from the shoreline with dense aquatic vegetation. Table 3 gives the total number of each species caught and fork length range. Appendix 1 and 2 gives the catch by river mile (RM) location.

Five residual steelhead (counted as rainbow trout) were caught on hook and line approximately one mile above Wells Dam. These fish had clipped adipose fins and IJ brands, first position, right anterior. Two local fishermen were contacted while fishing in this area; they caught 12 rainbow, two with IJ brands. Trout were control fish released during the Washington Department of Game imprinting study on the Methow River, 1979.

Three adult steelhead were trapped approximately one mile above Wells Dam along the left shoreline. One adult steelhead was caught on a lure in the first pool of the Methow River. The fork length of these fish indicates that they were one ocean fish (Bill Pedersen, Washington Department of Game, Pers. Comm.). Steelhead fishermen were observed during the study, boat and bank fishing in the first pool of the Methow River. They were also observed trolling through the Pateros Rapids, one mile below Pateros and in the forebay of Wells Dam.

Chinook salmon were not well represented in the sample. One juvenile was caught on a lure one mile above the dam along the left bank. The second was taken in a trap, one mile below the mouth of the Okanogan River along the right bank.

Mountain whitefish were only caught along the left shoreline one mile above Wells Dam. All of the whitefish were collected near deep protected water with dense aquatic vegetation.

Game Fish

Spiny rays, except for pumpkinseeds and smallmouth bass were found exclusively above RM 528. Pumpkinseeds were trapped throughout the pool though

Table 3. Fork length range and total catch by species.

Species	Total Catch	Fork Length Range
Chinook	2	7.6 and 10 Cm. (3 and 3.9 inches)
Steelhead	4	56.7 to 68.6 Cm. (23,5 to 27 inches)
Rainbow Trout	31	7 to 44 Cm. (3 to 17.3 inches)
Mt. Whitefish	7	5 to 25 Cm. (1.9 to 9.8 inches)
Pumpkinseed	321	2 to 14 Cm. (0.7 to 5.5 inches)
Smallmouth Bass	13	2 to 15 Cm. (0.7 to 5.9 inches)
Black Crappie	25	4 to 22 Cm. (1.5 to 8.6 inches)
Yellow Perch	3	6 to 19 Cm. (2.3 to 7.8 inches)
Black Bullhead	23	17 to 25 Cm. (6.7 to 9.8 inches)
Brown Bullhead	8	17 to 20 Cm. (6.7 to 7.8 inches)
Chiselmouth	1047	9 to 40 Cm. (3.5 to 15.7 inches)
Carp	15	8 to 34 Cm. (3.1 to 13.3 inches)
Peamouth	72	8 to 31 Cm. (3.1 to 12.2 inches)
Squawfish	216	8 to 37 Cm. (3.1 to 14.5 inches)
Dace Spp.	11	13 to 15 Cm. (5.1 to 5.9 inches)
Redsided Shiner	314	6 to 12 Cm. (2.4 to 4.7 inches)
Tench	12	13 to 38 Cm. (5.1 to 14.7 inches)
Bridgelip Sucker	2	23 and 38 Cm. (9.0 and 14.7 inches)
Largescale Sucker	312	6 to 49 Cm. (2.4 to 19.3 inches)
Sculpin Spp.	20	5 to 11 Cm. (1.9 to 4.3 inches)

none were larger than 15 cm in fork length. A smallmouth bass was taken two miles below Brewster (RM 528) on hook and line and eleven were captured in the mouth of the Okanogan River and Washburn Island pond outlet. One lone bass was captured one mile above the dam, but no other evidence of bass was found in this portion of the pool. Black crappie were found only above Brewster along the right shoreline. Locations where they were found included the Cassimer Bar area and the outlet of Washburn Island pond. Three yellow perch were collected during the study. One fish was found at each of the following locations; the Bridgeport Bar islands, mouth of the Okanogan River and along the right bank opposite the Kirk Islands.

All areas where spiny rays, other than pumpkinseeds, were found had similar habitat. These areas all had gently sloping bottom with dense aquatic vegetation and debris. This habitat was found mainly in backwater areas with reduced currents.

No walleye or large mouth bass were taken during the survey. Ken Williams (1977) reports a year round walleye fishery from Chief Joseph Dam to the mouth of the Okanogan River. He also stated that the spiny ray fishing at the mouth of the Okanogan River is good but confined mainly to local fishermen.

Both black and brown bullheads were captured above river mile 528. Bullhead were found only in or adjacent to calm backwater areas. No evidence of bullheads was found further downstream.

Non-Game Fish

The catch of resident fish was much greater than that of game fish. Suckers, chiselmouth, squawfish, peamouth, sculpins, shiners and carp were found to be distributed throughout the reservoir. Dace species were found only in the lower eight miles of the pool. Tench were only found, one mile above the dam and in the Bridgeport Bar area.

DISCUSSION

Abundance

The results of the fish trappping indicate that non-game fish are more abundant than anadromous and game fish (Table 1 & 2). Since the sample size is small, the abundance of five times as many resident as game fish can only be used as an index and not as the true proportion. Instantaneous fish collection provided by beach seining indicated a near one to one ratio for abundance of resident and game fish. The true abundance is probably somewhere between the two.

Sampling Bias

The use of the beach seine and trap nets created a few problems. The efficiency of the New York Trap was affected by water fluctuations caused by power production and waves from high wind. Two trap sets were found with the trap wing anchors torn free after a wind storm. The buildup of drifting aquatic vegetation on the lead and throat of the trap may have influenced the catch. Frequent cleaning was necessary.

Actual catch in the New York Trap was underestimated because of predation. Regurgitated stomach contents of squawfish showed that the following species were preyed upon in the trap, peamouth, squawfish, chiselmouth, suckers and shiners. A few fish in the trap showed signs of predation, deep abrasions and bites on the sides and belly were noted. No estimates of predation in the traps can be made.

The major concern when using the beach seine was to find a location where the bottom conditions allowed efficient net retrieval. Soft mud clinging to the lead line on occasions prevented the seine from being pulled to shore. Snagging on rocks and debris not only caused tears in the web but made it impossible to pull the net without the leadline lossing contact with the bottom, allowing fish to escape.

Sampling bias also has affected the results since collection was restricted to the 15-foot contour. Shallow areas provide excellent habitat for resident fish but salmonids appear to be only incidentally caught in these locations. The limitations of the sampling gear prevented their use in areas with strong current. Also areas where gear could be torn or tangled by underwater objects had to be avoided. This non-random sampling may be reflected in the abundance of resident fish in the catch.

The study was originally designed with the use of variable mesh gill nets along with the live traps. Gill nets were unavailable during the study period. The use of gill nets would have increased the flexibility of the areas we were able to sample. Deeper areas with less gradual contours could have been easily sampled, preventing some of the biases involved with the selection of survey sites.

Beach Seine

River Mile / Species	516.5 ( )	516.6 ( )	516.7 (LB)	517.0 ( )	517.3 (LB)	533.5 ( )	533.75 (RB)	534.0 ( )	534.25 ( )	534.5 (PB)	535.0 ( )	535.0 (RB)	535.0 ( )	537.0 (PB)	537.0 (	537.0 /	537.0	Meth	Met'	%	Total
Chinook	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Steelhead	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Rainbow Trout	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Mt. Whitefish	5	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6
Pumpkinseed	-	-	-	-	-	-	6	4	-	-	217	-	48	1	8	-	3	-	-	-	297
Smallmouth Bass	1	-	-	-	-	-	2	-	-	-	1	-	2	1	-	-	1	-	-	-	8
Black Crappie	-	-	-	-	-	-	-	-	-	-	-	-	1	-	3	-	-	-	-	-	4
Yellow Perch	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Black Bullhead	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	1	-	-	-	4
Brown Bullhead	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Chiselmouth	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Carp	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	-	2
Peamouth	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	1	6	-	-	-	12
Squawfish	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	2
Dace	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Redsided Shiner	-	-	-	3	-	-	-	-	-	-	2	-	-	-	-	-	-	-	50	100	155
Tench	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Bridgelip Sucker	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Largescale Sucker	2	1	-	1	1	-	1	2	-	-	-	-	2	-	2	-	2	1	1	8	24
Sculpin	2	1	3	-	-	-	-	1	-	-	5	-	-	1	-	2	-	1	-	-	16

Trap Net

River Mile / Species	517.0 (LB)	517.0 (RB)	524.0 (LB)	528.0 (LB)	528.0 (RB)	530.5 (RB)	531.0 (LB)	533.5 (RB)	535.0 (LB)	535.0 (RB)	535.1 (RB)	536.8 (RB)	537.0 (LB)	537.0 (PB)	537.2 (LB)	537.3 (LB)	Methow RM .25	Methow RM .5	Total
Chinook	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1
Steelhead	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3
Rainbow Trout	1	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	5	8
Mt. Whitefish	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
Pumpkinseed	-	3	-	-	2	-	3	2	2	-	5	14	-	1	2	-	-	-	34
Smallmouth Bass	-	-	-	-	-	-	-	-	-	1	2	-	-	1	-	-	-	-	4
Black Crappie	-	-	-	-	-	-	-	12	-	-	9	-	-	-	-	-	-	-	21
Yellow Perch	-	-	-	-	1	-	-	-	1	-	-	-	1	-	-	-	-	-	3
Black Bullhead	-	-	-	-	-	-	-	1	-	-	3	6	-	9	-	-	-	-	19
Brown Bullhead	-	-	-	-	1	-	-	-	6	-	-	-	-	-	-	1	-	-	8
Chiselmouth	86	12	49	3	196	63	1	7	4	116	414	84	3	-	6	1	-	-	1045
Carp	1	1	-	-	4	-	-	1	-	-	-	6	-	-	-	-	-	-	13
Peamouth	3	8	-	-	32	-	-	-	-	-	15	-	-	-	1	-	-	1	69
Squawfish	7	6	12	11	82	10	2	2	30	-	6	13	1	2	3	1	-	5	193
Dace	-	6	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11
Redsided Shiner	4	53	53	-	25	6	-	-	2	-	-	-	-	-	-	-	-	20	159
Tench	-	7	-	-	-	-	-	-	3	-	-	-	-	-	-	1	-	-	11
Bridgelip Sucker	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2
Largescale Sucker	10	8	34	9	-	23	2	3	43	-	16	76	-	8	1	7	2	25	287
Sculpin	-	1	-	-	2	-	-	-	-	-	-	-	-	1	-	-	-	-	4

Appendix 1. Beach seine and New York Trap Net catch by River Mile location.

Date	Hours	Location	Chinook	Rainbow Trout	Steelhead	Squawfish	Chiselmouth	Largescale Sucker	Smallmouth Bass
7/30	6	RM 516.8 517.2 LB	1	11 2 IJ Brand	-	1	-	-	-
7/31	6	Mouth of Methow	-	-	-	1	-	-	-
8/1	7	RM 516.8 517.2 LB	-	11 3 IJ Brand	-	-	-	-	-
8/6	2	RM 528 RB	-	-	-	-	-	-	1
8/7	6	RM 541 LB	-	-	-	6	-	1	-
8/13	2	RM 533 LB	-	-	-	3	-	-	-
8/16	2	RM 533 LB	-	-	-	6	1	-	-
9/21	8	Mouth of Methow	-	-	-	-	-	-	-
9/25	4	RM 539.5 LB	-	1	-	2	-	-	-
9/2	2	RM 516.8 LB	-	-	-	-	-	-	-
9/28	8	Mouth of Methow	-	-	1	-	-	-	-
10/1	2	RM 537.5 RB	-	-	-	-	-	-	-
10/1	1.5	Rm 537 LB	-	-	-	2	-	-	-
Total	56.5		1	23	1	21	1	1	1

Appendix 2. Angling fish catch by river mile location.

Murauskas, J. G. and P. N. Johnson. 2009. Assessment of Adult Pacific Lamprey Behavior in Response to Temporary Velocity Reductions at Fishway Entrances. Study plan prepared for the Aquatic Settlement Work Group, Wells Hydroelectric Project FERC No. 2149, with technical support from J. Skalski, R. Wielick, D. Allison, M. Hallock, and B. Le. East Wenatchee, Washington.

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Assessment of Adult Pacific Lamprey Behavior in Response to Temporary Velocity Reductions at Fishway Entrances

Prepared for:
Aquatic Settlement Work Group
Wells Hydroelectric Project
FERC No. 2149

Prepared by:
J.G. Murauskas[1]
P.N. Johnson[2]

With technical support from:
J.R. Skalski[3]
R.A. Wielick[4]
D. Allison[4]
M. Hallock[5]
B. Le[6]

July 24, 2009

[1] Public Utilities District No. 1 of Douglas County. East Wenatchee, Washington
[2] LGL Limited environmental research associates. Stevenson, Washington
[3] School of Aquatic and Fishery Sciences, University of Washington. Seattle
[4] Jacobs Civil Inc. Hydro Division. Bellevue, Washington
[5] Washington Department of Fish and Wildlife. Olympia
[6] Long View Associates. Portland, Oregon.

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Introduction

Pacific lamprey *Lampetra tridentata* are an anadromous member of the jawless fish Family Petromyzontidae that inhabit marine and freshwater systems from southern California to the Aleutian Islands in Alaska. Historically, these fish were widely distributed throughout Washington State and served as an important ecological and cultural resource to the region. Construction of hydroelectric projects, specifically on the Columbia and Snake rivers, has limited the ability of migrating adults to reach historical upstream spawning locations, presumably contributing to population declines observed in recent years. Research to better understand lamprey passage behavior was initiated at Wells Dam – the ninth passable project on the Columbia River (RM 515.6) – following the attention-grabbing collapse of lamprey passage numbers at Bonneville Dam in 2005. Despite exceptional fishway efficiency, fishway ascent speed, and a zero percent fallback rate, adult lampreys have been shown to exhibit difficulty negotiating fishway entrances at Wells Dam. This impediment has been attributed to the hydraulic conditions at fishway entrances caused by the head differential between the fishway collection gallery and tailrace. Average velocities currently experienced in the fishway entrances at Wells Dam are well above the known swimming capability of adult lampreys. These conditions are typical of fishway entrances in dams throughout the Columbia River Basin, and have been identified as a key area for improving passage efficiency of adult lampreys through hydroelectric projects.

Therefore, the purpose of this study is to assess the effects of temporary velocity reductions at fishway entrances on the (a) attraction and (b) relative entrance success of adult lampreys at Wells Dam. Three alternative entrance flow velocities (i.e., existing high, moderate, and low) will be assessed using Dual-frequency Identification Sonar (DIDSON) in a randomized block design during the fall of 2009. The goal is to identify optimal hydraulic conditions conducive to entry of adult lampreys into the fishways at Wells Dam. Based on historical counts and radio-telemetry data, both the temporary entrance velocity reductions and monitoring for this study will occur between 21:00 and 01:00 daily from August 26th to September 19th, with 5 additional days of monitoring (30 total) based on river conditions to better capture the run. The proposed reductions are further designed to have nominal impact on ESA-listed steelhead *Oncorhynchus mykiss* and other salmonids that migrate during the same period. Equipment deployment and project coordination is scheduled to begin August 10th, with implementation of treatments beginning between August 21st and 26th, depending on current river conditions and run status. Monthly updates will be provided beginning September 30th, and a final report will be provided no later than January 31st, 2010.

Background

Study Area

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 2). Wells Dam is located approximately 30 RM downstream from the Chief Joseph Hydroelectric Project and 42 RM upstream from the Rocky Reach Hydroelectric Project. The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Public Utility District No. 1 of Douglas County (Douglas PUD). Wells Dam includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the dam is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as a hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a crest elevation of 795 feet in height.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 above mean sea level (msl).

Fish Passage Facilities

The two fish ladders at Wells Dam are conventional staircase type fish ladders with 73 pools. The ladders are located at the east and west endwalls of the dam. The lower 56 pools discharge a constant 48 cubic feet per second (cfs), dropping one foot at each pool into the attraction chamber in the lower ladder (often referred to as the collection gallery). Discharge from Pool #73 through Pool #57 is through two 30” by 16.5” inch submerged orifices. Discharge from Pool #56 to Pool #1 is over a seven foot wide overflow section in the wall between pools with additional flow through two 18” by 15” submerged orifices. Pool #64 of both fishways contains facilities for counting fish. Pool #40 contains provisions for sorting and trapping various species of fish. The fisheries agencies and tribes develop broodstock collection protocols at the beginning of each season for collection of spring and summer Chinook *O. tshawytscha*, sockeye *O. nerka*, and coho *O. kisutch* salmon, and summer steelhead. Pool #40 was also the location of lamprey trapping efforts in 2007 through 2008, and generally considered the separating point between the “lower” and “upper” fishway.

At the bottom of the fish ladder, projecting downstream from the line of the hydrocombine, is the portion of the endwall structure which incorporates the functions of fish attraction and collection. Two-turbine pumps deliver attraction flow to the water supply chamber located adjacent to the ladder. The total flow from the turbine pump(s) plus the 48 cfs flowing down the ladder from the reservoir is discharged to the tailwater through a single fishway entrance per ladder. These entrances are eight-foot wide vertical slot openings with vertical miter gates. Originally a set of side gates were available as an alternative entrance, although the joint fisheries parties agreed to have them permanently closed on June 29, 2000. This decision was based upon several years of radio-telemetry studies with various species of anadromous fish that showed improved passage times with the side gates closed. Flow-directing baffles were installed at the upstream end of both fishways during the winters of 2007 (east ladder) and 2008 (west ladder). Research indicated that the resulting attraction flow decreases gallery passage time of migrating salmon.

The entrances to Wells Dam fishways are based on models using the original operating criterion of a one-foot head differential. The equivalent velocity for this original elevation head is 8.02 feet-per-second. Since the closure of the side entrance gates, the target operating head differential was increased to 1.5 feet. The equivalent velocity for the current elevation head is 9.83 feet-per-second, or roughly 122% of the original design velocity. Actual average velocities are likely less than these theoretical velocities, while velocities at boundary zones are likely much less. Based on theoretical distribution characteristics, velocities are slightly higher than average in the center of the water column, and perhaps less than 75% of the average in the boundary zones (Figure 1). While these rough estimates provide insight to entrance hydraulics, it is important to note that these figures cannot be qualified without precise modeling techniques.

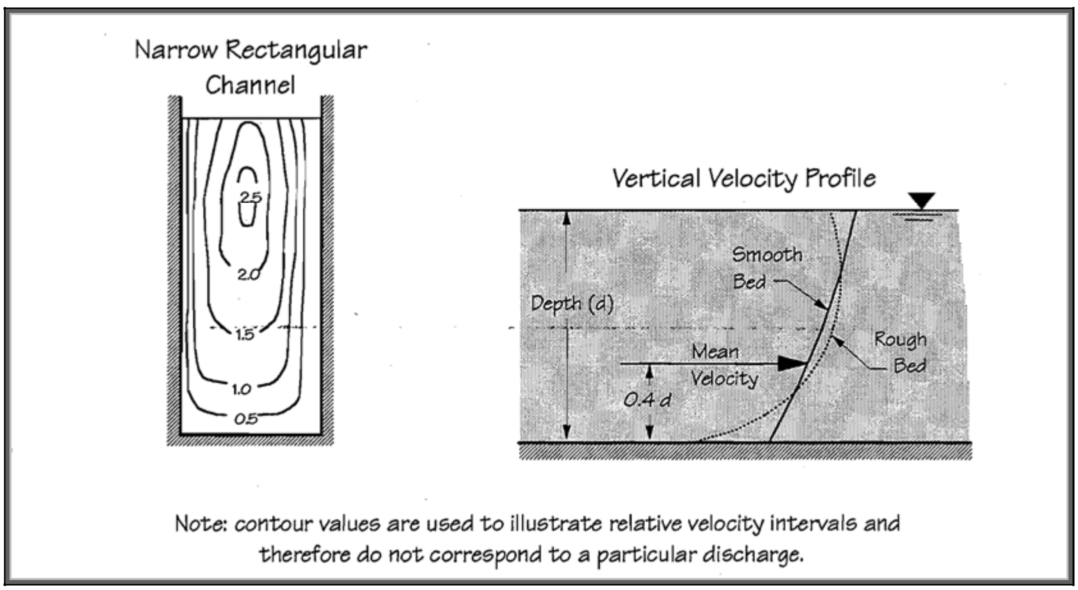

Figure 1. Theoretical velocity distribution characteristics similar to dynamics that would be observed in the fishway entrances of Wells Dam, including a head-on view (left) and profile of boundary conditions (right) (Katopodis 1992).

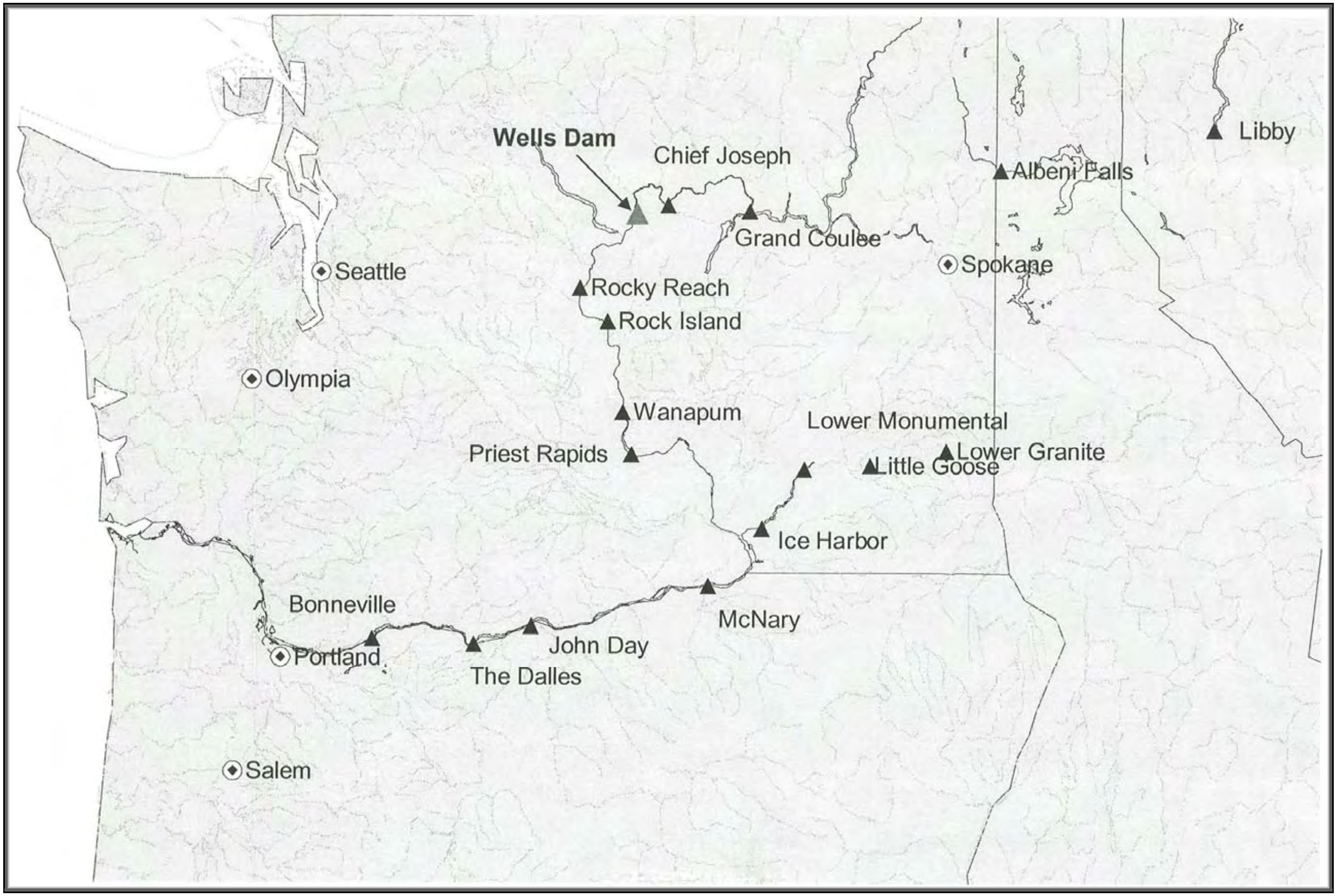

Figure 2. Regional map depicting Columbia River Basin hydroelectric projects. Wells Dam is the ninth project upstream and the last with fish passage facilities (RM 515.6).

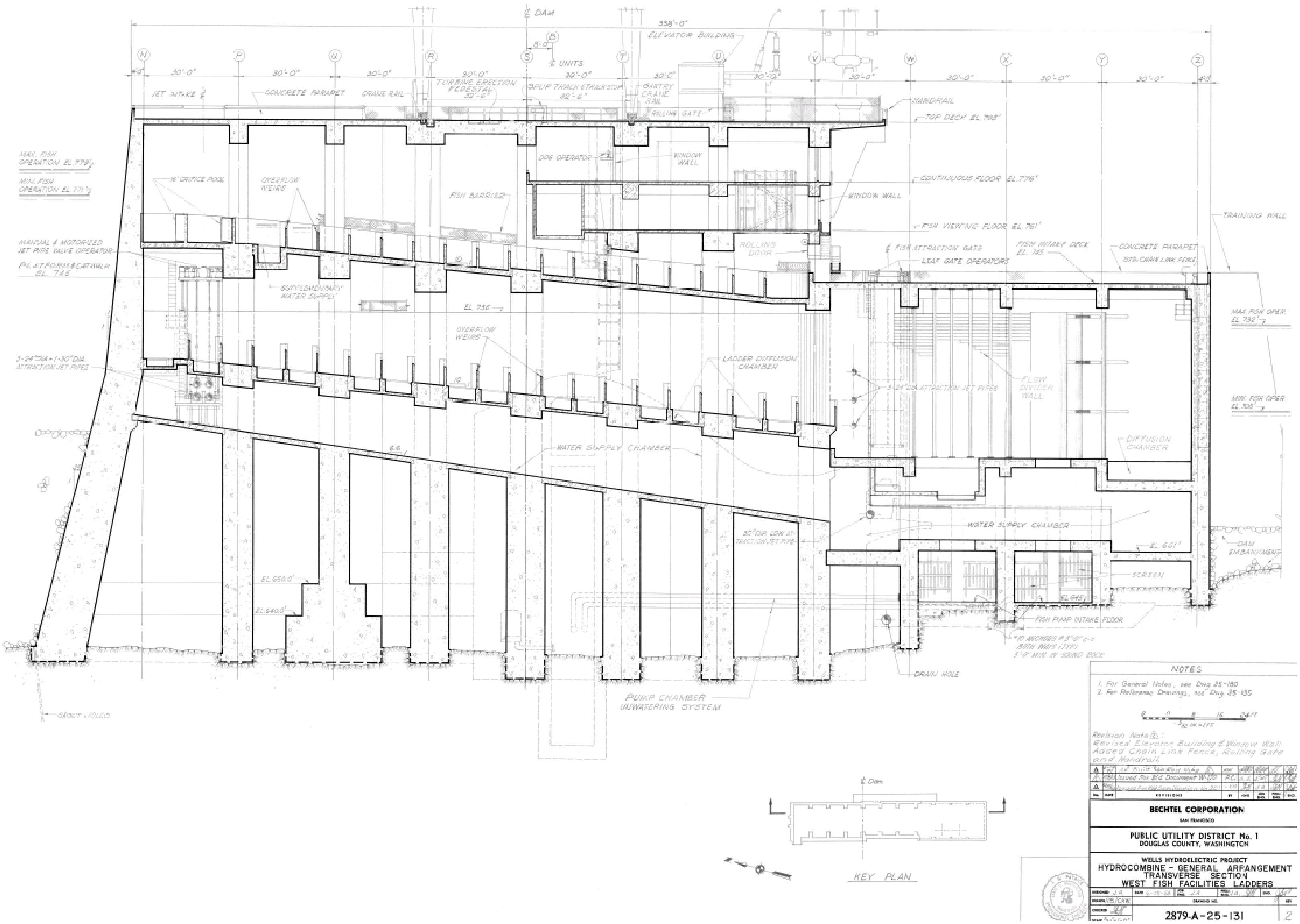

Figure 3. Side view of fishway design at Wells Dam.

Pacific Lamprey

Life History and Ecology

Pacific lamprey belong to the jawless fish Family Petromyzontidae, generally described as eel-like fishes lacking bones, scales, and paired fins. Nineteen of the thirty-eight known species of lampreys occur in fresh and marine waters throughout United States and Canada. Adults use their circular mouths to excavate pits in stream and river bottoms for use as spawning locations. Eggs hatch after a few weeks and the blind larvae (ammocoetes) reside in mud- or sand-bottomed pools where they filter feed on microorganisms. Ammocoetes metamorphose into adults at 3 to 8 years of age. Some lampreys do not feed as adults (e.g., brook lamprey *L. richardsoni*) and others enter a parasitic phase where they attach and rasp a hole into the side of a large fish or marine mammal to consume body fluids from the host (Page and Burr 1991; Close et al. 2002).

Pacific lamprey is an anadromous parasitic form that inhabits marine and fresh water systems from southern California to the Aleutian Islands in Alaska, as well as the Pacific Coast of Asia (Beamish and Levings 1991). Adults enter freshwater tributaries between July and October and migrate towards spawning grounds where they overwinter without feeding. Spawning begins the following spring when water temperatures reach 10 to 15°C. Spawning lampreys create nests using their suction mouths and body vibrations, generally in low gradient waters with sand and gravel substrate. Females deposit several thousand eggs to be fertilized in their nest and die 3 to 36 days thereafter (Close et al. 2002). Larvae hatch within 3 weeks and drift to backwater areas of low water velocity with soft sediments and high organic matter (e.g., shallow pools and eddies). The ammocoetes burrow in fine silt or sand and filter feed on microscopic plants and animals for up to 6 years, growing up to 200 mm in length. A variety of species, including fish, birds, and crayfish, will prey on juvenile lampreys, especially during emergence from nests and when scouring events dislodge larvae from their burrows (Close et al. 2002; Moser and Close 2003).

Ammocoetes slowly metamorphose into adults from July to November. The transformer life stage preceding maturity includes several morphological and physiological changes to prepare for parasitic life in the ocean. The young adults migrate to the ocean between fall and spring months, depending on environmental conditions. Birds and fishes are known to feed on lampreys during this period, and some biologists suspect this availability as a prey item historically buffered predation on juvenile salmonids (Close et al. 2002). Lampreys subsequently spend from one to three years in the ocean, traveling as far as 100 km from the Pacific coast and up to 800 m of depth. Adults feed on large fish and marine mammals, growing as much as 75 cm until their spawning migration. Adult lampreys are preyed upon in the ocean, though predation is likely the greatest during their spawning migration when mammals, larger fish, and birds feed on the concentrated and easily captured fish (Beamish 1980; Close et al. 2002). The transfer of marine-derived nutrients to freshwater systems is likely an important component in the Pacific Northwest ecosystem (Close et al. 2002).

Both adults and juvenile lampreys are relatively poor swimmers compared to more familiar bony fishes (Class Osteichthyes). The lack of true fins, a swim bladder, and a comparably inefficient swimming motion limits the ability of lampreys to overcome strong currents (Mesa et al. 2001; Dauble et al. 2006). Adult lampreys typically swim in bursts and attach to hard surfaces to rest when unable to negotiate swift waters, especially when in currents exceeding 0.8 m/s (Mesa et al. 2003). The lack of adequate attachment surfaces in areas where lampreys encounter high velocity waters likely impedes upstream movements. Objects such as metal diffuser grating, 90° corners, and corrugated pipes in fishways or culverts have been identified as obstacles to lamprey migration (Mesa and Moser 2004). These factors, along with high water velocities in fishways designed to facilitate salmon passage, delay or obstruct the upstream migration of adult lampreys at many hydroelectric projects in the Columbia River (Mesa et al. 2001).

Pacific lamprey currently have little economic value in the Pacific Northwest, though lampreys were commercially harvested by the ton in the mid-1900s for use as vitamin oil, and meal for livestock and cultured fish (Close et al. 1995; 2002). Despite little current commercial value to Euro-Americans, lampreys are important to indigenous people of the Pacific Northwest for subsistence, medicinal, religious, and ceremonial reasons. Links to the spiritual world through natural beings are interwoven into Sahaptin culture by myths and legends. Oils derived from lampreys are used by tribal people in the mid-Columbia River Plateau for conditioning and curing ailing parts of the body. Subsistence fisheries also exist where tribal members harvest lampreys by hand, dip net, or jigging. The decline of this cultural resource has raised concerns regarding the lack of Pacific lamprey management efforts (Close et al. 2002).

Distribution in the Columbia River Basin

The Pacific lamprey, along with river lamprey (*L. ayresii*) and brook lamprey are the only lampreys identified in the Columbia River Basin. The Pacific lamprey is a prevalent species, and was historically distributed throughout much of the Basin (Dauble et al. 2006). Access to the upper Basin was first blocked by the construction of the impassable Grand Coulee (1940s) and Chief Joseph (1950s) dams. These hydroelectric dams, presently the 10^{th} and 11^{th} on the mainstem Columbia River, blocked anadromous fishes from access to traditional spawning grounds, though distribution of Pacific lamprey in these upper reaches is not well-documented. Pacific lamprey now range upstream to Chief Joseph Dam on the Columbia River and to Hells Canyon Dam on the Snake River (Close et al. 1995). The distribution of lampreys throughout rivers below these points is uncertain, though their presence has been documented in several tributaries below Chief Joseph Dam, including the Okanogan, Methow, Entiat, and Wenatchee rivers (BioAnalysts 2000; M. Rayton, Confederated Tribes of the Colville Reservation, personal communication).

Accurate historical and present population estimates of lampreys in the Columbia River are lacking. Fish enumeration efforts at the Columbia Basins' passable hydroelectric dams are the only programs that obtain counts of migrating lampreys. The programs are inconsistent and unreliable to some extent, largely due to protocol differences and monitoring that has traditionally taken place during daylight hours, leading to underestimates of nocturnal fish such as Pacific lamprey. Although 24-hour counting has been established at most dams since the late 1990s, several other factors lead to inaccurate lamprey counts. Some lampreys pass undetected by traveling near the bottom of count station windows or through picketed leads at video bypass systems. Instances of over-counting exist also, especially with the erratic swimming behavior and tendency of lampreys to make up- and downstream movements within fishways (Starke and Dalen 1995; Jackson et al. 1997; Moser and Close 2003). The tendency for Pacific lamprey to overwinter prior to spawning also leaves the potential for counting fish that entered the system the previous year. Further, lamprey counts were only intermittent at most dams prior to the 1990s. Moser and Close (2003) declared lamprey counts at hydroelectric dams "unreliable" and "misleading." Despite the inability to obtain accurate population estimates, there has been an obvious decline in Pacific lamprey throughout the Columbia River Basin over the past decade. The dramatic declines and concerns over extirpation have led to recent petitions to list Pacific lamprey under the Endangered Species Act (Moser and Close 2003).

Research at Wells Dam

Pacific lamprey historically inhabited the mid-Columbia River and its tributaries at and near the Wells Dam Project Area. Lampreys are currently found in the Columbia River mainstem, at least the lower 16 miles of the Entiat River Basin, and much of the Methow River system (BioAnalysts 2000). Although little evidence exists to suggest Pacific lamprey occupy the Okanogan River (BioAnalysts 2000), juvenile lampreys have been captured by recently installed rotary screw traps in the spring of 2006 and 2007 (M. Rayton, Confederated Tribes of the Colville Reservation, personal communication). Over 3,500 adult Pacific lamprey were observed ascending the fishways at Wells Dam between 1998 and 2007 (lamprey counts began in 1998). Observations have been highly variable, averaging 350 per year (± 416 SD), and ranging from 21 to 1,410 fish (DART 2008). Though most of this variability may be explained by the size of the migrating population (as indicated by counts downstream), there also is variability in the proportion of lampreys counted downstream that make it to Wells Dam. For example, the average conversion rate between Rocky Reach Dam and Wells Dam (roughly 33%) was greatly exceeded in 2003. Over 50% of the lampreys observed at Rocky Reach Dam were counted at Wells Dam, resulting in a record 1,410 observations. Contrastingly, in 2006 only 6% of the lampreys observed at Rocky Reach Dam were counted at Wells, leading to the lowest count since monitoring began. The variability in conversion rates may be caused by, in addition to imprecise counts, environmental conditions, population dynamics, migratory success, overwintering, and varying portions of the population entering the Entiat River located between the two projects. Basin-wide, it is not surprising that on average less than 1% of the total lampreys observed at Bonneville Dam are counted at Wells Dam considering the 14 major tributaries, 7 hydroelectric dams, and 370 river miles that separate the two projects.

Considerable research has been conducted at Wells Dam over recent years despite the comparably low numbers of lampreys that interact with the project. These efforts were initiated following the attention-grabbing collapse of lamprey passage numbers in 2005. Following increasing lamprey counts at Bonneville Dam between 2001 and 2003 (47%, 260%, and 16% annual increases, respectively), the post-1960 record count of over 117,000 lampreys observed in 2003 decreased roughly 50% for the following two years, leading to a dismal count of 26,667 fish in 2005 (DART 2008). Douglas PUD activated an extensive network of radio-telemetry receivers at Wells Dam to monitor radio-tagged lampreys released by Chelan PUD downstream of Rocky Reach Dam. The efforts were designed to capitalize on these study fish to better understand passage at Wells Dam. Only ten study fish ultimately ascended Rocky Reach

Dam, entered the Wells Project, and approached a fishway entrance at Wells Dam. Three of these fish (30%) successfully ascended Wells Dam, doing so in 4.3, 7.7, and 7.4 hours; one fish was later detected in the Methow River (Nass et al. 2005).

Douglas PUD subsequently initiated a suite of lamprey studies at the Wells Project; including both voluntary efforts and studies required by the Federal Energy Regulatory Commission (FERC) as part of the Wells Project relicensing process. Four additional studies conducted to date include an adult lamprey spawning assessment (Le and Kreiter 2008), a juvenile lamprey survival and predation study (DCPUD and LGL 2008), and two consecutive adult passage and behavior studies (LGL and DCPUD 2008; Robichaud et al. 2009). The latter radio-telemetry studies provided substantial insight to adult lamprey passage at Wells Dam. Many of these results were among the best in the Columbia River Basin. For example, passage success through unobstructed (i.e., no trapping) portions of the ladder were shown to be 100%, fall back after exiting the ladders was not observed in three years of study (0%), and total fishway passage times (as quick as four hours) are on the order of magnitudes faster than those observed at downstream projects (Nass et al. 2005; Robichaud et al. 2009). This exceptional in-ladder passage efficiency is likely due to the lack of sills in submerged orifices and diffuser gratings on the pool floors, offering a smooth wall-to-wall environment known to assist lamprey passage. Only 2 of the 73 pools within each fishway at Wells Dam have a floor-oriented auxiliary water supply, both of which do not interfere with the orifice and only cover a portion of the pool floor. This allows for adequate attachment and resting surfaces as lampreys travel through the fishways utilizing burst and attach movements.

Despite excellent in-ladder passage results at Wells Dam, radio-telemetry data collected in 2007 and 2008 indicate that adult lampreys are having difficulty negotiating water velocities produced by head differentials at fishway entrances. Head differentials at Wells Dam – at 25% to 36% greater than median values recorded at neighboring Rocky Reach and Rock Island dams – were increased above the original 1.0 foot requirement as added attraction flow for adult salmon (FPC 2009). The resulting velocities and entrance environment has since been acknowledged as the “greatest impediment to successful passage of adult lamprey[s] at Wells Dam” (Robichaud et al. 2009). Although the Aquatic Settlement Agreement (Agreement) – a document crafted with tribal, state, and federal agencies to resolve remaining aquatic issues at Wells Dam – does not require implementation of the Pacific Lamprey Management Plan until 2012 (DCPUD 2008), Douglas PUD is proposing solutions to create an environment more conducive to lamprey entry into fishways at Wells Dam with the implementation of this study. These concepts were originally presented to the Signatory Parties of the Agreement (Aquatic Settlement Workgroup (SWG)) less than one month following submission of the 2008 passage and behavior report (Robichaud et al. 2009; Aquatic SWG 2009).

Adult Monitoring Techniques

Trapping and Fish Enumeration

The use of passive and active trapping techniques as a fisheries monitoring tool has proven to be both practical and effective in varying situations (Hubert 1996; Hayes et al. 1996). Trapping allows for calculation of simple metrics, such as catch per unit effort (Hubert 1996), or provides study fish for mark-recapture studies, such as the Lincoln-Peterson method, used for generating population estimates. These methods have been employed extensively for lamprey management efforts in other regions of the country, ranging from the marking of out-migrating juveniles (Bergstedt et al. 2003) to developing population estimates of spawning-phase adults (Mullett et al. 2003). Some trapping applications have been used in Pacific lamprey management (Moser et al. 2007), though there are limitations to trapping-based research in upper reaches of the known Pacific lamprey distribution. For example, trapping at dams has proven to be inefficient and extremely disruptive of migrating populations (Robichaud et al. 2009); and handling of lampreys has been shown to be stressful (Close et al. 2003), potentially biasing the behavior of these fish after release. Further, developing population estimates – a general product of trapping studies – are a lower priority than resolving passage issues and passage timing and abundance are already captured through dam count stations.

Fish enumeration programs at hydroelectric projects, designed to monitor salmonids passage, provide the only current and historical estimates of the adult lamprey migration in the Columbia River. The accuracy of these numbers is limited for several reasons, including the lack of historical nighttime counts and difficulty counting individuals with erratic swimming behavior (Moser and Close 2003). Further, some of the fish that overwinter are known to ascend fishways the following spring. For example, the first lamprey observed at Wells Dam during each year has occurred as early as April 28th – nearly 20 weeks ahead of the average mid-migration point (September 8th; DART 2008). This causes confusion among counts, particularly when attempting to measure conversion between dams or estimating the proportion of fish potentially blocked by a specific project. Lastly, adult lampreys have been shown to bypass count windows at dams via picketed leads prior to the narrow, lighted channel leading to the count station. Radio-telemetry studies have indicated that counts may be underestimated substantially. Roughly three of every four fish that ascend fishways at Wells Dam have been shown to avoid enumeration (Robichaud et al. 2009). Despite the limitations with fish enumeration programs, results provide useful insight to population trends, seasonality, and characterizing diel movements through fishways.

Tag Technologies

Both active and passive tag technologies have been used to monitor behavior of adult Pacific lamprey in the Columbia River Basin. The most widely-used tool to date has been radio-telemetry. Thousands of lampreys have been radio-tagged since 1997 when the National Marine Fisheries Service, United States Geological Survey, and University of Idaho systematically established more than 170 radio receiving stations at Bonneville and The Dalles dams to assess passage efficiency of migrating adults (Moser et al. 2002a). Adult lampreys have since been studied using radio-telemetry at most passable Columbia River hydroelectric projects and several Snake River projects (Moser et al. 2002b; Stevenson et al. 2005; Keefer et al. 2009; Robichaud et al. 2009). Although results from these studies have been incredibly useful in identifying passage issues at dams, increased sample sizes through repeated studies and advances in tag technologies indicate that the base assumption of radio-telemetry – tagged fish are representative of untagged fish – has been violated frequently. Moser et al. (2007) found that there was a significant long-term effect of tagging on Pacific lamprey performance and that effects are perhaps more prevalent than the literature suggests. Keefer et al. (2009) also identified issues with radio-telemetry when 63% of PIT-tagged lampreys were found to ascend John Day Dam from the Bonneville forebay compared to 25% of radio-tagged fish. Similar to Moser et al. (2007), the negative effects caused by radio-tag implantation were especially prevalent in smaller lampreys (Keefer et al. 2009). This effect is more prevalent at upstream locations where fish have expended considerably more bioenergetic reserves than those sampled downstream and are therefore, typically smaller in size. For example, fish used in radio-telemetry studies at Wells Dam (RM 515.6) have been as small as 54 cm total length (TL) and 0.27 kg of weight, 29.9% and 55.9% smaller, respectively, than mean values reported at Bonneville Dam (RM 146.1) in 2001 and 2002 studies. Even more importantly, the girth of lampreys radio-tagged in 2007 and 2008 at Wells Dam averaged 10.2 cm (9.0-12.0 cm), compared to a majority of fish tagged at Bonneville Dam in the 12.5 to 14.9 cm girth range (Moser et al. 2005; Robichaud et al. 2009). These issues with the current radio-telemetry technology has required researchers to consider alternative monitoring techniques, such as half-duplex (HD) PIT tags, acoustic technology, or DIDSON.

DIDSON

DIDSON is a multi-beam imaging technology developed for the U.S. Navy by the University of Washington's Applied Physics Laboratory. DIDSON is unlike conventional sonar systems in which echo returns from targets are coupled together to form fish traces based on acoustic qualities of the individual echoes. Instead, the output from DIDSON more closely resembles optical imagery, allowing for high-definition visual observations of objects through its $29^{o} \times 12^{o}$ field-of-view. The DIDSON allows for the acquisition of streaming data with a range of up to approximately 24 m. The clarity is possible because the field of view is composed of 96 separate 0.33-degree beams operating at 1.8 MHz or 48 separate 0.4-degree beams operating at 1.1 MHz. The output image from the DIDSON is in a planar-view perspective, giving the appearance of sampling from above. The multiple beams allow image processing that produces a near-field image similar to that of a black and white camera (Belcher et al. 2001; Moursund et al. 2003).

DIDSON has been used effectively in recent years in behavioral assessments of fishes, especially at hydroelectric projects in the U.S. Pacific Northwest. The images within 1-12 m of the device are of high enough resolution that swimming behavior, orientation, fin placement, and direction of fish movements can be accurately quantified in otherwise zero-visibility water caused by low light levels and high turbidity (Belcher et al. 2001; Moursund et al. 2003). For example, Ploskey et al. (2005) used DIDSON to evaluate the effectiveness of the corner collector at Bonneville Dam's 2nd powerhouse for passing juvenile salmonids and Johnson et al. (2006) evaluated the effectiveness of sluiceways for passing juvenile salmonids at The Dalles Dam.

Regional fish biologists have recently acknowledged the benefits of DIDSON sampling to analyze adult Pacific lamprey behavior. DIDSON sampling is unobtrusive to fish since its operating frequencies are above the frequency ranges in which fish can detect (Fay and Simmonds 1999). This is in direct contrast with other sampling methods that require trapping, handling, and surgery of all individuals involved in the study. As stated above, these methods have been shown to be highly problematic with adult lampreys and recent research has identified substantial concerns with handling and tagging effects, especially with smaller individuals at low sample sizes where effects are statistically undetectable (e.g., Moser et al. 2007; Keefer et al. 2009). Avoiding any handling of Pacific lamprey will not only benefit the resource, but also improve the scientific rigor of research by capturing individuals in their natural state. The unobtrusive and passive characteristics of DIDSON research will also allow for collection of greater sample sizes since all interactions are captured, as opposed to other monitoring techniques that are limited to the number of fish trapped and tagged. Images of adult lamprey behavior have been collected with DIDSON, demonstrating that this technology is able to captures the diagnostic Anguilliformes-like swimming behavior of lampreys (P. Johnson, unpublished data; C. Pfisterer, Alaska Dept. of Fish & Game, personal communication, www.soundmetrics.com/FM/lamprey.html).

Experimental Design

The purpose of the study is to assess the effects of temporary velocity reductions at fishway entrances on the (a) attraction and (b) relative entrance success of adult lampreys at Wells Dam. Three alternative entrance velocities (i.e., existing high, moderate, and low) will be assessed using DIDSON in a randomized block design during the fall of 2009. The goal is to identify optimal hydraulic conditions conducive to entry of adult lampreys into the fishways at Wells Dam.

Hypotheses

1. The ability of adult lampreys to successfully negotiate fishway entrances at Wells Dam is directly related to hydraulic conditions at fishway entrances.
2. Current fishway operations, producing average water velocities at the entrances that exceed the known swimming capability of adult lampreys, are not currently optimized for lamprey passage.

Prediction

A temporary, nighttime reduction in head differential between the fishway collection galleries and tailrace, leading to decreased velocity at the entrances, will create hydraulic conditions conducive to entry of adult lampreys into the fishways at Wells Dam.

Data and Evaluation

Both factor and response data will be the primary information collected during this study. The factor will be the treatment level, or entrance velocity, and the response will be (1) number of approaches, (2) number of successful entrants, and (3) the relative success, or proportion of successful entrants as compared to the control treatment level (i.e., current level of operation). Statistical analyses will be performed on results to test the strength of differences. The differences (or lack thereof) will be used to evaluate the prediction and whether temporary, nighttime reductions in head differential are an effective tool to facilitate passage of adult lampreys at the Wells Dam. Secondary information, specifically fine-scale behavioral observations, will be collected to further understand lamprey behavior at fishway entrances and identify problematic areas.

Methods

Timing and Reductions

Seasonal and Diel Movements

The length, timing, and abundance of the adult lamprey migration at Wells Dam were analyzed according to historical fish counts by LGL and Douglas PUD (2008). On average, the bulk of the Pacific lamprey migration at Wells Dam typically occurs between August 26th and September 19th, with the average mid-point occurring on September 8th, with considerable reliability (SD ± 13 days; LGL and Douglas PUD 2008). Diel movements of adult lampreys through Wells Dam can be described by both historical fish counts and radio-telemetry data. Analysis of historical hourly counts reveals that roughly 80% of all lampreys are counted between 19:00 and 08:00 the following day. Since the count window is located at Pool #64 in each ladder, raw data from Robichaud et al. (2009) were used to identify times when interactions with the fishway entrances were most frequently observed. Over 75% of these observations occurred between 20:00 and 24:00 in 2007 and 2008 (over 35,000 hits during 113 individual observations). Considering that substantial fish handling occurred during mid-day hours in the second year of this study, it is reasonable to expect that most adult lampreys approach the entrances to Wells fishways between 20:00 and 24:00. These results are consistent with other assessments of lamprey behavior. Moser et al. (2002) found entrance approach times of adult lampreys to peak between 22:00 and 01:00. Based on this information, and negotiations with the HCP Coordinating Committee, the temporary entrance velocity reductions will occur between 21:00 and 01:00 daily between August 26th and September 19th (a 25-day period), with 5 additional days of monitoring to add based on river conditions to better capture the run.

Velocity Reductions

Three alternative entrance velocities (equal treatments on both fishways) will be conducted during the study period. The high (existing condition) will serve as a control, with a head differential maintained at 1.50 feet. Alternatively, low and moderate range velocities will also be assessed. Head differentials ranging from as low as 0.50 feet to 1.25 feet will be selected for the low and moderate treatments following recommendations from fishway engineers and approval from the Habitat Conservation Plan (HCP) Coordinating Committee (B. Nordlund, NMFS, personal communication) (Table 1). The latter communication is to ensure that any proposed changes will have a nominal impact on passage of ESA-listed salmon.

Table 1. Estimated average velocity (fps) produced by various head differentials at Wells Dam fishway entrances.

Head Differential	Estimated Average Velocity (fps) [3]	Velocity Relative to Existing Conditions (%)
0.00	0.00	0%
0.25	4.01	41%
0.50	5.67	58%
0.75	6.98	71%
1.00[1]	8.02	82%
1.25	8.97	91%
1.50[2]	9.83	100%

[1] Median head differential at Rocky Reach and Rock Island Dam is 1.1' and 1.2', respectively (FPC 2008).

[2] Median head differential at Wells Dam is 1.5' (FPC 2008).

[3] Note that boundary conditions will be much less than estimated average velocity.

Influence on Salmonids

The nocturnal behavior of lampreys has been well-documented throughout the world, including Pacific lamprey at Columbia River Basin hydroelectric projects (Moser et al. 2002; Potter and Gill 2003; Robichaud et al. 2009). This behavioral pattern is particularly useful in the Columbia River Basin where passage of migrating adult salmonids has remained a management priority since construction of hydroelectric projects (FPC 2008). Migrating adult salmonids, contrary to lampreys, tend to approach and ascend fishways during daytime hours. Moser et al. (2002) captured this difference in a management context by stating, "The tendency for lamprey to be most active during the night when adult salmonids are less active may be exploited to improve lamprey passage without affecting salmonids." A closer examination of hourly passage data at Wells Dam over the past decade supports this trend (Figure 4). Both steelhead and Chinook salmon passage through Wells Dam has peaked during the 16th hour of the day (3:00-3:59 p.m.), whereas sockeye salmon passage has peaked during the 13th hour of the day. Contrastingly, lamprey passage has peaked during the first hour of the day. These data indicate that nearly 95% of steelhead and all salmon combined are observed in the fishways outside of the proposed entrance reductions – some of which will remain within original target levels (1.0'). Further, spring Chinook salmon will not be present during the study, and the majority of coho salmon migrate subsequent to the proposed study period. No operational changes will occur within the fishway itself, providing ladder operations consistent with HCP guidelines. Therefore, minor and seasonal temporary nighttime reductions in head differential would have a nominal affect on salmonids passage, if any, particularly that of ESA-listed steelhead. To ensure that this assessment is correct, DIDSON data collected during this study will also document and compare passage of salmonids under the proposed flow treatments. These results will then be compared to annual passage counts, improvements to adult lamprey passage, and subsequently presented to the HCP Coordinating Committee for review.

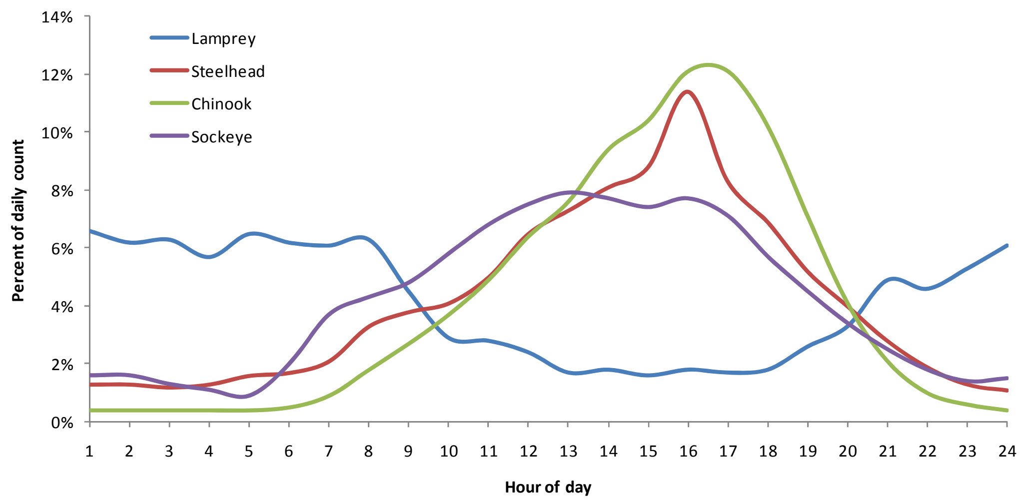

Figure 4. Frequency of fish observations at Wells Dam count stations by hour and species, 1998-2009.

Table 2. Frequency of fish observations at Wells Dam count stations by hour and species, 1998-2009. Hours of above-average passage are shaded, with peak hours in bold red font.

	Lamprey		Steelhead		Chinook		Sockeye	
Hour	Count	Percent	Count	Percent	Count	Percent	Count	Percent
H-01	217	**6.6%**	1,158	1.3%	1,780	0.4%	8,718	1.6%
H-02	204	6.2%	1,155	1.3%	1,603	0.4%	8,666	1.6%
H-03	206	6.3%	1,113	1.2%	1,518	0.4%	7,153	1.3%
H-04	188	5.7%	1,168	1.3%	1,428	0.4%	5,722	1.1%
H-05	214	6.5%	1,439	1.6%	1,602	0.4%	4,702	0.9%
H-06	204	6.2%	1,513	1.7%	2,191	0.5%	10,673	2.0%
H-07	199	6.1%	1,894	2.1%	3,727	0.9%	20,020	3.7%
H-08	206	6.3%	2,974	3.3%	7,145	1.8%	22,882	4.3%
H-09	148	4.5%	3,465	3.8%	11,097	2.7%	25,392	4.8%
H-10	95	2.9%	3,759	4.1%	15,257	3.7%	31,041	5.8%
H-11	93	2.8%	4,564	5.0%	20,007	4.9%	36,173	6.8%
H-12	79	2.4%	5,932	6.5%	26,140	6.4%	39,894	7.5%
H-13	54	1.7%	6,666	7.3%	31,065	7.6%	41,990	**7.9%**
H-14	58	1.8%	7,439	8.1%	38,173	9.4%	41,164	7.7%
H-15	51	1.6%	8,022	8.8%	42,478	10.4%	39,814	7.4%
H-16	59	1.8%	10,413	**11.4%**	49,258	**12.1%**	41,068	7.7%
H-17	57	1.7%	7,616	8.3%	49,155	12.1%	37,745	7.1%
H-18	60	1.8%	6,282	6.9%	41,629	10.2%	30,724	5.7%
H-19	86	2.6%	4,765	5.2%	28,746	7.1%	23,927	4.5%
H-20	107	3.3%	3,621	4.0%	16,717	4.1%	18,280	3.4%
H-21	159	4.9%	2,528	2.8%	8,500	2.1%	13,422	2.5%
H-22	151	4.6%	1,707	1.9%	4,103	1.0%	9,831	1.8%
H-23	174	5.3%	1,158	1.3%	2,343	0.6%	7,694	1.4%
H-24	201	6.1%	1,036	1.1%	1,822	0.4%	7,782	1.5%
Total	3,270	100%	91,387	100%	407,484	100%	534,477	100%
Average	136	4.2%	3,808	4.2%	16,979	4.2%	22,270	4.2%

DIDSON Setup

DIDSON units will be deployed inside the collection gallery of both fishways by commercial divers. The units will be fastened to a variable-angle metal bracket bolted to a rigid structure within the gallery. Once the brackets are in place, the diver will be in communication with the DIDSON operator on deck to test different aiming angles to ensure sufficient coverage of the fishway entrances. The diver will secure the bracket in place when the optimal aiming angle is identified. The diver will then secure the DIDSON cable up along the gallery wall to the deck. The topside DIDSON system components (DIDSON control box, laptop computer, and external hard drive) will be housed in a ventilated environmental box and powered with 110 VAC. The laptops will have Internet access and software that will allow for remote monitoring of the systems for functionality. Each DIDSON unit will be oriented 90^o from the typical orientation so the 29^o field-of-view component will spread vertically along the fishway entrances to cover the entire width as well as the inside edges of the entrances. This will allow for a high-resolution assessment of lamprey passage in their most critical position for completion of entry into the fishways.

Data Collection, Processing, and Statistical Design

The DIDSON systems will run continuously throughout the monitoring period as determined by historical records, prevailing river conditions, and downstream counts. The DIDSON data acquisition software will record for six-hour periods each night throughout the study at a rate of 10 frames per second in consecutive 10-minute files. All data files will be recorded directly to 1 GB external hard drives. Data will be extracted daily and archived.

Data processing will involve the use of data reduction functions and algorithms included in the DIDSON data processing software. The program initially entails application of a subtraction algorithm that will eliminate all static background features. A motion detector function based on a user-defined intensity threshold and minimum cluster size will subsequently reduce raw data files to a second data set including only fish passage events. The resulting data set will then be manually reviewed using the DIDSON data playback software. This process works much like reviewing video data with a VCR, with controls for playback speed, forward, reverse, and pause. The processor will review the data and note the location (east or west entrance), date, and time of each lamprey sighting event. Each lamprey approach and successful entry will be tallied, and other fine-scale behavioral observations will also be noted. These variables will be summed on an hourly and nightly basis for calculation of relative entrance success estimates.

Daily trials will be conducted to test attraction and relative entrance success of adult lampreys under three alternative entrance velocities (equal treatments on both fishways). The trials will be conducted in a randomized block design using ten blocks of three-day duration each. The three alternative flow treatments will be randomized to the three days within each block (Figure 5). Counts will be performed using a DIDSON between the hours of 21:00 and 01:00 when lampreys are active at the fishway entrances. Flow treatments will be changed with equal time during each trial to maximize the opportunity for flow conditions and lamprey behavior to adjust to the new hydraulic conditions.

Attraction[7] will be measured as the number of lampreys that enter the field of view of the DIDSON mounted inside of the fishway. Entrance will be measured as the numbers of lamprey that are seen moving forward into the fishway. Relative entrance success will be determined as the proportion of lampreys that enter compared to the number attracted, relative to treatment level.

	Block 1			Block 2			Block 3			Block 4			Block 5		
	M	H	L	M	H	L	H	M	L	L	H	M	L	M	H
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

	Block 6			Block 7			Block 8			Block 9			Block 10		
	L	M	H	M	H	L	M	H	L	L	M	H	L	H	M
Day	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

Figure 5. Schematic of proposed randomized block design with blocks and treatment order within blocks (H = high, M = moderate, L = low flow).

The tests of equal attraction and equal entrance success will be performed using a two-way analysis of deviance (ANODEV) for randomized block design (Table 3). The analysis will be based on a Poisson error distribution for count data and a log-link assuming multiple effects. An *F*-test will be used to test the null hypothesis of equality,

$$\mathrm{H_o}: \mu_1 = \mu_2 = \mu_3$$

vs.

$$\mathrm{H_a}: \mu_1 \neq \mu_2 \neq \mu_3 .$$

Separate tests of $\mu_1 = \mu_2$ and $\mu_1 = \mu_3$ comparing standard conditions (i.e., high flow) to moderate and low flows will be performed using 1 degree of freedom contrasts based on a *t*-statistic.

Table 3. Degree of freedom table for the analysis of deviance (ANODEV) of the proposed randomized block design.

Source	DF	DEV	MDEV	*F*	*P*
$\mathrm{Total_{Cor}}$	29				
Blocks	9	BLDEV			
Treatments	2	TDEV	TMDEV	$F_{2,18}$ = TMDEV/EMDEV	*P*
Error	18	ERDEV	EMDEV		

[7] The term “attraction” should not be confused with the terminology used in radio-telemetry studies, referring to a metric that quantifies the proportion of fish in a tailrace that ultimately approach a fishway entrance.

Scheduling and Budget

The *Assessment of Adult Pacific Lamprey Behavior in Response to Temporary Velocity Reductions at Fishway Entrances* will begin with DIDSON setup and coordination with Wells Dam operators during the week of August 10th, 2009. Blocks of temporary entrance velocity reductions will begin between August 21st and August 26th, depending on current river conditions and counts at downstream projects. Nightly treatments and monitoring will continue for 30 days. Data processing and analysis will continue with downloads, with monthly updates provided beginning September 30th. A final report will be provided no later than January 31st. The total cost for this project will be no greater than $112,950.

References

Aquatic SWG. 2009. Third meeting; May 13th, 2009. Including presentations: *Fishway Entrance Hydraulics* (R. Wielick, P.E. and D. Allison, P.E. Jacobs Civil Inc. Hydro Division); *Dual-Frequency Identification Sonar* (P. Johnson, M.S. LGL Limited environmental research associates); *Design of Experiment* (J. Murauskas, M.S. Public Utilities District No. 1 of Douglas County).

Beamish, R.J. 1980. Adult biology of the river lamprey (Lampetra ayresii) and the Pacific lamprey (Lampetra tridentata) from the Pacific coast of Canada. Canadian Journal of Fisheries and Aquatic Sciences 37: 1906-1923.

Beamish, R.J. and C.D. Levings. 1991. Abundance and freshwater migrations of the anadromous parasitic lamprey, Lampetra tridentata, in a tributary of the Fraser River, British Columbia. Canadian Journal of Fisheries and Aquatic Science. 48: 1250-1263.

Belcher, E. O., B. Matsuyama and G.M. Trimble. 2001. Object identification with acoustic lenses. . Page 6-11 *in* Conference Proceedings MTS/IEEE Oceans, volume 1, session 1. . Honolulu, Hawaii, 5-8 November 2001.

Bergstedt, R.A., R.B. McDonald, K.M. Mullett, G.M. Wright, W.D. Swink, and K.P. Burnham. 2003. Mark-recapture Population Estimates of Parasitic Sea Lampreys (*Petromyzon marinus*) in Lake Huron. Journal of Great Lakes Research 29:226-239.

BioAnalysts. 2000. Status of Pacific lamprey in the mid-Columbia region. Rocky Reach Hydroelectric Project, FERC No. 2145. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Close, D., M. Fitzpatrick, H. Li, B. Parker, D. Hatch, and G. James. 1995. Status report of the Pacific Lamprey (Lampetra tridentata) in the Columbia River basin. Project No. 94-026, Contract No. 95BI39067. Report to the US Department of Energy, Bonneville Power Administration, Portland Oregon. USA.

Close, D., M. Fitzpatrick, and H. Li. 2002. The ecological and cultural importance of a species at risk of extinction, Pacific Lamprey. North American Journal of Fisheries Management 27(7):19-25.

Close, D.A., M.S. Fitzpatrick, C.M. Lorion, H.W. Li, and C.B. Schreck. 2003. Effects of intraperitoneally implanted radio transmitters on the swimming performance and physiology of Pacific lamprey. North American Journal of Fisheries Management 23:1184-1192.

DART (Data Access in Real Time). 2008. Columbia River Adult Passage (USACE, NWD). Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, Seattle. Retrieved February 2008 at http://www.cbr.washington.edu/dart/.

Dauble, D.D., R.A. Moursund, and M.D. Bleich. 2006. Swimming behaviour of juvenile Pacific lamprey, Lampetra tridentata. Environmental Biology of Fishes 75:167-171.

DCPUD. 2008. Aquatic Settlement Agreement. Wells Hydroelectric Project, FERC Project No. 2149. Enacted by the Public Utility District No. 1 of Douglas County, Washington; State of Washington Department of Fish & Wildlife; State of Washington Department of Ecology; Confederated Tribes of the Colville Reservation; and Confederated Tribes and Bands of the Yakama Nation.

DCPUD and LGL. 2008. Survival and rates of predation for juvenile Pacific lamprey migrating through the Wells Hydroelectric Project (juvenile lamprey study). Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, Washington.

Fay, R. R. and A. M. Simmonds. 1999. . The sense of hearing in fishes and amphibians. In: Comparative hearing: fishes and amphibians. Fay, R. R. and A. N. Popper (eds). Springer-Verlag, New York. Pp. 269-318.

Fish Passage Center (FPC). 2008. Pertinent data for fish facility inspections. Retrieved 19 December from www.fpc.org/documents/Fishway_Inspection_Reports.html.

Hayes, D.B., C. Paola Ferreri, and W.W. Taylor. 1996. Active Fish Capture Methods. Pages 193-220 in B.R. Murphy and D.W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Hubert, W.A. 1996. Passive Capture Techniques. Pages 157-192 in B.R. Murphy and D.W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Jackson, A.D., D.R. Hatch, B.L. Parker, M.S. Fitzpatrick, D.A. Close, and H. Li. 1997. Pacific lamprey research and restoration: Annual report, 1997. Prepared for the Bonneville Power Administration, Division of Fish and Wildlife. Project Number 1994-026.

Johnson, G. E., F. Khan, J. B. Hedgepeth, R. P. Mueller, C. L. Rakowski, M. C. Richmond, J. A. Serkowski and J. R. Skalski. 2006. Hydroacoustic evaluation of juvenile salmonid passage at The Dalles Dam sluiceway, 2005. Report submitted to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon by Battelle, Pacific Northwest National Laboratory, Richland, Washington.

Katopodis, C. 1992. Introduction to fishway design. Freshwater Institute, Central and Arctic Region. Department of Fisheries and Oceans, Winnipeg, Manitoba.

Keefer, M.L., C.T. Boogs, C.A. Peery, and M.L. Moser. 2009. Adult Pacific lamprey migration in the lower Columbia River: 2007 radiotelemetry and half-duplex PIT tag studies. Report for study code ADS-P-00-8, prepared for the U.S. Army Corps of Engineers, Portland District.

Le, B. and S. Kreiter. 2008. An assessment of adult Pacific lamprey spawning within the Wells Project (lamprey spawning assessment). Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, Washington.

LGL and DCPUD. 2008. Adult Pacific lamprey passage and behavior study (Aquatic Issue 6.2.1.3). Wells Hydroelectric Project, FERC No. 2149. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, Washington.

Mesa, M.G., J.M. Bayer, J.G. Seelye, and L.K. Weiland. 2001. Swimming performance and exhaustive stress in Pacific lampreys (Lampetra tridentata): implications for upstream migrations past dams. Draft Annual Report to U.S. Army Corps of Engineers, Portland District, Portland, OR.

Mesa, M.G., J.M. Bayer and J.G. Seelye. 2003. Swimming performance and physiological responses to exhaustive exercise in radio-tagged and untagged Pacific lampreys. Transactions of the American Fisheries Society 132: 483 - 492.

Mesa, M.G. and Moser, M. 2004. Passage considerations for Pacific lamprey. Prepared by the Columbia River Basin Lamprey Technical Workgroup, September 2004. Endorsed by the Columbia Basin Fish and Wildlife Authority, October 2005.

Moser, M.L., A.L. Matter, L.C. Stuehrenberg, and T.C. Bjornn. 2002a. Use of an extensive radio receiver network to document Pacific Lamprey (Lampetra tridentata) entrance efficiency at fishways in the Lower Columbia River, USA. Hydrobiologia 483:45-53.

Moser, M.L., P.A. Ocker, L.C. Stuehrenberg, and T.C. Bjornn. 2002b. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA. Transactions of the American Fisheries Society 131:956-965.

Moser, M. and D. Close. 2003. Assessing Pacific lamprey status in the Columbia River Basin. Northwest Science 77(2):116-125.

Moser, M.L., R.W. Zabel, B.J. Burke, L.C. Stuehrenberg, and T.C. Bjornn. 2005. Factors affecting adult Pacific lamprey passage rates at hydropower dams: using “time to event” analysis of radio telemetry data. Pages 61-70 in M.T. Spedicato, G. Lembo, and G. Marmulla, editors. Aquatic telemetry: advances and applications. Proceedings of the Fifth Conference on Fish Telemetry held in Ustica, Italy 9-13 June 2003.

Moser, M.L, J.M. Butzerin, and D.B. Dey. 2007. Capture and collection of lampreys: the state of the science. Reviews in Fish Biology and Fisheries 17:45-56.

Moursund, R.A., T.J. Carolson, and R.D. Peters. 2003. A fisheries application of a dual-frequency identification sonar acoustic camera. ICES Journal of Marine Science 60(3):678-683.

Mullett, K.M., J.W. Heinrich, J.V. Adams, R.J. Young, M.P. Henson, R.B. McDonald, and M.F. Fodale. 2003. Estimating Lake-wide Abundance of Spawning-phase Sea Lampreys (*Petromyzon marinus*) in the Great Lakes: Extrapolating from Sampled Streams Using Regression Models. Journal of Great Lakes Research 29:240-252.

Nass, B.L., C. Sliwinski, D. Robichaud. 2005. Assessment of Adult Pacific Lamprey Migratory Behavior at Wells Dam Using Radio-telemetry Techniques, 2004. Report prepared by LGL Limited, Sidney, B.C. Canada, for Public Utility District No. 1 of Douglas County, WA.

Page, L.M. and B.M Burr. 1991. Peterson Field Guides: Freshwater Fishes. Houghton Mifflin Company, New York, NY.

Peery, C.A., M.L. Moser, and N. Adams. 2006. Research Pre-Proposal: Evaluation of adult Pacific lamprey passage success at McNary and lower Snake River dams – 2007. Study Code: ADS-P-00-8. Submitted to U.S. Army Corps of Engineers, Walla Walla District.

Ploskey, G.R., M.A. Weiland, C.R. Schilt, P.N. Johnson, M.E. Hanks, D. Patterson, J.R. Skalski and J. Hedgepeth. 2005. Hydroacoustic evaluation of fish passage through Bonneville Dam in 2004. Final Report.

Potter, I.C. and H.S. Gill. 2003. Adaptive radiation of lampreys. Journal of Great Lakes Research 29(Supplement 1):95-112.

Robichaud, D., B. Nass, and DCPUD. 2009. Adult Pacific lamprey passage and behavior study (adult lamprey passage study). Wells Hydroelectric Project, FERC No. 2149. Second year final report. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, Washington. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, Washington.

Starke, G. and J. Dalen. 1995. Pacific Lamprey (Lampetra tridentata) passage patterns past Bonneville Dam and incidental observations of lamprey at the Portland District Columbia River dams in 1993. U.S. Army Corps of Engineers, Cascade Locks, Oregon. USA.

Stevenson, J.R., P. Westhagen, D. Snyder, J. Skalski, and A. Giorgi. 2005. Evaluation of Adult Pacific Lamprey Passage at Rocky Reach Dam Using Radio-telemetry Techniques, 2004. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

Appendix 1. LGL budget for 30 days of monitoring adult lampreys at Wells Dam using DIDSON, 2009.

Tasks/Personnel	Sr. Research Scientist	Local Technician			Total
Personnel Time					
1. Planning, Design Refinement, Permitting	16				
2. Deploy and Test DIDSON Systems	16	16			
3. Operate and Monitor DIDSON Systems / Data Downloading	40	180			
4. DIDSON Demobilization	24				
5. Data Management and Transfer	16	30			
6. Data Processing and Analysis	160				
7. Reporting	120				
8. Project Management	16				
Total Hours	408	226			
Hourly Rate	$115	$50			
Personnel Costs					
1. Planning, Design Refinement, Permitting	$1,840	$0			$1,840
2. Deploy and Test DIDSON Systems	$1,840	$800			$2,640
3. Operate and Monitor DIDSON Systems / Data Downloading	$4,600	$9,000			$13,600
4. DIDSON Demobilization	$2,760	$0			$2,760
5. Data Management and Transfer	$1,840	$1,500			$3,340
6. Data Processing and Analysis	$18,400	$0			$18,400
7. Reporting	$13,800	$0			$13,800
8. Project Management	$1,840	$0			$1,840
Total Personnel Costs	**$46,920**	**$11,300**			**$58,220**
Disbursements					
At Cost:					
Ground Transport from and to N. Bonneville (Personal Vehicle Mileage)		8	days	$150	$1,200
Ground Transport local travel (Personal Vehicle Mileage)		10	days	$10	$100
Visiting Accomodation		11	days	$91	$1,001
Meals		11	days	$39	$429
DIDSON System Lease (2 @ 1 month each)		2	months	$12,000	$24,000
DIDSON Shipping		4	units	$300	$1,200
Data Shipping		4	units	$50	$200
Field materials and supplies		2	units	$1,400	$2,800
Diver Services		3	days	$6,000	$18,000
Laptop computers for operating DIDSON systems		2	units	$1,500	$3,000
Internet, Remote PC software		2	months	$150	$300
DIDSON data storage		10	units	$150	$1,500
Office (email, copying, phone, etc)		1		$1,000	$1,000
Total Disbursements					**$54,730**
Grand Total					**$112,950**

Parametrix, Inc. 2009. Continued Monitoring of DO, pH, and Turbidity in the Wells Forebay and Lower Okanogan River (DO, pH, and Turbidity Study). Wells Hydroelectric Project, FERC No. 2149. Initial Study Report required by FERC. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA.

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CONTINUED MONITORING OF DO, pH, AND TURBIDITY IN THE WELLS FOREBAY AND LOWER OKANOGAN RIVER
(DO, pH and Turbidity Study)

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

FINAL REPORT
NOT REQUIRED BY FERC

March 2009

Prepared by:
Parametrix, Inc.
Bellevue, Washington

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509)884-7191
E-Mail: relicensing@dcpud.org

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ABSTRACT

The current Wells Hydroelectric Project (Wells Project) license will expire on May 31, 2012. As part of the Wells Project relicensing process, the Public Utility District No. 1 of Douglas County (Douglas PUD) is required to obtain a water quality certificate pursuant to Section 401 of the Clean Water Act. As part of the 401 certification process, the Washington State Department of Ecology (Ecology) must determine whether the Wells Project meets state water quality standards, including the numeric standards, for dissolved oxygen (DO), pH, and turbidity.

The Aquatic Resource Work Group (Aquatic RWG), which is comprised of interested parties (including Ecology) and Douglas PUD, was formed for the purpose of identifying issues that may require study during the Wells Project relicensing. The Aquatic RWG proposed a study to collect additional DO, pH, and turbidity data from within the Wells Project. The goal of this study was to obtain required DO, pH, and turbidity information for the Wells Dam forebay and lower Okanogan River, both above and within the Wells Project boundary. The information gathered from this monitoring effort will assist Ecology in determining whether the Project, as proposed to be operated under the new license, will meet the numeric criteria for DO, pH and turbidity.

A Quality Assurance Project Plan (QAPP), revised to incorporate review comments from Ecology, identified the organization, schedule, data quality objectives, sampling design, field and laboratory procedures, quality control, and data management and reporting parameters required to implement the DO, pH, and turbidity study proposed by the Aquatic RWG (Parametrix, 2008a).

Three Hydrolab Minisonde5 instruments equipped with DO, pH, and turbidity sensors were installed throughout the lower Okanogan River and began recording data at 30-minute intervals on May 5, 2008. Protective instrument housings were attached to pilings at the Malott Bridge (River Mile [RM] 17.0, above the Project boundary), Monse Bridge (RM 5.0) and Highway 97 Bridge (RM 1.3). Similar instrumentation, operating in the Wells Dam forebay at RM 515.6, began recording DO and pH measurements at 1-hour intervals on May 30, 2008, and a Global Water WQ750 sensor began monitoring turbidity at 5-minute intervals on June 3, 2008. These forebay instruments complete the network of four continuous water quality monitoring locations that were operated until late October 2008.

Twelve Okanogan River instrument servicing events were conducted over the monitoring period. Each servicing event involved downloading data, calibrating and performing maintenance on the instruments, performing quality control checks (including Winkler titrations for dissolved oxygen determination) and replacing batteries. High river flows and woody debris accumulations at times precluded access to some of the instruments in the Okanogan River during two of the twelve servicing events. Battery failures and an electrical short in a data logger also caused some data gaps.

In general, DO measurements in the Okanogan River remained above the 8.0 mg/L water quality criterion throughout the monitoring season, with infrequent recordings (28 of 165 days at

Highway 97) below 8.0 mg/L occurring in July and August as snowmelt runoff receded and both air and water temperatures increased. The lowest minimum daily DO on the Okanogan River during this period was observed most frequently at Malott upstream of the Wells Project boundary. Project effects on DO concentrations in the Okanogan River were not evident as incoming DO concentrations closely resemble those within the inundated portions of the Okanogan River. Changes in background minimum DO levels at Malott have a strong and significant linear relationship ($P < .0001$) with minimum values recorded at both Monse and the Highway 97 Bridge (R^2 of 0.92 and 0.72, respectively). These results indicate that there is no statistically significant difference between minimum DO measurements collected above the Project (Malott) and within the Project (lower Okanogan River). Further, there is no statistical difference among DO measurements by location. Median DO levels during the peak months of concern (July, August, and September) are equal to or greater than background values observed at Malott.

DO concentrations at Wells Dam forebay monitoring station decreased from June through mid-August, although concentrations remained well above the minimum numeric water quality criterion until early October when a brief and minor excursion, thought to be instrument related, below 8.0 mg/L was recorded over an 4 day period (7.8 mg/L minimum value overall average).

The majority of observed pH exceedances were within + 0.3 units of the criteria (6.5 to 8.5) and occurred at Malott (18 of 123 days, or 14.6%), above the Wells Project boundary. There were nine excursions of pH above the 6.5 to 8.5 range of water quality criteria and no excursion below the standard. On all but one of the nine exceedance event (May 6^{th}), the pH was higher at Malott, upriver from the Project's influence, compared to Monse or Highway 97. On May 6^{th}, the pH at Monse exceeded readings at Malott, but only by 0.06 units, well within the water quality allowance for human caused conditions.

It is not clear what effect, if any, the Wells Project may have had on turbidity. No turbidity data from the Wells forebay are available from this study, due to instrumentation failure. Limited data availability from locations upstream of the Wells Project boundary prevented comparisons to incoming waters on the Okanogan River during high turbidity events. However, given that elevated turbidity values coincided with increasing spring temperatures, river flow and precipitation, these observations are believed to be a product of annual snowmelt and runoff. Turbidity levels exceeding 5 NTU (over background when the background is 50 NTU or less) at Malott were inconsistent with readings collected at both Monse (5 of 122 comparable days, or 4%) and Highway 97 (8 of 165 comparable days, or 5%), suggesting that such events are not widespread or persistent within the Wells Project.

1.0 INTRODUCTION

1.1 General Description of the Wells Hydroelectric Project

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 1.1-1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE); and 42 miles upstream from the Rocky Reach Hydroelectric Project owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for Public Utility District No. 1 of Douglas County (Douglas PUD). It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a top of dam elevation of 795 feet above mean sea level (msl).

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 (Figure 1.1-1).

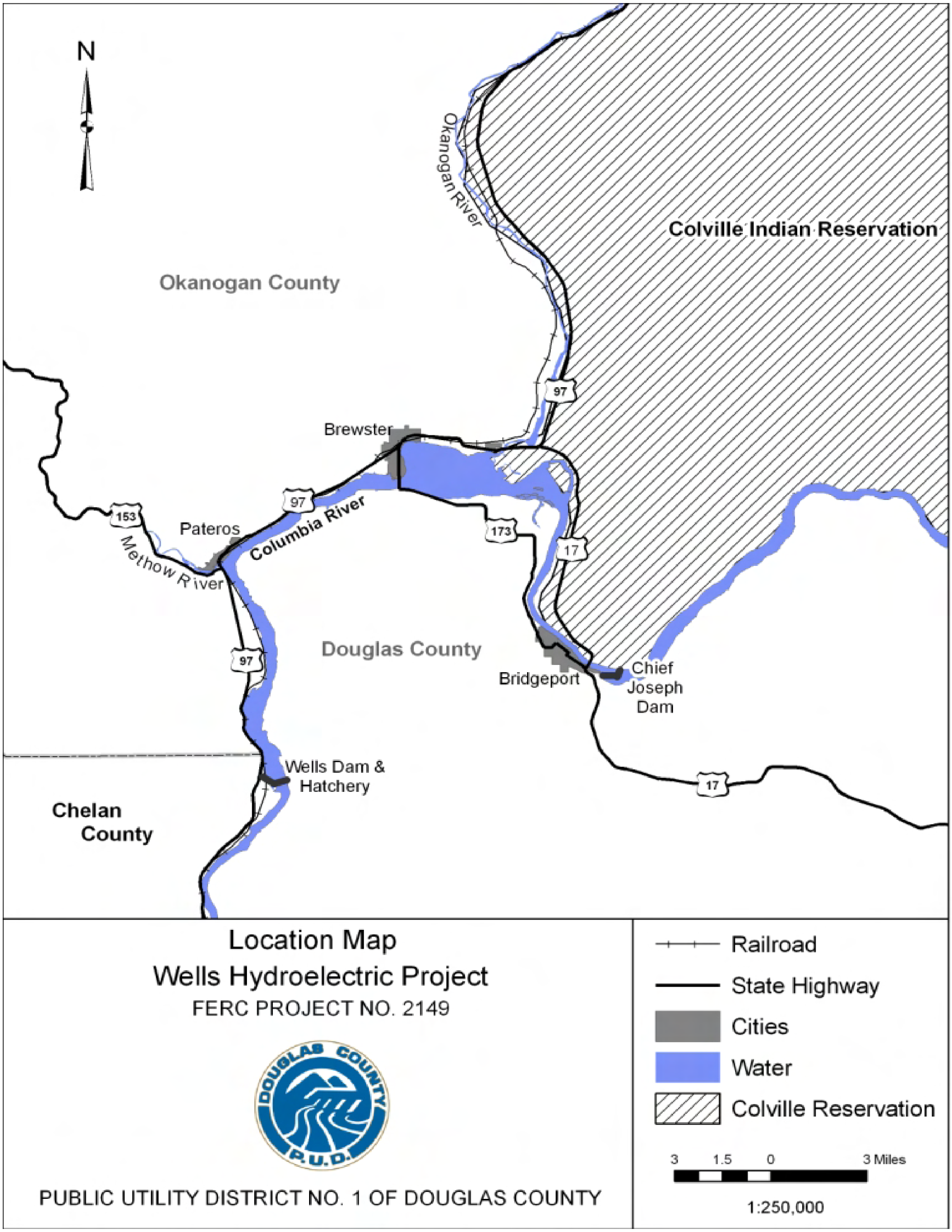


Figure 1.1-1 Location Map of the Wells Project

1.2 Relicensing Process

The current Wells Project license will expire on May 31, 2012. Douglas PUD is using the Integrated Licensing Process (ILP) promulgated by Federal Energy Regulatory Commission (FERC) Order 2002 (18 CFR Part 5). Stakeholders, including representatives from state and federal agencies, tribes, local governments, non-governmental organizations and the general public have participated in the Wells Project ILP, from a very early stage, to identify information needs related to the relicensing of the Wells Project.

In August 2005, Douglas PUD initiated a series of Resource Work Group (RWG) meetings with stakeholders regarding the upcoming relicensing of the Wells Project. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to identify resource issues, and to develop preliminary study plans prior to filing the Notice of Intent (NOI) and Pre-Application Document (PAD). The RWGs were formed to discuss issues related to the Wells Project and its operations, identify information needs, and develop agreed-upon study plans.

The primary goals of the RWGs were to identify resource issues and potential study needs in advance of Douglas PUD filing the NOI and PAD. Through 35 meetings, each RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWGs' efforts to apply the FERC's seven study criteria to mutually determine the applicability of each individual Issue Statement. Agreed-Upon Study Plans are the finished products of the informal RWG process.

Douglas PUD submitted the NOI and PAD to the FERC on December 1, 2006. The PAD included the RWGs' 12 Agreed-Upon Study Plans. The filing of these documents initiated the relicensing process for the Wells Project under the FERC's regulations governing the ILP.

On May 16, 2007, Douglas PUD submitted a Proposed Study Plan (PSP) Document. The PSP Document consisted of the Applicant's Proposed Study Plans, Responses to Stakeholder Study Requests, and a schedule for conducting the Study Plan Meeting. The ILP-required Study Plan Meeting was conducted on June 14, 2007. The purpose of the Study Plan Meeting was to provide stakeholders with an opportunity to review and comment on Douglas PUD's PSP Document, to review and answer questions related to stakeholder study requests and to attempt to resolve any outstanding issues with respect to the PSP Document.

On September 14, 2007, Douglas PUD submitted a Revised Study Plan (RSP) Document. The RSP Document consisted of a summary of each of Douglas PUD's RSPs and a response to stakeholder comments on the PSP Document.

On October 11, 2007, the FERC issued its Study Plan Determination based on its review of the RSP Document and comments from stakeholders. The FERC's Study Plan Determination required Douglas PUD to complete 10 of the 12 studies included in its RSP Document. The Dissolved Oxygen (DO), pH, and Turbidity Study was not required by the FERC. However, Douglas PUD has opted to complete this study to better prepare for the 401 Water Quality Certification process conducted by the Washington State Department of Ecology (Ecology) and to fulfill its commitment to the RWGs who collaboratively developed the 12 Agreed-Upon Study Plans with Douglas PUD. On October 15, 2008, Douglas PUD filed with the FERC the ISR Document that contained final reports for eight of the 12 studies and contained interim progress reports for four of the 12 studies. The ISR Document included results from all ten of the studies required by the FERC in the October 11, 2007 Study Plan Determination. The ISR Document also included results from two studies voluntarily conducted by Douglas PUD for the reasons stated above. On November 24, 2008, Douglas PUD filed a letter correcting a water temperature figure within the original ISR Document. On December 2, 2008, Douglas PUD filed the final Traditional Cultural Property Study for the Wells Project, which was prepared by the Confederated Tribes of the Colville Reservation under a contract with Douglas PUD.

The deadline for stakeholder comment on the ISR Document was December 15, 2008 pursuant to the approved Process Plan and Schedule for the Wells Project. Comments were filed by the City of Pateros on November 7, 2008 and by the City of Brewster on December 5, 2008.

On January 14, 2009, Douglas PUD filed a letter containing its responses to the comments from the cities on the ISR Document and proposed revisions to the schedule for the Wells ILP. On February 4, 2009, the FERC issued a determination on the requests for modification to the Wells Study Plan and on Douglas PUD's proposed revisions to the schedule. The FERC concluded that there was no need to modify the Wells Study Plan. The FERC also approved Douglas PUD's proposed modifications to the Wells ILP schedule.

This study was conducted voluntarily by Douglas PUD based on the agreed-upon study plan filed with the FERC in the Revised Study Plan. This report provides the final results from the DO, pH and Turbidity Study collected from May 5 through October 29, 2008.

This report is the final report for the DO, pH and Turbidity Study.

2.0 GOALS AND OBJECTIVES

The goal of this study was to obtain required DO, pH, and turbidity information for the Wells Dam forebay and lower Okanogan River, both above and within the Wells Project boundary. The information gathered from this monitoring effort will assist Ecology in determining whether the Project, as proposed to be operated under the new license, will meet the numeric criteria for DO, pH and turbidity.

3.0 STUDY AREA

The study area consists of waters within the Wells Project with a particular emphasis on the Wells Dam forebay and the lower Okanogan River from its confluence with the Columbia River up to RM 17.0 (Figure 1.1-1).

4.0 BACKGROUND AND EXISTING INFORMATION

DO levels are a critical variable for aquatic life and affect the chemical dynamics of a water body. DO levels are influenced by a suite of factors including the level of biological activity in the water, turbulence, and temperature (EES Consulting, 2006).

The term pH is used to describe the acidity or hydrogen ion content of a liquid. Factors influencing the pH of a water body include the chemical composition of soils in the watershed, photosynthetic activity, pollutants, and respiration of organisms (EES Consulting, 2006). Levels of pH which are extremely acidic or basic can adversely impact aquatic life and may indicate that other pollutants are present within a watershed.

Turbidity is the measure of the light scattering from suspended particles in water that reduce its transparency. After light enters water, it is absorbed, reflected or refracted by dissolved organic substances, pigmented (phytoplankton) and colored particulates, inorganic particulates, and by the water itself. Transparency also regulates primary productivity and trophic dynamics which ultimately can affect fish populations. There is a direct relationship between turbidity, water transparency and the depth at which macrophytes grow (EES Consulting, 2006). Factors and activities affecting water quality in the Wells Project include: (1) nonpoint source pollution from agricultural runoff and irrigation return flow,(2) point source pollution from mines, municipal and industrial sources upriver and outside of the Wells Project boundary, (3) depletion of in-stream flows from water diversions and consumptive uses, (4) watershed management in the tributaries and Upper Columbia River above Wells Dam, (5) the operation of large water storage facilities located upriver of Wells Dam on the mainstem Columbia and in the Okanogan watershed, (6) effects related to operations of the Wells Project, and (7) elevated sediment concentrations due to rain and snowmelt runoff.

Under section 303(d) of the Clean Water Act (CWA), states are required to list all water body segments that do not meet the state water quality standards. Within the Wells Project boundary, specific water reaches are on the state's 303(d) list for various parameters. However, no river segments within the Project boundary are on Ecology's current 303(d) list for DO, pH or turbidity (Ecology, 2008a).

Douglas PUD and state and federal agencies have implemented water quality monitoring programs to collect information within or adjacent to the Wells Project. The programs collect a variety of biological, chemical, and physical water quality parameters and typically include the three parameters of interest (DO, pH, and turbidity). Data collected from these monitoring activities have indicated that waters within the Wells Project are generally in compliance with the state standards. During the infrequent times when Wells Project waters do not meet numeric criteria for these parameters, waters entering the Wells Project are typically out of compliance (EES Consulting 2006).

4.1 Aquatic Resource Work Group

As part of the relicensing process for the Wells Project, Douglas PUD established an Aquatic RWG which began meeting informally in November, 2005. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to collaboratively identify potential resource issues related to Project operations and relevant to relicensing, and to develop preliminary study plans to be included in the PAD (DCPUD, 2006).

Through a series of meetings, the Aquatic RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWG's efforts to review the existing project information and to determine whether an issue met the FERC's seven criteria and would be useful in making future relicensing decisions. Agreed-Upon Study Plans are the finished products of the informal RWG process.

The Issue Statement and Issue Determination Statement described below were included in the PAD (section number included) filed with the FERC on December 1, 2006:

4.1.1 Issue Statement (PAD Section 6.2.1.7)

Project operations may affect compliance with DO, pH and turbidity standards in the Wells Project.

4.1.2 Issue Determination Statement (PAD Section 6.2.1.7)

The Wells Project may have an effect on compliance with the standards for DO, pH and turbidity. Currently, Douglas PUD has collected water quality data toward the evaluation of meeting the numeric criteria for these parameters. Initial data collected during the 2005 baseline limnological assessment indicates that Douglas PUD is in compliance with the Washington State standard for these parameters. However, additional monitoring is required to make a final determination.

The resource work group agreed that a study during the two-year ILP study period would be valuable. The study was to focus on the collection of DO, pH and turbidity in the Wells Project especially focusing on data collection from the Okanogan River and at Wells Dam.

4.2 Project Nexus

Ecology is responsible for the protection and restoration of the state's waters. Ecology has adopted water quality standards that set limits on pollution in lakes, rivers, and marine waters in order to protect water quality. On July 1, 2003, Ecology completed the first major overhaul of the state's WQS in a decade. A significant revision presented in the 2003 water quality standards classifies fresh water by actual use, rather than by class as was done in the 1997 standards. These revisions were adopted in 2003 and are maintained in the current 2006 standards in order to make the standards less complicated to interpret and provide future flexibility as the uses of a water body evolve.

Under the 2006 WQS, the Wells Project includes designated uses for spawning/rearing (aquatic life), primary contact recreation, and all types of water supply and miscellaneous uses (Ecology, 2006). Numeric criteria to support the protection of these designated uses consist of various physical, chemical, and biological parameters, including the water quality indicators that are the subject of this study: dissolved oxygen (DO), pH, and turbidity. The 2006 WQS for DO, pH, and turbidity are presented below in Section 4.4.

The information resulting from continued monitoring of DO, pH, and turbidity will assist Ecology during the development of any needed licensing requirements resulting from the 401 water certification process.

4.3 Water Quality Standards

Congress passed the CWA in 1972, and designated the U.S. Environmental Protection Agency (EPA) as the administering federal agency. This federal law requires that a state's WQS protect the surface waters of the U.S. for beneficial or designated uses, such as recreation, agriculture, domestic and industrial use, and habitat for aquatic life. Any state WQS, or amendments to these standards, do not become effective under the CWA until they have been approved by EPA. Ecology is responsible for the protection and restoration of the State's waters. Ecology establishes WQS that set limits on pollution in lakes, rivers, and marine waters in order to protect water quality and specified designated and potential uses of such water bodies. These standards are found at WAC 173-201A.

4.3.1 Water Quality Standards for the Project

The Wells Project includes the mainstem Columbia River above Wells Dam, one mile of the mainstem Columbia River below Wells Dam, the Methow River (up to RM 1.5) and the Okanogan River (up to RM 15.5).

Under the 2006 WQS, the Project includes designated uses for spawning/rearing (aquatic life), primary contact recreation, and all types of water supply and miscellaneous uses (Ecology, 2006). Numeric criteria to support the protection of these designated uses consist of various physical, chemical, and biological parameters, including the water quality indicators that are the subject of this study: dissolved oxygen, pH, and turbidity.

4.3.1.1 Dissolved Oxygen

Dissolved Oxygen criteria are measured in milligrams per liter (mg/L). Based upon criteria developed by Ecology, DO concentrations shall not be under the 1-day minimum of 8.0 mg/L, this being defined as the lowest DO reached on any given day.

When DO in a waterbody is lower than the 8.0 mg/L criteria (or within 0.2 mg/L of the criteria) and that condition is due to natural conditions, then human actions considered cumulatively may not cause the DO of that water body to decrease more than 0.2 mg/L.

Concentrations of DO are not to fall below 8.0 mg/L at a probability frequency of more than once every ten years on average.

DO measurements should be taken to represent the dominant aquatic habitat of the monitoring site. This typically means samples should:

(A) be taken from well mixed portions of rivers and streams.

(B) not be taken from shallow stagnant backwater areas, within isolated thermal refuges, at the surface, or at the water's edge.

4.3.1.2 pH

The pH of a water body is defined as the negative logarithm of the hydrogen ion concentration. Under the WQS, pH measurements shall be in the range of 6.5 to 8.5, with a human-caused variation within the above range of less than 0.5 units.

4.3.1.3 Turbidity

Turbidity is measured in nephelometric turbidity units (NTUs). Turbidity shall not exceed 5 NTU over background when the background is 50 NTU or less; or a 10% increase in turbidity when the background turbidity is more than 50 NTU.

4.4 Douglas PUD Monitoring Activities

In August, 2005, Douglas PUD began monitoring DO and pH in the Wells Dam forebay during the season when the possibility of low DO levels occurring was highest. The results of this monitoring effort indicated that DO levels were not below 8.0 mg/L and pH levels were not outside of the specified range of 6.5 to 8.5, which are the state water quality numeric criteria (Ecology, 2006). In response to requests made by Ecology, Douglas PUD implemented seasonal monitoring for these parameters at hourly intervals at the Wells Dam forebay. Monitoring at the forebay in 2008 began on May 30. The monitoring is performed using a Hydrolab Minisonde deployed at depths that have ranged from 5.08 to 7.76 meters through the 2008 monitoring period.

At Wells Dam, Secchi disk readings are also taken to measure water transparency, which is inversely correlated to turbidity. Sampling occurs daily during the adult fish passage assessment period of May 1 to November 15. Measurements are recorded in feet of visibility and reliable information adhering to a standard protocol has been collected since 1998. During the monitoring period, Secchi disk readings ranged from 2 feet during spring run-off to 16 feet by late summer.

In 2005, Douglas PUD contracted with EES Consulting to conduct a comprehensive limnological investigation of Wells Project waters (EES Consulting, 2006). The year-long study was conducted at nine sites (seven sites in the Columbia River and one site in both the Methow and Okanogan rivers) in order to characterize water quality and seasonal trends in the Wells Project. Water quality sampling was scheduled seasonally with one sample event scheduled for each season. Spring sampling was conducted in May, fall monitoring was conducted in October, and winter sampling occurred in February 2006. Summer sampling was conducted more frequently when water quality exceedances would be more likely and temporal changes more dynamic (July, August and September). Results of the study found DO levels at 1m depth in Wells Project waters increased from upriver to downriver at the sites sampled; the average difference (May through October) was 1.07 mg/L. All surface water measurements had DO values greater than 8.0 mg/L and pH for Wells Project waters generally varied between 7.5 and 8.25, which is slightly above neutral. There were no measured exceedances of the water quality criteria for pH. Turbidity in the Wells Reservoir showed relatively little seasonal variation with an annual average of 0.98 NTUs. Longitudinal variation in turbidity was also minimal. Low turbidity in the reservoir was attributed partially to the large upriver storage reservoir capacity that allows fines to settle out. Turbidity in the Okanogan River was consistently higher than in the Wells Reservoir. Turbidity in the Methow River was higher than in the Wells Reservoir in May (due to sediment load) and in August due to phytoplankton growth. The only turbidity reading over 5 NTUs was in the Methow River during May (EES Consulting 2006).

4.5 Ecology Monitoring Activities

Ecology has conducted monthly water quality monitoring at locations on the Okanogan River near Malott (station 49A070) upriver of the Wells Project boundary at approximately RM 17 and on the Methow River near Pateros (station 48A070) upriver of the Wells Project boundary at approximately RM 5. Both stations are considered "long-term" stations by Ecology and provide reliable information for the quality of water entering the Wells Reservoir from tributary inflow. It is important to note that data collected from these stations are representative of water quality conditions of waters entering the Wells Project boundary. Data are typically collected as grab samples on a monthly basis. A variety of water quality parameters including DO, pH, and turbidity information as well as site compliance are available at http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html. Table 4.5-1 provides the range of values for the parameters of interest observed at the Okanogan River long-term monitoring station since 2001 (Ecology 2008b).

Table 4.5-1 The range of DO, pH and turbidity values observed from monthly grab samples collected upriver of the Wells Project on the Okanogan (RM 17). Data from Ecology long-term monitoring stations 2001-2008.

	DO (mg/L)	pH	Turbidity (NTU)
2001	7.32 to 13.87	7.87 to 8.45	0.8 to 5.5
2002	8.80 to 13.63	7.83 to 8.39	1.0 to 19
2003	8.32 to 13.30	7.81 to 8.35	0.8 to 22
2004	8.16 to 14.08	7.48 to 8.55	0.9 to 75
2005	7.24 to 14.11	7.85 to 8.44	0.8 to 7.8
2006	7.89 to 13.53	8.09 to 8.58	<0.5 to 26
2007	7.43 to 13.13	7.94 to 8.45	1.6 to 85
2008*	7.80 to 13.08	7.93 to 8.39	1.0 to 27

* preliminary data for January through October

4.6 United States Geological Survey (USGS) Monitoring Activities

The USGS monitors surface water quality in cooperation with local and state governments and with other federal agencies. Monitoring programs consist of collection, analysis and data archiving and dissemination of data and information describing the quality of surface water resources. Similar to Ecology, the USGS has monitoring stations on both the Okanogan (12447200) and Methow (122449950) rivers near Malott and Pateros, respectively. However, the data collected at the Malott station since 1994 has been limited to stage, discharge and water temperature; therefore the USGS is a very limited source of water quality data for the Okanogan River. USGS data can be accessed via the Internet at: http://nwis.waterdata.usgs.gov/wa/nwis/qwdata.

5.0 METHODOLOGY

A Quality Assurance Project Plan (QAPP), revised to incorporate review comments from Ecology, identified the organization, schedule, data quality objectives, sampling design, monitoring locations, field procedures, quality control, and data management and reporting associated with implementing the DO, pH, and turbidity study proposed by the RWG (Parametrix, 2008a).

5.1 Monitoring Locations

In order to collect information related to the effects of Wells Project operations on the water quality parameters of interest and whether these parameters are in compliance with the Washington State water quality standards, monitoring instrumentation was installed in the following locations:

- Okanogan River above the Project boundary at Malott (RM 17.0);
- Okanogan River near Monse (RM 5.0);
- Okanogan River upriver of the confluence with the Columbia River (RM 1.3);
- Wells Dam forebay (RM 516).

The Okanogan River monitoring instruments are installed on pilings with bridge locations shown on Figures 5.1-1 and 5.2-1.

Figure 5.1-1 Water quality monitoring instrument housing mounted on the downriver side of a Monse Bridge piling.

5.2 Study Design

At each of the three stations located in the lower Okanogan River and at the station in the Wells Dam forebay, dissolved oxygen, pH, and turbidity were measured continuously using Hydrolab Minisonde5 instrumentation. Instruments are calibrated prior to each field visit according to the manufacturer's specifications. Winkler titrations are performed during each field event to ensure the dissolved oxygen probes are functioning properly, and the probes are re-calibrated if the result of the Winkler titration and probe reading differ by more than 0.2 mg/L.

The following sampling and analysis components were designed to address the water quality monitoring objectives:

- Multiprobe water quality instruments capable of continuous monitoring of DO, pH, and turbidity were installed at the three Okanogan River locations to supplement the existing Wells Dam forebay monitoring station. The instruments are deployed in locked housings mounted to bridge pilings near midstream at each Okanogan River location.

- Parametrix and Douglas PUD conducted a reconnaissance of each site in April 2008 to determine the best available location for deploying monitoring instruments, take measurements and determine the hardware needed for constructing and mounting the instrument housings.
- Housings were designed and constructed to protect continuous monitoring instrumentation at the three new locations identified above, and installed to allow the monitoring probes to be approximately 1 meter below the water surface during low flows.
- The instrument housings and multi-probe meters were installed and began recording measurements on May 5 and 6, 2008. The instruments were calibrated and programmed to record DO, pH, and turbidity at 30-minute intervals. They continued to record measurements until removed on October 29, 2008.
- The Wells Dam forebay multi-probe meter recorded DO and pH at one-hour intervals between May 30 and October 27, 2008; and a separate sensor recorded turbidity at the dam at 5-minute intervals beginning on June 3, 2008.
- Monitoring instruments were retrieved, calibrated, and maintained, and data downloaded every 2 to 4 weeks, depending on battery life and river conditions affecting accessibility and safety.
- Data were downloaded to a meter and transferred to a personal computer in the field. Backup copies of the data were recorded on a CD or flash drive while still in the field.
- A separate quality assurance/quality control (QA/QC) instrument was calibrated before each downloading event and used for comparisons to the fixed instrument readings. Winkler titrations were performed to verify the accuracy of the DO sensor readings.

Figure 5.2-1 **Locations of bridges with water quality monitoring instrumentation on the lower Okanogan River.**

5.3 Data Quality Objectives

Because the Okanogan and Columbia rivers are generally well-mixed riverine environments, the field-located sites are expected to be representative of water quality conditions in the monitored reaches. The same type of instruments and monitoring were used to collect data at each Okanogan River site to ensure data comparability between monitoring locations.

The primary instrument for measurement of in situ DO, pH, and turbidity was the Hydrolab Minisonde5 equipped with DO, pH, and turbidity sensors. Turbidity data was collected in the Wells Dam forebay using a Global Water WQ750 turbidity sensor. Both types of sensors are susceptible to fouling by debris, sediment, and growth of organisms (algae, etc.) during continuous deployment. Therefore, luminescent dissolved oxygen (LDO) and self-cleaning turbidity sensors were employed at all four sites because they are resistant to fouling or configured to retard fouling. The LDO sensor is not affected by fouling or other debris, unless the growth is an organism that locally consumes or produces oxygen, such as algae growing directly on the sensor cap. The self-cleaning turbidity sensor offers a wiper mechanism to reduce the effects of fouling.

The primary QA/QC instrument was a Hydrolab® Datasonde4a coupled with a Surveyor4a (SVR4a) display and recording unit (Figure 5.3-1). This unit was also equipped with DO, pH, and turbidity sensors as well as conductivity and temperature sensors. The Datasonde4a was used in the field to verify the accuracy of the continuously deployed Minisonde5 sensors. The SVR4a display and recording unit was used to download data from the Minisondes during data retrieval events.

Accuracy objectives for water quality field measurements are presented in Table 5.3-1. The monitoring data completeness goal was 90 percent.

Figure 5.3-1 Downloading data from a Hydrolab MiniSonde5, located within its protective casing, using a Surveyor4a, at the Highway 97 Bridge.

Table 5.3-1 Measurement quality objectives for dissolved oxygen, conductivity, pH, turbidity, temperature, and depth.

Parameter	Method	Duplicate Samples Relative Standard Deviation (RSD)	Method Reporting Limit and/or Resolution
Dissolved Oxygen[1]	Hydrolab® Datasonde 5	5% RSD	0.01 mg/L
Dissolved Oxygen[2]	Winkler Titration	+/- 0.1 mg/L	0.01 mg/L
Specific Conductivity[3]	Hydrolab® Datasonde 5	+/- 0.5%	0.01 µS/cm
pH[3]	Hydrolab® Datasonde 5	0.05 s.u.[4]	± 0.01 s.u.
Turbidity[5]	Hydrolab® Datasonde 5	+/- 1% (0 to 100 NTU[6]) +/- 3% (100 to 400 NTU)	0.1 NTU (0-400 NTU)
Water Temperature[3]	Hydrolab® Datasonde 5	+/- 0.1° C	0.01° C
Depth[3,7]	Hydrolab® Datasonde 5	± 0.05 meters	0.01 meters

[1] Luminescent Dissolved Oxygen Sensor
[2] As units of measurement, not RSD or percentages
[3] As percentage of reading, not RSD
[4] Standard Units
[5] Self-cleaning Turbidity Sensor
[6] NTU = Nephelometric Turbidity Unit
[7] Non-vented 0 -100 meter Depth Sensor

5.4 Quality Control Procedures

All sondes and the SVR4a were performance-tested and evaluated (PT&E) by the manufacturer before the initial deployment for continuous monitoring. Required factory calibrations and maintenance, as well as necessary repairs, take place during the PT&E event. Should a sonde or the SVR4a be damaged during deployment and monitoring, a replacement is obtained from the manufacturer while the damaged unit is being repaired.

The sensors of each Minisonde were calibrated before deployment and in the field during instrument servicing/data retrieval events. The QA/QC Datasonde was calibrated before each data retrieval event and used for comparisons to the fixed instruments readings. The Datasonde was also re-calibrated on return from the field. This post-event calibration verifies that the Datasonde was functioning correctly and that the accuracy of the sensors has not deteriorated. Winkler titrations are performed to verify the accuracy of the QA/QC instrument DO sensor readings and, in the field, at each monitoring location to verify Minisonde DO sensor readings.

A calibration log was maintained to document the dates and times of sonde calibration, and any calibration problems and corrective actions taken (e.g., replacing electrolyte solution in the pH probe). This log was kept with the filling and calibration solutions and spare parts that were taken to the field. The calibration log will be retained in the project files.

Datasonde maintenance and replacement of filling solutions occur before each data retrieval event, as necessary. Minisonde maintenance and replacement of filling solutions occurred in the field, as necessary, during data retrieval mobilizations. Calibration standards followed and buffers were replaced based on manufacturers' recommendations.

6.0 RESULTS

Complete monitoring results from the four study sites are available in CD format from Douglas PUD or may be viewed in hard copy at the office in East Wenatchee, Washington.

6.1 Monitoring Instrument Performance

Hydrolab Minisonde5 instruments equipped with DO, pH, and turbidity sensors were installed at lower Okanogan River locations in protective housings and activated on May 5, 2008. Through the 2008 monitoring period the deployment depth ranged from 3.0 to 5.9 meters at Highway 97, 1.0 to 3.2 meters at Monse, and 1.5 to 5.1 meters at Malott. There were 12 instrument servicing events through October 29, with each event including downloading data, instrument calibration and maintenance, performing quality control checks (e.g., Winkler titrations), and replacing batteries. A similar instrument deployed in the Wells Dam forebay was serviced bi-monthly. High river flows and woody debris accumulations sometimes limited access to instruments and resulting battery failures caused data gaps from one or more sensors.

Douglas PUD staff reported problems with the self-cleaning mechanism on the Global Water WQ750 turbidity sensor deployed in the Wells Dam forebay. Although there were frequent manual cleanings of the sensor window, problems with instrument fouling persisted. Data collected in 2008 by this instrument were judged to be unreliable and were rejected as unusable.

6.2 Dissolved Oxygen Results

Lower Okanogan River DO concentrations followed changes in water temperatures in a typical seasonal pattern. Minimum daily DO concentrations of at least 9 mg/L were recorded early in the monitoring season (May through June). In general, DO measurements in the Okanogan River remained above 8 mg/L. However, starting in early July, DO concentrations measured in the Okanogan River, both above and within Project boundary, dropped to below the 8.0 mg/L water quality criterion (Figure 6.2-1). In late August the river began to cool and DO increased, with no measurements below 8.0 mg/L recorded after August 26.

At the Wells forebay, DO concentrations steadily dropped from early June through mid-August (Figure 6.2-1). DO concentrations at this monitoring site generally declined through the summer as the river warmed, but remained above 8.0 mg/L at least through mid-August when the instrument was lost due to vandalism. In early October, a new DO instrument was installed in the Wells forebay. DO measurements below 8.0 mg/L at the Wells Dam were recorded immediately after the new instrument was installed during the first week of October. DO then began an increasing trend that coincided with continued cooling of the reservoir.

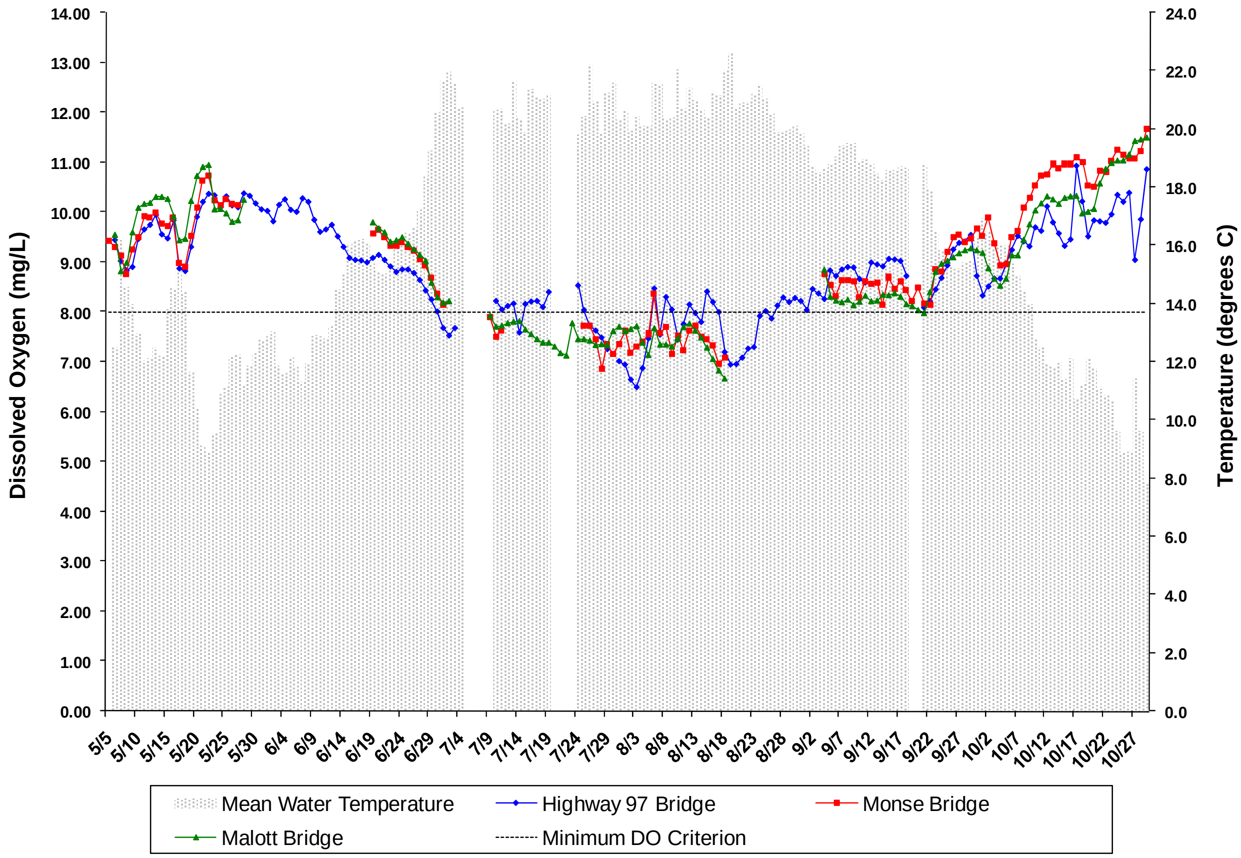


Figure 6.2-1 Daily minimum DO concentrations.

Minimum daily DO concentrations were measured below 8.0 mg/L at Malott and Monse from early July until late August with the lowest measurement of 6.67 mg/L on August 18 at Malott and 6.87 mg/L recorded on July 28 at Monse (Figures 6.2-2 and 6.2-3). Though less pronounced than at Highway 97, there were also much larger diurnal fluctuations in DO concentrations at Malott and to a lesser degree at Monse beginning in mid to late July, as illustrated by greater differences between daily minima and maxima.

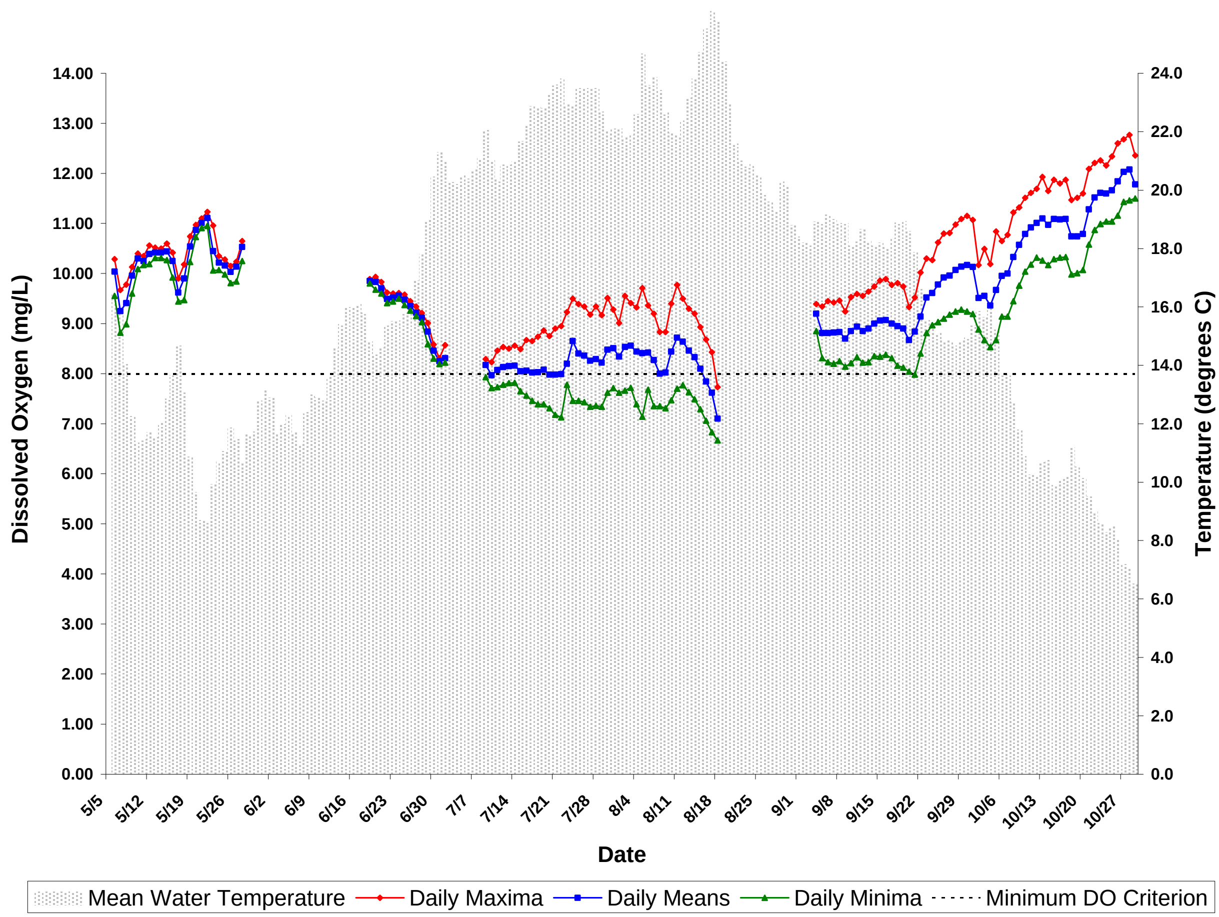


Figure 6.2-2 **Daily minimum, mean and maximum DO measurements at Malott Bridge, with daily mean temperatures.**

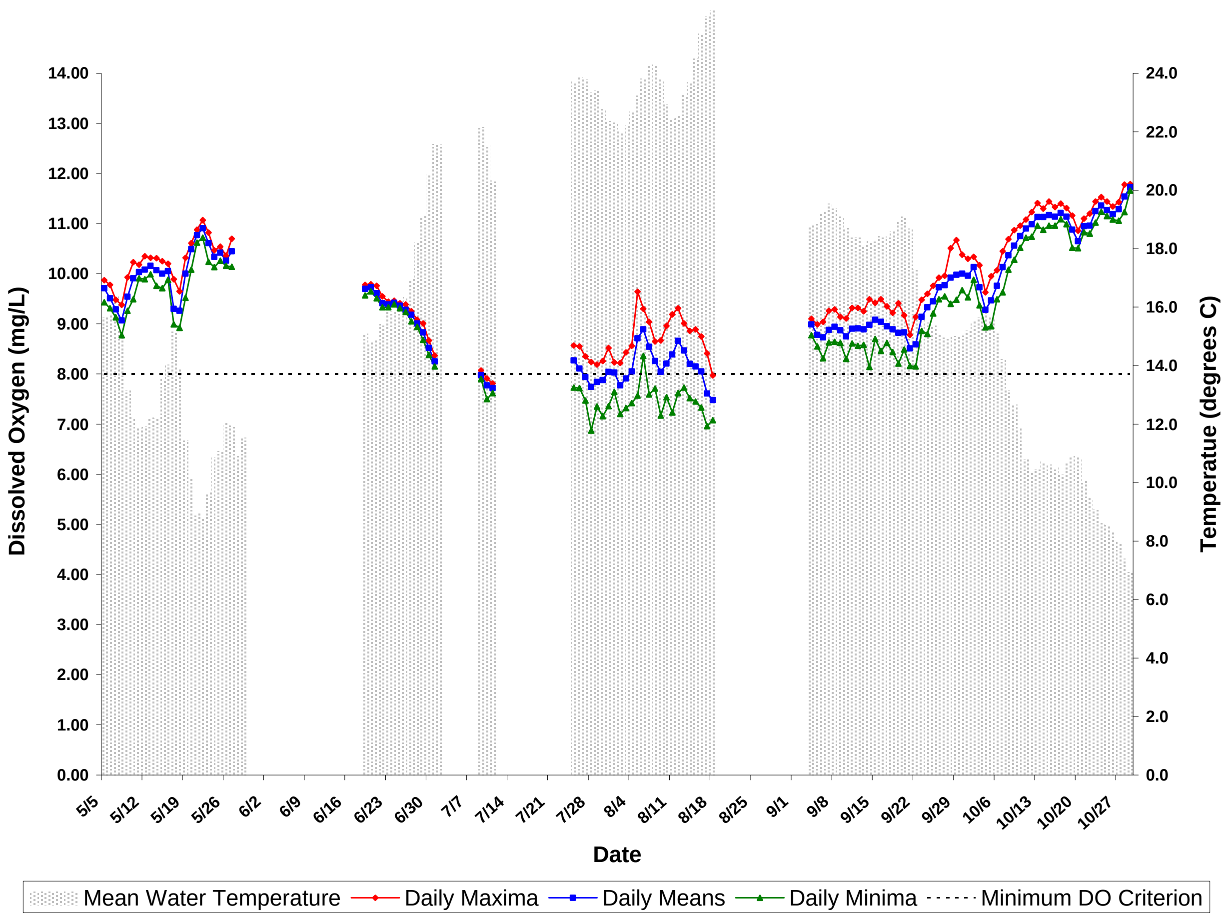


Figure 6.2-3 Daily minimum, mean and maximum DO measurements at Monse Bridge, with daily mean temperatures.

At Highway 97 the daily minimum DO began to occasionally drop below 8.0 mg/L on July 1, and was below 8.0 mg/L intermittently through August 26, with the lowest DO measurements coinciding with some of the warmest water temperatures (Figure 6.2-4). Very small differences between daily minima and maxima were observed during the high river flow season in May and June, compared with much greater daily DO fluctuation before and after the spring snowmelt runoff.

Relatively minor differences between daily minimum and maximum DO were observed at the Wells Dam forebay (Figure 6.2-5).

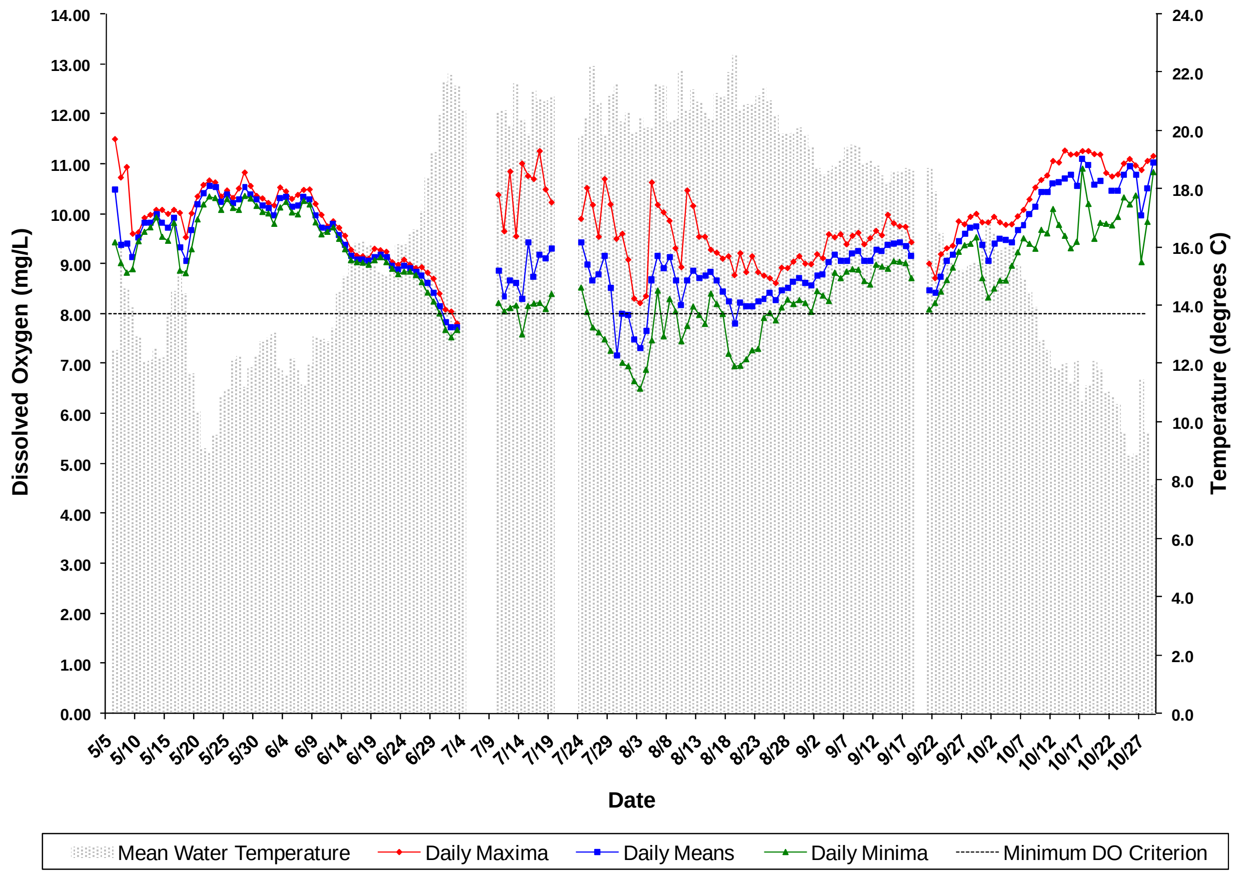


Figure 6.2-4 **Daily minimum, mean and maximum DO measurements at the Highway 97 Bridge, with daily mean temperatures.**

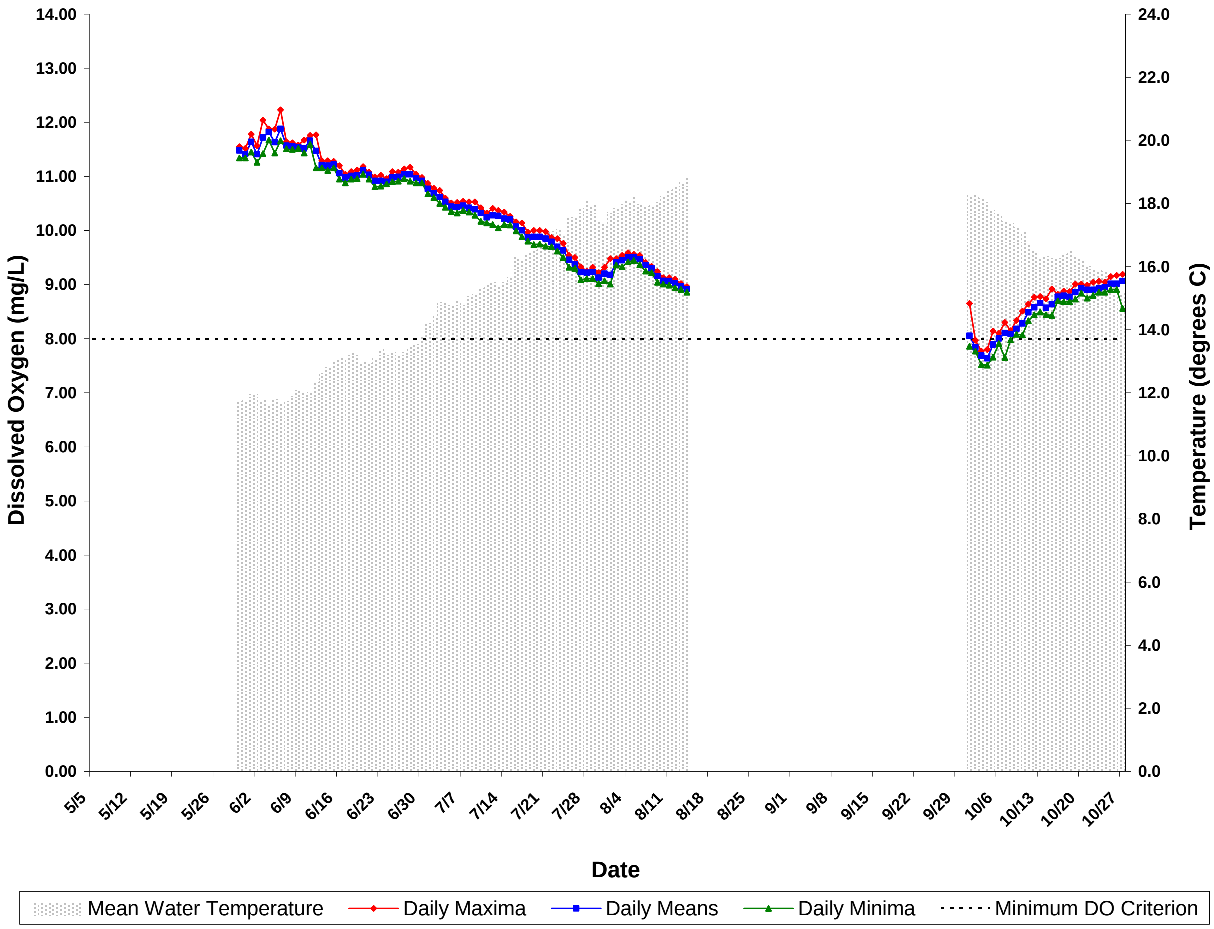
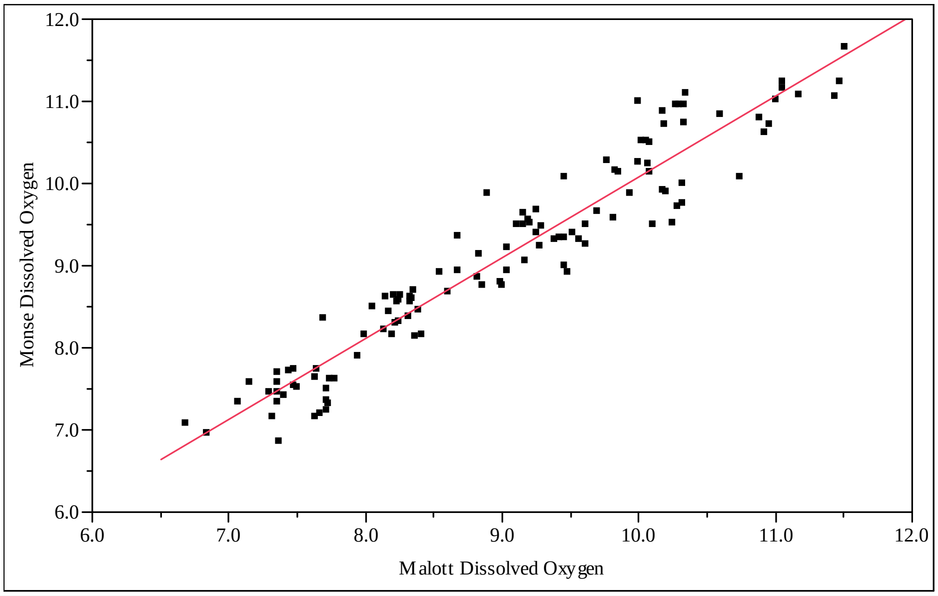


Figure 6.2-5 Daily minimum, mean and maximum DO measurements at the Wells Dam forebay, with daily mean temperatures.

Data collected from the Okanogan River sites were compared using linear regression techniques to identify the strength of the relationship between minimum DO measurements of water prior to entering the Project boundary and those observed within the Project. Changes in background minimum DO levels at Malott have a strong and significant linear relationship ($P < 0.0001$) with values recorded at both Monse and the Highway 97 Bridge (R^2 of 0.92 and 0.72, respectively). These results indicate that there is no statistically significant difference between minimum DO measurements collected from above Project (Malott) and in-Project (lower Okanogan River) locations. Further, though there is no statistical difference among DO measurements by location, median DO levels within the Project during summer months are equal to or greater than background values observed at Malott. When a linear regression is performed for summer minimum DO values (June through August) the relationship remains significant ($P < 0.0001$), and the equations at Monse and Highway 97 indicates an even greater positive influence on the DO within the Project (*Monse = 0.652 + 0.917 * Malott*, and *HWY 97 = 3.324 + 0.576 * Malott*).



Linear Fit

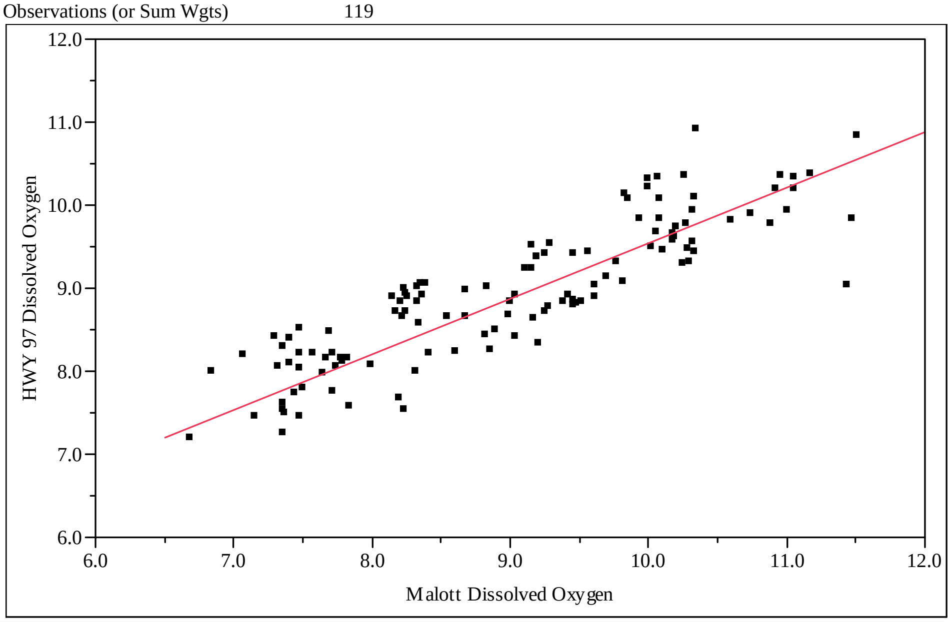
Monse = 0.2616841 + 0.9819724*Malott

Summary of Fit

RSquare	0.915939
RSquare Adj	0.915221
Root Mean Square Error	0.357698
Mean of Response	9.100756
Observations (or Sum Wgts)	119

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	163.11395	163.114	1274.848
Error	117	14.96988	0.128	**Prob > F**
C. Total	118	178.08383		**<.0001**



Linear Fit

HWY 97 = 2.8330135 + 0.6712533*Malott

Summary of Fit

RSquare	0.716313
RSquare Adj	0.714044
Root Mean Square Error	0.515227
Mean of Response	8.825984
Observations (or Sum Wgts)	127

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	83.78590	83.7859	315.6268
Error	125	33.18235	0.2655	**Prob > F**
C. Total	126	116.96825		**<.0001**

Figure 6.2-6 **Linear regression depicting strong significant relationship between minimum DO measurements collected above Project (Malott) and within Project boundary in the Okanogan River.**

6.3 pH Results

Okanogan River pH was neutral to slightly alkaline during 2008 monitoring. The pH measurements ranged from 7.23 to 8.78 at Malott Bridge, 7.07 to 8.68 at Monse Bridge, and 7.00 to 8.65 units at the Highway 97 Bridge. There were limited excursions of pH above the 6.5 to 8.5 range of water quality criteria, and on all but one of those days (May 6th), the pH was higher at Malott upriver from the Project area compared to Monse or Highway 97 (Figure 6.3-1). The most extensive periods of pH excursions occurred at the Malott Bridge between July 24 and August 15 when diurnal occurrences of higher late afternoon to nighttime pH reached up to 8.78, and again in early to mid-October when pH reached up to 8.76 (Figures 6.3-1 and 6.3-2). On May 6th, the pH at Monse exceeded readings at Malott, but only by 0.06 units – within the water quality standard. Between October 6 and 15, the pH at Monse exceeded 8.5 (Figure 6.3-3); however, this is attributed to influences upstream from the Project boundary as evidenced by the higher pH at Malott (Figure 6.3-1). On the nine days that pH exceeded 8.5 at Monse during this time frame, pH at Monse was lower than pH at Malott by 0.05 to 0.10 units (suggesting a positive influence on pH). The pH measurement at Highway 97 did not exceed 8.5 between May and mid-October (Figures 6.3-1 and 6.3-4). At no time did pH at any monitoring site approach the 6.5 minimum criterion.

Wells Dam forebay pH was also neutral to slightly alkaline during 2008 monitoring, ranging from 7.09 to 8.38 (Figure 6.3-5). All measurements were within the 6.5 to 8.5 range of water quality criteria.

Figure 6.3-1 Daily maximum pH concentrations in the lower Okanogan River.

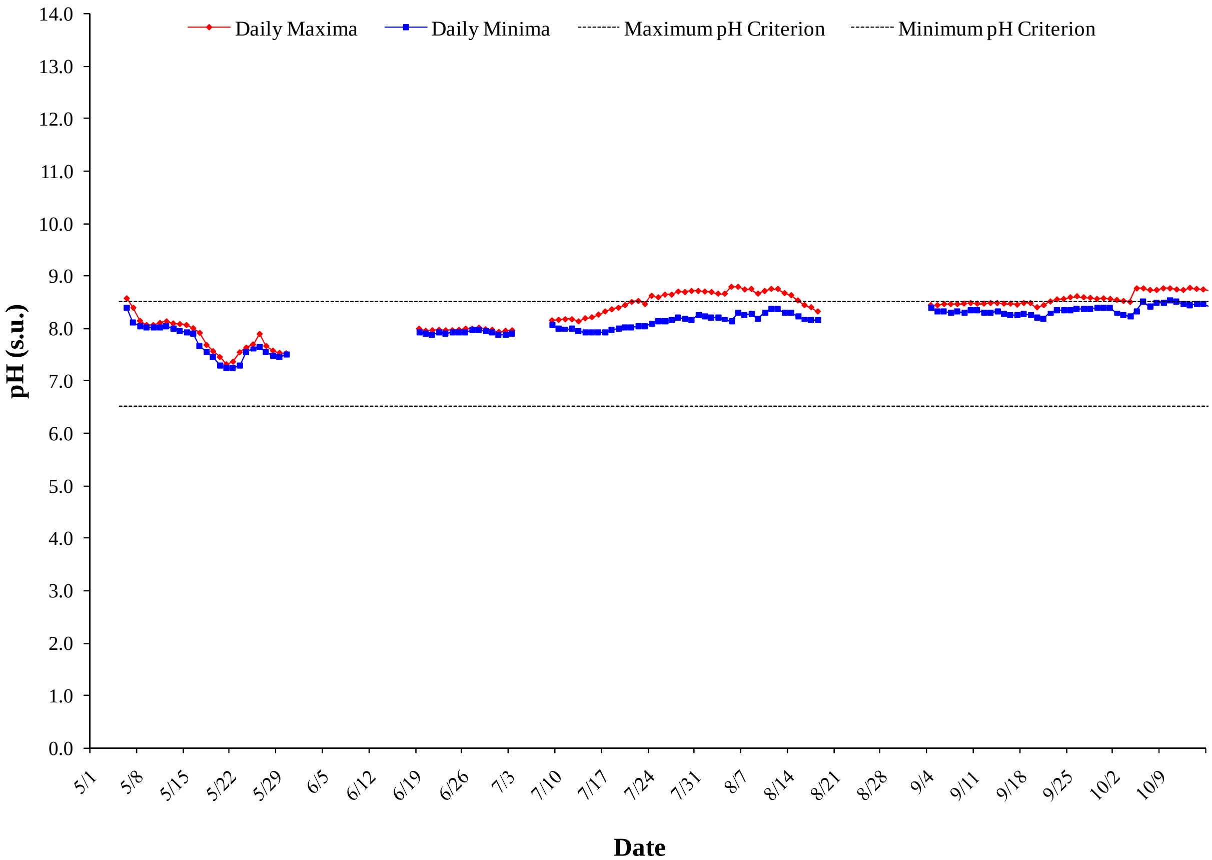


Figure 6.3-2 Daily minimum and maximum pH measurements at Malott Bridge.

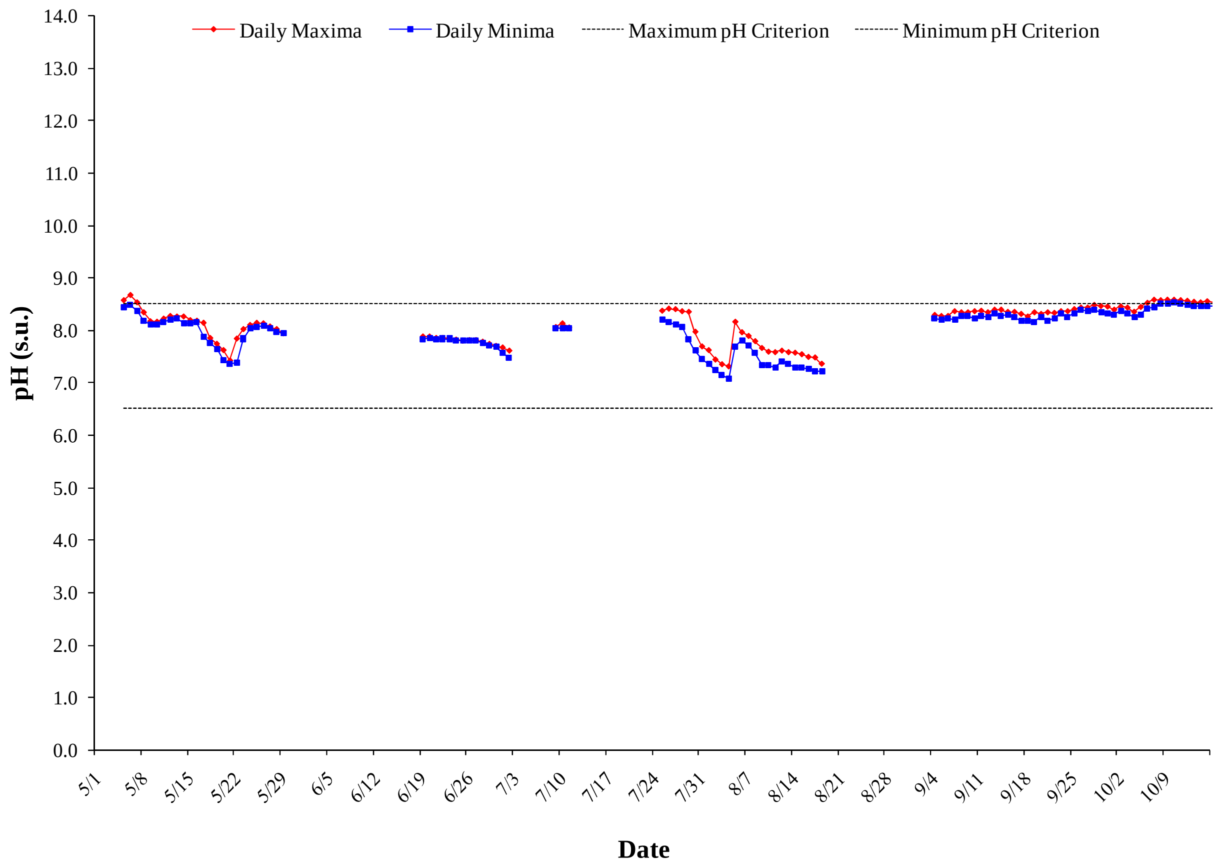


Figure 6.3-3 **Daily minimum and maximum pH measurements at Monse Bridge.**

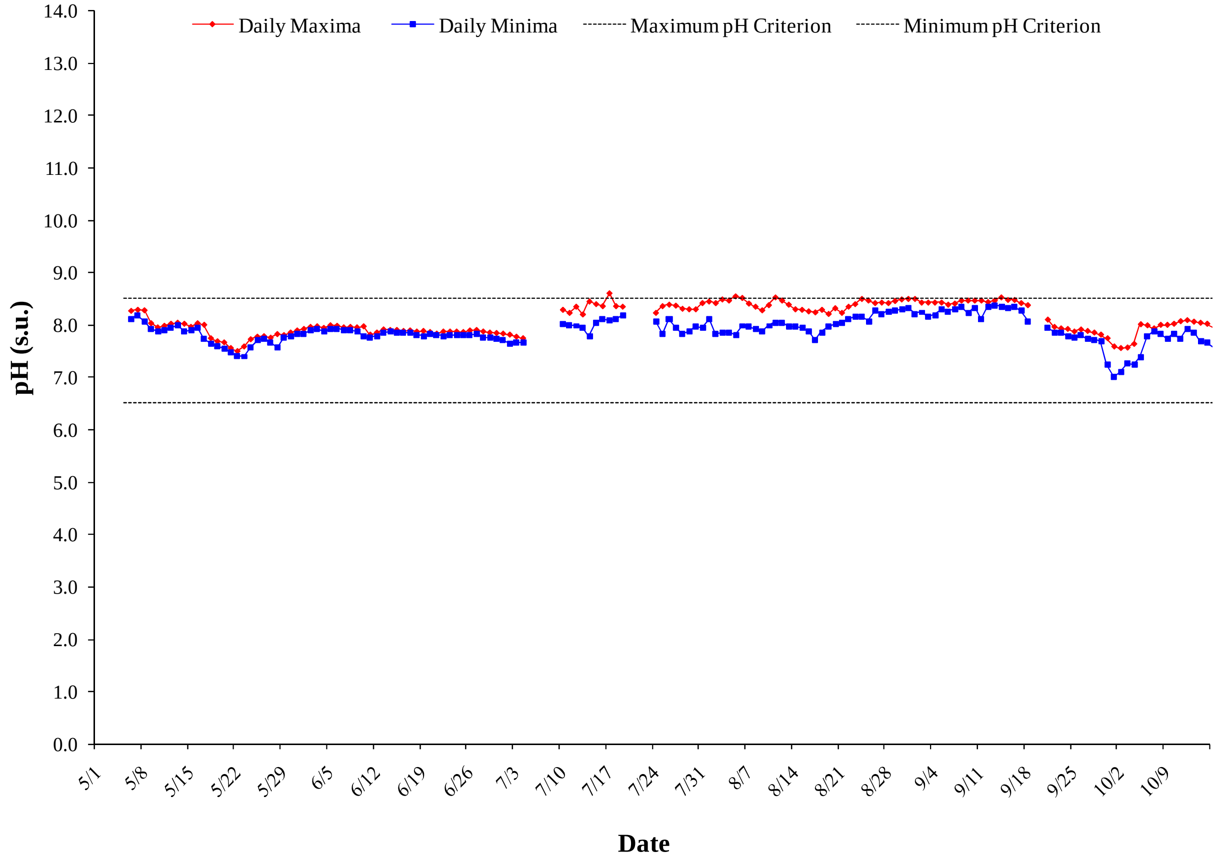


Figure 6.3-4 Daily minimum and maximum pH measurements at Highway 97 Bridge.

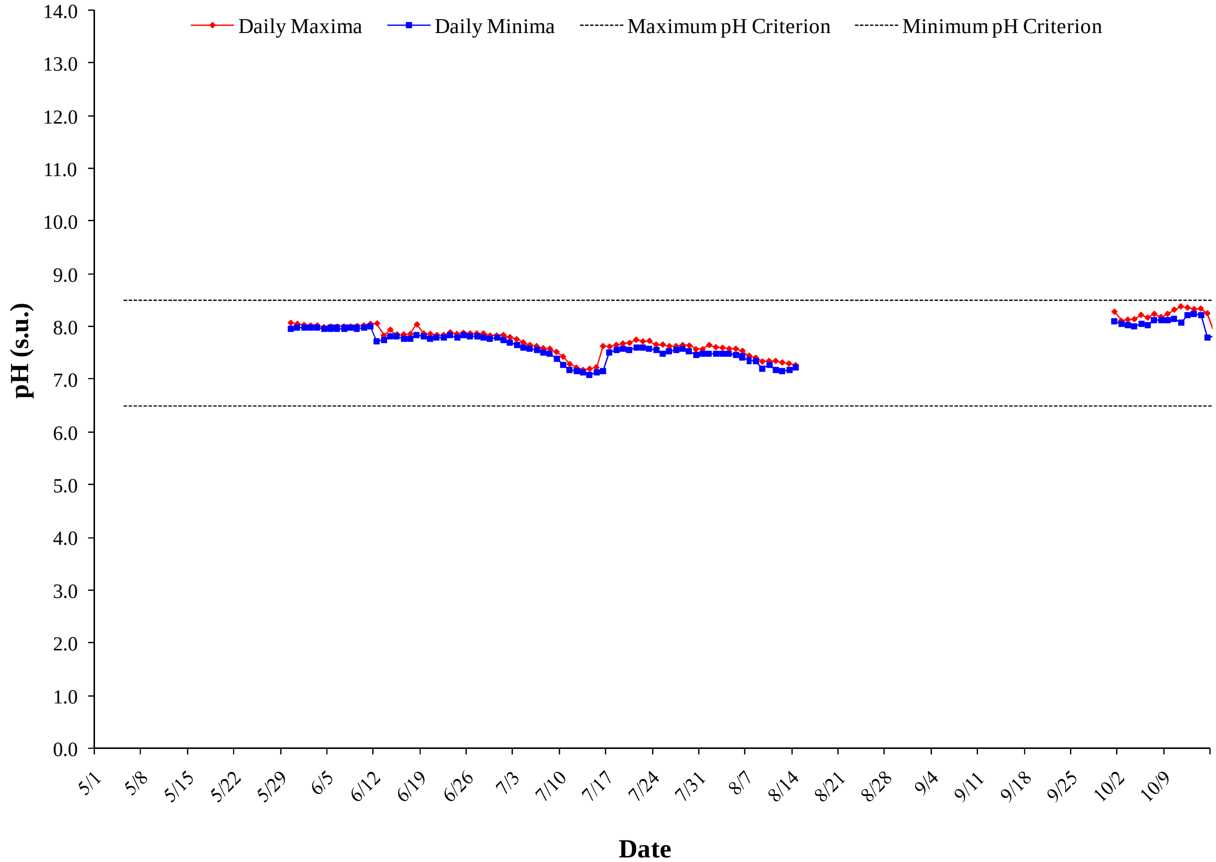


Figure 6.3-5 **Daily minimum and maximum pH measurements at the Wells Dam forebay.**

6.4 Turbidity Results

Lower Okanogan River turbidity increased sharply with the snowmelt runoff peak beginning on May 18, reaching peaks of 350 NTU on May 28 at Monse and 650 NTU on May 19 at Highway 97 (Figure 6.4-1). The turbidity sensor at Malott did not trigger properly when installed in early May and was inaccessible to the data monitoring crew for over a month due to flooding and a log jam on the Malott Bridge. As a result, no data were recorded at this site upriver from the Wells Project boundary to define incoming turbidity levels. Therefore, comparisons to background turbidity during the most critical time periods were limited.

A second period of high turbidity was recorded at Malott between August 9 and 16; however, those data were rejected as unreliable during quality assurance review because (1) turbidity remained low downstream at Monse and Highway 97 during this period, and (2) a review of weather records did not show any storm events on these days that might explain a spike in turbidity. It is likely that the turbidity sensor was temporarily fouled by clumps of filamentous algae that were observed floating through this river reach in late summer.

On a few occasions the turbidity at Monse (5 of 122 comparable days, or 4%) or Highway 97 (8 of 165 comparable days, or 5%) exceeded turbidity at Malott by more than 5 NTU. On two occasions in late June and early July, and again on three occasions in late September, turbidity at Monse exceeded turbidity at Malott by more than 5 NTU. Turbidity at Highway 97 exceeded Malott turbidity by more than 5 NTU on eight occasions between July 14 to August 2. These events were not widespread or persistent within the Wells Project.

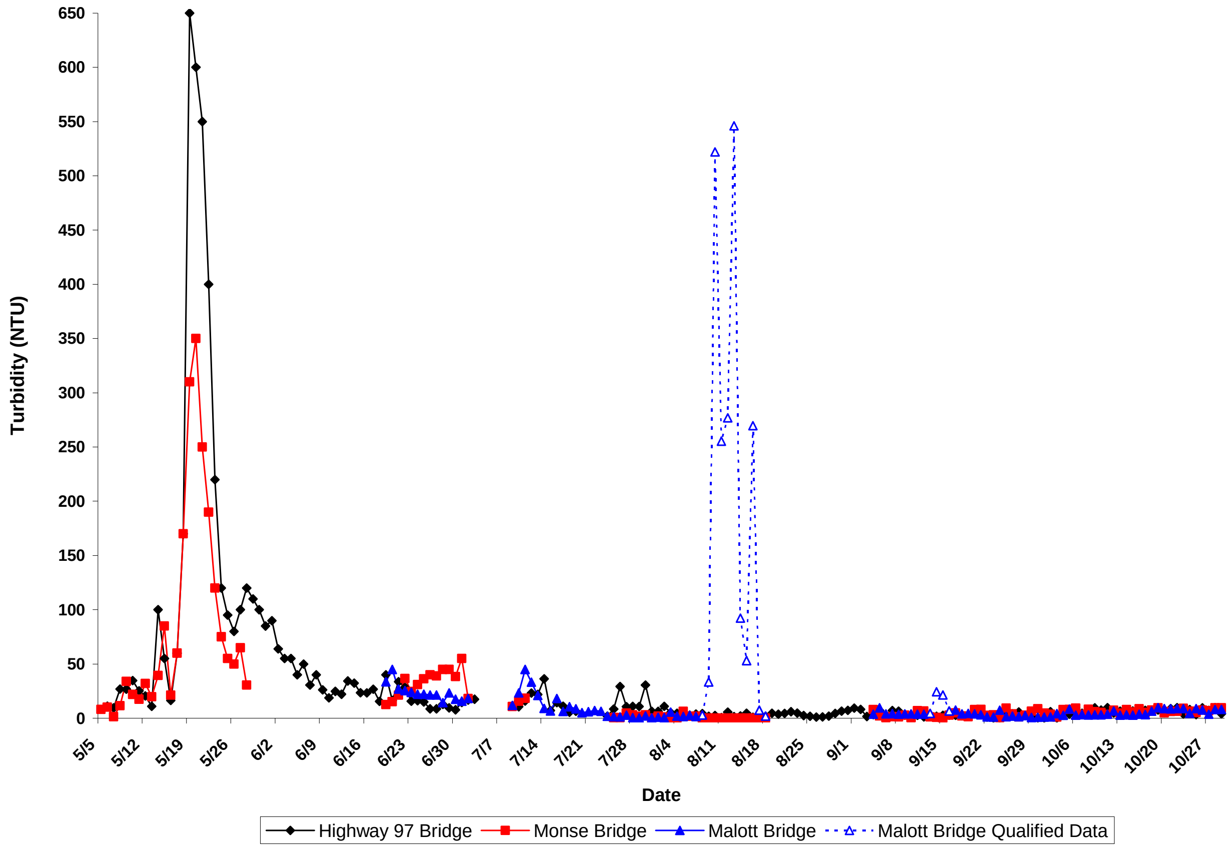


Figure 6.4-1 Daily maximum turbidity measurements (NTU) in the lower Okanogan River.

As discussed in greater detail in Section 7.1, instrument performance and maintenance issues with the Global Water WQ750 turbidity sensor at the Wells Dam forebay led to the data collected at that site to be judged unreliable and rejected as unusable. Therefore, no turbidity results are reported for that location during the 2008 study season.

6.5 Quality Assurance Results

6.5.1 Dissolved Oxygen Quality Assurance Results

The Datasonde primary instruments met data quality objectives for DO, and Winkler titrations generally confirmed DO measurements within 0.1 mg/L. Some readings from periods when the battery power was depleted were qualified as unusable. No other observable anomalous DO readings were identified. However, the DO recordings at the Wells Forebay were lower than expected immediately after installation of the replacement unit in early October, then began to rise consistent with water temperature as would be expected.

6.5.2 pH Quality Assurance Results

Datasonde pH accuracy was generally within 0.1 standard units. The pH electrode does not demand as much power as the other probes and generally did not seem to be affected by battery depletion. On two occasions the pH readings appear anomalous, the first from a five-day period in late July and early August at Monse when the pH dropped approximately one full pH unit. Because the pH at Malott and Highway 97 remained steady or increased slightly over this period, the drop in pH at Monse could not be explained and those data were qualified as questionable. The second occasion was between October 18 and 21 when pH electrode readings at Highway 97 drifted downward by more than one pH unit before servicing and re-calibration. Again the pH drift was isolated to one monitoring site and the data were qualified as questionable.

6.5.3 Turbidity Quality Assurance Results

Datasonde calibration and verification for turbidity standards were occasionally exceeded by ± 2%, though primary instruments generally met data quality objectives.

A period of high turbidity was recorded at Malott between August 9 and 16; however, those data were rejected during quality assurance review because (1) turbidity remained low downstream at Monse and Highway 97 during this period, and (2) a review of weather records did not show any storm events on those days. It is likely that the turbidity sensor was temporarily fouled by clumps of macrophytic algae that were observed floating through this river reach in late summer.

A few other data points at each lower Okanogan River station were qualified as unusable when the turbidity reading spiked up for only 30 minutes, possibly due to particle interference or temporary fouling of the probe. A few hours of anomalous data from the Highway 97 site were similarly qualified, due to battery depletion.

7.0 DISCUSSION

7.1 Dissolved Oxygen

In 2005, Douglas PUD contracted with EES Consulting to conduct a comprehensive limnological investigation of Wells Project waters. Results of the study found DO levels at 1m depth in Wells Project waters increased from upriver to downriver at the sites sampled; the average difference (May through October) was 1.07 mg/L. All surface water measurements had DO values greater than 8.0 mg/L (EES Consulting, 2006). A comparison of monthly grab samples collected by Ecology at Malott and EES in the lower Okanogan River does not indicate a reduction in DO moving downstream in the Okanogan River.

Measurements collected during the 2008 study did not identify a Project effect on DO when comparing measurements collected at Malott, Monse and Highway 97 monitoring stations. Regression analysis determined that minimum DO measurements collected within Project boundaries on the Okanogan River were statistically indistinguishable and strongly related to values recorded above the Project boundary (Malott). Strong seasonal trends in minimum DO were observed that coincided with temperature fluctuations of incoming waters from upstream of the Wells Project (e.g., above Malott). Lower DO concentrations were observed most frequently upstream of the Wells Project boundary at Malott, indicating that the source of low DO originates from upstream of the Project boundary. Daily DO and temperatures at Malott had a strong and significantly negative correlation (correlation coefficient = -0.98, $P < 0.001$). Excursions of daily minimum DO concentrations below 8.0 mg/L were observed 31% of days at Malott (42/134), 23% of days at Monse (27/120), and 17% of days at Highway 97 (28/165) indicating a lower frequency of excursions below the standard within the project despite the continued input of water that does not meet the DO standard from upstream of the Project.

Similarly, seasonal gradual declines in DO concentrations were observed with increasing temperatures in the Wells forebay (i.e., a negative correlation). Daily minimum DO concentrations remained well above 8.0 mg/L throughout the entire summer, until a brief and minor (4 days, 7.8 mg/L minimum value overall average) excursion occurred in the fall of 2008 (October 2nd to October 5th) upon the installation of a replacement instrument. These readings are likely related to instrument equilibration following installation as DO levels below 8.0 mg/L are uncharacteristic of the Columbia River and the Wells forebay, especially during periods of cooling such as October. Observed daily DO concentrations were consistently above 9.3 mg/L at all locations.

Diurnal patterns in DO concentrations were observed during the summer and early fall months at Malott, Highway 97, and, to a lesser extent, Monse. DO concentrations would reach their daily maximum values in the evenings followed by daily minima in the mornings. This was likely caused by greater daytime solar heating and fluctuation in water temperatures as spring snowmelt runoff recedes, and the diurnal photosynthesis/respiration cycle of aquatic vegetation. Diurnal fluctuations in DO concentrations were not evident at the Wells Dam forebay.

7.2 pH

Based upon results from the 2005 study, all surface water measurements for pH generally varied between 7.5 and 8.25, which is slightly above neutral. There were no measured exceedances of the water quality criteria for pH in 2005 either in the Okanogan, Methow or Columbia rivers within the Wells Project. Similarly, results collected from 2008 indicated that pH readings decreased as water moved downstream through the lower Okanogan River. The majority of higher pH readings in the Okanogan River were recorded above the Wells Project, and at no time did the daily maximum pH values from downstream monitoring locations exceed the pH at Malott by more than 0.06 units. These results indicate that pH levels of incoming water are the primary cause for any excursions above the 8.5 criterion observed within the Wells Project. All pH measurements at the Wells forebay were within the 6.5 to 8.5 water quality criteria, and at no time did pH values approach the 6.5 minimum criterion anywhere in the Wells Project. Based upon the results collected during the 2005 and 2008 studies, the Wells Project is not negatively influencing pH.

7.3 Turbidity

Based upon results from the 2005 limnological study, turbidity in the Wells Reservoir showed relatively little seasonal variation with an annual average of 0.98 NTUs. Longitudinal variation in turbidity was also minimal. Low turbidity in the reservoir was attributed partially to the large upriver storage reservoir capacity that allows fines to settle out. Turbidity in the Okanogan River was consistently higher than in the Wells Reservoir.

Based upon the results from the 2008 study, it is not clear what effect, if any, the Wells Project may have had on turbidity through the 2008 monitoring period. There are limited data available upriver from the Wells Project boundary to enable comparisons to background (Malott) during the high turbidity that accompanied the peak of snowmelt runoff in late May and early June. On only a few occasions after peak snowmelt runoff the turbidity at Monse (5 of 122 comparable days, or 4%) or Highway 97 (8 of 165 comparable days, or 5%) exceeded turbidity at Malott by more than 5 NTU, but the exceedances occurred on the same date at both monitoring sites only once. Because the events with elevated turbidity were scattered throughout the monitoring period and generally did not occur at both Monse and Highway 97 on the same days, these results are not suggestive of any widespread or persistent turbidity issues in the Wells Project.

8.0 STUDY VARIANCE

This study was not required by the FERC as part of the October 11, 2007 Study Plan Determination. This study was voluntarily conducted by Douglas PUD at the request of Ecology in support of the 401 water quality certification for the Wells Project.

Variances associated with the voluntarily conducted study for DO, pH, and Turbidity included the following:

- The upper sampling station location was changed from the Project boundary (RM 15.5) to the Malott Bridge (RM 17.0). No suitable structure could be found at RM 15.5 and as a result, the instrument housing was installed on the Malott Bridge located at RM 17.0. This change in location should have no effect on the results of this study.
- The Study Plan specified that DO monitoring would take place hourly between mid-July and mid-September when there is a greater possibility of lower DO levels occurring. In order to access the river prior to the peak of the spring hydrograph, the monitoring equipment was deployed earlier than required in the study plan. Equipment was deployed on May 5 and 6 at the Okanogan River locations and May 30 at the Wells forebay. The equipment also continued collecting data until October 15, more than a month later than required by the study plan.
- The study plan required that data be collected on an hourly basis. Battery failures and instrument inaccessibility during high flow and debris load periods caused gaps in the hourly database.
- All turbidity results for the Wells Dam forebay location were judged to be unreliable and rejected as unusable. The self-cleaning mechanism on the water quality probe was not functioning properly and became fouled frequently during the study.

9.0 REFERENCES

APHA. 1998. Standard methods for the examination of water and wastewater, 20th edition. American Public Health Association. Washington, D.C.

Douglas PUD. 2007. Continued monitoring of DO, pH, and turbidity in the Wells forebay and lower Okanogan River (DO, pH and Turbidity Study). Wells Hydroelectric Project, FERC No. 2149. Prepared by Public Utility District No. 1 of Douglas County. East Wenatchee, Washington. May 2007.

Douglas County PUD. 2006. Wells Hydroelectric Project. FERC Project No. 2149. Pre-Application Document.

Ecology. 2008a. Water quality assessments (303[d]) home page. Available online at http://www.ecy.wa.gov/Programs/wq/303d/index.html. Washington State Department of Ecology, Olympia.

Ecology. 2008b. River and stream water quality monitoring. Available online at http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html. Washington State Department of Ecology, Olympia.

Ecology (Washington State Department of Ecology). 2006. Water quality standards for surface waters of the state of Washington, Chapter 173-201A WAC. Available online at http://www.ecy.wa.gov/programs/wq/swqs/index.html. Washington State Department of Ecology, Olympia.

EES Consulting (EES Consulting, Inc.). 2006. Comprehensive limnological investigation, Wells Hydroelectric Project, FERC NO. 2149. Prepared by EES Consulting Inc., Kirkland, WA for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Parametrix. 2008a. Quality assurance project plan: Assessment of DDT and PCBs in fish and sediments from the lower Okanogan River. Wells Hydroelectric Project, FERC No. 2149. Prepared by Parametrix, Inc., Bellevue, WA for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Parametrix. 2008b. Assessment of DDT and PCBs in fish and sediments from the lower Okanogan River. Wells Hydroelectric Project, FERC No. 2149. Prepared by Parametrix, Inc., Bellevue, WA for Public Utility District No. 1 of Douglas County, East Wenatchee, WA.

Patterson, B. and S. Bickford. 2010. Wells Dam Spill Playbook, 2010 Mid-season Revision. Public Utility District No. 1 of Douglas County, Washington.

Memorandum

To: Pat Irle
From: Beau Patterson, Shane Bickford
Date: July 2, 2010
Subject: Wells Dam Spill Playbook, 2010 mid-season revision

As you know, we have had a few exceedances of hourly (125% max) and 12C-High (120% max) TDG concentrations in the Wells Dam tailrace, and more prolonged exceedances in the Rocky Reach forebay (115% max). These are likely due to a complex interaction of record cool temperatures, very high seasonal precipitation, unusual operations of the upstream dams, and dentated spill patterns at Wells when spill exceeds 53kcfs. As a result, we are changing the 2010 spill playbook with the objective of improved compliance with state and federal water quality standards for TDG.

These changes are included in the accompanying 2010 Spill Playbook. Items of note:

When spill levels are expected to reach the 53 kcfs threshold, the District should remove the Juvenile Bypass System barriers in spillbay 6 in order to remain in compliance with the TDG standards in the Wells tailrace and Rocky Reach forebay. There is no change in spill operations for spill less than 53 kcfs, except the JBS barrier in spillbay 6 has been removed to allow for quick response to spill requirements in excess of that amount. When spill exceeds 53 kcfs, excess spill is directed through spillbays 6 and 7 rather than through spillbays 5 and 7.

Please contact us if there are any questions. If spill is projected to no longer exceed 53kcfs for the remainder of the fish spill season, the spillbay 6 JBS barrier will be reinstalled. Thank you for your patience and understanding as we try to determine how to best manage TDG at Wells Dam.

I. No Forced Spill

The Wells Dam JBS (even numbered spillbays, 10.0 kcfs total) should be operated continuously throughout the juvenile salmon outmigration (normally April 12 to August 26). The Wells JBS is normally operated with 1.7 kcfs passed through *S2* and *S10*, and 2.2 kcfs through *S4*, *S6*, and *S8* (Figure 1).

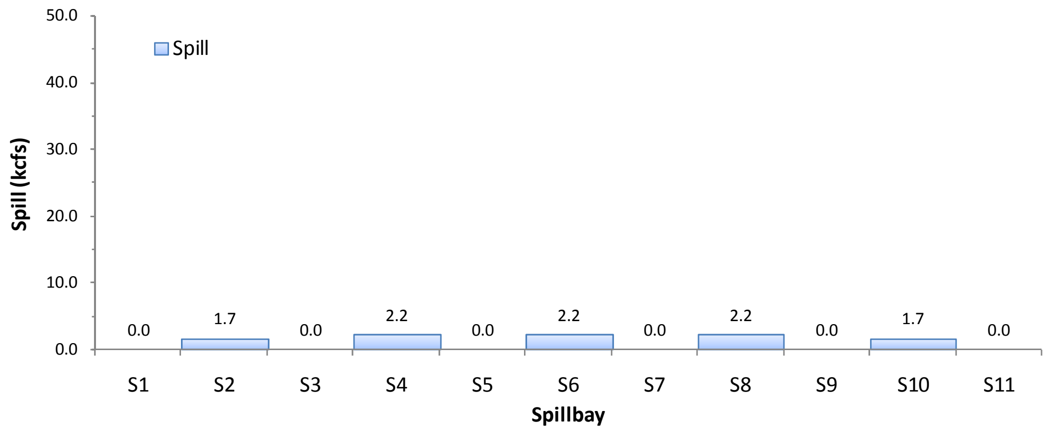


Figure 1. Operational configuration under no forced spill (JBS only).

II. Forced Spill (≤ 53.0 kcfs)

As forced spill increases, Project Operators should allocate all spill through *S7* until the maximum capacity is reached through that spillbay (~43.0 kcfs). This, along with the already established JBS spill (10.0 kcfs) would equal 53.0 kcfs (Figure 2). Over 90% of the spill events over the past decade could have been handled under this configuration.

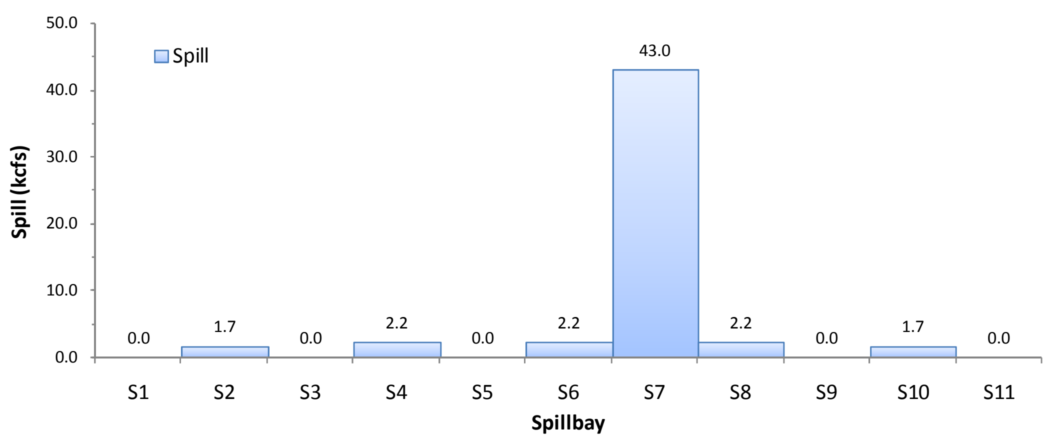


Figure 2. Operational configuration under spill ≤ 53.0 kcfs (including JBS).

III. Forced Spill (> 53.0 kcfs) and JBS Barriers in *S6* Removed

After *S7* reaches 43.0 kcfs, spill should be allocated to *S6*, following the required removal of the JBS barriers in *S6*. Since a minimum of 15.0 kcfs is needed to fully engage the submerged spillway lip below the ogee, spill through *S7* must be relocated to *S6* (Figure 3). As flow increases, spill should continually increase through *S6* until paired with *S7* (e.g., 28.0 kcfs through *S6* and *S7*). After this point (63.8 kcfs), both *S6* and *S7* can be increased until both spillbays have reached 43.0 kcfs (93.8 kcfs, Figure 4).

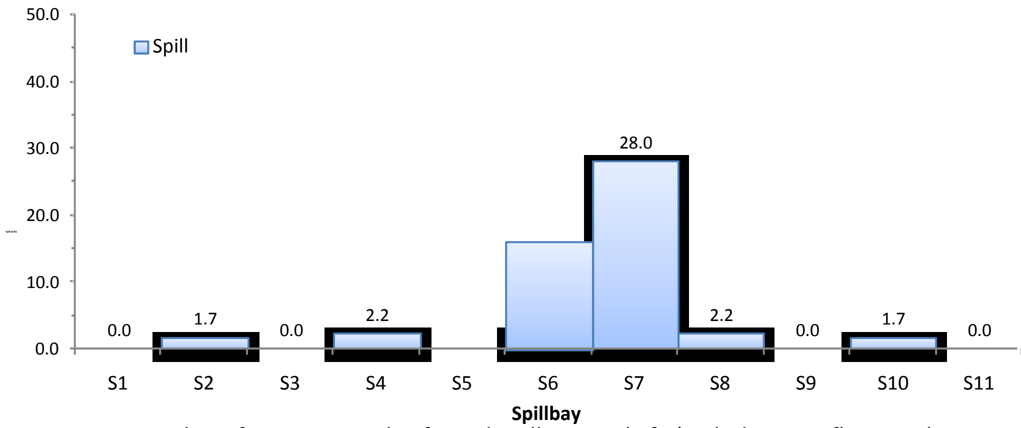


Figure 3. Operational configuration under forced spill > 53.0 kcfs (including JBS flow, with removal of JBS barriers in *S6*). In this instance (54.0 kcfs of total spill), 18.2 kcfs is allocated through *S6* in order to engage the submerged spillway lip.

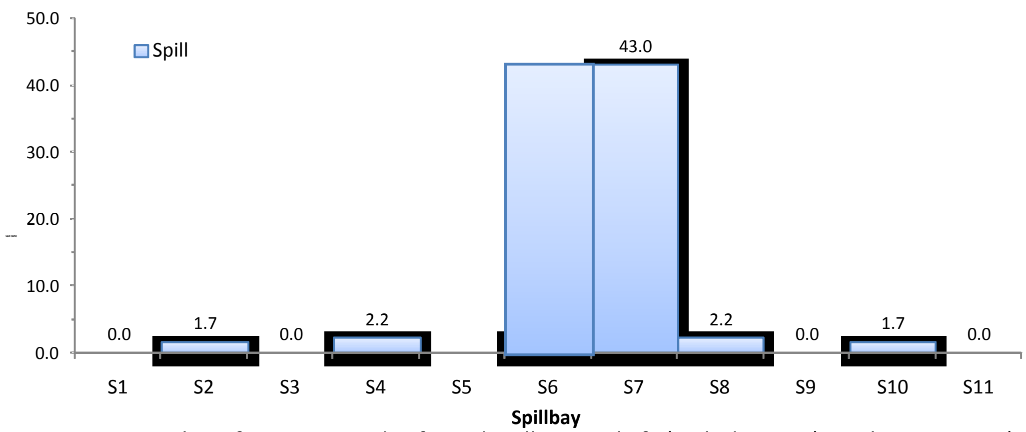


Figure 4. Operational configuration under forced spill > 53.0 kcfs (including JBS). In this instance (93.8 kcfs of spill), 43.0 kcfs is allocated through both *S6* and *S7*.

IV. Forced Spill (> 93.8 kcfs)

After both *S6* and *S7* reach 43.0 kcfs, spill can also be allocated to *S5*. Since a minimum of 15.0 kcfs is needed to fully engage the submerged spillway lip below the ogee, spill through *S6* should be relocated to *S5* (Figure 5). As flow increases, spill can be continually increased through *S5* until paired with *S6* (30.0 kcfs through S5 and S6, while S7 continues at 43.0 kcfs). After this point, both *S5* and *S6* can be increased until all three spillbays have reached 43.0 kcfs(136.8 kcfs of spill, Figure 6).

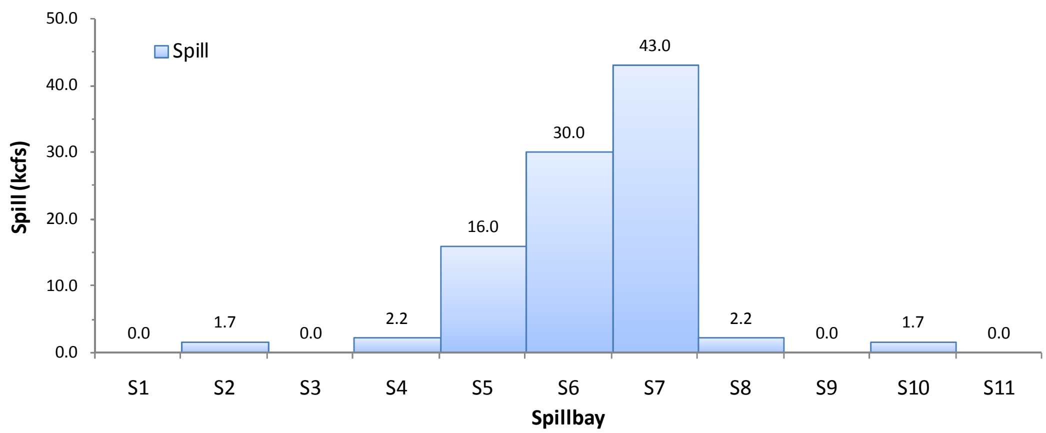


Figure 5. Operational configuration under forced spill > 96.0 kcfs. In this instance (96.8 kcfs of total spill), spill from *S5* is relocated to *S6* to maintain concentrated flow with *S7*. A spill of 16.0 kcfs is maintained in *S5* as to engage the spillway lip below the ogee.

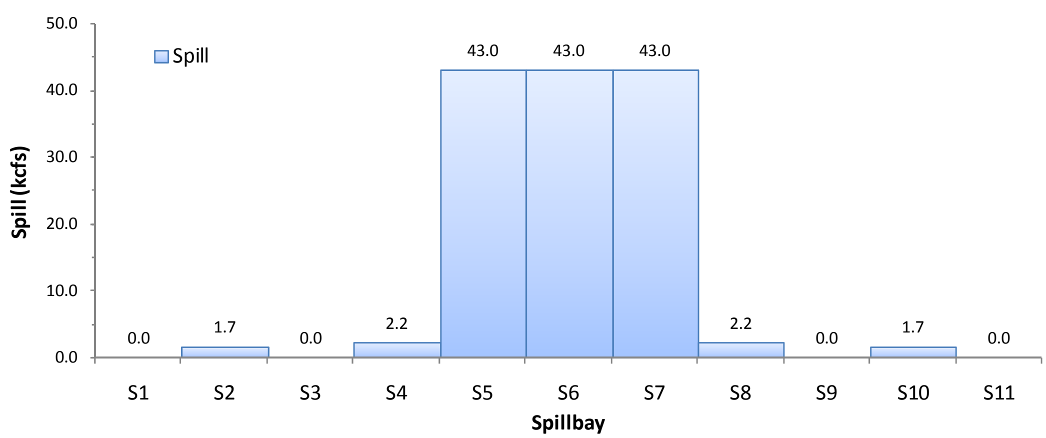


Figure 6. Operational configuration under forced spill > 96.0 kcfs (with removal of JBS barriers in *S6*). In this instance (136.8 kcfs of total spill), 43.0 kcfs is allocated through *S5*, *S6*, and *S7*.

V. Forced Spill (> 136.8 kcfs)

Forced spill exceeding 136.8 kcfs rarely occurs (less than 0.5%). If these conditions arise and total river flow exceeds 246.0 kcfs, then 7Q-10 conditions are occurring and Wells Dam is exempt from the TDG standards. Under this situation, Project Operators may perform any combination of operations to ensure that flood waters are safely passed. Also, at this point, JBS barriers will likely be removed allowing additional flexibity to spill up to 43 kcfs through *S2*, *S4*, *S6*, and *S8*. Project Operators may pass spill through *S3* in a similar fashion to operations mentioned above (starting at a minimum of 15.0 kcfs to ensure that spillway lips are engaged).

I. Spill Lookup Table

Operation	Total Spill	Spillbay Number *S1* -	*S2* *JBS*	***S3***	*S4* *JBS*	***S5***	*S6* *JBS*	***S7***	*S8* *JBS*	***S9***	*S10* *JBS*	*S11* -
I. No Forced Spill	10.0	0.0	1.7	0.0	2.2	0.0	2.2	0.0	2.2	0.0	1.7	0.0
II. Spill (≤ 53.0 kcfs), min.	11.0	0.0	1.7	0.0	2.2	0.0	2.2	1.0	2.2	0.0	1.7	0.0
II. Spill (≤ 53.0 kcfs), max.	53.0	0.0	1.7	0.0	2.2	0.0	2.2	43.0	2.2	0.0	1.7	0.0
III. Spill (> 53.0 kcfs, *S6* JBS out), min.	54.0	0.0	1.7	0.0	2.2	0.0	15.0	31.2	2.2	0.0	1.7	0.0
III. Spill (> 53.0 kcfs, *S6* JBS out), max.	93.8	0.0	1.7	0.0	2.2	0.0	43.0	43.0	2.2	0.0	1.7	0.0
IV. Spill (> 93.8 kcfs, *S6* JBS out), min.	96.8	0.0	1.7	0.0	2.2	15.0	38.8	43.0	2.2	0.0	1.7	0.0
IV. Spill (> 93.8 kcfs, *S6* JBS out), max.	136.8	0.0	1.7	0.0	2.2	43.0	43.0	43.0	2.2	0.0	1.7	0.0
V. Spill (>137.0 kcfs), min.	137.0	0.0	1.7	15.0	2.2	28.2	43	43.0	2.2	0.0	1.7	0.0
V. Spill (>137.0 kcfs), max.	-	*Operators may adjust as needed.* *TDG exemption in place when total river flows exceed 246.0 kcfs.*										

Notes: (1) No spill through *S1* and *S11* as to minimize interference with fish ladders. (2) Even-numbered spillbays are designated as the Juvenile Bypass System (JBS). (3) Primary spillbays for forced spill are *S7*, *S6*, *S5*, *S9*, and *S3* (in that order).

Politano, M., A. Arenas Amado, and D. Hay. 2009. Total Dissolved Gas Modeling and Compliance Evaluation for the Wells Hydroelectric Project. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA.

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TOTAL DISSOLVED GAS MODELING AND COMPLIANCE EVALUATION FOR THE WELLS HYDROELECTRIC PROJECT

FINAL REPORT

July 2009

Prepared by:
M. Politano and A. Arenas Amado
IIHR-Hydroscience & Engineering
The University of Iowa
300 South Riverside Drive
Iowa City, Iowa 52242-1585

and

Duncan Hay
Oakwood Consultants
237 Turtlehead Road
Belcarra, B.C. Canada V3H 4P3

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509) 884-7191
E-Mail: relicensing@dcpud.org

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ABSTRACT

Total dissolved gas (TDG) production dynamics at the Wells Hydroelectric Project (Wells Project) were examined between 2005 and 2009 to identify operational strategies to manage TDG for compliance with state water quality standards (WQS). This report presents a numerical model able to predict the dynamics of spillway surface jets, the hydrodynamics and TDG distribution within the Wells tailrace. The primary goal of this study was to identify Project operations that minimize TDG downstream of the Wells dam. Attention is focused on the underlying physics that govern the TDG distribution under different scenarios.

An unsteady state three-dimensional (3D) two-phase flow model was calibrated and validated using field data collected in the Wells tailrace in 2006. A gas volume fraction of 3% and bubble diameter of 0.5 mm in the spillbays produced TDG values that bracketed the field observations. Once calibrated, the predictive ability of the model was validated by running three different operational conditions tested in 2006. The numerical results demonstrated that the model provides a reliable predictor of tailrace TDG and therefore can be used as a tool to support evaluation of Project operations.

After validation and calibration, the model was used to analyze the sensitivity of TDG concentration to the operation of the Project. Nine model runs were completed for four river flows in which spill was either spread across the spillbays or concentrated in one or more spillbays to analyze the sensitivity of TDG concentration to the operation of the Project. Concentrated spill operations resulted in the lowest predicted TDG concentration downstream of the dam. According to the model, concentrated spill operations reduce the TDG production and increase the degasification at the free surface.

Based on the results from the sensitivity simulations, several additional operating configurations were tested toward identification of the Optimal Operating Configuration for a 7Q10 flow of 246 kcfs. Spill concentrated in adjacent bays resulted in interaction between spillway jets, bubbles traveling deeper into the tailrace, and slightly higher production of TDG. On the other hand, minimum TDG concentrations were observed when the flow was concentrated in bay 7 and the remaining flow distributed in distant bays. The Optimal Operating Configuration produced an average TDG concentration at transect T3 of 117.7%. Numerical results indicated that dilution by downstream mixing and degasification were enhanced with this optimal operation.

Finally, an additional scenario was modeled to provide the Washington State Department of Ecology (Ecology) with results consistent with settings used at other projects for evaluation of compliance with numeric WQS. This model scenario was called the Standard Compliance Scenario. The simulation was conducted using a concentrated spill in adjacent bays, with a 115% forebay TDG and 90% of maximum powerhouse capacity during a 7Q10 flow. The Standard Compliance Simulation produced an average TDG concentration at transect T3 of 116.7%.

In addition to complying with the TDG standards for the Wells tailrace during the fish passage season, Ecology has also requested an analysis of TDG concentrations during periods of (1) spill outside the fish passage season; (2) TDG changes during non-spill events; and, (3) the

relationship between TDG values in the Wells tailrace and those observed in the forebay of Rocky Reach Dam.

TDG production in the Wells tailrace during non-spill is virtually non-existent, with both median and average delta TDG values at 0.0% and 0.0% (SEM ± 0.0%), respectively. The lack of TDG production during non-spill is further supported by a linear regression showing a significant positive correlation between forebay TDG and tailrace TDG ($y = 0.8873x+11.775$; $P < 0.000$, $R^2 = 0.81$). Median forebay TDG and tailrace TDG values during non-spill events over the past 10 years have both been 104%. Only 7 of the 9,599 (0.07%) hourly values recorded during non-spill events between April and September, 1999-2008 surpassed 110% when forebay TDG was ≤ 110% (DART 2009). These results indicate that Wells Dam is able to meet compliance with the 110% TDG tailrace criteria during non-spill events and outside of the fish passage season.

During the fish passage season, daily average TDG values for the Rocky Reach forebay have averaged 106.6% during the years 1999 to 2008. There is a strong and significant positive linear relationship between the hourly tailrace measurements at Wells Dam and hourly forebay measurements at Rocky Reach Dam within each of the 10 years analyzed ($P < 0.00$) and for all ten years combined ($P < 0.00$). The linear equation for the relationship between Wells tailrace and Rocky Reach forebay TDG, based upon the ten year record, indicates that Wells tailrace TDG values can be as high as 117.5% and still maintain compliance with the 115% standard at the Rocky Reach Dam forebay.

In addition to developing a compliance equation based upon the historical hourly TDG values, an equation was developed specifically for hours when the Optimum Operation Condition was utilized in 2007 and 2008. Based upon this equation, not only does the Optimum Operating Condition reduce TDG generation in the Wells tailrace but it also appears to alter the depth that supersatured waters enters the Rocky Reach reservoir, thereby increasing the amount of degassing that takes place within the Rocky Reach reservoir. When operating under the Optimum Operating Condition in 2007 and 2008 the Wells tailrace TDG values can be as high as 119.1% (average 118.2%) and still maintain compliance with the 115% Rocky Reach forebay standard.

Based on the historic rate of TDG attenuation for the Rocky Reach reservoir, the Wells Project is reasonably expected to remain in full compliance with the numeric criteria set forth to ensure that a 115% TDG standard is met at the forebay of the downstream project (Rocky Reach Dam) provided that the Optimal Operating Conditions is used to spill water and incoming TDG values in the Wells forebay are in compliance with the 115% standard.

1.0 INTRODUCTION

1.1 General Description of the Wells Hydroelectric Project

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 1.1-1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from the Rocky Reach Hydroelectric Project, owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for the Public Utility District No. 1 of Douglas County (Douglas PUD). It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a top of dam elevation of 795 feet above mean sea level (msl).

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 feet msl (Figure 1.1-1).

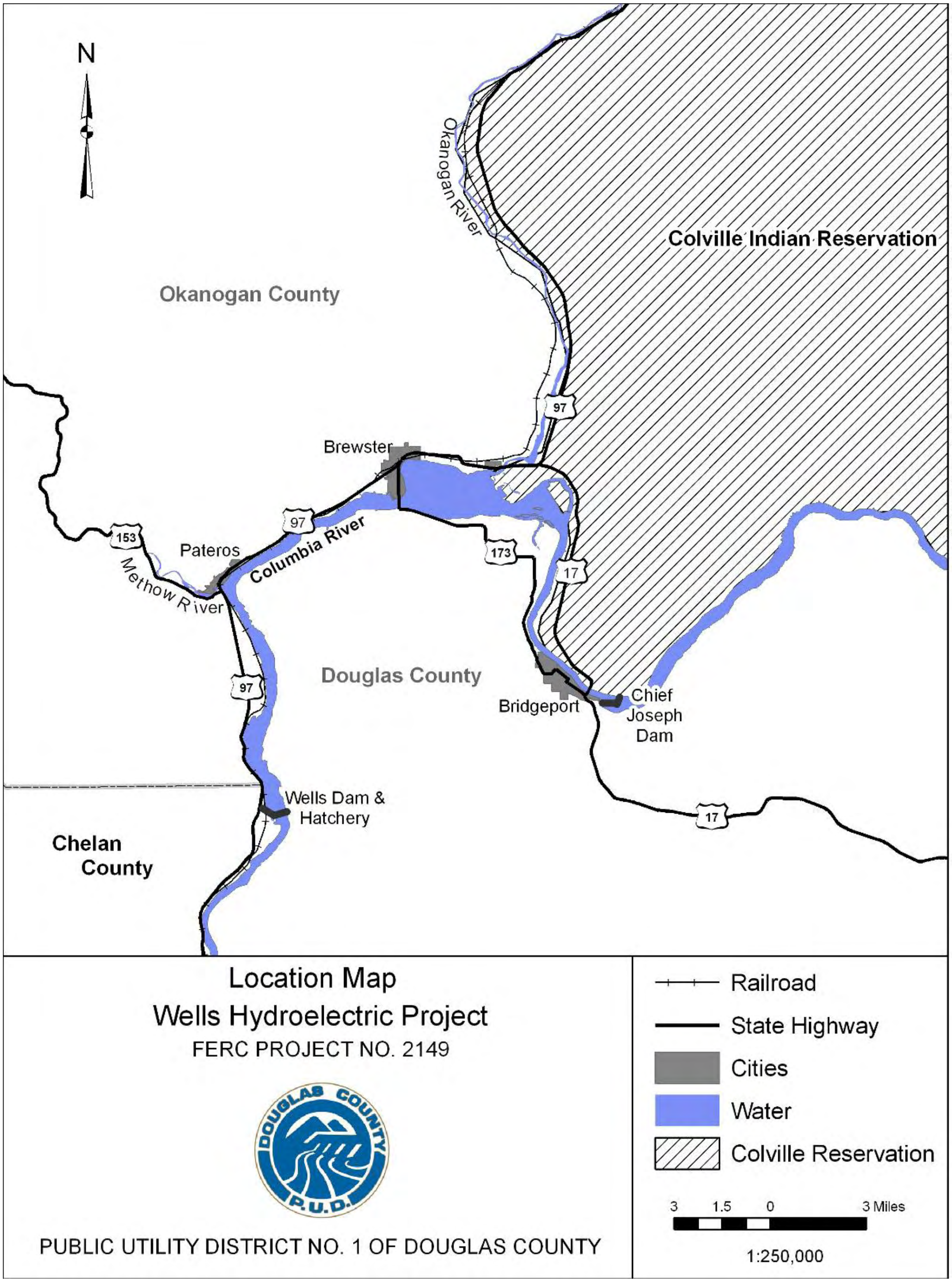

Figure 1.1-1 Location Map of the Wells Hydroelectric Project.

1.2 Overview of Total Dissolved Gas at Wells Dam

The spillway gates at Wells Dam are used to pass water when river flows exceed the maximum turbine hydraulic capacity (forced spill), to assist outmigration of juvenile salmonids (fish bypass spill), and to prevent flooding along the mainstem Columbia River (flood control spill). The Wells Project can pass approximately 22 kcfs through each operating turbine (220 kcfs through 10 turbines) with an additional 10-11 kcfs used to operate the juvenile fish bypass system and 1.0 kcfs to operate the adult fish ladders (ASL Environmental Sciences Inc. 2007). Therefore, spill is forced when inflows are higher than 232 kcfs. Spill may occur at flows less than the hydraulic capacity when the volume of water is greater than the amount required to meet electric system loads. Hourly coordination among hydroelectric projects on the mid-Columbia River was established to minimize unnecessary spill.

Wells Dam is a hydrocombine-designed dam with the spillway situated directly above the powerhouse. Research at Wells Dam in the mid-1980s showed that a modest amount of spill would effectively guide between 92 percent and 96 percent of the downstream migrating juvenile salmonids through the Juvenile Bypass System (JBS) and away from the turbines (Skalski et al., 1996). The operation of the Wells JBS utilizes five spillways that have been modified with constricting barriers to improve the attraction flow while using modest levels of water (Klinge 2005). The JBS will typically use approximately 6-8 percent of the total river flow for fish guidance. The high level of fish protection at Wells Dam has won the approval of the fisheries agencies and tribes and was vital to Douglas PUD meeting the survival standards contained within the Anadromous Fish Agreement and Habitat Conservation Plan (HCP).

State of Washington water quality standards require TDG levels to not exceed 110% at any point of measurement. Due to air entrainment in plunge pools below spillways of hydroelectric dams, TDG levels can sometimes exceed the state standard during spill events at dams. In the State of Washington, there are exceptions allowed to the State's TDG standard. TDG levels are allowed to exceed the standard in order to (1) pass flood flows at the Project of 7Q10 or greater and (2) pass voluntary spill to assist out migrating juvenile salmonids. The 7Q10 flood flow, which is defined as the highest average flow that occurs for seven consecutive days in a once-in-ten-year period, is 246 kcfs at the Wells Project.

2.0 GOALS AND OBJECTIVES

The goal of this study was to optimize spill release configurations at the Wells Project using a validated numerical model to minimize the percent saturation of dissolved gas in the tailrace. Further, descriptive statistics and linear regression techniques are used to demonstrate compliance with TDG criteria outside the fish passage season and at the Rocky Reach forebay monitoring station.

3.0 STUDY AREA

The study area of the numerical model includes approximately 16,500 ft of the Wells tailrace, extending from Wells Dam downstream to transect TW3 (Transect T3) (Figure 3.0-1). Transect TW3 coincides with the Wells TDG compliance monitoring station. The Rocky Reach Dam is located approximately 42 miles downstream of Wells Dam, where the forebay monitor was used to examine degasification through the Wells Dam tailrace and Rocky Reach Dam forebay.

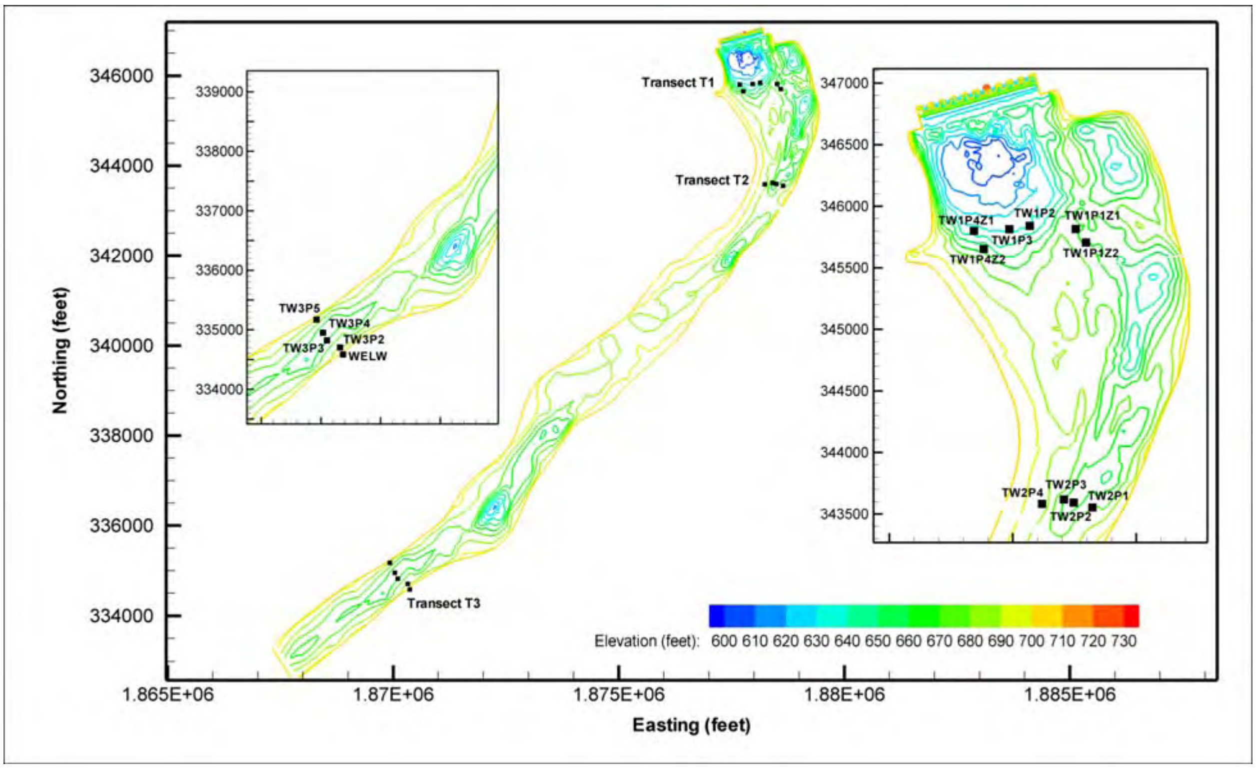

Figure 3.0-1 Study Area for the TDG model.

4.0 BACKGROUND AND EXISTING INFORMATION

4.1 Summary of TDG studies in the Wells Tailrace

Douglas PUD conducted a series of assessments aimed at gaining a better understanding of TDG production dynamics resulting from spill operations at Wells Dam. Each year from 2003 to 2008, Douglas PUD has performed experimental spill operations to document the relationship between water spilled over the dam and the production of TDG.

In 2003 and 2004, Columbia Basin Environmental (CBE) deployed TDG sensors along two transects downstream of Wells Dam. The objectives of this study were to determine the effectiveness of the tailwater sensor and to better understand the relationship between spillway releases and TDG production (CBE 2003, 2004). In a two-week period, the studies showed that the tailwater station provided a reliable record of daily average TDG values in the Wells Dam tailrace.

In spring 2005, Douglas PUD conducted a study to measure TDG pressures resulting from various spill patterns at Wells Dam (CBE 2006). An array of water quality data loggers was installed in the Well tailrace for a period of two weeks between May 23, 2005 and June 6, 2005. The Wells powerhouse and spillway were operated through a controlled range of operational scenarios that varied both total flow and allocation of the spillway discharge. A total of eight configurations were tested including flat spill patterns (near equal distribution of spill across the entire spillway), crowned spill patterns (spill is concentrated towards the center of the spillway), and spill over loaded and unloaded generating units. Results from the study indicated that spill from the west side of the spillway resulted in consistently higher TDG saturations than similar spill from the east side. Flat spill patterns yielded higher TDG saturations than crowned spill for similar total discharges. The results of this study also indicated that TDG levels of powerhouse flows may be influenced by spill.

In 2006, Douglas PUD continued TDG assessments at the Wells Project by examining alternative spill configurations and project operations to minimize the production of TDG. The purpose of the 2006 study was to evaluate how the Project could be operated to successfully pass the 7Q10 river flow while remaining in compliance with Washington State TDG standards. Thirteen sensors were placed along transects in the tailrace located at 1,000, 2,500 and 15,000 feet below Wells Dam. There were also three sensors placed across the forebay. The sensors were programmed to collect data in 15 minute intervals for both TDG and water temperature. Each test required the operations of the dam to maintain stable flows through the powerhouse and spillway for at least a three hour period. While there were 30 scheduled spill events, there were an additional 50 events in which the powerhouse and spillway conditions were held constant for a minimum three hour period. These additional events provided an opportunity to collect TDG data on a variety of Project operations that met study criteria. These are included in the results of the 2006 TDG Abatement Study (EES et al. 2007). Spill amounts ranged from 5.2 to 52.0% of project flow and flows ranged from 2.2 to 124.7 kcfs for spill and 16.4 to 254.0 kcfs for total discharge. There were six tests that were performed at flows that exceeded the Wells Dam 7Q10 flows of 246 kcfs. Results of the study indicated that two operational scenarios, spread spill and concentrated spill (spill from 1 or 2 gates), produced the lowest levels of TDG.

The 2006 study also indicated that the current location of the tailwater TDG compliance monitoring station is appropriate in providing representative TDG production information both longitudinally and laterally downstream of Wells Dam.

4.2 Numerical studies of TDG in Tailraces

Early studies to predict TDG below spillways were based on experimental programs and physical models (Hibbs and Gulliver 1997; Orlins and Gulliver 2000). The primary shortcoming of this approach is that the laboratory models cannot quantitatively predict the change in TDG due to model scaling issues. The approach relies on performance curves that relate flow conditions with past field experiences. This has led to inconsistent results at hydroelectric projects, some being quite successful while others less successful.

Computational fluid dynamics (CFD) modeling offers a powerful tool for TDG and hydrodynamics prediction. In the application to tailrace flows, an understanding of the underlying physics and the capability to model three-dimensional physical phenomena is of paramount importance in performing reliable numerical studies.

The TDG concentration depends on complex processes such as mass transfer between bubbles and water, degasification at the free surface, and TDG mixing. Tailrace flows in the region near the spillway cannot be assumed to have a flat air/water interface which results in the required computation of the free surface shape. As an additional complexity, spillway surface jets may cause a significant change in the flow pattern since they attract water toward the jet region, a phenomenon referred to as water entrainment. Water entrainment leads to mixing and modification of the TDG field. The presence of bubbles has a strong effect on water entrainment. Bubbles reduce the density (and pressure) and effective viscosity in the spillway region and affect the liquid turbulence.

A TDG predictive model must account for the two-phase flow in the stilling basin and the mass transfer between bubbles and water. An unsteady 3D two-phase flow model to predict TDG concentrations in hydropower tailraces was developed by Politano et al. (2007a, 2007b). Variable bubble size and gas volume fraction were calculated by the model to analyze dissolution and the consequent source of TDG. The model assumes anisotropic turbulence and takes into account the effect of bubbles on the flow field and attenuation of normal fluctuations at the free surface. Bubble size and gas volume fraction at the spillway gates were inputs to the model.

5.0 METHODOLOGY

5.1 Model Overview

The models used in this study are based upon the general purpose CFD code FLUENT, which solves the discrete Reynolds Averaged Navier Stokes (RANS) equations using a cell centered finite volume scheme. Two models were used to predict the hydrodynamics and TDG distribution within the tailrace of the Wells Project: a volume of fluid (VOF) model and a rigid-lid non-flat lid model.

The VOF model predicted the flow regime and free-surface for the first 1,000 feet downstream of the dam. The free-surface shape was then used to generate a grid conformed to this geometry and fixed throughout the computation (rigid, non-flat lid approach). After the statistically-steady state was reached, the VOF solution that minimizes the difference between measured and predicted tailwater elevation was selected. Water surface elevations and local slopes derived from simulations using the Hydrologic Engineering Centers River Analysis System (HEC-RAS) were used at the downstream region of the model. The HEC-RAS computations were performed using geometric input files provided by Douglas PUD with a roughness coefficient of 0.035.

The rigid-lid model allowed proper assessment of water entrainment and TDG concentration. The model assumed one variable bubble size, which could change due to local bubble/water mass transfer and pressure. The air entrainment (gas volume fraction and bubble size) was assumed to be a known inlet boundary condition. It must be noted that the choice of bubble size and volume fraction at the spillway bays has an important effect on the level of entrainment and TDG distribution. In this study a reasonable single-size bubble diameter and volume fraction were used at the spillway gates to bracket the experimental TDG data during the model calibration and the same values are used for all computations.

Specific two phase flow models and boundary conditions were implemented into FLUENT through User Defined Functions (UDFs). Two-phase User Defined Scalars (UDSs) transport equations were used to calculate the distribution of TDG and bubble number density.

The model included the main features of the Wells Dam, including the draft tube outlets of the generating units, spillway, top spill in bays 2 and 10 and fish passage facilities (Figure 5.1-1). Bathymetric data supplied by Douglas PUD were used to generate the river bed downstream of the dam. Detail of Figure 5.1-1 shows a cross section through a spillway unit illustrating the Wells Hydrocombine.

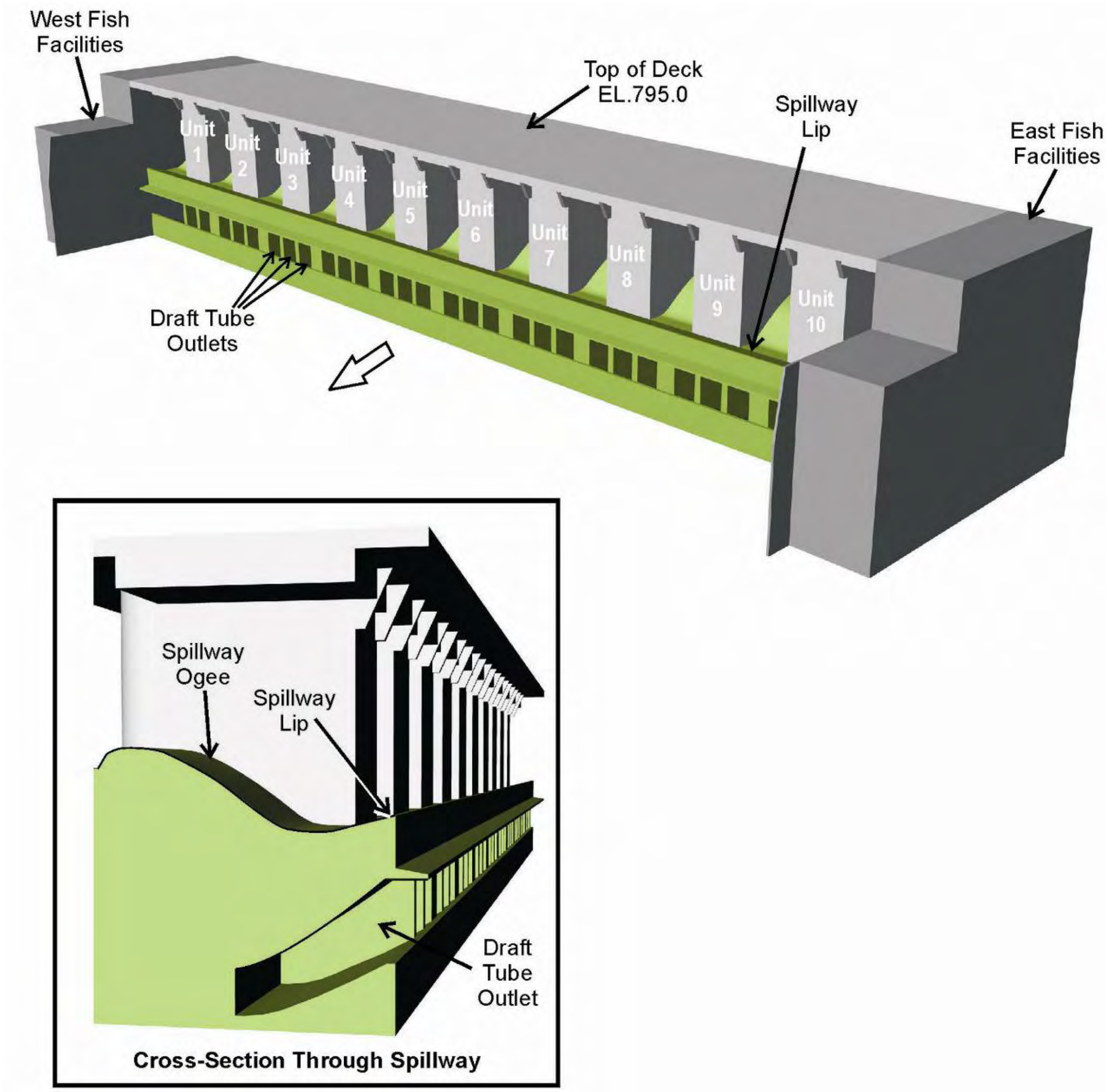

Figure 5.1-1 Structures included in the TDG model.

5.2 VOF Model

5.2.1 Mathematical Model

In the VOF model, the interface between fluids is calculated with a water volume fraction (α_w) transport equation:

$$\frac{\partial \alpha_w}{\partial t} + \vec{v} \cdot \nabla \alpha_w = 0 \qquad (1)$$

Mass conservation requires that $\sum \alpha_i = 1$. The jump conditions across the interface are embedded in the model by defining the fluid properties as: $\varphi = \sum \alpha_i \varphi_i$, where φ is either the density or the viscosity. In the VOF approach, each control volume contains just one phase (or the interface). Points in water have $\alpha_w = 1$, points in air have $\alpha_w = 0$, and points near the interface have $0 < \alpha_w < 1$. The free surface was generally defined in the VOF using an α_w of 0.5.

5.2.2 Grid Generation

The domain was divided into a number of blocks and a structured mesh was generated in each block with common interfaces between the blocks. Each individual block consists of hexahedral cells. To resolve the critical regions of interest, the grids were refined near the solid boundaries, near the turbine intakes and spillway where large accelerations are expected, and near the free surface. The grids containing between 6×10^5 to 8×10^5 nodes were generated using Gridgen V15. Grid quality is an important issue for free surface flow simulations. As fine grids are needed near the interface to minimize numerical diffusion, each simulation required the construction of a particular grid. The grids were constructed nearly orthogonal in the vicinity of the free surface to improve convergence. Figure 5.2-1 shows an overall 3D view of the grid used for the June 5, 2006 simulation. An extra volume at the top of the grid was included to accommodate the air volume for the VOF method.

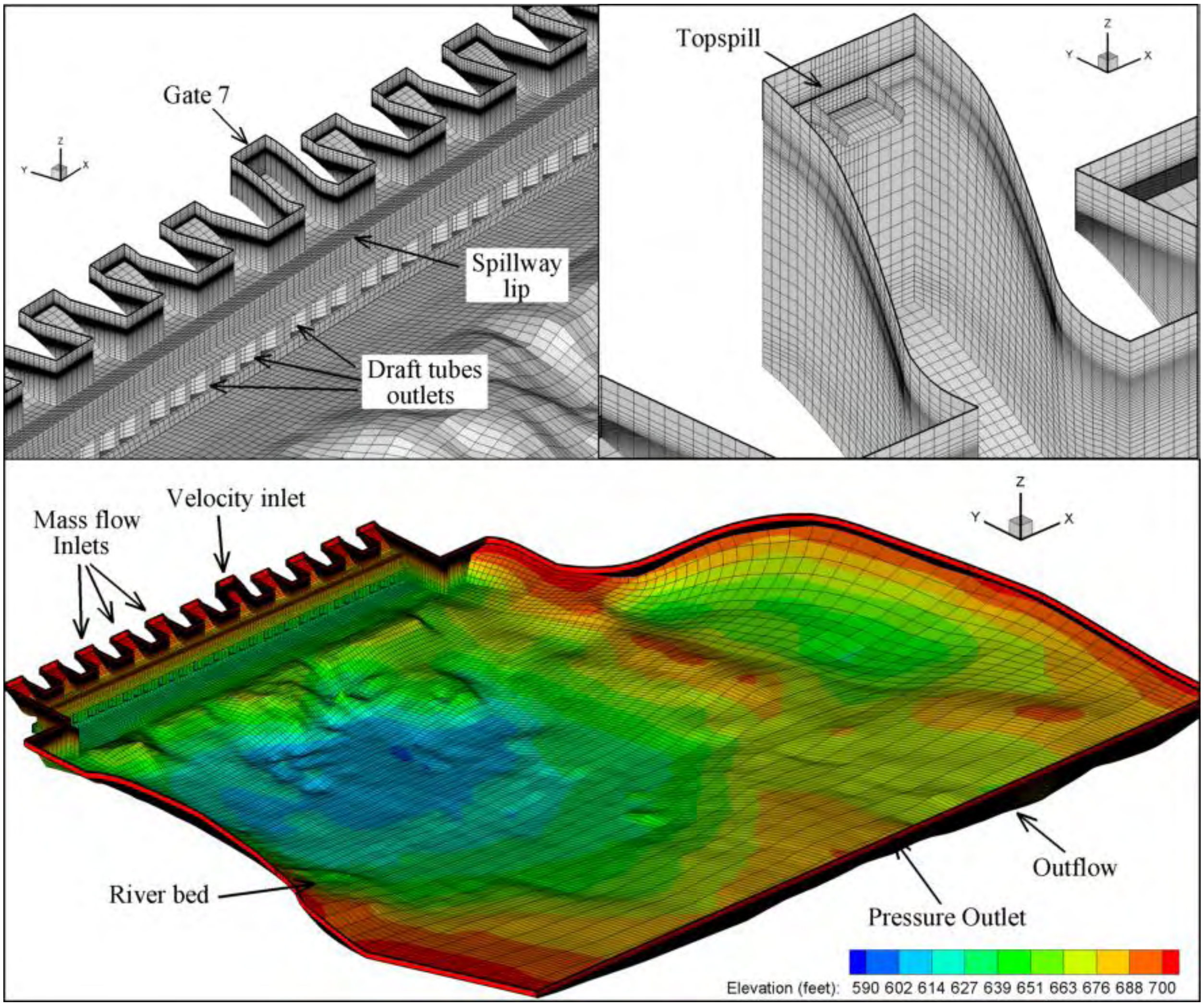

Figure 5.2-1 3D view of a typical grid used for the VOF simulations.

5.2.3 Boundary Conditions

5.2.3.1 Inlet

A given mass flow rate of water assuming uniform velocity distribution was used at each of the turbine units and spillway bays.

5.2.3.2 Walls and River Bed

A no-slip (zero velocity) surface condition was imposed on all walls and tailrace bed.

5.2.3.3 Exit

The free water surface elevation (WSE) was imposed by specifying the water volume fraction distribution. The WSE measured at the tailwater elevation gage was used at the exit (outflow condition in Figure 5.2-1). A hydrostatic pressure was imposed at the outflow using a UDF. At the top of the outflow a pressure outlet boundary condition was used to avoid air pressurization.

5.2.3.4 Top Surface

A pressure outlet boundary condition with atmospheric pressure was applied at the top to allow free air flow and avoid unrealistic pressure.

5.3 Rigid-lid Model

The rigid-lid model is an algebraic slip mixture model (ASMM) that accounts for buoyancy, pressure, drag and turbulent dispersion forces to calculate the gas volume fraction and velocity of the bubbles. The model considers the change of the effective buoyancy and viscosity caused by the presence of the bubbles on the liquid and the forces on the liquid phase due to the non-zero relative bubble-liquid slip velocity.

5.3.1 Mathematical Model

5.3.1.1 Mass and Momentum Conservation for the Mixture

The two phase model provides mass and momentum equations for the liquid and gas phases (Drew & Passman 1998). Summing the mass and momentum equations for each phase results in continuity and momentum equations for the mixture gas-liquid phase:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left[\rho_m \vec{u}_m \right] = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho_m \vec{u}_m \right) + \nabla \cdot \left(\rho_m \vec{u}_m \vec{u}_m \right) = -\nabla P + \nabla \cdot \left[\boldsymbol{\sigma}_m^{\mathrm{Re}} + \boldsymbol{\tau}_m \right] + \rho_m \vec{g} - \nabla \cdot \left(\sum_{k=g,l} \alpha_k \rho_k \vec{u}_k \vec{u}_{dr,k} \right) \tag{3}$$

where P is the total pressure, $\vec{g}$ is the gravity acceleration, and $\boldsymbol{\sigma}_m^{\mathrm{Re}}$ and $\boldsymbol{\tau}_m = \rho_m \nu_m \left(\nabla \vec{u}_m + \nabla \vec{u}_m^T \right)$ are the turbulent and molecular shear stresses, respectively. ρ_m, μ_m and $\vec{u}_m$ are the mixture density, viscosity and mass-averaged velocity defined as $\rho_m = \sum_{k=g,l} \alpha_k \rho_k$, $\mu_m = \sum_{k=g,l} \alpha_k \mu_g$ and $\vec{u}_m = \frac{1}{\rho_m} \sum_{k=g,l} \alpha_k \rho_k \vec{u}_k$, with α_g the gas volume fraction. The subscripts *g*, *l* and *m* denote gas, liquid and mixture, respectively. $\vec{u}_{dr,k}$ is the drift velocity defined as the velocity of the phase k relative to the mixture velocity.

The gas density is calculated using the ideal gas law $\rho_g = M\,P/(RT)$ with P the pressure, M the molecular weight of air, R the universal gas constant, and T the absolute temperature.

5.3.1.2 Mass Conservation for the Gas Phase

The continuity equation for the gas phase is (Drew & Passman 1998):

$$\frac{\partial}{\partial t}\left(\alpha_g\,\rho_g\right)+\nabla\cdot\left(\alpha_g\,\rho_g\,U_{g,i}\right)=-S \qquad (4)$$

where $\vec{u}_g$ is the bubble velocity and S is a negative gas mass source; in this application the TDG source due to the air transfer from the bubbles to the liquid.

5.3.1.3 Momentum Conservation for the Gas Phase

The ASMM assumes that the inertia and viscous shear stresses are negligible compared to pressure, body forces and interfacial forces in the momentum equation of the gas phase (Antal et al. 1991; Lopez de Bertodano et al. 1994; Manninen et al. 1997):

$$0=-\alpha_g\,\nabla P+\alpha_g\,\rho_g\,\vec{g}+\vec{M}_g \qquad (5)$$

where $\vec{M}_g$ represents the interfacial momentum transfer between the phases.

5.3.1.4 Bubble Number Density Transport Equation

Most of the two fluid models in commercial codes (Fluent, CFX, CFDLib, among others) assume a mean constant bubble size with a given relative velocity (Chen et al. 2005). In tailrace flows the use of a mean constant bubble size for the evaluation of the bubble-liquid mass transfer and interfacial forces is not valid. As a consequence of the complex processes of generation, breakup, and coalescence, the bubbles resulting from air entrainment have different sizes. These processes occur at the plunging jet region immediately after the spillway, where the gas volume fraction and turbulence can be large. The model used in this study is intended for the region downstream of the plunging jet, where bubble size changes mainly due to mass transfer and pressure variations, and therefore bubble breakup and coalescence processes can be neglected. This assumption is considered a reasonable hypothesis for low gas volume fractions (Politano et al. 2007b).

Let $f\,dm\,d\vec{r}$ represent the number of bubbles with original (at the insertion point, before any physical process modifies the bubble mass) mass m, located within $d\vec{r}$ of $\vec{r}$ at time t. The Boltzmann transport equation for f is:

$$\frac{\partial f}{\partial t}+\nabla\cdot\left[\vec{u}_g\,f\right]+\frac{\partial}{\partial m}\left[\frac{\partial m}{\partial t}\,f\right]=0 \qquad (6)$$

Note that this is a Lagrangian representation, and thus *f* has a different interpretation than the usual Eulerian approach (Guido-Lavalle et al. 1994; Politano et al. 2000). Integration of Eq. (6) for bubbles of all masses results in a transport equation for the bubble number density N :

$$\frac{\partial N}{\partial t} + \nabla \cdot \left[\vec{u}_g \, N \right] = 0 \tag{7}$$

The bubble radius is calculated from $R = \left[3\alpha / (4\pi N) \right]^{1/3}$.

5.3.1.5 Two-phase TDG Transport Equation

TDG is calculated with a two-phase transport equation (Politano et al. 2007b):

$$\frac{\partial \alpha_l \, C}{\partial t} + \nabla \cdot \left(\vec{u}_l \, \alpha_l \, C \right) = \nabla \cdot \left(\left(\nu_m + \frac{\nu_t}{Sc_C} \right) \alpha_l \, \nabla C \right) + S \tag{8}$$

where C is the TDG concentration, and ν_m and ν_t are the molecular and turbulent kinematic viscosity, respectively. In this study, a standard Schmidt number of $Sc_C = 0.83$ is used.

5.3.1.6 Turbulence Closure

In this study a Reynolds Stress Model (RSM) was used. The ASMM assumes that the phases share the same turbulence field. The turbulence in the mixture phase is computed using the transport equations for a single phase but with properties and velocity of the mixture. The transport equations for the Reynolds stresses $\boldsymbol{\sigma}_{i,j}^{\mathrm{Re}} = \rho_m \overline{u_{m,i}^{'} \, u_{m,j}^{'}}$ are:

$$\frac{\partial \boldsymbol{\sigma}^{\mathrm{Re}}}{\partial t} + \left(\nabla \cdot \vec{u}_m \right) \boldsymbol{\sigma}^{\mathrm{Re}} + \vec{u}_m \left(\nabla \cdot \boldsymbol{\sigma}^{\mathrm{Re}} \right) = \nabla \cdot \left[\rho_m \frac{\nu_m^t}{\sigma_R} \nabla \boldsymbol{\sigma}^{\mathrm{Re}} \right] - \mathbf{P} + \boldsymbol{\varphi} + \boldsymbol{\varepsilon} + \mathbf{S}_{\boldsymbol{\sigma}} \tag{9}$$

where the stress production tensor is given by $\mathbf{P} = \boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T + \left(\boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T \right)^T$, $\boldsymbol{\varepsilon} = 2/3 \, \mathbf{I} \, \rho_m \, \varepsilon$ and $\sigma_R = 0.85$. The pressure-strain tensor $\boldsymbol{\varphi}$ is calculated using the models proposed by Gibson and Lander (1978), Fu et al. (1987) and Launder (1989). In this study, $\mathbf{S}_{\boldsymbol{\sigma}}$ represents the effect of the bubbles on the Reynolds stresses. The transport equation for the turbulent dissipation rate reads:

$$\frac{\partial}{\partial t}\left(\rho_m \, \varepsilon \right) + \nabla \cdot \left(\rho_m \, \vec{u}_m \, \varepsilon \right) = \nabla \cdot \left[\rho_m \left(\nu_m + \frac{\nu_m^t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] - C_{\varepsilon 1} \, \rho_m \, \frac{1}{2} \mathrm{Tr}\left(\mathbf{P} \right) \frac{\varepsilon}{k} - C_{\varepsilon 2} \, \rho_m \, \frac{\varepsilon^2}{k} + S_\varepsilon \tag{10}$$

with $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $\sigma_\varepsilon = 1$. The turbulent kinetic energy is defined as $k = \frac{1}{2\rho_m} \mathrm{Tr}(\boldsymbol{\sigma})$. The source term S_ε accounts for the effect of the bubbles on the turbulent dissipation rate. The turbulent kinematic viscosity is computed as in the $k-\varepsilon$ models using $\nu_t = C_\mu k^2 / \varepsilon$, with $C_\mu = 0.09$.

5.3.1.7 Constitutive Equations

In order to close the model, interfacial transfer terms emerging from the relative motion between the bubbles and the continuous liquid need to be modeled.

Interfacial momentum

Since in this particular application there are no significant velocity gradients or flow accelerations (in the bubble scale), most interfacial forces such as lift and virtual mass are negligible compared with drag and turbulent dispersion forces:

$$\vec{M}_g = \vec{M}_g^D + \vec{M}_g^{TD} \tag{11}$$

where $\vec{M}_g^D$ and $\vec{M}_g^{TD}$ are the drag and turbulent dispersion terms. The drag force can be modeled as (Ishii and Zuber 1979):

$$\vec{M}_g^D = -\frac{3}{8} \rho_m \alpha_g \frac{C^D}{R} \vec{u}_r |\vec{u}_r| \tag{12}$$

where $\vec{u}_r$ is the relative velocity of the gas phase respect to the liquid phase. Most of the numerical studies use drag correlations based on rising bubbles through a stagnant liquid proposed by Ishii & Zuber (1979) (see Lane et al. 2005):

$$C^D = \begin{cases} \dfrac{24}{\mathrm{Re}_b} & if\ R < 0.0002 \\ \dfrac{24\left(1 + 0.15\,\mathrm{Re}_b^{0.867}\right)}{\mathrm{Re}_b} & if\ 0.0002 < R < 0.0011 \end{cases} \tag{13}$$

where $\mathrm{Re}_b = 2\rho_l |\vec{u}_r| R / \mu_l$ is the bubble Reynolds number. The turbulent dispersion term is modeled as (Carrica et al. 1999):

$$\vec{M}_g^{TD} = -\frac{3}{8} \frac{\nu^t}{Sc_b} \rho_m \frac{C^D}{R} |\vec{u}_r| \nabla \alpha_g \tag{14}$$

where $Sc_b = \nu^t / \nu^b$ is the bubble Schmidt number. Following Carrica et al. (1999), $Sc_b = 1$ is used.

Bubble dissolution and absorption

The rate of mass transfer is computed considering that the air is soluble in water and obeys Henry's law and that the air molar composition is that of equilibrium at atmospheric pressure, which implies that the air is considered a single gas with molar averaged properties. The mass flux from gas to liquid can be expressed by (Deckwer 1992; Politano et al. 2007b):

$$S = 4\pi N R^2 k_l \left(\frac{P + \sigma/R}{He} - C \right) \tag{15}$$

where σ is the interfacial tension and He is the Henry constant. The second term on the RHS of Eq. (15) accounts for the effect of the interfacial tension on the equilibrium concentration. The effect of temperature on the Henry constant is modeled using the Van 't Hoff equation:

$$He(T) = He(T_o) \exp\left[-C_T \left(\frac{1}{T} - \frac{1}{T_o} \right) \right] \tag{16}$$

where T is the absolute temperature and T_o refers to the standard temperature (298 K). A constant for air $C_T = 1388\,K$ is used in this model.

Takemura and Yabe (1998) proposed a correlation for the mass transfer coefficient of spherical rising bubbles, where the turbulence is generated by the rising bubbles:

$$k_l^{rb} = \frac{D\, Pe_b^{0.5}}{\sqrt{\pi} R} \left(1 - \frac{2}{3\left(1 + 0.09\, \mathrm{Re}_b^{2/3}\right)^{0.75}} \right) \tag{17}$$

where D is the molecular diffusivity and the bubble Peclet number is $Pe_b = 2 \left|\overrightarrow{u_r}\right| R / D$.

External turbulence could be important in flows downstream of spillways, mainly in regions of high shear near the walls and where the plunging jet impacts and enhances the mass transfer. In this application, the mass transfer coefficient can be calculated using the expression proposed by Lamont and Scott (1970):

$$k_l^t = 0.4\, Sc^{-1/2} (\nu\, \varepsilon)^{1/4} \tag{18}$$

where $Sc = D/\nu$. In this study, the same order of magnitude is obtained from Eqs. (17) and (18), thus the maximum mass transfer coefficient between bubbles rising in stagnant liquid (k_l^{rb}) and bubbles in turbulent flow (k_l^t) is used: $k_l = \max\left(k_l^{rb}, k_l^t\right)$.

5.3.2 Grid Generation

The Wells tailrace structures and the bathymetry are meshed with structured and unstructured multi-block grids containing only hexahedral elements, using Gambit and Gridgen V15. Typical grid sizes are in the range of 7 10^5 to 1 10^6 nodes. Figure 5.3-1 shows typical grids used for the rigid-lid model. Details (a) and (b) show free surface shapes for spread and concentrated flows, respectively. Detail (c) shows the unstructured grid, extended from approximately 1,500 feet to 3,500 feet downstream of the Wells Dam, used to reduce grid size and improve aspect ratio.

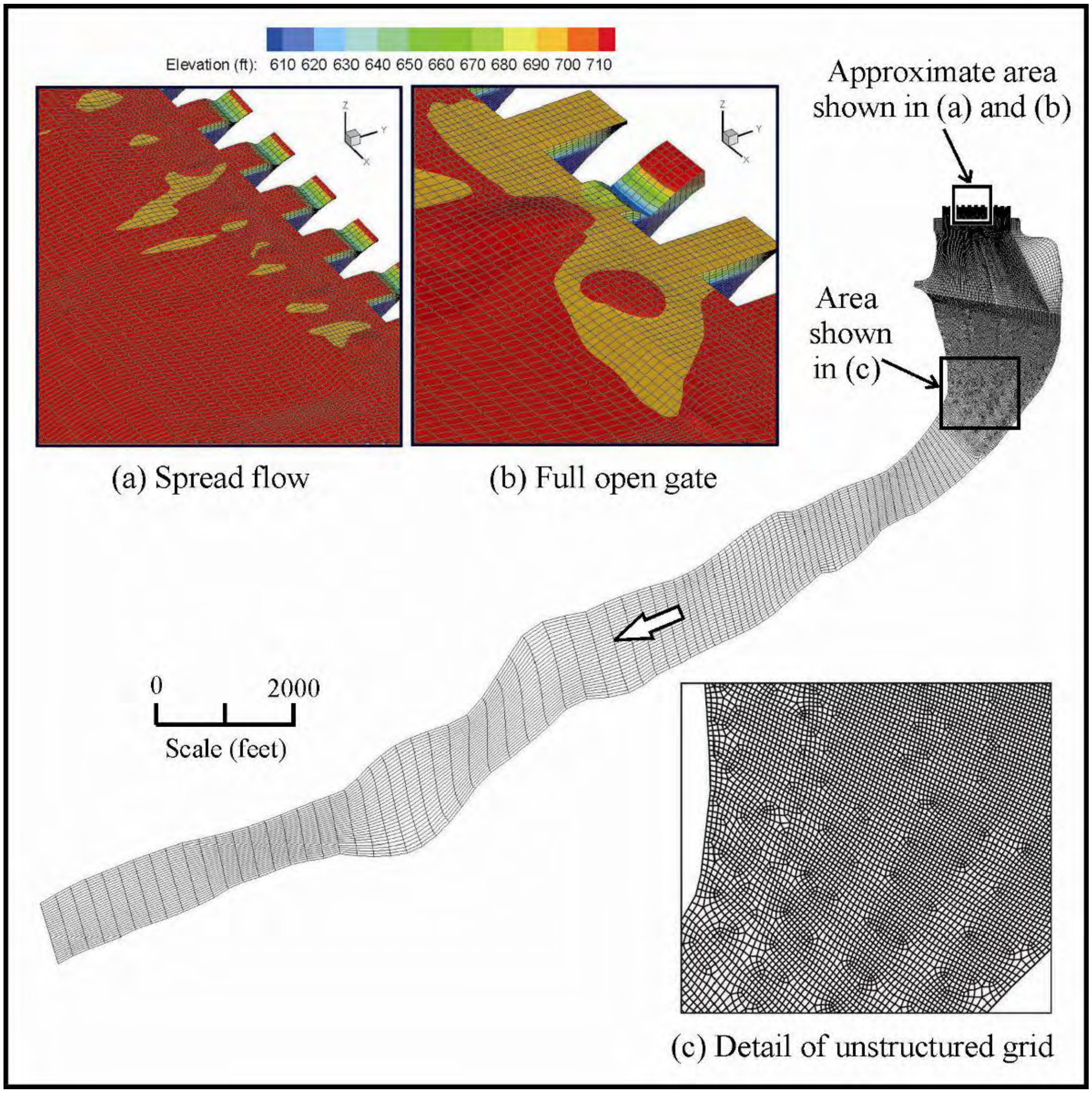

Figure 5.3-1 3D view of a typical grid used for the rigid-lid simulations.

5.3.3 Boundary Conditions

5.3.3.1 Free Surface

Kinematic and dynamic boundary conditions enforcing zero normal velocity fluctuations at the free surface are programmed through UDFs. Details of the implementation of the boundary conditions used for the Reynolds stress and velocity components are found in Turan et al. (2007).

In order to allow the gas phase to flow across the interface, the normal component of the gas velocity at the free surface is calculated using a mass balance for the gas phase in each control volume contiguous to the interface. The resulting equation is implemented using UDFs.

For the TDG concentration, a Neumann boundary condition is used. A mass transfer coefficient at the free surface of $k_l = 0.0001$ m/s as measured by DeMoyer et al. (2003) for tanks and bubble columns is used.

5.3.3.2 Walls and River Bed

The sides and the river bed are considered impermeable walls with zero TDG flux. For the gas phase, no penetration across walls is imposed.

5.3.3.3 Exit

The river exit is defined as an outflow. A zero gradient condition was programmed for the TDG concentration and bubble number density.

5.3.3.4 Spillbays and Powerhouse Units

Uniform velocities with constant gas volume fraction of $\alpha = 0.03$ and bubble diameter 5 mm are used for the 11 bays in the spillway region. The gate opening for a give spill flow rate was selected based on the forebay elevation and spillway gate rating provided by Douglas PUD.

It is assumed that air is not entrained with the turbine inflow. The TDG concentration measured in the forebay is used at the spillway bays and powerhouse units.

5.4 Modeling Assumptions and Model Inputs

5.4.1 Model Assumptions

The model used in this study assumes that:

- Gas and liquid phases are interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of volume fraction is used.
- A local equilibrium over short spatial length scale is assumed. Therefore, the gas-liquid relative velocity can be calculated with algebraic equations.
- The liquid phase is considered incompressible.
- The turbulence can be described by the RSM turbulence model.

- The free surface shape, computed from VOF simulations, is not affected by the presence of bubbles. The presence of bubbles is accounted in the two-phase rigid-lid model.
- The air is considered a unique gas with molar averaged properties.
- Bubble size changes mainly due to mass transfer and pressure and breakup and coalescence are negligible.

5.4.2 Model Inputs

The bubble size and gas volume fraction at the inlet (spillway bay gates) are model parameters selected based upon the calibration of the model.

Environmental factors such as forebay TDG, forebay elevation, and water temperature are based upon historical data most likely to occur during flows equal to or greater than the 7Q10 flow of 246 kcfs.. The conditions were based on hourly observations recorded between April and September throughout the ten-year period 1999-2008 (daily average flows ≥ 200 kcfs did not occur outside of the April to September time frame; DART Hourly Water Quality Composite Report www.cbr.washington.edu/dart/hgas_com.html).

5.4.2.1 Environmental Conditions

The environmental data described above (43,200 hourly records) were subsequently filtered to include values in which outflow was equal to or greater than 200 kcfs to represent high flow conditions at Wells Dam (2,941 hourly records). Temporal distribution of hourly values (by week of the year) range from early April to early September, with the middle quartiles (25% to 75%) occurring between weeks 23 and 26 (4-June and 25-June). Median values of the distribution occur at week 24. Hourly flow measurements averaged 221 kcfs (±18 kcfs SD) during these 'high flow' events, though 50% (median) of flows were ≤ 215 kcfs and only 12% of values exceeded 246 kcfs. Water temperatures during these occurrences range from 4.1-19.7°C, with a median temperature of 13.0°C (Figure 5.4-1). Forebay TDG during these occurrences (≥ 200 kcfs) range from 99.9-120.1% with a median TDG of 112.5 % (Figure 5.4-2). Average daily forebay elevations were also collected from DART throughout the same period (1999-2008; www.cbr.washington.edu/dart/river.html). When average daily flows were ≥ 200 kcfs, forebay elevation ranges from 775-781 feet, with a median elevation of 779.6 feet (Figure 5.4-3; note that the five outliers ~ 775 feet occurred consecutively between June 4th and June 8th, 2002). Since the distributions of the three values needed for model input (water temperature, forebay TDG, and forebay elevation) have a slightly negative or 'left' skew (that is, mean values are slightly less than median values), the median values, rounded to the nearest whole number or percent, were used to best represent environmental conditions under high-flow events.

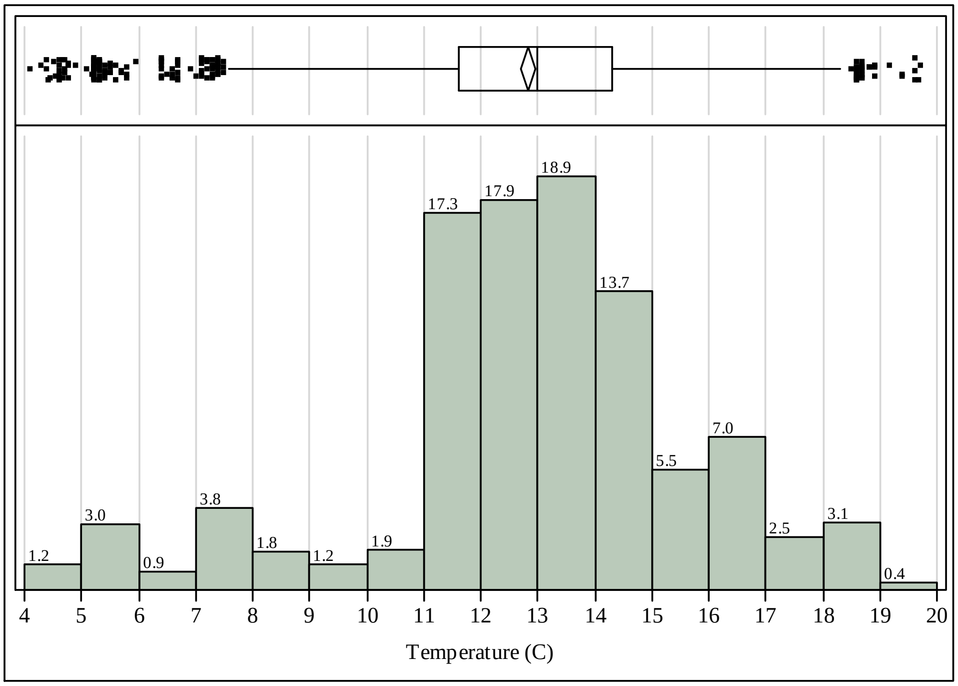

Figure 5.4-1 **Distribution of water temperatures (°C) during flows equal to or greater than 200 kcfs between April and September, 1999-2008. Percent occurrence of values is shown above histogram bars.**

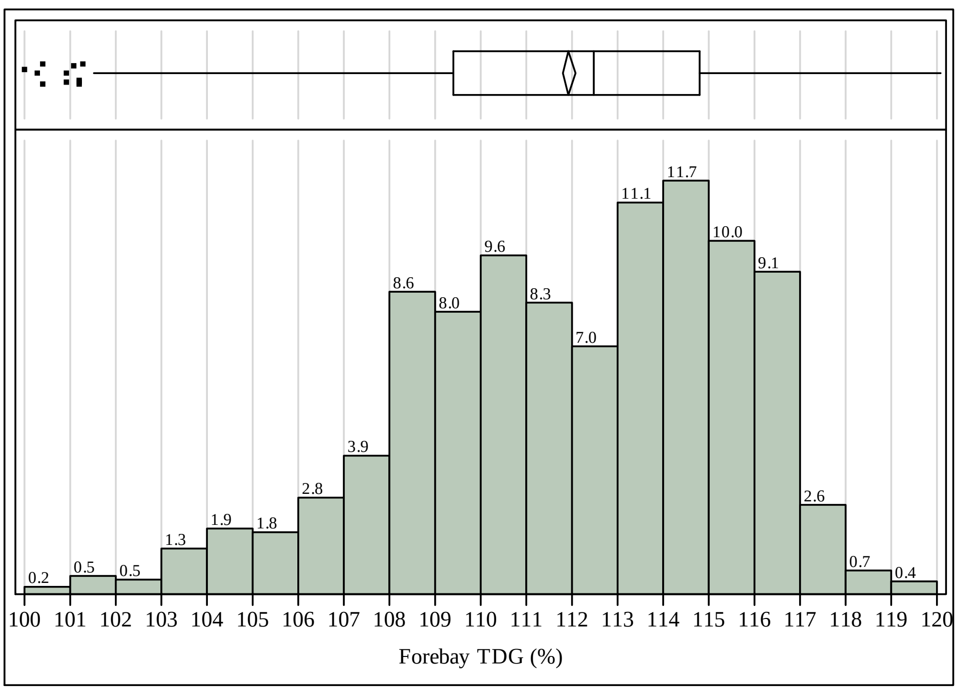

Figure 5.4-2 **Distribution of forebay TDG (%) during flows equal to or greater than 200 kcfs between April and September, 1999-2008. Percent occurrence of values is shown above histogram bars.**

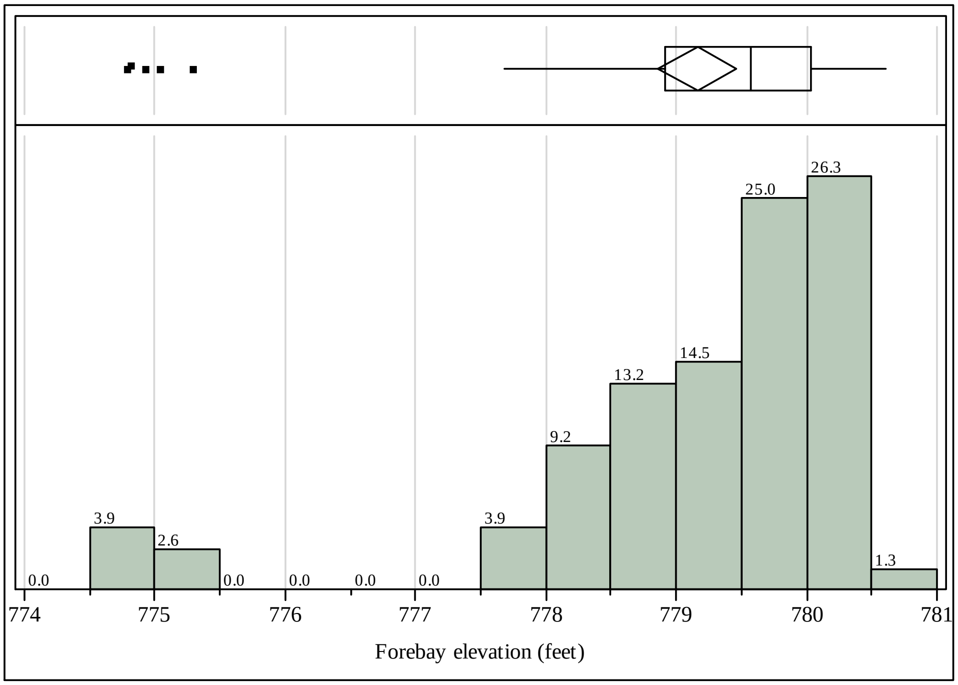

Figure 5.4-3 Distribution of forebay elevations (feet) during daily average flows equal to or greater than 200 kcfs, 1999-2008. Percent occurrence of values is shown above histogram bars.

6.0 NUMERICAL METHOD

The computations were performed using 4 processors of a Linux cluster with 2 GB of memory per processor and in three dual socket dual core Xeon Mac Pro systems.

6.1 VOF Model

The discrete RANS equations and Eq. (1) were solved sequentially (the segregated option in Fluent) and coupled to a realizable $k-\varepsilon$ model with wall functions for turbulence closure. The pressure at the faces is obtained using the body force weighted scheme. The continuity equation was enforced using a Semi-Implicit Method for Pressure-Linked (SIMPLE) algorithm. A modified High Resolution Interface Capturing (HRIC) scheme was used to solve the gas volume fraction.

Unsteady solutions were obtained using variable time-step between 0.001 to 0.01 seconds. Typically, two to three nonlinear iterations were needed within each time step to converge all variables to a L_2 norm of the error $<10^{-3}$. The flow rate at the exit and the elevation at the tailwater elevation gauge location were selected as convergence parameters.

6.2 Rigid-lid Model

The ASMM model equations were solved sequentially. The VOF and rigid-lid simulations were performed using the same discretization schemes for the continuity and pressure equations. A first order upwind scheme was used for the gas volume fraction and Reynolds stress components.

Unsteady solutions were obtained using a fixed time-step of 10 seconds. In order to improve convergence, the model was first run assuming single-phase flow and then bubbles were injected into the domain. The rigid-lid model was computed in typically 7 hours (2 days of computation time) to obtain a steady condition for the flow field and TDG concentration.

7.0 VALIDATION AND CALIBRATION OF THE MODEL

7.1 Simulation Conditions

The ability of the model to predict the TDG distribution and hydrodynamics was evaluated using field data collected for a period of six weeks between May 14, 2006 and June 28, 2006, during the TDG production dynamics study (EES et al. 2007). Velocities were measured on three transects in the near field region of the Wells tailrace on June 4, 2006 and June 5, 2006. Figure 3.0-1 shows the 15 stations where TDG sensors were deployed during the field study.

7.1.1 Calibration

The model was calibrated with data collected on June 4 and June 5, 2006, referred to as treatments 46 and 47 in the report by EES et al. (2007). The spillway flow was spread across all spillbays on June 4 and concentrated in a single spillbay on June 5. Total river flows during these treatments were 172.4 kcfs and 222.3 kcfs, respectively. Tables in Appendix A summarize plant operations, TDG saturation in the forebay, and tailwater and forebay elevations on these days. Powerhouse and spillway units are numbered from west to east.

7.1.2 Validation

The predictive ability of the numerical model was validated using three different spillway conditions tested in 2006. The three spillway conditions are: treatment 1-Full Gate (FG); treatment 11-FG; and treatment 63-Concentrated (C). The FG designates the use of a single spill bay whereas C designates a crowned spill pattern. Total river flows during these treatments were 120.4 kcfs, 157.2 kcfs and 205.5 kcfs, respectively. Plant operation and tailwater elevations associated with each of the treatments are tabulated on Tables in Appendix A.

7.2 VOF Model Results

The objectives for the calibration and verification VOF simulations were to establish a steady state solution that yield a flow field, including spillway jet regimes, consistent with that was observed in the field.

7.2.1 Calibration

The calibration cases were run in a domain of approximately 3,000 ft downstream of the dam. Zero velocities and turbulence were used as initial conditions in the entire domain.

The convergence parameters for the calibration cases were:

$$46S - June\ 4, 2006 \rightarrow (\ flowrate: 172.4\ kcfs, WSE: 717.3\ ft)$$
$$47FG - June\ 5, 2006 \rightarrow (\ flowrate: 222.3\ kcfs, WSE: 720.2\ ft)$$

Horizontal lines in Figure 7.2-1 show the target flow rate (blue line) and WSE at the tailwater elevation gage (green line). The evolution of the simulations for the calibration cases is illustrated in Figure 7.2-1; blue lines represent the flow rate at the exit and the green lines the free surface elevation. It was found that statistically steady solutions were obtained at approximately 30 minutes, which required about 60 days of computation time.

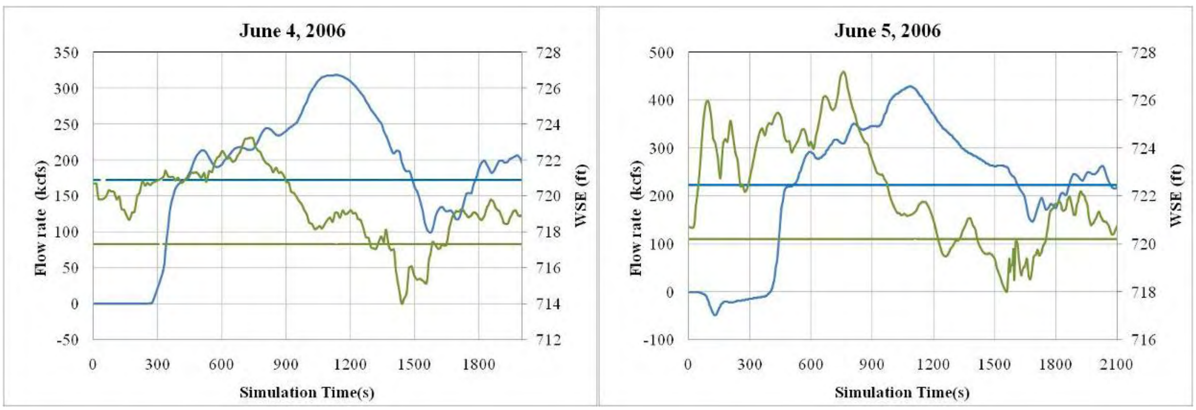

Figure 7.2-1 Evolution of the flow rate at the exit (blue line) and free surface elevation (green line) for June 4, 2006 and June 5, 2006. Horizontal lines represent target values.

Figure 7.2-2 shows an isosurface of gas volume fraction $\alpha_w = 0.5$ representing the free-surface location used to create the top of the rigid-lid grid for the June 4, 2006 simulation. In Figure 7.2-3 a horizontal slice at 27 ft from the free-surface (top) and a vertical section at the center of spillway bay 7 (bottom) show the predicted flow field with the VOF method. Red and blue contours represent water and air, respectively. For clarity, predicted velocity vectors were interpolated in structured uniform grids. Almost uniform flow is observed close to the spillway during the spread flow operation. Surface jets are predicted in all the spillway bays due to elevated tailwater levels. In addition, water flow from the powerhouse units prevented the spillway jet from plunging to depth within the stilling basin.

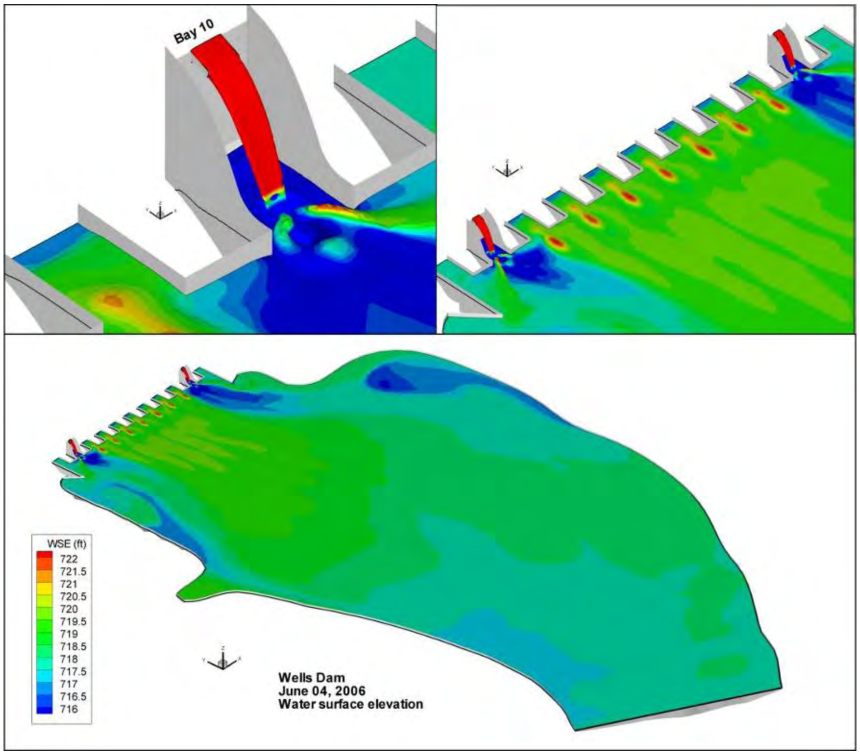

Figure 7.2-2 Predicted free surface shape for June 4, 2006.

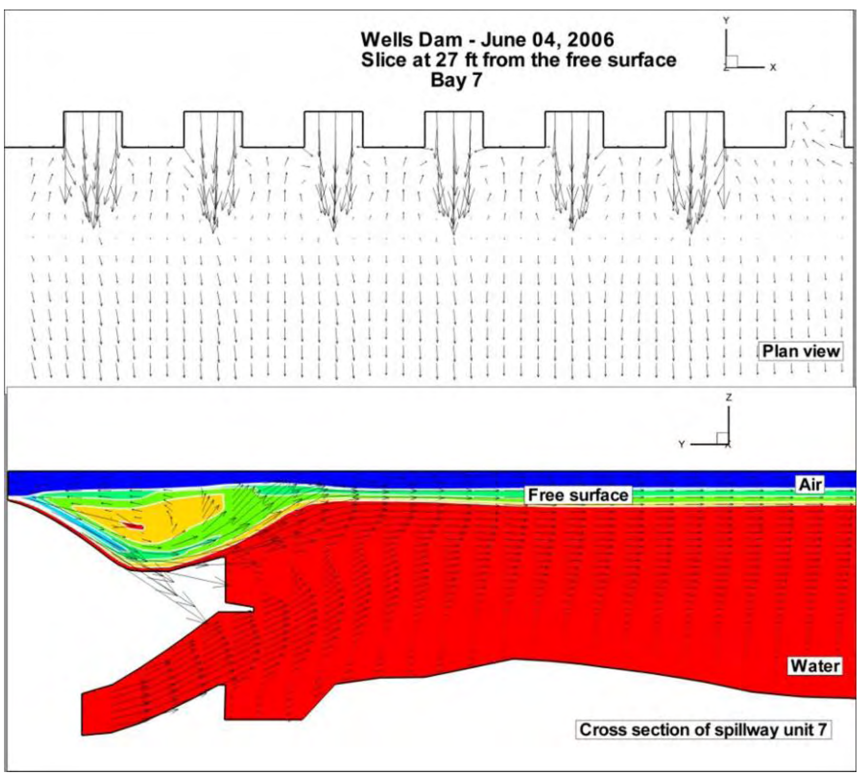

Figure 7.2-3 Predicted flow field for June 4, 2006.

The free surface used to create the rigid-lid grid for June 5, 2006 is shown in Figure 7.2-4. The top of Figure 7.2-5 shows the water attraction toward the surface jet on bay 7 (water entrainment) caused by the full open gate operation. The water entrainment causes the formation of two large eddies near the east and west bank of the Wells tailrace. As observed on June 4, 2006, the strong surface jet originated in bay 7 remains close to the free surface (see bottom picture in Figure 7.2-5) due to the favorable tailwater elevation and plant operation on this day.

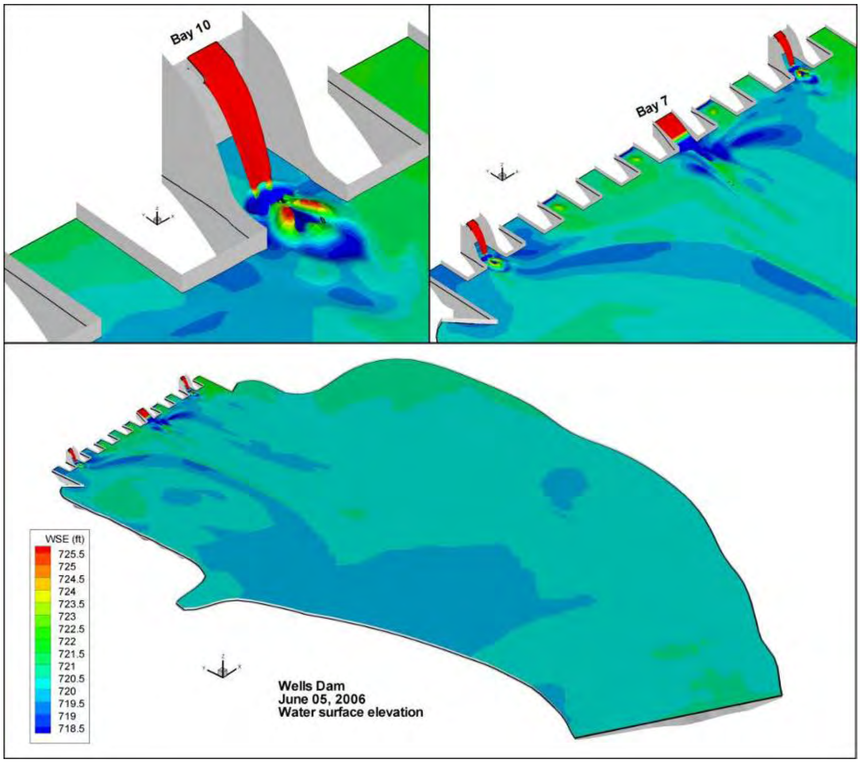

Figure 7.2-4 Predicted free surface shape for June 5, 2006.

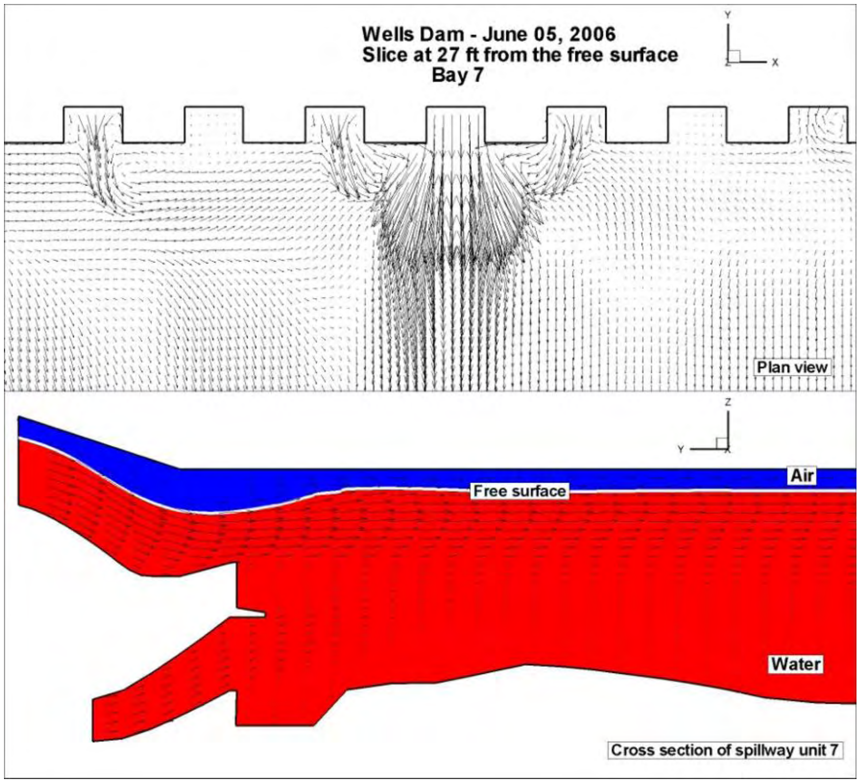

Figure 7.2-5 Predicted flow field for June 5, 2006.

7.2.2 Validation

The domain used to simulate the validation cases was reduced to 1,700 ft downstream of the dam with the purpose of speeding up the VOF computations. During the calibration it was observed that the effect of the top spill on the free surface shape is limited to a small region near spillway bays 2 and 10. Therefore the validation cases assumed that spillway bays 2 and 10 were closed and the free surface shape obtained during the calibration process was used near the top spills.

The numerical solution (pressure, velocity, free surface location and turbulent quantities) obtained on June 5, 2006 was used as an initial condition for the validation cases.

The convergence parameters for the calibration cases were:

$$1FG - May\ 14, 2006 \rightarrow (\ flowrate: 120.4\ kcfs, WSE: 711.5\ ft)$$

$$11FG - May\ 17, 2006 \rightarrow (\ flowrate: 157.2\ kcfs, WSE: 715.4\ ft)$$

$$63C - June\ 17, 2006 \rightarrow (\ flowrate: 205.5\ kcfs, WSE: 718.6\ ft)$$

Figure 7.2-6 shows the evolution of the flow rate and WSE at the tailwater elevation gauge for the validation cases. Blue and green lines represent the flow rate and WSE, respectively. The above mentioned simplifications allowed the calibration cases to reach the statistically steady solutions in typically 20 minutes using 30 days of computation time.

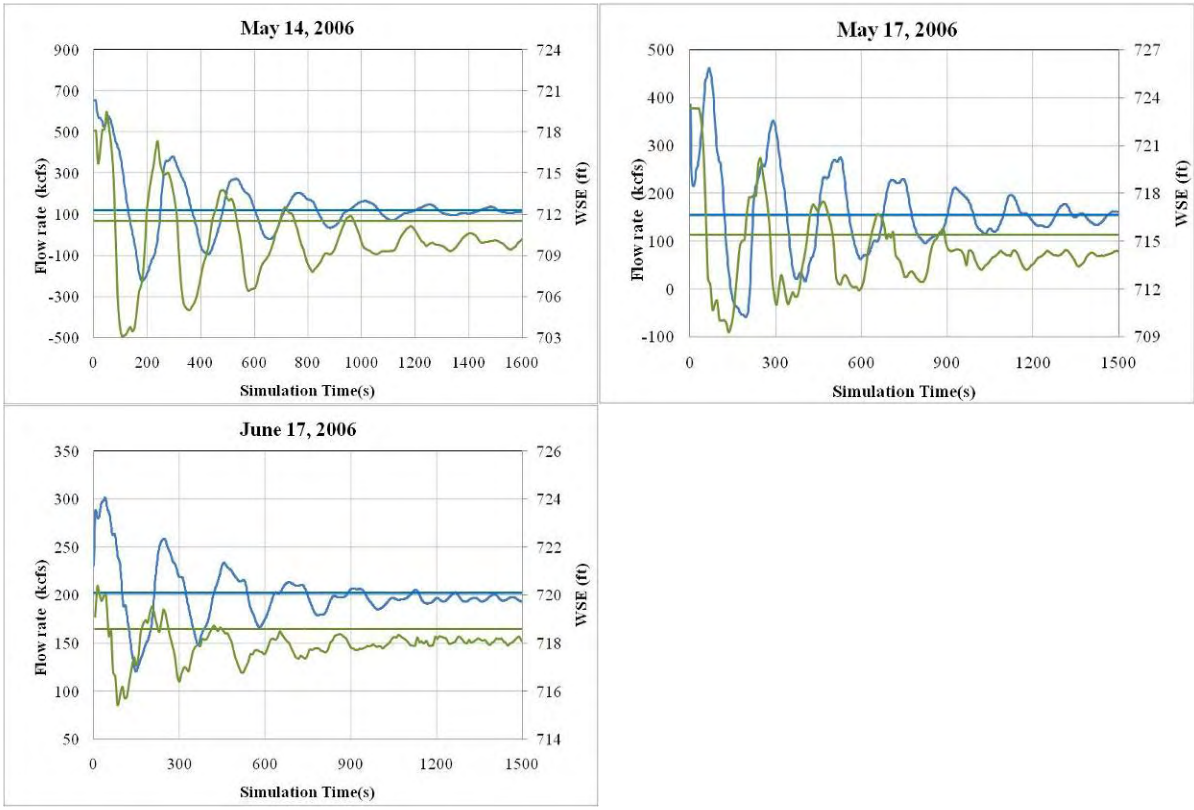

Figure 7.2-6 Evolution of the flow rate at the exit (blue line) and free surface elevation (green line) for May 14, 2006, May 17, 2006, and June 17, 2006. Horizontal lines represent target values.

7.3 Rigid-lid Model Results

7.3.1 Hydrodynamics

Figures 7.3-1 and 7.3-2 show depth-averaged velocity data collected in the field on June 4, 2006 and June 5, 2006 and those predicted by the rigid-lid model. Good agreement between observed and predicted velocity vectors was found, especially at the downstream transect where flow conditions were more stable and the Acoustic Doppler Current Profiler (ADCP) velocity data are less affected by turbulence and non-steady conditions.

As observed in the field, the model captured the counterclockwise eddy near the east bank and the almost uniform profile at the most downstream transect.

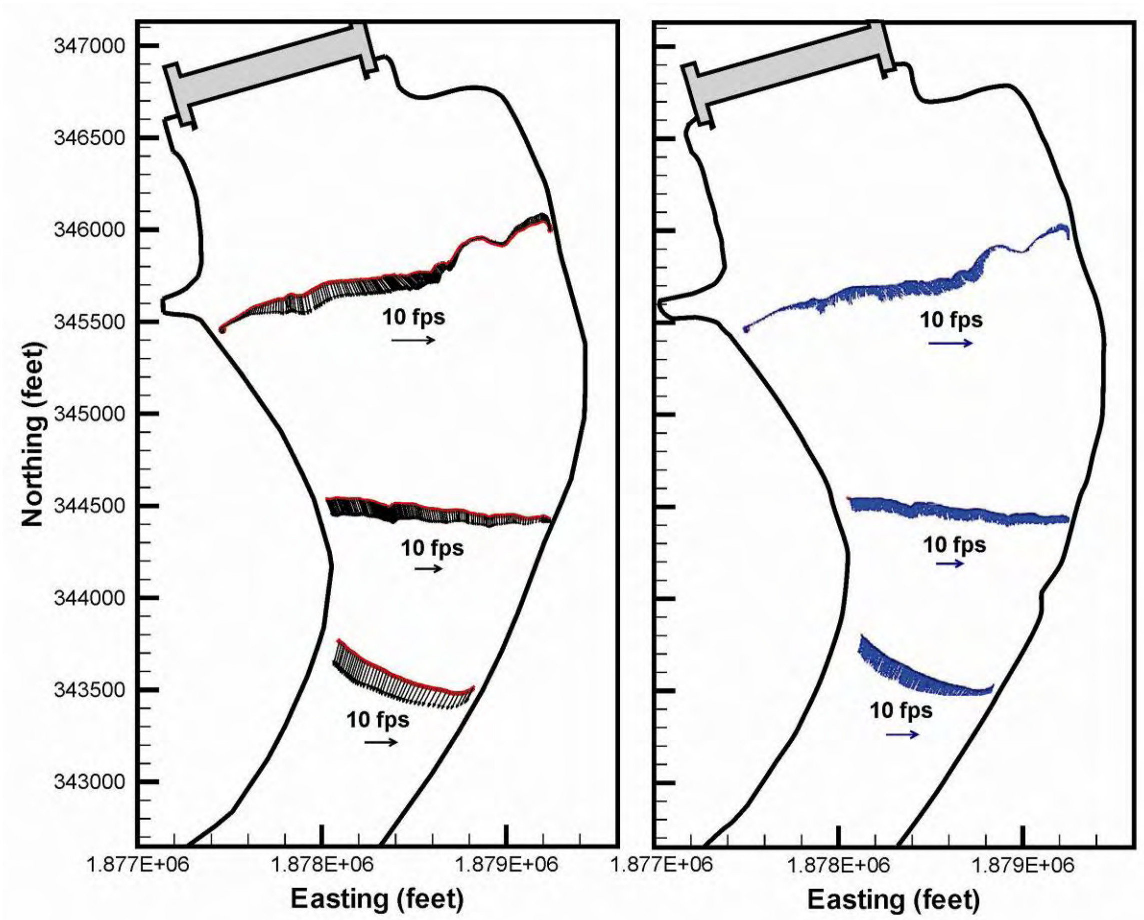

Figure 7.3-1 Flow field on June 4, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data.

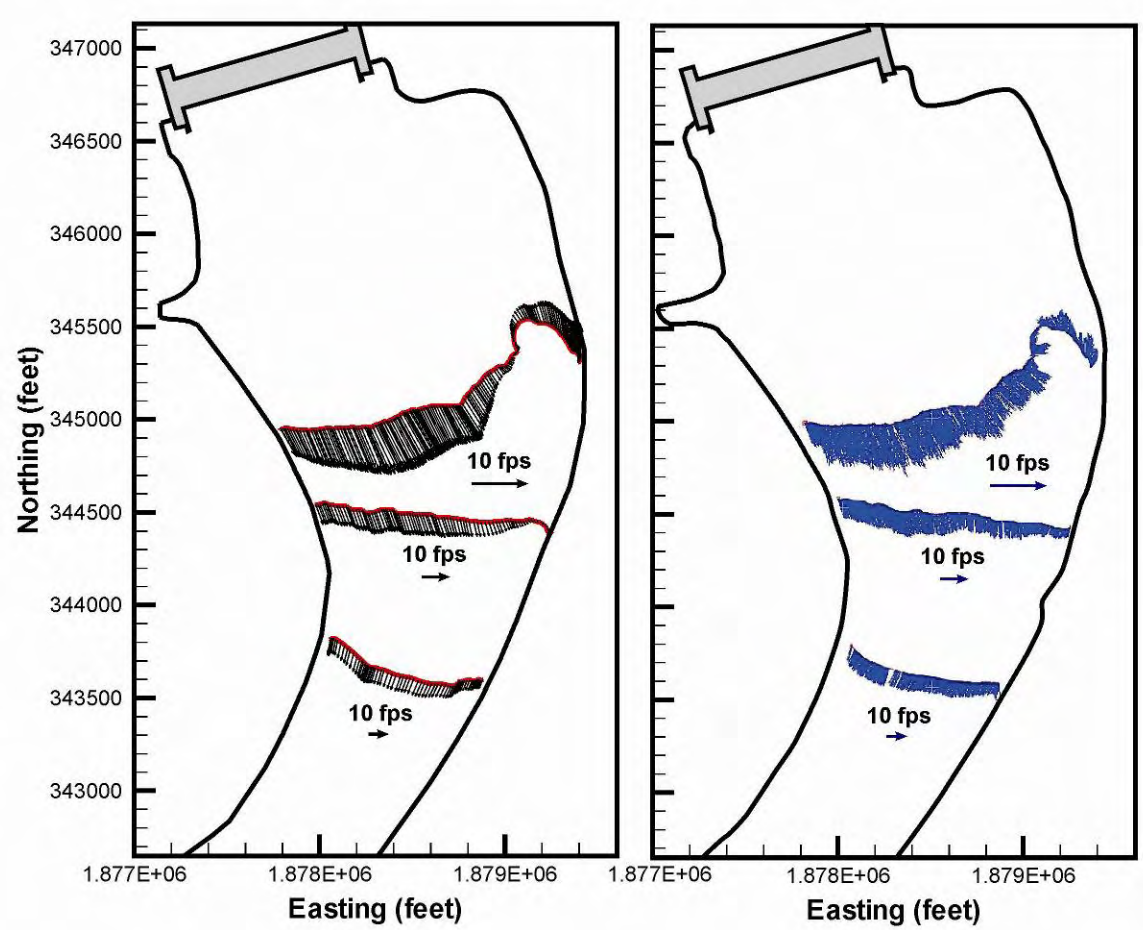

Figure 7.3-2 Flow field on June 5, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data

7.3.2 TDG Model

The percent saturation of TDG measured in the field at each station and the mean TDG in each of the three transects together with the values generated by the CFD model for the calibration and validation cases are shown in Appendix B. Figures 7.3-3 to 7.3-7 show measured and predicted values at each probe location. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations.

The model captures the reduction of TDG with distance downstream and the lateral gradient observed in the field. As measured, the highest predicted TDG value at Transect TW1 occurred in the center of the channel and the lateral gradients in transects TW2 and TW3 were negligible.

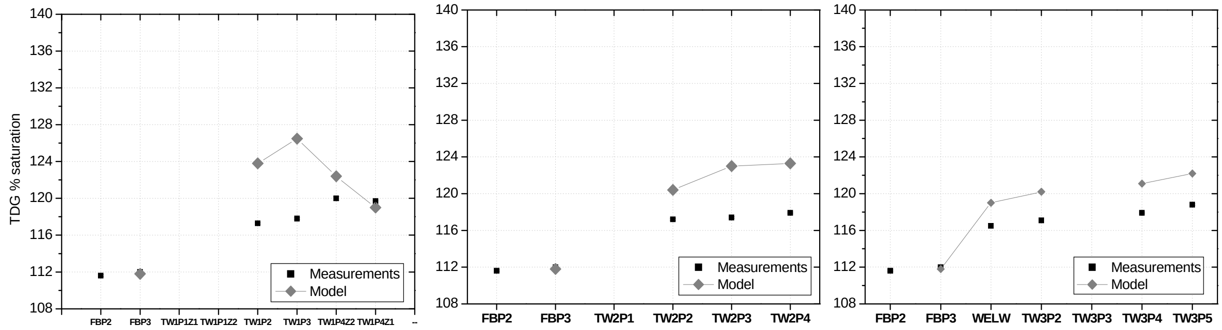

Figure 7.3-3 **Comparison between measured and predicted TDG on June 4, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

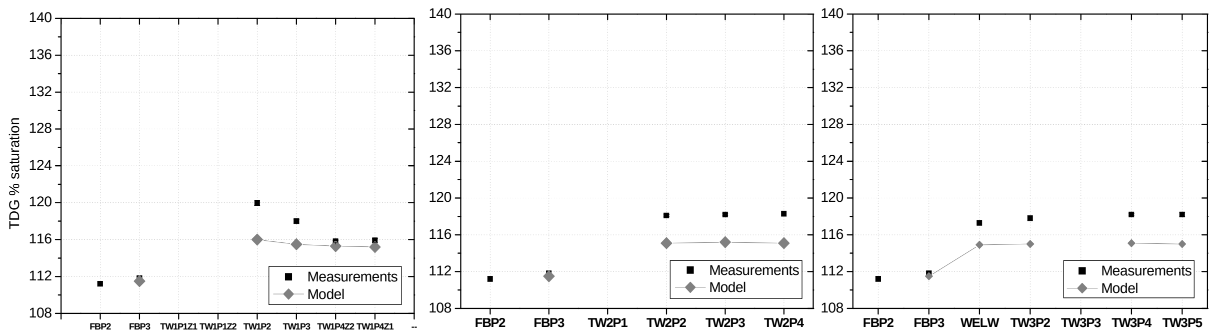

Figure 7.3-4 **Comparison between measured and predicted TDG on June 5, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

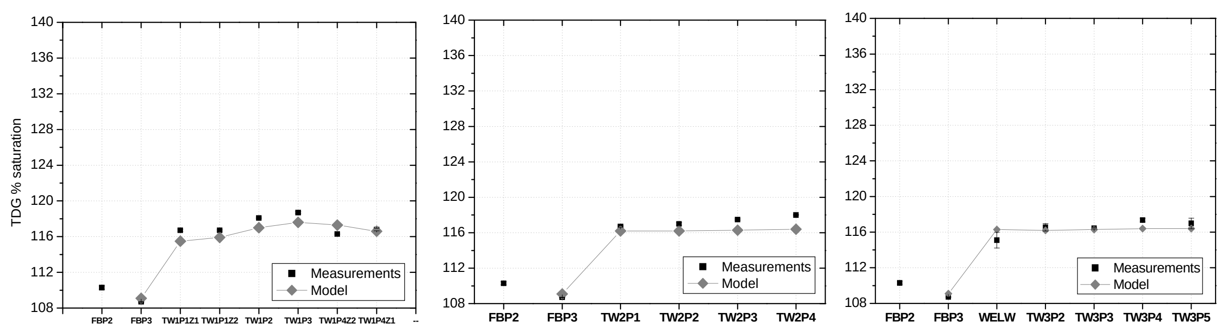

Figure 7.3-5 **Comparison between measured and predicted TDG on May 14, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

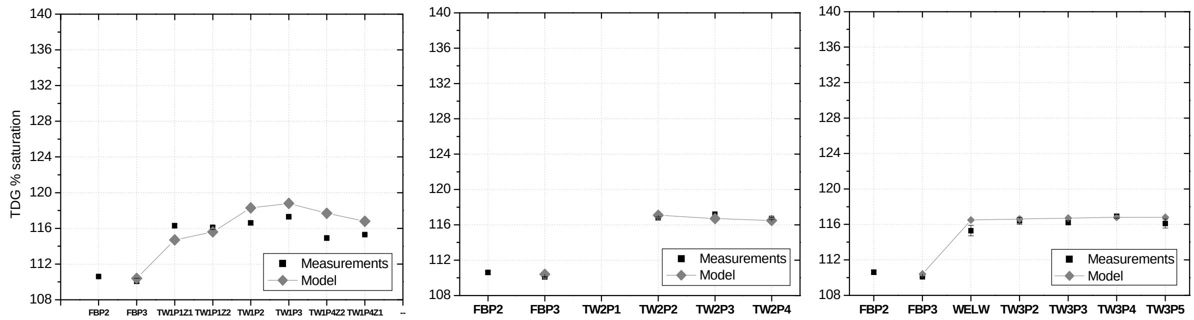

Figure 7.3-6 Comparison between measured and predicted TDG on May 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

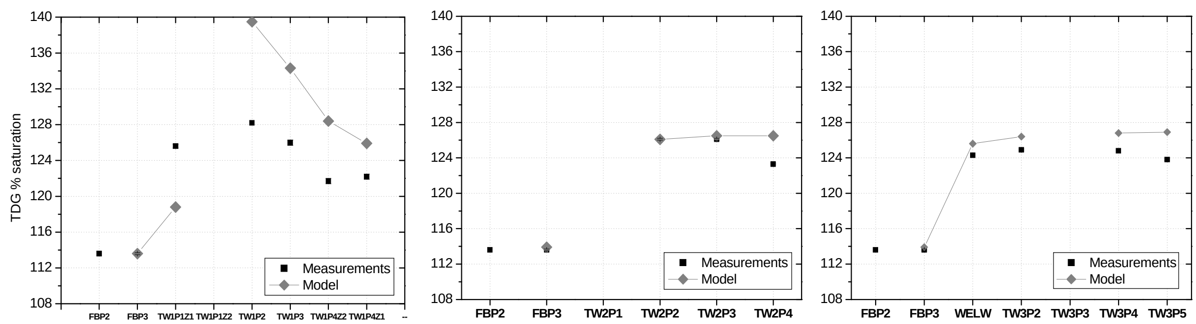

Figure 7.3-7 Comparison between measured and predicted TDG on June 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

Figures 7.3-8 and 7.3-9 show isosurfaces of TDG, gas volume fraction and bubble diameter for June 4, 2006 and June 5, 2006 where the spill operation was adjusted to test both a spillway discharge pattern that was spread across the spill bays (Figure 7.3-8) and a concentrated spill pattern (Figure 7.3-9). As shown by the gas volume fraction isosurfaces, the model predicts uniformly distributed bubbles on the spillway region during spread spill operations. On the other hand, bubbles concentrate near the center of the spillway for full open gate operation. The maximum TDG occurs at the center region due to the exposure of water to the aerated flow as it travels within the stilling basin (see TDG isosurfaces). The rate of mass exchange depends on the gas volume fraction, the bubble size and the difference in concentration between the bubble boundary and the water. The gas dissolution region occurs mainly within 500 to 1,000 ft downstream of the spillway; afterwards the bubbles moved up to regions of lower pressure and the dissolution rate decreased. The bubbles shrink near the bed due to the air mass transfer and high pressure. The smaller the bubble size the stronger its tendency to dissolve. Substantial desorption of TDG takes place near the free surface downstream of the spillway. Once the air bubbles are vented back into the atmosphere the rate of mass exchange decreases significantly. The TDG concentration reaches a developed condition approximately 1,300 ft from the spillway. According to the simulation results, the draft tube deck extensions and spillway lip tend to act as deflectors for the spill, and powerhouse operation prevented spilled flow from plunging deep, reducing the exposure of bubbles to high pressure.

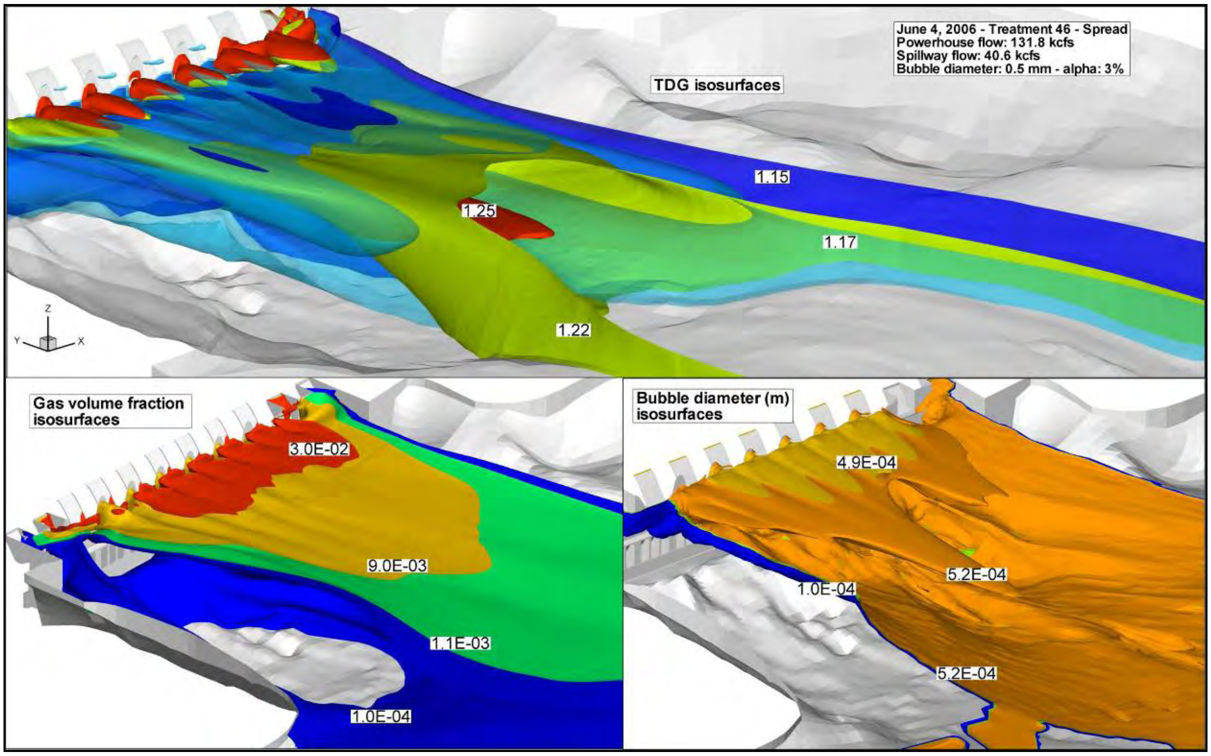

Figure 7.3-8 **TDG, gas volume fraction and bubble diameter isosurfaces for June 4, 2006.**

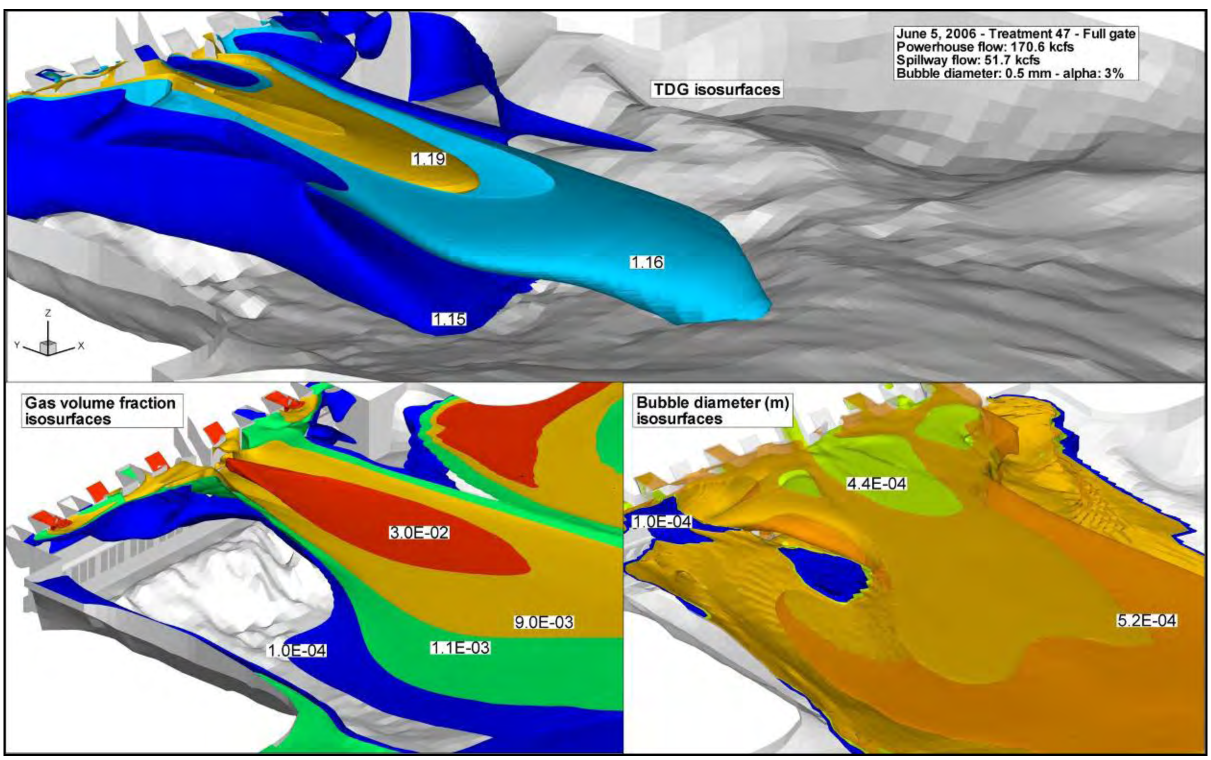

Figure 7.3-9 **TDG, gas volume fraction and bubble diameter isosurfaces for June 5, 2006.**

Table 7.3-1 summarizes simulation conditions and averaged predicted TDG at transects T1, T2 and T3. The last column in the table shows the difference between averaged TDG at transect T3 and forebay TDG, $\Delta TDG = TDG_{T3} - TDG_{forebay}$ indicating the approximate net production of TDG in the tailrace.

Table 7.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the calibration and validation cases

Case	Date	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
46 S	4-Jun	40.6	172.4	23.5	0.11	717.3	26.3	111.8	122.9	122.2	120.7	8.9
47 FG	5-Jun	51.7	223.3	23.2	0.77	720.2	29.2	111.5	115.5	115.1	115.0	3.5
1 FG	14-May	44.6	120.4	37.0	0.62	711.5	20.5	109.1	116.7	116.3	116.3	7.2
11FG	17-May	42.6	157.2	27.1	0.60	715.4	24.4	110.4	117.0	116.9	116.7	6.3
63C	17-Jun	87.4	205.5	42.5	0.55	718.6	27.6	113.9	130.5	126.4	126.4	12.5

8.0 SENSITIVITY SIMULATIONS

8.1 Simulation Conditions

Nine model runs (MR) with two spillway configurations (spread and concentrated spill) and four total river flows were simulated to analyze the sensitivity of TDG production as a function of total flow, spill releases, and tailwater elevation. These simulations were run assuming forebay TDG was 115% and water temperature was 12^{o}C. Tables in Appendix A summarize plant operations, TDG saturation in the forebay, and tailwater elevation used for these simulations.

8.2 VOF Model Results

The free surface shape for the sensitivity simulations was extracted from VOF computations in a domain extending about 1,700 ft downstream of the dam. The convergence parameters for these simulations were:

$$MR1 \text{ and } MR5 \rightarrow \left(flowrate: 208.5\ kcfs, WSE: 718.8\ ft \right)$$

$$MR2,\ MR6 \text{ and } MR8 \rightarrow \left(flowrate: 246.0\ kcfs, WSE: 721.4\ ft \right)$$

$$MR3 \text{ and } MR7 \rightarrow \left(flowrate: 128.0\ kcfs, WSE: 713.4\ ft \right)$$

$$MR4 \text{ and } MR9 \rightarrow \left(flowrate: 165.5\ kcfs, WSE: 715.9\ ft \right)$$

The initial conditions from the MR simulations were obtained from interpolation of the numerical solutions for the calibration/validation cases. The MR cases reached the statistically steady solutions in typically 20 to 30 minutes (30 to 45 days of computation time).

8.3 Rigid-lid Model Results

Tables in Appendix C show the percent saturation of TDG predicted by the model at each station and the mean TDG in each of the three transects for the MR simulations. Figures 8.3-1 to 8.3-3 show predicted TDG values at each probe location. Table 8.3-1 summarizes simulation conditions, averaged predicted TDG at transects T1, T2, T3 and ΔTDG .

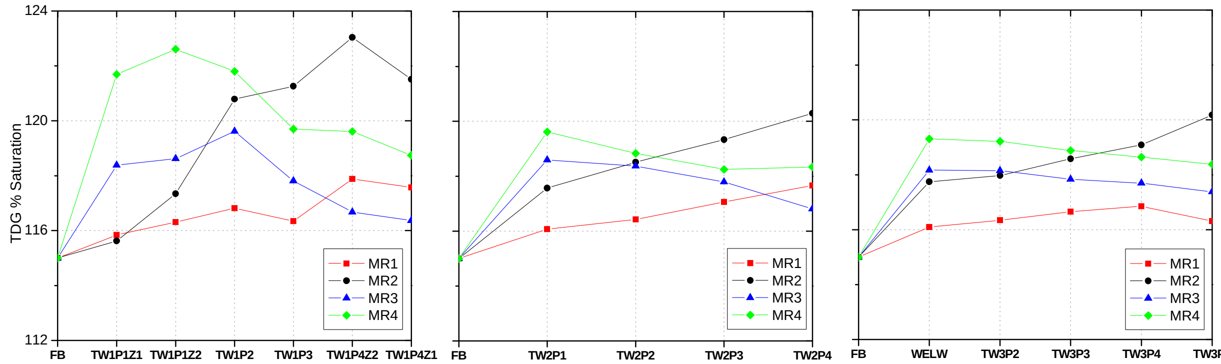

Figure 8.3-1 Predicted TDG concentration for spread operation.

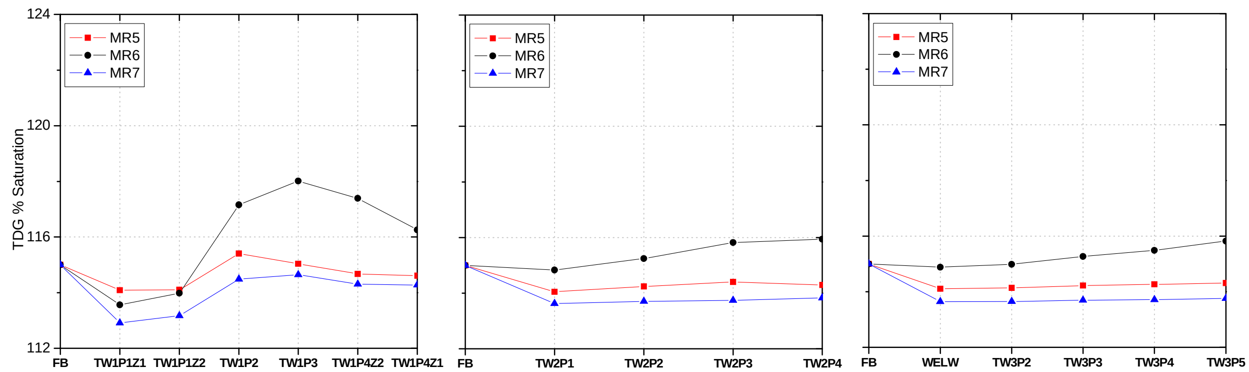

Figure 8.3-2 Predicted TDG concentration for full open gate operation.

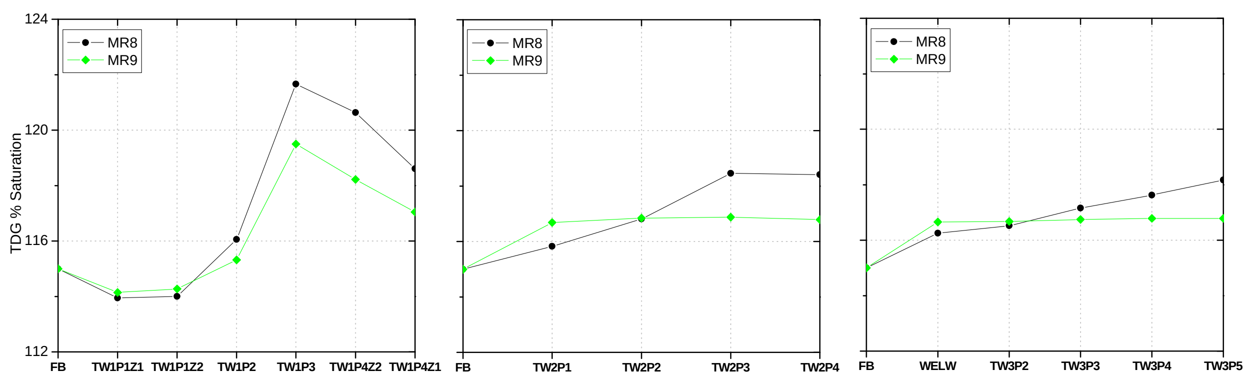

Figure 8.3-3 Predicted TDG concentration for two full open gates operation.

Table 8.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the sensitivity simulations.

Case	Type	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
1	S	23.0	208.5	11.0	0.07	718.8	27.8	115.0	117.3	118.1	117.9	2.9
2	S	60.5	246.0	24.6	0.19	721.4	30.4	115.0	123.7	124.1	123.7	8.7
3	S	23.0	119.0	19.3	0.07	713.4	22.4	115.0	121.3	120.7	120.7	5.7
4	S	60.5	156.5	38.7	0.19	715.9	24.9	115.0	126.3	124.5	124.7	9.7
5	1-FG	23.0	208.5	11.0	0.50	718.8	27.8	115.0	116.0	116.8	116.7	1.7
6	1-FG	60.5	246.0	24.6	1.32	721.4	30.4	115.0	121.1	121.4	121.3	6.3
7	1-FG	23.0	119.0	19.3	0.50	713.4	22.4	115.0	117.5	117.1	117.3	2.3
8	2-FG	60.5	246.0	24.6	0.66	721.4	30.4	115.0	121.2	123.0	122.6	7.6
9	2-FG	60.5	156.5	38.7	0.66	715.9	24.9	115.0	122.2	122.9	122.9	7.9

In order to understand the effect of plant operations on TDG production and mixing, the simulations were grouped as follow:

1. Simulations with the same spill and powerhouse flows:
   $\{[\text{MR1 and MR5}],\ [\text{MR2, MR6 and MR8}],\ [\text{MR3 and MR7}],\ \text{and}\ [\text{MR4 and MR9}]\}$

2. Simulations with the same spill operation (concentrated or spread spill) and same powerhouse flows:
   $\{\mathit{Spread}:[\text{MR1(S=23 kcfs) and MR2(S=60.5 kcfs)}]\ \text{and}\ [\text{MR3(S=23 kcfs) and MR4(S=60.5 kcfs)}]\}$
   $\{\mathit{FG}:[\text{MR5(S=23 kcfs) and MR6(S=60.5 kcfs)}]\}$

3. Simulations with the same spill operation (concentrated or spread spill) and same spill flows:
   $\{\mathit{Spread}:[\text{MR1(P=185.5 kcfs) and MR3(S=96 kcfs)}]\ \text{and}\ [\text{MR2(S=185.5 kcfs) and MR4(S=96 kcfs)}]\}$
   $\{\mathit{FG}:[\text{MR5(S=185.5 kcfs) and MR7(S=96 kcfs)}]\}$

where S and P denote spillway and powerhouse flows, respectively.

<u>Simulations with the same spill and powerhouse flows</u>

Substantial differences in downstream TDG levels were observed with spread or full open gate operations. Numerical results indicate that, for the same spill and powerhouse flows, full open gate operation resulted in the lowest TDG concentration. On the other hand, the highest TDG concentrations were observed with spread flow operation. Simulations MR6 and MR8 show that distributing the same spill flow into two gates produced more TDG than concentrating the flow through a single bay.

To understand the underlying physics that cause larger TDG concentrations with spread operation, the volume of air available for dissolution and TDG sources for simulations MR1 (spread) and MR5 (FG) were analyzed at two transects downstream of the dam.

Figure 8.3-4 shows the cumulative volume of air in bubbles per unit length and cumulative TDG source per unit length as a function of the distance from the free surface at 50 m downstream of the dam. Solid lines show the cumulative volume of air in bubbles per unit length for simulations MR1 and MR5. Almost no air was present below 10 m. Note that the amount of air available for dissolution for concentrated spill operation (MR5) is always smaller than that for spread flows (MR1). The distribution of gas volume fraction and TDG at a vertical slice at 50 m from the dam for both types of operation is shown in 8.3-5. Note that the gas volume fraction, and consequently the TDG, is significantly larger for spread operation. As shown in Figure 8.3-6, for the simulated flow rates, the spread operation produces a submerged jet while the full open gate operation produces a surface jump. The residence time of bubbles entrained in a submerged jet is longer than those entrained in a surface jump. Bubbles reach the free surface more quickly in a surface jump because, on average, they travel closer to the free surface and because the water depth on the spillway face is smaller. In addition, large vertical liquid velocities downstream of the spillway lip help bubbles leave the tailrace more quickly for the concentrated spill operation.

The dotted lines in Figure 8.3-4 show the cumulative TDG source for simulations MR1 and MR5. Since the amount of air in bubbles available to produce TDG is larger for the spread operation, both the degasification (negative source of TDG) and production of TDG (positive source of TDG) are increased for this case. The net TDG production for spread and concentrated spill operations are approximately 0.15 kg air/(s m) and 0.06 kg air/(s m), respectively.

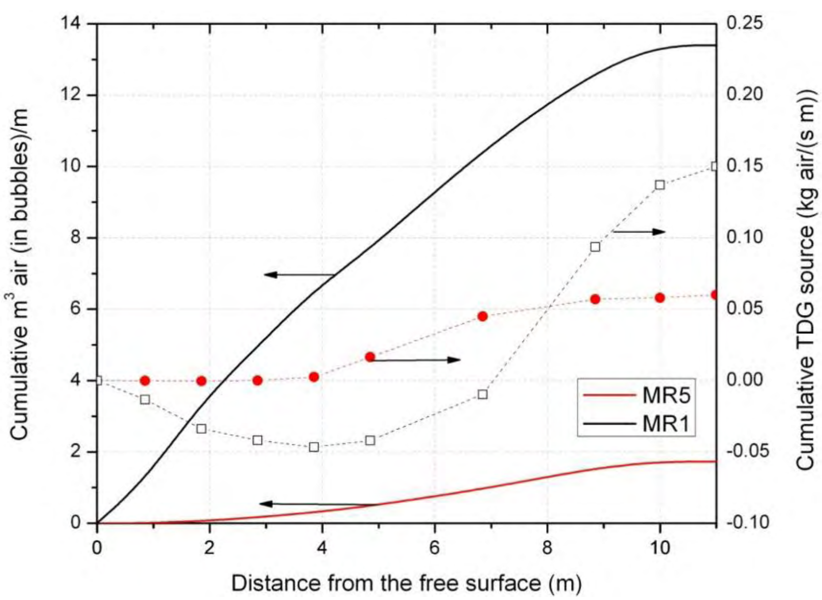

Figure 8.3-4 Cumulative volume of air in bubbles per unit length (left) and cumulative TDG source per unit length (right) as a function of the distance from the free surface at a plane at 50 m from the dam.

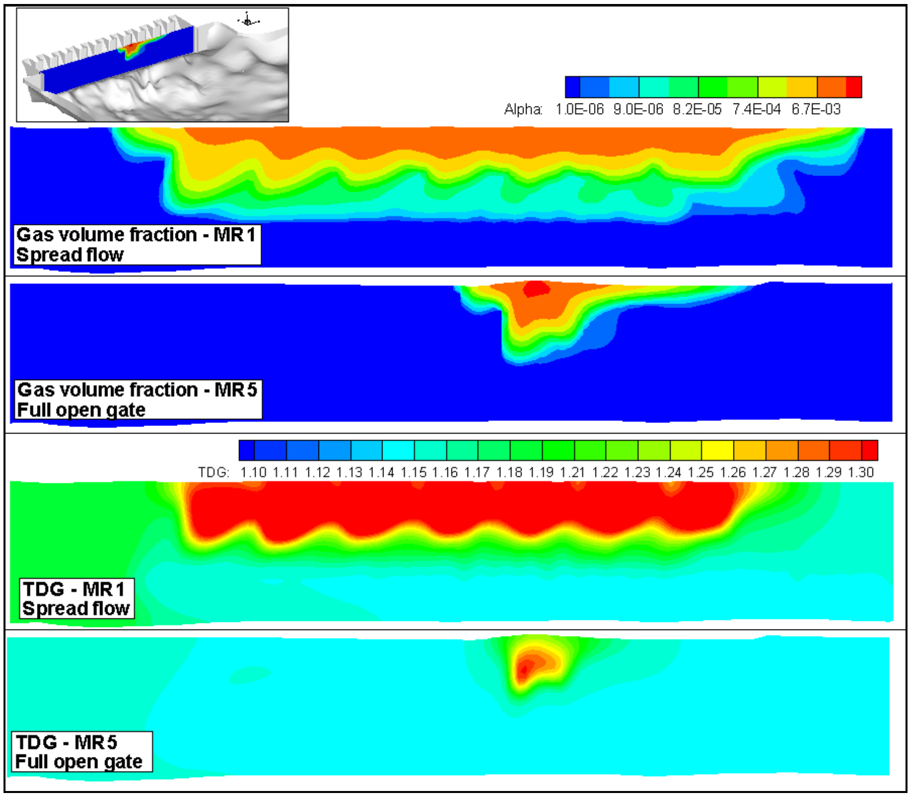

Figure 8.3-5 **Contours of gas volume fraction and TDG at 50 m from the dam for simulations MR1 and MR5.**

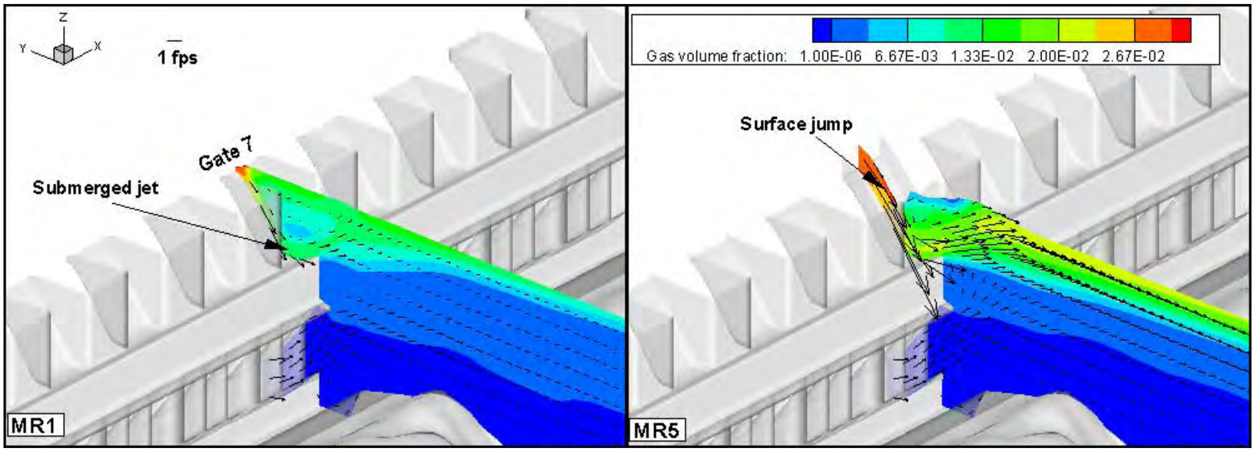

Figure 8.3-6 **Contours of gas volume fraction and velocity vectors at a slice through gate 7 for MR1 (top) and MR5 (bottom).**

Figure 8.3-7 shows the cumulative curves at Transect 1 location, 370 m downstream of the dam. Contrary to observations at 50 m from the dam, more bubbles are present at transect T1 for concentrated spill operation than for spread flows. The distributions of gas volume fraction and resulting TDG for MR1 and MR5 are shown in Figure 8.3-8. Higher liquid velocities with concentrated spill operation transport bubbles further in the tailrace. In addition, higher turbulent dispersion, created by a stronger jet in a full open gate operation, entrains bubbles deeper into the tailrace increasing bubble residence times. Note that 100% of the bubbles at Transect T1 are 2m or less from the free surface for the spread operation. On the other hand, due to turbulent dispersion, about 65% of the bubbles are 2 m from the free surface for full open gate operation. The TDG source is negative (degasification) for both type of operations. However, more degasification is observed with concentrated spill due to more availability of gas and an elevated mass transfer coefficient at the free surface for higher turbulent flows. As shown in Figure 8.3-8, TDG is higher for the spread operation as a result of more TDG production and less degasification at the free surface.

The flow pattern and TDG distribution in the tailrace for cases MR1 and MR5 are shown with streamlines colored by TDG concentration in Figures 8.3-9 and 8.3-10, respectively.

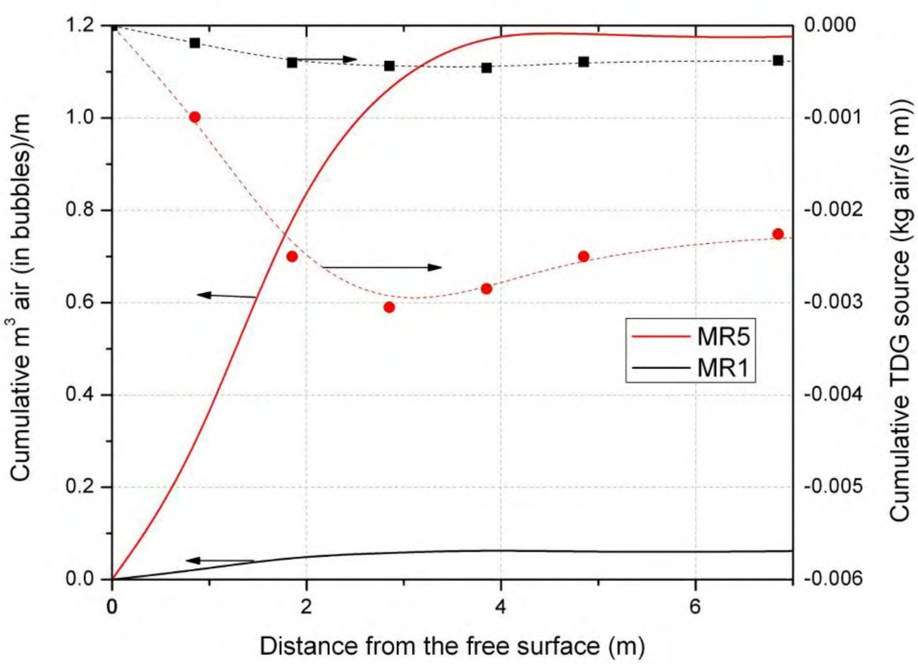

Figure 8.3-7 **Cumulative volume of air in bubbles per unit length (left) and cumulative TDG source per unit length (right) as a function of the distance from the free surface at a plane at 370 m from the dam.**

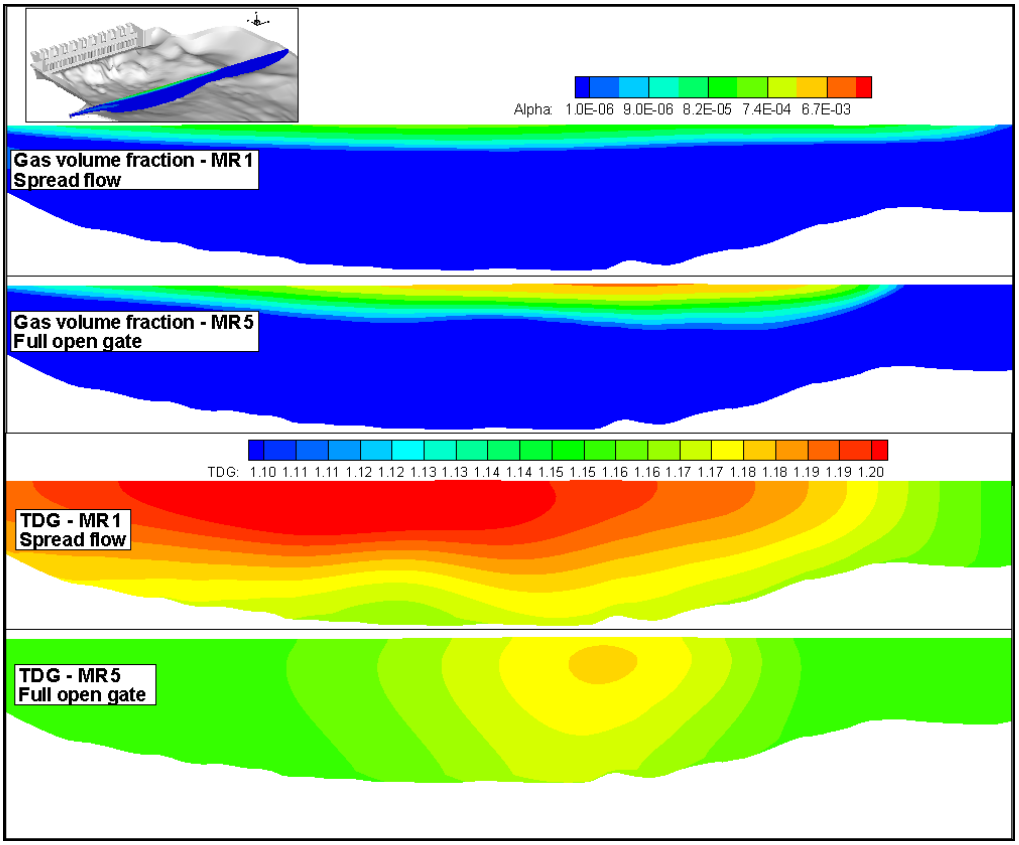

Figure 8.3-8 Contours of gas volume fraction and TDG at 370 m from the Dam for simulations MR1 and MR5.

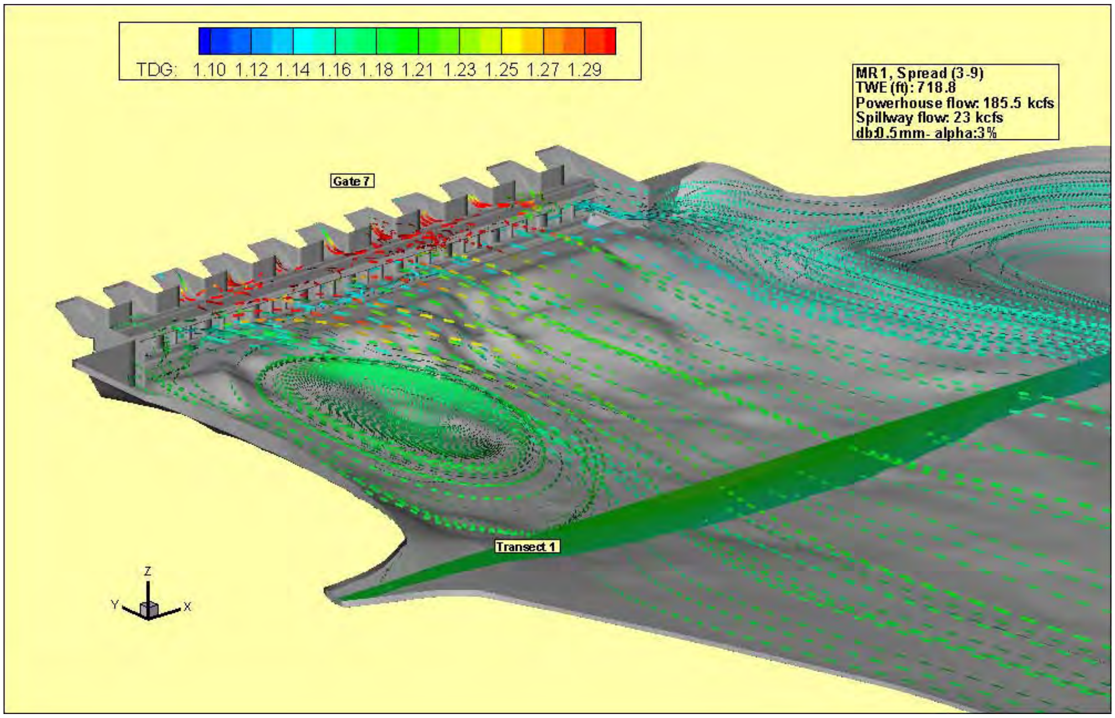

Figure 8.3-9 **Streamlines colored by TDG concentration for MR1.**

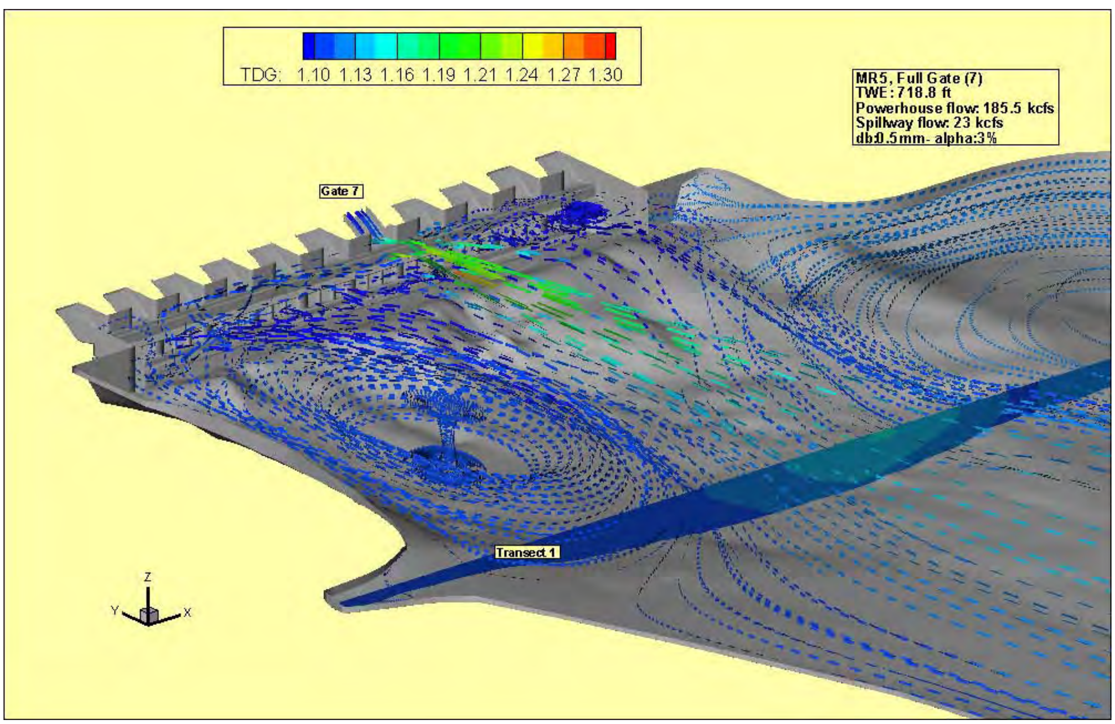

Figure 8.3-10 **Streamlines colored by TDG concentration for MR5.**

Simulations with the same spill operation and same powerhouse flows

Downstream TDG levels depend on the percentage of spilled water. For constant powerhouse flows, the greater the amount of spill, the greater the amount of bubbles entrained and the turbulence generated in the tailrace, and therefore, the greater the TDG production. Thus, the simulations for spread flows MR1 and MR3 with 23 kcfs spill flow produces less TDG than the equivalent MR2 and MR4 simulations with 60.5 kcfs (see Figure 8.3-1). Streamlines colored by TDG show the flow pattern and TDG distribution for MR1 (Figure 8.3-1) and MR2 (Figure 8.3-11). For these cases, the maximum TDG levels occurred at the west bank of the Wells tailrace.

Figures 8.3-12 and 8.3-13 show the submergence depth of the flip lip as a function of spill per unit width for full open gate and spread operations, respectively. The submergence depth is defined as the tailwater elevation minus the elevation of the top of the flip lip (691 ft) and the spill per unit width is:

$$\text{Spill per unit width} = \frac{1}{S_T\,W}\sum_i S_i^2 \qquad (19)$$

where W is the width of the spillbay, S_T is the total spill, and S_i is the spill of a generic bay *i*. Orange triangles represent field data black stars: predicted data at the model calibration/validation, black squares: sensitivity simulations. Labels indicate ΔTDG values. Data were grouped based on the percentage spill between 0 to 19%, 20 to 39%, 40 to 59%, and 60 to 100%. These plots confirm that the TDG production is strongly dependent on the percentage of spilled water.

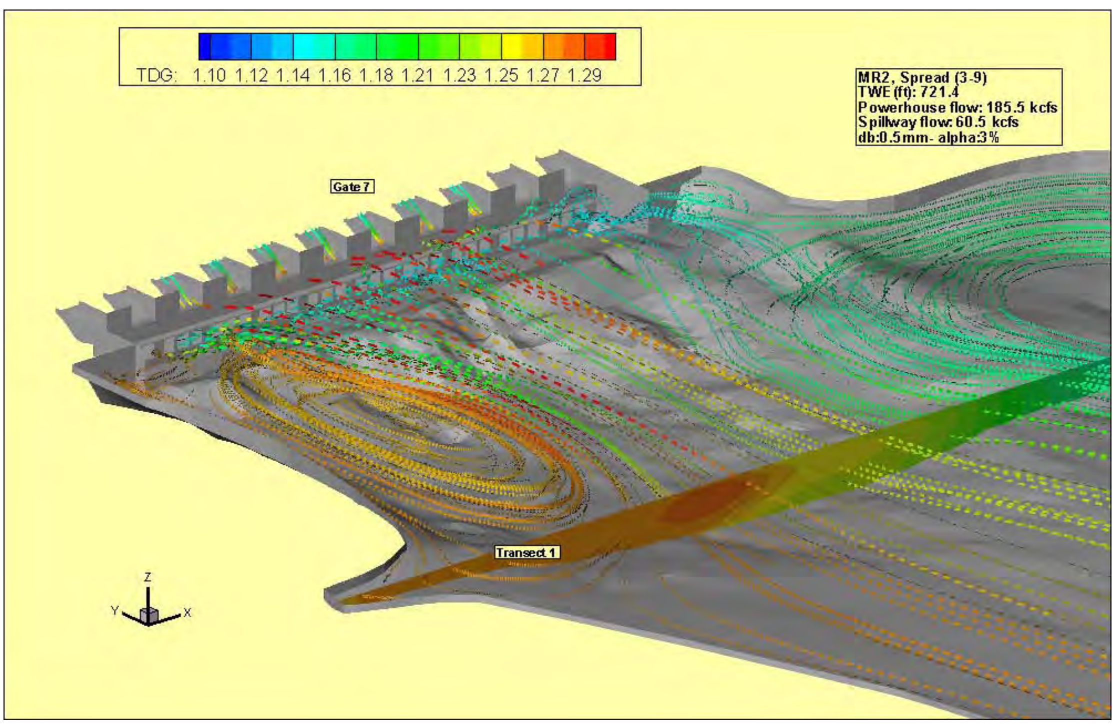

Figure 8.3-11 Streamlines colored by TDG concentration for MR2.

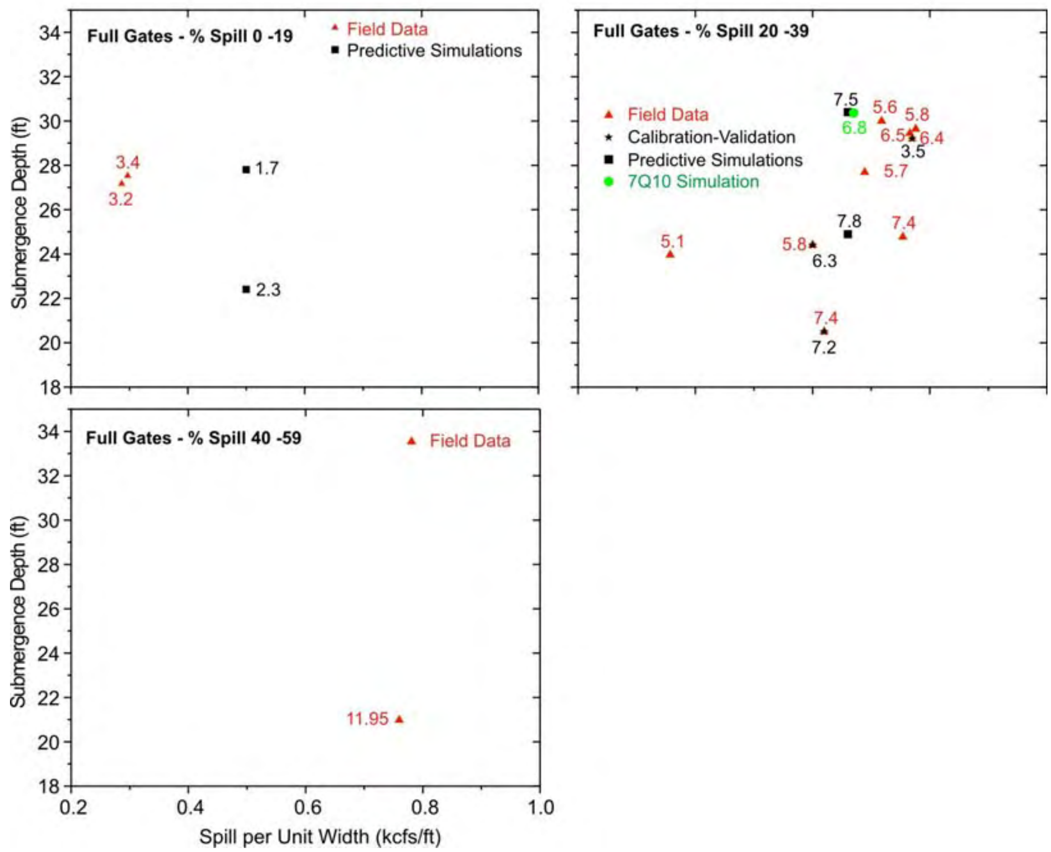

Figure 8.3-12 **Submergence depth as a function of spill per unit width for full open gate operation. Red triangles: field data, black stars: predicted data at the model calibration/validation, black squares: sensitivity simulations, and green circle 7Q10 simulation. Labels indicate ΔTDG values.**

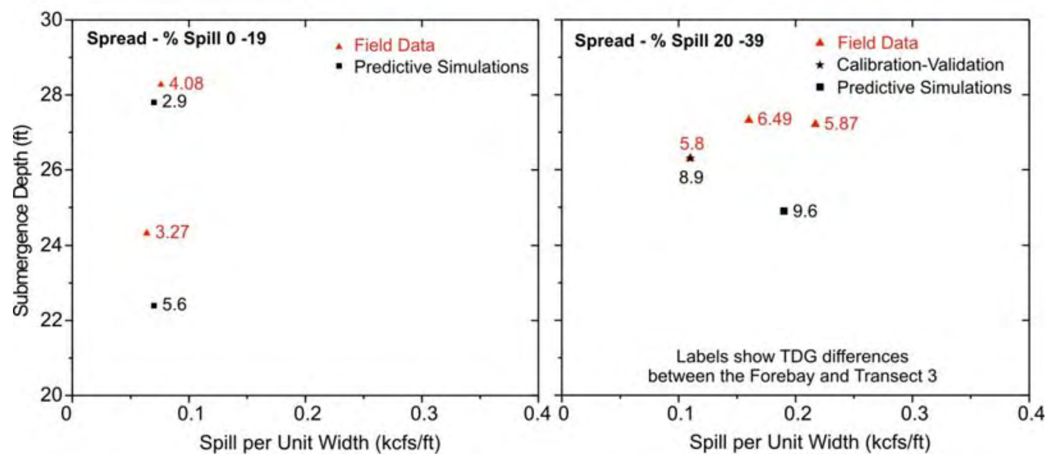

Figure 8.3-13 **Submergence depth as a function of spill per unit width for spread operation. Red triangles: field data, black stars: predicted data at the model calibration/validation, and black squares: sensitivity simulations. Labels indicate ΔTDG values.**

Simulations with the same spill operation and spilled flows

Mixing and dilution from increased powerhouse flows resulted in reduced TDG levels downstream for both spread and concentrated spill operations. The most notable effect of the powerhouse flow reduction was the increment of TDG values at the east bank for spread flow operation. The TDG distribution predicted in simulation MR4 with 96 kcfs powerhouse flow compared with the predicted values for MR2 with 185.5 kcfs powerhouse flow are shown in Figures 8.3-14 and 8.3-11, respectively.

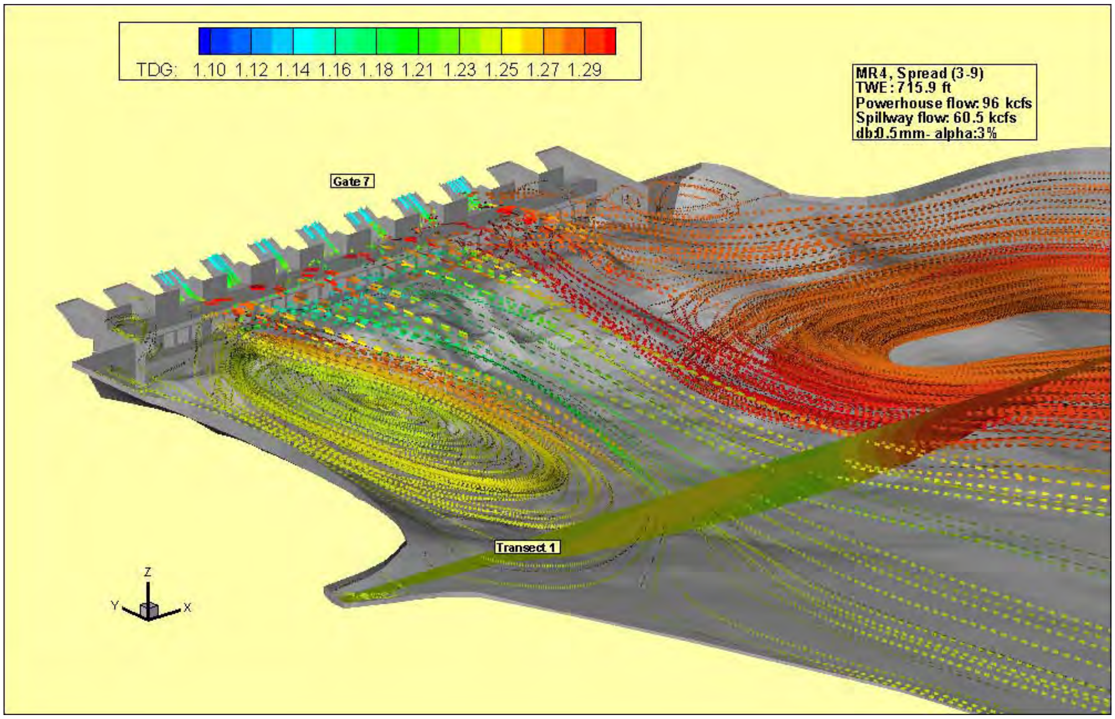

Figure 8.3-14 Streamlines colored by TDG concentration for MR4.

9.0 7Q10 FLOW SIMULATIONS

Numerical results of the sensitivity simulations confirmed what seemed to be demonstrated by field data, that is, saturation of gases in the tailrace could be minimized by concentrating the spill through one or more gates rather than spread across the spillway. This lead to further model runs in which various concentrated spill patterns were tested with the objective of reducing TDG production for a 7Q10 flow in the Wells Tailrace.

9.1 Simulation Conditions

The inputs for three 7Q10 simulations are tabulated in Appendix A. A forebay TDG of 113% and water temperature equal of 13^{o}C were used in the simulations based upon median values for these parameters extracted from the historical data (Section 5.4.2.1). Operational conditions included 9 of 10 turbine units[1] (each unit running at 20 kcfs[2]), 10 kcfs running through the Juvenile Bypass System[3], and 1 kcfs flowing down the fish ladders, and 55 kcfs through the spillways (combined spillway and bypass flow of 66 kcfs).

9.2 VOF Model Results

The convergence parameters for the 7Q10 simulations were:

$$\text{7Q10 S} \rightarrow \left(flowrate : 246\ kcfs, WSE : 721.4\ ft \right)$$

The numerical solution of MR6 was used as an initial condition for the 7Q10-A simulation. This case reached the statistically steady solution in approximately 15 minutes (21 days of computation time). Solution obtained for 7Q10-A was used as an initial condition for simulations 7Q10-B and 7Q10-C.

9.3 Rigid-lid Model Results

Tables in Appendix B show the percent saturation of TDG predicted by the model at each station for the 7Q10 simulations. Figure 9.3-1 illustrates TDG values predicted by the model at each probe location and Table 9.3-1 shows the average TDG at transects T1, T2 and T3. Numerical results indicate that, spilling most of the water in adjacent bays results in the highest TDG downstream. On the other hand, the lowest TDG values were observed with a full open gate through spillbay 7 and most of the remaining flow in bay 3. Operation 7Q10-B appeared to be the Optimal Operating Condition for the Wells Project as this condition consistently produced the lowest TDG profile in the Wells tailrace (117.7%) (Table 9.3-1).

[1] Ecology has requested that the TDG model be operated utilized only 9 of the 10 available turbine units at Wells Dam. This request was intended to simulate a condition where one turbine unit is off-line for maintenance.

[2] Note that the maximum flow for each of the 10 turbines at Wells Dam is 22.0 kcfs for a total powerhouse capacity of 220 kcfs. The TDG model used a more conservative 20 kcfs per turbine which represents a more normal operation condition when flows at Wells Dam are approaching the hydraulic capacity of the powerhouse (>200 kcfs).

[3] Note that the Juvenile Bypass System uses up to 11 kcfs of water when operating through all five bottom gates. The TDG model assumed that only 10 kcfs of water was used to operate the Juvenile Bypass System. This can be achieved by running the system in a top spill configuration on gates 2 and 10 and in bottom spill configuration for gates 4, 6 and 8.

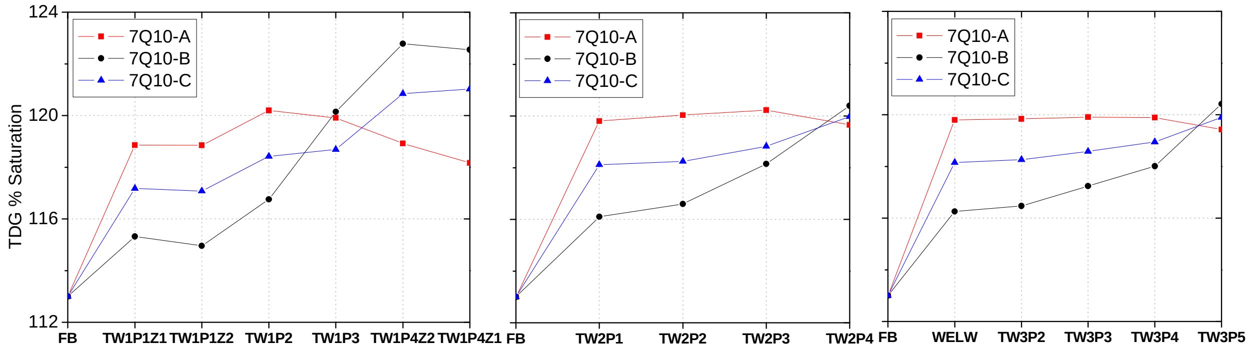

Figure 9.3-1 Predicted TDG concentration for 7Q10 simulations.

Table 9.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for three initial 7Q10 simulations.

Case	Type	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
7Q10-A	1-FG	64.6	245.6	26.3	0.67	721.4	30.4	113.0	119.2	119.9	119.8	6.8
7Q10-B	1-FG	65.0	246.0	26.4	0.67	721.4	30.4	113.0	118.8	117.8	117.7	4.7
7Q10-C	1-FG	65.0	246.0	26.4	0.67	721.4	30.4	113.0	118.9	118.8	118.8	5.8

Figures 9.3-2 and 9.3-3 show gas volume fraction and TDG distribution at a plane located 50 m downstream of the dam for the 7Q10 simulations. According to the model, the production of TDG is similar for the simulated cases. Operations 7Q10-A and 7Q10-CC both contained a higher concentration of spill flow in adjacent bays and both produced resultant bubbles traveling deeper in the tailrace with a slightly higher TDG concentration in the center of the spillway.

Figures 9.3-4 shows the TDG distribution at 370 m from the dam. Note that the lateral distribution of TDG is significantly different for the simulated cases, suggesting different level of TDG mixing. Figures 9.3-5 to 9.3-6 show streamlines colored by TDG concentration. The highest lateral TDG gradient is observed when the spillway is operated with gate 7 full opened and most of the remaining flow placed in bay 3 (7Q10-B). In this case, both the degasification at the free surface and the downstream dilution are improved. Note that most of the water of the east bank is basically undisturbed water, with gas saturations nearly to forebay TDG.

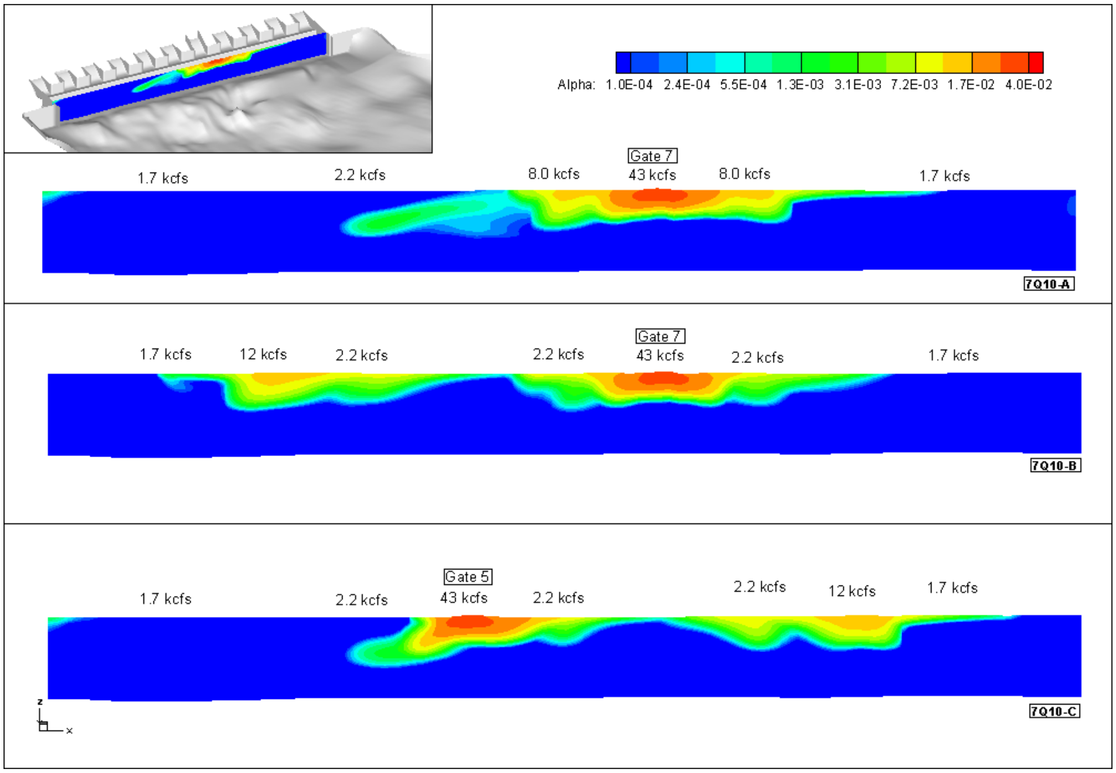

Figure 9.3-2 **Contours of gas volume fraction at 50 m from the Dam for 7Q10 simulations.**

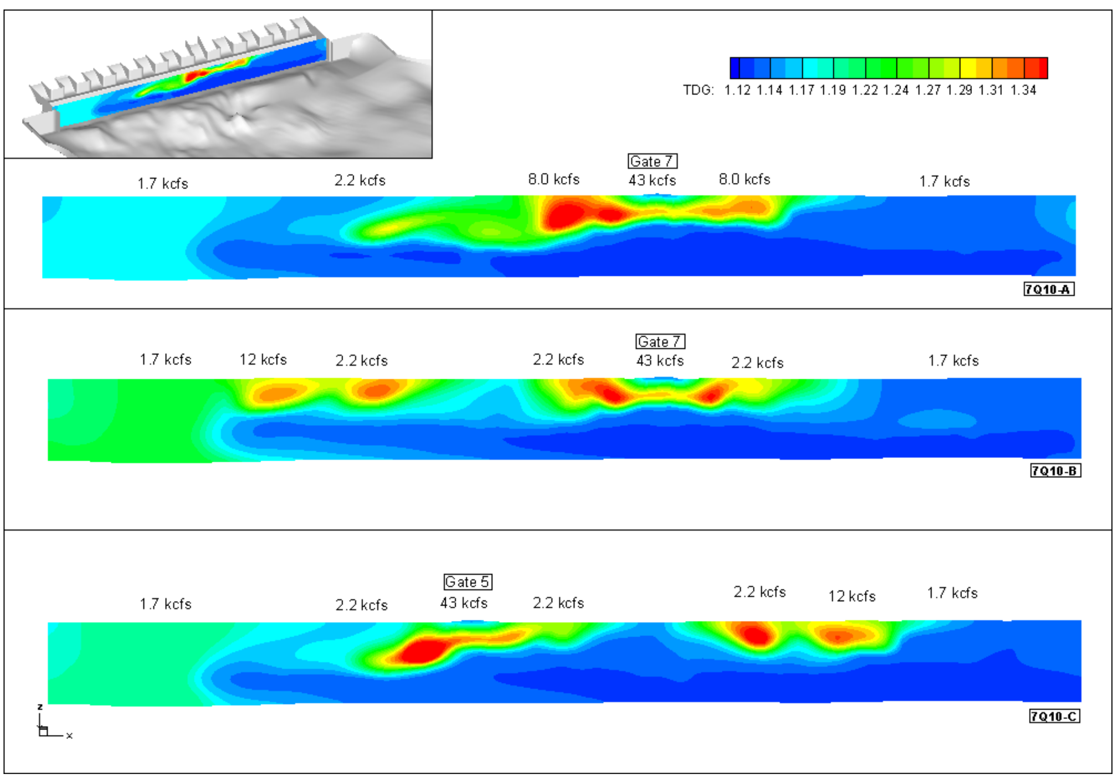

Figure 9.3-3 **Contours of TDG at 50 m from the Dam for the 7Q10 simulations.**

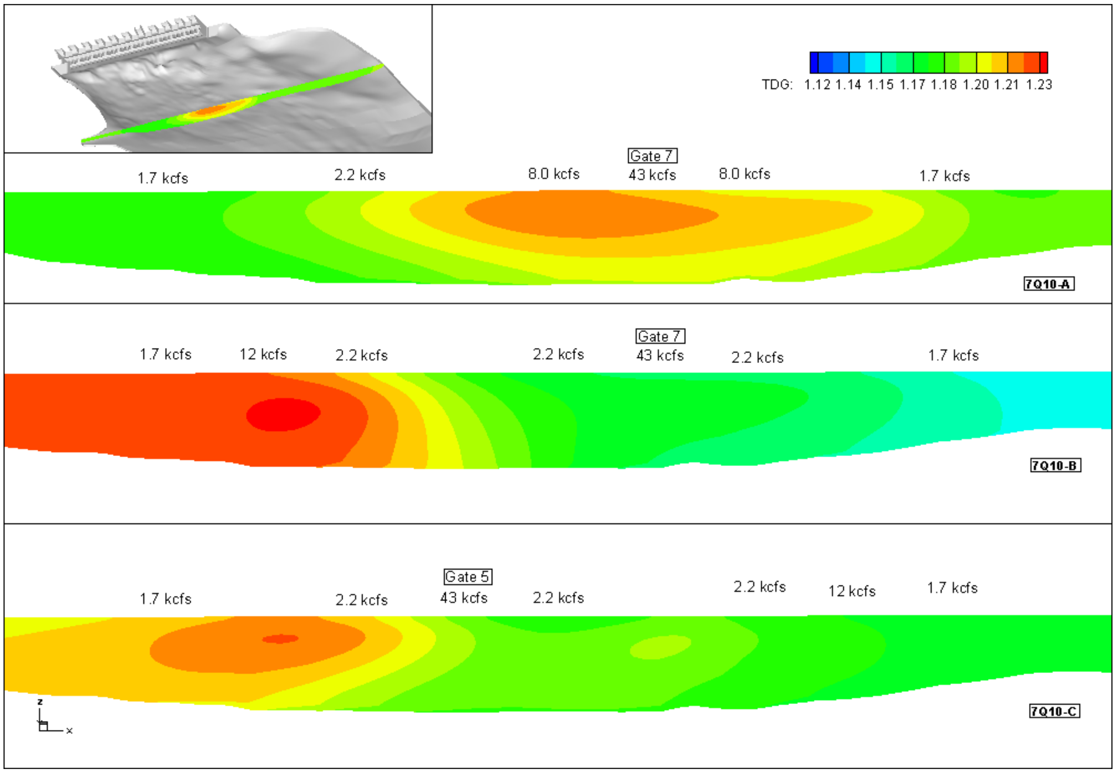

Figure 9.3-4 **Contours of TDG at 370 m from the Dam for the 7Q10 simulations.**

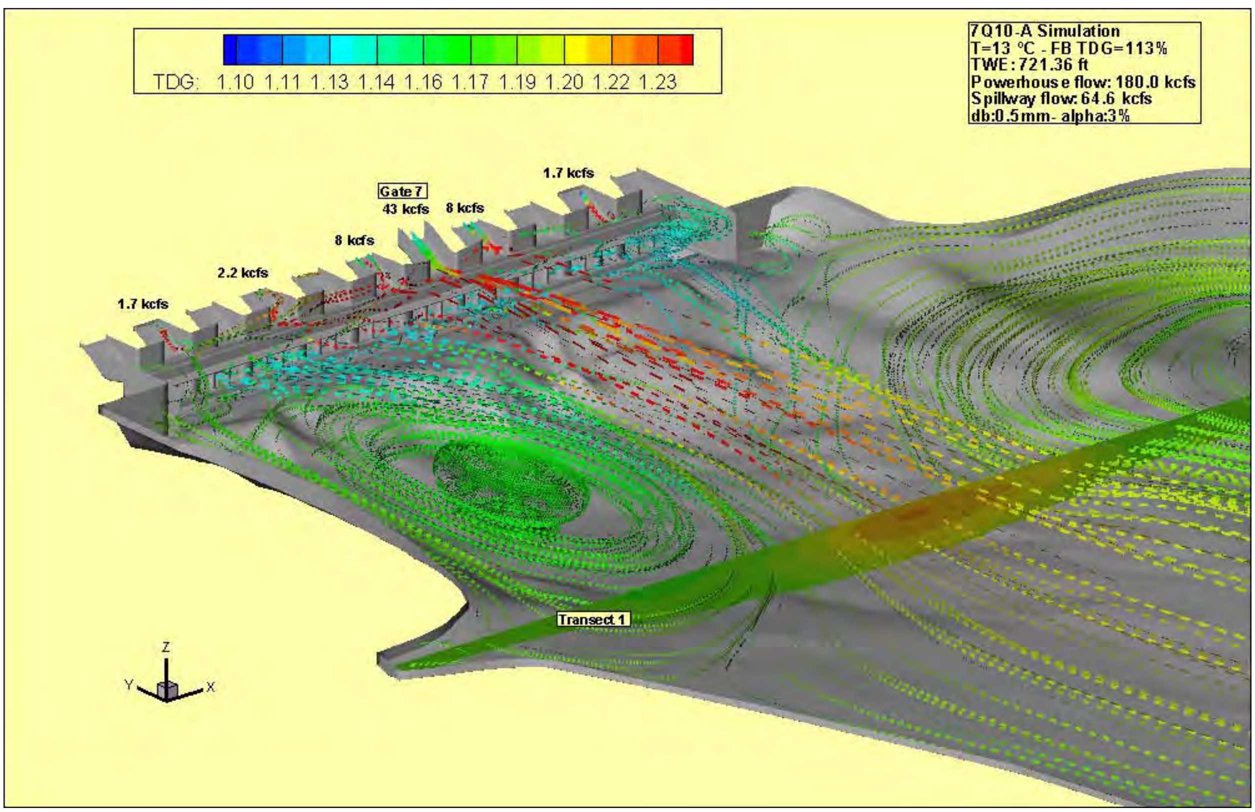

Figure 9.3-5 **Streamlines colored by TDG concentration for the 7Q10-A simulation.**

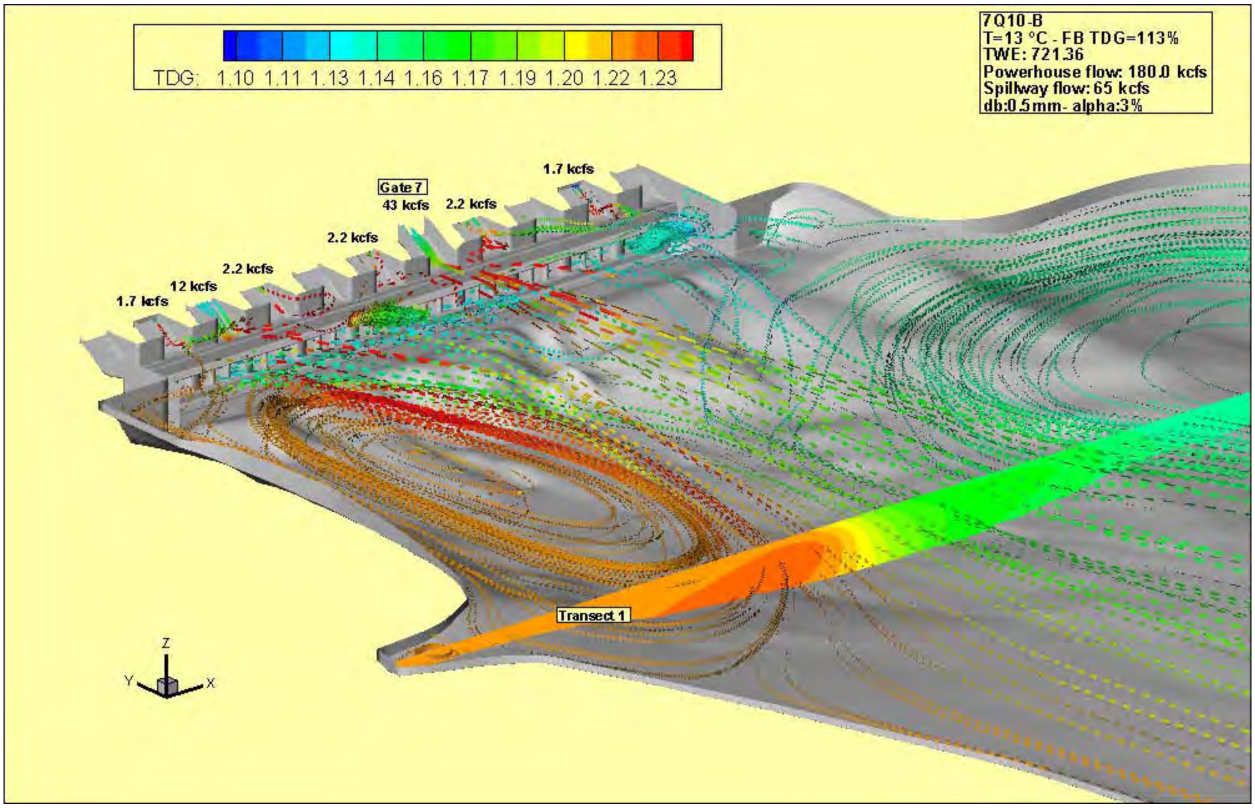

Figure 9.3-6 Streamlines colored by TDG concentration for the 7Q10-B simulation.

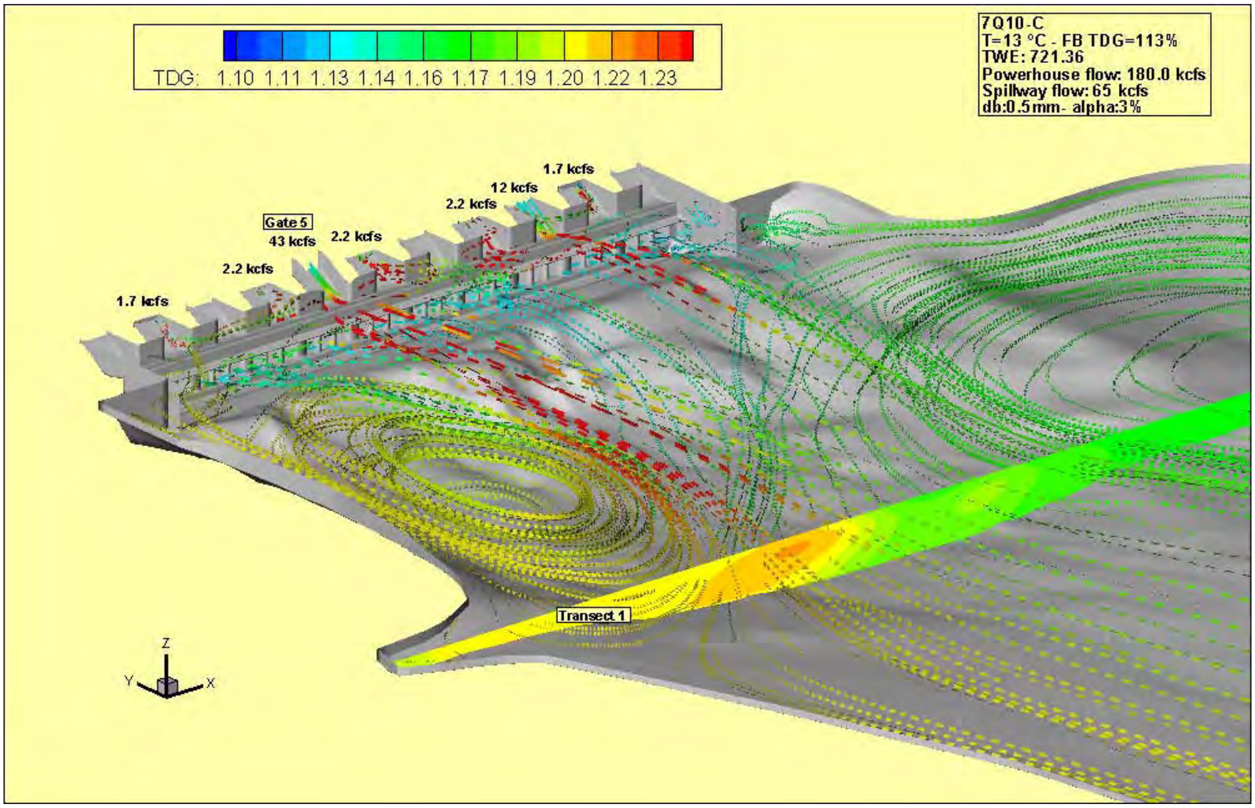

Figure 9.3-7 Streamlines colored by TDG concentration for the 7Q10-C simulation.

10.0 STANDARD COMPLIANCE EVALUATIONS

10.1 Simulation Conditions

In addition to identifying the Optimal Operating Conditions representative of high flow conditions at the Wells Project, Ecology also requested that a Standard Compliance Scenario also be modeled consistent with settings used at other projects for evaluation of compliance with numeric WQS. The spill configuration was similar to simulation 7Q10-A presented in section 9 however, the simulation was conducted with a 115% forebay TDG and 90% of maximum powerhouse capacity (22 kcfs per turbine, with nine of ten units in operation). Temperature was 15.5 ^{o}C, consistent with median values observed at 115% forebay TDG. Table 10.1-1 summarizes project operations used for the compliance simulation (CS).

Table 10.1-1 Conditions used for the Standard Compliance Numerical Simulation

Treatment CS									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 780.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Powerhouse Total: 198.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	2.2	37.0	2.2	0.0	1.7
Spillway Total: 47.0 kcfs									
Total River Flow: 245.0 kcfs									
Forebay TDG: 115.0%									

10.2 VOF Model Results

The convergence parameters for the Standard Compliance Simulation were:

$$\text{Compliance Simulation} \rightarrow \left(flowrate : 245.0\ kcfs, WSE : 721.4\ ft \right)$$

Figure 10.2-1 shows the spillway jet characteristics predicted with the VOF method for the Standard Compliance Simulation. Similar to observations on June 5, 2006, the surface jet originating from bay 7 attracts water toward the center of the dam. The cross section of spillway 7 in Figure 10.2-1 shows that the surface jet remains close to the free surface minimizing air entrainment. Minor contributions to TDG production are expected from bays 6 and 8 (see cross section of spillway unit 6 in Figure 9.2-1) because of their relatively small volume of spilled water.

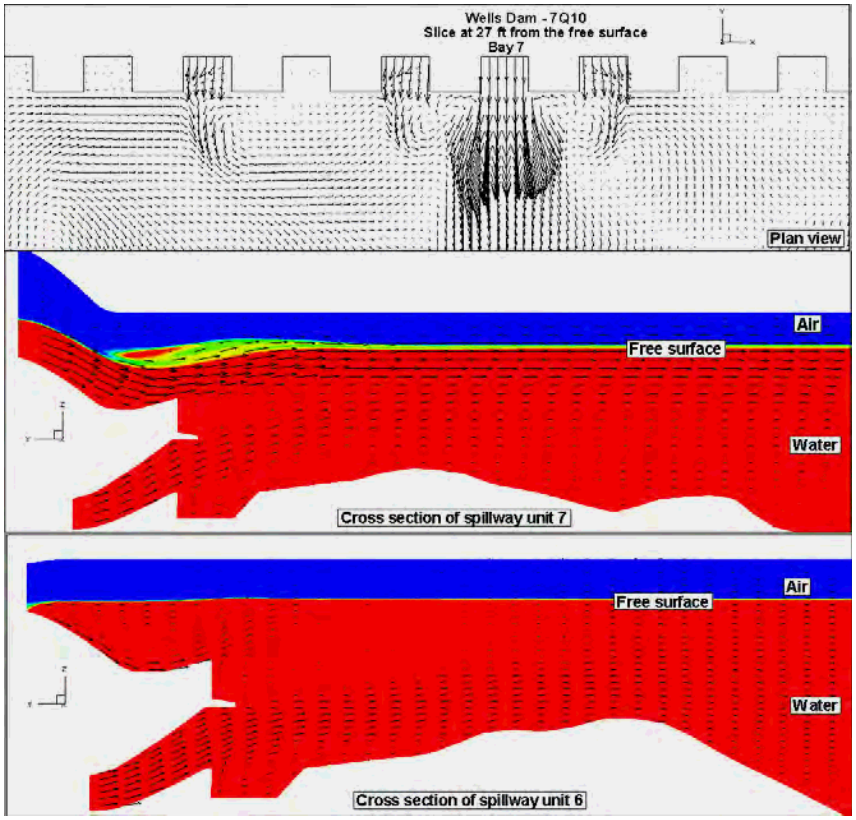

Figure 10.2-1 Predicted flow field for the Standard Compliance Simulation.

10.3 Rigid-lid Model Results

Tables in Appendix B show the percent saturation of TDG predicted by the model at each station for the Standard Compliance Simulation. Figure 10.3-1 shows TDG values predicted by the model at each probe location for this simulation. The TDG distribution at the Wells tailrace together with predicted TDG values at each station are shown in Figure 10.3-2. The main process affecting TDG production and mixing occurs upstream of transect T2, after which TDG production reaches a developed condition with minor changes associated with small mass transfer at the free surface. Table 10.3-1 shows the average TDG at transects T1, T2 and T3. According to the model, the average gas saturation at the three transects is approximately 117%.

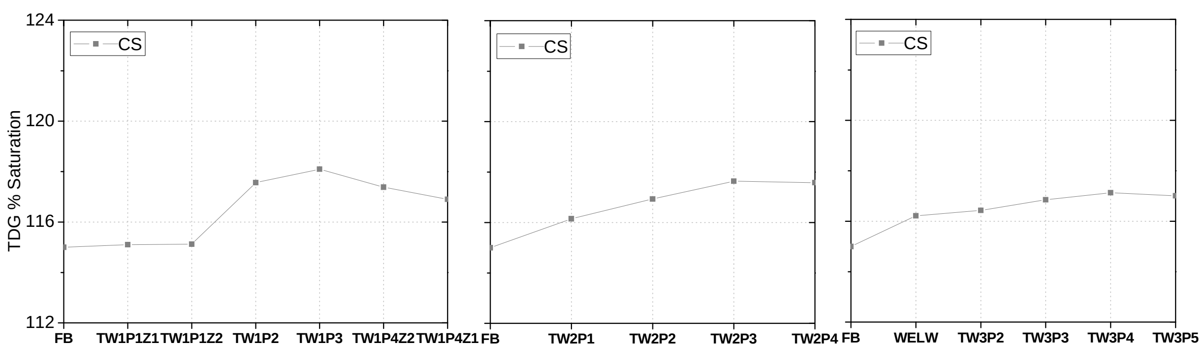

Figure 10.3-1 Predicted TDG concentration for the Standard Compliance Simulation.

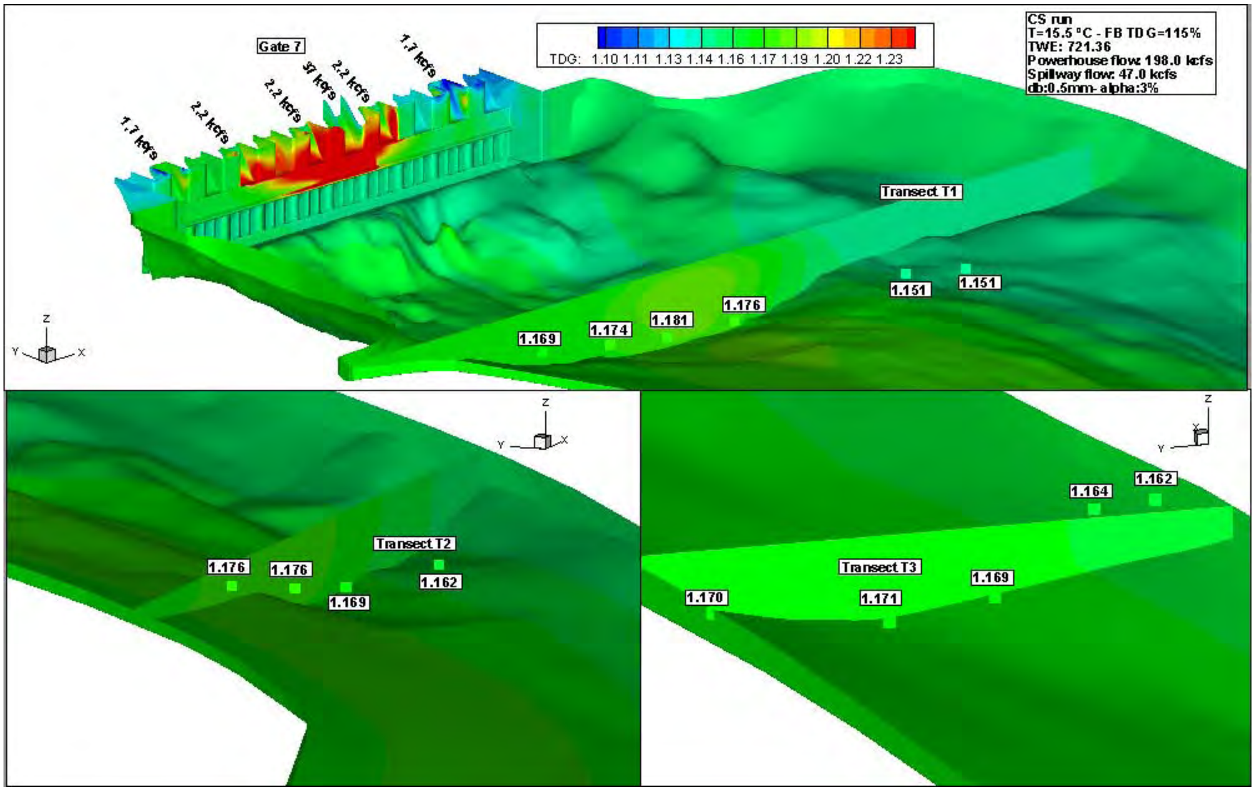

Figure 10.3-2 TDG distribution for the compliance simulation.

Table 9.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the compliance simulation.

Case	Type	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
CS	1-FG	47	246	19.1	0.64	721.4	30.4	115.0	116.7	117.1	116.7	1.7

Figure 10.3-3 show isosurfaces of TDG, gas volume fraction and bubble diameter for the Standard Compliance Simulation. The highest TDG isosurfaces are observed directly below spillbay 7 corresponding with the zone of higher gas volume fraction (aerated zone). In this area, the entrained bubbles generate high levels of TDG. However, the supersaturated water quickly degasses by mass exchange with bubbles near the free surface and mass transfer at the turbulent free surface near the spillway. Moreover, as shown the streamlines of Figure 10.3-4, strong lateral currents caused by the surface jet on bay 7 directed water toward the center of the dam contributing further to fully mixed flow and TDG dilution.

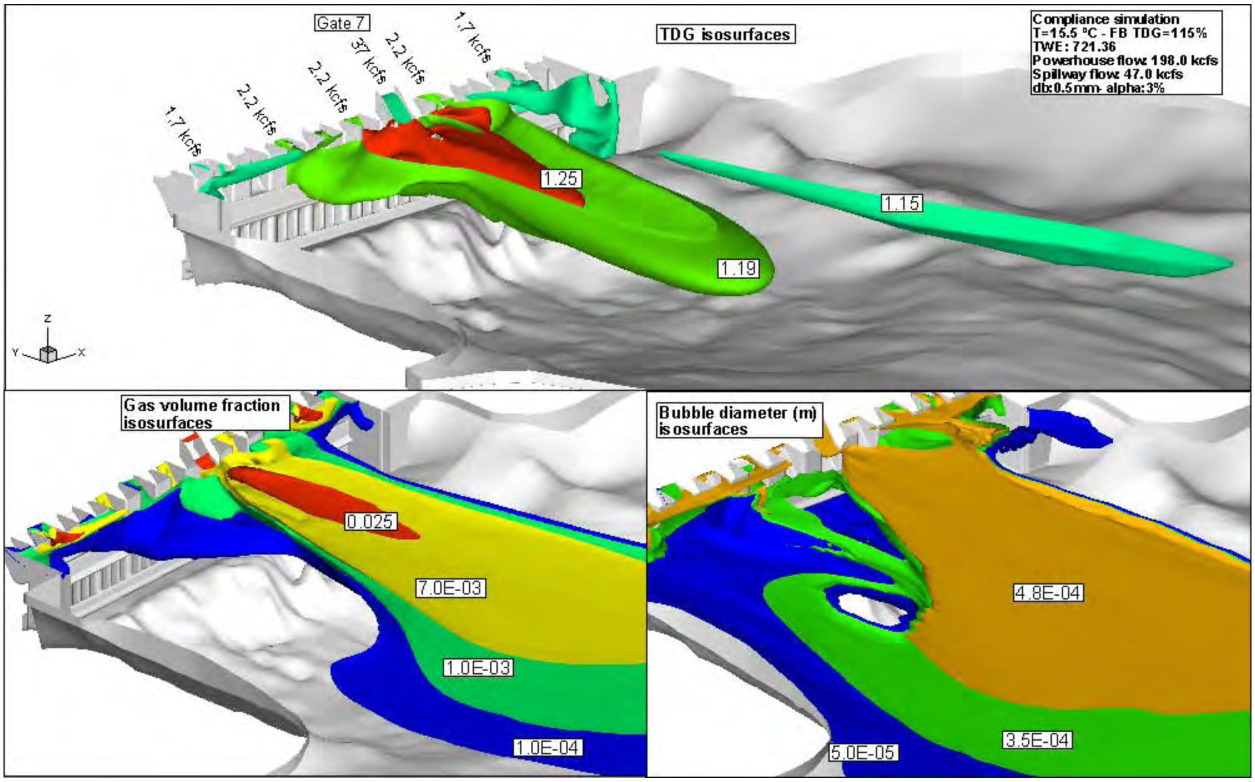

Figure 10.3-3 Streamlines colored by TDG concentration for the Standard Compliance Simulation.

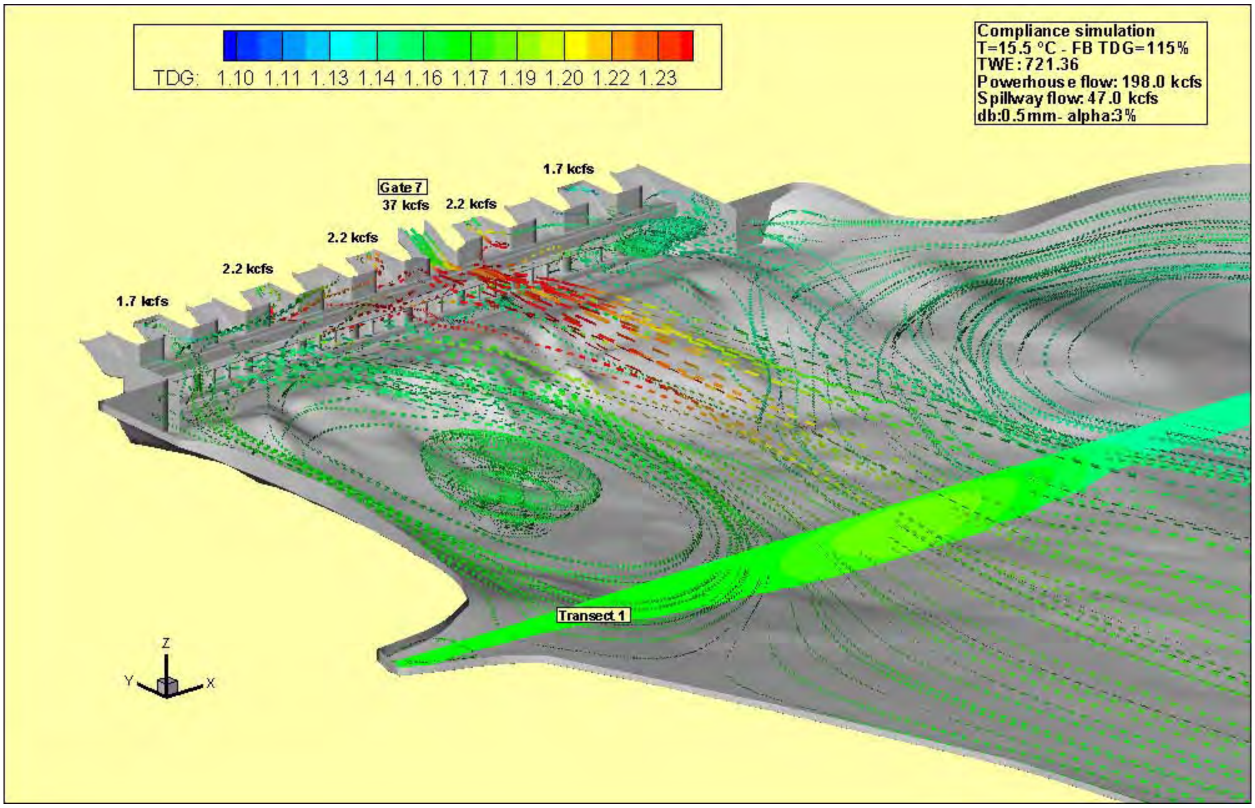

Figure 10.3-4 Streamlines colored by TDG concentration for the Standard Compliance Simulation.

10.4 TDG Dynamics During Non-Spill

Spill at Wells Dam typically occurs only during the fish passage season (April 1 to August 31), coinciding with high river flows observed during this period (Figure 10.4-1). TDG production during non-spill is virtually non-existent, with both median and average delta TDG values at 0.0% and 0.0% (SEM ± 0.0%), respectively. Delta TDG generally ranges ± 1%, often at negative values (Figure 10.4-2). The lack of TDG production during non-spill is further supported by a linear regression showing a significant positive correlation between forebay TDG and tailrace TDG ($y = 0.8873x+11.775$; $P < 0.000$, $R^2 = 0.81$). Median forebay TDG and tailrace TDG values during non-spill events over the past 10 years have both been 104% (average values for both measurements also 104%, SEM ± 0.0%; DART 2009). Only 7 of the 9,599 (0.07%) hourly values recorded during non-spill events between April and September, 1999-2008 surpassed 110% when forebay TDG was ≤ 110% (DART 2009). This negligible number of events is not biologically meaningful when encapsulated in any sort of daily average, including the 12-C High metric currently used by Ecology for compliance measures. These results indicate that Wells Dam is able to meet compliance with the 110% TDG tailrace criteria during non-spill events and outside of the fish passage season.

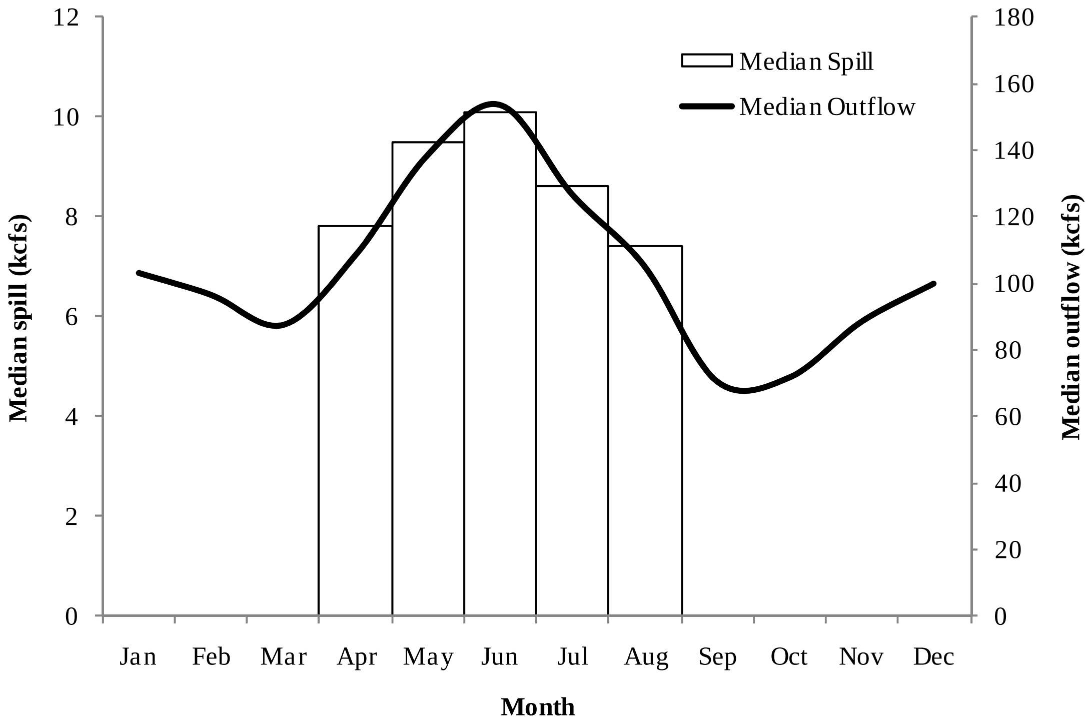

Figure 10.4-1 Median spill and outflow at Wells Dam by month, 1999-2008 (DART 2009).

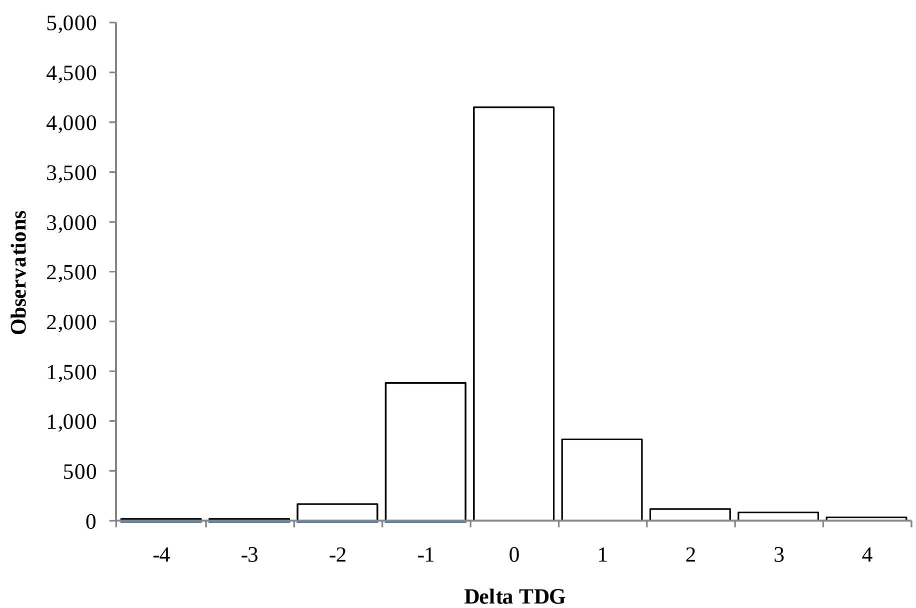

Figure 10.4-2 Delta TDG (tailrace TDG – forebay TDG) during non-spill at Wells Dam, 1999-2008 (n = 9,598 hourly values; DART 2009).

10.5 TDG Dynamics in the Rocky Reach Dam Forebay

Hourly TDG values in the Rocky Reach Dam forebay averaged 109.2% (± 0.0% SEM; median = 109.2%) during the fish passage season between 1999 and 2008, whereas daily TDG values averaged 106.6% (± 0.1% SEM; median = 107.5%; DART 2009). There is a strong and significant positive linear relationship between the tailrace measurements at Wells Dam and forebay measurements at Rocky Reach Dam amongst each of these years ($P < 0.00$) and combined ($P < 0.00$). The linear equations (Table 10.5-1) for these relationships indicate that:

- Wells tailrace TDG values up to 117.5% are required in order to reach 115% at the Rocky Reach Dam forebay monitoring station based on the historic 1999-2008 database.
- Years of spill testing (2004-2006) allowed for a lower than average maximum Wells Dam tailrace TDG (116.2%). At these relatively low levels of spill, the TDG standard at Rocky Reach forebay was not violated.
- Maximum tailrace TDG at Wells Dam to reach compliance at the Rocky Reach Dam forebay subsequent to implementing the Spill Playbook (2007) has ranged from 117.3% to 119.1% (average 118.2%).

Based on the historic operation at Wells Dam and the historic rate of TDG attenuation for the Rocky Reach reservoir, the Wells Project is reasonably expected to remain in full compliance with the numeric criteria set forth to ensure that a 115% TDG standard is met at the forebay of the downstream project (Rocky Reach Dam) under the Optimal Operating Conditions if incoming water to the forebay of Wells Dam is in compliance (115%). An annual TDG report is provided to Ecology each year to report observed values and any non-compliance events.

Table 10.5-1 Linear equations for hourly TDG values collected at the Wells Dam tailrace (WELW) and Rocky Reach Dam forebay (RRH). Spill testing occurred from 2004-2006, TDG Spill Playbooks were implemented in 2007.

Year	Equation	Maximum Tailrace TDG for 115% at RRH
’99-‘08	DisGasP, RRH = 27.120291 + 0.7478797*DisGasP, WELW	117.5
2004	DisGasP, RRH = 12.180962 + 0.8921431*DisGasP, WELW	115.2
2005	DisGasP, RRH = 22.815513 + 0.7906628*DisGasP, WELW	116.6
2006	DisGasP, RRH = 15.817845 + 0.8496649*DisGasP, WELW	116.7
2007	DisGasP, RRH = 36.643504 + 0.6579736*DisGasP, WELW	119.1
2008	DisGasP, RRH = 24.728595 + 0.7696586*DisGasP, WELW	117.3

11.0 LOCATION OF THE COMPLIANCE MONITORING STATION

The TDG distribution at transect T3 was analyzed to evaluate the location of the tailrace TDG compliance monitoring station WELW. The standard deviation, defined as:

$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(C - C_{ave}\right)^2}$, and the error of the TDG predicted at the compliance monitoring station calculated from $\text{Error}(\%) = \frac{\left(C_{WELW} - C_{ave}\right)}{C_{ave}} * 100$ are tabulated in Table 9.4-1.

Table 11.4-1 Averaged predicted TDG in Transect T3 and TDG at WELW.

Simulation	TDG Average	σ_{TDG}	WELW	Average-WELW Relative Difference (%)
MR1	1.179	0.00537	1.172	-0.580
MR2	1.237	0.01819	1.219	-1.459
MR3	1.207	0.00757	1.214	0.632
MR4	1.247	0.00493	1.251	0.365
MR5	1.167	0.00225	1.167	0.050
MR6	1.213	0.00103	1.212	-0.057
MR7	1.173	0.00490	1.178	0.435
MR8	1.226	0.00928	1.214	-0.920
MR9	1.229	0.00306	1.231	0.166
7Q10-A	1.198	0.00196	1.198	0.024
7Q10-B	1.177	0.01680	1.163	-1.189
7Q10-C	1.188	0.00706	1.181	-0.589
CS	1.167	0.00394	1.162	-0.428

In most of the cases the TDG gradient at transect T3 is small, indicating that the TDG gauge station is located in a region where substantial mixing has occurred.

12.0 CONCLUSIONS

A numerical study was performed with the objective of developing a spillway operation that would minimize TDG production in the Wells Tailrace. A two-phase flow model capable of predicting the dynamics of spillway surface jets, the hydrodynamics and TDG distribution within the Wells tailrace is presented. Variable bubble size and gas volume fraction were used to analyze dissolution and the consequent source of TDG. The model uses an anisotropic RSM turbulence model and attenuation of fluctuations at the free surface.

The model was calibrated and validated using field data collected on May 14, May 17, June 4 June 5 and June 17, 2006 during the TDG Production Dynamics Study (EES et al. 2007). The spillway flow was spread across spillbays on June 4, concentrated through a single spillbay on May 17, June 4 and June 5, and crowned on June 17. Velocity distribution measured in the tailrace on June 4 and June 5 was captured by the model. The bubble size and gas volume fraction at the inlet were the parameters of the model. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations. In this study, the gas volume fraction and bubble size were selected to be above and below the averaged TDG measured on June 4 and 5, 2006.

The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The model brackets the results of the field measurements for the validation cases with a deviation of about +/- 3% of the average TDG values for Transect 3. Numerical results obtained during calibration and validation demonstrated that the model used in the study captured the main features of the two-phase flow in the Wells tailrace and the trends of TDG values across all three transects.

Different spill releases and TDG production as a function of flow and tailwater elevation were analyzed to determine spillway operations that would minimize gas saturation in the tailrace. Nine runs with two spillway configurations (spread and FG) and four total river flows were simulated in an effort to identify how sensitive the model is to various spillway operating conditions. From this analysis it was concluded that:

- Full open gate operations result in the lowest TDG values downstream, followed by two open gates operation. The spread operation with moderate flow through each gate produced the highest TDG values as a result of more entrained air in the tailrace and smaller degasification at the free surface.

- TDG production is directly related to percentage of water spilled. In general, higher downstream TDG is observed as the spill percentage increases. Likewise, TDG production increases as the amount of spill increases. In addition, TDG levels downstream are reduced by dilution as powerhouse flow increases.

Based upon general gas dynamics defined by the results from the nine sensitivity runs, three additional simulations were performed to optimize spillway operations and further reduce TDG concentration downstream of the Wells Project during a 7Q10 (246 kcfs) event. Though the TDG production was similar for the simulated operations, the predicted lateral TDG distribution was significantly different. The Optimal Operating Condition that produced the lowest downstream TDG was a full open gate in bay 7 with most of the remaining flow in bay 3. This operation maximizes the lateral TDG gradient close to the dam promoting the degasification and downstream mixing. According to the model, spilling in a full open gate in bay 7 performs better than a mirror operation with full open gate in bay 5.

Finally, an additional scenario was modeled to provide Ecology with results consistent with settings used at other projects for evaluation of compliance with numeric WQS. The Standard Compliance Scenario was conducted using a concentrated spill in adjacent bays, with a 115% forebay TDG and 90% of maximum powerhouse capacity during a 7Q10 flow. The Standard Compliance Simulation produced an average TDG concentration at transect T3 of 116.7% well within the 120% TDG standard. This operation also maintained compliance with the TDG standard for the Rocky Reach forebay under the conditions described by the Standardized Compliance Simulation.

In addition to complying with the TDG standards for the Wells tailrace during the fish passage season, the Wells Project has also demonstrated an ability to meet the 119% TDG standard outside the fish passage season and, that ability to comply with the Rocky Reach forebay standard (115%). These three analyses, along with the considerable improvements identified in the TDG modeling, demonstrate the ability of the Wells Project to meet all numeric criteria for TDG under both the Optimal Operating Condition and the Standard Compliance Scenario.

13.0 ACKNOWLEDGMENTS

The authors thank Shane Bickford and Joshua Murauskas from Douglas PUD for their valuable contributions and support for this research. Bao Le of Long View Associates was instrumental in the development of optimization following initial model runs, Mary Mayo and Bob Clubb of Douglas County PUD provided technical and editorial support for this report.

14.0 REFERENCES

Antal, S.P., R.T. Lahey Jr., and J.E. Flaherty. 1991. Analysis of Phase Distribution in Fully Developed Laminar Bubbly Two-Phase Flow, International Journal of Multiphase Flow. 17(5): 553-682

ASL Environmental Sciences Inc. 2007. Turbine discharge measurements by acoustic scintillation flow meter at Until 1 and 2, Wells Hydroelectric Project, Pateros, Washington (2006). Prepared for the Public Utility District No. 1 of Douglas County.

Carrica, P. M., D. Drew, F. Bonetto, and R.T. Lahey Jr. 1999. A Polydisperse model for bubbly two–phase flow around a surface ship. International. Journal of Multiphase Flow. 25: 257-305.

Chen, P., M.P. Dudukovic, and J. Sanyal. 2005. Three-dimensional simulation of bubble column flows with bubble coalescence and breakup. American Institute of Chemical Engineers Journal. 51(3):696-712.

Columbia Basin Environmental (CBE). 2003. Wells Dam Spillway Total Dissolved Gas Evaluation 27 May to 10 June 2003. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

CBE. 2004. Wells Dam Spillway Total Dissolved Gas Evaluation 23 May to 6 June 2004. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

CBE. 2006. Wells Dam Spillway Total Dissolved Gas Evaluation – 23 May to 6 June 2005, Final Report, Prepared for Douglas County PUD.

Douglas County PUD (DCPUD). 2006. Wells Hydroelectric Project. FERC Project No. 2149. Pre-Application Document.

Deckwer, W.D. 1992. Bubble Column Reactors. John Wiley & Sons.

DeMoyer, C.D., E.L. Schierholz, J.S. Gulliver, and S.C.Wilhelms. 2003. Impact of Bubble and Free Surface Oxygen Transfer on Diffused Aeration Systems. Water Research. 37(8):1890-1904.

Drew, D.A., and S.L. Passman. 1998. Theory of Multicomponent Fluids. Applied Mathematical Sciences, Springer 135.

EES Consulting, Inc., J. Carroll, ENSR, and Parametrix. 2007. Total dissolved gas production dynamics Study of the Wells hydroelectric project. Prepared for Public Utility District No. 1 of Douglas County. Kirkland, Washington.

Fu, S., B.E. Launder, and D.P. Tselepidakis. 1987. Accommodating the effects of high strain rates in modeling the pressure-strain correlations. The University of Manchester Institute of Science and Technology. TFD/87/5.

Gibson, M.M., and B.E. Launder. 1978. Ground effects on pressure fluctuations in the atmospheric boundary layer. Journal of Fluid Mechanics. 86: 491-511.

Guido-Lavalle, G., P. Carrica, A. Clausse, and M.K. Qazi. 1994. A bubble number density constitutive equation, Nuclear Engineering and Design. 152: 213–224.

Hibbs, D.E., and J.S. Gulliver. 1997. Prediction of Effective Saturation Concentration at Spillway Plunge Pools. Journal of Hydraulic Engineering 123: 940-949.

Ishii, M., and N. Zuber. 1979. Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows. American Institute of Chemical Engineers Journal. 25(5):843-855.

Klinge, R. 2005. Wells Dam total dissolved gas abatement plan for 2005 and 2006 project. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA

Lamont, J.C. and D.S. Scott. 1970. An eddy cell model of mass transfer into the surface of a turbulent liquid. The American Institute for Chemical Engineers Journal. 16:513-519.

Lane, G.L., M.P. Schwarz, and G.M. Evans. 2005. Numerical modeling of gas-liquid flow in stirred tanks. Chemical. Engineering. Science. 60: 2203–2214.

Launder, B. E. 1989. Second-moment closure and its use in modeling turbulent industrial flows. International Journal for Numerical Methods in Fluids 9:963-985.

Lopez de Bertodano, M.L., R.T. Lahey Jr, and O.C. Jones. 1994. Development of a $k-\varepsilon$ model for bubbly two-phase flow. Journal of Fluids Engineering. 116: 128-134.

Orlins, J.J. and J.S. Gulliver. 2000. Dissolved Gas Supersaturation Downstream of a Spillway II: Computational Model. Journal of Hydraulic Engineering 38: 151-159.

Politano, M.S., P.M. Carrica, and J.L. Baliño. 2000. A polydisperese model of the two-phase flow in a bubble column. Heat and Technology 18(2): 101-113.

Politano, M.S., P.M. Carrica, C. Turan, and L. Weber. 2007a. A multidimensional two-phase flow model for the total dissolved gas downstream of spillways. Journal of Hydraulic Research 45(2): 165-177.

Politano, M.S., C. Turan, P.M. Carrica, and L. Weber. 2007b. A three-dimensional anisotropic model of the two phase flow and total dissolved gas downstream of spillways. FLUCOME.

Skalski, J. R., G. E. Johnson, C. M. Sullivan, E. Kudera and M. W. Erho. 1996. Statistical evaluation of turbine bypass efficiency at Wells Dam on the Columbia River, Washington. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 53, No. 10, pp. 2188 – 2198.

Takemura, F., and A. Yabe. 1998. Gas Dissolution Process of Spherical Rising Gas Bubbles. Chemical Engineering Science. 53(15):2691-2699.

Turan, C., M.S. Politano, P. M. Carrica, and L. Weber. 2007. Water Entrainment and Mixing due to Surface Jets. Computational Fluid Dynamics, 21: 3-4, 137-153.

Appendix A

Conditions Used for the Calibration, Validation, Sensitivity and 7Q10 Simulations

Treatment 46 S - June 4, 2006									
Tailwater Elevation: 717.3 ft – Forebay Elevation: 779.6 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	14.7	14.7	14.4	14.7	14.7	14.8	14.8	14.4	14.7
Powerhouse Total: 131.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.6	5.4	5.2	5.4	5.2	5.4	5.2	5.4	1.6
Spillway Total: 40.6 kcfs									
Total River Flow: 172.4 kcfs									
Forebay TDG: 111.8%									

Treatment 47 FG - June 5, 2006									
Tailwater Elevation: 720.2 ft – Forebay Elevation: 778.6 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	18.0	18.5	18.3	19.0	20.2	19.6	19.9	18.2
Powerhouse Total: 170.6 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	42.5	2.2	0.0	1.3
Spillway Total: 51.7 kcfs									
Total River Flow: 222.3 kcfs									
Forebay TDG: 111.5%									

Treatment 1 FG - May 14, 2006									
Tailwater Elevation: 711.5 ft – Forebay Elevation: 778.7 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	15.0	15.0	14.8	0.0	0.0	0.0	0.0	14.8	15.2
Powerhouse Total: 74.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	35.4	2.2	0.0	1.3
Spillway Total: 44.6 kcfs									
Total River Flow: 120.4 kcfs									
Forebay TDG: 109.1%									

Treatment 11 FG - May 17, 2006									
Tailwater Elevation: 715.4 ft – Forebay Elevation: 777.3 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	19.1	18.7	19.2	0.0	0.0	0.0	18.7	19.2
Powerhouse Total: 113.7 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.9	0.0	2.2	0.0	2.2	34.1	2.2	0.0	0.9
Spillway Total: 42.6 kcfs									
Total River Flow: 157.2 kcfs									
Forebay TDG: 110.4%									

Treatment 63 C - June 17, 2006									
Tailwater Elevation: 718.6 ft – Forebay Elevation: 780.1 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	13.0	13.0	12.9	13.0	13.0	13.1	13.1	12.8	13.1
Powerhouse Total: 117.1 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	2.2	29.8	19.9	29.8	1.7
Spillway Total: 87.4 kcfs									
Total River Flow: 205.5 kcfs									
Forebay TDG: 113.9%									

Simulation MR1									
Tailwater Elevation: 718.8 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 208.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR2									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	8.6	8.6	8.6	8.6	8.6	8.6	8.6	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR3									
Tailwater Elevation: 713.4 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 119.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR4									
Tailwater Elevation: 715.9 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	8.6	8.6	8.6	8.6	8.6	8.6	8.6	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 156.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR5									
Tailwater Elevation: 718.8 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 208.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR6									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	60.5	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR7									
Tailwater Elevation: 713.4 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 119.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR8									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	30.3	0.0	30.3	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR9									
Tailwater Elevation: 715.9 ft – Forebay Elevation: 781.0 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	30.3	0.0	30.3	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 156.5 kcfs									
Forebay TDG: 115%									

Treatment 7Q10-A									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 780.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Powerhouse Total: 180.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	8.0	43.0	8.0	0.0	1.7
Spillway Total: 64.6 kcfs									
Total River Flow: 244.6 kcfs									
Forebay TDG: 113.0%									

Treatment 7Q10-B									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 780.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Powerhouse Total: 180.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	12.0	2.2	0.0	2.2	43.0	2.2	0.0	1.7
Spillway Total: 65.0 kcfs									
Total River Flow: 245.0 kcfs									
Forebay TDG: 113.0%									

Treatment 7Q10-C									
Tailwater Elevation: 721.4 ft – Forebay Elevation: 780.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Powerhouse Total: 180.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	43.0	2.2	0.0	2.2	12.0	1.7
Spillway Total: 65.0 kcfs									
Total River Flow: 245.0 kcfs									
Forebay TDG: 113.0%									

Appendix B

Measured and Predicted TDG Concentrations at Probe Locations

Comparison between measured and predicted TDG on June 4, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P2	1878138.7	345839.8	648.7	1.238	1.173	5.58			
TW1P3	1877972.7	345812.5	648.4	1.265	1.178	7.41			
TW1P4Z1	1877766.1	345652.5	692.0	1.224	1.200	1.97			
TW1P4Z2	1877685.6	345800.1	657.0	1.190	1.197	-0.61	1.229	1.187	3.56
TW2P2	1878494.5	343593.5	675.9	1.204	1.172	2.72			
TW2P3	1878414.7	343618.3	679.9	1.230	1.174	4.78			
TW2P4	1878237.5	343582.5	698.6	1.233	1.179	4.55	1.222	1.175	4.02
WELW	1870372.9	334581.1	692.0	1.190	1.165	2.18			
TW3P2	1870323.5	334702.2	698.7	1.202	1.171	2.69			
TW3P4	1870037.3	334949.0	673.4	1.211	1.179	2.74			
TW3P5	1869929.7	335169.1	697.9	1.222	1.188	2.87	1.207	1.176	2.62

Comparison between measured and predicted TDG on June 5, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P2	1878138.7	345839.8	648.7	1.160	1.200	-3.38			
TW1P3	1877972.7	345812.5	648.4	1.155	1.180	-2.05			
TW1P4Z1	1877766.1	345652.5	692.0	1.153	1.158	-0.46			
TW1P4Z2	1877685.6	345800.1	657.0	1.152	1.159	-0.68	1.155	1.174	-1.66
TW2P2	1878494.5	343593.5	675.9	1.151	1.181	-2.53			
TW2P3	1878414.7	343618.3	679.9	1.152	1.182	-2.57			
TW2P4	1878237.5	343582.5	698.6	1.151	1.183	-2.73	1.151	1.182	-2.61
WELW	1870372.9	334581.1	692.0	1.149	1.173	-2.04			
TW3P2	1870323.5	334702.2	698.7	1.150	1.178	-2.35			
TW3P4	1870037.3	334949.0	673.4	1.151	1.182	-2.68			
TW3P5	1869929.7	335169.1	697.9	1.150	1.182	-2.67	1.150	1.179	-2.44

Comparison between measured and predicted TDG on May 14, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P1Z1	1878593.6	345704.7	692.0	1.155	1.167	-1.00			
TW1P1Z2	1878511.2	345814.2	669.1	1.159	1.167	-0.67			
TW1P2	1878138.7	345839.8	648.7	1.170	1.181	-0.96			
TW1P3	1877972.7	345812.5	648.4	1.176	1.187	-0.91			
TW1P4Z1	1877766.1	345652.5	692.0	1.173	1.163	0.88			
TW1P4Z2	1877685.6	345800.1	657.0	1.166	1.168	-0.21	1.167	1.172	-0.48
TW2P1	1878645.0	343552.6	675.6	1.162	1.167	-0.43			
TW2P2	1878494.5	343593.5	675.9	1.162	1.170	-0.71			
TW2P3	1878414.7	343618.3	679.9	1.163	1.175	-1.05			
TW2P4	1878237.5	343582.5	698.6	1.164	1.180	-1.38	1.163	1.173	-0.89
WELW	1870372.9	334581.1	692.0	1.163	1.151	1.01			
TW3P2	1870323.5	334702.2	698.7	1.162	1.165	-0.28			
TW3P3	1870104.4	334818.9	679.0	1.163	1.164	-0.12			
TW3P4	1870037.3	334949.0	673.4	1.164	1.173	-0.80			
TW3P5	1869929.7	335169.1	697.9	1.164	1.170	-0.48	1.163	1.165	-0.14

Comparison between measured and predicted TDG on May 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1-1S	1878593.6	345704.7	692.0	1.147	1.163	-1.38			
TW 1-1	1878511.2	345814.2	669.1	1.156	1.161	-0.44			
TW 1-2	1878138.7	345839.8	648.7	1.183	1.166	1.45			
TW 1-3	1877972.7	345812.5	648.4	1.188	1.173	1.21			
TW1-4S	1877766.1	345652.5	692.0	1.177	1.149	2.47			
TW 1-4	1877685.6	345800.1	657.0	1.168	1.153	1.30	1.170	1.161	0.77
TW 2-2	1878494.5	343593.5	675.9	1.168	1.168	0.01			
TW 2-3	1878414.7	343618.3	679.9	1.171	1.172	-0.11			
TW 2-4	1878237.5	343582.5	698.6	1.167	1.167	0.04	1.169	1.169	-0.02
WELW	1870372.9	334581.1	692.0	1.165	1.153	1.05			
TW 3-2	1870323.5	334702.2	698.7	1.166	1.164	0.15			
TW 3-3	1870104.4	334818.9	679.0	1.167	1.162	0.47			
TW 3-4	1870037.3	334949.0	673.4	1.168	1.169	-0.11			
TW 3-5	1869929.7	335169.1	697.9	1.168	1.161	0.59	1.167	1.162	0.43

Comparison between measured and predicted TDG on June 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P1Z1	1878593.6	345704.7	692.0	1.188	1.256	-5.39			
TW1P2	1878138.7	345839.8	648.7	1.398	1.282	12.97			
TW1P3	1877972.7	345812.5	648.4	1.343	1.260	6.57			
TW1P4Z1	1877766.1	345652.5	692.0	1.284	1.217	5.54			
TW1P4Z2	1877685.6	345800.1	657.0	1.259	1.222	3.03	1.305	1.247	4.58
TW2P2	1878494.5	343593.5	675.9	1.261	1.261	-0.02			
TW2P3	1878414.7	343618.3	679.9	1.265	1.261	0.34			
TW2P4	1878237.5	343582.5	698.6	1.265	1.233	2.58	1.264	1.252	0.95
WELW	1870372.9	334581.1	692.0	1.256	1.243	1.06			
TW3P2	1870323.5	334702.2	698.7	1.264	1.249	1.16			
TW3P4	1870037.3	334949.0	673.4	1.268	1.248	1.58			
TW3P5	1869929.7	335169.1	697.9	1.269	1.238	2.53	1.264	1.245	1.58

MR1

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.169	
TW1P1Z2	1878511.2	345814.2	669.1	1.162	
TW1P2	1878138.7	345839.8	648.7	1.174	
TW1P3	1877972.7	345812.5	648.4	1.168	
TW1P4Z1	1877766.1	345652.5	692.0	1.182	
TW1P4Z2	1877685.6	345800.1	657.0	1.182	1.173
TW2P1	1878645.0	343552.6	675.6	1.170	
TW2P2	1878494.5	343593.5	675.9	1.176	
TW2P3	1878414.7	343618.3	679.9	1.187	
TW2P4	1878237.5	343582.5	698.6	1.190	1.181
WELW	1870372.9	334581.1	692.0	1.172	
TW3P2	1870323.5	334702.2	698.7	1.175	
TW3P3	1870104.4	334818.9	679.0	1.180	
TW3P4	1870037.3	334949.0	673.4	1.183	
TW3P5	1869929.7	335169.1	697.9	1.185	1.179

MR2

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.203	
TW1P1Z2	1878511.2	345814.2	669.1	1.180	
TW1P2	1878138.7	345839.8	648.7	1.240	
TW1P3	1877972.7	345812.5	648.4	1.246	
TW1P4Z1	1877766.1	345652.5	692.0	1.273	
TW1P4Z2	1877685.6	345800.1	657.0	1.278	1.237
TW2P1	1878645.0	343552.6	675.6	1.217	
TW2P2	1878494.5	343593.5	675.9	1.232	
TW2P3	1878414.7	343618.3	679.9	1.247	
TW2P4	1878237.5	343582.5	698.6	1.266	1.241
WELW	1870372.9	334581.1	692.0	1.219	
TW3P2	1870323.5	334702.2	698.7	1.223	
TW3P3	1870104.4	334818.9	679.0	1.234	
TW3P4	1870037.3	334949.0	673.4	1.244	
TW3P5	1869929.7	335169.1	697.9	1.264	1.237

MR3

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.246	
TW1P1Z2	1878511.2	345814.2	669.1	1.247	
TW1P2	1878138.7	345839.8	648.7	1.232	
TW1P3	1877972.7	345812.5	648.4	1.193	
TW1P4Z1	1877766.1	345652.5	692.0	1.181	
TW1P4Z2	1877685.6	345800.1	657.0	1.182	1.213
TW2P1	1878645.0	343552.6	675.6	1.227	
TW2P2	1878494.5	343593.5	675.9	1.216	
TW2P3	1878414.7	343618.3	679.9	1.201	
TW2P4	1878237.5	343582.5	698.6	1.185	1.207
WELW	1870372.9	334581.1	692.0	1.214	
TW3P2	1870323.5	334702.2	698.7	1.214	
TW3P3	1870104.4	334818.9	679.0	1.206	
TW3P4	1870037.3	334949.0	673.4	1.203	
TW3P5	1869929.7	335169.1	697.9	1.197	1.207

MR4

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.297	
TW1P1Z2	1878511.2	345814.2	669.1	1.295	
TW1P2	1878138.7	345839.8	648.7	1.262	
TW1P3	1877972.7	345812.5	648.4	1.230	
TW1P4Z1	1877766.1	345652.5	692.0	1.248	
TW1P4Z2	1877685.6	345800.1	657.0	1.248	1.263
TW2P1	1878645.0	343552.6	675.6	1.258	
TW2P2	1878494.5	343593.5	675.9	1.244	
TW2P3	1878414.7	343618.3	679.9	1.237	
TW2P4	1878237.5	343582.5	698.6	1.243	1.245
WELW	1870372.9	334581.1	692.0	1.251	
TW3P2	1870323.5	334702.2	698.7	1.251	
TW3P3	1870104.4	334818.9	679.0	1.247	
TW3P4	1870037.3	334949.0	673.4	1.244	
TW3P5	1869929.7	335169.1	697.9	1.239	1.247

MR5

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.158	
TW1P1Z2	1878511.2	345814.2	669.1	1.157	
TW1P2	1878138.7	345839.8	648.7	1.171	
TW1P3	1877972.7	345812.5	648.4	1.163	
TW1P4Z1	1877766.1	345652.5	692.0	1.155	
TW1P4Z2	1877685.6	345800.1	657.0	1.157	1.160
TW2P1	1878645.0	343552.6	675.6	1.168	
TW2P2	1878494.5	343593.5	675.9	1.172	
TW2P3	1878414.7	343618.3	679.9	1.170	
TW2P4	1878237.5	343582.5	698.6	1.163	1.168
WELW	1870372.9	334581.1	692.0	1.1672	
TW3P2	1870323.5	334702.2	698.7	1.16764	
TW3P3	1870104.4	334818.9	679.0	1.1681	
TW3P4	1870037.3	334949.0	673.4	1.16751	
TW3P5	1869929.7	335169.1	697.9	1.16264	1.167

MR6

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.208	
TW1P1Z2	1878511.2	345814.2	669.1	1.205	
TW1P2	1878138.7	345839.8	648.7	1.221	
TW1P3	1877972.7	345812.5	648.4	1.217	
TW1P4Z1	1877766.1	345652.5	692.0	1.205	
TW1P4Z2	1877685.6	345800.1	657.0	1.211	1.211
TW2P1	1878645.0	343552.6	675.6	1.213	
TW2P2	1878494.5	343593.5	675.9	1.215	
TW2P3	1878414.7	343618.3	679.9	1.216	
TW2P4	1878237.5	343582.5	698.6	1.213	1.214
WELW	1870372.9	334581.1	692.0	1.212	
TW3P2	1870323.5	334702.2	698.7	1.213	
TW3P3	1870104.4	334818.9	679.0	1.214	
TW3P4	1870037.3	334949.0	673.4	1.214	
TW3P5	1869929.7	335169.1	697.9	1.212	1.213

MR7

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.193	
TW1P1Z2	1878511.2	345814.2	669.1	1.192	
TW1P2	1878138.7	345839.8	648.7	1.191	
TW1P3	1877972.7	345812.5	648.4	1.165	
TW1P4Z1	1877766.1	345652.5	692.0	1.155	
TW1P4Z2	1877685.6	345800.1	657.0	1.156	1.175
TW2P1	1878645.0	343552.6	675.6	1.181	
TW2P2	1878494.5	343593.5	675.9	1.176	
TW2P3	1878414.7	343618.3	679.9	1.168	
TW2P4	1878237.5	343582.5	698.6	1.159	1.171
WELW	1870372.9	334581.1	692.0	1.178	
TW3P2	1870323.5	334702.2	698.7	1.178	
TW3P3	1870104.4	334818.9	679.0	1.173	
TW3P4	1870037.3	334949.0	673.4	1.171	
TW3P5	1869929.7	335169.1	697.9	1.167	1.173

MR8

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.180	
TW1P1Z2	1878511.2	345814.2	669.1	1.178	
TW1P2	1878138.7	345839.8	648.7	1.194	
TW1P3	1877972.7	345812.5	648.4	1.248	
TW1P4Z1	1877766.1	345652.5	692.0	1.227	
TW1P4Z2	1877685.6	345800.1	657.0	1.243	1.212
TW2P1	1878645.0	343552.6	675.6	1.210	
TW2P2	1878494.5	343593.5	675.9	1.223	
TW2P3	1878414.7	343618.3	679.9	1.244	
TW2P4	1878237.5	343582.5	698.6	1.241	1.230
WELW	1870372.9	334581.1	692.0	1.214	
TW3P2	1870323.5	334702.2	698.7	1.218	
TW3P3	1870104.4	334818.9	679.0	1.227	
TW3P4	1870037.3	334949.0	673.4	1.233	
TW3P5	1869929.7	335169.1	697.9	1.236	1.226

MR9

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.213	
TW1P1Z2	1878511.2	345814.2	669.1	1.212	
TW1P2	1878138.7	345839.8	648.7	1.218	
TW1P3	1877972.7	345812.5	648.4	1.244	
TW1P4Z1	1877766.1	345652.5	692.0	1.217	
TW1P4Z2	1877685.6	345800.1	657.0	1.228	1.222
TW2P1	1878645.0	343552.6	675.6	1.232	
TW2P2	1878494.5	343593.5	675.9	1.233	
TW2P3	1878414.7	343618.3	679.9	1.230	
TW2P4	1878237.5	343582.5	698.6	1.223	1.229
WELW	1870372.9	334581.1	692.0	1.231	
TW3P2	1870323.5	334702.2	698.7	1.231	
TW3P3	1870104.4	334818.9	679.0	1.230	
TW3P4	1870037.3	334949.0	673.4	1.229	
TW3P5	1869929.7	335169.1	697.9	1.224	1.229

7Q10-A Simulation

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.189	
TW1P1Z2	1878511.2	345814.2	669.1	1.188	
TW1P2	1878138.7	345839.8	648.7	1.202	
TW1P3	1877972.7	345812.5	648.4	1.199	
TW1P4Z1	1877766.1	345652.5	692.0	1.182	
TW1P4Z2	1877685.6	345800.1	657.0	1.189	1.192
TW2P1	1878645.0	343552.6	675.6	1.198	
TW2P2	1878494.5	343593.5	675.9	1.200	
TW2P3	1878414.7	343618.3	679.9	1.202	
TW2P4	1878237.5	343582.5	698.6	1.197	1.199
WELW	1870372.9	334581.1	692.0	1.198	
TW3P2	1870323.5	334702.2	698.7	1.198	
TW3P3	1870104.4	334818.9	679.0	1.199	
TW3P4	1870037.3	334949.0	673.4	1.199	
TW3P5	1869929.7	335169.1	697.9	1.194	1.198

7Q10-B Simulation

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.150	
TW1P1Z2	1878511.2	345814.2	669.1	1.153	
TW1P2	1878138.7	345839.8	648.7	1.168	
TW1P3	1877972.7	345812.5	648.4	1.202	
TW1P4Z1	1877766.1	345652.5	692.0	1.228	
TW1P4Z2	1877685.6	345800.1	657.0	1.225	1.188
TW2P1	1878645.0	343552.6	675.6	1.161	
TW2P2	1878494.5	343593.5	675.9	1.166	
TW2P3	1878414.7	343618.3	679.9	1.181	
TW2P4	1878237.5	343582.5	698.6	1.204	1.178
WELW	1870372.9	334581.1	692.0	1.163	
TW3P2	1870323.5	334702.2	698.7	1.165	
TW3P3	1870104.4	334818.9	679.0	1.172	
TW3P4	1870037.3	334949.0	673.4	1.180	
TW3P5	1869929.7	335169.1	697.9	1.204	1.177

7Q10-C Simulation

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.171	
TW1P1Z2	1878511.2	345814.2	669.1	1.172	
TW1P2	1878138.7	345839.8	648.7	1.184	
TW1P3	1877972.7	345812.5	648.4	1.187	
TW1P4Z1	1877766.1	345652.5	692.0	1.208	
TW1P4Z2	1877685.6	345800.1	657.0	1.210	1.189
TW2P1	1878645.0	343552.6	675.6	1.181	
TW2P2	1878494.5	343593.5	675.9	1.182	
TW2P3	1878414.7	343618.3	679.9	1.188	
TW2P4	1878237.5	343582.5	698.6	1.200	1.188
WELW	1870372.9	334581.1	692.0	1.181	
TW3P2	1870323.5	334702.2	698.7	1.183	
TW3P3	1870104.4	334818.9	679.0	1.186	
TW3P4	1870037.3	334949.0	673.4	1.189	
TW3P5	1869929.7	335169.1	697.9	1.199	1.188

Compliance Simulation

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.151	
TW1P1Z2	1878511.2	345814.2	669.1	1.151	
TW1P2	1878138.7	345839.8	648.7	1.176	
TW1P3	1877972.7	345812.5	648.4	1.181	
TW1P4Z1	1877766.1	345652.5	692.0	1.174	
TW1P4Z2	1877685.6	345800.1	657.0	1.169	1.167
TW2P1	1878645.0	343552.6	675.6	1.162	
TW2P2	1878494.5	343593.5	675.9	1.169	
TW2P3	1878414.7	343618.3	679.9	1.176	
TW2P4	1878237.5	343582.5	698.6	1.176	1.171
WELW	1870372.9	334581.1	692.0	1.162	
TW3P2	1870323.5	334702.2	698.7	1.164	
TW3P3	1870104.4	334818.9	679.0	1.169	
TW3P4	1870037.3	334949.0	673.4	1.171	
TW3P5	1869929.7	335169.1	697.9	1.170	1.167

Politano, M. A. Arenas Amado, and L. Weber. 2009. An Investigation into the Total Dissolved Gas Dynamics of the Wells Project (Total Dissolved Gas Investigation): Wells Hydroelectric Project, FERC No. 2149. Updated Study Report required by FERC. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA.

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AN INVESTIGATION INTO THE TOTAL DISSOLVED GAS DYNAMICS OF THE WELLS PROJECT
(Total Dissolved Gas Investigation)

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

FINAL REPORT
REQUIRED BY FERC

April 2009

Prepared by:
M. Politano, A. Arenas Amado and L. Weber
IIHR-Hydroscience & Engineering
The University of Iowa
300 South Riverside Drive
Iowa City, Iowa 52242-1585

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509) 884-7191
E-Mail: relicensing@dcpud.org

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ABSTRACT

The current Wells Hydroelectric Project (Wells Project) license will expire on May 31, 2012. As part of the Wells Project relicensing process, the Public Utility District No. 1 of Douglas County (Douglas PUD) is required to obtain a water quality certificate pursuant to Section 401 of the Clean Water Act. As part of the 401 certification process, the Washington State Department of Ecology (Ecology) must determine whether the Wells Project meets state water quality standards (WQS), including standards for total dissolved gas (TDG).

Douglas PUD examined TDG production dynamics at the Wells Project to comply with State water quality standards (WQS). As part of the relicensing of the Wells Project, Douglas PUD initiated a series of assessments aimed at gaining a better understanding of the effect of spill operations on the production, transport and mixing of TDG in the Wells Dam tailrace.

The primary methodology employed in this study was the development of an unsteady state three-dimensional (3D), two-phase flow computational fluid dynamics (CFD) tool to predict the hydrodynamics of gas saturation and TDG distribution within the Wells tailrace. Two models were used in the study; a volume of fluid (VOF) model and a rigid-lid two-phase flow model.

The VOF model predicts the flow regime and the free-surface characteristics, recognizing that a spillway jet may plunge to depth in the tailrace or remain closer to the surface depending upon the geometry of the outlet and the tailwater elevation. The VOF model boundary extended approximately 1,700 feet downstream of the dam.

The rigid-lid model included 16,500 feet of the Wells tailrace, from Wells Dam downstream to the TDG compliance monitoring station. This two-phase flow model characterizes the hydrodynamics and three-dimensional distribution of gas volume fraction, bubble size and TDG in the Wells tailrace. This model assumes that the free surface can be modeled using a rigid-lid non-flat boundary condition. The free-surface shape for the first 1,000 feet downstream of the dam was extracted from VOF computations and slopes derived from HEC-RAS simulations for the remaining downstream regions. The velocity profiles derived from the VOF model were input into the rigid-lid model. Predictions of the gas volume fraction, bubble diameter at the spillbays, and typical environmental conditions observed at high flow events ($\geq$ 200 kcfs) are the external parameters of the model.

The model was calibrated and validated using field data collected in 2006 during a TDG production dynamics study (EES et al. 2007). Agreement was attained between the depth-averaged velocity data collected in the field and those generated by the model. A gas volume fraction of 3% and bubble diameter of 0.5 mm in the spillbays produced TDG values that bracketed the 2006 field observations.

Once calibrated, the predictive ability of the model was validated by running three different operational conditions tested in 2006. The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The numerical results demonstrate that the model provides a reliable predictor of tailrace TDG and therefore can be used as a tool to identify Project operations that minimize TDG concentrations downstream of Wells Dam.

After validation and calibration, the model was used to analyze the sensitivity of TDG concentration to the operation of the Project. Nine runs were completed for four river flows in which spill was either spread across the spillbays or concentrated in one or more spillbays. Numerical results indicate that concentrated spill operations resulted in the lowest TDG concentration downstream of the dam. According to the model, concentrated spill operations reduce the TDG production and increase the degasification at the free surface.

Based on the results from the sensitivity simulations, the model was used to predict TDG in the tailrace using the preferred operating condition for a 7Q10 flow of 246 kcfs. The preferred operating condition utilized a spillway configuration where water was concentrated rather than spread evenly across the entire length of the spillway. Using environmental conditions expected to occur during the passage of a 7Q10 flow and using the preferred operating condition, the TDG values predicted by the model at the location of the compliance station was within the Washington State water quality standards (<120%). The results of this study indicate that specific changes in Project operations can be utilized to meet the numeric water quality standards for TDG under 7Q10 flows.

The numerical results of the model also confirm the findings of the 2005 and 2006 TDG studies indicating that TDG values at the compliance monitoring station downstream of Wells Dam are representative of the TDG production in the Wells tailrace.

1.0 INTRODUCTION

1.1 General Description of the Wells Hydroelectric Project

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 1.1-1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from the Rocky Reach Hydroelectric Project, owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for the Public Utility District No. 1 of Douglas County (Douglas PUD). It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a top of dam elevation of 795 feet above mean sea level (msl).

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 feet msl (Figure 1.1-1).

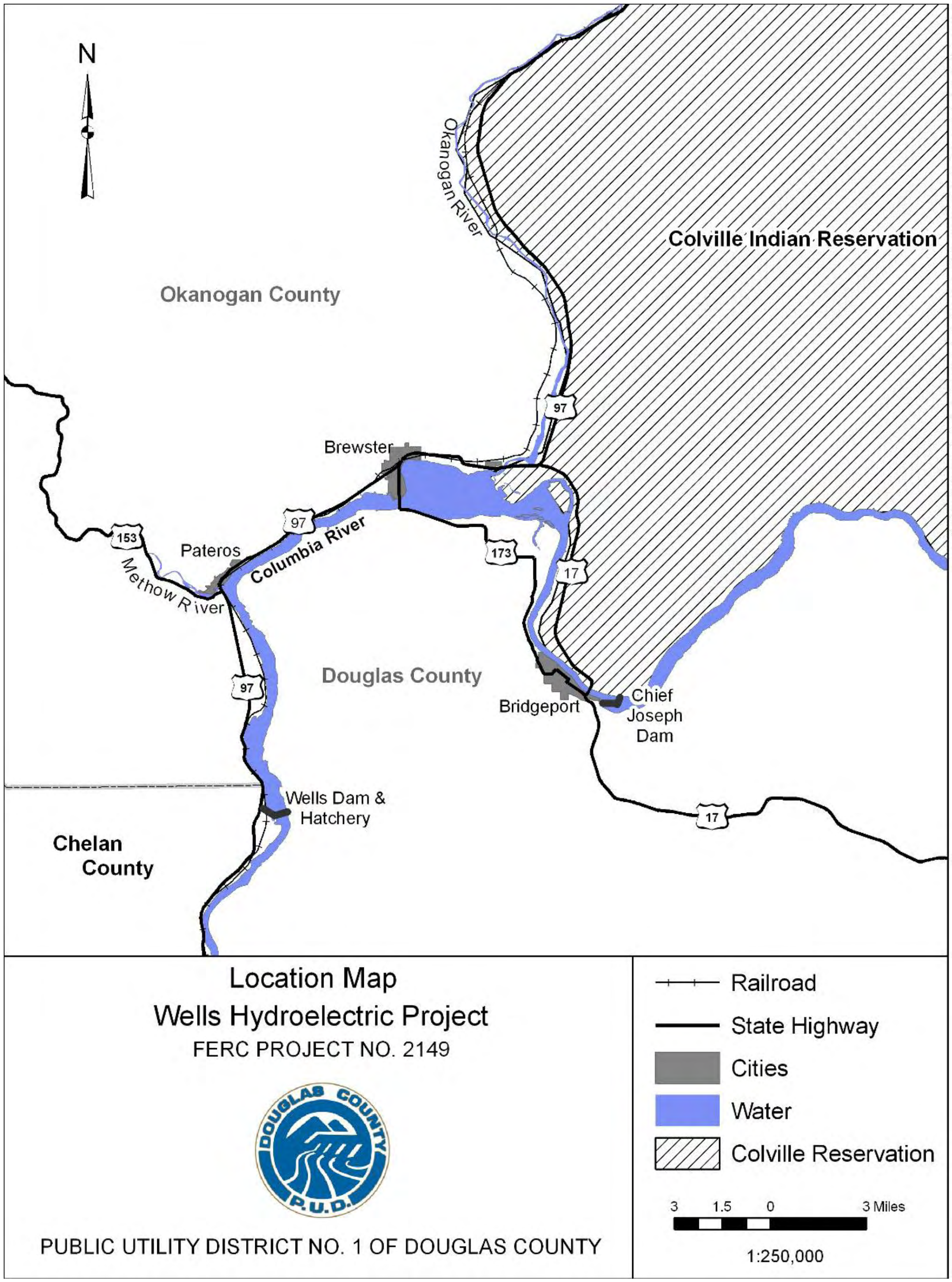

Figure 1.1-1 Location Map of the Wells Hydroelectric Project.

1.2 Relicensing Process

The current Wells Project license will expire on May 31, 2012. Douglas PUD is using the Integrated Licensing Process (ILP) promulgated by Federal Energy Regulatory Commission (FERC) Order 2002 (18 CFR Part 5). Stakeholders consisting of representatives from state and federal agencies, tribes, local governments, non-governmental organizations and the general public have participated in the Wells Project ILP, from a very early stage, to identify information needs related to the relicensing of the Wells Project.

In August 2005, Douglas PUD initiated a series of Resource Work Group (RWG) meetings with stakeholders regarding the upcoming relicensing of the Wells Project. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to identify resource issues and to develop preliminary study plans prior to filing the Notice of Intent (NOI) and Pre-Application Document (PAD). The RWGs were formed to discuss issues related to the Wells Project and its operations, identify information needs, and develop agreed-upon study plans.

The primary goals of the RWGs were to identify resource issues and potential study needs in advance of Douglas PUD filing the NOI and PAD. Through 35 meetings, each RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWG's efforts to apply the FERC's seven study criteria to mutually determine the applicability of each individual Issue Statement. Agreed-Upon Study Plans are the finished products of the informal RWG process.

Douglas PUD submitted the NOI and PAD to the FERC on December 1, 2006. The PAD included the RWGs' 12 Agreed-Upon Study Plans. The filing of these documents initiated the relicensing process for the Wells Project under the FERC's regulations governing the ILP.

On May 16, 2007, Douglas PUD submitted a Proposed Study Plan (PSP) Document. The PSP Document consisted of the Applicant's Proposed Study Plans, Responses to Stakeholder Study Requests and a schedule for conducting the Study Plan Meeting. The ILP required Study Plan Meeting was conducted on June 14, 2007. The purpose of the Study Plan Meeting was to provide stakeholders with an opportunity to review and comment on Douglas PUD's PSP Document, to review and answer questions related to stakeholder study requests and to attempt to resolve any outstanding issues with respect to the PSP Document.

On September 14, 2007, Douglas PUD submitted a Revised Study Plan (RSP) Document. The RSP Document consisted of a summary of each of Douglas PUD's RSPs and a response to stakeholder PSP Document comments.

On October 11, 2007, the FERC issued its Study Plan Determination based on its review of the RSP Document and comments from stakeholders. The FERC's Study Plan Determination required Douglas PUD to complete 10 of the 12 studies included in its RSP Document. Douglas PUD has opted to complete all 12 studies to better prepare for the 401 Water Quality Certification process conducted by the Washington State Department of Ecology (Ecology) and to fulfill its commitment to the RWGs who collaboratively developed the 12 Agreed-Upon Study

Plans with Douglas PUD. On October 15, 2008, Douglas PUD filed with the FERC the ISR Document that contained final reports for eight of the 12 studies and interim progress reports for four of the 12 studies. The ISR Document included results from all ten of the studies required by the FERC in the October 11, 2007 Study Plan Determination. The ISR Document also included results from two studies voluntarily conducted by Douglas PUD for the reasons stated above. On November 24, 2008, Douglas PUD filed a letter correcting a water temperature figure within the original ISR Document. On December 2, 2008, Douglas PUD filed the final Traditional Cultural Property Study for the Wells Project, which was prepared by the Confederated Tribes of the Colville Reservation under a contract with Douglas PUD.

The deadline for stakeholder comment on the ISR Document was December 15, 2008 pursuant to the approved Process Plan and Schedule for the Wells Project. Comments were filed by the City of Pateros on November 7, 2008 and by the City of Brewster on December 5, 2008.

On January 14, 2009, Douglas PUD filed a letter containing its responses to the comments from the cities on the ISR Document and proposed revisions to the schedule for the Wells ILP. On February 4, 2009, the FERC issued a determination on the requests for modification to the Wells Study Plan and on Douglas PUD's proposed revisions to the schedule. The FERC concluded that there was no need to modify the Wells Study Plan. The FERC also approved Douglas PUD's proposed modifications to the Wells ILP schedule.

This report is the final report for the Total Dissolved Gas Investigation. There were no variances from the FERC approved study plan for the Total Dissolved Gas Investigation.

1.3 Overview of Total Dissolved Gas at Wells Dam

Wells Dam, owned and operated by Douglas PUD, is located at RM 515.6 on the Columbia River, Washington (Figure 1.3-1). The spillway gates at Wells Dam are used to pass water when river flows exceed the maximum turbine hydraulic capacity (forced spill), to assist outmigration of juvenile salmonids (fish bypass spill), and to prevent flooding along the mainstem Columbia River (flood control spill). The Wells Project can pass approximately 22 kcfs through each operating turbine (220 kcfs through 10 turbines) with an additional 10-11 kcfs used to operate the juvenile fish bypass system and 1.0 kcfs to operate the adult fish ladders (ASL Environmental Sciences Inc. 2007). Therefore, spill is forced when inflows are higher than 232 kcfs. Spill may occur at flows less than the hydraulic capacity when the volume of water is greater than the amount required to meet electric system loads. Hourly coordination among hydroelectric projects on the mid-Columbia River was established to minimize unnecessary spill.

Wells Dam is a hydrocombine-designed dam with the spillway situated directly above the powerhouse. Research at Wells Dam in the mid-1980s showed that a modest amount of spill would effectively guide between 92 percent and 96 percent of the downstream migrating juvenile salmonids through the Juvenile Bypass System (JBS) and away from the turbines (Skalski et al., 1996). The operation of the Wells JBS utilizes five spillways that have been modified with constricting barriers to improve the attraction flow while using modest levels of water (Klinge 2005). The JBS will typically use approximately 6-8 percent of the total river flow for fish guidance. The high level of fish protection at Wells Dam has won the approval of the fisheries agencies and tribes and was vital to Douglas PUD meeting the survival standards contained within the Anadromous Fish Agreement and Habitat Conservation Plan (HCP).

State of Washington water quality standards require TDG levels to not exceed 110% at any point of measurement. Due to air entrainment in plunge pools below spillways of hydroelectric dams, TDG levels can sometimes exceed the state standard during spill events at dams. In the State of Washington, there are exceptions allowed to the State's TDG standard. TDG levels are allowed to exceed the standard in order to (1) pass flood flows at the Project of 7Q10 or greater and (2) pass voluntary spill to assist out migrating juvenile salmonids. The 7Q10 flood flow, which is defined as the highest average flow that occurs for seven consecutive days in a once-in-ten-year period, is 246 kcfs at the Wells Project.

Figure 1.3-1 Map of Washington showing the location of the Wells Dam

2.0 GOALS AND OBJECTIVES

The goal of this study was to develop a numerical model capable of predicting the hydrodynamics and TDG concentrations in the tailrace of the Wells Project. The purpose of the model was to assist in the understanding of the underlying dynamics of TDG production allowing the evaluation of the effectiveness of spill type and plant operations in reducing TDG concentrations at Wells Dam.

3.0 STUDY AREA

The study area includes approximately 16,500 ft of the Wells tailrace, extending from Wells Dam downstream to transect TW3 (Transect T3) (Figure 3.0-1). Transect TW3 coincides with the Wells TDG compliance monitoring station.

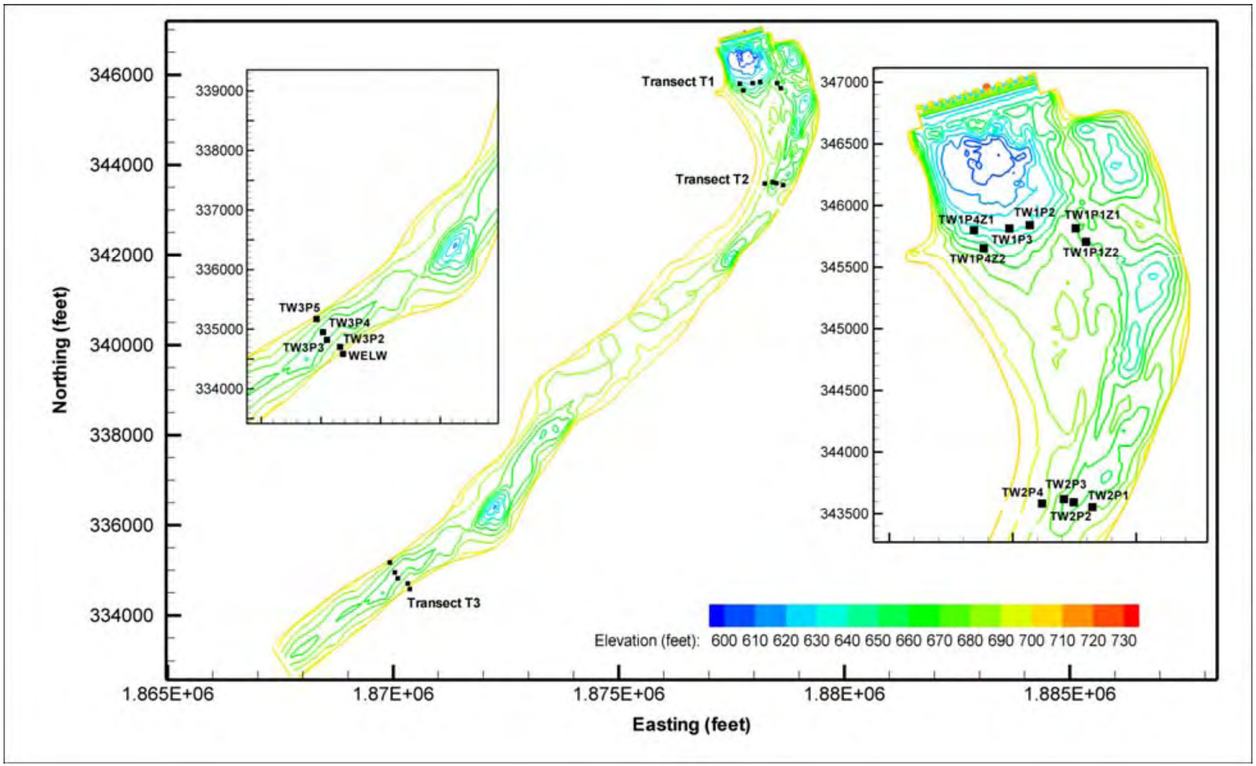

Figure 3.0-1 Study Area for the TDG model

4.0 BACKGROUND AND EXISTING INFORMATION

4.1 Summary of TDG studies in the Wells Tailrace

Douglas PUD conducted a series of assessments aimed at gaining a better understanding of TDG production dynamics resulting from spill operations at Wells Dam. Each year from 2003 to 2008, Douglas PUD has performed experimental spill operations to document the relationship between water spilled over the dam and the production of TDG.

In 2003 and 2004, Columbia Basin Environmental (CBE) deployed TDG sensors along two transects downstream of Wells Dam. The objectives of this study were to determine the effectiveness of the tailwater sensor and to better understand the relationship between spillway releases and TDG production (CBE 2003, 2004). In a two-week period, the studies showed that the tailwater station provided a reliable record of daily average TDG values in the Wells Dam tailrace.

In spring 2005, Douglas PUD conducted a study to measure TDG pressures resulting from various spill patterns at Wells Dam (CBE, 2006). An array of water quality data loggers was installed in the Well tailrace for a period of two weeks between May 23, 2005 and June 6, 2005. The Wells powerhouse and spillway were operated through a controlled range of operational scenarios that varied both total flow and allocation of the spillway discharge. A total of eight configurations were tested including flat spill patterns (near equal distribution of spill across the entire spillway), crowned spill patterns (spill is concentrated towards the center of the spillway), and spill over loaded and unloaded generating units. Results from the study indicated that spill from the west side of the spillway resulted in consistently higher TDG saturations than similar spill from the east side. Flat spill patterns yielded higher TDG saturations than crowned spill for similar total discharges. The results of this study also indicated that TDG levels of powerhouse flows may be influenced by spill.

In 2006, Douglas PUD continued TDG assessments at the Wells Project by examining alternative spill configurations and project operations to minimize the production of TDG. The purpose of the 2006 study was to evaluate how the Project could be operated to successfully pass the 7Q10 river flow while remaining in compliance with Washington State TDG standards. Thirteen sensors were placed along transects in the tailrace located at 1,000, 2,500 and 15,000 feet below Wells Dam. There were also three sensors placed across the forebay. The sensors were programmed to collect data in 15 minute intervals for both TDG and water temperature. Each test required the operations of the dam to maintain stable flows through the powerhouse and spillway for at least a three hour period. While there were 30 scheduled spill events, there were an additional 50 events in which the powerhouse and spillway conditions were held constant for a minimum three hour period. These additional events provided an opportunity to collect TDG data on a variety of Project operations that met study criteria. These are included in the results of the 2006 TDG Abatement Study (EES et al., 2007). Spill amounts ranged from 5.2 to 52.0% of project flow and flows ranged from 2.2 to 124.7 kcfs for spill and 16.4 to 254.0 kcfs for total discharge. There were six tests that were performed at flows that exceeded the Wells Dam 7Q10 flows of 246 kcfs. Results of the study indicated that two operational scenarios, spread spill and concentrated spill (spill from 1 or 2 gates), produced the lowest levels of TDG.

The 2006 study also indicated that the current location of the tailwater TDG compliance monitoring station is appropriate in providing representative TDG production information both longitudinally and laterally downstream of Wells Dam.

4.2 Numerical studies of TDG in Tailraces

Early studies to predict TDG below spillways were based on experimental programs and physical models (Hibbs and Gulliver 1997; Orlins and Gulliver 2000). The primary shortcoming of this approach is that the laboratory models cannot quantitatively predict the change in TDG due to model scaling issues. The approach relies on performance curves that relate flow conditions with past field experiences. This has led to inconsistent results at hydroelectric projects, some being quite successful while others less successful.

Computational fluid dynamics (CFD) modeling offers a powerful tool for TDG and hydrodynamics prediction. In the application to powerhouse and spillway flows, an understanding of the underlying physics and the capability to model three-dimensional physical phenomena is of paramount importance in performing reliable numerical studies. The most important source of TDG production is the gas transfer from the entrained bubbles, therefore a TDG predictive model must account for the two-phase flow in the stilling basin and the mass transfer between bubbles and water.

The TDG concentration depends on complex processes such as air entrainment in the spillway (pre-entrainment), entrainment when the jet impacts the tailwater pool, breakup and coalescence of entrained bubbles, mass transfer between bubbles and water, degasification at the free surface, and bubble and TDG transport. In addition, tailrace flows in the region near the spillway cannot be assumed to have a flat air/water interface which results in the required computation of the free surface shape. Moreover, it has been demonstrated that surface jets may cause a significant change in the flow pattern since they attract water toward the jet region, a phenomenon referred to as water entrainment (Liepmann 1990; Walker and Chen 1994; Walker 1997). Water entrainment leads to mixing and modification of the TDG field. As an additional complexity, the presence of bubbles has a strong effect on water entrainment. Bubbles reduce the density (and pressure) and effective viscosity in the spillway region and affect the liquid turbulence.

Free surface models can predict the shape and development of the free surface and, though costly, have feasible application to complex three dimensional (3D) flows. In the field of hydraulic engineering, free surface models are not yet widely applied but are steadily developing (Turan et al., 2008; Ferrari et. al., 2008). However, direct simulation of individual bubbles in a spillway/tailrace environment is well beyond current computer capabilities. Therefore, a two-fluid model with space-time averaged quantities that do not resolve the interface is needed to model the effect of the bubbles on the flow field and bubble dissolution. Numerical simulations of two phase flows using two-fluid models have been extensively used, mainly in the chemical and nuclear engineering community. Jakobsen et al. (2005) provided an extensive review of the state-of-the-art of two-phase flow modeling. Politano et al. (2007a) used a two-dimensional (2D) two-fluid model assuming isotropic turbulence to predict the gas distribution and TDG concentration in a cross-section passing through a spillway bay at Wanapum Dam. The model was compared against field data measured before deflector installation. The model allowed examination of the effect of the bubble size on TDG concentration. However, 2D simulations cannot capture the water entrainment caused by deflectors and therefore the TDG dilution due to powerhouse flows could not be predicted with the model. Turan et al. (2007) conducted the first numerical study to predict the hydrodynamics and water entrainment in a hydropower tailrace. The authors used an anisotropic mixture model that accounts for the gas volume fraction and attenuation of normal fluctuations at the free surface. Politano et al. (2007b) used an anisotropic mixture model for the 3D prediction of the two phase flow and TDG in the tailrace of Wanapum Dam. The simulations captured the measured water entrainment in the tailrace of Wanapum Dam. In this study, quantitative agreement between predicted and measured TDG was obtained for two different operational conditions.

4.3 Aquatic Resource Work Group

As part of the relicensing process for the Wells Project, Douglas PUD established an Aquatic Resource Work Group (Aquatic RWG) which began meeting informally in November, 2005. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to collaboratively identify potential resource issues related to Project operations and relevant to relicensing, and to develop preliminary study plans to be included in the Wells Pre-Application Document (PAD) (DCPUD, 2006).

Through a series of meetings, the Aquatic RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWGs' efforts to review the existing project information and to determine whether an issue meets the requirements of the FERC's seven study plan criteria and would be useful for informing future relicensing decisions. Agreed-Upon Study Plans are the finished products of the voluntary RWG process.

Based upon these meetings and discussions, the Aquatic RWG proposed to conduct studies of the TDG dynamics of Wells Dam. The need for this study was agreed to by all members of the Aquatic RWG, including Douglas PUD. These studies are intended to inform future relicensing decisions, including the water quality certification process.

The Issue Statement and Issue Determination Statement listed below were included in the PAD (section number included) filed with the FERC on December 1, 2006:

4.3.1 Issue Statement (PAD Section 6.2.1.5)

Wells Dam may affect compliance with Total Dissolved Gas (TDG) standards in the Wells tailrace and Rocky Reach forebay.

4.3.2 Issue Determination Statement (PAD Section 6.2.1.5)

Wells Dam can have an effect on compliance with the TDG standard. The resource work group believes that additional information is necessary in the form of continued monitoring and that these data will be meaningful with respect to the State 401 Water Quality Certification process.

Douglas PUD has been implementing studies at Wells Dam to address TDG production dynamics.

4.4 Project Nexus

TDG concentrations may become a water quality concern when gases supersaturate a river, lake or stream. The plunging water caused by spill at hydroelectric facilities may elevate TDG to levels that may result in impaired health or even death for aquatic life residing or migrating within the affected area.

The Washington State Department of Ecology is responsible for the protection and restoration of the state's waters. Ecology has adopted water quality standards that set limits on pollution in lakes, rivers, and marine waters in order to protect water quality. On July 1, 2003, Ecology completed the first major overhaul of the state's water quality standards in a decade. A significant revision presented in the 2003 water quality standards classifies fresh water by actual use, rather than by class as was done in the 1997 standards. These revisions were adopted in order to make the 2003 standards less complicated to interpret and provide future flexibility as the uses of a water body evolve. The applicable water quality standards (WQS) for TDG at hydroelectric projects states that total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.

However, as discussed in Section 4.0, an exception to the above standard is allowed to aid fish passage over hydroelectric dams when it is determined that this action is consistent with an Ecology-approved gas abatement plan. The information collected during this study will assist Douglas PUD in operating the Wells Project in a manner that minimizes TDG in the Wells tailrace and Rocky Reach forebay.

5.0 METHODOLOGY

5.1 Model Overview

The models used in this study are based upon the general purpose CFD code FLUENT, which solves the discrete Reynolds Averaged Navier Stokes (RANS) equations using a cell centered finite volume scheme. Two models were used to predict the hydrodynamics and TDG distribution within the tailrace of the Wells Project: a volume of fluid (VOF) model and a rigid-lid non-flat lid model.

The VOF model predicted the flow regime and free-surface for the first 1,000 feet downstream of the dam. The free-surface shape was then used to generate a grid conformed to this geometry and fixed throughout the computation (rigid, non-flat lid approach). After the statistically-steady state was reached, the VOF solution that minimizes the difference between measured and predicted tailwater elevation was selected. Water surface elevations and local slopes derived from simulations using the Hydrologic Engineering Centers River Analysis System (HEC-RAS) were used at the downstream region of the model. The HEC-RAS computations were performed using geometric input files provided by Douglas PUD with a roughness coefficient of 0.035.

The rigid-lid model allowed proper assessment of water entrainment and TDG concentration. The model assumed one variable bubble size, which could change due to local bubble/water mass transfer and pressure. The air entrainment (gas volume fraction and bubble size) was assumed to be a known inlet boundary condition. It must be noted that the choice of bubble size and volume fraction at the spillway bays has an important effect on the level of entrainment and TDG distribution. In this study a reasonable single-size bubble diameter and volume fraction were used at the spillway gates to bracket the experimental TDG data during the model calibration and the same values are used for all computations.

Specific two phase flow models and boundary conditions were implemented into FLUENT through User Defined Functions (UDFs). Two-phase User Defined Scalars (UDSs) transport equations were used to calculate the distribution of TDG and bubble number density.

The model included the main features of the Wells Dam, including the draft tube outlets of the generating units, spillway, top spill in bays 2 and 10 and fish passage facilities (Figure 5.1-1). Bathymetric data supplied by Douglas PUD were used to generate the river bed downstream of the dam. Detail of Figure 5.1-1 shows a cross section through a spillway unit illustrating the Wells Hydrocombine.

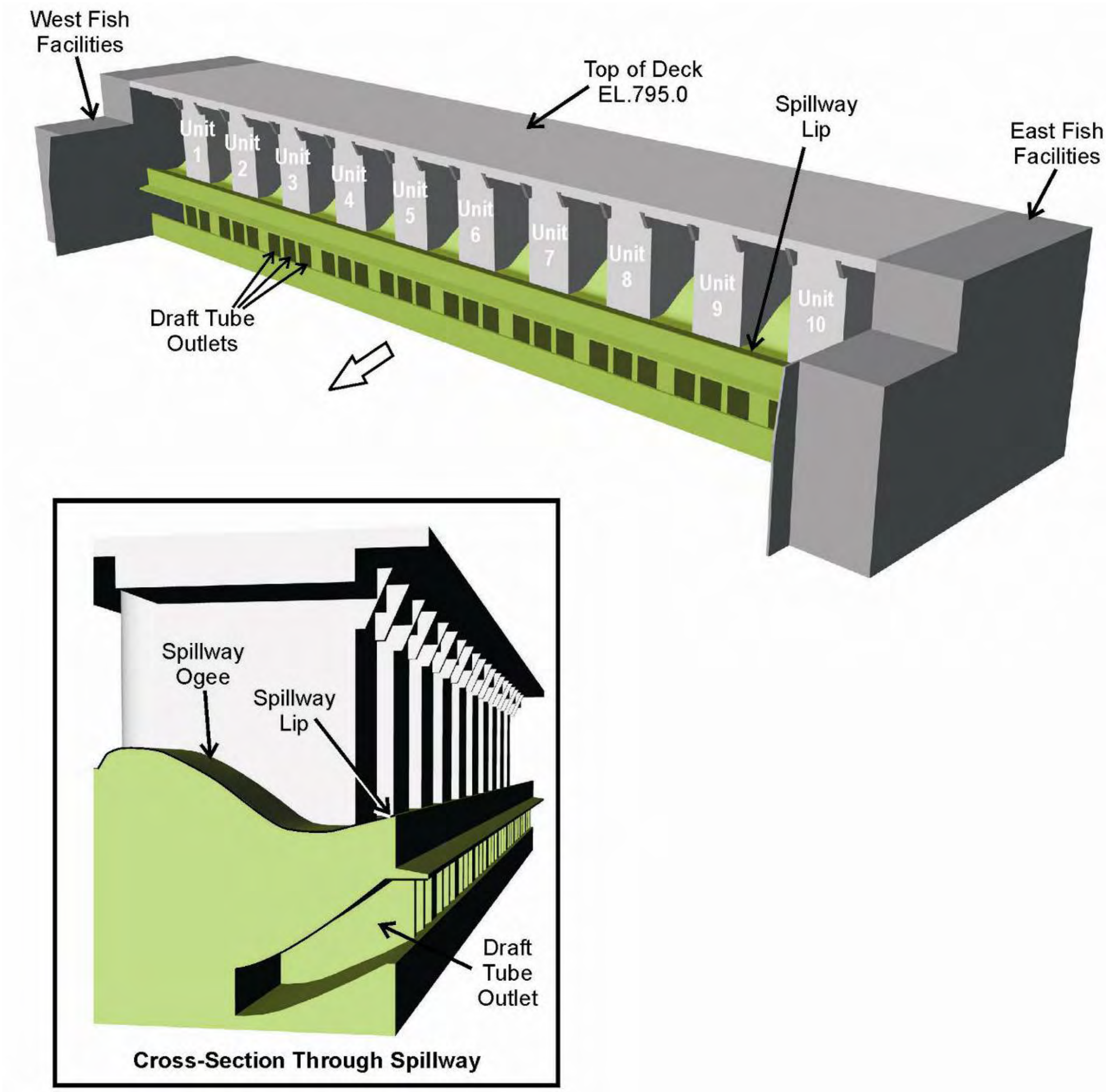

Figure 5.1-1 Structures included in the TDG model

5.2 VOF Model

5.2.1 Mathematical Model

In the VOF model, the interface between fluids is calculated with a water volume fraction (α_w) transport equation:

$$\frac{\partial \alpha_w}{\partial t} + \vec{v} \cdot \nabla \alpha_w = 0 \qquad (1)$$

Mass conservation requires that $\sum \alpha_i = 1$. The jump conditions across the interface are embedded in the model by defining the fluid properties as: $\varphi = \sum \alpha_i \varphi_i$, where φ is either the density or the viscosity. In the VOF approach, each control volume contains just one phase (or the interface). Points in water have $\alpha_w = 1$, points in air have $\alpha_w = 0$, and points near the interface have $0 < \alpha_w < 1$. The free surface was generally defined in the VOF using an α_w of 0.5.

5.2.2 Grid Generation

The domain was divided into a number of blocks and a structured mesh was generated in each block with common interfaces between the blocks. Each individual block consists of hexahedral cells. To resolve the critical regions of interest, the grids were refined near the solid boundaries, near the turbine intakes and spillway where large accelerations are expected, and near the free surface. The grids containing between 6×10^5 to 8×10^5 nodes were generated using Gridgen V15. Grid quality is an important issue for free surface flow simulations. As fine grids are needed near the interface to minimize numerical diffusion, each simulation required the construction of a particular grid. The grids were constructed nearly orthogonal in the vicinity of the free surface to improve convergence. Figure 5.2-1 shows an overall 3D view of the grid used for the June 5, 2006 simulation. An extra volume at the top of the grid was included to accommodate the air volume for the VOF method.

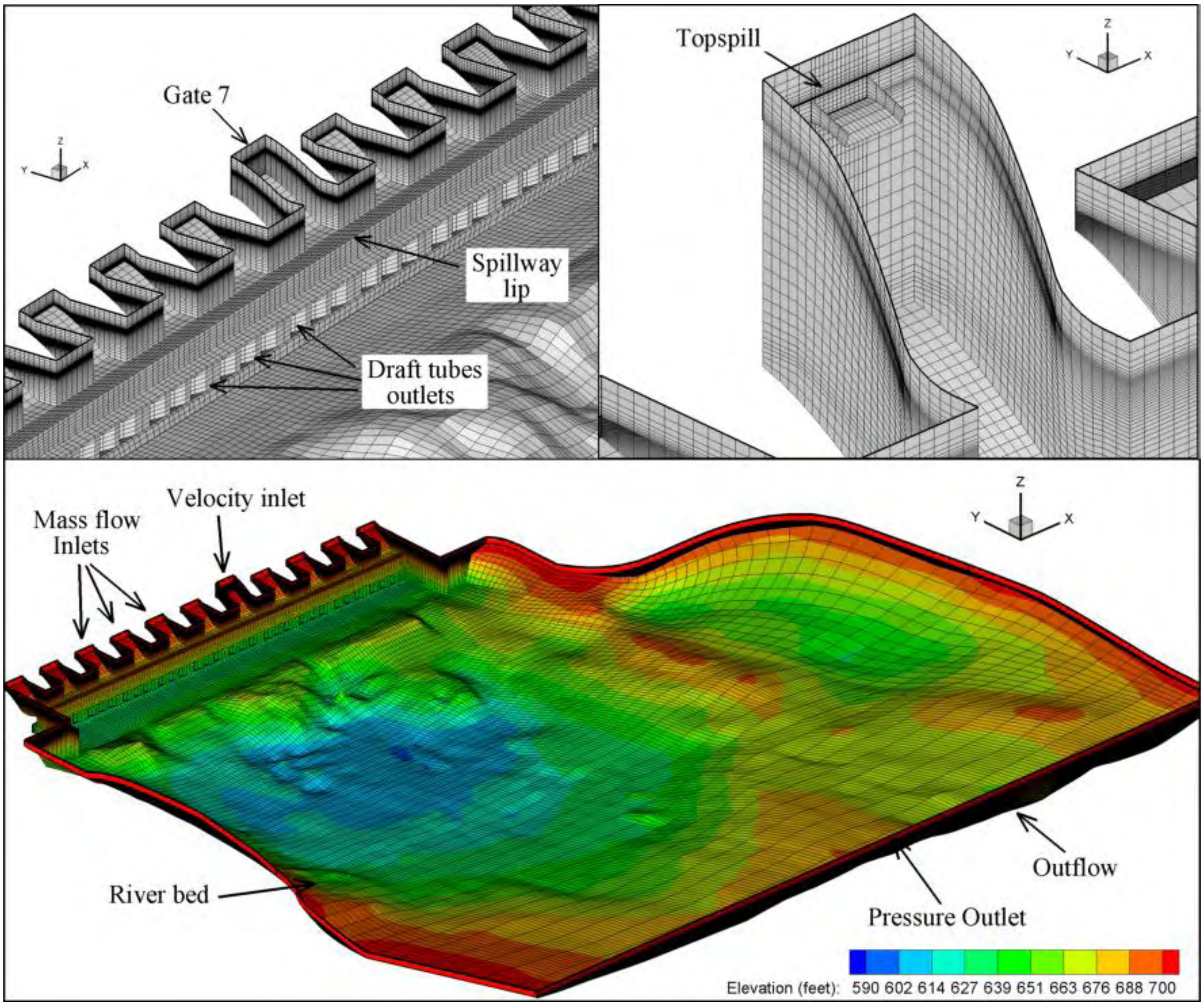

Figure 5.2-1 3D view of a typical grid used for the VOF simulations

5.2.3 Boundary Conditions

5.2.3.1 Inlet

A given mass flow rate of water assuming uniform velocity distribution was used at each of the turbine units and spillway bays.

5.2.3.2 Walls and River Bed

A no-slip (zero velocity) surface condition was imposed on all walls and tailrace bed.

5.2.3.3 Exit

The free water surface elevation (WSE) was imposed by specifying the water volume fraction distribution. The WSE measured at the tailwater elevation gage was used at the exit (outflow condition in Figure 5.2-1). A hydrostatic pressure was imposed at the outflow using a UDF. At the top of the outflow a pressure outlet boundary condition was used to avoid air pressurization.

5.2.3.4 Top Surface

A pressure outlet boundary condition with atmospheric pressure was applied at the top to allow free air flow and avoid unrealistic pressure.

5.3 Rigid-lid Model

The rigid-lid model is an algebraic slip mixture model (ASMM) (Mannheim et al. 1997) that accounts for buoyancy, pressure, drag and turbulent dispersion forces to calculate the gas volume fraction and velocity of the bubbles. The model considers the change of the effective buoyancy and viscosity caused by the presence of the bubbles on the liquid and the forces on the liquid phase due to the non-zero relative bubble-liquid slip velocity.

5.3.1 Mathematical Model

5.3.1.1 Mass and Momentum Conservation for the Mixture

The two phase model provides mass and momentum equations for the liquid and gas phases (Drew & Passman 1998). Summing the mass and momentum equations for each phase results in continuity and momentum equations for the mixture gas-liquid phase:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left[\rho_m \vec{u}_m \right] = 0 \qquad (2)$$

$$\frac{\partial}{\partial t}\left(\rho_m \vec{u}_m\right) + \nabla \cdot \left(\rho_m \vec{u}_m \vec{u}_m\right) = -\nabla P + \nabla \cdot \left[\boldsymbol{\sigma}_m^{\mathrm{Re}} + \boldsymbol{\tau}_m \right] + \rho_m \vec{g} - \nabla \cdot \left(\sum_{k=g,l} \alpha_k \rho_k \vec{u}_k \vec{u}_{dr,k} \right) \qquad (3)$$

where P is the total pressure, $\vec{g}$ is the gravity acceleration, and $\boldsymbol{\sigma}_m^{\mathrm{Re}}$ and $\boldsymbol{\tau}_m = \rho_m \nu_m \left(\nabla \vec{u}_m + \nabla \vec{u}_m^T \right)$ are the turbulent and molecular shear stresses, respectively. ρ_m, μ_m and $\vec{u}_m$ are the mixture density, viscosity and mass-averaged velocity defined as $\rho_m = \sum_{k=g,l} \alpha_k \rho_k$, $\mu_m = \sum_{k=g,l} \alpha_k \mu_g$ and $\vec{u}_m = \frac{1}{\rho_m} \sum_{k=g,l} \alpha_k \rho_k \vec{u}_k$, with α_g the gas volume fraction. The subscripts *g*, *l* and *m* denote gas, liquid and mixture, respectively. $\vec{u}_{dr,k}$ is the drift velocity defined as the velocity of the phase k relative to the mixture velocity.

The gas density is calculated using the ideal gas law $\rho_g = M\,P/(RT)$ with P the pressure, M the molecular weight of air, R the universal gas constant, and T the absolute temperature.

5.3.1.2 Mass Conservation for the Gas Phase

The continuity equation for the gas phase is (Drew & Passman, 1998):

$$\frac{\partial}{\partial t}\left(\alpha_g\,\rho_g\right) + \nabla\cdot\left(\alpha_g\,\rho_g\,U_{g,i}\right) = -S \qquad (4)$$

where $\vec{u}_g$ is the bubble velocity and S is a negative gas mass source; in this application the TDG source due to the air transfer from the bubbles to the liquid.

5.3.1.3 Momentum Conservation for the Gas Phase

The ASMM assumes that the inertia and viscous shear stresses are negligible compared to pressure, body forces and interfacial forces in the momentum equation of the gas phase (Antal et al., 1991; Lopez de Bertodano et al., 1994; Manninen et al., 1997):

$$0 = -\alpha_g\,\nabla P + \alpha_g\,\rho_g\,\vec{g} + \vec{M}_g \qquad (5)$$

where $\vec{M}_g$ represents the interfacial momentum transfer between the phases.

5.3.1.4 Bubble Number Density Transport Equation

Most of the two fluid models in commercial codes (Fluent, CFX, CFDLib, among others) assume a mean constant bubble size with a given relative velocity (Chen et al., 2005). In tailrace flows the use of a mean constant bubble size for the evaluation of the bubble-liquid mass transfer and interfacial forces is not valid. As a consequence of the complex processes of generation, breakup, and coalescence, the bubbles resulting from air entrainment have different sizes. These processes occur at the plunging jet region immediately after the spillway, where the gas volume fraction and turbulence can be large. The model used in this study is intended for the region downstream of the plunging jet, where bubble size changes mainly due to mass transfer and pressure variations, and therefore bubble breakup and coalescence processes can be neglected. This assumption is considered a reasonable hypothesis for low gas volume fractions (Politano et al. 2007b).

Let $f\,dm\,d\vec{r}$ represent the number of bubbles with original (at the insertion point, before any physical process modifies the bubble mass) mass m, located within $d\vec{r}$ of $\vec{r}$ at time t. The Boltzmann transport equation for f is:

$$\frac{\partial f}{\partial t} + \nabla\cdot\left[\vec{u}_g\,f\right] + \frac{\partial}{\partial m}\left[\frac{\partial m}{\partial t}\,f\right] = 0 \qquad (6)$$

Note that this is a Lagrangian representation, and thus *f* has a different interpretation than the usual Eulerian approach (Guido-Lavalle et al., 1994; Politano et al., 2000). Integration of Eq. (6) for bubbles of all masses results in a transport equation for the bubble number density N :

$$\frac{\partial N}{\partial t} + \nabla \cdot \left[\vec{u}_g \; N \right] = 0 \tag{7}$$

The bubble radius is calculated from $R = \left[3\alpha / (4\pi N) \right]^{1/3}$.

5.3.1.5 Two-phase TDG Transport Equation

TDG is calculated with a two-phase transport equation (Politano et al. 2007b):

$$\frac{\partial \alpha_l \, C}{\partial t} + \nabla \cdot \left(\vec{u}_l \, \alpha_l \, C \right) = \nabla \cdot \left(\left(\nu_m + \frac{\nu_t}{Sc_C} \right) \alpha_l \, \nabla C \right) + S \tag{8}$$

where C is the TDG concentration, and ν_m and ν_t are the molecular and turbulent kinematic viscosity, respectively. In this study, a standard Schmidt number of $Sc_C = 0.83$ is used.

5.3.1.6 Turbulence Closure

In this study a Reynolds Stress Model (RSM) was used. The ASMM assumes that the phases share the same turbulence field. The turbulence in the mixture phase is computed using the transport equations for a single phase but with properties and velocity of the mixture. The transport equations for the Reynolds stresses $\boldsymbol{\sigma}_{i,j}^{\mathrm{Re}} = \rho_m \overline{u_{m,i}^{'} \, u_{m,j}^{'}}$ are:

$$\frac{\partial \boldsymbol{\sigma}^{\mathrm{Re}}}{\partial t} + \left(\nabla \cdot \vec{u}_m \right) \boldsymbol{\sigma}^{\mathrm{Re}} + \vec{u}_m \left(\nabla \cdot \boldsymbol{\sigma}^{\mathrm{Re}} \right) = \nabla \cdot \left[\rho_m \frac{\nu_m^t}{\sigma_R} \nabla \boldsymbol{\sigma}^{\mathrm{Re}} \right] - \mathbf{P} + \boldsymbol{\varphi} + \boldsymbol{\varepsilon} + \mathbf{S}_{\boldsymbol{\sigma}} \tag{9}$$

where the stress production tensor is given by $\mathbf{P} = \boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T + \left(\boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T \right)^T$, $\boldsymbol{\varepsilon} = 2/3 \, \mathbf{I} \, \rho_m \, \varepsilon$ and $\sigma_R = 0.85$. The pressure-strain tensor $\boldsymbol{\varphi}$ is calculated using the models proposed by Gibson and Lander (1978), Fu et al. (1987) and Launder (1989). In this study, $\mathbf{S}_{\boldsymbol{\sigma}}$ represents the effect of the bubbles on the Reynolds stresses. The transport equation for the turbulent dissipation rate reads:

$$\frac{\partial}{\partial t}\left(\rho_m \, \varepsilon \right) + \nabla \cdot \left(\rho_m \, \vec{u}_m \, \varepsilon \right) = \nabla \cdot \left[\rho_m \left(\nu_m + \frac{\nu_m^t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] - C_{\varepsilon 1} \, \rho_m \, \frac{1}{2} \mathrm{Tr}\left(\mathbf{P} \right) \frac{\varepsilon}{k} - C_{\varepsilon 2} \, \rho_m \, \frac{\varepsilon^2}{k} + S_\varepsilon \tag{10}$$

with $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $\sigma_\varepsilon = 1$. The turbulent kinetic energy is defined as $k = \frac{1}{2\rho_m}\mathrm{Tr}(\boldsymbol{\sigma})$. The source term S_ε accounts for the effect of the bubbles on the turbulent dissipation rate. The turbulent kinematic viscosity is computed as in the $k-\varepsilon$ models using $\nu_t = C_\mu k^2/\varepsilon$, with $C_\mu = 0.09$.

5.3.1.7 Constitutive Equations

In order to close the model, interfacial transfer terms emerging from the relative motion between the bubbles and the continuous liquid need to be modeled.

Interfacial momentum

Since in this particular application there are no significant velocity gradients or flow accelerations (in the bubble scale), most interfacial forces such as lift and virtual mass are negligible compared with drag and turbulent dispersion forces:

$$\vec{M}_g = \vec{M}_g^D + \vec{M}_g^{TD} \tag{11}$$

where $\vec{M}_g^D$ and $\vec{M}_g^{TD}$ are the drag and turbulent dispersion terms. The drag force can be modeled as (Ishii and Zuber, 1979):

$$\vec{M}_g^D = -\frac{3}{8}\rho_m \alpha_g \frac{C^D}{R}\vec{u}_r\left|\vec{u}_r\right| \tag{12}$$

where $\vec{u}_r$ is the relative velocity of the gas phase respect to the liquid phase. Most of the numerical studies use drag correlations based on rising bubbles through a stagnant liquid proposed by Ishii & Zuber (1979) (see Lane et al., 2005):

$$C^D = \begin{cases} \dfrac{24}{\mathrm{Re}_b} & if\ R < 0.0002 \\ \dfrac{24\left(1+0.15\,\mathrm{Re}_b^{0.867}\right)}{\mathrm{Re}_b} & if\ 0.0002 < R < 0.0011 \end{cases} \tag{13}$$

where $\mathrm{Re}_b = 2\rho_l\left|\vec{u}_r\right|R/\mu_l$ is the bubble Reynolds number. The turbulent dispersion term is modeled as (Carrica et al., 1999):

$$\vec{M}_g^{TD} = -\frac{3}{8}\frac{\nu^t}{Sc_b}\rho_m \frac{C^D}{R}\left|\vec{u}_r\right|\nabla\alpha_g \tag{14}$$

where $Sc_b = \nu^t / \nu^b$ is the bubble Schmidt number. Following Carrica et al. (1999), $Sc_b = 1$ is used.

Bubble dissolution and absorption

The rate of mass transfer is computed considering that the air is soluble in water and obeys Henry's law and that the air molar composition is that of equilibrium at atmospheric pressure, which implies that the air is considered a single gas with molar averaged properties. The mass flux from gas to liquid can be expressed by (Deckwer 1992; Politano et al. 2007b):

$$S = 4\pi N R^2 k_l \left(\frac{P + \sigma/R}{He} - C \right) \quad (15)$$

where σ is the interfacial tension and He is the Henry constant. The second term on the RHS of Eq. (15) accounts for the effect of the interfacial tension on the equilibrium concentration. The effect of temperature on the Henry constant is modeled using the Van 't Hoff equation:

$$He(T) = He(T_o) \exp\left[-C_T \left(\frac{1}{T} - \frac{1}{T_o} \right) \right] \quad (16)$$

where T is the absolute temperature and T_o refers to the standard temperature (298 K). A constant for air $C_T = 1388\,K$ is used in this model.

Takemura and Yabe (1998) proposed a correlation for the mass transfer coefficient of spherical rising bubbles, where the turbulence is generated by the rising bubbles:

$$k_l^{rb} = \frac{D\,Pe_b^{0.5}}{\sqrt{\pi} R} \left(1 - \frac{2}{3\left(1 + 0.09\,\mathrm{Re}_b^{2/3}\right)^{0.75}} \right) \quad (17)$$

where D is the molecular diffusivity and the bubble Peclet number is $Pe_b = 2\left|\overrightarrow{u_r}\right| R / D$.
External turbulence could be important in flows downstream of spillways, mainly in regions of high shear near the walls and where the plunging jet impacts and enhances the mass transfer. In this application, the mass transfer coefficient can be calculated using the expression proposed by Lamont and Scott (1970):

$$k_l^t = 0.4\,Sc^{-1/2} (\nu\,\varepsilon)^{1/4} \quad (18)$$

where $Sc = D/\nu$. In this study, the same order of magnitude is obtained from Eqs. (17) and (18), thus the maximum mass transfer coefficient between bubbles rising in stagnant liquid (k_l^{rb}) and bubbles in turbulent flow (k_l^t) is used: $k_l = \max\left(k_l^{rb}, k_l^t\right)$.

5.3.2 Grid Generation

The Wells tailrace structures and the bathymetry are meshed with structured and unstructured multi-block grids containing only hexahedral elements, using Gambit and Gridgen V15. Typical grid sizes are in the range of $7\ 10^5$ to $1\ 10^6$ nodes. Figure 5.3-1 shows typical grids used for the rigid-lid model. Details (a) and (b) show free surface shapes for spread and concentrated flows, respectively. Detail (c) shows the unstructured grid, extended from approximately 1,500 feet to 3,500 feet downstream of the Wells Dam, used to reduce grid size and improve aspect ratio.

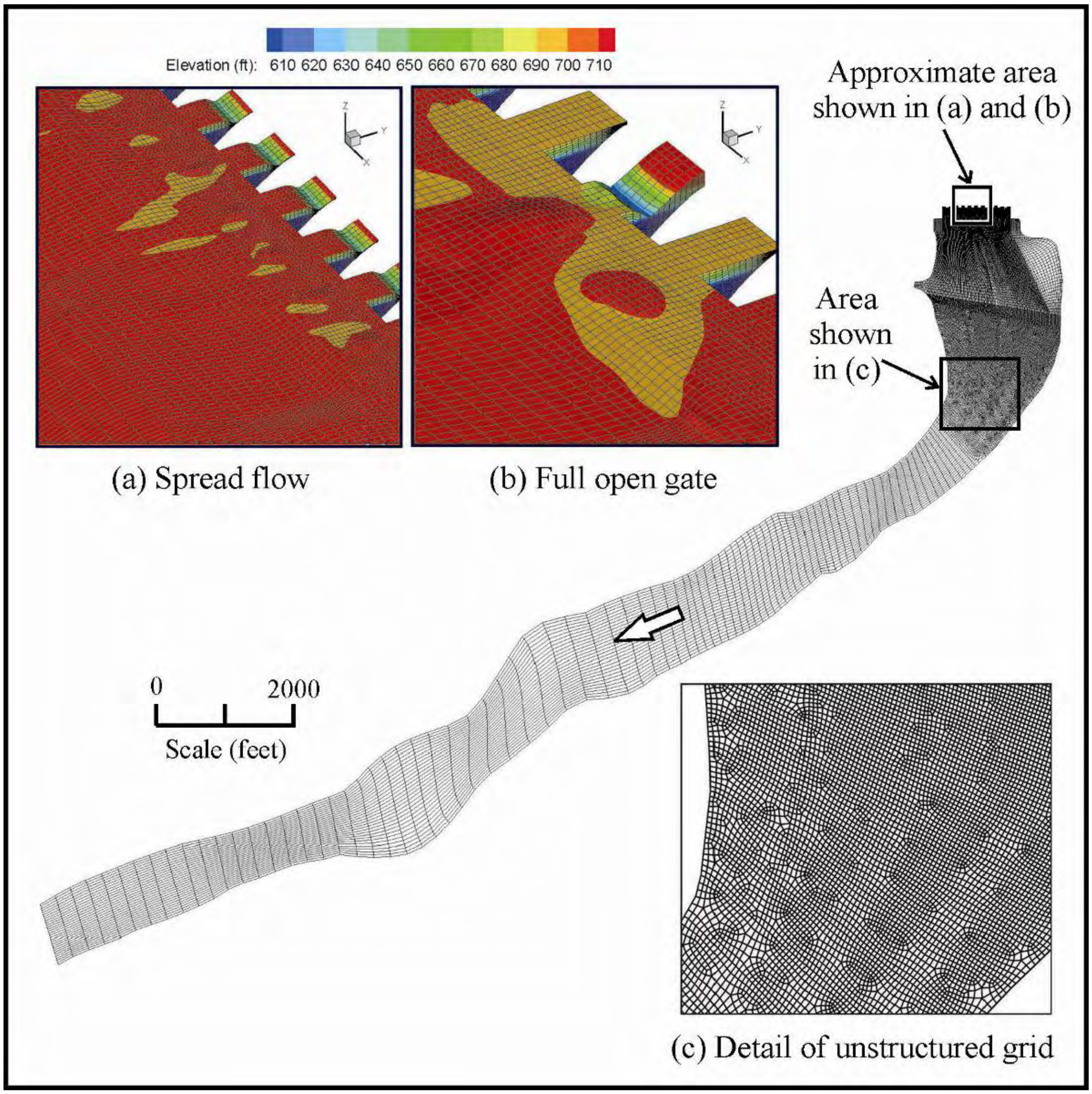

Figure 5.3-1 3D view of a typical grid used for the rigid-lid simulations

5.3.3 Boundary Conditions

5.3.3.1 Free Surface

Kinematic and dynamic boundary conditions enforcing zero normal velocity fluctuations at the free surface are programmed through UDFs. Details of the implementation of the boundary conditions used for the Reynolds stress and velocity components are found in Turan et al. (2007).

In order to allow the gas phase to flow across the interface, the normal component of the gas velocity at the free surface is calculated using a mass balance for the gas phase in each control volume contiguous to the interface. The resulting equation is implemented using UDFs.

For the TDG concentration, a Neumann boundary condition is used. A mass transfer coefficient at the free surface of $k_l = 0.0001$ m/s as measured by DeMoyer et al. (2003) for tanks and bubble columns is used.

5.3.3.2 Walls and River Bed

The sides and the river bed are considered impermeable walls with zero TDG flux. For the gas phase, no penetration across walls is imposed.

5.3.3.3 Exit

The river exit is defined as an outflow. A zero gradient condition was programmed for the TDG concentration and bubble number density.

5.3.3.4 Spillbays and Powerhouse Units

Uniform velocities with constant gas volume fraction of $\alpha = 0.03$ and bubble diameter 5 mm are used for the 11 bays in the spillway region.

It is assumed that air is not entrained with the turbine inflow. The TDG concentration measured in the forebay is used at the spillway bays and powerhouse units.

5.4 Modeling Assumptions and Model Inputs

5.4.1 Model Assumptions

The model used in this study assumes that:

- Gas and liquid phases are interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of volume fraction is used.
- A local equilibrium over short spatial length scale is assumed. Therefore, the gas-liquid relative velocity can be calculated with algebraic equations.
- The liquid phase is considered incompressible.
- The turbulence can be described by the RSM turbulence model.
- The free surface shape is not affected by the presence of bubbles.

- The air is considered a unique gas with molar averaged properties.
- Bubble size changes mainly due to mass transfer and pressure and breakup and coalescence are negligible.

5.4.2 Model Inputs

The bubble size and gas volume fraction at the inlet (spillway bay gates) are model parameters selected based upon the calibration of the model.

Environmental factors such as forebay TDG, forebay elevation, and water temperature are based upon historical data relative to the choice of values for modeling the most likely 7Q10 conditions. The conditions were based on hourly observations recorded between April and September throughout the ten-year period 1999-2008 (daily average flows ≥ 200 kcfs did not occur outside of the April to September time frame; DART Hourly Water Quality Composite Report www.cbr.washington.edu/dart/hgas_com.html).

5.4.2.1 Environmental Conditions

The environmental data described above (43,200 hourly records) were subsequently filtered to include values in which outflow was equal to or greater than 200 kcfs to represent high flow conditions at Wells Dam (2,941 hourly records). Temporal distribution of hourly values (by week of the year) range from early April to early September, with the middle quartiles (25% to 75%) occurring between weeks 23 and 26 (4-June and 25-June). Median values of the distribution occur at week 24. Hourly flow measurements averaged 221 kcfs (±18 kcfs SD) during these 'high flow' events, though 50% (median) of flows were ≤ 215 kcfs and only 12% of values exceeded 246 kcfs. Water temperatures during these occurrences range from 4.1-19.7 °C, with a median temperature of 13.0 °C (Figure 5.4-1). Forebay TDG during these occurrences (≥ 200 kcfs) range from 99.9-120.1% with a median TDG of 112.5 % (Figure 5.4-2). Average daily forebay elevations were also collected from DART throughout the same period (1999-2008; www.cbr.washington.edu/dart/river.html). When average daily flows were ≥ 200 kcfs, forebay elevation ranges from 775-781 feet, with a median elevation of 779.6 feet (Figure 5.4-3; note that the five outliers ~ 775 feet occurred consecutively between June 4th and June 8th, 2002). Since the distributions of the three values needed for model input (water temperature, forebay TDG, and forebay elevation) have a slightly negative or 'left' skew (that is, mean values are slightly less than median values), the median values, rounded to the nearest whole number or percent, were used to best represent environmental conditions under high-flow events.

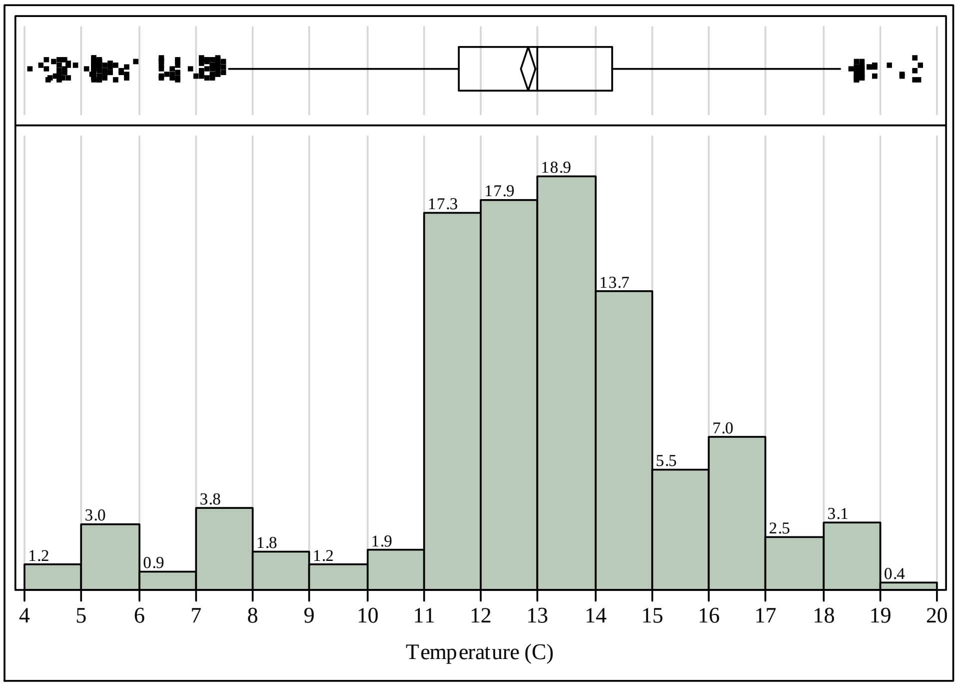

Figure 5.4-1 **Distribution of water temperatures (°C) during flows equal to or greater than 200 kcfs between April and September, 1999-2008. Percent occurrence of values is shown above histogram bars.**

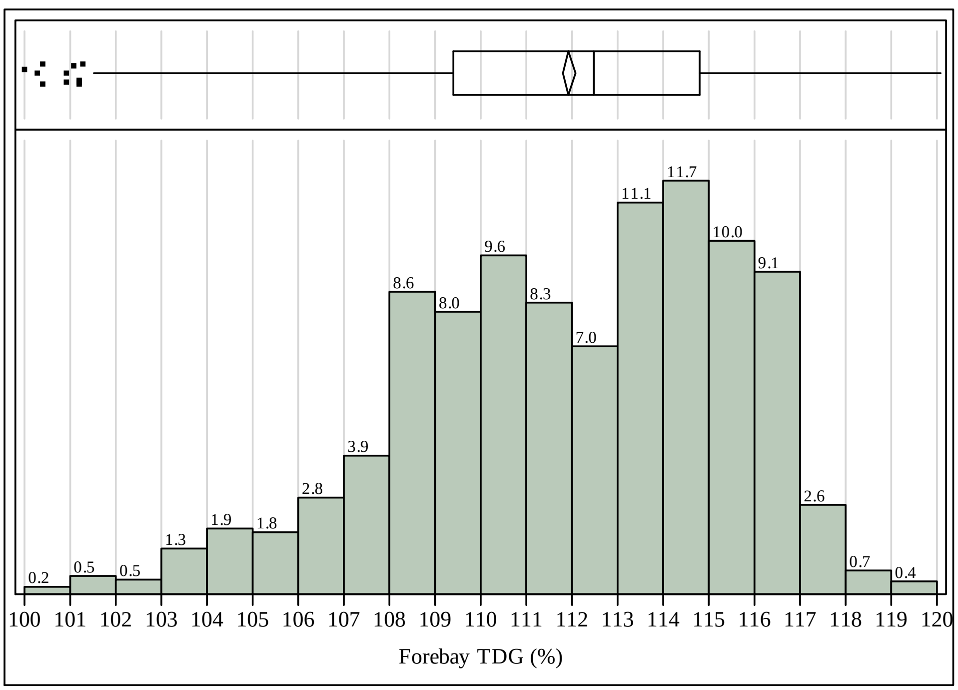

Figure 5.4-2 **Distribution of forebay TDG (%) during flows equal to or greater than 200 kcfs between April and September, 1999-2008. Percent occurrence of values is shown above histogram bars.**

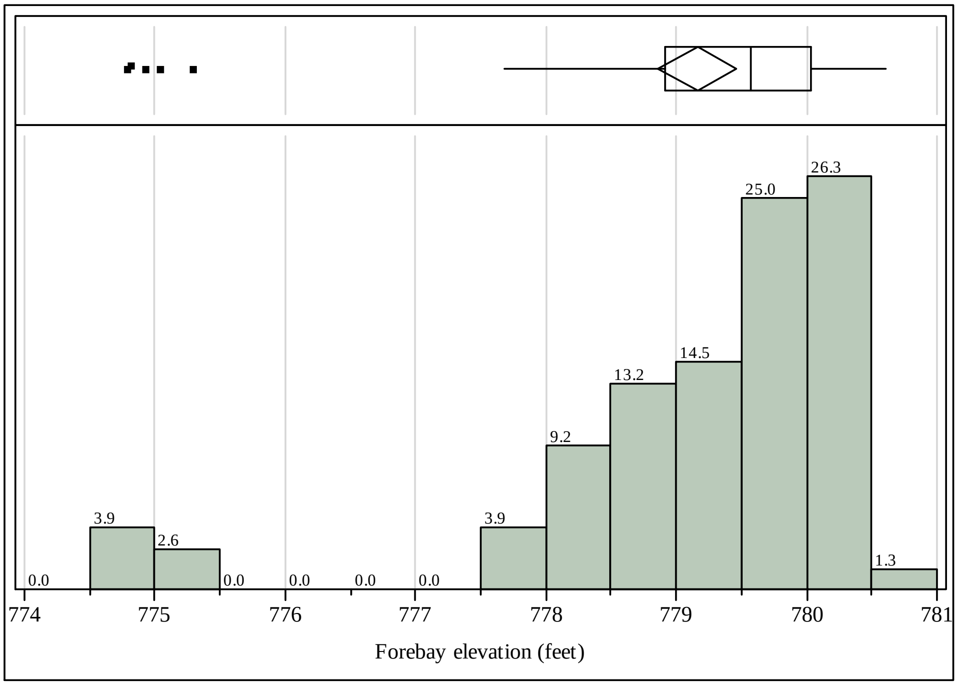

Figure 5.4-3 Distribution of forebay elevations (feet) during daily average flows equal to or greater than 200 kcfs, 1999-2008. Percent occurrence of values is shown above histogram bars.

6.0 NUMERICAL METHOD

The computations were performed using 4 processors of a Linux cluster with 2 GB of memory per processor and in three dual socket dual core Xeon Mac Pro systems.

6.1 VOF Model

The discrete RANS equations and Eq. (1) were solved sequentially (the segregated option in Fluent) and coupled to a realizable $k-\varepsilon$ model with wall functions for turbulence closure. The pressure at the faces is obtained using the body force weighted scheme. The continuity equation was enforced using a Semi-Implicit Method for Pressure-Linked (SIMPLE) algorithm. A modified High Resolution Interface Capturing (HRIC) scheme was used to solve the gas volume fraction.

Unsteady solutions were obtained using variable time-step between 0.001 to 0.01 seconds. Typically, two to three nonlinear iterations were needed within each time step to converge all variables to a L_2 norm of the error $<10^{-3}$. The flow rate at the exit and the elevation at the tailwater elevation gauge location were selected as convergence parameters.

6.2 Rigid-lid Model

The ASMM model equations were solved sequentially. The VOF and rigid-lid simulations were performed using the same discretization schemes for the continuity and pressure equations. A first order upwind scheme was used for the gas volume fraction and Reynolds stress components.

Unsteady solutions were obtained using a fixed time-step of 10 seconds. In order to improve convergence, the model was first run assuming single-phase flow and then bubbles were injected into the domain. The rigid-lid model was computed in typically 7 hours (2 days of computation time) to obtain a steady condition for the flow field and TDG concentration.

7.0 VALIDATION AND CALIBRATION OF THE MODEL

7.1 Simulation Conditions

The ability of the model to predict the TDG distribution and hydrodynamics was evaluated using field data collected for a period of six weeks between May 14, 2006 and June 28, 2006, during the TDG production dynamics study (EES et al., 2007). Velocities were measured on three transects in the near field region of the Wells tailrace on June 4, 2006 and June 5, 2006. Figure 3.0-1 shows the 15 stations where TDG sensors were deployed during the field study.

7.1.1 Calibration

The model was calibrated with data collected on June 4 and June 5, 2006, referred to as treatments 46 and 47 in the report by EES et al. (2007). The spillway flow was spread across all spillbays on June 4 and concentrated in a single spillbay on June 5. Total river flows during these treatments were 172.4 kcfs and 222.3 kcfs, respectively. Tables in Appendix A summarize plant operations, TDG saturation in the forebay, and tailwater elevation on these days. Powerhouse and spillway units are numbered from west to east.

7.1.2 Validation

The predictive ability of the numerical model was validated using three different spillway conditions tested in 2006. The three spillway conditions are: treatment 1-Full Gate (FG); treatment 11-FG; and treatment 63-Concentrated (C). The FG designates the use of a single spill bay whereas C designates a crowned spill pattern. Total river flows during these treatments were 120.4 kcfs, 157.2 kcfs and 205.5 kcfs, respectively. Plant operation and tailwater elevations associated with each of the treatments are tabulated on Tables in Appendix A.

7.2 VOF Model Results

The objectives for the calibration and verification VOF simulations were to establish a steady state solution that yield a flow field, including spillway jet regimes, consistent with that was observed in the field.

7.2.1 Calibration

The calibration cases were run in a domain of approximately 3,000 ft downstream of the dam. Zero velocities and turbulence were used as initial conditions in the entire domain.

The convergence parameters for the calibration cases were:

$$46S - June\ 4, 2006 \rightarrow (\, flowrate : 172.4\ kcfs, WSE : 717.3\, ft)$$
$$47FG - June\ 5, 2006 \rightarrow (\, flowrate : 222.3\ kcfs, WSE : 720.2\, ft)$$

Horizontal lines in Figure 7.2-1 show the target flow rate (blue line) and WSE at the tailwater elevation gage (green line). The evolution of the simulations for the calibration cases is illustrated in Figure 7.2-1; blue lines represent the flow rate at the exit and the green lines the free surface elevation. It was found that statistically steady solutions were obtained at approximately 30 minutes, which required about 60 days of computation time.

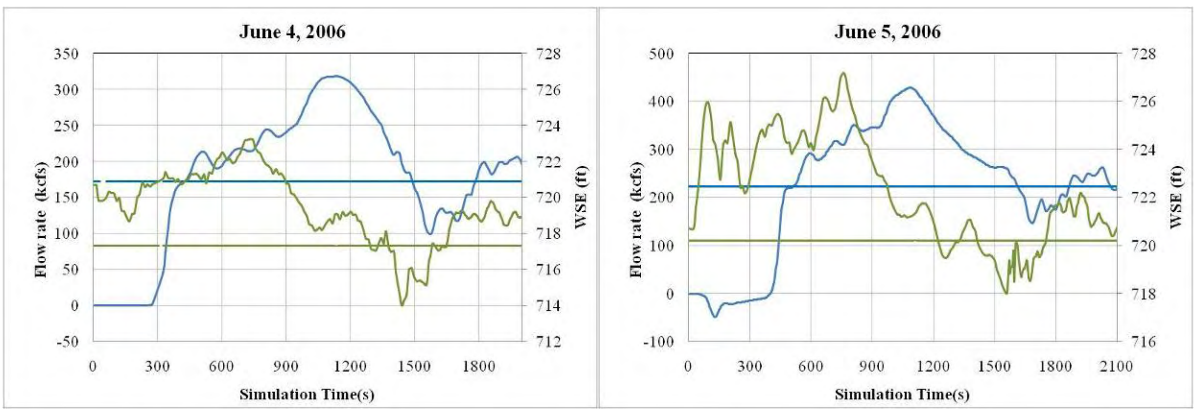

Figure 7.2-1 Evolution of the flow rate at the exit (blue line) and free surface elevation (green line) for June 4, 2006 and June 5, 2006. Horizontal lines represent target values.

Figure 7.2-2 shows an isosurface of gas volume fraction $\alpha_w = 0.5$ representing the free-surface location used to create the top of the rigid-lid grid for the June 4, 2006 simulation. In Figure 7.2-3 a horizontal slice at 27 ft from the free-surface (top) and a vertical section at the center of spillway bay 7 (bottom) show the predicted flow field with the VOF method. Red and blue contours represent water and air, respectively. For clarity, predicted velocity vectors were interpolated in structured uniform grids. Almost uniform flow is observed close to the spillway during the spread flow operation. Surface jets are predicted in all the spillway bays due to elevated tailwater levels. In addition, water flow from the powerhouse units prevented the spillway jet from plunging to depth within the stilling basin.

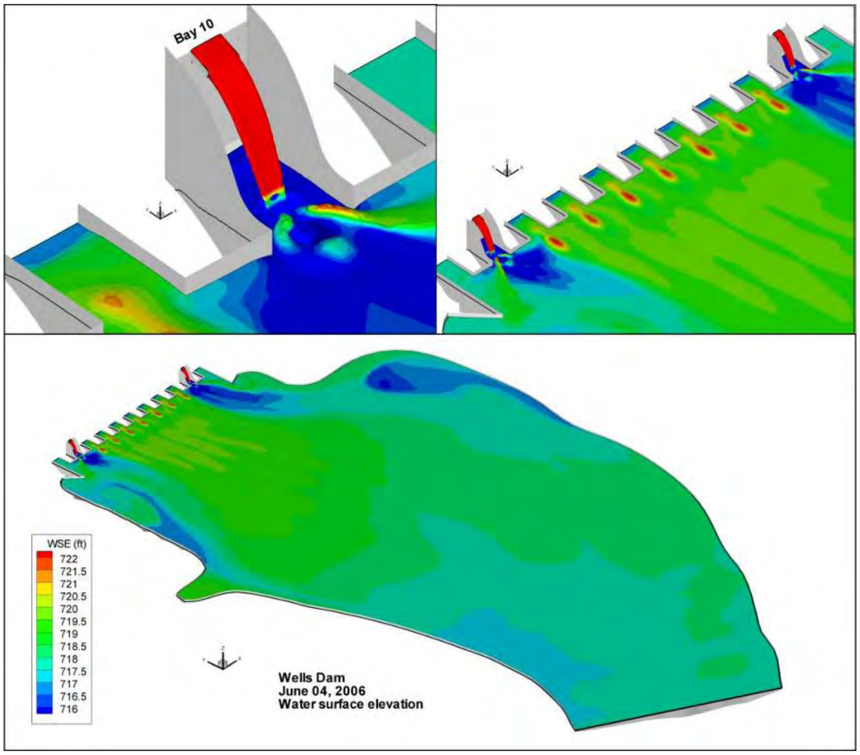

Figure 7.2-2 Predicted free surface shape for June 4, 2006

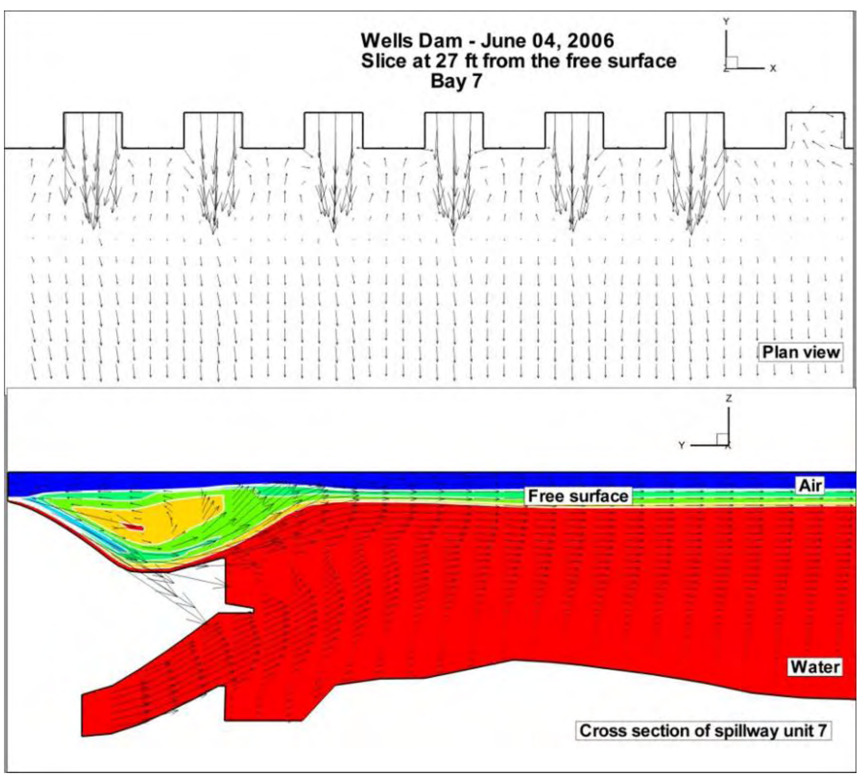

Figure 7.2-3 Predicted flow field for June 4, 2006

The free surface used to create the rigid-lid grid for June 5, 2006 is shown in Figure 7.2-4. The top of Figure 7.2-5 shows the water attraction toward the surface jet on bay 7 (water entrainment) caused by the full open gate operation. The water entrainment causes the formation of two large eddies near the east and west bank of the Wells tailrace. As observed on June 4, 2006, the strong surface jet originated in bay 7 remains close to the free surface (see bottom picture in Figure 7.2-5) due to the favorable tailwater elevation and plant operation on this day.

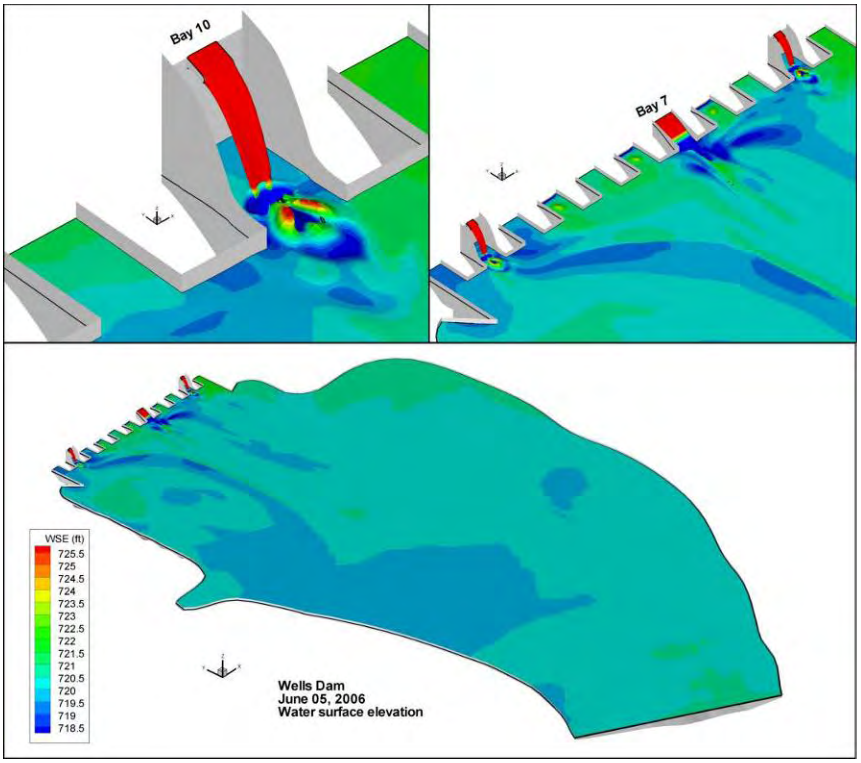

Figure 7.2-4 Predicted free surface shape for June 5, 2006

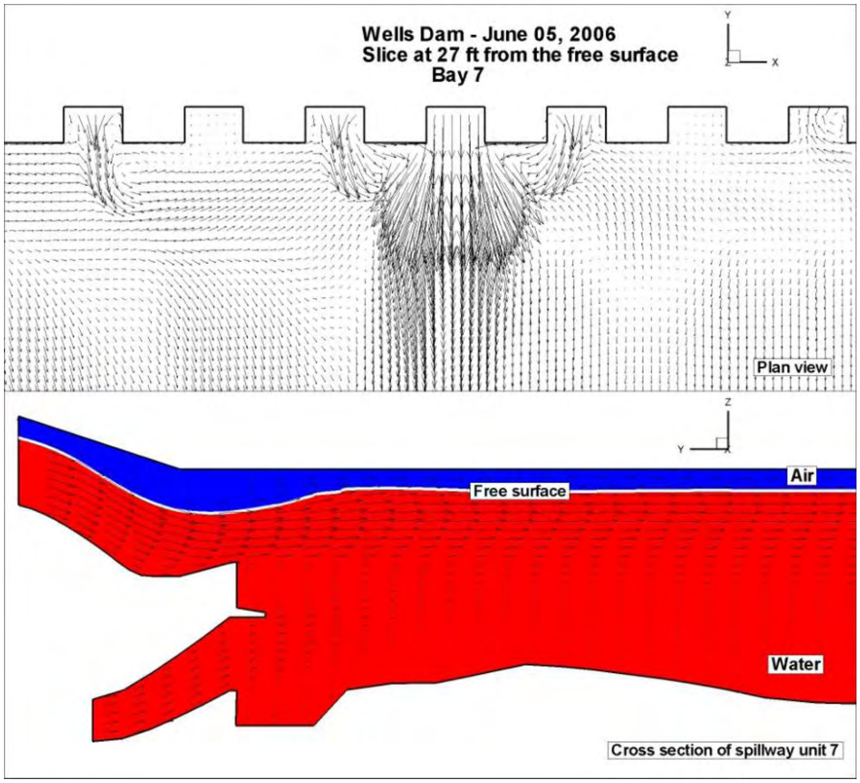

Figure 7.2-5 Predicted flow field for June 5, 2006

7.2.2 Validation

The domain used to simulate the validation cases was reduced to 1,700 ft downstream of the dam with the purpose of speeding up the VOF computations. During the calibration it was observed that the effect of the top spill on the free surface shape is limited to a small region near spillway bays 2 and 10. Therefore the validation cases assumed that spillway bays 2 and 10 were closed and the free surface shape obtained during the calibration process was used near the top spills.

The numerical solution (pressure, velocity, free surface location and turbulent quantities) obtained on June 5, 2006 was used as an initial condition for the validation cases.

The convergence parameters for the calibration cases were:

$$1FG - May\ 14, 2006 \rightarrow \left(flowrate: 120.4\ kcfs, WSE: 711.5\ ft \right)$$

$$11FG - May\ 17, 2006 \rightarrow \left(flowrate: 157.2\ kcfs, WSE: 715.4\ ft \right)$$

$$63C - June\ 17, 2006 \rightarrow \left(flowrate: 205.5\ kcfs, WSE: 718.6\ ft \right)$$

Figure 7.2-6 shows the evolution of the flow rate and WSE at the tailwater elevation gauge for the validation cases. Blue and green lines represent the flow rate and WSE, respectively. The above mentioned simplifications allowed the calibration cases to reach the statistically steady solutions in typically 20 minutes using 30 days of computation time.

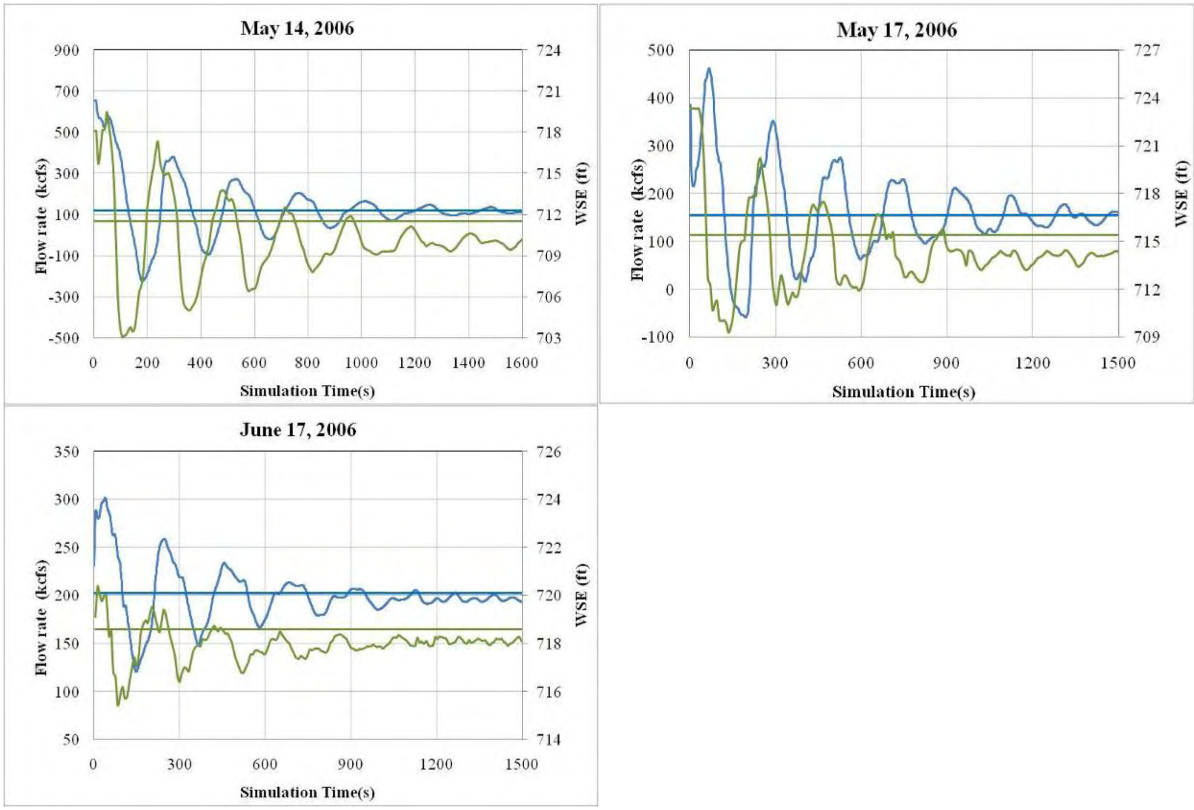

Figure 7.2-6 Evolution of the flow rate at the exit (blue line) and free surface elevation (green line) for May 14, 2006, May 17, 2006, and June 17, 2006. Horizontal lines represent target values.

7.3 Rigid-lid Model Results

7.3.1 Hydrodynamics

Figures 7.3-1 and 7.3-2 show depth-averaged velocity data collected in the field on June 4, 2006 and June 5, 2006 and those predicted by the rigid-lid model. Good agreement between observed and predicted velocity vectors was found, especially at the downstream transect where flow conditions were more stable and the Acoustic Doppler Current Profiler (ADCP) velocity data are less affected by turbulence and non-steady conditions.

As observed in the field, the model captured the counterclockwise eddy near the east bank and the almost uniform profile at the most downstream transect.

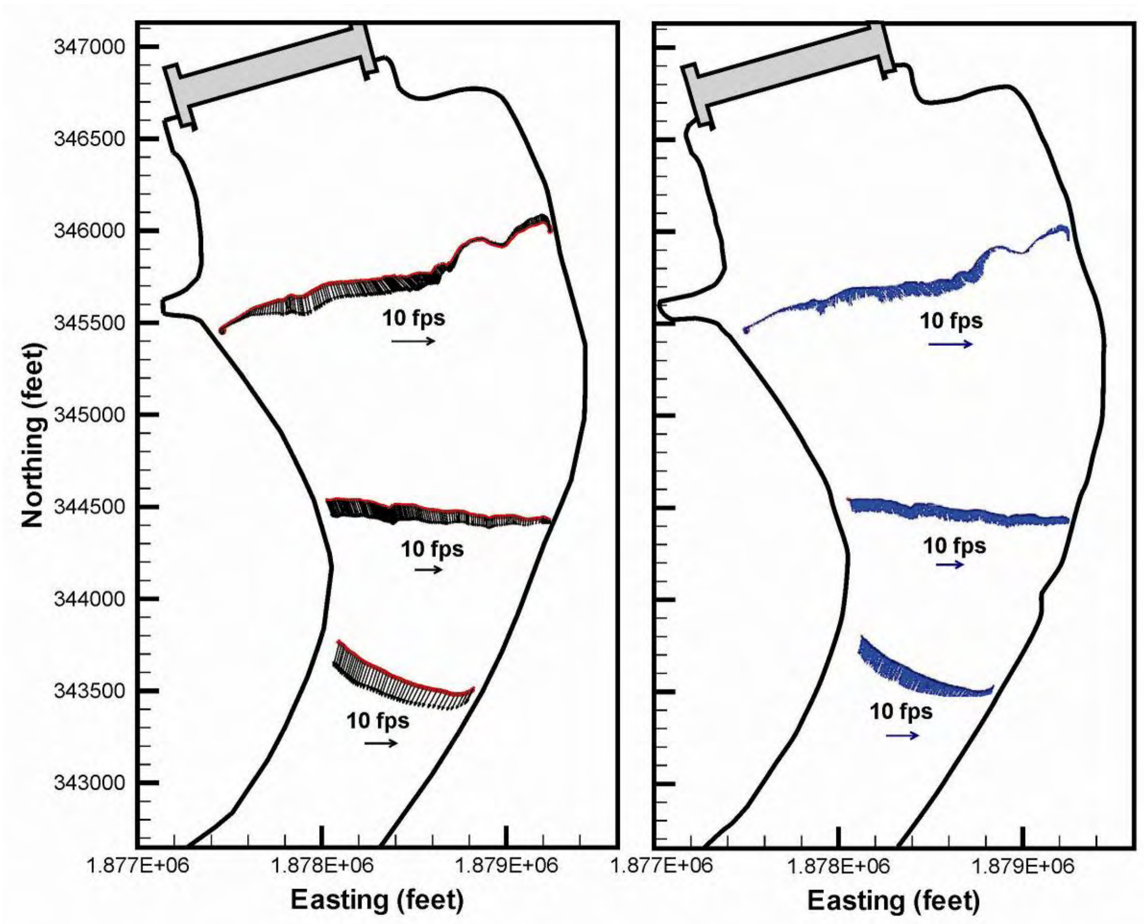

Figure 7.3-1 **Flow field on June 4, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data**

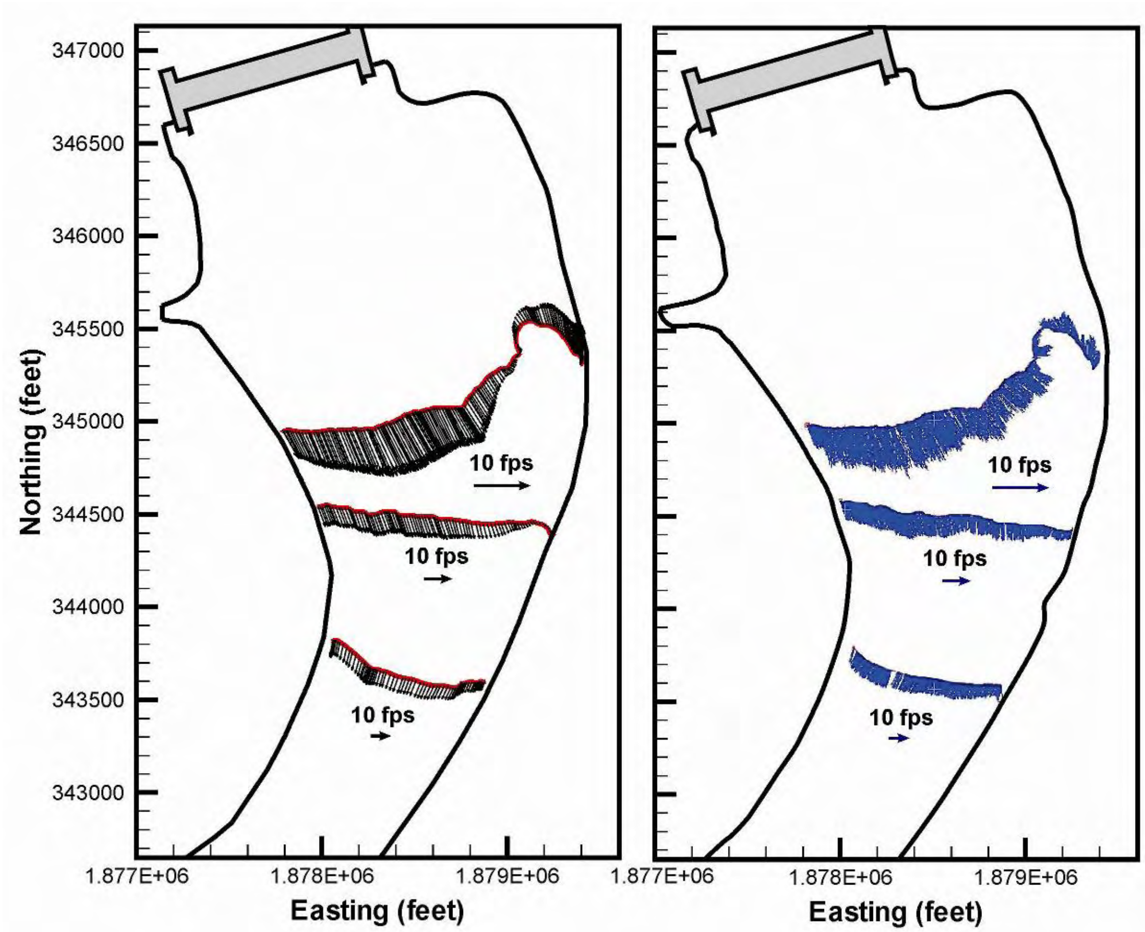

Figure 7.3-2 Flow field on June 5, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data

7.3.2 TDG Model

The percent saturation of TDG measured in the field at each station and the mean TDG in each of the three transects together with the values generated by the CFD model for the calibration and validation cases are shown in Appendix B. Figures 7.3-3 to 7.3-7 show measured and predicted values at each probe location. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations.

The model captures the reduction of TDG with distance downstream and the lateral gradient observed in the field. As measured, the highest predicted TDG value at Transect TW1 occurred in the center of the channel and the lateral gradients in transects TW2 and TW3 were negligible.

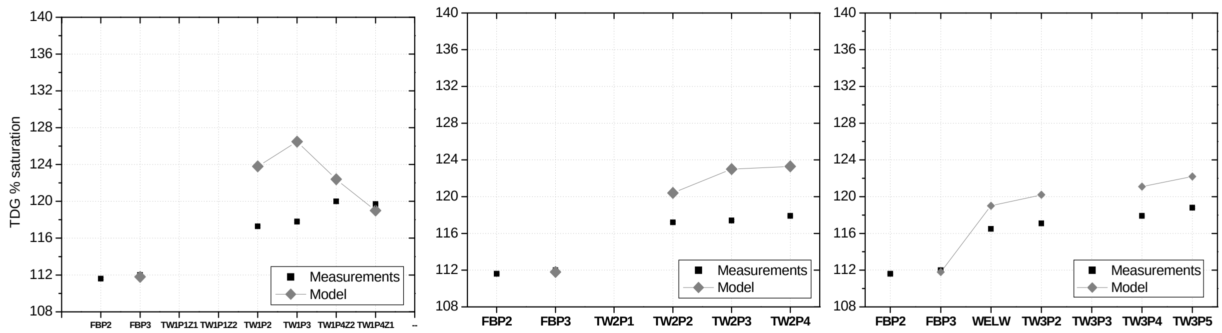

Figure 7.3-3 **Comparison between measured and predicted TDG on June 4, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

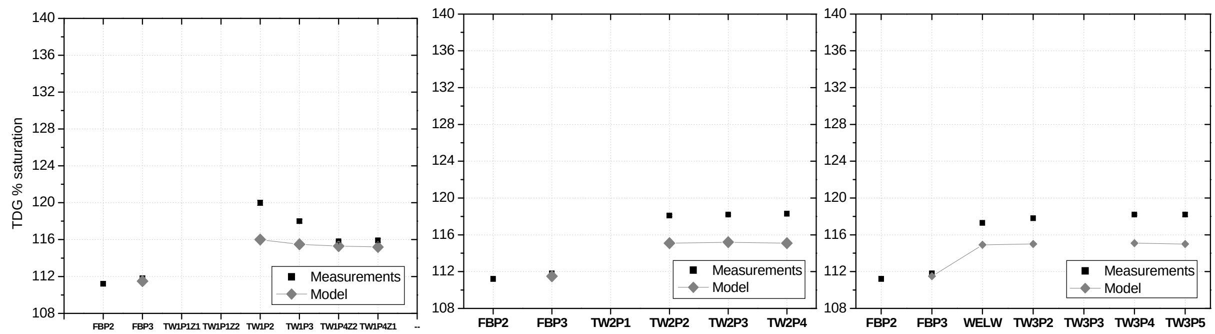

Figure 7.3-4 **Comparison between measured and predicted TDG on June 5, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

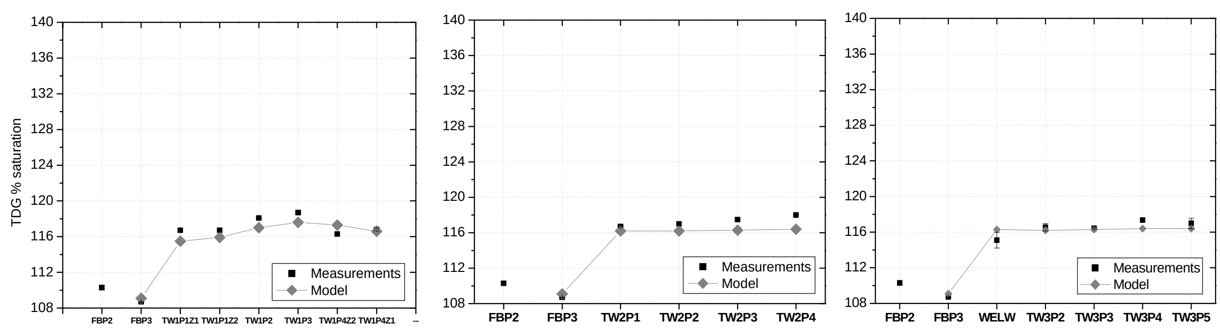

Figure 7.3-5 **Comparison between measured and predicted TDG on May 14, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

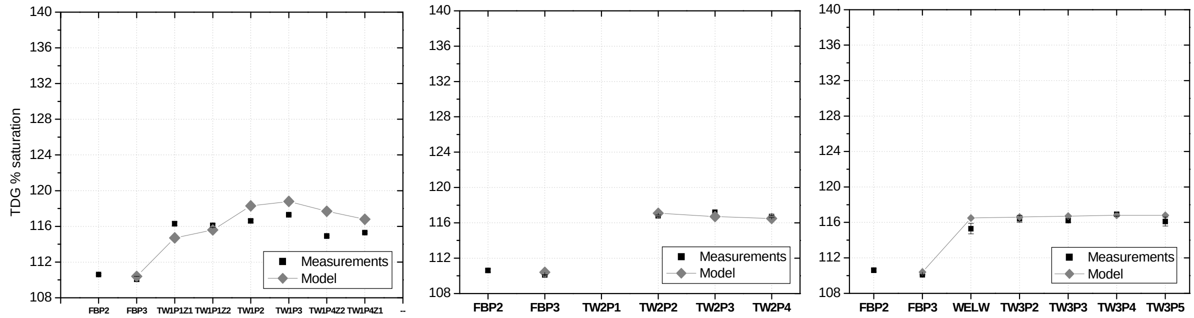

Figure 7.3-6 Comparison between measured and predicted TDG on May 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

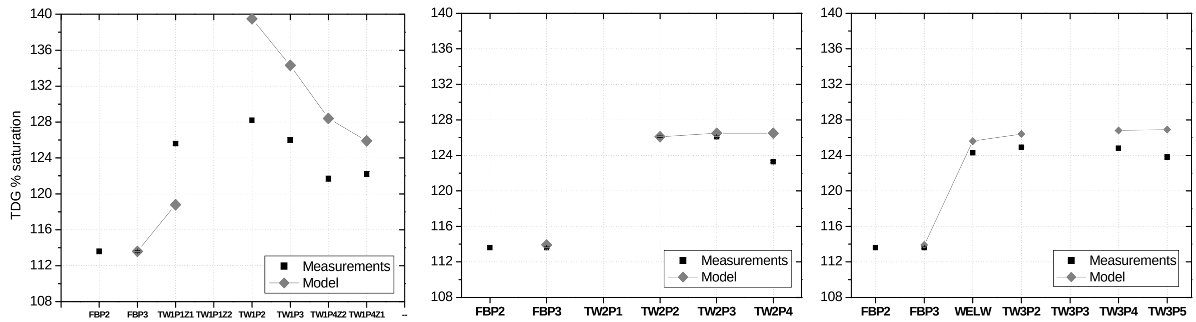

Figure 7.3-7 Comparison between measured and predicted TDG on June 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

Figures 7.3-8 and 7.3-9 show isosurfaces of TDG, gas volume fraction and bubble diameter for June 4, 2006 and June 5, 2006 where the spill operation was adjusted to test both a spillway discharge pattern that was spread across the spill bays (Figure 7.3-8) and a concentrated spill pattern (Figure 7.3-9). As shown by the gas volume fraction isosurfaces, the model predicts uniformly distributed bubbles on the spillway region during spread spill operations. On the other hand, bubbles concentrate near the center of the spillway for full open gate operation. The maximum TDG occurs at the center region due to the exposure of water to the aerated flow as it travels within the stilling basin (see TDG isosurfaces). The rate of mass exchange depends on the gas volume fraction, the bubble size and the difference in concentration between the bubble boundary and the water. The gas dissolution region occurs mainly within 500 to 1,000 ft downstream of the spillway; afterwards the bubbles moved up to regions of lower pressure and the dissolution rate decreased. The bubbles shrink near the bed due to the air mass transfer and high pressure. The smaller the bubble size the stronger its tendency to dissolve. Substantial desorption of TDG takes place near the free surface downstream of the spillway. Once the air bubbles are vented back into the atmosphere the rate of mass exchange decreases significantly. The TDG concentration reaches a developed condition approximately 1,300 ft from the spillway. According to the simulation results, the draft tube deck extensions and spillway lip, tend to act as deflectors for the spill, and powerhouse operation prevented spilled flow from plunging deep, reducing the exposure of bubbles to high pressure.

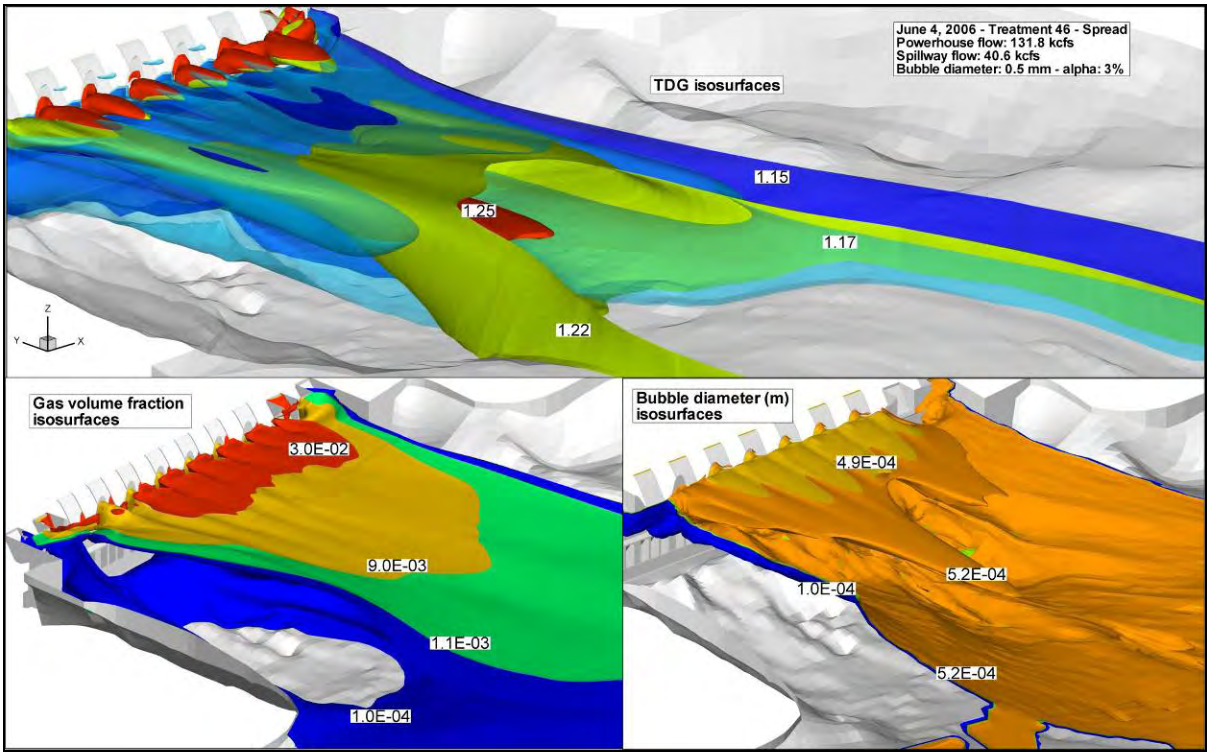

Figure 7.3-8 **TDG, gas volume fraction and bubble diameter isosurfaces for June 4, 2006**

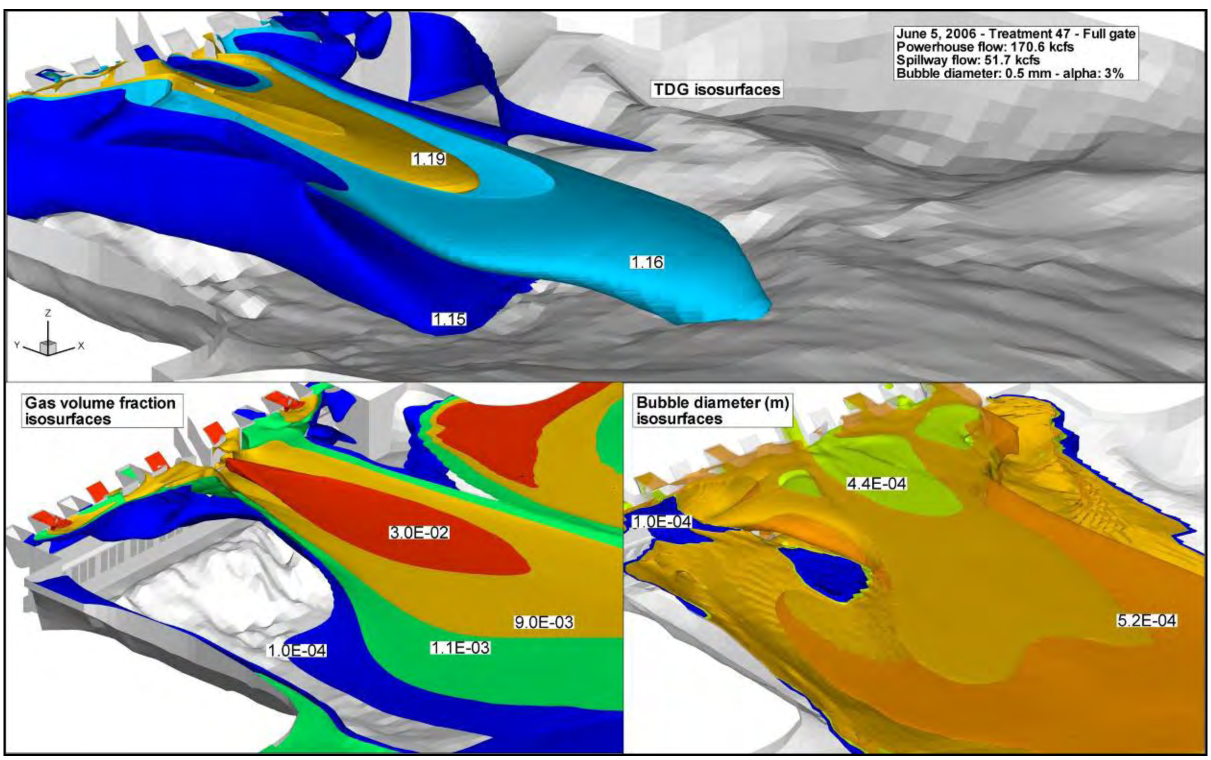

Figure 7.3-9 **TDG, gas volume fraction and bubble diameter isosurfaces for June 5, 2006**

Table 7.3-1 summarizes simulation conditions and averaged predicted TDG at transects T1, T2 and T3. The last column in the table shows the difference between averaged TDG at transect T3 and forebay TDG, $\Delta TDG = TDG_{T3} - TDG_{forebay}$ indicating the approximate net production of TDG in the tailrace.

Table 7.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the calibration and validation cases

Case	Date	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
46 S	4-Jun	40.6	172.4	23.5	0.11	717.3	26.3	111.8	122.9	122.2	120.7	8.9
47 FG	5-Jun	51.7	223.3	23.2	0.77	720.2	29.2	111.5	115.5	115.1	115.0	3.5
1 FG	14-May	44.6	120.4	37.0	0.62	711.5	20.5	109.1	116.7	116.3	116.3	7.2
11FG	17-May	42.6	157.2	27.1	0.60	715.4	24.4	110.4	117.0	116.9	116.7	6.3
63C	17-Jun	87.4	205.5	42.5	0.55	718.6	27.6	113.9	130.5	126.4	126.4	12.5

8.0 SENSITIVITY SIMULATIONS

8.1 Simulation Conditions

Nine model runs (MR) with two spillway configurations (spread and concentrated spill) and four total river flows were simulated to analyze the sensitivity of TDG production as a function of total flow, spill releases, and tailwater elevation. These simulations were run assuming forebay TDG was 115% and water temperature was 14 ^{o}C. Tables in Appendix A summarize plant operations, TDG saturation in the forebay, and tailwater elevation used for these simulations.

Numerical results of the MR simulations confirmed what seemed to be demonstrated by field data, that is, saturation of gases in the tailrace could be minimized by concentrating the spill through one or more gates rather than spread across the spillway. This lead to further model runs in which various spill patterns were tested with the objective of reducing TDG production in the Wells Tailrace. In Section 9, the Preferred Operating Conditions are discussed and presented.

8.2 VOF Model Results

The free surface shape for the sensitivity simulations was extracted from VOF computations in a domain extending about 1,700 ft downstream of the dam. The convergence parameters for these simulations were:

$$MR1 \text{ and } MR5 \rightarrow \left(flowrate : 208.5\ kcfs, WSE : 718.8\ ft \right)$$

$$MR2,\ MR6 \text{ and } MR8 \rightarrow \left(flowrate : 246.0\ kcfs, WSE : 721.4\ ft \right)$$

$$MR3 \text{ and } MR7 \rightarrow \left(flowrate : 128.0\ kcfs, WSE : 713.4\ ft \right)$$

$$MR4 \text{ and } MR9 \rightarrow \left(flowrate : 165.5\ kcfs, WSE : 715.9\ ft \right)$$

The initial conditions from the MR simulations were obtained from interpolation of the numerical solutions for the calibration/validation cases. The MR cases reached the statistically steady solutions in typically 20 to 30 minutes (30 to 45 days of computation time).

8.3 Rigid-lid Model Results

8.3.1 MR Simulations

Tables in Appendix C show the percent saturation of TDG predicted by the model at each station and the mean TDG in each of the three transects for the MR simulations. Figures 8.3-1 to 8.3-3 show predicted TDG values at each probe location. Table 8.3-1 summarizes simulation conditions, averaged predicted TDG at transects T1, T2, T3 and ΔTDG.

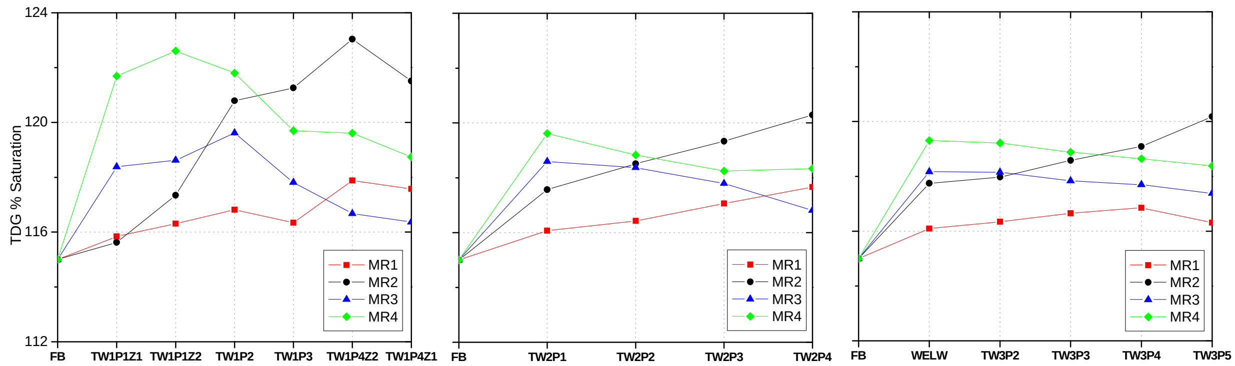

Figure 8.3-1 Predicted TDG concentration for spread operation

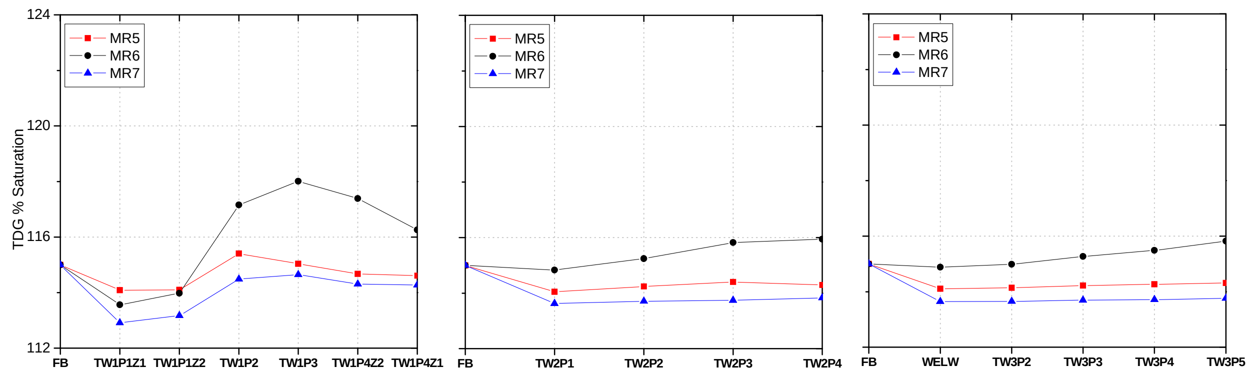

Figure 8.3-2 Predicted TDG concentration for full open gate operation

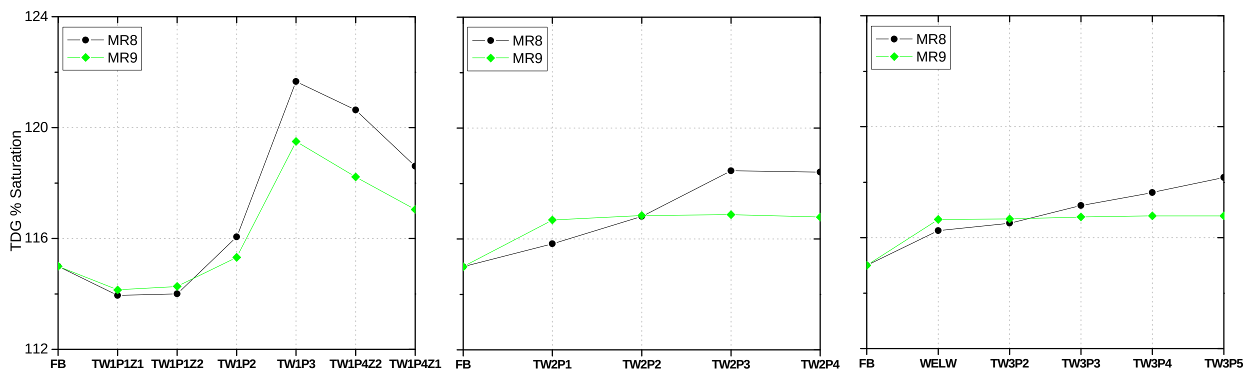

Figure 8.3-3 Predicted TDG concentration for two full open gates operation

Table 8.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the sensitivity simulations.

Case	Type	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
1	S	23.0	208.5	11.0	0.07	718.8	27.8	115.0	117.3	118.1	117.9	2.9
2	S	60.5	246.0	24.6	0.19	721.4	30.4	115.0	123.7	124.1	123.7	8.7
3	S	23.0	119.0	19.3	0.07	713.4	22.4	115.0	121.3	120.7	120.7	5.7
4	S	60.5	156.5	38.7	0.19	715.9	24.9	115.0	126.3	124.5	124.7	9.7
5	1-FG	23.0	208.5	11.0	0.50	718.8	27.8	115.0	116.0	116.8	116.7	1.7
6	1-FG	60.5	246.0	24.6	1.32	721.4	30.4	115.0	121.1	121.4	121.3	6.3
7	1-FG	23.0	119.0	19.3	0.50	713.4	22.4	115.0	117.5	117.1	117.3	2.3
8	2-FG	60.5	246.0	24.6	0.66	721.4	30.4	115.0	121.2	123.0	122.6	7.6
9	2-FG	60.5	156.5	38.7	0.66	715.9	24.9	115.0	122.2	122.9	122.9	7.9

In order to understand the effect of plant operations on TDG production and mixing, the simulations were grouped as follow:

1. Simulations with the same spill and powerhouse flows:
   $\{[\text{MR1 and MR5}],\ [\text{MR2, MR6 and MR8}],\ [\text{MR3 and MR7}],\ \text{and}\ [\text{MR4 and MR9}]\}$

2. Simulations with the same spill operation (concentrated or spread spill) and same powerhouse flows:
   $\{Spread: [\text{MR1(S=23 kcfs) and MR2(S=60.5 kcfs)}]\ \text{and}\ [\text{MR3(S=23 kcfs) and MR4(S=60.5 kcfs)}]\}$
   $\{FG: [\text{MR5(S=23 kcfs) and MR6(S=60.5 kcfs)}]\}$

3. Simulations with the same spill operation (concentrated or spread spill) and same spilled flows:
   $\{Spread: [\text{MR1(P=185.5 kcfs) and MR3(S=96 kcfs)}]\ \text{and}\ [\text{MR2(S=185.5 kcfs) and MR4(S=96 kcfs)}]\}$
   $\{FG: [\text{MR5(S=185.5 kcfs) and MR7(S=96 kcfs)}]\}$

where S and P denote spillway and powerhouse flows, respectively.

<u>Simulations with the same spill and powerhouse flows</u>

Substantial differences in downstream TDG levels were observed with spread or full open gate operations. Numerical results indicate that, for the same spill and powerhouse flows, full open gate operation resulted in the lowest TDG concentration. On the other hand, the highest TDG concentrations were observed with spread flow operation. Simulations MR6 and MR8 show that distributing the same spill flow into two gates produced more TDG than concentrating the flow through a single bay.

To understand the underlying physics that cause larger TDG concentrations with spread operation, the volume of air available for dissolution and TDG sources for simulations MR1 (spread) and MR5 (FG) were analyzed at two transects downstream of the dam.

Figure 8.3-4 shows the cumulative volume of air in bubbles per unit length and cumulative TDG source per unit length as a function of the distance from the free surface at 50 m downstream of the dam. Solid lines show the cumulative volume of air in bubbles per unit length for simulations MR1 and MR5. Almost no air was present below 10 m. Note that the amount of air available for dissolution for concentrated spill operation (MR5) is always smaller than that for spread flows (MR1). The distribution of gas volume fraction and TDG at a vertical slice at 50 m from the dam for both types of operation is shown in 8.3-5. Note that the gas volume fraction, and consequently the TDG, is significantly larger for spread operation. As shown in Figure 8.3-6, for the simulated flow rates, the spread operation produces a submerged jet while the full open gate operation produces a surface jump. The residence time of bubbles entrained in a submerged jet is longer than those entrained in a surface jump. Bubbles reach the free surface more quickly in a surface jump because, on average, they travel closer to the free surface and because the water depth on the spillway face is smaller. In addition, large vertical liquid velocities downstream of the spillway lip help bubbles leave the tailrace more quickly for the concentrated spill operation.

The dotted lines in Figure 8.3-4 show the cumulative TDG source for simulations MR1 and MR5. Since the amount of air in bubbles available to produce TDG is larger for the spread operation, both the degasification (negative source of TDG) and production of TDG (positive source of TDG) are increased for this case. The net TDG production for spread and concentrated spill operations are approximately 0.15 kg air/(s m) and 0.06 kg air/(s m), respectively.

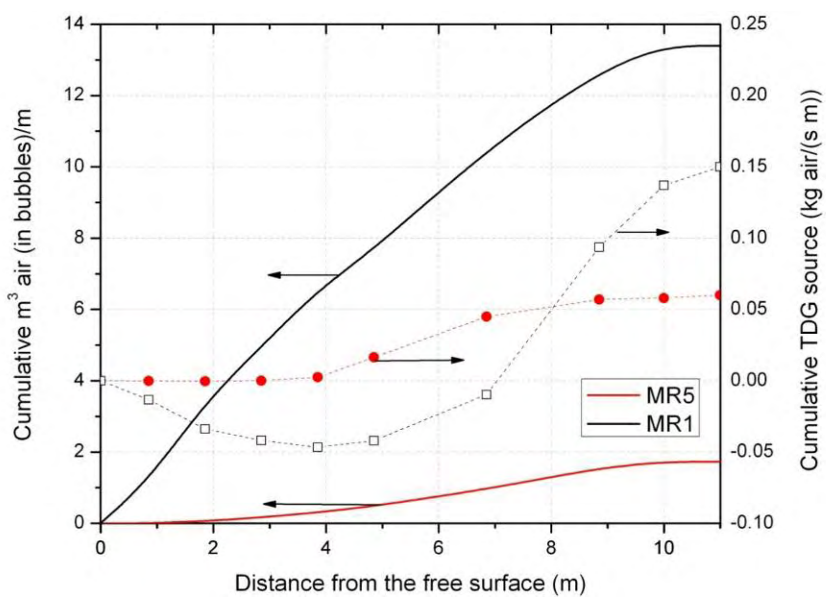

Figure 8.3-4 Cumulative volume of air in bubbles per unit length (left) and cumulative TDG source per unit length (right) as a function of the distance from the free surface at a plane at 50 m from the dam.

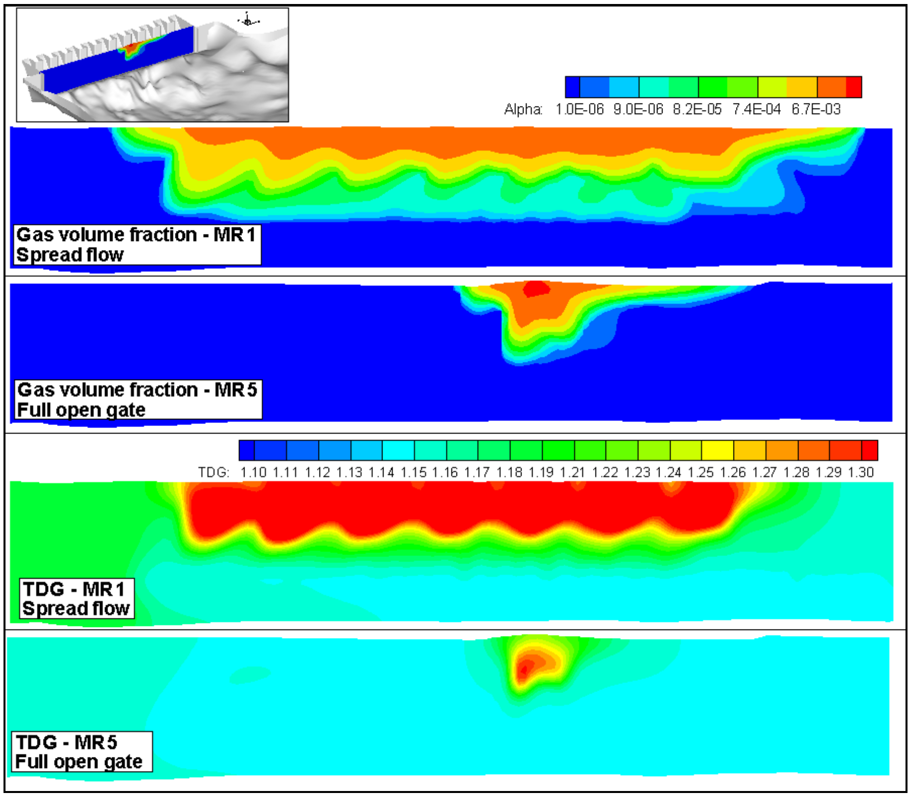

Figure 8.3-5 **Contours of gas volume fraction and TDG at 50 m from the dam for simulations MR1 and MR5.**

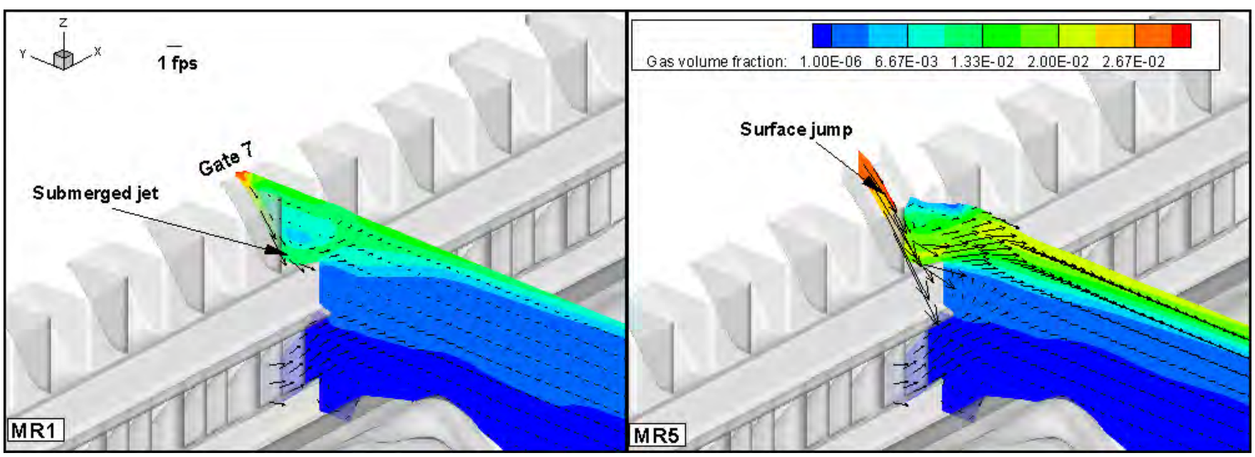

Figure 8.3-6 **Contours of gas volume fraction and velocity vectors at a slice through gate 7 for MR1 (top) and MR5 (bottom).**

Figure 8.3-7 shows the cumulative curves at Transect 1 location, 370 m downstream of the dam. Contrary to observations at 50 m from the dam, more bubbles are present at transect T1 for concentrated spill operation than for spread flows. The distributions of gas volume fraction and resulting TDG for MR1 and MR5 are shown in Figure 8.3-8. Higher liquid velocities with concentrated spill operation transport bubbles further in the tailrace. In addition, higher turbulent dispersion, created by a stronger jet in a full open gate operation, entrains bubbles deeper into the tailrace increasing bubble residence times. Note that 100% of the bubbles at Transect T1 are 2m or less from the free surface for the spread operation. On the other hand, due to turbulent dispersion, about 65% of the bubbles are 2 m from the free surface for full open gate operation. The TDG source is negative (degasification) for both type of operations. However, more degasification is observed with concentrated spill due to more availability of gas and an elevated mass transfer coefficient at the free surface for higher turbulent flows. As shown in Figure 8.3-8, TDG is higher for the spread operation as a result of more TDG production and less degasification at the free surface.

The flow pattern and TDG distribution in the tailrace for cases MR1 and MR5 are shown with streamlines colored by TDG concentration in Figures 8.3-9 and 8.3-10, respectively.

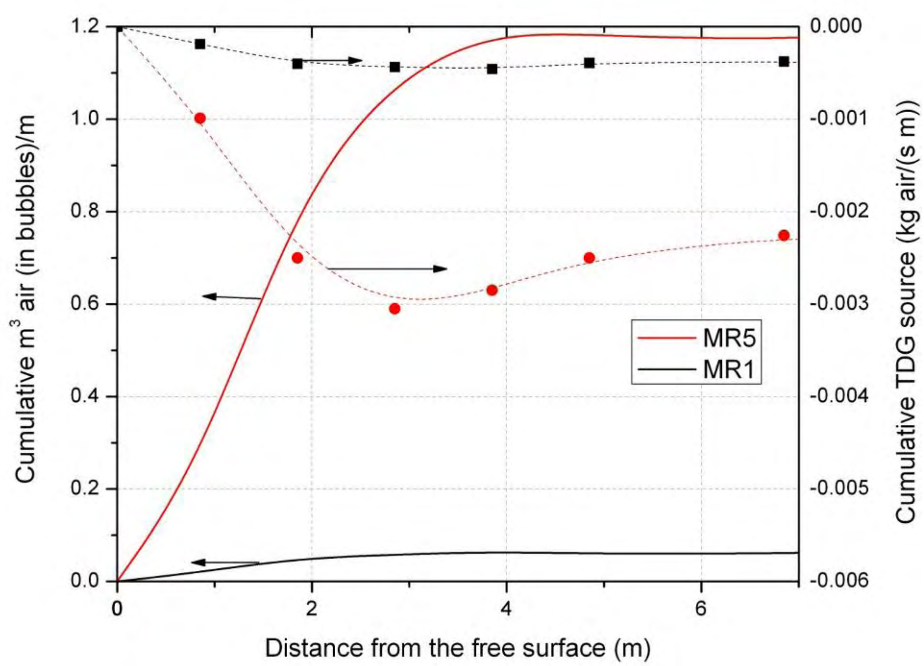

Figure 8.3-7 **Cumulative volume of air in bubbles per unit length (left) and cumulative TDG source per unit length (right) as a function of the distance from the free surface at a plane at 370 m from the dam.**

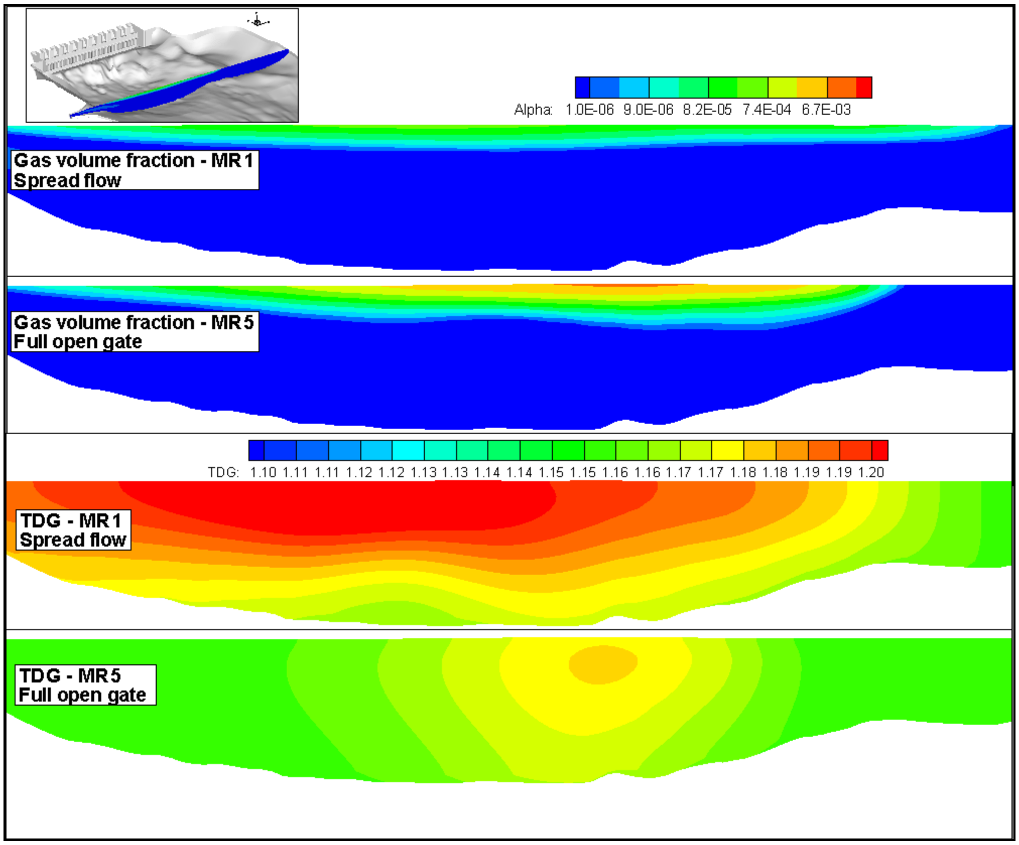

Figure 8.3-8 Contours of gas volume fraction and TDG at 370 m from the Dam for simulations MR1 and MR5.

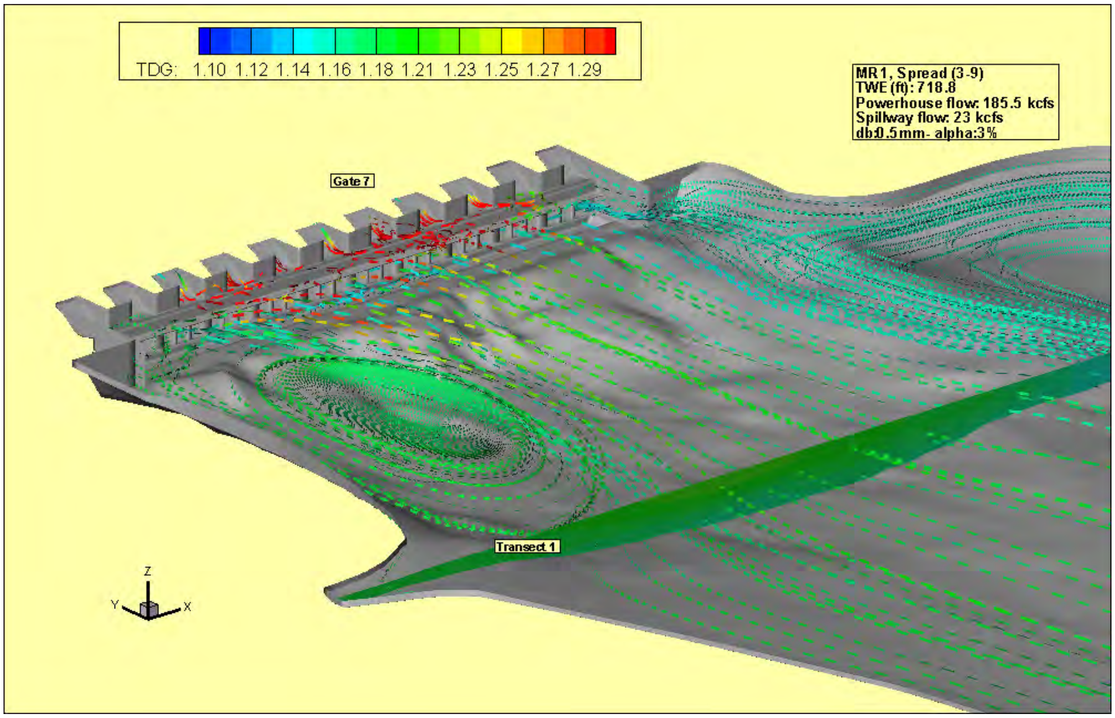

Figure 8.3-9 Streamlines colored by TDG concentration for MR1.

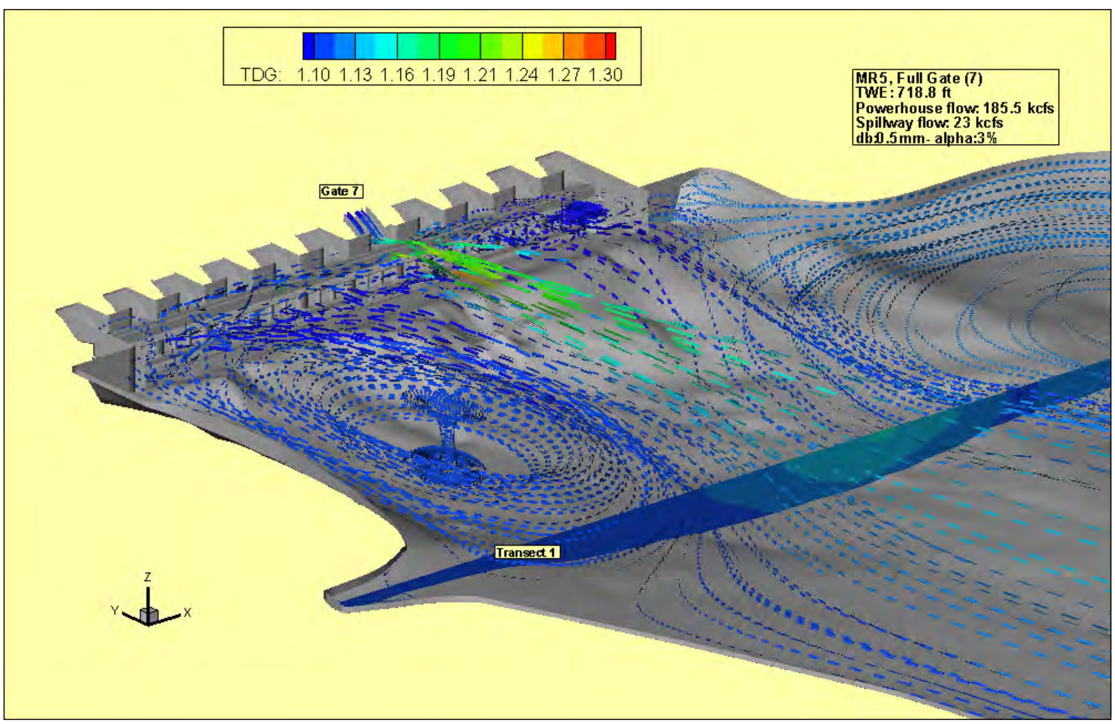

Figure 8.3-10 Streamlines colored by TDG concentration for MR5.

Simulations with the same spill operation and same powerhouse flows

Downstream TDG levels depend on the percentage of spilled water. For constant powerhouse flows, the greater the amount of spill, the greater the amount of bubbles entrained and the turbulence generated in the tailrace, and therefore, the greater the TDG production. Thus, the simulations for spread flows MR1 and MR3 with 23 kcfs spill flow produces less TDG than the equivalent MR2 and MR4 simulations with 60.5 kcfs (see Figure 8.3-1). Streamlines colored by TDG show the flow pattern and TDG distribution for MR1 (Figure 8.3-1) and MR2 (Figure 8.3-11). For these cases, the maximum TDG levels occurred at the west bank of the Wells tailrace.

Figures 8.3-12 and 8.3-13 show the submergence depth of the flip lip as a function of spill per unit width for full open gate and spread operations, respectively. The submergence depth is defined as the tailwater elevation minus the elevation of the top of the flip lip (691 ft) and the spill per unit width is:

$$\text{Spill per unit width} = \frac{1}{S_T W}\sum_i S_i^2 \qquad (19)$$

where W is the width of the spillbay, S_T is the total spill, and S_i is the spill of a generic bay i. Orange triangles represent field data black stars: predicted data at the model calibration/validation, black squares: sensitivity simulations. Labels indicate ΔTDG values. Data were grouped based on the percentage spill between 0 to 19%, 20 to 39%, 40 to 59%, and 60 to 100%. These plots confirm that the TDG production is strongly dependent on the percentage of spilled water.

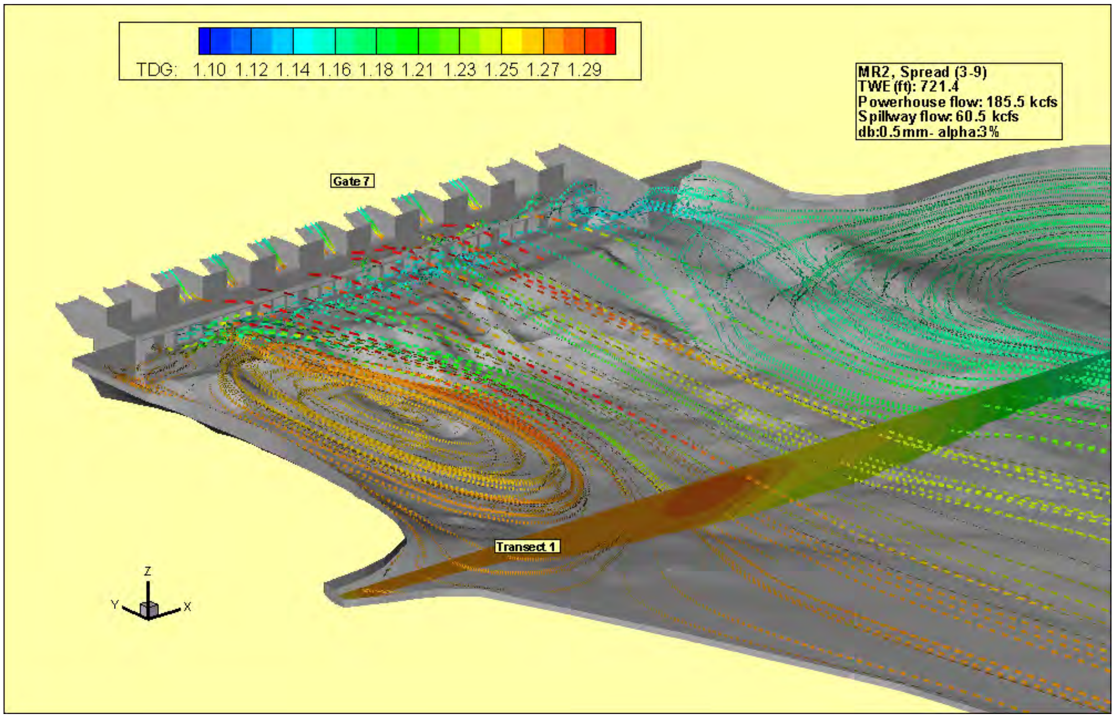

Figure 8.3-11 Streamlines colored by TDG concentration for MR2.

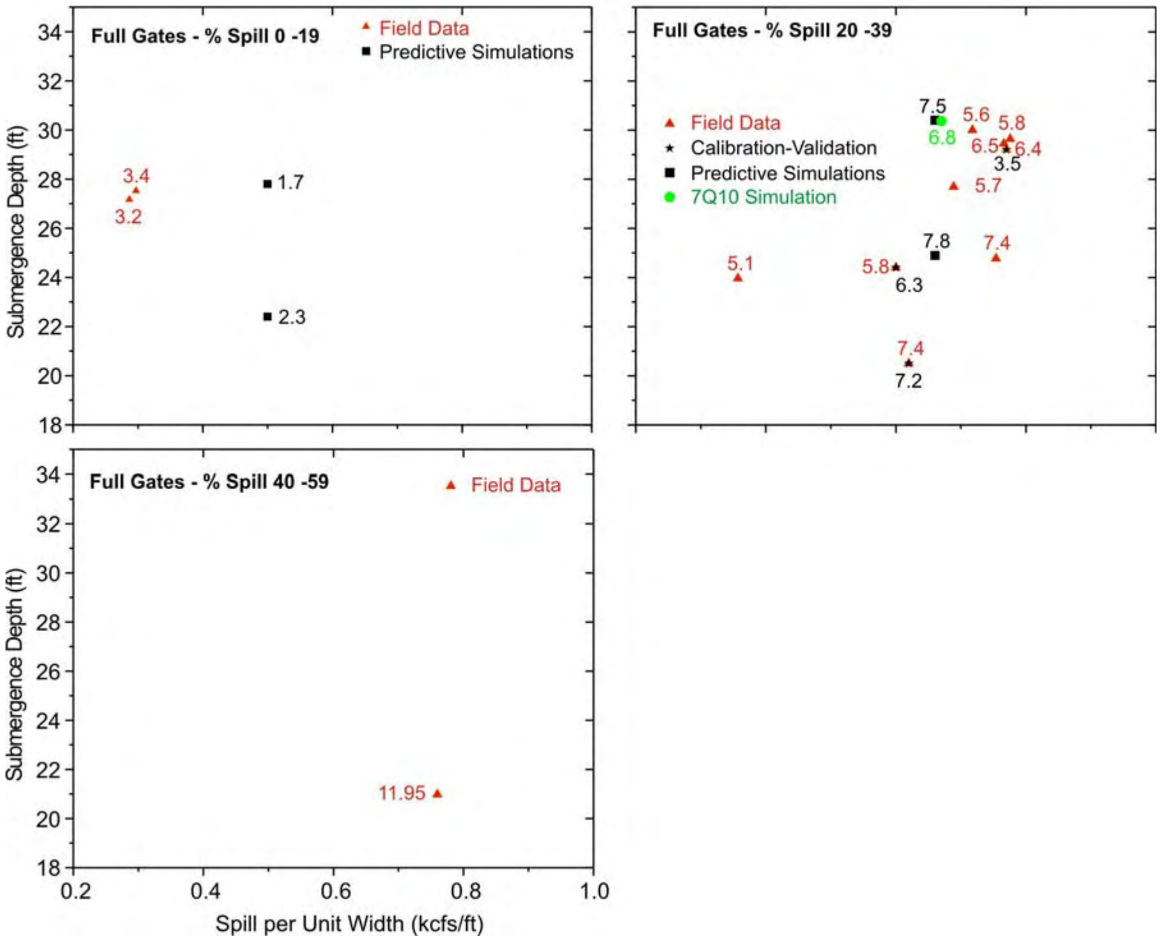

Figure 8.3-12 **Submergence depth as a function of spill per unit width for full open gate operation for percentage spill between 0 to 19%, 20 to 39%, and 40 to 59%. Red triangles: field data, black stars: predicted data at the model calibration/validation, black squares: sensitivity simulations, and green circle 7Q10 simulation. Labels indicate ΔTDG values.**

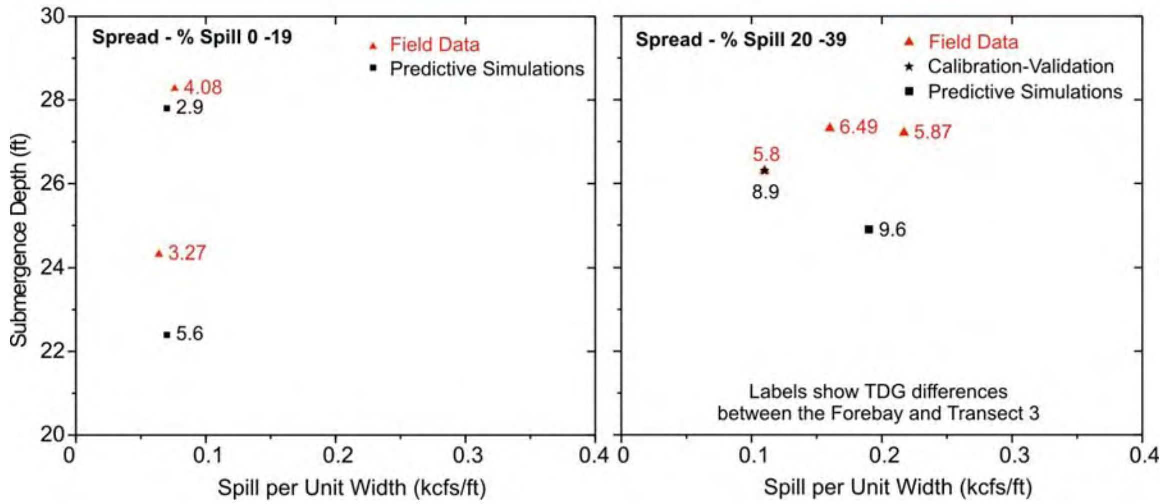

Figure 8.3-13 Submergence depth as a function of spill per unit width for spread operation for percentage spill between 0 to 19% and 20 to 39. Red triangles: field data, black stars: predicted data at the model calibration/validation, and black squares: sensitivity simulations. Labels indicate ΔTDG values.

<u>Simulations with the same spill operation and spilled flows</u>

Mixing and dilution from increased powerhouse flows resulted in reduced TDG levels downstream for both spread and concentrated spill operations. The most notable effect of the powerhouse flow reduction was the increment of TDG values at the east bank for spread flows. The TDG distribution predicted in simulation MR4 with 96 kcfs powerhouse flow compared with the predicted values for MR2 with 185.5 kcfs powerhouse flow are shown in Figures 8.3-14 and 8.3-11, respectively.

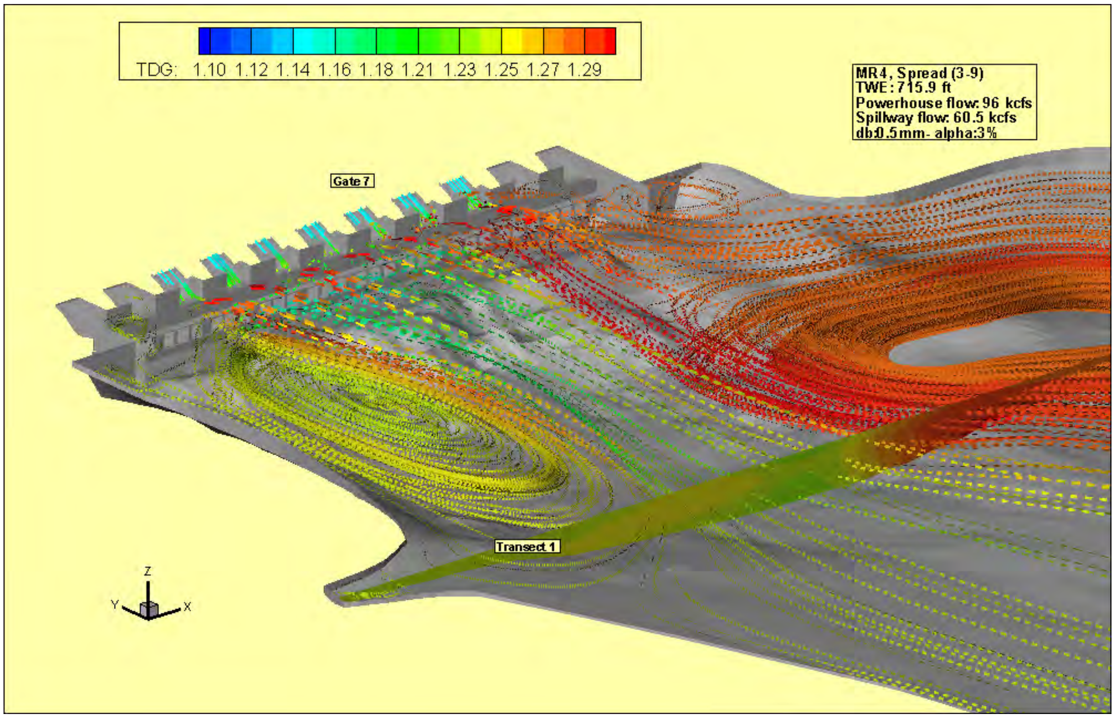

Figure 8.3-14 Streamlines colored by TDG concentration for MR4.

9.0 PREFERRED OPERATING CONDITION - 7Q10 FLOW SIMULATION

9.1 Simulation Conditions

Based upon the results of the sensitivity simulations, several additional operating configurations were tested toward identification of a Preferred Operating Condition (POC) for a 7Q10 flow at Wells Dam. The environmental conditions used for these model runs were different than the sensitivity simulations because the environmental parameters consistent with high flow events (>200 kcfs) are very different than the environmental conditions observed during average operating conditions. Because of these differences, the inputs for the 7Q10 preferred operating simulation included forebay TDG of 113% and water temperature equal to 13 ^{o}C. Table 9.1-1 shows simulation conditions used for the 7Q10 run. Operational conditions included operating only 9 of 10 turbine units[1], (each unit running at 20 kcfs[2]), 10 kcfs running through the Juvenile

[1] Ecology has requested that the TDG model be operated utilized only 9 of the 10 available turbine units at Wells Dam. This request was intended to simulate a condition where one turbine unit is off-line for maintenance.

[2] Note that the maximum flow for each of the 10 turbines at Wells Dam is 22.6 kcfs for a total powerhouse capacity of 226 kcfs. The TDG model used a more conservative 20 kcfs per turbine which represents a more normal operation condition when flows at Wells Dam are approaching the hydraulic capacity of the powerhouse (>200 kcfs).

Bypass System[3], and 1 kcfs flowing down the fish ladders, and 54.6 kcfs through the spillways (combined spillway and bypass flow of 64.6 kcfs).

Table 9.1-1 Conditions used for the POC-7Q10 numerical simulation

POC-7Q10 Simulation									
Forebay TDG: 113.0%									
Tailwater Elevation: 721.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Powerhouse Total: 180.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	8.0	43.0	8.0	0.0	1.7
Spillway Total: 64.6 kcfs									
Fishway Flow: 1 kcfs									
Total River Flow: 245.6 kcfs									

9.2 VOF Model Results

The convergence parameters for the POC-7Q10 simulations were:

$$POC-7\text{Q10 S} \rightarrow \left(flowrate: 246\ kcfs, WSE: 721.4\ ft \right)$$

The numerical solution of MR6 was used as an initial condition for the 7Q10 simulation. This case reached the statistically steady solution in approximately 15 minutes (21 days of computation time).

Figure 9.2-1 shows the spillway jet characteristics predicted with the VOF method for the 7Q10 simulation. Similar to observations on June 5, 2006, the surface jet originating from bay 7 attracts water toward the center of the dam. The cross section of spillway 7 in Figure 9.2-1 shows that the surface jet remains close to the free surface minimizing air entrainment. On the other hand, submerged jumps are predicted at bays 6 and 8 (see cross section of spillway unit 6 in Figure 9.2-1). Though surface jumps may entrain more bubbles in the tailrace, minor contributions to TDG production are expected from these bays because of their relatively small volume of spilled water.

[3] Note that the Juvenile Bypass System uses up to 11 kcfs of water when operating through all five bottom gates. The TDG model assumed that only 10 kcfs of water was used to operate the Juvenile Bypass System. This can be achieved by running the system in a top spill configuration on gates 2 and 10 and in bottom spill configuration for gates 4, 6 and 8.

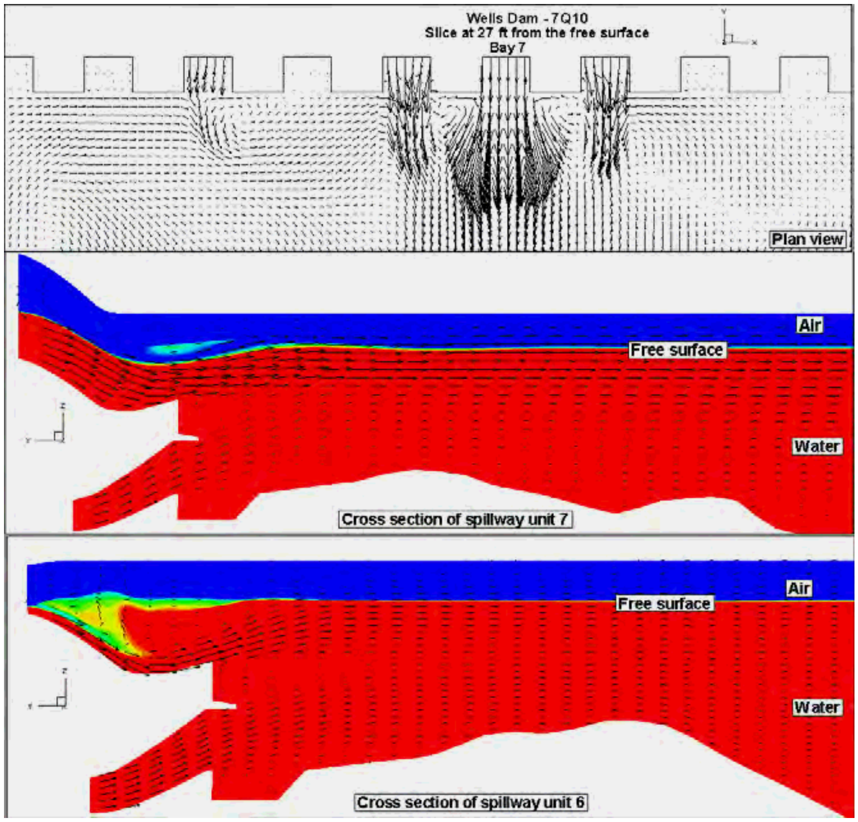

Figure 9.2-1 Predicted flow field for the POC-7Q10 simulation

9.3 Rigid-lid Model Results

Tables in Appendix B show the percent saturation of TDG predicted by the model at each station for the preferred operating conditions during a 7Q10 flow event. Figure 9.3-1 shows TDG values predicted by the model at each probe location. The TDG distribution at the Wells tailrace together with the predicted TDG at each station is shown in Figure 9.3-2. The main process affecting TDG production and mixing occurs upstream of transect T2, after which TDG production reaches a developed condition with minor changes associated with small mass transfer at the free surface. Table 9.3-1 shows the average TDG at transects T1, T2 and T3. According to the model, the average gas saturation does not exceed 120% at any of the three transects.

Figure 9.3-3 show isosurfaces of TDG, gas volume fraction and bubble diameter for the preferred operating condition to address flows up to 7Q10 (246 kcfs). The highest TDG isosurfaces are observed directly below spillbay 7 corresponding with the zone of higher gas volume fraction (aerated zone). In this area, the entrained bubbles generate high levels of TDG. However, the supersaturated water quickly degasses by mass exchange with bubbles near the free surface and mass transfer at the turbulent free surface near the spillway. Moreover, as shown the streamlines of Figure 9.3-4, strong lateral currents caused by the surface jet on bay 7 directed water toward the center of the dam contributing further to fully mixed flow and TDG dilution.

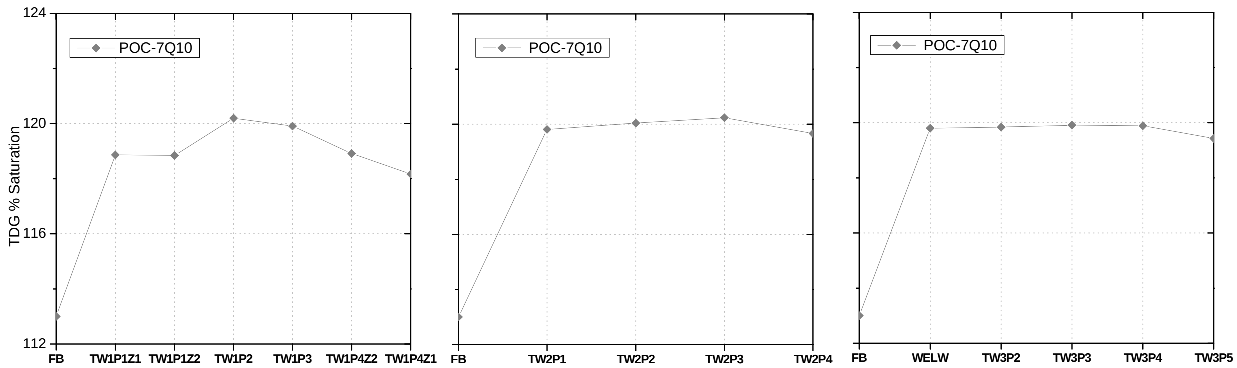

Figure 9.3-1 Predicted TDG concentration for the POC-7Q10.

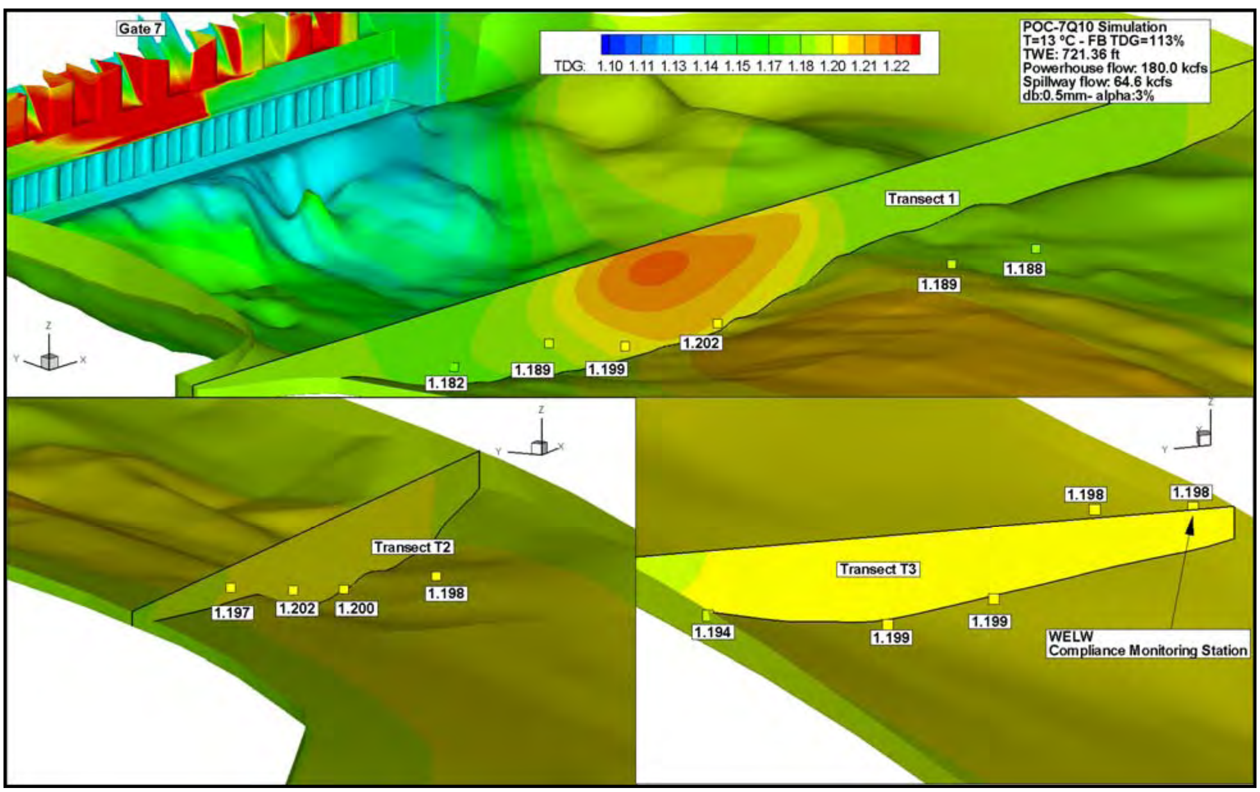

Figure 9.3-2 TDG distribution for the POC-7Q10 simulation.

Table 9.3-1 Averaged predicted TDG in Transects 1, 2 and 3 for the POC-7Q10 simulation.

Case	Type	Spill (kcfs)	Total Q (kcfs)	% Spilled	Unit Spill (kcfs/ft)	Tailwater Elevation (feet)	Spillway Submergence (feet)	% TDG Forebay	% TDG Transect 1	% TDG Transect 2	% TDG Transect 3	Difference % TDG Forebay to Transect 3
7Q10 Simulation	1-FG	64.6	245.6	26.3	0.67	721.4	30.4	113.0	119.2	119.9	119.8	6.8

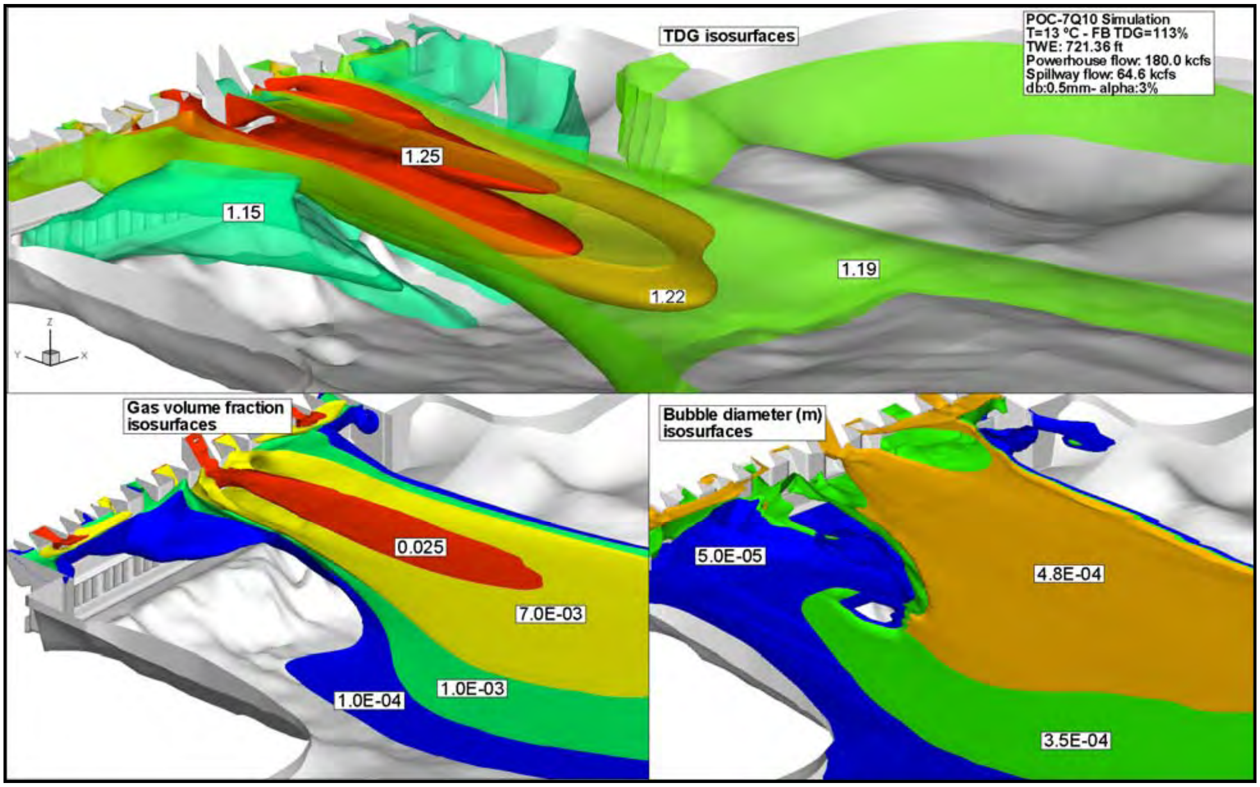

Figure 9.3-3 Streamlines colored by TDG concentration for the POC-7Q10 simulation.

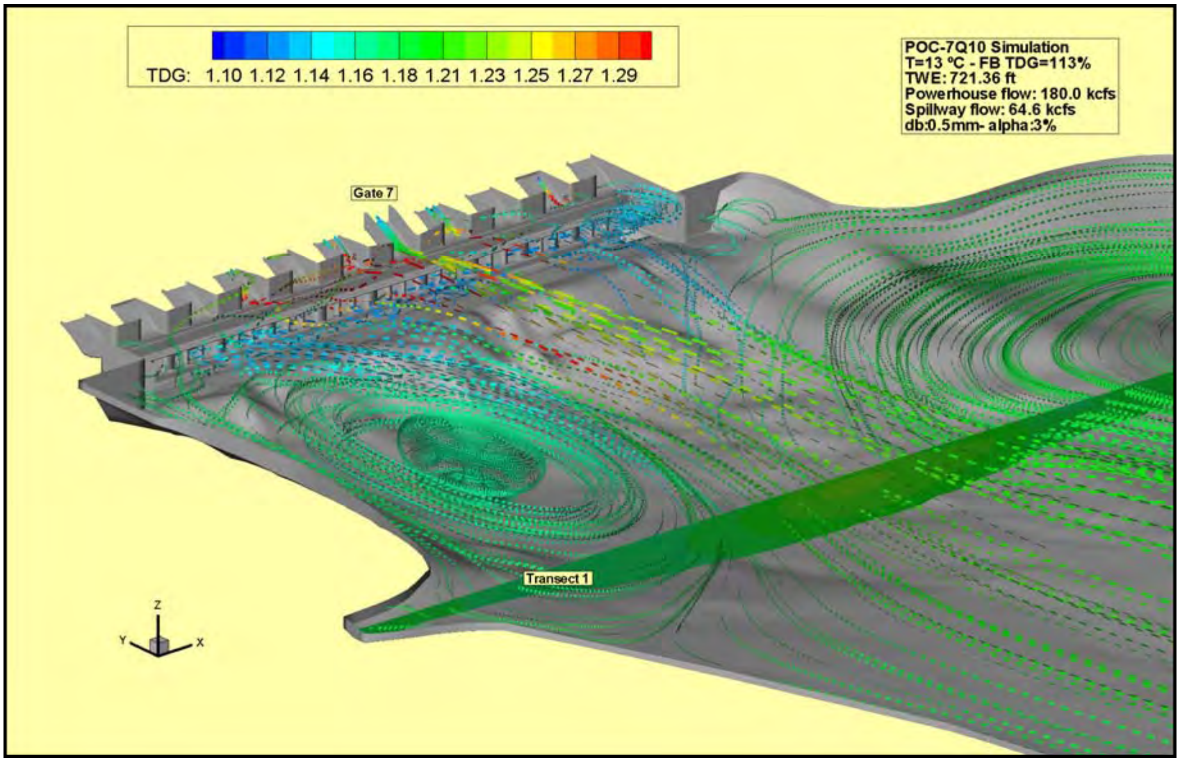

Figure 9.3-4 Streamlines colored by TDG concentration for the POC-7Q10 simulation.

9.4 Location of the compliance monitoring station

The TDG distribution at transect T3 was analyzed to evaluate the location of the tailrace TDG compliance monitoring station WELW. The standard deviation, defined as $\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(C - C_{ave}\right)^2}$, and the error of the TDG predicted at the compliance monitoring station calculated from $\text{Error}(\%) = \frac{\left(C_{WELW} - C_{ave}\right)}{C_{ave}} * 100$ are tabulated in Table 9.4-1.

Table 9.4-1 Averaged predicted TDG in Transect T3 and TDG at WELW

Simulation	TDG Average	σ_{TDG}	WELW	Average-WELW Relative Difference (%)
MR1	1.179	0.00537	1.172	-0.580
MR2	1.237	0.01819	1.219	-1.459
MR3	1.207	0.00757	1.214	0.632
MR4	1.247	0.00493	1.251	0.365
MR5	1.167	0.00225	1.167	0.050
MR6	1.213	0.00103	1.212	-0.057
MR7	1.173	0.00490	1.178	0.435
MR8	1.226	0.00928	1.214	-0.920
MR9	1.229	0.00306	1.231	0.166
POC-7Q10	1.198	0.00196	1.198	0.024

In most of the cases the TDG gradient at transect T3 is small, indicating that the TDG gauge station is located in a region where substantial mixing has occurred.

10.0 DISCUSSION

A mixture two-phase flow model aimed at the prediction of TDG in the Wells tailrace was developed. Variable bubble size and gas volume fraction were used to analyze dissolution and the consequent source of TDG. The model uses an anisotropic RSM turbulence model.

The model was calibrated and validated using field data collected on May 14, May 17, June 4 June 5 and June 17, 2006 during the TDG Production Dynamics Study (EES et al., 2007). The spillway flow was spread across spillbays on June 4, concentrated through a single spillbay on May 17, June 4 and June 5, and crowned on June 17. The observed flow field in the tailrace on June 4 and June 5 was properly predicted by the model. The bubble size and gas volume fraction at the inlet were the parameters of the model. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations.

The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The model brackets the results of the field measurements for the validation cases with a deviation of about +/- 3% of the average TDG values for Transect 3. Numerical results obtained during calibration and validation have demonstrated that the presented model can capture the main features of the two-phase flow in the Wells tailrace and the trends of TDG values across all three transects. The model used in this study assumes that bubble size changes mainly due to mass transfer and pressure and considers that breakup and coalescence are negligible. This hypothesis is frequently used for low volume fraction flows. In this study, the gas volume fraction and bubble size were selected to be above and below the averaged TDG measured on June 4 and 5, 2006. It is expected that the inclusion of the breakup and coalescence phenomena change the bubble size distribution at the plunging jet region immediately downstream of the spillway. However, as the bubble size at the inlet was selected to bracket the field data, breakup and coalescence may play a minor role on the TDG distribution and production in the Wells tailrace.

Different spill releases and TDG production as a function of flow and tailwater elevation were analyzed to determine the spillway operation that would minimize gas saturation in the tailrace. Nine runs with two spillway configurations (spread and FG) and four total river flows were simulated in an effort to identify how sensitive the model is to various spillway operating conditions. From this analysis it was concluded that:

- For the sensitivity simulations modeled, full open gate operations result in the lowest TDG values downstream, followed by two open gates operation. The spread operation with moderate flow through each gate produced the highest TDG values as a result of more entrained air in the tailrace and smaller degasification at the free surface.

- TDG production is directly related to percentage of water spilled. In general, higher downstream TDG is observed as the spill percentage increases. Likewise, TDG production increases as the amount of spill increases. In addition, TDG levels downstream are reduced by dilution as powerhouse flow increases.

Based upon general gas dynamics defined by the results from the nine sensitivity runs a Preferred Operating Condition was selected to predict TDG in the tailrace during a 7Q10 (246 kcfs) event. The assumption was that if TDG standards can be achieved during a 7Q10 event, then the standards can be achieved at flows lower than the 246 kcfs level.

According to the numerical model results, the TDG concentration at the fixed monitoring station does not exceed 120% when the Project is operated in the preferred operating configuration during a 7Q10 flow event.

The model described above will continued to be used as a predictive numerical tool to identify additional Project operations that can be used to further reduce TDG concentration downstream of the Wells Project.

11.0 STUDY VARIANCE

There were no variances from the final FERC approved study plan for the Total Dissolved Gas Investigation.

12.0 ACKNOWLEDGMENTS

This numerical study was sponsored by Douglas PUD. The authors thank Shane Bickford, Josh Murauskas, and Bao Le for their support and cooperation to this study. The constructive suggestions of Duncan Hay of Oakwood Consulting Inc. are gratefully appreciated.

13.0 REFERENCES

Antal, S.P., R.T. Lahey Jr., and J.E. Flaherty. 1991. Analysis of Phase Distribution in Fully Developed Laminar Bubbly Two-Phase Flow, International Journal of Multiphase Flow. 17(5): 553-682

ASL Environmental Sciences Inc. 2007. Turbine discharge measurements by acoustic scintillation flow meter at Until 1 and 2, Wells Hydroelectric Project, Pateros, Washington (2006). Prepared for the Public Utility District No. 1 of Douglas County.

Carrica, P. M., D. Drew, F. Bonetto, and R.T. Lahey Jr. 1999. A Polydisperse model for bubbly two–phase flow around a surface ship. International. Journal of Multiphase Flow. 25: 257-305.

Chen, P., M.P. Dudukovic, and J. Sanyal. 2005. Three-dimensional simulation of bubble column flows with bubble coalescence and breakup. American Institute of Chemical Engineers Journal. 51(3):696-712.

Columbia Basin Environmental (CBE). 2003. Wells Dam Spillway Total Dissolved Gas Evaluation 27 May to 10 June 2003. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

Columbia Basin Environmental (CBE). 2004. Wells Dam Spillway Total Dissolved Gas Evaluation 23 May to 6 June 2004. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

Columbia Basin Environmental (CBE). 2006. Wells Dam Spillway Total Dissolved Gas Evaluation – 23 May to 6 June 2005, Final Report, Prepared for Douglas County PUD.

Douglas County PUD (DCPUD). 2006. Wells Hydroelectric Project. FERC Project No. 2149. Pre-Application Document.

Deckwer, W.D. 1992. Bubble Column Reactors. John Wiley & Sons.

DeMoyer, C.D., E.L. Schierholz, J.S. Gulliver, and S.C.Wilhelms. 2003. Impact of Bubble and Free Surface Oxygen Transfer on Diffused Aeration Systems. Water Research. 37(8):1890-1904.

Drew, D.A., and S.L. Passman. 1998. Theory of Multicomponent Fluids. Applied Mathematical Sciences, Springer 135.

EES Consulting, Inc., J. Carroll, ENSR, and Parametrix. 2007. Total dissolved gas production dynamics Study of the Wells hydroelectric project. Prepared for Public Utility District No. 1 of Douglas County. Kirkland, Washington.

Ferrari, G., M.S. Politano, and L. Weber. 2008. Numerical simulation of free flows on a fish bypass. Computers & Fluids. In press.

Fu, S., B.E. Launder, and D.P. Tselepidakis. 1987. Accommodating the effects of high strain rates in modeling the pressure-strain correlations. The University of Manchester Institute of Science and Technology. TFD/87/5.

Gibson, M.M., and B.E. Launder. 1978. Ground effects on pressure fluctuations in the atmospheric boundary layer. Journal of Fluid Mechanics. 86: 491-511.

Guido-Lavalle, G., P. Carrica, A. Clausse, and M.K. Qazi. 1994. A bubble number density constitutive equation, Nuclear Engineering and Design. 152: 213–224.

Hibbs, D.E., and J.S. Gulliver. 1997. Prediction of Effective Saturation Concentration at Spillway Plunge Pools. Journal of Hydraulic Engineering 123: 940-949.

Ishii, M., and N. Zuber. 1979. Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows. American Institute of Chemical Engineers Journal. 25(5):843-855.

Jakobsen, H.A., H. Lindborg, and C.A. Dorao. 2005. Modeling of bubble column reactors: progress and limitations. Industrial & Engineering Chemistry Research 44: 5107-5151.

Klinge, R. 2005. Wells Dam total dissolved gas abatement plan for 2005 and 2006 project. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA

Lamont, J.C. and D.S. Scott. 1970. An eddy cell model of mass transfer into the surface of a turbulent liquid. The American Institute for Chemical Engineers Journal. 16:513-519.

Lane, G.L., M.P. Schwarz, and G.M. Evans. 2005. Numerical modeling of gas-liquid flow in stirred tanks. Chemical. Engineering. Science. 60: 2203–2214.

Launder, B. E. 1989. Second-moment closure and its use in modeling turbulent industrial flows. International Journal for Numerical Methods in Fluids 9:963-985.

Liepmann, D. 1990. The near-field dynamics and entrainment field of submerged and near surface jets. Ph.D. thesis, University of California, San Diego.

Lopez de Bertodano, M.L., R.T. Lahey Jr, and O.C. Jones. 1994. Development of a $k-\varepsilon$ model for bubbly two-phase flow. Journal of Fluids Engineering. 116: 128-134.

Mannheim, C., and L. Weber. 1997. Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design, Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 264.

Orlins, J.J. and J.S. Gulliver. 2000. Dissolved Gas Supersaturation Downstream of a Spillway II: Computational Model. Journal of Hydraulic Engineering 38: 151-159.

Politano, M.S., P.M. Carrica, C. Turan, and L. Weber. 2007a. A multidimensional two-phase flow model for the total dissolved gas downstream of spillways. Journal of Hydraulic Research 45(2): 165-177.

Politano, M.S., C. Turan, P.M. Carrica, and L. Weber. 2007b. A three-dimensional anisotropic model of the two phase flow and total dissolved gas downstream of spillways. FLUCOME.
Politano, M.S., P.M. Carrica, and J.L. Baliño. 2000. A polydisperese model of the two-phase flow in a bubble column. Heat and Technology 18(2): 101-113.

Skalski, J. R., G. E. Johnson, C. M. Sullivan, E. Kudera and M. W. Erho. 1996. Statistical evaluation of turbine bypass efficiency at Wells Dam on the Columbia River, Washington. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 53, No. 10, pp. 2188 – 2198.

Takemura, F., and A. Yabe. 1998. Gas Dissolution Process of Spherical Rising Gas Bubbles. Chemical Engineering Science. 53(15):2691-2699.

Turan, C., P. M. Carrica, T. Lyons, D. Hay, and L. Weber. 2008. Study of the Free Surface Flow on an Ogee-Crested Fish Bypass. Journal of Hydraulic Engineering. 134: 1172-1175

Turan, C., M.S. Politano, P. M. Carrica, and L. Weber. 2007. Water Entrainment and Mixing due to Surface Jets. Computational Fluid Dynamics, 21: 3-4, 137-153.

Walker, D.T. 1997. On the origin of the 'surface current' in turbulent free-surface flows. Journal of Fluids Engineering 339, 275-285.

Walker, D.T., and C.Y. Chen. 1994. Evaluation of algebraic stress modelling in free-surface jet flows. Journal of Fluids Engineering 118: 48-54

Appendix A

Conditions Used for the Calibration, validation, and Sensitivity Simulations

Treatment 46 S - June 4, 2006									
Tailwater Elevation: 717.3 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	14.7	14.7	14.4	14.7	14.7	14.8	14.8	14.4	14.7
Powerhouse Total: 131.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.6	5.4	5.2	5.4	5.2	5.4	5.2	5.4	1.6
Spillway Total: 40.6 kcfs									
Total River Flow: 172.4 kcfs									
Forebay TDG: 111.8%									

Treatment 47 FG - June 5, 2006									
Tailwater Elevation: 720.2 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	18.0	18.5	18.3	19.0	20.2	19.6	19.9	18.2
Powerhouse Total: 170.6 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	42.5	2.2	0.0	1.3
Spillway Total: 51.7 kcfs									
Total River Flow: 222.3 kcfs									
Forebay TDG: 111.5%									

Treatment 1 FG - May 14, 2006									
Tailwater Elevation: 711.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	15.0	15.0	14.8	0.0	0.0	0.0	0.0	14.8	15.2
Powerhouse Total: 74.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	35.4	2.2	0.0	1.3
Spillway Total: 44.6 kcfs									
Total River Flow: 120.4 kcfs									
Forebay TDG: 109.1%									

Treatment 11 FG - May 17, 2006									
Tailwater Elevation: 715.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	19.1	18.7	19.2	0.0	0.0	0.0	18.7	19.2
Powerhouse Total: 113.7 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.9	0.0	2.2	0.0	2.2	34.1	2.2	0.0	0.9
Spillway Total: 42.6 kcfs									
Total River Flow: 157.2 kcfs									
Forebay TDG: 110.4%									

Treatment 63 C - June 17, 2006									
Tailwater Elevation: 718.6 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	13.0	13.0	12.9	13.0	13.0	13.1	13.1	12.8	13.1
Powerhouse Total: 117.1 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	2.2	29.8	19.9	29.8	1.7
Spillway Total: 87.4 kcfs									
Total River Flow: 205.5 kcfs									
Forebay TDG: 113.9%									

Simulation MR1									
Tailwater Elevation: 718.8 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 208.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR2									
Tailwater Elevation: 721.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	8.6	8.6	8.6	8.6	8.6	8.6	8.6	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR3									
Tailwater Elevation: 713.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 119.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR4									
Tailwater Elevation: 715.9 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	8.6	8.6	8.6	8.6	8.6	8.6	8.6	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 156.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR5									
Tailwater Elevation: 718.8 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 208.5 kcfs									
Forebay TDG: 115.0%									

Simulation MR6									
Tailwater Elevation: 721.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	60.5	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR7									
Tailwater Elevation: 713.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0	0.0
Spillway Total: 23.0 kcfs									
Total River Flow: 119.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR8									
Tailwater Elevation: 721.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6
Powerhouse Total: 185.5 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	30.3	0.0	30.3	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 246.0 kcfs									
Forebay TDG: 115.0%									

Simulation MR9									
Tailwater Elevation: 715.9 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	0.0	19.2	19.2	19.2	19.2	19.2	0.0	0.0	0.0
Powerhouse Total: 96.0 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.0	0.0	0.0	30.3	0.0	30.3	0.0	0.0	0.0
Spillway Total: 60.5 kcfs									
Total River Flow: 156.5 kcfs									
Forebay TDG: 115%									

Appendix B

Differences Between Measured and Predicted TDG Concentrations

Comparison between measured and predicted TDG on June 4, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P2	1878138.7	345839.8	648.7	1.238	1.173	5.58			
TW1P3	1877972.7	345812.5	648.4	1.265	1.178	7.41			
TW1P4Z1	1877766.1	345652.5	692.0	1.224	1.200	1.97			
TW1P4Z2	1877685.6	345800.1	657.0	1.190	1.197	-0.61	1.229	1.187	3.56
TW2P2	1878494.5	343593.5	675.9	1.204	1.172	2.72			
TW2P3	1878414.7	343618.3	679.9	1.230	1.174	4.78			
TW2P4	1878237.5	343582.5	698.6	1.233	1.179	4.55	1.222	1.175	4.02
WELW	1870372.9	334581.1	692.0	1.190	1.165	2.18			
TW3P2	1870323.5	334702.2	698.7	1.202	1.171	2.69			
TW3P4	1870037.3	334949.0	673.4	1.211	1.179	2.74			
TW3P5	1869929.7	335169.1	697.9	1.222	1.188	2.87	1.207	1.176	2.62

Comparison between measured and predicted TDG on June 5, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P2	1878138.7	345839.8	648.7	1.160	1.200	-3.38			
TW1P3	1877972.7	345812.5	648.4	1.155	1.180	-2.05			
TW1P4Z1	1877766.1	345652.5	692.0	1.153	1.158	-0.46			
TW1P4Z2	1877685.6	345800.1	657.0	1.152	1.159	-0.68	1.155	1.174	-1.66
TW2P2	1878494.5	343593.5	675.9	1.151	1.181	-2.53			
TW2P3	1878414.7	343618.3	679.9	1.152	1.182	-2.57			
TW2P4	1878237.5	343582.5	698.6	1.151	1.183	-2.73	1.151	1.182	-2.61
WELW	1870372.9	334581.1	692.0	1.149	1.173	-2.04			
TW3P2	1870323.5	334702.2	698.7	1.150	1.178	-2.35			
TW3P4	1870037.3	334949.0	673.4	1.151	1.182	-2.68			
TW3P5	1869929.7	335169.1	697.9	1.150	1.182	-2.67	1.150	1.179	-2.44

Comparison between measured and predicted TDG on May 14, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P1Z1	1878593.6	345704.7	692.0	1.155	1.167	-1.00			
TW1P1Z2	1878511.2	345814.2	669.1	1.159	1.167	-0.67			
TW1P2	1878138.7	345839.8	648.7	1.170	1.181	-0.96			
TW1P3	1877972.7	345812.5	648.4	1.176	1.187	-0.91			
TW1P4Z1	1877766.1	345652.5	692.0	1.173	1.163	0.88			
TW1P4Z2	1877685.6	345800.1	657.0	1.166	1.168	-0.21	1.167	1.172	-0.48
TW2P1	1878645.0	343552.6	675.6	1.162	1.167	-0.43			
TW2P2	1878494.5	343593.5	675.9	1.162	1.170	-0.71			
TW2P3	1878414.7	343618.3	679.9	1.163	1.175	-1.05			
TW2P4	1878237.5	343582.5	698.6	1.164	1.180	-1.38	1.163	1.173	-0.89
WELW	1870372.9	334581.1	692.0	1.163	1.151	1.01			
TW3P2	1870323.5	334702.2	698.7	1.162	1.165	-0.28			
TW3P3	1870104.4	334818.9	679.0	1.163	1.164	-0.12			
TW3P4	1870037.3	334949.0	673.4	1.164	1.173	-0.80			
TW3P5	1869929.7	335169.1	697.9	1.164	1.170	-0.48	1.163	1.165	-0.14

Comparison between measured and predicted TDG on May 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1-1S	1878593.6	345704.7	692.0	1.147	1.163	-1.38			
TW 1-1	1878511.2	345814.2	669.1	1.156	1.161	-0.44			
TW 1-2	1878138.7	345839.8	648.7	1.183	1.166	1.45			
TW 1-3	1877972.7	345812.5	648.4	1.188	1.173	1.21			
TW1-4S	1877766.1	345652.5	692.0	1.177	1.149	2.47			
TW 1-4	1877685.6	345800.1	657.0	1.168	1.153	1.30	1.170	1.161	0.77
TW 2-2	1878494.5	343593.5	675.9	1.168	1.168	0.01			
TW 2-3	1878414.7	343618.3	679.9	1.171	1.172	-0.11			
TW 2-4	1878237.5	343582.5	698.6	1.167	1.167	0.04	1.169	1.169	-0.02
WELW	1870372.9	334581.1	692.0	1.165	1.153	1.05			
TW 3-2	1870323.5	334702.2	698.7	1.166	1.164	0.15			
TW 3-3	1870104.4	334818.9	679.0	1.167	1.162	0.47			
TW 3-4	1870037.3	334949.0	673.4	1.168	1.169	-0.11			
TW 3-5	1869929.7	335169.1	697.9	1.168	1.161	0.59	1.167	1.162	0.43

Comparison between measured and predicted TDG on June 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average error %
TW1P1Z1	1878593.6	345704.7	692.0	1.188	1.256	-5.39			
TW1P2	1878138.7	345839.8	648.7	1.398	1.282	12.97			
TW1P3	1877972.7	345812.5	648.4	1.343	1.260	6.57			
TW1P4Z1	1877766.1	345652.5	692.0	1.284	1.217	5.54			
TW1P4Z2	1877685.6	345800.1	657.0	1.259	1.222	3.03	1.305	1.247	4.58
TW2P2	1878494.5	343593.5	675.9	1.261	1.261	-0.02			
TW2P3	1878414.7	343618.3	679.9	1.265	1.261	0.34			
TW2P4	1878237.5	343582.5	698.6	1.265	1.233	2.58	1.264	1.252	0.95
WELW	1870372.9	334581.1	692.0	1.256	1.243	1.06			
TW3P2	1870323.5	334702.2	698.7	1.264	1.249	1.16			
TW3P4	1870037.3	334949.0	673.4	1.268	1.248	1.58			
TW3P5	1869929.7	335169.1	697.9	1.269	1.238	2.53	1.264	1.245	1.58

MR1

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.169	
TW1P1Z2	1878511.2	345814.2	669.1	1.162	
TW1P2	1878138.7	345839.8	648.7	1.174	
TW1P3	1877972.7	345812.5	648.4	1.168	
TW1P4Z1	1877766.1	345652.5	692.0	1.182	
TW1P4Z2	1877685.6	345800.1	657.0	1.182	1.173
TW2P1	1878645.0	343552.6	675.6	1.170	
TW2P2	1878494.5	343593.5	675.9	1.176	
TW2P3	1878414.7	343618.3	679.9	1.187	
TW2P4	1878237.5	343582.5	698.6	1.190	1.181
WELW	1870372.9	334581.1	692.0	1.172	
TW3P2	1870323.5	334702.2	698.7	1.175	
TW3P3	1870104.4	334818.9	679.0	1.180	
TW3P4	1870037.3	334949.0	673.4	1.183	
TW3P5	1869929.7	335169.1	697.9	1.185	1.179

MR2

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.203	
TW1P1Z2	1878511.2	345814.2	669.1	1.180	
TW1P2	1878138.7	345839.8	648.7	1.240	
TW1P3	1877972.7	345812.5	648.4	1.246	
TW1P4Z1	1877766.1	345652.5	692.0	1.273	
TW1P4Z2	1877685.6	345800.1	657.0	1.278	1.237
TW2P1	1878645.0	343552.6	675.6	1.217	
TW2P2	1878494.5	343593.5	675.9	1.232	
TW2P3	1878414.7	343618.3	679.9	1.247	
TW2P4	1878237.5	343582.5	698.6	1.266	1.241
WELW	1870372.9	334581.1	692.0	1.219	
TW3P2	1870323.5	334702.2	698.7	1.223	
TW3P3	1870104.4	334818.9	679.0	1.234	
TW3P4	1870037.3	334949.0	673.4	1.244	
TW3P5	1869929.7	335169.1	697.9	1.264	1.237

MR3

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.246	
TW1P1Z2	1878511.2	345814.2	669.1	1.247	
TW1P2	1878138.7	345839.8	648.7	1.232	
TW1P3	1877972.7	345812.5	648.4	1.193	
TW1P4Z1	1877766.1	345652.5	692.0	1.181	
TW1P4Z2	1877685.6	345800.1	657.0	1.182	1.213
TW2P1	1878645.0	343552.6	675.6	1.227	
TW2P2	1878494.5	343593.5	675.9	1.216	
TW2P3	1878414.7	343618.3	679.9	1.201	
TW2P4	1878237.5	343582.5	698.6	1.185	1.207
WELW	1870372.9	334581.1	692.0	1.214	
TW3P2	1870323.5	334702.2	698.7	1.214	
TW3P3	1870104.4	334818.9	679.0	1.206	
TW3P4	1870037.3	334949.0	673.4	1.203	
TW3P5	1869929.7	335169.1	697.9	1.197	1.207

MR4

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.297	
TW1P1Z2	1878511.2	345814.2	669.1	1.295	
TW1P2	1878138.7	345839.8	648.7	1.262	
TW1P3	1877972.7	345812.5	648.4	1.230	
TW1P4Z1	1877766.1	345652.5	692.0	1.248	
TW1P4Z2	1877685.6	345800.1	657.0	1.248	1.263
TW2P1	1878645.0	343552.6	675.6	1.258	
TW2P2	1878494.5	343593.5	675.9	1.244	
TW2P3	1878414.7	343618.3	679.9	1.237	
TW2P4	1878237.5	343582.5	698.6	1.243	1.245
WELW	1870372.9	334581.1	692.0	1.251	
TW3P2	1870323.5	334702.2	698.7	1.251	
TW3P3	1870104.4	334818.9	679.0	1.247	
TW3P4	1870037.3	334949.0	673.4	1.244	
TW3P5	1869929.7	335169.1	697.9	1.239	1.247

MR5

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.158	
TW1P1Z2	1878511.2	345814.2	669.1	1.157	
TW1P2	1878138.7	345839.8	648.7	1.171	
TW1P3	1877972.7	345812.5	648.4	1.163	
TW1P4Z1	1877766.1	345652.5	692.0	1.155	
TW1P4Z2	1877685.6	345800.1	657.0	1.157	1.160
TW2P1	1878645.0	343552.6	675.6	1.168	
TW2P2	1878494.5	343593.5	675.9	1.172	
TW2P3	1878414.7	343618.3	679.9	1.170	
TW2P4	1878237.5	343582.5	698.6	1.163	1.168
WELW	1870372.9	334581.1	692.0	1.1672	
TW3P2	1870323.5	334702.2	698.7	1.16764	
TW3P3	1870104.4	334818.9	679.0	1.1681	
TW3P4	1870037.3	334949.0	673.4	1.16751	
TW3P5	1869929.7	335169.1	697.9	1.16264	1.167

MR6

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.208	
TW1P1Z2	1878511.2	345814.2	669.1	1.205	
TW1P2	1878138.7	345839.8	648.7	1.221	
TW1P3	1877972.7	345812.5	648.4	1.217	
TW1P4Z1	1877766.1	345652.5	692.0	1.205	
TW1P4Z2	1877685.6	345800.1	657.0	1.211	1.211
TW2P1	1878645.0	343552.6	675.6	1.213	
TW2P2	1878494.5	343593.5	675.9	1.215	
TW2P3	1878414.7	343618.3	679.9	1.216	
TW2P4	1878237.5	343582.5	698.6	1.213	1.214
WELW	1870372.9	334581.1	692.0	1.212	
TW3P2	1870323.5	334702.2	698.7	1.213	
TW3P3	1870104.4	334818.9	679.0	1.214	
TW3P4	1870037.3	334949.0	673.4	1.214	
TW3P5	1869929.7	335169.1	697.9	1.212	1.213

MR7

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.193	
TW1P1Z2	1878511.2	345814.2	669.1	1.192	
TW1P2	1878138.7	345839.8	648.7	1.191	
TW1P3	1877972.7	345812.5	648.4	1.165	
TW1P4Z1	1877766.1	345652.5	692.0	1.155	
TW1P4Z2	1877685.6	345800.1	657.0	1.156	1.175
TW2P1	1878645.0	343552.6	675.6	1.181	
TW2P2	1878494.5	343593.5	675.9	1.176	
TW2P3	1878414.7	343618.3	679.9	1.168	
TW2P4	1878237.5	343582.5	698.6	1.159	1.171
WELW	1870372.9	334581.1	692.0	1.178	
TW3P2	1870323.5	334702.2	698.7	1.178	
TW3P3	1870104.4	334818.9	679.0	1.173	
TW3P4	1870037.3	334949.0	673.4	1.171	
TW3P5	1869929.7	335169.1	697.9	1.167	1.173

MR8

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.180	
TW1P1Z2	1878511.2	345814.2	669.1	1.178	
TW1P2	1878138.7	345839.8	648.7	1.194	
TW1P3	1877972.7	345812.5	648.4	1.248	
TW1P4Z1	1877766.1	345652.5	692.0	1.227	
TW1P4Z2	1877685.6	345800.1	657.0	1.243	1.212
TW2P1	1878645.0	343552.6	675.6	1.210	
TW2P2	1878494.5	343593.5	675.9	1.223	
TW2P3	1878414.7	343618.3	679.9	1.244	
TW2P4	1878237.5	343582.5	698.6	1.241	1.230
WELW	1870372.9	334581.1	692.0	1.214	
TW3P2	1870323.5	334702.2	698.7	1.218	
TW3P3	1870104.4	334818.9	679.0	1.227	
TW3P4	1870037.3	334949.0	673.4	1.233	
TW3P5	1869929.7	335169.1	697.9	1.236	1.226

MR9

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.213	
TW1P1Z2	1878511.2	345814.2	669.1	1.212	
TW1P2	1878138.7	345839.8	648.7	1.218	
TW1P3	1877972.7	345812.5	648.4	1.244	
TW1P4Z1	1877766.1	345652.5	692.0	1.217	
TW1P4Z2	1877685.6	345800.1	657.0	1.228	1.222
TW2P1	1878645.0	343552.6	675.6	1.232	
TW2P2	1878494.5	343593.5	675.9	1.233	
TW2P3	1878414.7	343618.3	679.9	1.230	
TW2P4	1878237.5	343582.5	698.6	1.223	1.229
WELW	1870372.9	334581.1	692.0	1.231	
TW3P2	1870323.5	334702.2	698.7	1.231	
TW3P3	1870104.4	334818.9	679.0	1.230	
TW3P4	1870037.3	334949.0	673.4	1.229	
TW3P5	1869929.7	335169.1	697.9	1.224	1.229

POD-7Q10 Simulation

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	Average predicted
TW1P1Z1	1878593.6	345704.7	692.0	1.189	
TW1P1Z2	1878511.2	345814.2	669.1	1.188	
TW1P2	1878138.7	345839.8	648.7	1.202	
TW1P3	1877972.7	345812.5	648.4	1.199	
TW1P4Z1	1877766.1	345652.5	692.0	1.182	
TW1P4Z2	1877685.6	345800.1	657.0	1.189	1.192
TW2P1	1878645.0	343552.6	675.6	1.198	
TW2P2	1878494.5	343593.5	675.9	1.200	
TW2P3	1878414.7	343618.3	679.9	1.202	
TW2P4	1878237.5	343582.5	698.6	1.197	1.199
WELW	1870372.9	334581.1	692.0	1.198	
TW3P2	1870323.5	334702.2	698.7	1.198	
TW3P3	1870104.4	334818.9	679.0	1.199	
TW3P4	1870037.3	334949.0	673.4	1.199	
TW3P5	1869929.7	335169.1	697.9	1.194	1.198

Politano, M., A. Arenas Amado, and L. Weber. 2008. An Investigation into the Total Dissolved Gas Dynamics of the Wells Project (Total Dissolved Gas Investigation): Wells Hydroelectric Project, FERC No. 2149. Initial Study Report required by FERC. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA.

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AN INVESTIGATION INTO THE TOTAL DISSOLVED GAS DYNAMICS OF THE WELLS PROJECT
(Total Dissolved Gas Investigation)

WELLS HYDROELECTRIC PROJECT

FERC NO. 2149

INTERIM REPORT
REQUIRED BY FERC

September 2008

Prepared by:
M. Politano, A. Arenas Amado and L. Weber
IIHR-Hydroscience & Engineering
The University of Iowa
300 South Riverside Drive
Iowa City, Iowa 52242-1585

Prepared for:
Public Utility District No. 1 of Douglas County
East Wenatchee, Washington

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For copies of this Study Report, contact:

Public Utility District No. 1 of Douglas County
Attention: Relicensing
1151 Valley Mall Parkway
East Wenatchee, WA 98802-4497
Phone: (509) 884-7191
E-Mail: relicensing@dcpud.org

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ABSTRACT

The current Wells Hydroelectric Project (Wells Project) license will expire on May 31, 2012. As part of the Wells Project relicensing process, the Public Utility District No. 1 of Douglas County (Douglas PUD) is required to obtain a water quality certificate pursuant to Section 401 of the Clean Water Act. As part of the 401 certification process, the Washington State Department of Ecology (Ecology) must determine whether the Wells Project is in compliance with state water quality standards, including the numeric standards, for total dissolved gas (TDG).

Douglas PUD examined TDG production dynamics at the Wells Project to comply with State water quality standards (WQS). As part of the relicensing of the Wells Project, Douglas PUD has initiated a series of assessments aimed at gaining a better understanding of the effect of spill operations on the production, transport and mixing of TDG in the Wells Dam tailrace.

The primary goal of this study was to develop an unsteady three-dimensional (3D) two-phase flow computational fluid dynamics (CFD) tool to predict the hydrodynamics and TDG distribution within the Wells tailrace. Two models were used in the study; a volume of fluid (VOF) model and a rigid-lid two-phase flow model.

The VOF model predicts the flow regime and the free-surface characteristics, recognizing that a spillway jet may plunge to depth in the tailrace or remain closer to the surface depending upon the geometry of the outlet and the tailwater elevation. The VOF model boundary extended approximately 1,700 ft downstream of the dam.

The rigid-lid model included 16,500 ft of the Wells tailrace, from Wells Dam downstream to the TDG compliance monitoring station. This two-phase flow model characterizes the hydrodynamics and three-dimensional distribution of gas volume fraction, bubble size and TDG in the Wells tailrace. This model assumes that the free surface can be modeled using a rigid-lid non-flat boundary condition. The free-surface shape for the first 1,000 feet downstream of the dam was extracted from VOF computations and slopes derived from HEC-RAS simulations were used for the downstream region. The upstream velocity profiles derived from the VOF model were input to the rigid-lid model. The gas volume fraction and bubble diameter at the spillbays are the external parameters of the model.

The model was calibrated and validated using field data collected in 2006 during a TDG production dynamics study (EES et al. 2007). The model was then calibrated using data collected during spill tests conducted on June 4 and June 5, 2006. The spillway flow was spread across spillbays on June 4 and concentrated through a single spillbay on June 5. Agreement was attained between the depth-averaged velocity data collected in the field and those generated by the model. A gas volume fraction of 3% and bubble diameter of 0.5 mm in the spillbays produced TDG values that bracketed the 2006 field observations.

Once calibrated, the predictive ability of the model was validated by running the model for three different operational conditions tested in 2006. The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The numerical results demonstrate that the model provides a reliable predictor of tailrace TDG and therefore can be

used as a tool to identify Project operations that can minimize TDG concentrations downstream of Wells Dam.

1.0 INTRODUCTION

1.1 General Description of the Wells Hydroelectric Project

The Wells Hydroelectric Project (Wells Project) is located at river mile (RM) 515.6 on the Columbia River in the State of Washington (Figure 1.1-1). Wells Dam is located approximately 30 river miles downstream from the Chief Joseph Hydroelectric Project, owned and operated by the United States Army Corps of Engineers (COE), and 42 miles upstream from the Rocky Reach Hydroelectric Project, owned and operated by Public Utility District No. 1 of Chelan County (Chelan PUD). The nearest town is Pateros, Washington, which is located approximately 8 miles upstream from the Wells Dam.

The Wells Project is the chief generating resource for the Public Utility District No. 1 of Douglas County (Douglas PUD). It includes ten generating units with a nameplate rating of 774,300 kW and a peaking capacity of approximately 840,000 kW. The design of the Wells Project is unique in that the generating units, spillways, switchyard, and fish passage facilities were combined into a single structure referred to as the hydrocombine. Fish passage facilities reside on both sides of the hydrocombine, which is 1,130 feet long, 168 feet wide, with a crest elevation of 795 feet msl.

The Wells Reservoir is approximately 30 miles long. The Methow and Okanogan rivers are tributaries of the Columbia River within the Wells Reservoir. The Wells Project boundary extends approximately 1.5 miles up the Methow River and approximately 15.5 miles up the Okanogan River. The surface area of the reservoir is 9,740 acres with a gross storage capacity of 331,200 acre-feet and usable storage of 97,985 acre feet at the normal maximum water surface elevation of 781 above mean sea level (msl) (Figure 1.1-1).

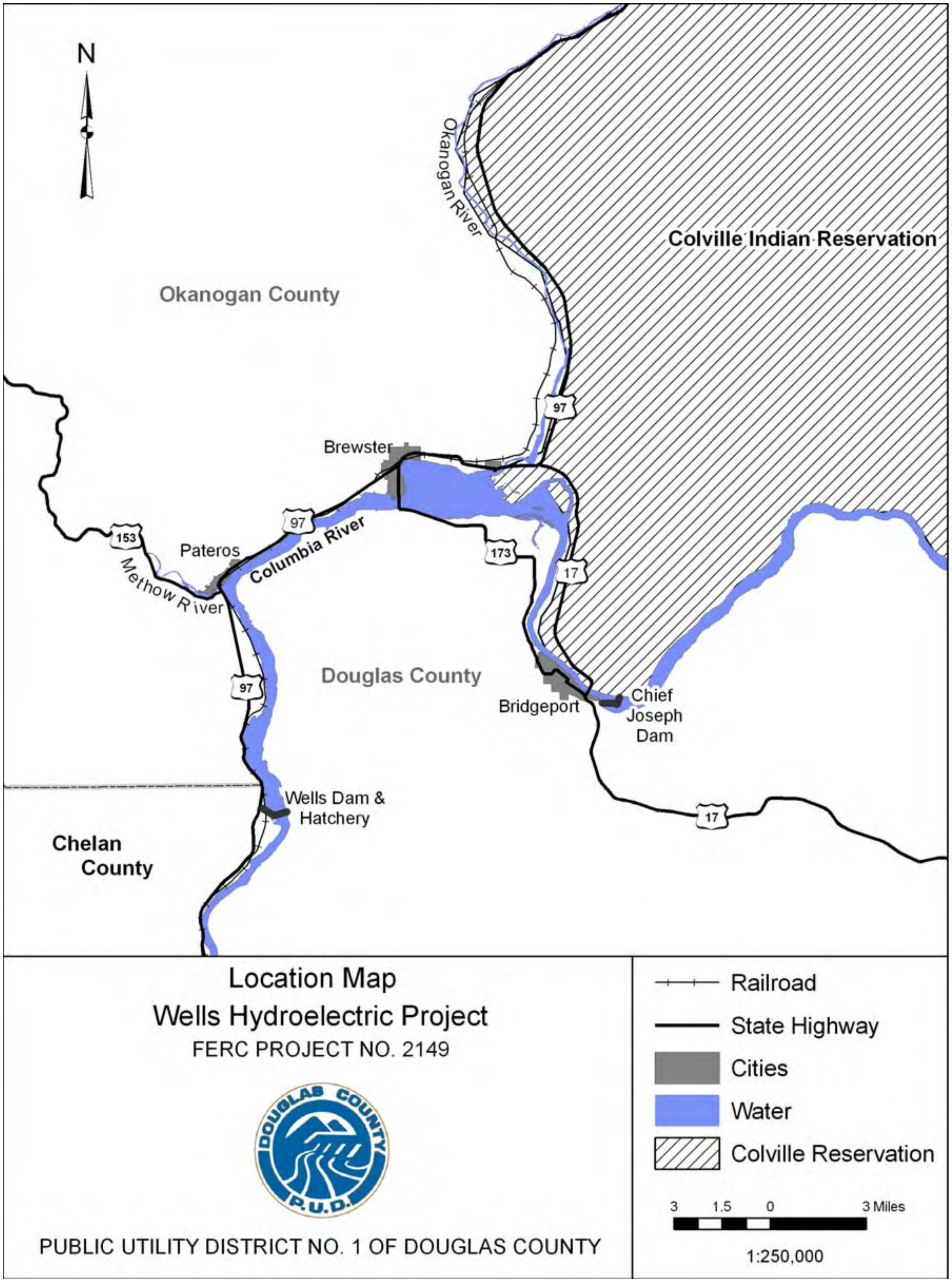

Figure 1.1-1 Location Map of the Wells Hydroelectric Project.

1.2 Relicensing Process

The current Wells Project license will expire on May 31, 2012. Douglas PUD is using the Integrated Licensing Process (ILP) promulgated by Federal Energy Regulatory Commission (FERC) Order 2002 (18 CFR Part 5). Stakeholders consisting of representatives from state and federal agencies, tribes, local governments, non-governmental organizations and the general public have participated in the Wells Project ILP, from a very early stage, to identify information needs related to the relicensing of the Wells Project.

In August 2005, Douglas PUD initiated a series of Resource Work Group (RWG) meetings with stakeholders regarding the upcoming relicensing of the Wells Project. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to identify resource issues and to develop preliminary study plans prior to filing the Notice of Intent (NOI) and Pre-Application Document (PAD). The RWGs were formed to discuss issues related to the Wells Project and its operations.

The primary goals of the RWGs were to identify resource issues and potential study needs in advance of Douglas PUD filing the NOI and PAD. Through 35 meetings, each RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWG's efforts to apply FERC's seven study criteria to mutually determine the applicability of each individual Issue Statement. Agreed-Upon Study Plans are the finished products of the informal RWG process.

Douglas PUD submitted the NOI and PAD to FERC on December 1, 2006. The PAD included the RWGs' 12 Agreed-Upon Study Plans. The filing of these documents initiated the relicensing process for the Wells Project under FERC's regulations governing the ILP.

On May 16, 2007, Douglas PUD submitted a Proposed Study Plan (PSP) Document. The PSP Document consisted of the Applicant's Proposed Study Plans, Responses to Stakeholder Study Requests and a schedule for conducting the Study Plan Meeting. The ILP required Study Plan Meeting was conducted on June 14, 2007. The purpose of the Study Plan Meeting was to provide stakeholders with an opportunity to review and comment on Douglas PUD's PSP Document, to review and answer questions related to stakeholder study requests and to attempt to resolve any outstanding issues with respect to the PSP Document.

On September 14, 2007, Douglas PUD submitted a Revised Study Plan (RSP) Document. The RSP Document consisted of a summary of each of Douglas PUD's revised study plans and a response to stakeholder PSP Document comments.

On October 11, 2007, FERC issued its Study Plan Determination based on its review of the RSP Document and comments from stakeholders. FERC's Study Plan Determination required Douglas PUD to complete 10 of the 12 studies included in its RSP Document. Douglas PUD has opted to complete all 12 studies to better prepare for the 401 Water Quality Certification process conducted by the Washington State Department of Ecology and to fulfill its commitment to the RWGs who collaboratively developed the 12 Agreed-Upon Study Plans with Douglas PUD.

These study plans have been implemented during the designated ILP study period. The results from the study plans have been developed into 12 Study Reports. Each report is included in Douglas PUD's Initial Study Report (ISR) Document, which is scheduled for filing with FERC on October 15, 2008.

This interim report provides initial results from the Total Dissolved Gas Investigation. Additional modeling efforts are still underway. The final report will be completed and available to the public in early 2009.

There were no variances from the FERC approved study plan for the Total Dissolved Gas Investigation.

1.3 Overview of Total Dissolved Gas at Wells Dam

The Columbia and Snake river basins are the most productive sources of hydropower in the United States. The Wells Dam, which is owned and operated by Douglas PUD, is located at RM 515.6 on the Columbia River, Washington (Figure 1.3-1). The spillway gates at Wells Dam are used to pass water when river flows exceed the maximum powerhouse capacity (forced spill), to assist outmigration of juvenile salmonids (fish bypass spill), and to prevent flooding along the mainstem Columbia River (flood control spill). Forced spill occurs when the total flow is in excess of the powerhouse hydraulic capacity. The Wells Project can pass 20.5 kcfs through each operating turbine (184.5 kcfs in 9 turbines) with an additional 10.0 kcfs used to operate the juvenile fish bypass system and 1.0 kcfs to operate the adult fish ladders. Therefore, spill is forced when the inflows are higher than 195.5 kcfs. Spill may occur at flows less than the hydraulic capacity when the volume of water is greater than the amount required to meet electric power system loads. Hourly coordination among hydroelectric projects on the mid-Columbia River was established to minimize the latter situation for spill.

Wells Dam is a hydrocombine-designed dam with the spillway situated directly above the powerhouse. Research at Wells Dam in the mid-1980s showed that a modest amount of spill would effectively guide between 92 percent and 96 percent of the downstream migrating juvenile salmonids through the Juvenile Bypass System (JBS) and away from the turbines. The operation of the Wells JBS utilizes five spillways that have been modified with constricting barriers to improve the attraction flow while using modest levels of water (Klinge 2005). The JBS will typically use approximately 6-8 percent of the total river flow for fish guidance. The high level of fish protection at Wells Dam has won the approval of the fisheries agencies and tribes and was vital to the recently approved Anadromous Fish Agreement and Habitat Conservation Plan (HCP).

State of Washington water quality standards require TDG levels to not exceed 110% at any point of measurement. Due to air entrainment in the plunge pools below spillways, TDG levels can sometimes exceed the State's standard during spill events at dams. The exceptions to the State's standard when levels are allowed to be exceeded are (1) to pass flood flows at the Project and (2) to pass voluntary spill to assist out migrating juvenile salmonids. The 7Q10 flood flow, which is defined as the highest average flow that occurs for seven consecutive days in a once-in-ten-year period, is 246 kcfs at the Wells Project. Considering that 175.5 kcfs can be passed through nine of the ten turbines at Wells, 10 kcfs through the juvenile fish bypass system and 1 kcfs in the fishway, spillway bays must pass 59.5 kcfs in the 7Q10 flood flow.

Figure 1.3-1 Map of Washington showing the location of the Wells Dam

2.0 GOALS AND OBJECTIVES

The goal of this study is to develop a numerical model capable of predicting the hydrodynamics and TDG concentrations in the tailrace of the Wells Project. The purpose of the model is to assist in the understanding of the underlying phenomena leading to TDG supersaturation allowing the evaluation of the effectiveness of spill type and plant operations in reducing TDG production at Wells Dam.

3.0 STUDY AREA

The study area includes approximately 16,500 ft of the Wells tailrace, extending from Wells Dam downstream to transect TW3 (Transect T3) (Figure 3.0-1). Transect TW3 coincides with the TDG compliance monitoring station.

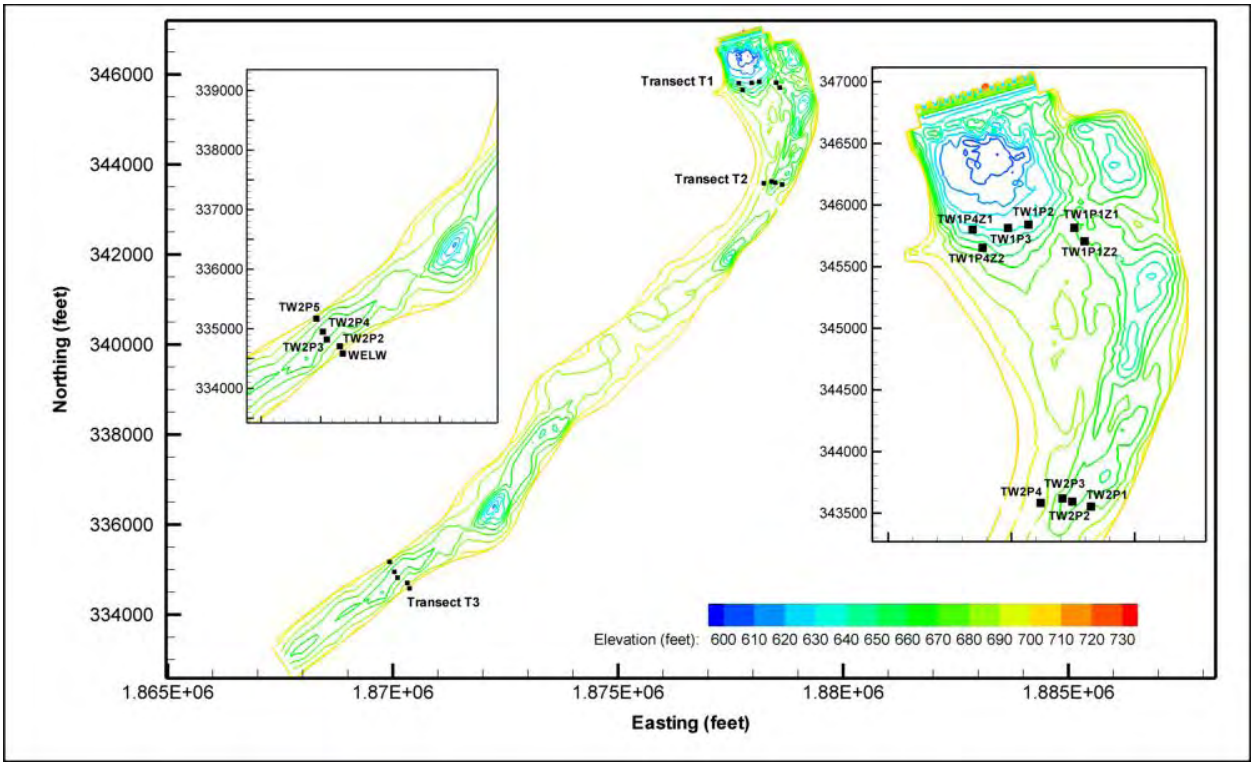

Figure 3.0-1 **Study Area for the TDG model**

4.0 BACKGROUND AND EXISTING INFORMATION

4.1 Summary of TDG studies in the Wells Tailrace

Douglas PUD conducted a series of assessments aimed at gaining a better understanding of TDG production dynamics resulting from spill operations at Wells Dam. Each year from 2003 to 2008, Douglas PUD has performed experimental spill operations to understand the relationship between water spilled over the dam and the production of TDG.

In 2003 and 2004, Columbia Basin Environmental (CBE) deployed TDG sensors along two transects downstream of Wells Dam. The objectives of this study were to determine the effectiveness of the tailwater sensor and better understand the relationship between spillway releases and TDG production (CBE 2003, 2004). In a two-week period, the studies showed that the tailwater station provided a reliable record of daily average TDG values in the Wells Dam tailrace.

In spring 2005, Douglas PUD conducted a study to measure TDG pressures resulting from various spill patterns at Wells Dam (CBE, 2006). An array of water quality data loggers was installed in the Well tailrace for a period of two weeks between May 23, 2005 and June 6, 2005. The Wells powerhouse and spillway were operated through a controlled range of operational scenarios that varied both total flow and allocation of the spillway discharge. A total of eight configurations were tested including flat spill patterns (near equal distribution of spill across the entire spillway), crowned spill patterns (spill is concentrated towards the center of the spillway), and spill over loaded and unloaded generating units. Results from the study indicated that spill from the west side of the spillway resulted in consistently higher TDG saturations than similar spill from the east side. Flat spill patterns yielded higher TDG saturations than crowned spill for similar total discharges. The results of this study also indicated that TDG levels of powerhouse flows may be influenced by spill.

In 2006, Douglas PUD continued TDG assessments at the Wells Project by examining alternative spill configurations and project operations to minimize the production of TDG. The purpose of the 2006 study was to evaluate how the Project could be operated to successfully pass the 7Q10 river flow while remaining in compliance with Washington State TDG standards. Thirteen sensors were placed along transects in the tailrace located at 1,000, 2,500 and 15,000 feet below Wells Dam. There were also three sensors placed across the forebay. The sensors were programmed to collect data in 15 minute intervals for both TDG and water temperature. Each test required the operations of the dam to maintain stable flows through the powerhouse and spillway for at least a three hour period. While there were 30 scheduled spill events, there were an additional 50 events where the powerhouse and spillway conditions were held constant for a minimum three hour period. These additional events provided an opportunity to collect TDG data on a variety of Project operations that met study criteria. These are included in the results of the 2006 TDG Abatement Study (EES et al., 2007). Spill amounts ranged from 5.2 to 52.0% of project flow and flows ranged from 2.2 to 124.7 kcfs for spill and 16.4 to 254.0 kcfs for total discharge. There were six tests that were performed at flows that exceeded the Wells Dam 7Q10 flows of 246 kcfs. Results of the study indicated that two operational scenarios, spread spill and concentrated spill (spill from 1 or 2 gates), produced the lowest levels of TDG. The 2006 study also indicated that the current location of the tailwater TDG compliance monitoring station is appropriate in providing representative TDG production information both longitudinally and laterally downstream of Wells Dam.

4.2 Numerical studies of TDG in Tailraces

Early studies to predict TDG below spillways were based on experimental programs and physical models (Hibbs and Gulliver 1997; Orlins and Gulliver 2000). The primary shortcoming of this approach is that the laboratory models cannot quantitatively predict the change in TDG due to model scaling issues. The approach relies on performance curves that relate flow conditions with past field experiences. This has led to inconsistent results at hydroelectric projects, some being quite successful while others less successful.

Computational fluid dynamics (CFD) modeling offers a powerful tool for TDG and hydrodynamics prediction. In the application to powerhouse/spillway flows, an understanding of the underlying physics and the capability to model three-dimensional physical phenomena is of paramount importance in performing reliable numerical studies. The most important source of TDG production is the gas transfer from the entrained bubbles, therefore a TDG predictive model must account for the two-phase flow in the stilling basin and the mass transfer between bubbles and water.

The TDG concentration depends on complex processes such as air entrainment in the spillway (pre-entrainment), entrainment when the jet impacts the tailwater pool, breakup and coalescence of entrained bubbles, mass transfer between bubbles and water, degasification at the free surface, and bubble and TDG transport. In addition, tailrace flows in the region near the spillway cannot be assumed to have a flat air/water interface which results in the required computation of the free surface shape. Moreover, it has been demonstrated that surface jets may cause a significant change in the flow pattern since they attract water toward the jet region, a phenomenon referred to as water entrainment (Liepmann 1990; Walker and Chen 1994; Walker 1997). Water entrainment leads to mixing and modification of the TDG field. As an additional complexity, the presence of bubbles has a strong effect on water entrainment. Bubbles reduce the density (and pressure) and effective viscosity in the spillway region and affect the liquid turbulence.

Free surface models can predict the shape and development of the free surface and, though costly, have feasible application to complex three dimensional (3D) flows. In the field of hydraulic engineering, free surface models are not yet widely applied but are steadily developing (Turan et al., 2008; Ferrari et. al., 2008). However, direct simulation of individual bubbles in a spillway/tailrace environment is well beyond current computer capabilities. Therefore, a two-fluid model with space-time averaged quantities that do not resolve the interface is needed to model the effect of the bubbles on the flow field and bubble dissolution. Numerical simulations of two phase flows using two-fluid models have been extensively used, mainly in the chemical and nuclear engineering community. Jakobsen et al. (2005) provided an extensive review of the state-of-the-art of two-phase flow modeling. Politano et al. (2007a) used a two-dimensional (2D) two-fluid model assuming isotropic turbulence to predict the gas distribution and TDG concentration in a cross-section passing through a spillway bay at Wanapum Dam. The model was compared against field data measured before deflector installation. The model allowed examination of the effect of the bubble size on TDG concentration. However, 2D simulations cannot capture the water entrainment caused by deflectors and therefore the TDG dilution due to powerhouse flows could not be predicted with the model. Turan et al. (2007) conducted the first numerical study to predict the hydrodynamics and water entrainment in a hydropower tailrace. The authors used an anisotropic mixture model that accounts for the gas volume fraction and attenuation of normal fluctuations at the free surface. Politano et al. (2007b) used an anisotropic mixture model for the 3D prediction of the two phase flow and TDG in the tailrace of Wanapum Dam. The simulations captured the measured water entrainment in the tailrace of Wanapum Dam. In this study, quantitative agreement between predicted and measured TDG was obtained for two different operational conditions.

4.3 Aquatic Resource Work Group

As part of the relicensing process for the Wells Project, Douglas PUD established an Aquatic Resource Work Group (Aquatic RWG) which began meeting informally in November, 2005. This voluntary effort was initiated to provide stakeholders with information about the Wells Project, to collaboratively identify potential resource issues related to Project operations and relevant to relicensing, and to develop preliminary study plans to be included in the Wells Pre-Application Document (PAD) (DCPUD, 2006).

Through a series of meetings, the Aquatic RWG cooperatively developed a list of Issue Statements, Issue Determination Statements and Agreed-Upon Study Plans. An Issue Statement is an agreed-upon definition of a resource issue raised by a stakeholder. An Issue Determination Statement reflects the RWGs' efforts to review the existing project information and to determine whether an issue matches with FERC's seven criteria and would be useful in making future relicensing decisions. Agreed-Upon Study Plans are the finished products of the informal RWG process.

Based upon these meetings and discussions, the Aquatic RWG proposed to conduct studies of the TDG dynamics of Wells Dam. The need for this study was agreed to by all members of the Aquatic RWG, including Douglas PUD. These studies are intended to inform future relicensing decisions, including the water quality certification process and will fill data gaps that have been identified by the Aquatic RWG.

The Issue Statement and Issue Determination Statement listed below were included in the PAD (section number included) filed with FERC on December 1, 2006:

4.3.1 Issue Statement (PAD Section 6.2.1.5)

Wells Dam may affect compliance with Total Dissolved Gas (TDG) standards in the Wells tailrace and Rocky Reach forebay.

4.3.2 Issue Determination Statement (PAD Section 6.2.1.5)

Wells Dam can have an effect on compliance with the TDG standard. The resource work group believes that additional information is necessary in the form of continued monitoring and that these data will be meaningful with respect to the State 401 Water Quality Certification process. Douglas PUD has been implementing studies at Wells Dam to address TDG production dynamics.

4.4 Project Nexus

TDG concentrations may become a water quality concern when gases supersaturate a river, lake or stream. The plunging water caused by spill at hydroelectric facilities may elevate TDG to levels that may result in impaired health or even death for aquatic life residing or migrating within the affected area.

The Washington State Department of Ecology (Ecology) is responsible for the protection and restoration of the state’s waters. Ecology has adopted water quality standards that set limits on pollution in lakes, rivers, and marine waters in order to protect water quality. On July 1, 2003, Ecology completed the first major overhaul of the state’s water quality standards in a decade. A significant revision presented in the 2003 water quality standards classifies fresh water by actual use, rather than by class as was done in the 1997 standards. These revisions were adopted in order to make the 2003 standards less complicated to interpret and provide future flexibility as the uses of a water body evolve.

The applicable water quality standard for TDG for the Columbia River at hydroelectric projects states:

- Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.

However, as discussed in Section 4.0, an exception to the above standard is allowed to aid fish passage over hydroelectric dams when it is determined that this action is consistent with an Ecology-approved gas abatement plan. The information collected during this study will assist Douglas PUD in operating the Wells Project in a manner that minimizes TDG in the Wells tailrace and Rocky Reach forebay.

5.0 METHODOLOGY

5.1 Simulation Conditions

The performance of the model to predict the TDG distribution and hydrodynamics was evaluated using field data collected for a period of six weeks between May 14, 2006 and June 28, 2006, during the TDG production dynamics study (EES et al., 2007). Velocities were measured on three transects in the near field region of the Wells tailrace on June 4, 2006 and June 5, 2006. Figure 3.0-1 shows the 15 stations where TDG sensors were deployed during the field study.

5.1.1 Calibration

The model was calibrated against data collected on June 4 and June 5, 2006, referred to as treatments 46 and 47 in the report by EES et al. (2007). The spillway flow was spread across all spillbays on June 4 and concentrated in a single spillbay on June 5. Total river flows during these treatments were 172.4 kcfs and 222.3 kcfs, respectively. Tables 6.1-1 and 6.1-2 summarize plant operations, TDG saturation in the forebay, and tailwater elevation on these days. Powerhouse and spillway units are numbered from west to east.

Table 5.1-1 Conditions used for the numerical simulations of June 4, 2006

Treatment 46 S - June 4, 2006									
Tailwater Elevation: 717.3 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	14.7	14.7	14.4	14.7	14.7	14.8	14.8	14.4	14.7
Powerhouse Total: 131.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.6	5.4	5.2	5.4	5.2	5.4	5.2	5.4	1.6
Spillway Total: 40.6 kcfs									
Total River Flow: 172.4 kcfs									
Forebay TDG: 111.8%									

Table 5.1-2 Conditions used for the numerical simulations of June 5, 2006

Treatment 47 FG - June 5, 2006									
Tailwater Elevation: 720.2 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	18.0	18.5	18.3	19.0	20.2	19.6	19.9	18.2
Powerhouse Total: 170.6 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	42.5	2.2	0.0	1.3
Spillway Total: 51.7 kcfs									
Total River Flow: 222.3 kcfs									
Forebay TDG: 111.5%									

5.1.2 Numerical Model Validation

The predictive ability of the numerical model was validated using three different spillway conditions tested in 2006. The three spillway conditions are: treatment 1-Full Gate (FG); treatment 11-FG; and treatment 63-Concentrated (C). The FG designates the use of a single spill bay whereas C designates a crowned spill pattern. Plant operation and tailwater elevations associated with each of the treatments are tabulated on Tables 5.1-3 to 5.1-5.

Table 5.1-3 Conditions used for the numerical simulations of May 14, 2006

Treatment 1 FG - May 14, 2006									
Tailwater Elevation: 711.5 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	15.0	15.0	14.8	0.0	0.0	0.0	0.0	14.8	15.2
Powerhouse Total: 74.8 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.3	0.0	2.2	0.0	2.2	35.4	2.2	0.0	1.3
Spillway Total: 44.6 kcfs									
Total River Flow: 120.4 kcfs									
Forebay TDG: 109.1%									

Table 5.1-4 Conditions used for the numerical simulations of May 17, 2006

Treatment 11 FG - May 17, 2006									
Tailwater Elevation: 715.4 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	18.9	19.1	18.7	19.2	0.0	0.0	0.0	18.7	19.2
Powerhouse Total: 113.7 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	0.9	0.0	2.2	0.0	2.2	34.1	2.2	0.0	0.9
Spillway Total: 42.6 kcfs									
Total River Flow: 157.2 kcfs									
Forebay TDG: 110.4%									

Table 5.1-5 Conditions used for the numerical simulations of June 17, 2006

Treatment 63 C - June 17, 2006									
Tailwater Elevation: 718.6 ft									
Powerhouse Unit Discharge (kcfs)									
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
0.0	13.0	13.0	12.9	13.0	13.0	13.1	13.1	12.8	13.1
Powerhouse Total: 117.1 kcfs									
Spillway Unit Discharge (kcfs)									
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
0.0	1.7	0.0	2.2	0.0	2.2	29.8	19.9	29.8	1.7
Spillway Total: 87.4 kcfs									
Total River Flow: 205.5 kcfs									
Forebay TDG: 113.9%									

5.2 Model Overview

The models used in this study are based upon the general purpose CFD code FLUENT, which solves the discrete Reynolds Averaged Navier Stokes (RANS) equations using a cell centered finite volume scheme. Two models were used to predict the hydrodynamics and TDG distribution within the tailrace of the Wells Project: a volume of fluid (VOF) model and a rigid-lid non-flat lid model.

The VOF model predicted the flow regime and free-surface for the first 1,000 feet downstream of the dam. The free-surface shape was then used to generate a grid conformed to this geometry and fixed throughout the computation (rigid, non-flat lid approach). After the statistically-steady state was reached, the VOF solution that minimizes the difference between measured and predicted tailwater elevation was selected. Water surface elevations and local slopes derived from simulations using the Hydrologic Engineering Centers River Analysis System (HEC-RAS) were used at the downstream region of the model. The HEC-RAS computations were performed using geometric input files provided by Douglas PUD with a roughness coefficient of 0.035.

The rigid-lid model allowed proper assessment of water entrainment and TDG concentration. The model assumed one variable bubble size, which could change due to local bubble/water mass transfer and pressure. The air entrainment (gas volume fraction and bubble size) was assumed to be a known inlet boundary condition. It must be noted that the choice of bubble size and volume fraction at the spillway bays has an important effect on the level of entrainment and TDG distribution. In this study a reasonable single-size bubble diameter and volume fraction were used at the spillway gates to bracket the experimental TDG data during the model calibration and the same values are used for all computations.

Specific two phase flow models and boundary conditions were implemented into FLUENT through User Defined Functions (UDFs). Two-phase User Defined Scalars (UDSs) transport equations were used to calculate the distribution of TDG and bubble number density.

The model included the main features of the Wells Dam, including the draft tube outlets of the generating units, spillway, top spill in bays 2 and 10 and fish passage facilities (Figure 5.2-1). Bathymetric data supplied by Douglas PUD were used to generate the river bed downstream of the dam. Detail of Figure 5.2-1 shows a cross section through a spillway unit illustrating the Wells Hydrocombine.

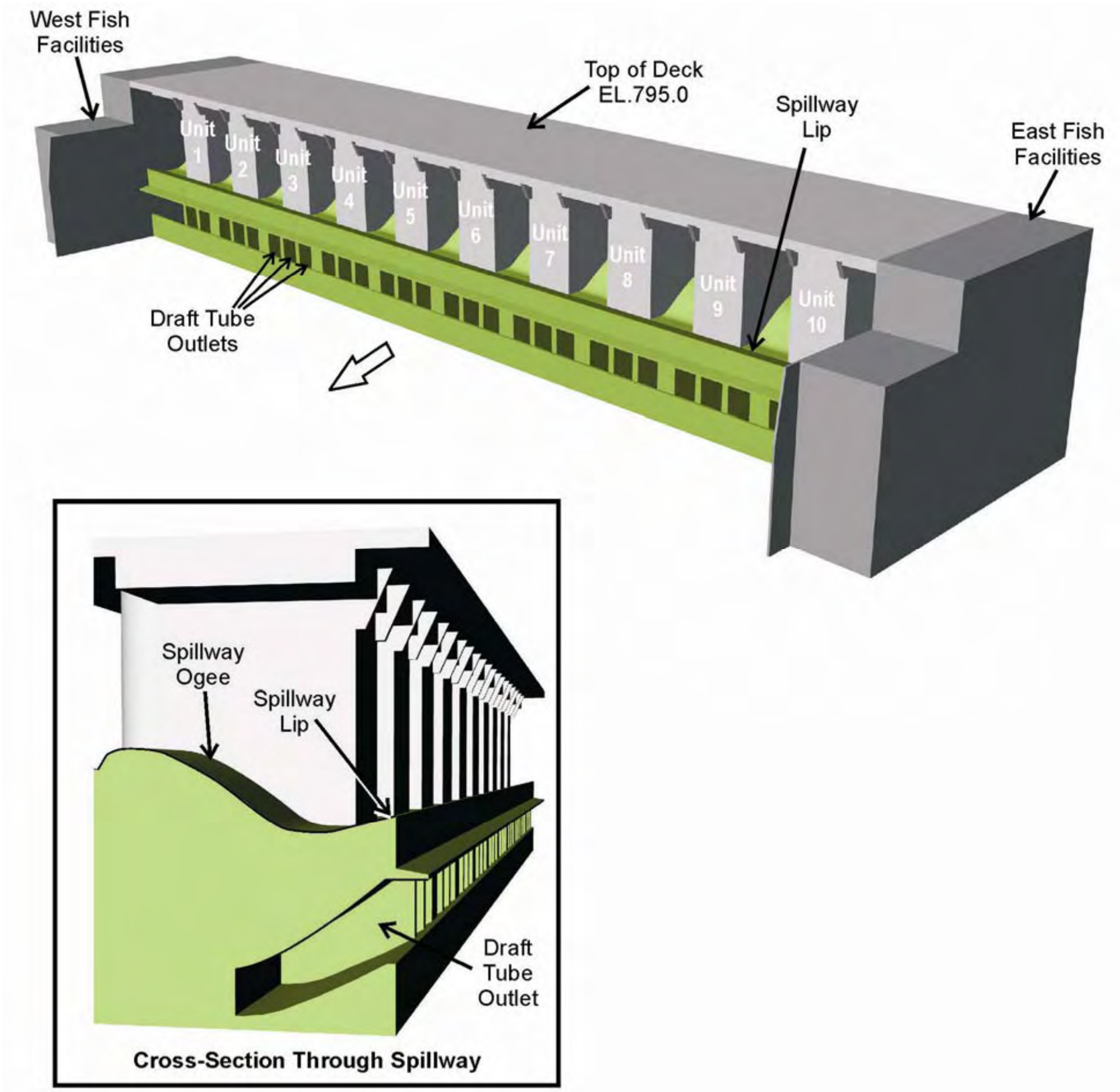

Figure 5.2-1 Structures included in the TDG model

5.3 VOF Model

5.3.1 Mathematical Model

In the VOF model, the interface between fluids is calculated with a water volume fraction (α_w) transport equation:

$$\frac{\partial \alpha_w}{\partial t} + \vec{v} \cdot \nabla \alpha_w = 0 \qquad (1)$$

Mass conservation requires that $\sum \alpha_i = 1$. The jump conditions across the interface are embedded in the model by defining the fluid properties as: $\varphi = \sum \alpha_i \varphi_i$, where φ is either the density or the viscosity. In the VOF approach, each control volume contains just one phase (or the interface). Points in water have $\alpha_w = 1$, points in air have $\alpha_w = 0$, and points near the interface have $0 < \alpha_w < 1$. The free surface was generally defined in the VOF using an α_w of 0.5.

5.3.2 Grid Generation

The domain was divided into a number of blocks and a structured mesh was generated in each block with common interfaces between the blocks. Each individual block consists of hexahedral cells. To resolve the critical regions of interest, the grids were refined near the solid boundaries, near the turbine intakes and spillway where large accelerations are expected, and near the free surface. The grids containing between 6×10^5 to 8×10^5 nodes were generated using Gridgen V15. Grid quality is an important issue for free surface flow simulations. As fine grids are needed near the interface to minimize numerical diffusion, each simulation required the construction of a particular grid. The grids were constructed nearly orthogonal in the vicinity of the free surface to improve convergence. Figure 5.3-1 shows an overall 3D view of the grid used for the June 5, 2006 simulation. An extra volume at the top of the grid was included to accommodate the air volume for the VOF method.

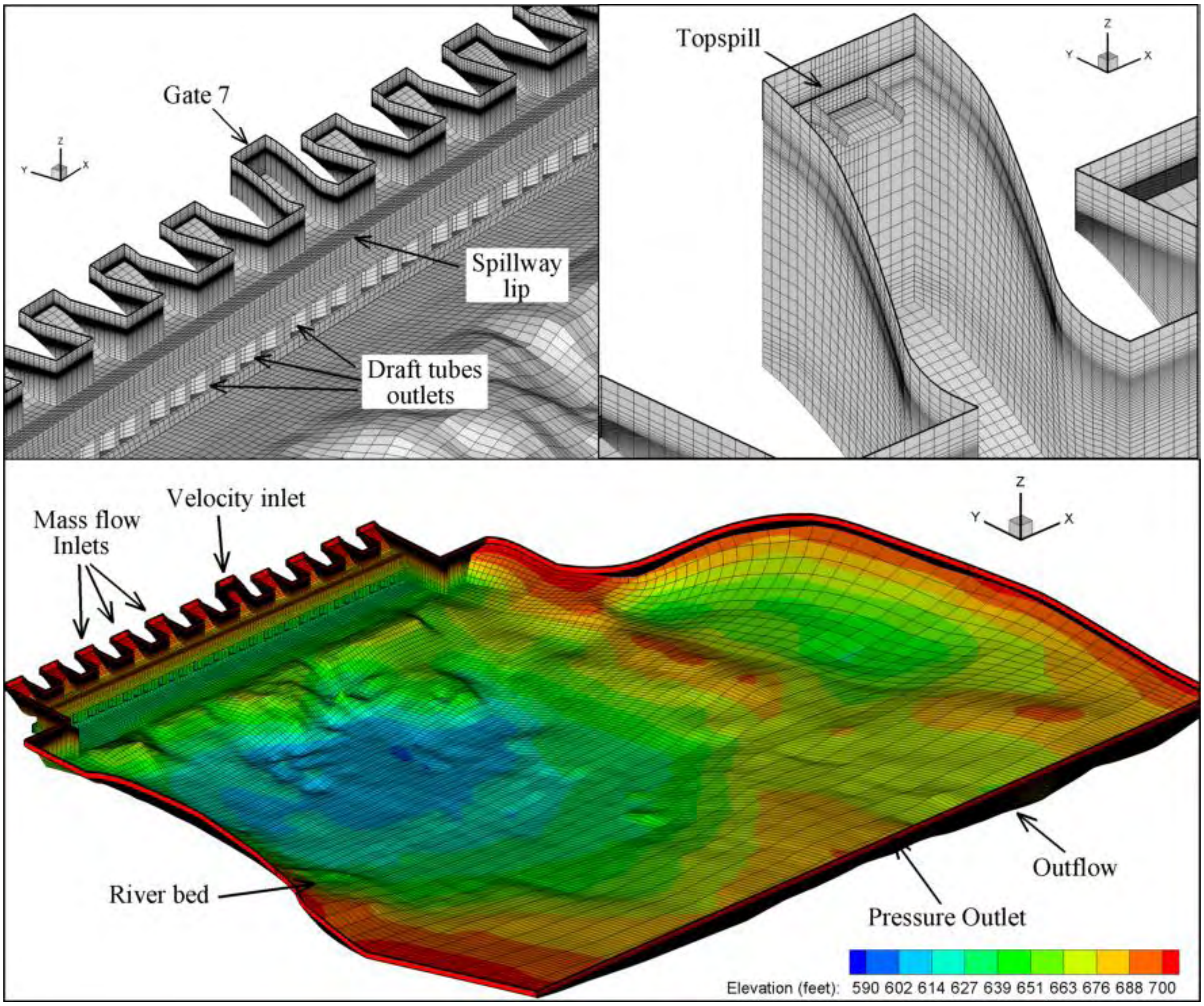

Figure 5.3-1 3D view of a typical grid used for the VOF simulations

5.3.3 Boundary Conditions

5.3.3.1 Inlet

A given mass flow rate of water assuming uniform velocity distribution was used at each of the turbine units and spillway bays.

5.3.3.2 Walls and River Bed

A no-slip (zero velocity) surface condition was imposed on all walls and tailrace bed.

5.3.3.3 Exit

The free water surface elevation (WSE) was imposed by specifying the water volume fraction distribution. The WSE measured at the tailwater elevation gage was used at the exit (outflow condition in Figure 5.3-1). A hydrostatic pressure was imposed at the outflow using a UDF. At the top of the outflow a pressure outlet boundary condition was used to avoid air pressurization.

5.3.3.4 Top Surface

A pressure outlet boundary condition with atmospheric pressure was applied at the top to allow free air flow and avoid unrealistic pressure.

5.4 Rigid-lid Model

The rigid-lid model is an algebraic slip mixture model (ASMM) (Mannheim et al. 1997) that accounts for buoyancy, pressure, drag and turbulent dispersion forces to calculate the gas volume fraction and velocity of the bubbles. The model considers the change of the effective buoyancy and viscosity caused by the presence of the bubbles on the liquid and the forces on the liquid phase due to the non-zero relative bubble-liquid slip velocity.

5.4.1 Mathematical Model

5.4.1.1 Mass and Momentum Conservation for the Mixture

The two phase model provides mass and momentum equations for the liquid and gas phases (Drew & Passman 1998). Summing the mass and momentum equations for each phase results in continuity and momentum equations for the mixture gas-liquid phase:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left[\rho_m \vec{u}_m \right] = 0 \qquad (2)$$

$$\frac{\partial}{\partial t}\left(\rho_m \vec{u}_m\right) + \nabla \cdot \left(\rho_m \vec{u}_m \vec{u}_m\right) = -\nabla P + \nabla \cdot \left[\boldsymbol{\sigma}_m^{\mathrm{Re}} + \boldsymbol{\tau}_m \right] + \rho_m \vec{g} - \nabla \cdot \left(\sum_{k=g,l} \alpha_k \rho_k \vec{u}_k \vec{u}_{dr,k} \right) \qquad (3)$$

where P is the total pressure, $\vec{g}$ is the gravity acceleration, and $\boldsymbol{\sigma}_m^{\mathrm{Re}}$ and $\boldsymbol{\tau}_m = \rho_m \nu_m \left(\nabla \vec{u}_m + \nabla \vec{u}_m^T \right)$ are the turbulent and molecular shear stresses, respectively. ρ_m, μ_m and $\vec{u}_m$ are the mixture density, viscosity and mass-averaged velocity defined as $\rho_m = \sum_{k=g,l} \alpha_k \rho_k$, $\mu_m = \sum_{k=g,l} \alpha_k \mu_g$ and $\vec{u}_m = \frac{1}{\rho_m} \sum_{k=g,l} \alpha_k \rho_k \vec{u}_k$, with α_g the gas volume fraction. The subscripts *g*, *l* and *m* denote gas, liquid and mixture, respectively. $\vec{u}_{dr,k}$ is the drift velocity defined as the velocity of the phase k relative to the mixture velocity.

The gas density is calculated using the ideal gas law $\rho_g = M P / (RT)$ with P the pressure, M the molecular weight of air, R the universal gas constant, and T the absolute temperature.

5.4.1.2 Mass Conservation for the Gas Phase

The continuity equation for the gas phase is (Drew & Passman, 1998):

$$\frac{\partial}{\partial t}\left(\alpha_g\, \rho_g\right)+\nabla\cdot\left(\alpha_g\, \rho_g\, U_{g,i}\right)=-S \tag{4}$$

where $\vec{u}_g$ is the bubble velocity and S is a negative gas mass source; in this application the TDG source due to the air transfer from the bubbles to the liquid.

5.4.1.3 Momentum Conservation for the Gas Phase

The ASMM assumes that the inertia and viscous shear stresses are negligible compared to pressure, body forces and interfacial forces in the momentum equation of the gas phase (Antal et al., 1991; Lopez de Bertodano et al., 1994; Manninen et al., 1997):

$$0=-\alpha_g\,\nabla P+\alpha_g\,\rho_g\,\vec{g}+\vec{M}_g \tag{5}$$

where $\vec{M}_g$ represents the interfacial momentum transfer between the phases.

5.4.1.4 Bubble Number Density Transport Equation

Most of the two fluid models in commercial codes (Fluent, CFX, CFDLib, among others) assume a mean constant bubble size with a given relative velocity (Chen et al., 2005). In tailrace flows the use of a mean constant bubble size for the evaluation of the bubble-liquid mass transfer and interfacial forces is not valid. As a consequence of the complex processes of generation, breakup, and coalescence, the bubbles resulting from air entrainment have different sizes. These processes occur at the plunging jet region immediately after the spillway, where the gas volume fraction and turbulence can be large. The model used in this study is intended for the region downstream of the plunging jet, where bubble size changes mainly due to mass transfer and pressure variations, and therefore bubble breakup and coalescence processes can be neglected. This assumption is considered a reasonable hypothesis for low gas volume fractions (Politano et al. 2007).

Let $f\,dm\,d\vec{r}$ represent the number of bubbles with original (at the insertion point, before any physical process modifies the bubble mass) mass m, located within $d\vec{r}$ of $\vec{r}$ at time t. The Boltzmann transport equation for f is:

$$\frac{\partial f}{\partial t}+\nabla\cdot\left[\vec{u}_g\ f\right]+\frac{\partial}{\partial m}\left[\frac{\partial m}{\partial t}\ f\right]=0 \tag{6}$$

Note that this is a Lagrangian representation, and thus f has a different interpretation than the usual Eulerian approach (Guido-Lavalle et al., 1994; Politano et al., 2000). Integration of Eq. (6) for bubbles of all masses results in a transport equation for the bubble number density N :

$$\frac{\partial N}{\partial t} + \nabla \cdot \left[\vec{u}_g \, N \right] = 0 \qquad (7)$$

The bubble radius is calculated from $R = \left[3\alpha / (4\pi N)\right]^{1/3}$.

5.4.1.5 Two-phase TDG Transport Equation

TDG is calculated with a two-phase transport equation (Politano et al. 2007):

$$\frac{\partial \alpha_l C}{\partial t} + \nabla \cdot \left(\vec{u}_l \, \alpha_l \, C \right) = \nabla \cdot \left(\left(\nu_m + \frac{\nu_t}{Sc_C} \right) \alpha_l \nabla C \right) + S \qquad (8)$$

where C is the TDG concentration, and ν_m and ν_t are the molecular and turbulent kinematic viscosity, respectively. In this study, a standard Schmidt number of $Sc_C = 0.83$ is used.

5.4.1.6 Turbulence Closure

In this study a Reynolds Stress Model (RSM) was used. The ASMM assumes that the phases share the same turbulence field. The turbulence in the mixture phase is computed using the transport equations for a single phase but with properties and velocity of the mixture. The transport equations for the Reynolds stresses $\boldsymbol{\sigma}_{i,j}^{\mathrm{Re}} = \rho_m \overline{u'_{m,i} \, u'_{m,j}}$ are:

$$\frac{\partial \boldsymbol{\sigma}^{\mathrm{Re}}}{\partial t} + \left(\nabla \cdot \vec{u}_m \right) \boldsymbol{\sigma}^{\mathrm{Re}} + \vec{u}_m \left(\nabla \cdot \boldsymbol{\sigma}^{\mathrm{Re}} \right) = \nabla \cdot \left[\rho_m \frac{\nu_m^t}{\sigma_R} \nabla \boldsymbol{\sigma}^{\mathrm{Re}} \right] - \mathbf{P} + \boldsymbol{\varphi} + \boldsymbol{\varepsilon} + \mathbf{S}_{\boldsymbol{\sigma}} \qquad (9)$$

where the stress production tensor is given by $\mathbf{P} = \boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T + \left(\boldsymbol{\sigma}^{\mathrm{Re}} \cdot \nabla \vec{u}_m^T \right)^T$, $\boldsymbol{\varepsilon} = 2/3 \, \mathbf{I} \, \rho_m \, \varepsilon$ and $\sigma_R = 0.85$. The pressure-strain tensor $\boldsymbol{\varphi}$ is calculated using the models proposed by Gibson and Lander (1978), Fu et al. (1987) and Launder (1989). In this study, $\mathbf{S}_{\boldsymbol{\sigma}}$ represents the effect of the bubbles on the Reynolds stresses. The transport equation for the turbulent dissipation rate reads:

$$\frac{\partial}{\partial t} \left(\rho_m \, \varepsilon \right) + \nabla \cdot \left(\rho_m \, \vec{u}_m \, \varepsilon \right) = \nabla \cdot \left[\rho_m \left(\nu_m + \frac{\nu_m^t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] - C_{\varepsilon 1} \, \rho_m \, \frac{1}{2} \mathrm{Tr}\left(\mathbf{P} \right) \frac{\varepsilon}{k} - C_{\varepsilon 2} \, \rho_m \, \frac{\varepsilon^2}{k} + S_\varepsilon \qquad (10)$$

with $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $\sigma_\varepsilon = 1$. The turbulent kinetic energy is defined as $k = \frac{1}{2 \rho_m} \mathrm{Tr}\left(\boldsymbol{\sigma} \right)$. The source term S_ε accounts for the effect of the bubbles on the turbulent dissipation rate. The turbulent kinematic viscosity is computed as in the $k-\varepsilon$ models using $\nu_t = C_\mu k^2 / \varepsilon$, with $C_\mu = 0.09$.

5.4.1.7 Constitutive Equations

In order to close the model, interfacial transfer terms emerging from the relative motion between the bubbles and the continuous liquid need to be modeled.

Interfacial momentum

Since in this particular application there are no significant velocity gradients or flow accelerations (in the bubble scale), most interfacial forces such as lift and virtual mass are negligible compared with drag and turbulent dispersion forces:

$$\vec{M}_g = \vec{M}_g^{D} + \vec{M}_g^{TD} \qquad (11)$$

where $\vec{M}_g^{D}$ and $\vec{M}_g^{TD}$ are the drag and turbulent dispersion terms. The drag force can be modeled as (Ishii & Zuber, 1979):

$$\vec{M}_g^{D} = -\frac{3}{8}\rho_m \alpha_g \frac{C^D}{R}\vec{u}_r \left|\vec{u}_r\right| \qquad (12)$$

where $\vec{u}_r$ is the relative velocity of the gas phase respect to the liquid phase. Most of the numerical studies use drag correlations based on rising bubbles through a stagnant liquid proposed by Ishii & Zuber (1979) (see Lane et al., 2005):

$$C^D = \begin{cases} \dfrac{24}{\mathrm{Re}_b} & if\ R < 0.002 \\ \dfrac{24\left(1+0.15\,\mathrm{Re}_b^{0.867}\right)}{\mathrm{Re}_b} & if\ 0.002 < R < 0.00222 \\ 0.56 & if\ R > 0.00222 \end{cases} \qquad (13)$$

where $\mathrm{Re}_b = 2\rho_l \left|\vec{u}_r\right| R / \mu_l$ is the bubble Reynolds number. The turbulent dispersion term is modeled as (Carrica et al., 1999):

$$\vec{M}_g^{TD} = -\frac{3}{8}\frac{\nu^t}{Sc_b}\rho_m \frac{C^D}{R}\left|\vec{u}_r\right| \nabla \alpha_g \qquad (14)$$

where $Sc_b = \nu^t / \nu^b$ is the bubble Schmidt number. Following Carrica et al. (1999), $Sc_b = 1$ is used.

Bubble dissolution and absorption

The rate of mass transfer is computed considering that the air is soluble in water and obeys Henry's law and that the air molar composition is that of equilibrium at atmospheric pressure, which implies that the air is considered a single gas with molar averaged properties. The mass flux from gas to liquid can be expressed by (Deckwer 1992; Politano et al. 2007):

$$S = 4\pi N R^2 k_l \left(\frac{P + \sigma/R}{He} - C \right) \tag{15}$$

where σ is the interfacial tension and He is the Henry constant. The second term on the RHS of Eq. (15) accounts for the effect of the interfacial tension on the equilibrium concentration. Takemura and Yabe (1998) proposed a correlation for the mass transfer coefficient of spherical rising bubbles, where the turbulence is generated by the rising bubbles:

$$k_l^{rb} = \frac{D\, Pe_b^{0.5}}{\sqrt{\pi} R} \left(1 - \frac{2}{3\left(1 + 0.09\,\mathrm{Re}_b^{2/3}\right)^{0.75}} \right) \tag{16}$$

where D is the molecular diffusivity and the bubble Peclet number is $Pe_b = 2\left|\overrightarrow{u_r}\right| R / D$.
External turbulence could be important in flows downstream of spillways, mainly in regions of high shear near the walls and where the plunging jet impacts and enhances the mass transfer. In this application, the mass transfer coefficient can be calculated using the expression proposed by Lamont and Scott (1970):

$$k_l^t = 0.4\, Sc^{-1/2} (\nu\, \varepsilon)^{1/4} \tag{17}$$

where $Sc = D/\nu$. In this study, the same order of magnitude is obtained from Eqs. (16) and (17), thus the maximum mass transfer coefficient between bubbles rising in stagnant liquid (k_l^{rb}) and bubbles in turbulent flow (k_l^t) is used: $k_l = \max\left(k_l^{rb}, k_l^t\right)$.

5.4.2 Grid Generation

The Wells tailrace structures and the bathymetry are meshed with structured and unstructured multi-block grids containing only hexahedral elements, using Gambit and Gridgen V15. Typical grid sizes are in the range of 7 10^5 to 1 10^6 nodes. Figure 5.4-1 shows typical grids used for the rigid-lid model. Details (a) and (b) show free surface shapes for spread and concentrated flows, respectively. Detail (c) shows the unstructured grid, extended from approximately 1,500 feet to 3,500 feet downstream of the Wells Dam, used to reduce grid size and improve aspect ratio.

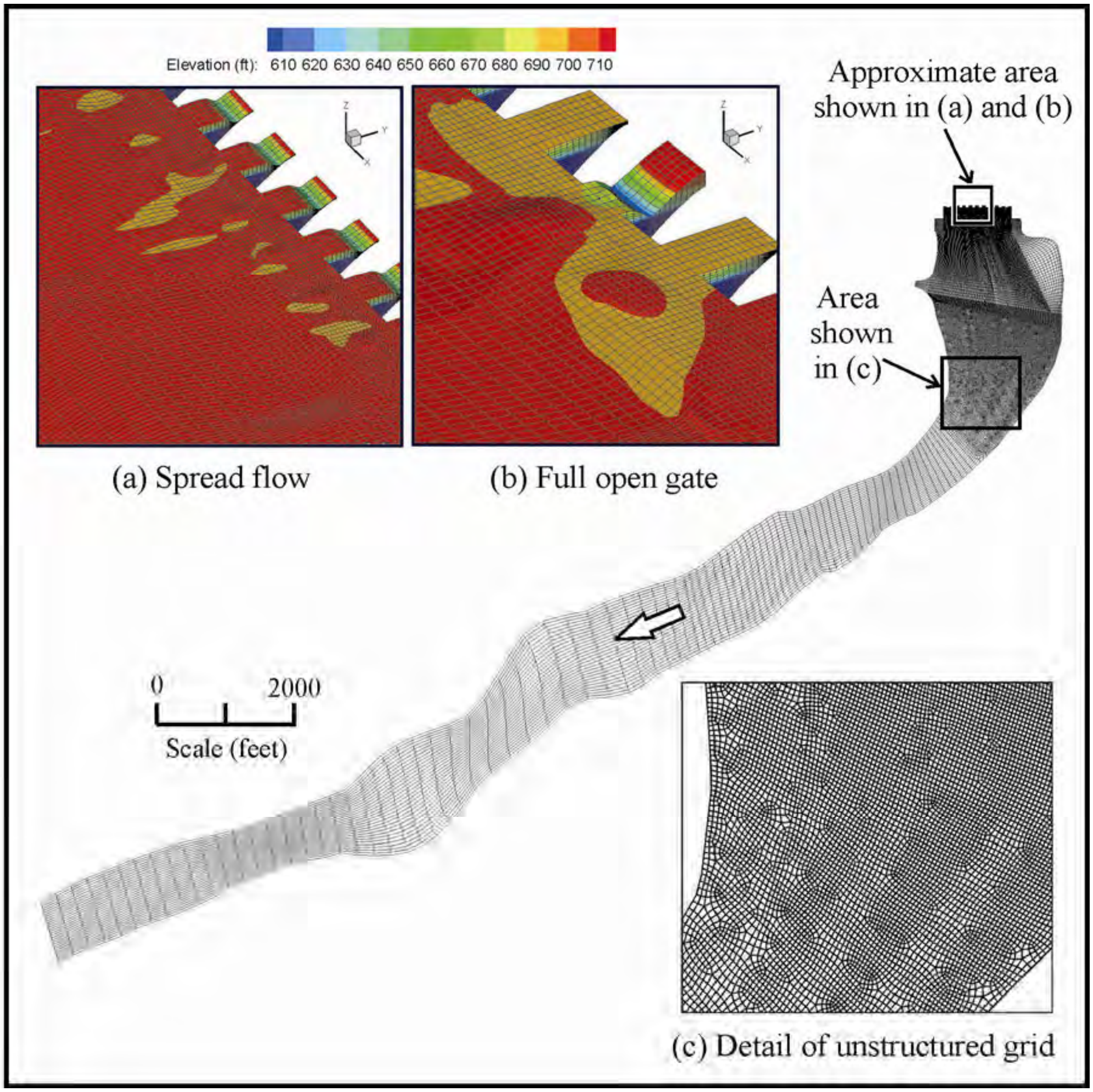

Figure 5.4-1 3D view of a typical grid used for the rigid-lid simulations

5.4.3 Boundary Conditions

5.4.3.1 Free Surface

Kinematic and dynamic boundary conditions enforcing zero normal velocity fluctuations at the free surface are programmed through UDFs. Details of the implementation of the boundary conditions used for the Reynolds stress and velocity components are found in Turan et al. (2007).

In order to allow the gas phase to flow across the interface, the normal component of the gas velocity at the free surface is calculated using a mass balance for the gas phase in each control volume contiguous to the interface. The resulting equation is implemented using UDFs.

For the TDG concentration, a Neumann boundary condition is used. A mass transfer coefficient at the free surface of $k_l = 0.0001$ m/s as measured by DeMoyer et al. (2003) for tanks and bubble columns is used.

5.4.3.2 Walls and River Bed

The sides and the river bed are considered impermeable walls with zero TDG flux. For the gas phase, no penetration across walls is imposed.

5.4.3.3 Exit

The river exit is defined as an outflow. A zero gradient condition was programmed for the TDG concentration and bubble number density.

5.4.3.4 Spillbays and Powerhouse Units

Uniform velocities with constant gas volume fraction of $\alpha = 0.03$ and bubble diameter 5 mm are used for the 11 bays in the spillway region.

It is assumed that air is not entrained with the turbine inflow. The TDG concentration measured in the forebay is used at the spillway bays and powerhouse units.

6.0 RESULTS

The computations were performed using 4 processors of a Linux cluster with 2 Gb of memory per processor and in three dual socket dual core Xeon Mac Pro systems.

6.1 VOF Model

The discrete RANS equations and Eq. (1) were solved sequentially (the segregated option in Fluent) and coupled to a realizable $k-\varepsilon$ model with wall functions for turbulence closure. The pressure at the faces is obtained using the body force weighted scheme. The continuity equation was enforced using a Semi-Implicit Method for Pressure-Linked (SIMPLE) algorithm. A modified High Resolution Interface Capturing (HRIC) scheme was used to solve the gas volume fraction.

Unsteady solutions were obtained using variable time-step between 0.001 to 0.01 seconds. Typically, two to three nonlinear iterations were needed within each time step to converge all variables to a L_2 norm of the error $<10^{-3}$. The flow rate at the exit and the elevation at the tailwater elevation gauge location were selected as convergence parameters.

6.1.1 Calibration

The calibration cases were run in a domain of approximately 3,000 ft downstream of the dam. Zero velocities and turbulence were used as initial conditions in the entire domain.

The convergence parameters for the calibration cases were:

$$46S-June\ 4,2006 \rightarrow \left(flowrate : 172.4, WSE : 717.3\,ft \right)$$
$$47FG-June\ 5,2006 \rightarrow \left(flowrate : 222.3, WSE : 720.2\,ft \right)$$

Horizontal lines in Figure 6.1-1 show the target flowrate (blue line) and WSE at the tailwater elevation gage (green line). The evolution of the simulations for the calibration cases is illustrated in Figure 6.1-1; blue lines represent the flow rate at the exit and the green lines the free surface elevation. It was considered that statistically steady solutions were obtained at approximately 30 minutes, which required about 60 days of computation time.

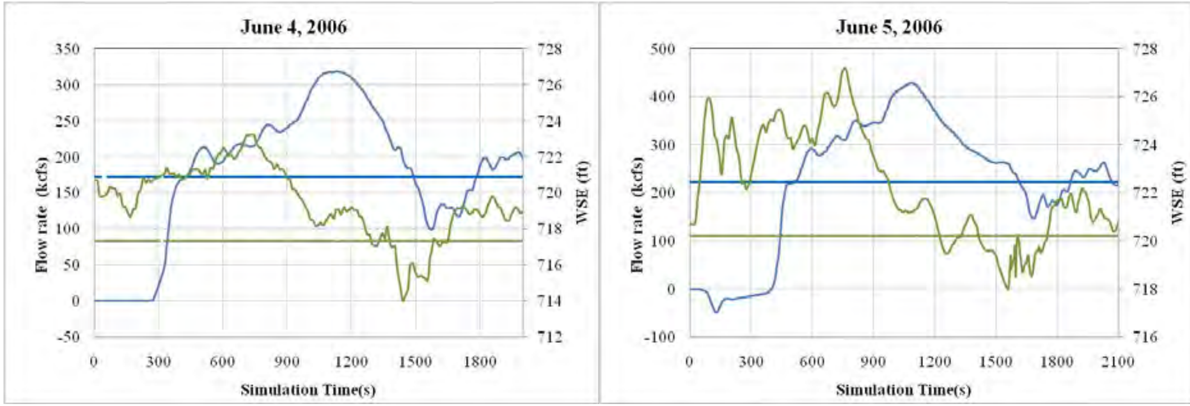

Figure 6.1-1 **Evolution of the flowrate at the exit (blue line) and free surface elevation (green line) for June 4, 2006 and June 5, 2006. Horizontal lines represent target values.**

Figure 6.1-2 shows an isosurface of gas volume fraction $\alpha_w = 0.5$ representing the free-surface location used to create the top of the rigid-lid grid for the June 4, 2006 simulation. In Figure 6.1-3 a horizontal slice at 27 ft from the free-surface (top) and a vertical section at the center of spillway bay 7 (bottom) show the predicted flow field with the VOF method. Red and blue contours represent water and air, respectively. For clarity, predicted velocity vectors were interpolated in structured uniform grids. Almost uniform flow is observed close to the spillway during the spread flow operation. Surface jets are predicted in all the spillway bays due to elevated tailwater levels. In addition, water flow from the powerhouse units prevented the spillway jet from plunging to depth within the stilling basin.

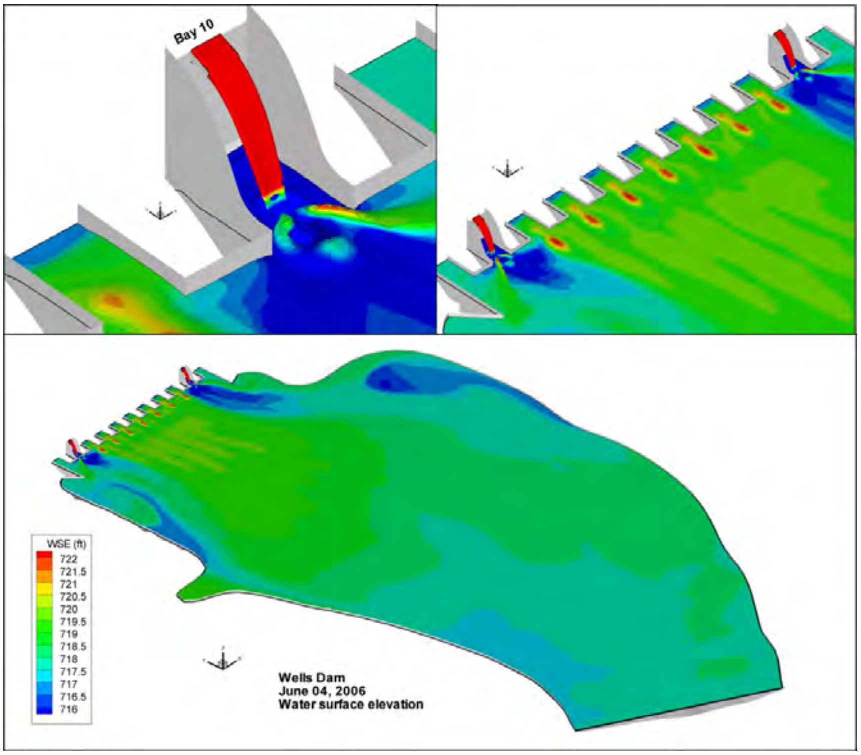

Figure 6.1-2 Predicted free surface shape for June 4, 2006

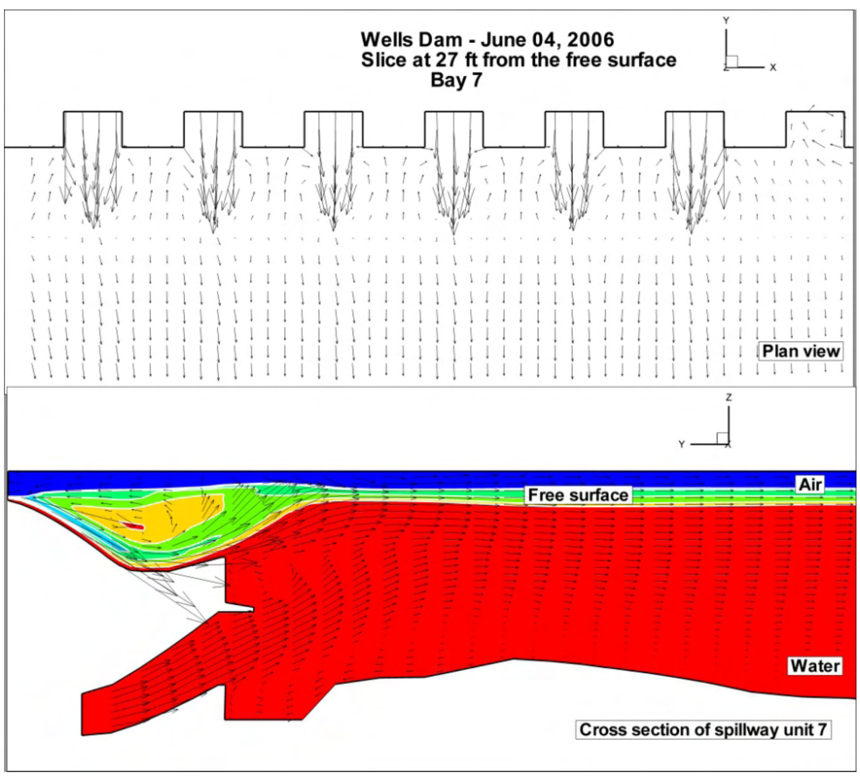

Figure 6.1-3 Predicted flow field for June 4, 2006

The free surface used to create the rigid-lid grid for June 5, 2006 is shown in Figure 6.1-4. The horizontal slice at the top of Figure 6.1-5 shows the water attraction toward the surface jet on bay 7 (water entrainment) caused by the full open gate operation. The water entrainment originates two large eddies near the east and west bank of the Wells tailrace. As observed on June 4, 2006, the strong surface jet originated in bay 7 remains close to the free surface (see bottom picture in Figure 6.1-5) due to the favorable tailwater elevation and plant operation on this day.

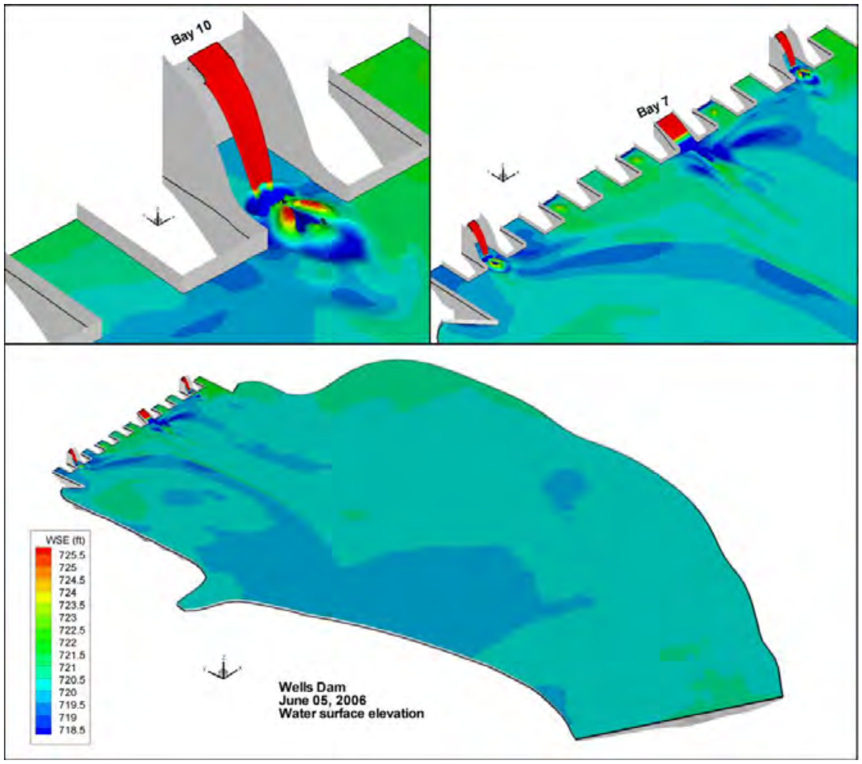

Figure 6.1-4 Predicted free surface shape for June 5, 2006

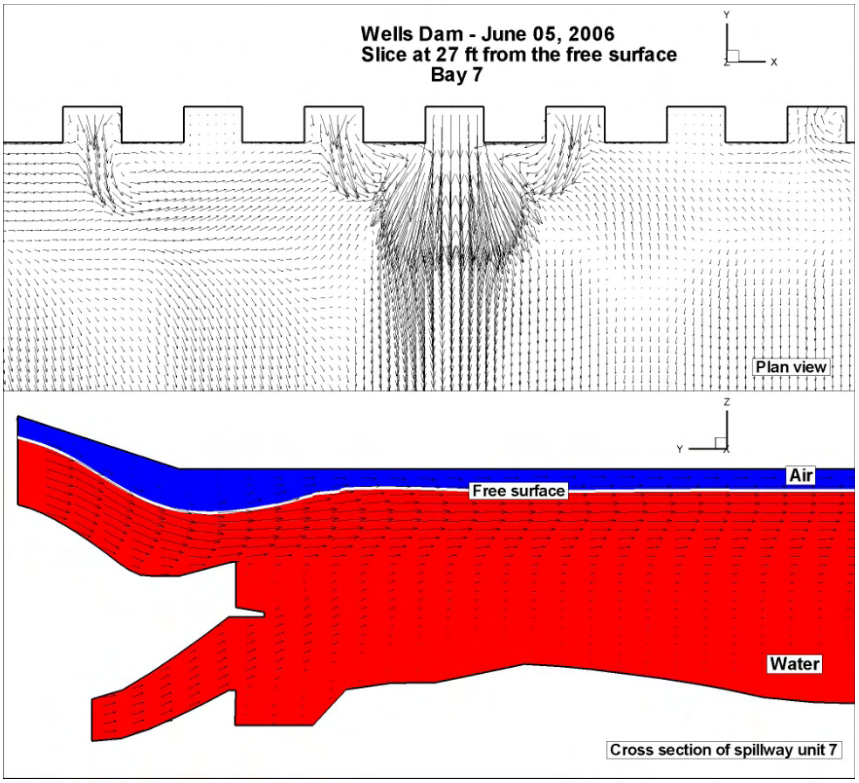

Figure 6.1-5 Predicted flow field for June 5, 2006

6.1.2 Model Validation

The domain used to simulate the validation cases was reduced to 1,700 ft downstream of the dam with the purpose of speeding up the VOF computations. During the calibration it was observed that the effect of the top spill on the free surface shape is limited to a small region near spillway bays 2 and 10. Therefore the validation cases assumed that spillway bays 2 and 10 were closed and the free surface shape obtained during the calibration process was used near the top spills.

The numerical solution (pressure, velocity, free surface location and turbulent quantities) obtained on June 5, 2006 was used as an initial condition for the validation cases.

The convergence parameters for the calibration cases were:

$$1FG - May\ 14, 2006 \rightarrow (\ flowrate : 120.4, WSE : 711.5\ ft)$$

$$11FG - May\ 17, 2006 \rightarrow (\ flowrate : 157.2, WSE : 715.4\ ft)$$

$$63C - June\ 17, 2006 \rightarrow (\ flowrate : 205.5, WSE : 718.6\ ft)$$

Figure 6.1-6 shows the evolution of the flowrate and WSE at the tailwater elevation gauge for the validation cases. Blue and green lines represent the flowrate and WSE, respectively. The above mentioned simplifications allowed the calibration cases to reach the statistically steady solutions in typically 20 minutes using 30 days of computation time.

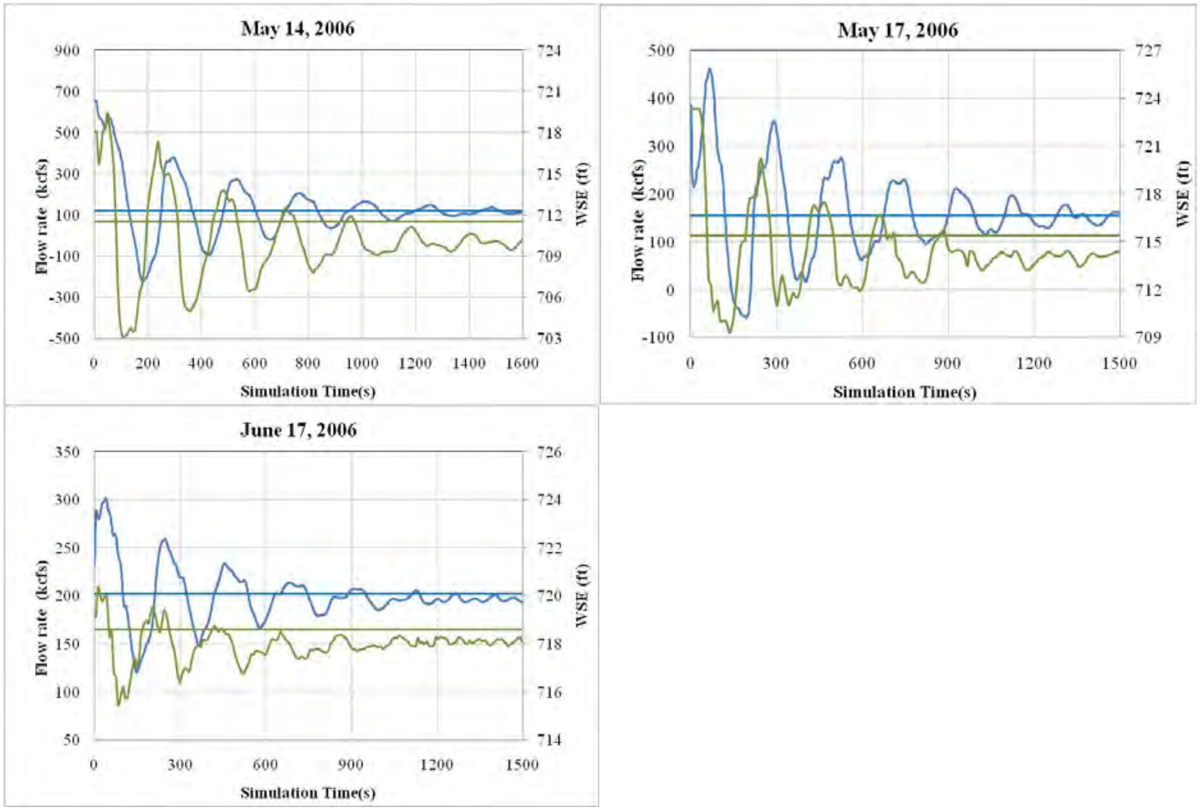

Figure 6.1-6 Evolution of the flowrate at the exit (blue line) and free surface elevation (green line) for May 14, 2006, May 17, 2006, and June 17, 2006. Horizontal lines represent target values.

6.2 Rigid-lid Model

The ASSM model equations were solved sequentially. The VOF and rigid-lid simulations were performed using the same discretization schemes for the continuity and pressure equations. A first order upwind scheme was used for the gas volume fraction and Reynolds stress components.

Unsteady solutions were obtained using a fixed time-step of 10 seconds. In order to improve convergence, the model was first run assuming single-phase flow and then bubbles were injected into the domain. The rigid-lid model was computed in typically 7 hours (2 days of computation time) to obtain a steady condition for the flow field and TDG concentration.

6.2.1 Hydrodynamics

Figures 6.2-1 and 6.2-2 show depth-averaged velocity data collected in the field on June 4, 2006 and June 5, 2006 and those predicted by the rigid-lid model. Good agreement between observed and predicted velocity vectors was found, especially at the downstream transect where flow conditions were more stable and the Acoustic Doppler Current Profiler (ADCP) velocity data are less affected by turbulence and non-steady conditions.

As observed in the field, the model captured the counterclockwise eddy near the east bank and the almost uniform profile at the most downstream transect.

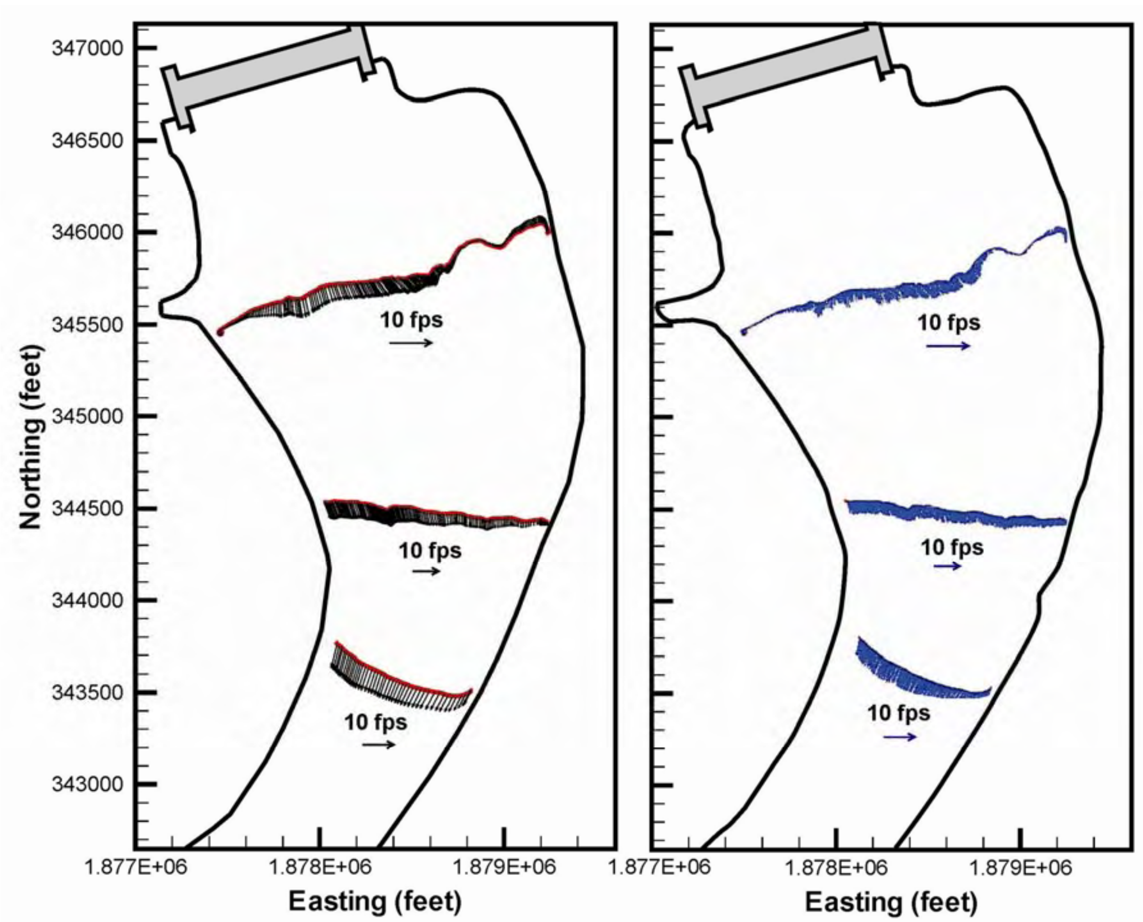

Figure 6.2-1 Flow field on June 4, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data

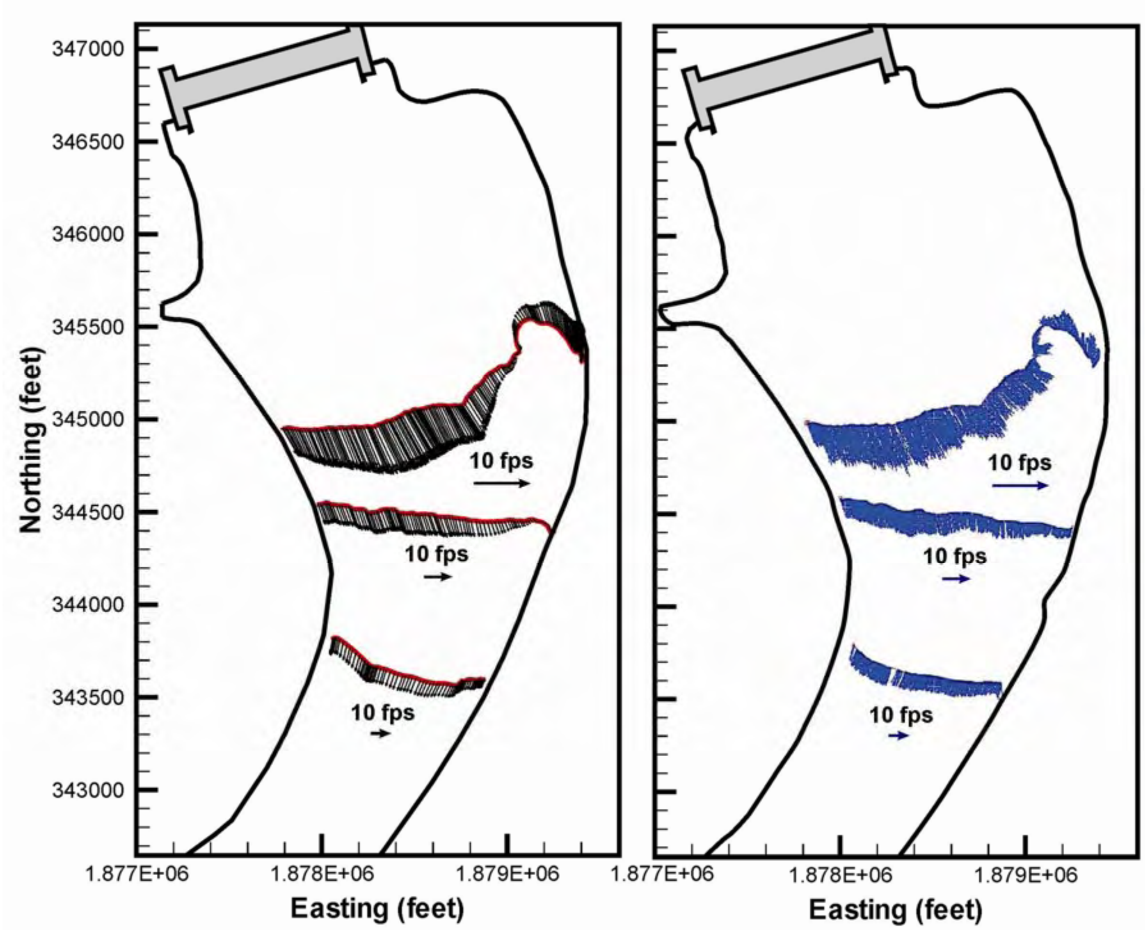

Figure 6.2-2 **Flow field on June 5, 2006. Black vectors: rigid-lid model predictions and blue vectors: velocity field data**

6.2.2 TDG Model

The percent saturation of TDG measured in the field at each station and the mean TDG in each of the three transects together with the values generated by the CFD model for the calibration and validation cases are shown in Appendix A. Figures 6.2-3 to 6.2-7 show measured and predicted values at each probe location. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations.

The model captures the reduction of TDG with distance downstream and the lateral gradient observed in the field. As measured, the highest predicted TDG value at Transect TW1 occurred in the center of the channel and the lateral gradients in transects TW2 and TW3 were negligible.

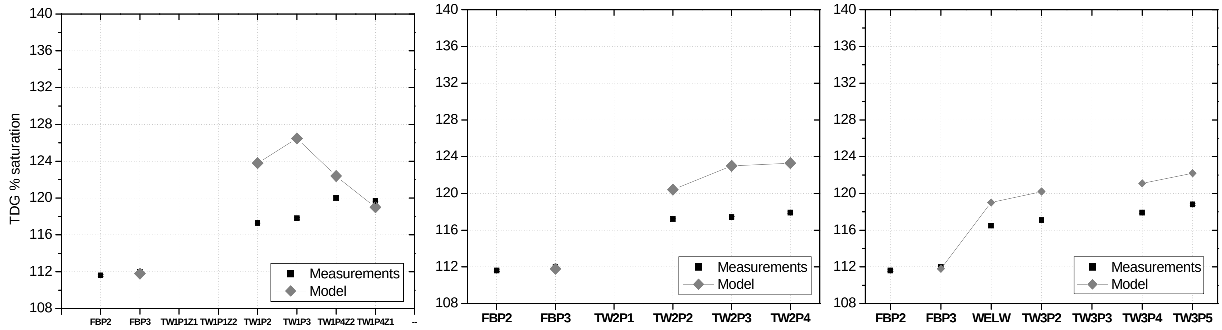

Figure 6.2-3 **Comparison between measured and predicted TDG on June 4, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

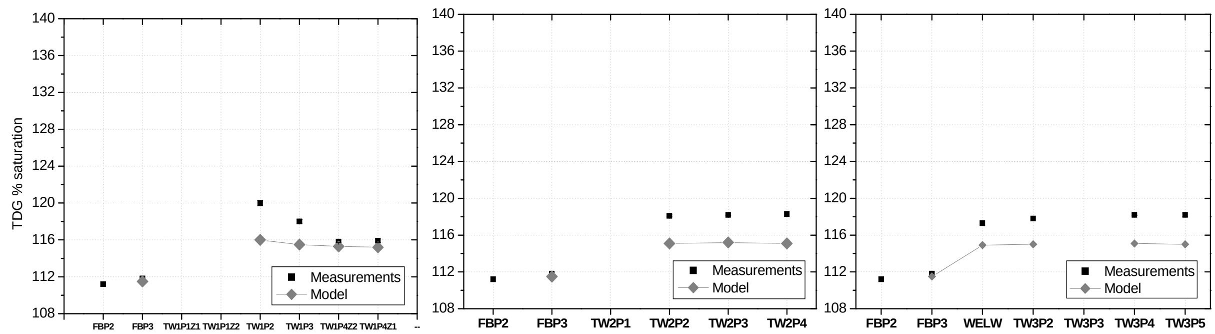

Figure 6.2-4 **Comparison between measured and predicted TDG on June 5, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

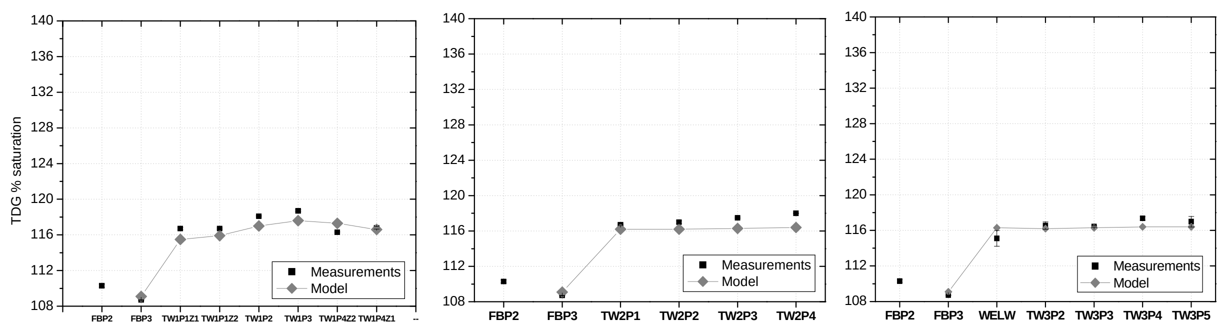

Figure 6.2-5 **Comparison between measured and predicted TDG on May 14, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.**

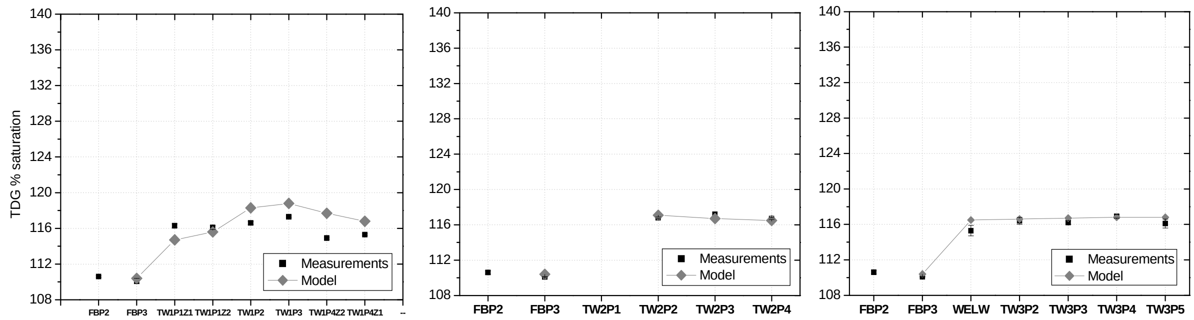

Figure 6.2-6 Comparison between measured and predicted TDG on May 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

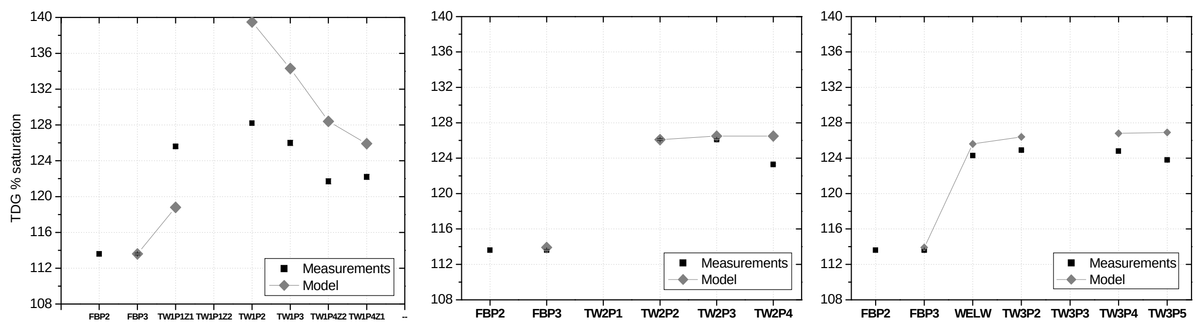

Figure 6.2-7 Comparison between measured and predicted TDG on June 17, 2006. Gray diamonds represent TDG model predictions and black squares represent field observations.

Figures 6.2-8 and 6.2-9 show isosurfaces of TDG, gas volume fraction and bubble diameter for June 4, 2006 and June 5, 2006 where the spill operation of the dam was spread and full open gate, respectively. As shown by the gas volume fraction isosurfaces, the model predicts uniformly distributed bubbles on the spillway region during spread spill operations. On the other hand, bubbles concentrate near the center of the spillway for full open gate operation. The maximum TDG occurs at the center region due to the exposure of water to the aerated flow as it travels within the stilling basin (see TDG isosurfaces). The rate of mass exchange depends on the gas volume fraction, the bubble size and the difference in concentration between the bubble boundary and the water. The gas dissolution region occurs mainly within 500 to 1,000 ft downstream of the spillway; afterwards the bubbles moved up to regions of lower pressure and the dissolution rate decreased. The bubbles shrink near the bed due to the air mass transfer and high pressure. The smaller the bubble size the stronger its tendency to dissolve. Substantial desorption of TDG takes place near the free surface downstream of the spillway. Once the air bubbles are vented back into the atmosphere the rate of mass exchange decreases significantly. The TDG concentration reaches a developed condition approximately 1,300 ft from the spillway. According to the simulation results, the draft tube deck extensions, which tend to act as deflectors for the spill, and powerhouse operation prevented spilled flow from plunging deep, reducing the exposure of bubbles to high pressure.

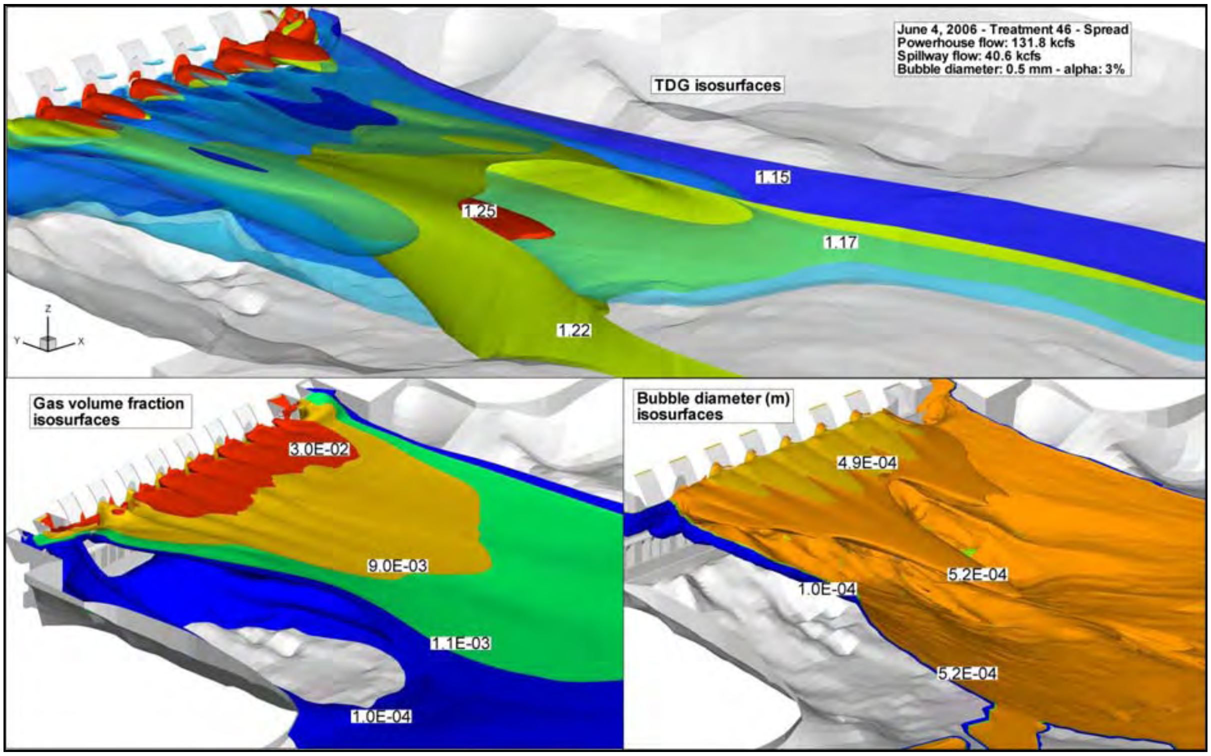

Figure 6.2-8 **TDG, gas volume fraction and bubble diameter isosurfaces for June 4, 2006**

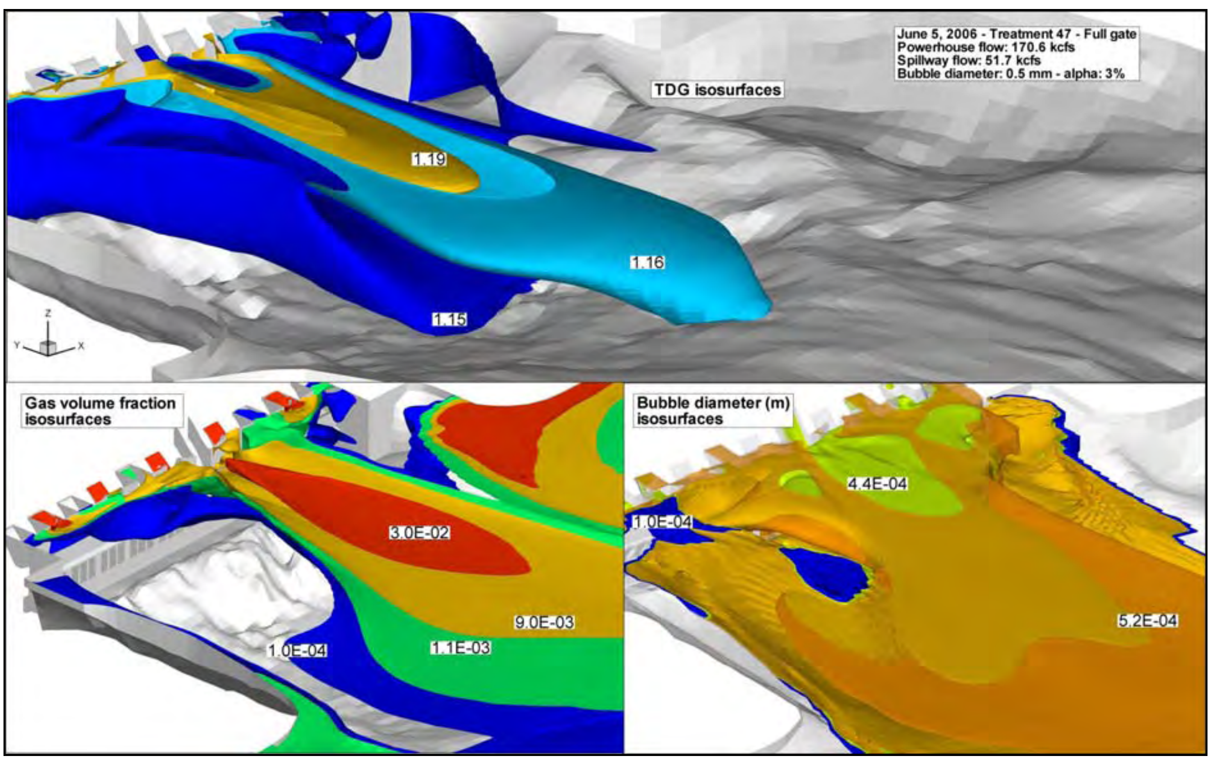

Figure 6.2-9 **TDG, gas volume fraction and bubble diameter isosurfaces for June 5, 2006**

7.0 DISCUSSION

A mixture two-phase flow model aimed at the prediction of TDG in the Wells tailrace was developed. Variable bubble size and gas volume fraction were used to analyze dissolution and the consequent source of TDG. The model uses an anisotropic RSM turbulence model.

The model was calibrated and validated using field data collected on May 14, May 17, June 4 June 5 and June 17, 2006 during the TDG Production Dynamics Study (EES et al., 2007). The spillway flow was spread across spillbays on June 4, concentrated through a single spillbay on May 17, June 4 and June 5, and crowned on June 17. The observed flow field in the tailrace on June 4 and June 5 was properly predicted by the model. The bubble size and gas volume fraction at the inlet were the parameters of the model. A bubble diameter of 0.5 mm and gas volume fraction of 3% in the spillbays produced TDG values that bracketed field observations.

The model captured the lateral TDG distribution and the reduction of TDG longitudinally as observed in the field. The model brackets the results of the field measurements for the validation cases with a deviation of about +/- 3% of the average TDG values for Transect 3. A reasonable evaluation of the model predictability and selection of the best parameters is complicated since the accuracy of the field data is not provided in the field study (EES et al., 2007). The model used in this study assumes that bubble size changes mainly due to mass transfer and pressure and considers that breakup and coalescence are negligible. This hypothesis is frequently used for low volume fraction flows. In this study, the gas volume fraction and bubble size were selected to be above and below the averaged TDG measured on June 4 and 5, 2006. It is expected that the inclusion of the breakup and coalescence phenomena change the bubble size distribution at the plunging jet region immediately downstream of the spillway. However, as the bubble size at the inlet was selected to bracket the field data, breakup and coalescence should play a minor role on the TDG distribution and production in the Wells tailrace.

Possible efforts to further improve the predictive capability of the model include:

- The model assumes that the bubble size and gas volume fraction are the same at the inlet (spillway bay gates) irrespective of spillway operation. The VOF simulations seem to indicate that the flow regime and bubble entrainment in the near field of the plungers are substantially different for spread and full open gate operations. The best agreement is for the full open gate cases. The gas volume fraction (or bubble size) at the inlet could be slightly different for the spread and crown operation. Preliminary sensitivity analyses indicate that a change in the volume fraction from 3% to 4% (or 0.1 mm in bubble diameter) at the inlet could considerably improve the model predictions for spread and crowned operations.
- The incorporation of a temperature model considering the change of the solubility with the temperature. This could capture the TDG fluctuations due to seasonal thermal cycles.
- Bubbles change chemical composition as they dissolved due to the different solubilities of the air components. In this study, the air is considered a unique gas with molar averaged properties. The incorporation of a multi-component model that takes into account the different solubilities of oxygen and nitrogen and therefore

considers the different chemical composition of the bubbles as they transfer mass is proposed as future improvement of the model.

The analysis presented herein seems to indicate that properly modeling the air entrainment boundary condition is the most important improvement to the model at this stage.

In spite of the air entrainment boundary condition uncertainties, this study has demonstrated that the presented model can capture the main features of the two-phase flow in the Wells tailrace and the general trends of TDG values across the transects.

Future work:

With some additional minor adjustments the model described above will be used as a predictive numerical tool to identify Project operations that can be used to minimize TDG concentration downstream of the Wells Project.

The next phases of this study will be executed in two testing stages; Phase 1 and Phase 2.

The purpose of the Phase 1 will be to analyze different spill releases and TDG production as a function of flow and tailwater elevation. In this phase the sensitivity of TDG concentration to the operation of the spillway and tailwater elevation will be studied. Nine runs with two spillway configurations (spread and FG) and four total river flows will be simulated.

Nine additional model runs will be completed in Phase 2. Flow conditions and spill scenarios will depend upon the results of Phase 1. However, Phase 2 will involve more realistic scenarios with practical operational condition to assist in the understanding of optimal spill configurations and plan operation in reducing TDG production.

The final results of the Phase 1 and Phase 2 modeling efforts will be the focus of the final report for this study.

8.0 STUDY VARIANCE

There were no variances from the final FERC approved study plan for the Total Dissolved Gas Investigation. The final study report will be complete and available to the public in early 2009.

9.0 ACKNOWLEDGMENTS

This numerical study was sponsored by Douglas PUD. The authors thank Shane Bickford and Bao Le for their support and cooperation to this study. The constructive suggestions of Duncan Hay of Oakwood Consulting Inc. are gratefully appreciated.

10.0 REFERENCES

Antal, S.P., R.T. Lahey Jr., and J.E. Flaherty. 1991. Analysis of Phase Distribution in Fully Developed Laminar Bubbly Two-Phase Flow, International Journal of Multiphase Flow. 17(5): 553-682

ASL Environmental Sciences Inc. 2007. Turbine discharge measurements by acoustic scintillation flow meter at Until 1 and 2, Wells Hydroelectric Project, Pateros, Washington (2006). Prepared for the Public Utility District No. 1 of Douglas County.

Carrica, P. M., D. Drew, F. Bonetto, and R.T. Lahey Jr. 1999. A Polydisperse model for bubbly two–phase flow around a surface ship. International. Journal of Multiphase Flow. 25: 257-305.

Chen, P., M.P. Dudukovic, and J. Sanyal. 2005. Three-dimensional simulation of bubble column flows with bubble coalescence and breakup. American Institute of Chemical Engineers Journal. 51(3):696-712.

Columbia Basin Environmental (CBE). 2003. Wells Dam Spillway Total Dissolved Gas Evaluation 27 May to 10 June 2003. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

Columbia Basin Environmental (CBE). 2004. Wells Dam Spillway Total Dissolved Gas Evaluation 23 May to 6 June 2004. Final Report. Prepared for Public Utility District No. 1 of Douglas County.

Columbia Basin Environmental (CBE). 2006. Wells Dam Spillway Total Dissolved Gas Evaluation – 23 May to 6 June 2005, Final Report, Prepared for Douglas County PUD.

Douglas County PUD. 2006. Wells Hydroelectric Project. FERC Project No. 2149. Pre-Application Document.

Deckwer, W.D. 1992. Bubble Column Reactors. John Wiley & Sons.

DeMoyer, C.D., E.L. Schierholz, J.S. Gulliver, and S.C.Wilhelms. 2003. Impact of Bubble and Free Surface Oxygen Transfer on Diffused Aeration Systems. Water Research. 37(8):1890-1904.

Drew, D.A., and S.L. Passman. 1998. Theory of Multicomponent Fluids. Applied Mathematical Sciences, Springer 135.

EES Consulting, Inc., J. Carroll, ENSR, and Parametrix. 2007. Total dissolved gas production dynamics Study of the Wells hydroelectric project. Prepared for Public Utility District No. 1 of Douglas County. Kirkland, Washington.

Ferrari, G., M.S. Politano, and L. Weber. 2008. Numerical simulation of free flows on a fish bypass. Computers & Fluids. In press.

Fu, S., B.E. Launder, and D.P. Tselepidakis. 1987. Accommodating the effects of high strain rates in modeling the pressure-strain correlations. The University of Manchester Institute of Science and Technology. TFD/87/5.

Gibson, M.M., and B.E. Launder. 1978. Ground effects on pressure fluctuations in the atmospheric boundary layer. Journal of Fluid Mechanics. 86: 491-511.

Guido-Lavalle, G., P. Carrica, A. Clausse, and M.K. Qazi. 1994. A bubble number density constitutive equation, Nuclear Engineering and Design. 152: 213–224.
Hibbs, D.E., and J.S. Gulliver. 1997. Prediction of Effective Saturation Concentration at Spillway Plunge Pools. Journal of Hydraulic Engineering 123: 940-949.

Ishii, M., and N. Zuber. 1979. Drag Coefficient and Relative Velocity in Bubbly, Droplet or Particulate Flows. American Institute of Chemical Engineers Journal. 25(5):843-855.

Jakobsen, H.A., H. Lindborg, and C.A. Dorao. 2005. Modeling of bubble column reactors: progress and limitations. Industrial & Engineering Chemistry Research 44: 5107-5151.

Klinge, R. 2005. Wells Dam total dissolved gas abatement plan for 2005 and 2006 project. Prepared for Public Utility District No. 1 of Douglas County. East Wenatchee, WA

Lamont, J.C., and D.S. Scott. 1970. An eddy cell model of mass transfer into the surface of a turbulent liquid. The American Institute for Chemical Engineers Journal. 16:513-519.

Lane, G.L., M.P. Schwarz, and G.M. Evans. 2005, Numerical modeling of gas-liquid flow in stirred tanks. Chemical. Engineering. Science. 60: 2203–2214.

Launder, B. E. 1989. Second-moment closure and its use in modeling turbulent industrial flows. International Journal for Numerical Methods in Fluids 9:963-985.

Liepmann, D. 1990. The near-field dynamics and entrainment field of submerged and near surface jets. Ph.D. thesis, University of California, San Diego.

Lopez de Bertodano, M.L., R.T. Lahey Jr, and O.C. Jones. 1994. Development of a $k-\varepsilon$ model for bubbly two-phase flow. Journal of Fluids Engineering. 116: 128-134.

Mannheim, C., and L. Weber. 1997. Hydraulic Model Studies for Fish Diversion at Wanapum/Priest Rapids Development, Part XI: Spillway Deflector Design, Contracted by Public Utility District No. 2 of Grant County, Ephrata, WA. IIHR Limited Distribution Report No. 264.

Orlins, J.J., and J.S. Gulliver. 2000. Dissolved Gas Supersaturation Downstream of a Spillway II: Computational Model. Journal of Hydraulic Engineering 38: 151-159.

Politano, M.S., P.M. Carrica, C. Turan, and L. Weber. 2007a. A multidimensional two-phase flow model for the total dissolved gas downstream of spillways. Journal of Hydraulic Research 45(2): 165-177.

Politano, M.S., C. Turan, P.M. Carrica, and L. Weber. 2007b. A three-dimensional anisotropic model of the two phase flow and total dissolved gas downstream of spillways. FLUCOME.
Politano, M.S., P.M. Carrica, and J.L. Baliño. 2000. A polydisperese model of the two-phase flow in a bubble column. Heat and Technology 18(2): 101-113.

Takemura, F., and A. Yabe. 1998. Gas Dissolution Process of Spherical Rising Gas Bubbles. Chemical Engineering Science. 53(15):2691-2699.

Turan, C., P. M. Carrica, T. Lyons, D. Hay, and L. Weber. 2008. Study of the Free Surface Flow on an Ogee-Crested Fish Bypass. Journal of Hydraulic Engineering. 134: 1172-1175

Turan, C., M.S. Politano, P. M. Carrica, and L. Weber. 2007. Water Entrainment and Mixing due to Surface Jets. Computational Fluid Dynamics, 21: 3-4, 137-153.

Walker, D.T. 1997. On the origin of the 'surface current' in turbulent free-surface flows. Journal of Fluids Engineering 339, 275-285.

Walker, D.T., and C.Y. Chen. 1994. Evaluation of algebraic stress modelling in free-surface jet flows. Journal of Fluids Engineering 118: 48-54

Appendix A

Differences Between Measured and Predicted TDG Concentrations

Comparison between measured and predicted TDG on June 4, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average difference (%)
TW1P2	1878138.733	345839.846	648.7	1.238	1.173	5.580			
TW1P3	1877972.651	345812.512	648.4	1.265	1.178	7.41			
TW1P4Z1	1877766.08	345652.528	692.0	1.224	1.200	1.97			
TW1P4Z2	1877685.593	345800.096	657.0	1.190	1.197	-0.61	1.229	1.187	3.56
TW2P2	1878494.473	343593.521	675.9	1.204	1.172	2.72			
TW2P3	1878414.713	343618.277	679.9	1.230	1.174	4.78			
TW2P4	1878237.515	343582.52	698.6	1.233	1.179	4.55	1.222	1.175	4.02
WELW	1870372.891	334581.117	692.0	1.190	1.165	2.18			
TW3P2	1870323.519	334702.235	698.7	1.202	1.171	2.69			
TW3P4	1870037.256	334948.965	673.4	1.211	1.179	2.74			
TW3P5	1869929.689	335169.057	697.9	1.222	1.188	2.87	1.207	1.176	2.62

Comparison between measured and predicted TDG on June 5, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average difference (%)
TW1P2	1878138.733	345839.846	648.7	1.160	1.200	-3.38			
TW1P3	1877972.651	345812.512	648.4	1.155	1.180	-2.05			
TW1P4Z1	1877766.08	345652.528	692.0	1.153	1.158	-0.46			
TW1P4Z2	1877685.593	345800.096	657.0	1.152	1.159	-0.68	1.155	1.174	-1.66
TW2P2	1878494.473	343593.521	675.9	1.151	1.181	-2.53			
TW2P3	1878414.713	343618.277	679.9	1.152	1.182	-2.57			
TW2P4	1878237.515	343582.52	698.6	1.151	1.183	-2.73	1.151	1.182	-2.61
WELW	1870372.891	334581.117	692.0	1.149	1.173	-2.04			
TW3P2	1870323.519	334702.235	698.7	1.150	1.178	-2.35			
TW3P4	1870037.256	334948.965	673.4	1.151	1.182	-2.68			
TW3P5	1869929.689	335169.057	697.9	1.150	1.182	-2.67	1.150	1.179	-2.44

Comparison between measured and predicted TDG on May 14, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average difference (%)
TW1P1Z1	1878593.614	345704.68	692.0	1.155	1.167	-1.00			
TW1P1Z2	1878511.224	345814.175	669.1	1.159	1.167	-0.67			
TW1P2	1878138.733	345839.846	648.7	1.170	1.181	-0.96			
TW1P3	1877972.651	345812.512	648.4	1.176	1.187	-0.91			
TW1P4Z1	1877766.08	345652.528	692.0	1.173	1.163	0.88			
TW1P4Z2	1877685.593	345800.096	657.0	1.166	1.168	-0.21	1.167	1.172	-0.48
TW2P1	1878645.036	343552.591	675.6	1.162	1.167	-0.43			
TW2P2	1878494.473	343593.521	675.9	1.162	1.170	-0.71			
TW2P3	1878414.713	343618.277	679.9	1.163	1.175	-1.05			
TW2P4	1878237.515	343582.52	698.6	1.164	1.180	-1.38	1.163	1.173	-0.89
WELW	1870372.891	334581.117	692.0	1.163	1.151	1.01			
TW3P2	1870323.519	334702.235	698.7	1.162	1.165	-0.28			
TW3P3	1870104.368	334818.929	679.0	1.163	1.164	-0.12			
TW3P4	1870037.256	334948.965	673.4	1.164	1.173	-0.80			
TW3P5	1869929.689	335169.057	697.9	1.164	1.170	-0.48	1.163	1.165	-0.14

Comparison between measured and predicted TDG on May 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average difference (%)
TW1-1S	1878593.614	345704.68	692.0	1.147	1.163	-1.38			
TW 1-1	1878511.224	345814.175	669.1	1.156	1.161	-0.44			
TW 1-2	1878138.733	345839.846	648.7	1.183	1.166	1.45			
TW 1-3	1877972.651	345812.512	648.4	1.188	1.173	1.21			
TW1-4S	1877766.08	345652.528	692.0	1.177	1.149	2.47			
TW 1-4	1877685.593	345800.096	657.0	1.168	1.153	1.30	1.170	1.161	0.77
TW 2-2	1878494.473	343593.521	675.9	1.168	1.168	0.01			
TW 2-3	1878414.713	343618.277	679.9	1.171	1.172	-0.11			
TW 2-4	1878237.515	343582.52	698.6	1.167	1.167	0.04	1.169	1.169	-0.02
WELW	1870372.891	334581.117	692.0	1.165	1.153	1.05			
TW 3-2	1870323.519	334702.235	698.7	1.166	1.164	0.15			
TW 3-3	1870104.368	334818.929	679.0	1.167	1.162	0.47			
TW 3-4	1870037.256	334948.965	673.4	1.168	1.169	-0.11			
TW 3-5	1869929.689	335169.057	697.9	1.168	1.161	0.59	1.167	1.162	0.43

Comparison between measured and predicted TDG on June 17, 2006

Transect	Easting (feet)	Northing (feet)	Z (feet)	TDG predicted	TDG measured	diff %	Average predicted	Average measured	Average difference (%)
TW1P1Z1	1878593.614	345704.68	692.0	1.188	1.256	-5.39			
TW1P2	1878138.733	345839.846	648.7	1.398	1.282	12.97			
TW1P3	1877972.651	345812.512	648.4	1.343	1.260	6.57			
TW1P4Z1	1877766.08	345652.528	692.0	1.284	1.217	5.54			
TW1P4Z2	1877685.593	345800.096	657.0	1.259	1.222	3.03	1.305	1.247	4.58
TW2P2	1878494.473	343593.521	675.9	1.261	1.261	-0.02			
TW2P3	1878414.713	343618.277	679.9	1.265	1.261	0.34			
TW2P4	1878237.515	343582.52	698.6	1.265	1.233	2.58	1.264	1.252	0.95
WELW	1870372.891	334581.117	692.0	1.256	1.243	1.06			
TW3P2	1870323.519	334702.235	698.7	1.264	1.249	1.16			
TW3P4	1870037.256	334948.965	673.4	1.268	1.248	1.58			
TW3P5	1869929.689	335169.057	697.9	1.269	1.238	2.53	1.264	1.245	1.58