Total Maximum Daily Load for Total Dissolved Gas in the Mid-Columbia River and Lake Roosevelt

Submittal Report

Washington State Department of Ecology

Spokane Tribe of Indians

U. S. Environmental Protection Agency

June 2004

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Submittal Report

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Table of Contents

Page

Appendices:

On the Web, these appendices are linked as separate files.

List of Tables and Figures

Page

Figures

Tables

Acronyms and Abbreviations

Corps	U.S. Army Corps of Engineers (also USACE)
CRIEMP	Columbia River Integrated Environmental Monitoring Program
CRITFC	Columbia River Inter-Tribal Fish Commission
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FCRPS	Federal Columbia River Power System
FERC	Federal Energy Regulatory Commission
FMS	Fixed Monitoring Station
fmsl	feet above mean sea level
HCP	Habitat Conservation Plan
kcfs	thousand cubic feet per second
mm Hg	millimeters of mercury
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
PUD	Public Utility District
TDG	Total Dissolved Gas
TGP	Total Gas Pressure
TMDL	Total Maximum Daily Load
USACE	U.S. Army Corps of Engineers (also "Corps")
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WBID	Waterbody Identification
WRIA	Water Resource Inventory Area
303(d)	Section 303(d) of the federal Clean Water Act
7Q10	Seven-day, ten-year frequency flow
ΔP	Excess gas pressure over barometric pressure

Abstract

This Total Maximum Daily Load (TMDL) study addresses total dissolved gas (TDG) in the mainstem Columbia River from the Canadian border to the Snake River confluence. Washington State has listed this area on its federal Clean Water Act 303(d) list due to TDG levels exceeding state water quality standards.

EPA is issuing this TMDL for all waters above Grand Coulee Dam and for all tribal waters. Washington State is issuing this TMDL for state waters below Grand Coulee Dam and submitting it to EPA for approval.

Elevated TDG levels are caused by spill events at seven dams on the Mid-Columbia River and by other sources upstream of the international border and in the Spokane River. Water plunging from a spill generates TDG at high levels, which can cause “gas bubble trauma” in fish. Voluntary spills are provided to meet juvenile fish passage goals. Involuntary spills are caused by lack of powerhouse capacity for river flows.

This TMDL sets TDG loading capacities and allocations for the Mid-Columbia River and Lake Roosevelt, both in terms of percent saturation for fish passage and excess pressure above ambient for non-fish passage. Allocations are specified for each dam and for upstream boundaries. Fish passage allocations must be met at fixed monitoring stations. Non-fish passage allocations must be met in all locations, except for an area below each dam (other than Grand Coulee) from the spillway downstream to the end of the aerated zone. Attainment of allocations will be assessed at monitoring sites in each dam’s forebay and tailrace and at the upstream boundaries.

A *Summary Implementation Strategy* prepared by the Washington State Department of Ecology and the Spokane Tribe describes proposed measures that could be used to reduce TDG levels in the Columbia River. Short-term actions primarily focus on meeting Endangered Species Act requirements, while long-term goals address both Endangered Species Act and TMDL requirements.

Acknowledgements

The U.S. Environmental Protection Agency and the Washington State Department of Ecology wish to acknowledge the cooperation of the following agencies in the production of this TMDL.

- The Spokane Tribe of Indians provided limnology data that their scientists have been collecting in Lake Roosevelt. The Tribe also provided review and technical input throughout the TMDL process, and assisted in implementation planning for Lake Roosevelt in conjunction with Ecology.

- The Confederated Tribes of the Colville Reservation provided comments and technical input.

- The U.S. Army Corps of Engineers (Seattle, Walla Walla, and Portland Districts; Northwest Division; and Engineer Research and Development Center) provided extensive technical information for this TMDL. This TMDL would have been much more difficult without the understanding of total dissolved gas production resulting from USACE's Dissolved Gas Abatement Study and site-specific near-field TDG generation studies.

- NOAA Fisheries provided valuable advice and review. The Biological Opinion issued in December 2000 pursuant to the Endangered Species Act was invaluable in describing the studies that have been conducted to date, and in specifying the effects of total dissolved gas on fish.

- Staff from the Kalispel Tribe also contributed to the process.

- The Bonneville Power Administration; U.S. Bureau of Reclamation; Douglas, Chelan, and Grant County Public Utilities Districts; Teck Cominco; Seattle City Power and Light; Avista; BC Hydro; Golder Engineers; Aspen Sciences; Aquila; the BC Ministry of Water, Land and Air Protection; Columbia River Integrated Environmental Monitoring Program (CRIEMP); and Environment Canada provided technical input and assistance.

Executive Summary

Description of Waterbody, Pollutant of Concern, and Pollutant Sources

This Total Maximum Daily Load (TMDL) study addresses total dissolved gas (TDG) in the mainstem Columbia River from the international border with Canada to its confluence with the Snake River near Pasco. This section of the Columbia River includes waters of Washington State, the Colville Tribe, and the Spokane Tribe. Washington State has listed multiple reaches of the Mid-Columbia River and Lake Franklin D. Roosevelt (Lake Roosevelt) on its federal Clean Water Act 303(d) lists due to TDG levels exceeding state water quality standards. The entire reach is considered impaired for TDG.

The U.S. Environmental Protection Agency (EPA) is issuing this TMDL for both state and tribal waters above Grand Coulee Dam including all of Lake Roosevelt. EPA is also issuing a TMDL for tribal waters below Grand Coulee Dam. Washington State is issuing this TMDL for state waters below Grand Coulee Dam and submitting it to EPA for approval.

TDG studies in the Mid-Columbia River (above the Snake River), Lake Roosevelt, the Spokane and Pend Oreille rivers, and in Canada were reviewed for information to support the development of a TDG TMDL report. The particular focus is on studies that collected TDG data and characterized the generation of TDG by the Mid-Columbia dams and by sources that effect TDG levels in Lake Roosevelt. The seven Mid-Columbia dams that are sources within the TMDL area are Grand Coulee, Chief Joseph, Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids.

Elevated TDG levels are caused by spill events at seven hydroelectric projects on the Mid-Columbia River, at hydroelectric projects upstream of the Columbia River's international border crossing, and upstream sources on the Spokane River. Water spilled over the spillway of a dam entrains air bubbles. When these are carried to depth in the dam's stilling basin, the higher hydrostatic pressure forces air from the bubbles into solution. The result is water supersaturated with dissolved nitrogen, oxygen, and the other gaseous constituents of air.

Fish in this water may not display signs of difficulty if the higher water pressures at depth offset high TDG pressure passing through the gills into the blood stream. However, if the fish inhabit supersaturated water for extended periods, or rise in the water column to a lower water pressure at shallower depths, TDG may come out of solution within the fish, forming bubbles in their body tissues. This gives rise to gas bubble trauma, which can be lethal at high levels or give rise to chronic impairment at lower levels. There is extensive research reported in the literature on the forms of physical damage to fish from gas bubble trauma.

Spills can occur at any time for several reasons:

- Spills for fish passage or other fish survival purposes (voluntary spills), conducted under the Biological Opinion in compliance with the federal Endangered Species Act or as a condition of a Federal Energy Regulatory Commission (FERC) license for operation of a non-federal dam.
- Spills required when flow exceeds powerhouse capacity (involuntary spills).

There are three main reasons for involuntary spills:

- The powerhouse cannot pass flood flows.
- Turbines are off-line due to lack of power demand.
- Turbines are off-line for maintenance or repair.

The six dams below Grand Coulee Dam on the Mid-Columbia are run-of-the-river dams with very little storage capacity. Therefore, the timing and volume of releases at Grand Coulee Dam can force spill at downstream dams. Operational decisions at the Mid-Columbia dams are based on regional management of the Columbia River system for flood control, power generation, fish flows, and other requirements. The Mid-Columbia Coordination Agreement guides management of the hydropower projects with the goal of minimizing operational spills.

This document describes TDG generation processes at the seven hydroelectric projects in the Mid-Columbia River and the sources of TDG impairment affecting Lake Roosevelt. It describes the development of equations to predict TDG production for sources within the TMDL scope area. Other sources of TDG in the TMDL area, such as tributaries, are also considered.

TDG is also affected by wind, water turbulence, barometric pressure, and water temperature; these influences are considered in this TMDL.

Description of the Applicable Water Quality Standards and Numeric Target

The water quality standards for Washington State, the Colville Tribe, and the Spokane Tribe have an identical TDG criterion: *110% of saturation not to be exceeded at any point of measurement.* The criteria for the Washington State and Colville Tribe do not apply to flows above the seven-day, ten-year frequency flow (7Q10) flood. In addition, special limits for TDG are established as a special condition in Washington rules, to allow higher criteria with specific averaging periods during periods of spill for fish passage if approved within a gas abatement plan.

Neither tribal standard has a provision that specifies higher TDG levels to account for fish passage spills. However, discussions with the Colville Tribe indicate the Tribe will consider variances under the provisions of their Tribal Regulations. Because any such variance would be temporary, it cannot be used as a compliance endpoint in the TMDL. In waters under Tribal jurisdiction and shared with the Tribe this, TMDL addresses only the 110% criterion. However, the Implementation Plan (Appendix A) provides flexibility for the Colville to consider appropriate means to determine compliance with this TMDL, including allowing for exceedances of the criteria during certain periods of the year.

Loading Capacity

The loading capacity for TDG under non-fish passage conditions has been defined in terms of excess pressure over barometric pressure (ΔP). This parameter was chosen because it can be directly linked to the physical processes by which spills generate high TDG, and it has a simple mathematical relationship to TDG percent saturation. Loading capacities ranging from 72 to 75 mm Hg have been set in the TMDL for the Mid-Columbia and Lake Roosevelt. These capacities are calculated to meet the 110% saturation criterion during critically low barometric pressure conditions.

Loading capacity during fish passage conditions is directly based on Washington's fish passage TDG criteria for the forebay and tailrace of each of the five dams downstream of the Okanogan River confluence.

Pollutant Allocations

Like loading capacity, allocations are stated in terms of percent saturation for fish passage and in terms of ΔP at all other times and locations. Load allocations are equal to loading capacity throughout the TMDL area, including each dam's forebay and tailrace. A load allocation is specified for the upstream boundary of the TMDL area and the Spokane River. The wasteload allocation under this TMDL is zero because no NPDES-permitted sources produce TDG.

For fish passage allocations, the compliance locations are at the fixed monitoring station sites in the forebay and tailrace (or other downstream site) of each dam.

For non-fish passage conditions, this TMDL will be in effect in eight reaches of the Columbia River, termed "compliance areas". The compliance area of Lake Roosevelt will begin at the head of the lake below the Canadian border and extend to the forebay of Grand Coulee Dam. From Grand Coulee to Priest Rapids Dam, the compliance areas will begin in the tailrace below the upstream dam and extend to the forebay of the downstream dam. The compliance area downstream of Priest Rapids Dam extends from the tailrace to the confluence of the Snake River.

For the six dams below Grand Coulee, the compliance area will begin at the end of the aerated zone at a specified distance below the spillway. Between the spillway and the end of the aerated zone at these six dams, compliance with the allocations is not required. Exclusion of these areas from the compliance area is authorized in accordance with the mixing zone provisions of state and tribal standards.

Non-fish passage load allocations are tied to structural and operational changes at each dam, and are intended as long-term targets. Long-term attainment of these allocations will be assessed at the downstream end of the aerated zone below each spillway after significant changes occur.

Margin of Safety

A margin of safety is supplied implicitly by use of conservative critical conditions for ambient barometric pressure. The common occurrence of wind-induced degassing of supersaturated waters in the TMDL area also provides a margin of safety. The TDG criterion itself provides a margin of safety due to its stringency as compared to site-specific biological effects documented by extensive research on TDG and aquatic life in the Columbia River.

Seasonal Variation

Spills and associated high TDG levels can potentially occur at any time, but are most likely to occur in the spring and early summer. An analysis of long-term TDG data shows that the risk of high TDG is negligible from October through February downstream of Grand Coulee Dam. Data from Lake Roosevelt and the International Boundary station suggest that high TDG sometimes occurs in other months. Therefore, TMDL load allocations apply year-round from the international border to Grand Coulee Dam, and from March through September downstream of Grand Coulee Dam.

In the development of critical conditions, seasonal effects have been evaluated, but seasonal variations appear to be small.

This TMDL only applies for flows below the 7Q10 flood flows for waters below the Spokane River confluence. These flows have been calculated for each dam.

Monitoring Plan

For both fish passage and non-fish passage allocations in the short term, fixed monitoring station sites will be used for continuous monitoring of implementation and operational controls. The long-term goal for continuous monitoring of compliance with allocations is to use (1) tailwater monitors that measure only spill conditions, (2) forebay monitors that measure cross-sectional average conditions, or (3) a statistical relationship developed between continuous monitors and locations of maximum TDG in the compliance areas. Long-term compliance with non-fish passage load allocations will be monitored following structural modifications at locations below the aerated zone using special studies in the tailrace of the dam.

Implementation Plan

The Summary Implementation Strategy attached as Appendix A is a compilation of the activities planned, underway, and already accomplished that address control and reduction of TDG at the hydroelectric projects on the Mid-Columbia River. This Strategy was developed with input from the agencies and groups that participated in the review of this TMDL.

The schedule for implementation of this and the previously issued Lower Columbia and Snake River TDG TMDLs are linked to the current timeline of the Endangered Species Act Federal

Columbia River Power System Biological Opinion. Emphasis in the short-term (now to 2010) is on supporting the need to spill at the dams for downstream migration of juvenile salmonids. It is expected that in the future there will be less reliance on the spill route for successful recovery of endangered salmonid populations.

The only significant sources of TDG within the TMDL area are the hydroelectric projects. The details of implementation of this TMDL will be developed as the PUD projects on the Mid-Columbia reapply for FERC licenses and water quality certifications under Clean Water Act Section 401, and as federal dams continue to either comply with TDG criteria or apply for gas abatement plan approvals. A detailed Implementation Plan will be developed in conjunction with these future activities.

Public Participation

Public involvement activities were organized by Ecology, the U.S. Environmental Protection Agency, and the Spokane Tribe. Activities include websites, focus sheets, news releases, stakeholder meetings, hearings, and conference presentations. Public hearings were held in March 2004. (See *Summary of Public Involvement* near the end of this report).

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Introduction

State and tribal water quality standards establish criteria at levels that ensure the protection of the water's beneficial uses. The Colville and Spokane tribes and the U.S. Environmental Protection Agency (EPA) are responsible for managing water quality for waters of the Colville and Spokane reservations. The Washington State Department of Ecology is charged to assess, manage, and protect the beneficial uses of the waters of Washington State.

A number of waterbody segments in the mainstem Columbia River fail to meet water quality standards and thus are included on Washington's 303(d) list. Under the Clean Water Act, Washington State is charged with returning state waters to compliance with state standards through development and implementation of Total Maximum Daily Loads (TMDLs). In developing a TMDL, the state should also consider attainment of downstream tribal or state water quality standards.

For tribal waters, the authority to issue TMDLs remains with EPA until individual tribes receive specific authorization to do so, thus EPA will be issuing this TMDL for tribal waters. In addition, the state of Washington has requested that EPA issue the TMDL for state waters in Lake Roosevelt.

Washington State, the Colville Tribe, and the Spokane Tribe have each established water quality criteria for total dissolved gas (TDG), which at high levels has deleterious effects on fish and other aquatic life. This document details a TMDL for TDG in the mainstem Columbia River from the international border with Canada to the mouth of the Snake River (Figure 1). This report will explain what TDG is, why high TDG is a problem, and a strategy for managing it so water quality standards will be met.

Figure 1: Map of the Mid-Columbia River and Lake Roosevelt TMDL Area

Geographic Extent

This TMDL applies to the Columbia River mainstem from the international border with Canada to its confluence with the Snake River near Pasco, including all waters up to the high water mark in Lake Roosevelt together with the Spokane River Arm (Figure 1).

The laws of Washington State apply to the Columbia River from the U.S.-Canada border to the mouth of the Snake River, excepting waters located on the Colville and Spokane reservations (Figure 2). All of the state waters have been included on Washington's 1996 303(d) list, 1998 303(d) list, or have been identified as impaired. The segments covered by this TMDL are listed in Table 1, along with the Water Resource Inventory Area (WRIA) and Waterbody Identification (WBID) numbers.

Table 1: Washington's Mid-Columbia River and Lake Roosevelt TDG Listed and Impaired Segments

Segment description	WRIA	WBID	1996 303(d) listings	1998 303(d) listings
Snake River Confluence to Priest Rapids Dam		WA-CR-1030	1	
Alkali-Squilchuck	40	NN57SG		2
Chief Joseph Dam to Priest Rapids Dam		WA-CR-1040	1	
Alkali-Squilchuck	40	NN57SG		2
Lower Crab	41	NN57SG		1
Wenatchee	45	NN57SG		2
Chelan	47	NN57SG		2
Foster	50	NN57SG		1
Grand Coulee Dam to Chief Joseph Dam		WA-CR-1050	1	
Foster	50	NN57SG		1
Lower Lake Roosevelt Watershed	53	NN57SG		3
Canadian Border to Grand Coulee Dam		WA-CR-1060	1	
Upper Lake Roosevelt Watershed	61	NN57SG		3
Totals			4	17

The Colville Reservation borders Lake Roosevelt on the west and north for 100 miles upstream of Grand Coulee Dam. The reservation forms the northern shore of the Columbia River downstream of Grand Coulee Dam to the confluence of the Okanogan River between Chief Joseph and Wells dams. Therefore, Colville tribal waters include those portions of Lake Roosevelt and the Columbia River within reservation boundaries, and the Colville Tribe's water quality standards apply in these waters.

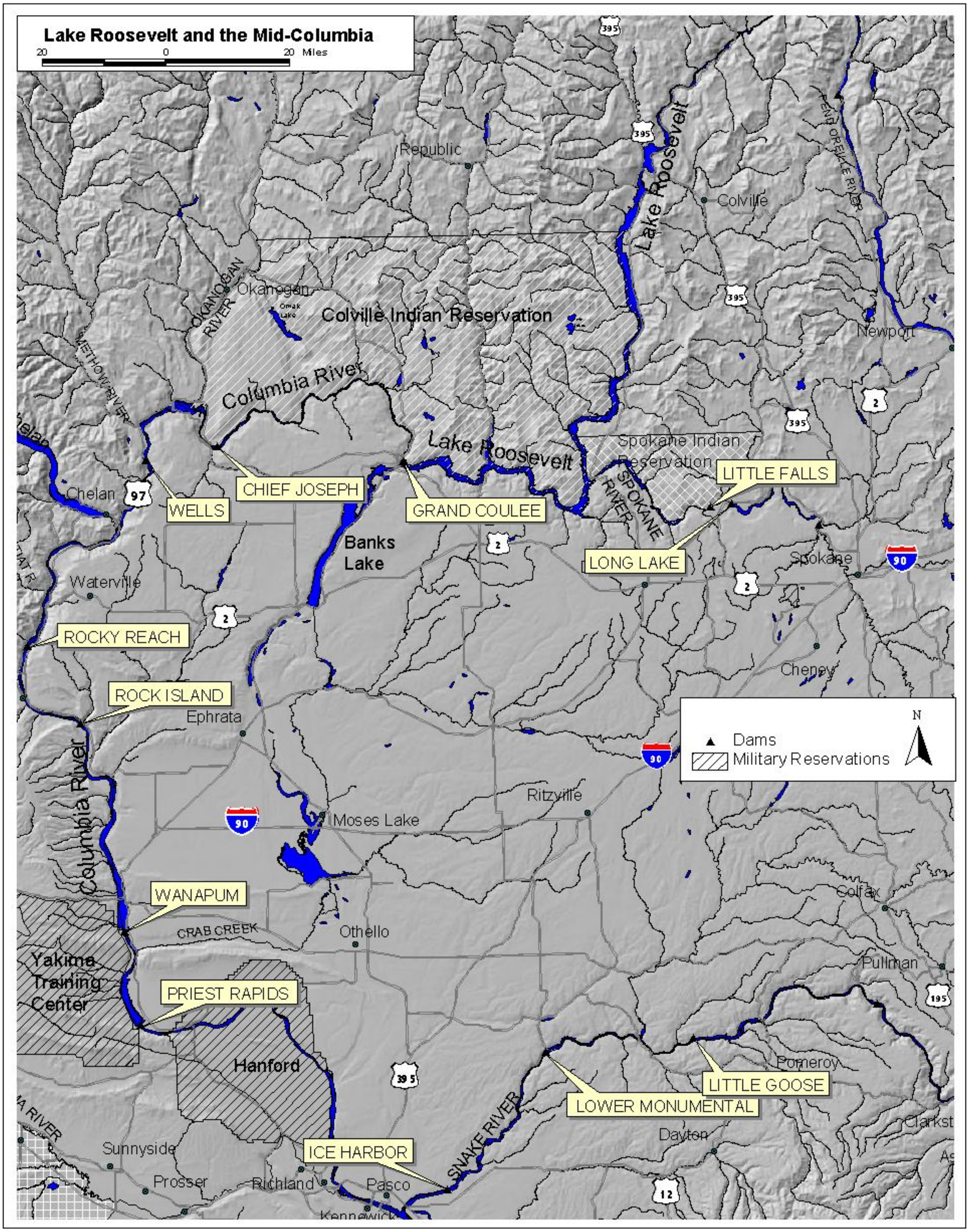

Figure 2: Lake Roosevelt and the Mid-Columbia River

The Spokane Indian Reservation borders Lake Roosevelt on the eastern shore, in the area upstream of the Spokane River confluence. Spokane tribal waters include a portion of Lake Roosevelt including all of the Spokane River Arm. The Spokane Tribe has approved water quality standards for those waters within its southern and western reservation boundaries that lie within the TMDL area.

The Yakama Nation, Confederated Tribes of the Umatilla Reservation, Nez Perce, and Confederated Tribes of Warm Spring Reservation are the four tribes with treaty rights to the Columbia River salmon fishery and, as such, have an interest in the results of this TMDL. Because they do not have tribal waters within the scope of the TMDL area, they have not directly participated in the formulation of this TMDL. However these tribes have been offered the opportunity to consult on the TMDL, and their comments have been solicited during the public outreach phase of the TMDL process.

TMDLs for TDG have been completed for the Lower Columbia River by the states of Oregon and Washington (Pickett and Harding, 2002), and for the Lower Snake River (Clearwater River to confluence with the Columbia River) by Washington (Pickett, 2002). Those two TMDLs provide guidance as to the TDG levels that will need to be attained at the downstream end of this reach in order to achieve downstream water quality standards.

Clean Water Act Requirements

Water quality monitoring has shown that during certain times of the year TDG levels in the Columbia River between the Canadian border and the confluence with the Snake River exceed these standards. Table 1 summarizes the portions of the river listed as impaired for TDG pursuant to section 303(d) of the federal Clean Water Act. On its 1998 303(d) list, Washington listed 17 segments of Lake Roosevelt and the Columbia River above the Snake River confluence for impairment by TDG.

As a result of these listings and under the authority of the Clean Water Act (33 U.S.C. 1251 et seq.) as amended by the Water Quality Act of 1987 (P.L. 100-4), the EPA and Washington Department of Ecology (Ecology) are establishing these TMDLs for TDG in the mainstem of the Columbia River, from the Canadian border to the confluence of the Snake River. EPA is establishing the TMDL for all waters above Grand Coulee Dam, and for waters below Grand Coulee Dam within the Colville Indian Reservation. Ecology is establishing TMDLs for state waters below Grand Coulee Dam, and will submit this TMDL to EPA for their approval. Washington operates under a Memorandum of Agreement with EPA, which guides the TMDL submittal. EPA and Ecology have been working in coordination with the Spokane Tribe throughout the process of developing this TMDL. The Colville Tribe has had limited involvement with the TMDL.

Ecology requested by letter that EPA establish the TMDL for TDG in Lake Roosevelt. Ecology also cited the inter-jurisdictional nature of the waterways as the reason for its request. The request was made pursuant to Section 13 of the TMDL Memorandum of Agreement between Ecology and EPA dated October 29, 1997.

EPA has authority under section 303(d)(2) of the Clean Water Act to approve or disapprove TMDLs submitted by the states and tribes and to establish its own TMDLs in the event that it disapproves a state or tribal submission. EPA also has the authority under section 303(d)(2) to establish TMDLs in response to an explicit state request. EPA's exercise of authority to establish TMDLs in response to a state's request is consistent with the larger purpose of section 303(d)(2) – to ensure the timely establishment of TMDLs – and it honors the primary responsibility imputed by Congress to the states. In addition, when the TMDL focuses on inter-jurisdictional waters, EPA's involvement can facilitate the resolution of complex cross-jurisdictional problems that might be difficult for an individual state or tribe, acting alone, to resolve. For similar reasons, EPA has authority to establish TMDLs on behalf of tribes that have not been authorized to establish TMDLs under section 518(e) of the Clean Water Act.

Therefore, the goal of this project is to provide a single analysis and set of TMDL allocations which will lead to attainment of the TDG criteria established for waters of Washington State and the Colville and Spokane tribes. An implementation plan has been developed by Ecology and the Spokane Tribe which identifies actions to be taken to achieve the allocated loads (Appendix A).

Coordination with Endangered Species Act

A TMDL is a planning tool, not a rule of law or other stand-alone enforceable document. It does not take precedence over the federal Endangered Species Act, Indian Treaties, or federal hydropower system enabling legislation. It takes no action that would trigger a review under the National Environmental Policy Act or Washington State Environmental Policy Act. TMDLs may be used to condition exemptions, modifications, variances, permits, licenses, and certifications.

There is much overlap between protection of the fisheries designated use in this TMDL established pursuant to the federal Clean Water Act and the protection of salmonids listed as threatened or endangered under the Endangered Species Act, administered by the NOAA Fisheries. It is therefore important that there is a clear understanding of the requirements of this TMDL relative to measures required by Biological Opinions issued in relation to the threatened and endangered species of the Columbia River.

The 2000 Federal Columbia River Power System (hydropower system) Biological Opinion requires that the action agencies (U.S. Army Corps of Engineers, Bonneville Power Administration, and the U.S. Bureau of Reclamation) meet specific hydropower system biological performance standards for both adult and juvenile salmon. The purpose of these standards is to help reverse the downward trend in listed salmon populations and therefore ensure viable salmon resources in the Columbia River basin. The hydropower system goals for juvenile salmon are one part of a three-tiered approach to assess implementation of the Reasonable and Prudent Alternative Section items presented in the Biological Opinion. These hydropower system standards are combined with standards for harvest, habitat, and hatcheries, as well as other life-stage indicators to arrive at a population level standard.

The hydrosystem survival performance standards can be met by a combination of controlled spills, fish passage facilities to divert juvenile salmon from passing through the turbines, or juvenile transportation by truck or barge. Due to the current configuration of the hydroelectric projects along the Columbia River, NOAA Fisheries sees spill as the safest, most effective tool available for improving survival of juvenile out-migrants. However, these performance standards are sometimes not being met at the current implementation level of the spill program. Therefore, in the short-term, structural gas abatement solutions may often result in higher spill discharges rather than lower TDG levels. But as new, more effective fish passage facilities are completed and evaluated, their contribution to the attainment of hydropower system performance standards will hopefully allow spill levels for fish passage and associated TDG levels to be reduced, but only as long as the performance standards are met.

Spills for fish passage under the Biological Opinion cause TDG supersaturation above the 110% criterion. The state and tribal water quality standards are meant to be sufficiently protective so as to prevent damage to beneficial uses of the tribal and state waters. The effects of elevated dissolved gas on migrating juvenile and adult salmon due to voluntary spill have been monitored each year of spill program implementation. Based on five years of data from the biological monitoring program, the average incidence of gas bubble disease signs has been low, although the state-allowed maximum TDG due to spill was 120% in the tailrace and 115% in forebays. From 1995 to 1996, only 1.6% of all the 200,000 juveniles sampled showed signs of disease (Schneider, 2001). These results suggest that, in weighing the benefit gained in increased salmonid survival by spills for fish passage against the benefit from strict adherence to the 110% TDG criterion in the standards, it would be reasonable to find flexibility in application of the standards.

Chief Joseph and Grand Coulee dams are barriers to fish migration. There are no anadromous species present in the river above Chief Joseph Dam. Release of water is required from both dams to facilitate the requirements of the NOAA Fisheries Biological Opinion for fish passage in the downstream portions of the river. These dams are in waters shared between Washington State and the Colville Tribe. Under the terms of the proposed power trading arrangement between the two dams, Grand Coulee Dam should be able to meet the need for additional flow without spilling. Fish augmentation flow through Grand Coulee Dam’s turbines sometimes necessitates involuntary spill at Chief Joseph Dam.

Funding was approved this year for the flow deflector project at Chief Joseph, with installation targeted for 2005, subject to continued funding. This structural retrofit, in conjunction with the power trading agreement, is expected to significantly reduce TDG levels in Chief Joseph tailrace and in the river downstream.

Recently, NOAA Fisheries issued 50-year incidental take permits to Douglas and Chelan PUDs for operating the Wells, Rocky Reach, and Rock Island hydroelectric projects in accordance with their proposed Habitat Conservation Plans (HCPs). The HCPs require the PUDs to achieve and maintain a 91% Combined Adult and Juvenile Project Survival standard by 2013 (2018 in the case of the Wells project) for each of the Endangered Species Act-listed and unlisted anadromous salmon species that migrate through the individual projects. At this time, some level of voluntary spill/bypass appears to be necessary at these projects to assure that juvenile project survival is sufficient to achieve this standard. The HCPs were designed to address all anadromous salmonid fish issues and do not address water quality issues relating to these projects. However, the HCPs do recognize that water quality issues may arise during the term of the HCPs: "The Parties recognize that there are potential water quality issues (temperature and dissolved gas) related to cumulative hydropower operations in the Columbia River. The Parties will work together to address water quality issues" (Section 5.3 of the Wells HCP, and Section 6.3 of the Rocky Reach and Rock Island HCPs).

In June 2003, Judge James A. Redden remanded the 2000 Biological Opinion to NOAA Fisheries to resolve several deficiencies. A subsequent motion to vacate the Biological Opinion was denied; therefore, it will remain in place as deficiencies are addressed. This TMDL will address the fish passage spill program as it currently is being implemented.

In summary, the provisions of both Acts must be met. Notwithstanding that, it is not the purpose of the Clean Water Act to usurp functions properly undertaken pursuant to the Endangered Species Act. On the contrary, EPA has consulted with NOAA Fisheries and the U.S. Fish and Wildlife Service under section 7 of the Endangered Species Act to ensure the TMDL does not cause jeopardy to any listed species. Over time the state, tribes, and EPA will continue to coordinate with NOAA Fisheries and the Fish and Wildlife Service, as implementation measures needed to attain load allocations are pursued.

This TMDL is written to reflect the ultimate attainment of the TDG water quality standard. Fish passage requirements can be facilitated under an implementation plan, but the clear expectation of the Clean Water Act is that water quality standards will be attained in a limited amount of time. Efforts to do so are outlined in the attached Summary Implementation Plan (Appendix A).

Total Dissolved Gas Water Quality Standards

The goal of this TMDL is to achieve all of the TDG criteria established within water quality standards of Washington State, the Colville Tribe, and Spokane Tribe. The criteria for all three entities are similar, although there are differences which will need to be considered during the implementation of this TMDL. The water quality standards relative to TDG for each jurisdiction are outlined below. This is followed by a discussion of the target to be used in this TMDL to assure attainment of all three sets of criteria.

In the water quality standards, TDG is defined as the percent of saturation relative to atmospheric pressure. The "seven-day, ten-year frequency flood" is usually termed the "7Q10" flood flow.

State of Washington Standards

Chapter 173-201A Washington Administrative Code (WAC) contains the water quality standards for the state of Washington. Pertinent sections are as follows:

WAC 173-201A-200(1)(f): Aquatic life total dissolved gas (TDG) criteria.

TDG is measured in percent saturation. Table 200(1)(f) (see Table 2) lists the maximum TDG criteria for each of the aquatic life use categories.

(i) The water quality criteria herein established for TDG shall not apply when the stream flow exceeds the seven-day, ten-year frequency flood.

(ii) The TDG criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a department approved gas abatement plan. This plan must be accompanied by fisheries management and physical and biological monitoring plans. The elevated TDG levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. The following special fish passage exemptions for the Snake and Columbia rivers apply when spilling water at dams is necessary to aid fish passage:

- TDG must not exceed an average of 115% as measured in the forebays of the next downstream dams.
- TDG must not exceed an average of 120% as measured in the tailraces of each dam.
- TDG is measured as an average of the 12 highest consecutive hourly readings in any one day, relative to atmospheric pressure.
- A maximum TDG one-hour average of 125% must not be exceeded during spillage for fish passage.

Table 2: Aquatic Life TDG Criteria from the Washington State Code

Table 200(1)(f): Aquatic Life Total Dissolved Gas Criteria in Fresh Water	
Category	Percent Saturation
Char	TDG shall not exceed 110% of saturation at any point of sample collection.
Salmon, Steelhead, and Trout Spawning, and Rearing	Same as above
Salmon, Steelhead, and Trout Rearing – Only	Same as above
Non-anadromous Interior Redband Trout	Same as above
Indigenous Warm Water Species	Same as above

Colville Tribe Standards

The Colville Tribe's Water Quality Standards, CFR 131.35 (f)(1)(ii) (C) and (f)(2)(ii) (C), set the following criteria for tribal waters covered under this TMDL:

Total dissolved gas concentrations shall not exceed 110% of the saturation value for gases at the existing atmospheric and hydrostatic pressures at any point of sample collection.

Spokane Tribe Standards

The Spokane Tribe's Surface Water Quality Standards, Chapter 30, Resolution 2001-144 of the Spokane Tribal Council, set the following criteria for tribal waters covered under this TMDL:

Total dissolved gas shall not exceed 110% of saturation at any point of sample collection.
[Spokane Tribe's Surface Water Standards 9 (1) (c) (iii) & (2) (c) (iii)]

TMDL Targets

The three water quality standards all set 110% saturation as the criterion applicable to TDG in waters under their jurisdictions unless a waiver or special condition is allowed. Therefore the target for this TMDL has been set at 110% of saturation in the absence of a waiver or special condition.

The Washington State and Colville Tribal water quality regulations allow exceedance of the 110% standard at flows above the 7Q10 flood flow. The Spokane Tribe's standard does not contain this exemption.

Washington State allows exceedance of the 110% criteria to facilitate fish passage spills where there is an approved gas abatement plan. Neither tribal standard has a provision that specifies higher TDG level to account for fish passage spills. However, discussions with the Colville Tribe indicate that the tribe can grant variances according to the provisions of the tribal regulations. Since any variance granted would be temporary and localized, it cannot be used as a compliance endpoint in the TMDL. TMDLs must by law ensure compliance with the existing permanent standards. There are separate processes to revise the water quality standards and establish new criteria. If the TDG standards are ever revised in a way that affects this TMDL, then the TMDL may be revisited and modified appropriately. The Implementation Plan (Appendix A) provides the flexibility for the Colville Tribe to determine appropriate means to determine compliance with this TMDL, including allowing for exceedances of the criteria during certain periods of the year.

Therefore, in waters upstream of the Okanogan River, the TMDL will not provide an exemption for fish passage spills, except as a temporary waiver or special condition as part of the short-term compliance period described in the Implementation Plan. Downstream of the Okanogan River, allocations will be provided based on both the 110% criteria and the criteria established for fish passage in the Washington State water quality standards. Any allocations or exemptions for fish passage may be used only after approval of a gas abatement plan.

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Background

Sources of TDG

Total dissolved gas (TDG) levels can be increased above the water quality criteria by spilling water over spillways of dams on the Columbia River. There are a variety of other ways that TDG may be elevated: passage of water through turbines, low-level ports, fishways, or locks; and natural processes such a low barometric pressure, high water temperatures, or high levels of biological productivity. However, the vast majority of elevated TDG levels found in the Columbia River are caused by spills from dams. Man-made sources other than spill are minor and can be considered negligible. Natural processes may have a significant effect on TDG and are addressed in setting load allocations.

Spills at dams occur for several reasons:

1. To enhance downstream fish passage (to meet *Performance Standards* for fish survival under the Endangered Species Act).
2. To bypass water that exceeds the available hydraulic capacity of the powerhouse due to:
    - o High river flows
    - o Flood control releases
    - o Lack of power market
    - o Maintenance, break-down, or other reasons

The first type of spill is sometimes called *voluntary spill*, while the second types are termed *involuntary spills*". Figure 3 illustrates the typical configuration of a dam on the Columbia River.

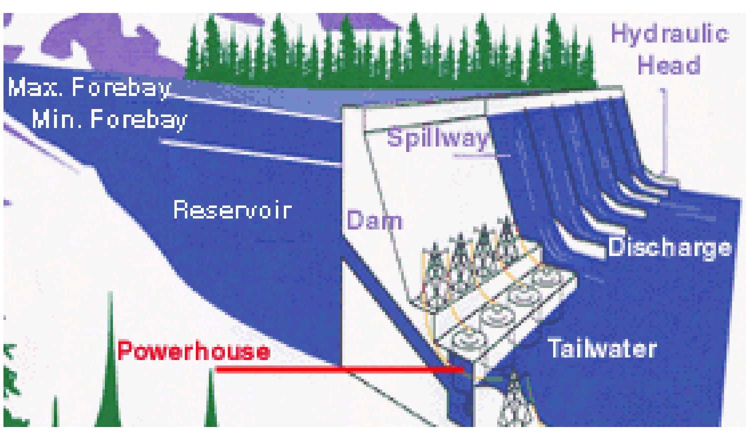

Figure 3: Typical Dam Configuration

Spill for Fish Passage

Spill for purposes of fish passage involves water deliberately released over dam spillways, rather than being discharged through turbines or fish bypass facilities. The intent is to expedite juvenile migration down river and to reduce turbine and bypass mortalities. For example, Schoeneman et al. (1961) found that mortality in Chinook juveniles spilled over McNary Dam (Columbia River) and Big Cliff Dam (Santiam River) was less than 2%. Subsequent studies confirmed this estimate, and additional research is ongoing.

The requirement for spring and summer spills to pass juvenile salmon was included in the 1995 and 2000 Biological Opinions for the Columbia River Dam operations. In order to account for these needs, the Washington State has established the special TDG limits to allow limited fish passage spill.

Washington's approach to allow the dams to operate in accordance with the Biological Opinion was to adopt a rule revision specifying the TDG criteria for fish passage spill. These limits usually require that TDG levels not exceed 120% saturation as a 12-hour average and 125% saturation as a one-hour maximum relative to atmospheric pressure in the tailrace of the spilling dam, and 115% TDG saturation as measured in the forebay of the next dam downstream. Periods in which the fish passage criteria are in effect usually extend from the middle of April through the end of August each year. No similar exemptions currently exist with either the Spokane or Colville tribes.

Involuntary Spill

Like spills for fish passage, involuntary spill involves water being discharged over dam spillways. However, the causes and intended consequences are different. As its name suggests, there is no choice involved in *involuntary* spill. At times of very high river flows, the quantity of water exceeds the capacity of a dam to either temporarily store the water upstream of the dam or pass the water through its turbines. In these circumstances, water is released over the spillway because there is nowhere else for it to go.

The Columbia River hydropower system in Washington is somewhat unique in that regard. With the exception of Grand Coulee Dam, it contains very little storage potential relative to the quantity of spring runoff. The dams from Chief Joseph downstream through Priest Rapids do have limited storage capability that can be used to reduce spill on a short-term (daily) basis by drafting and filling at appropriate times. However, at times of rapid runoff, the dams cannot constrain the quantity of water, and it is spilled with attendant high TDG levels.

Often dissolved gas levels from involuntary spill exceed those experienced during periods of spill for fish. However, high river flows under these circumstances are often in excess of the 7Q10 flood flow, in which case the TDG standards of the state and Colville Tribe do not apply. The Spokane Tribe has no exemption for 7Q10 flood flows in their water quality standards. Involuntary spill as a result of lack of power market is a variant of the above. In this scenario, the power marketing authority cannot sell any more power, and even though turbines are available, water is released over the spillway because there is nowhere for electricity generated to go. Running water through the turbines with no load increases wear and tear with attendant higher maintenance costs, and also may reduce fish survival. Lack of power load demand can occur at times of both high and low flows (e.g., in the spring or fall when power demands are low both in California and the Pacific Northwest). Also releases from upstream storage dams during high load times (morning and evening) can result in high flows at downstream dams during low load times (middle of the night), causing an involuntary spill.

Involuntary spill can also occur at low flows when turbines are taken off-line for maintenance, breakdown, or other needs. Maintenance is usually scheduled to prevent a spill, by doing maintenance on one or two generating units at a time during low flow and low power demand periods. Nonetheless, releases from upstream dams can complicate management of spills during maintenance. Also, unscheduled maintenance and repairs sometimes occur, which may require a turbine shut-down and involuntary spill.

In general, involuntary spill conditions at the "run-of-the-river" dams in the Mid-Columbia River result from reservoir control decisions made for Grand Coulee Dam as part of overall Columbia River system management. The "Agreement for the Hourly Coordination of Projects on the Mid-Columbia River", signed by Bonneville Power Administration and the Mid-Columbia dam owners, is the basis for managing flows in the Mid-Columbia. One of its primary goals is to minimize involuntary spill.

Under the Hourly Coordination Agreement, a central dispatcher based at Grant PUD allocates generation and spill with the support of real-time data and computer programs. However, after reducing the overall amount of spill that would have otherwise occurred, the Central Dispatcher manages the distribution of any remaining spill at non-federal projects, while it is primarily the Bonneville Power Administration's PBL Scheduler that manages any spill that is necessary at the two federal dams. Also, operations sometimes occur outside the Hourly Coordination Agreement, which can result in flows arriving at downstream dams during low power demand times resulting in additional involuntary spill.

Spill levels are set in accordance with Spill Priority guidelines established by the U.S. Army Corps of Engineers with water quality in mind. Bonneville Power adjusts generation throughout the federal system to make sure spill occurs according to these guidelines (distribution among projects, amount, and timing). Generation is also shifted between federal and non-federal resources through special arrangements with other parties in order to follow the Spill Priorities.

Flow levels in the Mid-Columbia above Grand Coulee Dam are dependent on management of upstream dams in the U.S. and Canada. The three Canadian "treaty dams" are managed according to flood control rule curves set by international treaty. Other dams managed by a variety of owners, including two federal dams, operate in general to minimize spill but are constrained by other needs, such as flood control, recreation, and fisheries protection. Changes in management for other needs, such as flow augmentation proposals or the VARQ proposal at the federal dams, can result in higher or lower frequencies of spill throughout the system.

Overall, the probability of spill is also affected by the accuracy in water supply forecasting and how operation models use those forecasts. Forecasting tools and operational models are under ongoing development, and new proposals are often the subject of lively debate. The effects of these proposals on spills and TDG usually become a part of those discussions.

Water Quality and Resource Impairments

TDG Generation from Spills

Spills for fish passage typically occur during the spring and summer months. During periods of fish spills, deviations of ambient conditions from the state of Washington's TDG criteria for fish passage are frequent but usually small. This is because spill quantities are managed to meet those criteria.

The excursions beyond fish passage criteria during voluntary spill usually have been no more than one or two percentage points of saturation above the criteria, and occur as a result of the imprecision in reproducing exact TDG levels at specific spillway gate set points due to all the sources of TDG variability described. Generally, the fishery management agencies have sought spill quantities that keep TDG levels as close to the criteria as possible at the fixed monitoring station (FMS) sites. Any small change in conditions that influence TDG, such as change in barometric pressure, water temperature, incoming gas, total river flow, or tailwater elevation can cause an exceedance when operated this way.

No similar relaxation of the standard currently exists for fish passage spills in either the Spokane or the Colville water quality standards. Most of the time during the spring and summer, TDG levels exceed the 110% criterion of both tribes.

TDG levels above criteria most often are caused by involuntary spills, which can occur at any time. Involuntary spills caused by river flows above powerhouse capacity are most likely to occur from late spring to early summer, depending on rainfall or snowmelt in the tributary watersheds. However, high flows could also occur due to releases from upstream dams with significant storage, such as Grand Coulee or the Canadian dams. Involuntary spill due to low power demand is most likely in the spring, although this is also dependent on regional power management by the Bonneville Power Administration. Loss of powerhouse capacity to maintenance or repair is usually scheduled so that no more than one or two turbines are out at any given time, but an emergency turbine shutdown and spill could occur at any time as the result of a fire or other disaster.

At times of involuntary spill, exceedances above the standard can rise dramatically, peaking above 130% of saturation, and even 140%. TDG pressures at these levels can be lethal to fish, although these levels as absolute pressures only occur in relatively shallow waters,. Usually fish are protected from fatal pressures in deeper waters where absolute TDG pressures are lower due to compensation from hydrostatic pressures.

For all spills, the highest TDG levels, and therefore the area most likely to exceed standards, are directly below the spillway. In this area, the plunging and air entrainment of the spill (aerated zone) generates high levels of TDG, but then quickly degasses while the water remains turbulent and full of bubbles. However, as this water moves from the stilling basin into the tailrace, degassing slows and the TDG levels stabilize.

In the pools, gas exchange rates increase as wind speeds rise, which produces degassing. If conditions are still and TDG concentrations are constant, the percent saturation of TDG can increase if the water temperature increases or barometric pressure drops (Figure 4). Also, primary productivity (periods of algal growth) can increase dissolved oxygen levels, which results in a higher TDG percent saturation. However, because oxygen is metabolized by aquatic life, the physical effects of supersaturated oxygen are minor compared to nitrogen and can be considered *de minimus.*

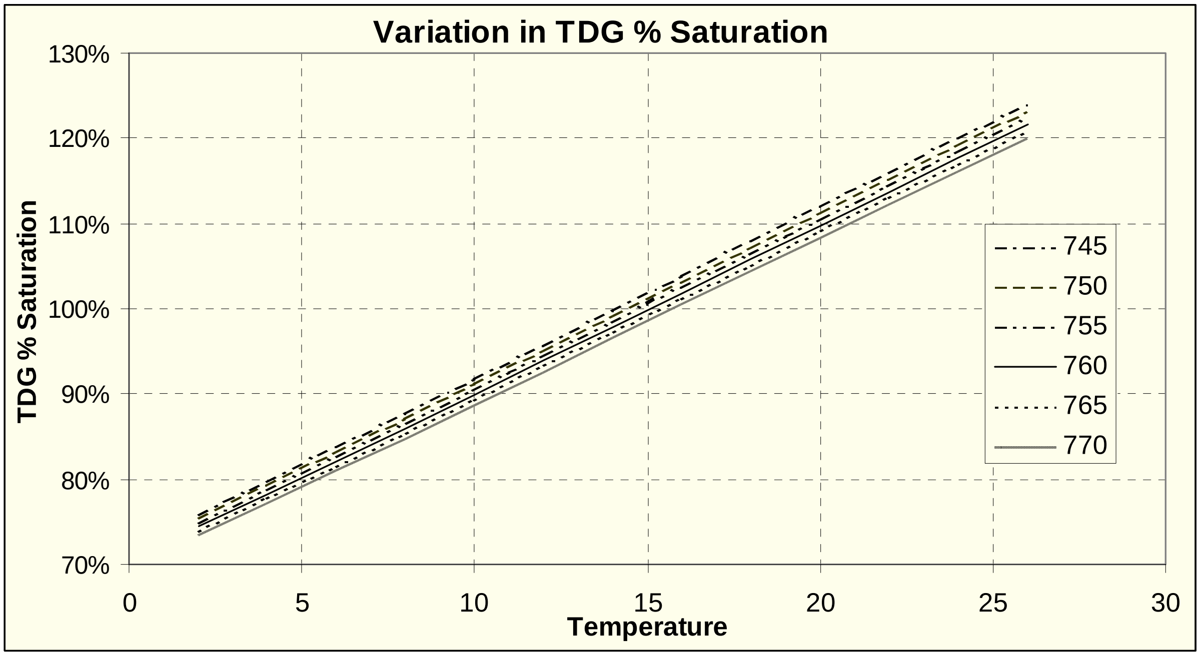

Figure 4: Variation in TDG Percent Saturation with Temperature and Barometric Pressure at Constant Concentration

The fate of powerhouse releases is a critical component at some projects in determining the TDG loading produced for a given operation. At some projects, because of the hydraulic properties of the spill, a proportion of the powerhouse flow may be entrained into the spillway flows and experience comparable rates of TDG exchange as spill waters. The rest of the powerhouse flow mixes with the spillway flows at varying rates, sometimes quite slowly, as the river moves downstream from the dam. Powerhouse TDG levels are typically identical with forebay TDG levels – very little gas exchange occurs as water passes through the powerhouse. Therefore, if the forebay TDG levels are lower than levels below the spillway, the flows that mix downstream will show lower TDG levels than the spillway waters.

TDG Impacts on Aquatic Life

Fish and other aquatic life inhabiting water supersaturated with TDG may tend to display signs of difficulty, especially if higher dissolved gas pressure gradients occur. Gas bubbles form only when the TDG pressure relative to atmospheric pressure is greater than the sum of the compensating pressures. Compensating pressures include water (hydrostatic) and barometric pressure. For organisms, tissue or blood pressure may add to the compensating pressures. Gas bubble development in aquatic organisms is then a result of excessive uncompensated gas pressure. The primary actions which will enhance the likelihood of bubbles forming in the fish are (1) continued exposure to the highly saturated water, (2) rising higher in the water column bringing about a higher pressure gradient (decreased hydrostatic pressure), (3) decreases in barometric pressure, and (4) increasing water temperature.

The damage caused by release of gas bubbles in the affected organism is termed *gas bubble trauma* or *gas bubble disease*. There is a wide body of research on this condition. Effects of gas bubble trauma include emphysema, circulatory emboli, tissue necrosis, and hemorrhages in brain, muscle, gonads, and eyes (Weitkamp and Katz, 1980). Nebeker et al. (1976) found that death in adults was due to massive blockages of blood flow from gas emboli in the heart, gills, and other capillary beds. Investigators in the 1970s reported many and varied lesions in fish exposed in the 115-to-120% TDG range in shallow water. At higher gas exposures (e.g., 120 to 130% TDG), death frequently ensued before gas bubble trauma signs appeared (Bouck et al., 1976). External signs of gas bubble trauma (e.g., blisters forming in the mouth and fins of fish exposed to chronic high gas) often disappeared rapidly after death. The signs were largely gone within 24 hours (Countant and Genoway, 1968).

A water quality criterion for TDG was set at 110%, the threshold for chronic effects found in the literature. The severity of gas bubble trauma increases as the TDG level increases above compensating pressures, until at higher levels lethality can occur swiftly. However, there are a number of factors that affect a particular organism's response to high TDG levels. Different species respond to changing TDG differently, and the response also varies by life stage. Juvenile salmonids appear to be relatively resilient compared to adults or to non-salmonids.

Scholz et al. (2000) conducted surveys of fish in Lake Roosevelt to assess the extent of gas bubble trauma in fish after the extremely high TDG levels during 1997 runoff. The FMS at Grand Coulee forebay was continuously above 120% TDG saturation from mid-May through the end of June in 1997. Data from the international border FMS showed levels of TDG exceeding 130% from mid-May through mid-June in 1997. This study looked at 9,319 fish from 29 species, and found over 65% of fish exhibiting symptoms of gas bubble trauma. Ten species had sample sizes of over 100. Of these 10 species, the two species with the lowest percent of gas bubble trauma symptoms were both from *Salmonidae* – Kokanee and Rainbow trout – and had 14.2% and 22.0% with symptoms, respectively. The two species with the highest percent of symptoms from this subsample were Largescale Sucker and Burbot, which showed 85.5% and 86.9% with symptoms, respectively. Sampling of Largescale Sucker in Lake Roosevelt between 1996 and 1999 indicated a loss of 90-95% of the population of that species, with a gap in the age distribution corresponding to the high TDG years of 1996 and 1997.

The U.S. Geological Survey (USGS) conducted a multifaceted study of the effects of TDG on resident fish in Rufus Woods Lake below Grand Coulee Dam (Beeman et al., 2003). Field work included examination of over 8000 resident fish for signs of gas bubble disease, examination of the annual growth increments relative to ambient TDG, and recording the in-situ depths and temperatures of several species using miniature recorders surgically implanted in fish. Laboratory experiments included bioassays of the progression of signs and mortality of several species at various TDG levels. Monitoring found that all fish migrated vertically at sunrise and sunset, although the average depth varied by species. Progression of gas bubble trauma symptoms was unpredictable, except that 115% resulted in the most exaggerated signs, while fish exposed to 125 and 130% TDG died prior to extensive sign formation. Sensitivity to TDG varied by species, and a correlation was found to lateral line pore size. Although species composition has changed over time, no evidence could be found that tied species composition or growth rates to TDG effects. Overall risk from TDG was ranked by species, but qualitative predictions were not obtained.

Other research has been conducted on the effects of TDG on anadromous fish in the Columbia River. It is beyond the scope of this TMDL to conduct a comprehensive review of that literature. The Clean Water Act requires compliance with existing standards, although existing research can be used to aid in interpretation of those standards. A review of the standards to look at adoption of different criteria, duration, frequency, and spatial application, if appropriate, would occur through a separate process. If new standards were adopted, the TMDL could be reviewed and revised, in accordance with revised criteria.

It is possible that TDG became elevated under historical natural conditions in the Columbia River, such as below Kettle Falls. However, the levels of TDG produced and the rate that elevated TDG dissipated is unknown and cannot be easily predicted. Conditions different from natural conditions exist at the Columbia dams that create high TDG levels. These conditions include the height of the dams, the shape of the spillways, and the presence of the long deep pools below the dams. Allowing a monitoring point below the aerated portion of the tailrace can be considered to reflect gas generation patterns in a natural system.

TDG levels can become elevated due to oxygen produced as part of primary productivity. Research cited by EPA (1986) indicates that although high TDG produced by productivity can produce gas bubble trauma symptoms, generally this form of TDG is considered to be less harmful to aquatic life, since oxygen can be metabolized by aquatic organisms.

Monitoring of TDG

TDG is monitored *in* situ using a direct-sensing membrane diffusion method described in Standard Method 2810B (APHA, AWWA, and WEF, 1998). There are several manufacturers of available equipment, and field methodologies vary between the organizations that conduct monitoring. Most of the major monitoring programs (e.g., USACE, USGS) have well-documented methodologies and quality control procedures.

Routine monitoring of instream TDG levels occur at FMS sites above and below each dam and at the international border with Canada. The tailwater FMS sites in some cases may be a mile or two downstream of the dam. The FMS sites have been the primary point of monitoring and assessment of TDG levels, especially for compliance with TDG criteria during fish passage spills. The locations have been chosen for a variety of reasons, a primary one being the logistics and feasibility of long-term monitoring. However, studies suggest that the sites are not consistent in what river conditions the data collected represent. Some sites represent mostly spilled water, while others are measuring varying mixtures of spill and powerhouse flows.

To gain additional knowledge of TDG conditions in the river, USACE has conducted a number of detailed special studies of TDG levels below the dams (e.g., Schneider and Carroll, 1999; Schneider and Carroll, 2000; USACE, 2001c; USACE, 2003a; USACE, 2003b). These studies have found that strong spatial and temporal TDG gradients are common in flows released from a project during spillway operations. TDG levels measured at the FMS sites are usually lower than levels longitudinally upstream towards the spillway, may be lower than levels laterally across the river if powerhouse flows are not fully mixed, and in some conditions may be lower than levels longitudinally downstream. These complex spatial patterns are generated by the differential TDG exchange in bubbly spillway flow and the interaction of powerhouse and spillway releases. The appropriate interpretation of tailwater FMS data will be dependent upon an understanding of these processes.

The interagency Water Quality Team manages issues regarding the fish passage program and FMS sites. The Water Quality Team is jointly chaired by NOAA Fisheries and the states of Washington, Oregon, and Idaho. It is charged with providing technical advice and guidance on temperature and TDG water quality in the context of the NOAA Fisheries 2000 Biological Opinion relating to the Columbia River Hydropower System. A subgroup of that team has been addressing concerns with the FMS sites, and the appropriateness of the current FMS locations has been the subject of vigorous debate between the NOAA Fisheries, U.S. Fish and Wildlife Service, and USACE. The subgroup has found that the “representativeness” of FMS data is difficult to agree upon, both because of policy issues regarding what conditions a sample should represent and because of the difficulty in obtaining adequate data to characterize conditions. The TDG measurements at a given location in the river are influenced significantly by environmental factors such as water temperature, biological productivity, barometric pressure, and wind, as well as the spill. The Water Quality Team will continue to study and discuss these issues in order to achieve a mutually satisfactory and technically defensible monitoring end product.

The FMS sites will continue to be the primary location for determining attainment of TDG saturation limits used for fish passage management. For short-term purposes of TMDL compliance, FMS sites will be the primary location for compliance monitoring for both fish passage and non-fish passage allocations, and TMDL requirements do not need to drive FMS siting issues. In the long term, the goal for TMDL monitoring will be to have tailwater monitors measuring primarily spill water (to the extent feasible) and forebay monitors measuring fully mixed or cross-sectional averaged conditions.

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Analysis of Current Conditions

TDG Data Sources

TDG data were available on many of the projects from several sources: the fixed monitoring station (FMS) system; other long-term monitoring stations; near-field (tailrace) and spillway performance tests; limnology sampling; and in-pool transport and dispersion tests. Operational data were obtained from many projects detailing the individual spillway and turbine discharge on an interval ranging from five minutes to one hour.

Sources of data included: U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, Environment Canada, Spokane Tribe, BC Ministry of Water, Land and Air Protection, Columbia River Integrated Environmental Monitoring Program, U.S. Geological Survey, BC Hydro, Teck Cominco, Aquila, City of Seattle, Avista, Chelan County Public Utility District (PUD), Grant County PUD, Douglas County PUD, Golder Engineers, and Aspen Applied Sciences.

Data Quality

Data quality assurance/quality control procedures varied greatly for the source information used in this TMDL. This is particularly true of the data collected above Grand Coulee Dam that was used in the discussion of sources to Lake Roosevelt. TMDLs require use of the best available data. As additional data are collected and improvements are made in modeling, the TMDL can be updated to reflect these changes. The data quality assurance and control procedures for each source are discussed in detail in Appendix D.

Lake Roosevelt TMDL Data

Data from a large number of sources were used to evaluate the contribution of sources in Canada as well as conditions at the boundaries and within the lake. The quality and type of data was variable. A synopsis of the data types is provided below.

U.S. Bureau of Reclamation Data

There are two fixed monitoring stations at either end of the lake maintained by the U.S. Bureau of Reclamation. The station at the Canadian border has collected TDG data since 1995. The other station, in the forebay of Grand Coulee Dam, has collected TDG data since 1997. The data used in this report have not been through quality control. Data collected at these stations include TDG, temperature, and barometric pressure.

The forebay monitor is set 15 feet below minimum pool and 97 feet below maximum pool. The downstream monitor is understood to represent conditions where all flows – spillway, outlet works, and powerhouses – are fully mixed.

Concerns have been raised about whether the international border FMS data represent an average cross-sectional TDG value. Water quality data from the Boundary station can be compared to data from the Kootenay and Pend Oreille rivers, and from the Columbia River upstream of those two tributaries. During certain times of the year, the Boundary station shows a bias towards conditions in the Pend Oreille, suggesting that river flows are not fully mixed at the international border. This may only occur during certain flow conditions, and may only be observable when conditions in the tributaries are significantly different from the mainstem.

A one-day study was done at this site in the late 1990s (Zimmer, 2003). A cross-section was made with a hydrolab collecting grab samples. The study concluded that TDG was consistent across the river. There is concern that the study was not extensive enough and may only be representative during a portion of the spill season. More study is needed to determine under which conditions data from the Boundary station are not representative because of incomplete mixing across the channel.

U.S. Geological Survey Data

The U.S. Geological Survey (USGS) maintains a fixed monitoring station for flow on the Columbia River just below the international border. The data used in this report have not been through quality control.

Spokane Tribe Limnology Data

TDG pressure, barometric pressure, temperature, and dissolved oxygen along with a number of other water quality parameters were recorded at 11 sites in the reservoir in 2001 and 2002. Sampling was every other week during the spring, summer, and fall, and monthly during the winter months. The tribe released the 2001 data to Ecology and EPA with the understanding that it had not been through a quality control process.

Avista Data

Avista collected hourly water quality data in the tailrace of Little Falls Dam on the Spokane River from spring 1999 through winter 2002 as part of their upcoming FERC relicensing. The parameters tested include TDG, barometric pressure, temperature, and dissolved oxygen. Records of spill and generation flow for this dam were also kept by Avista and used in the TMDL. These data have undergone a review of data quality. Additional data were collected in 2003 on five of Avista's Spokane River hydroelectric projects (but not at Little Falls Dam), but were not used in this TMDL.

Columbia River Integrated Environmental Monitoring Program (CRIEMP) Data

CRIEMP includes Canadian utilities, the BC Ministry of Water, Land and Air Protection, and Environment Canada. This group has collaborated in efforts to gather data in the transboundary Columbia system between 1995 and 2000. Most of the data were collected and reported on by Golder Engineers, although equipment from many sources was used. Collection intervals varied from five minutes to one hour depending on the sampling site and the study. Data were collected at nine long-term and eight short-term monitoring stations. This was augmented by grab sample data from a number of sites. Data collected included TDG, temperature, barometric pressure and dissolved oxygen.

In addition to the water quality data, spill and generation flow data were recorded by the dam operators in CRIEMP: BC Hydro, Teck Cominco, Aquila (previously Utilicorps), and Columbia Power Corporation/Columbia Basin Trust. Spill and generation data were used from Brilliant, Corra Linn, and Kootenay Canal projects on the Kootenay River, and Waneta and Seven Mile dams on the Pend Oreille River. Spill and low-level opening flow data collected at Hugh Keenleyside Dam on the Columbia River were also used. Streamflow data were collected at Birchbank station on the Columbia River below the Kootenay River Confluence by Environment Canada.

Seattle City Light Data

Seattle City Light contracted with the USGS to collect TDG and barometric pressure data in the forebay and the tailrace of Boundary Dam on the Pend Oreille River from 1999 to 2003. Seattle City Light released the data to Ecology with the understanding that it had not been through a quality control process.

Use of the Data

Data from the U.S. Bureau of Reclamation FMS sites was used to understand the magnitude and season of impairment at both ends of Lake Roosevelt. Data from the international border FMS was used in conjunction with the CRIEMP, USGS, U.S. Bureau of Reclamation, and Seattle City Light data to understand and discuss the impacts of sources in Canada and sources upstream of Canada. Aspen Applied Sciences used these data sets to calibrate their model of TDG in the transboundary Columbia system, which is described below in the discussion of Lake Roosevelt.

Mid-Columbia TMDL Data

Data on the Mid-Columbia dams were collected by USACE, USGS, the U.S. Bureau of Reclamation, and the three Public Utility Districts. It includes both FMS data and near-field studies. The USACE and the USGS collect FMS data jointly following rigorous quality control. Basic data quality procedures are provided in the annual Plan of Action (USACE, 2001b). Detailed methods and quality assurance data are reported by USGS (Tanner and Johnston, 2001). The USACE annual water quality reports provide detailed data quality analysis (USACE, 2000). The TDG data quality target for the FMS sites is a precision of no greater than 1% for paired readings.

The development of TMDL loading capacity and load allocations is based on data whose quality assurance/quality control procedures met or exceeded the standards applied by the Washington State Department of Ecology for their own data collection and analysis for TMDL development. Other data of less certain quality were used for background information, to aid in implementation, and for other purposes.

Fixed Monitoring Station (FMS) Data

The TDG data from the FMSs consisted of remotely monitored TDG pressure, water temperature, atmospheric pressure, and sometimes dissolved oxygen from a fixed location at at least hourly intervals. FMS sites have been established in the forebay of each dam and in the tailwater or at a downstream location below each dam. FMS sites have also been established at the international border (just above the head of Lake Roosevelt) and near Pasco (at the downstream end of the Hanford Reach). Data from the FMSs provide a long-term hourly record of TDG throughout the season, capturing detailed temporal and extreme events. However, the FMSs provide only limited spatial resolution of TDG distribution. The TDG observed at the FMS location may be representative of primarily spill water, partially mixed flows, or average conditions, and representativeness can vary by location and over time.

Spillway Performance Tests and Near-Field Studies

Spillway performance tests and near-field tailwater studies were conducted at several projects to define the relationship between spill operation and dissolved gas production more clearly. Water temperature, TDG, and dissolved oxygen were monitored in the immediate tailrace region, just downstream of the project stilling basin. These observations provided a means to relate the local TDG saturation to spill operations directly and to define gas transfer in different regions of the tailrace area.

In these studies, automated sampling of TDG pressures in spillway discharges during uniform and standard spill patterns was conducted with an array of instruments in the stilling basin and tailwater channel. Automated sampling of TDG levels provides the opportunity to assess three-dimensional characteristics of the exchange of TDG immediately downstream of the stilling basin on a sampling interval ranging from five to 15 minutes. The integration of the distribution of flow and TDG pressure can yield estimates of the total mass loading associated with a given event. These tests were of short duration, generally lasting only several days and, therefore, pertain to the limited range of operations scheduled during testing. Also, the ability of a study to characterize conditions is limited by the number of available meters and their placement to assess spatial variability, and by the variability inherent in field TDG measurements.

Data Interpretation

The objective of these analyses was to develop mathematical relationships between observed TDG and operational parameters such as discharge, spill pattern, and tailwater channel depth for dams within the TMDL area. These relationships were derived with observations from the FMSs and spillway performance tests. However, before the analysis could be conducted, the monitored data had to be evaluated to determine its reliability for this kind of analysis. For example, the monitored TDG data from the FMSs provide a basis for defining the effects of spillway operation on dissolved gas levels in the river below a dam, but the following limitations should be noted:

- Because the FMS sites are located near shore, they may not consistently represent TDG levels of the spill. The monitor sites were, in general, located on the spillway side of the river to measure the effects of spillway operation. However, with a non-uniform spill distribution and geometry across the gates of the spillway, the FMS may be more representative of the spill bays closest to the shore. Outside spill bays without flow deflectors can create elevated TDG levels downstream from these bays compared to adjacent deflectored bays. A spill pattern that dictates higher unit discharges on these outside bays can further elevate the TDG levels downstream of these bays relative to the releases originating from the deflectored interior bays.

- Depending upon the lateral mixing characteristics, the FMS downstream of a project may be measuring spillway releases that have been diluted with hydropower releases. For example, the tailwater FMS below Rocky Reach Dam is located where substantial mixing has occurred between generation and spillway discharges. Under many conditions, the TDG saturation of generation releases is less than the TDG level associated with spillway releases but greater than the cross-sectional average of TDG. The TDG at the tailwater FMS will be a function of the discharge and level of TDG from both generation and spillway releases. Obviously, if there is no spill, then the monitored TDG levels will reflect the TDG saturation released by the hydropower facility.
- Passage of generation flows through a power plant does not significantly change the TDG levels associated with this water. However, there can be a significant near-field entrainment of powerhouse flow by spillway releases at some projects, especially if flow deflectors are present. Observed data suggest that, under these conditions, some portion of the powerhouse discharges will be subjected to the same processes that cause absorption of TDG by spillway releases. In these cases, the TDG levels measured immediately downstream of a spillway will be associated with the spillway release plus some component of the powerhouse discharge.

The observations of tailwater TDG pressure need to be paired with project operations to conduct an evaluation of the data. A set of filters or criteria were established to select correctly-paired data for inclusion in this analysis. The travel time for project releases from the dam to the tailwater FMS was typically less than two hours, and steady-state tailwater stage conditions were usually reached within this time period. Thus, the data records were filtered to include data pairs corresponding with constant operations of duration greater than two hours to exclude data corresponding with unsteady flow conditions. This filtering criterion eliminated data associated with changing operations and retained only a single observation for constant operating conditions equal to three hours in duration.

- *Manual and Automated Inspections for Obviously Inaccurate Observations.* An automated search for values above or below expected extremes identified potential erroneous and inaccurate data in the database. These data were inspected and, if appropriate, excised from the database.
- *Comparison of Measurements from Forebay and Tailwater Instruments During Non-Spill Periods.* During the non-spill periods, downstream measurements should approach the forebay concentration when only the hydropower project is releasing water. Inspection of the data was conducted to identify errors when this condition was not met.
- *Comparison of Measurements from Redundant Tailwater TDG Monitors, if Available.* TDG tailwater data were rejected when measurements of two instruments at the same site varied by more than 3% saturation.

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Identification of Sources

There are seven sources of TDG within the geographic scope of this TMDL:

1. Grand Coulee Dam
2. Chief Joseph Dam
3. Wells Dam
4. Rocky Reach Dam
5. Rock Island Dam
6. Wanapum Dam
7. Priest Rapids Dam

In addition to the sources listed above, there is a large contribution of TDG crossing the international border upstream of Lake Roosevelt, and TDG entering the system from the Spokane River. Sources upstream of impairment to Lake Roosevelt include dams on the Columbia, Kootenay (Kootenai), and Pend Oreille rivers, both in Canada and the U.S.

No other significant sources of elevated TDG exist in the mainstem or tributaries of the Mid-Columbia River or Lake Roosevelt. The major tributaries to the Mid-Columbia River have been evaluated indirectly as part of TDG studies on the river. Although it is likely that TDG may be supersaturated in these tributaries under certain conditions (such as high water temperatures or high dissolved oxygen from productivity), there have been no indications of TDG levels in these tributaries that contribute to impairment. In fact, data suggest that they often serve to provide low-TDG dilution water during spring runoff. Regardless, the percentage of Columbia River flow during the TMDL season that these tributaries represent is very low. Therefore it is reasonable to consider these tributaries to be negligible contributions to impairment.

Increases in TDG percent saturation can also be caused by decreasing barometric pressure, increasing water temperature, or increased dissolved oxygen levels from aquatic biological activity.

Waters of the Columbia River flowing across the international border into Lake Roosevelt frequently exceed the TDG standard. This TMDL will establish a load allocation to attain the TDG criteria in Lake Roosevelt. However, since some of the sources of impairment are in Canadian waters and outside the purview of U.S. regulation including the Clean Water Act, the U.S. has no direct authority over attainment of this load allocation. The load allocation at the international border will provide a target that can be used during discussions and negotiations with Canadian sources. Such discussions currently occur on a regular basis via the Transboundary Gas Group and other forums.

Current available data suggest that the Pend Oreille and Spokane rivers also contain sources of TDG in the U.S. which enter Lake Roosevelt. These sources are outside of the geographic scope of this TMDL. TMDLs are in the planning stage for the Pend Oreille River in Washington and Idaho and under development for the Spokane River in Washington. These future projects will specifically address and quantify impairment in these watersheds. The Spokane TMDL at its downstream end will address the load allocation for the Spokane Arm, which is set in this TMDL.

An earlier TMDL issued for the Lower Columbia established the TDG load allocation for the Columbia River at the confluence of the Snake River (river mile 325). This allocation was based on loading limitations needed in order to attain the TDG criteria in the Columbia River below this point. This allocation, along with loading information contained in the Lower Snake TMDL, will be used to establish the maximum allowable loading at the downstream boundary of the TMDL. The TMDL will be established such that the allocation will attain criteria throughout the reach and ensure criteria are also met in the lower river.

The information provided illustrates processes and configurations at the dams at the time of the studies described. As structural modifications are made at the dams, the specific gas generation equations may change. If such modifications significantly impact the allocations made in this TMDL, the TMDL and/or Implementation Plan may be reviewed and revised.

Lake Roosevelt

Description of Area

Lake Roosevelt is the impoundment of the Columbia River behind Grand Coulee Dam. At the high water mark, the lake extends from the Canadian border downstream to Grand Coulee Dam, a distance of 148 river miles (Figure 2). Included in the impoundment is the backwater of the Spokane River, known as the "Spokane Arm", which extends approximately 29 miles upstream of the Spokane River's confluence with the Columbia River.

Much of the land northwest of Lake Roosevelt is part of the Colville Indian Reservation. The reservation includes most of the lake for approximately 100 miles upstream of Grand Coulee Dam. The Spokane Indian Reservation is on the east side of the lake, extending approximately ten miles upstream of the confluence of the Spokane River, and includes all of the Spokane Arm and most of Lake Roosevelt along its boundaries.

Water Quality Impairment

Lake Roosevelt was included on Washington State's 303(d) list for TDG, in both 1996 and 1998. Data collected at the U.S. Bureau of Reclamation's fixed monitoring station (FMS) downstream of the international border shows that the numeric criterion for TDG is continuously exceeded from mid-April through mid-September in a typical year (Figure 5). It is not uncommon to have episodes of TDG exceeding the standard during high runoff events in the fall and winter as well. In six out of the eight years of data at this station, TDG levels have remained above 120% for the entire month of June. Typically, recorded levels of TDG are higher at the international border station than any other FMS on the U.S. portion of the Columbia River from April through January.

The next FMS downstream is in the forebay of Grand Coulee Dam. Data from this station indicate TDG impairment remains a problem throughout the 148 miles of lake. Values recorded at Grand Coulee forebay are less than readings from the border but typically exceed 110% from early May through mid-August (Figure 5).

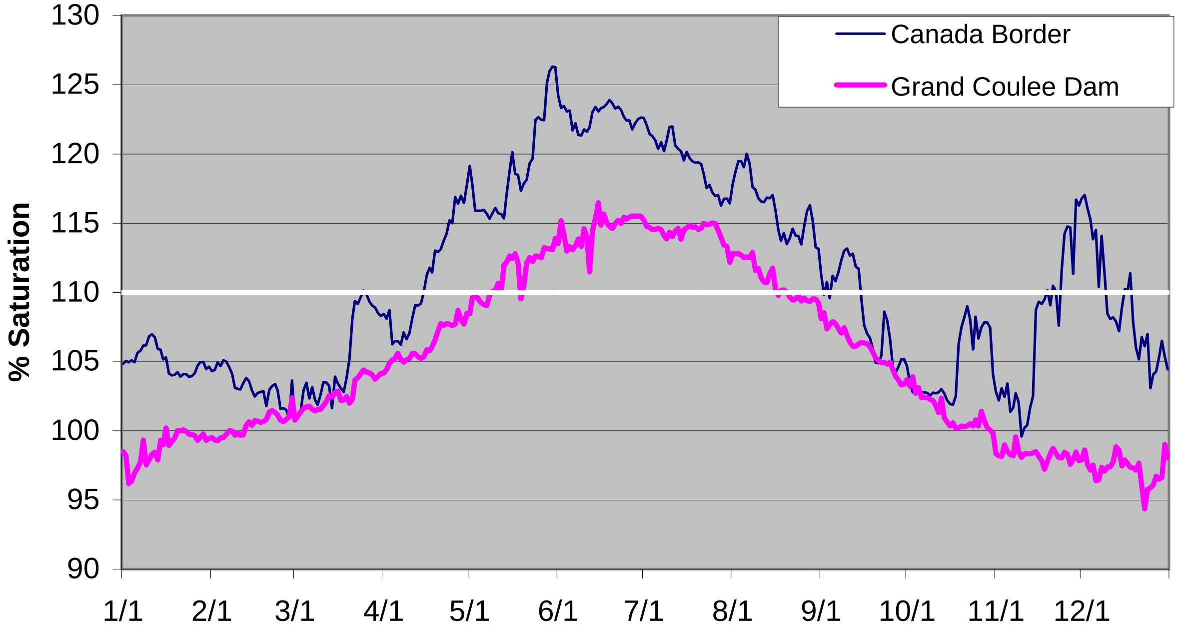

Figure 5: Average TDG Levels at International Border (1995-2003) and Grand Coulee Dam Forebay (1997-2003)

The sources of TDG to Lake Roosevelt are the flows across the international border and flows from the Spokane River. The Spokane River is the largest tributary entering directly into Lake Roosevelt. It flows into the Spokane Arm of Lake Roosevelt approximately 45 miles above Grand Coulee Dam. High TDG levels have been recorded in the Spokane River upstream of the Spokane Arm. This TMDL will set an allocation in the Spokane Arm which will be used as a boundary condition in an upstream TMDL for TDG in the Spokane basin.

Although there are sources of TDG coming into Lake Roosevelt from the Spokane River, the most significant sources of TDG influencing the lake are upstream of the international border. These include sources in Canada on the Pend Oreille, Kootenay (Kootenai), and Columbia rivers and sources in the U.S. on the Pend Oreille River system.

The sources in Canada and their influence on TDG levels in Lake Roosevelt will be discussed below. Although the sources under discussion are outside the U.S. and cannot be directly addressed through the Clean Water Act, a discussion of them is necessary to understand the impairment to Lake Roosevelt. Information in this TMDL about sources in Canada will be used in our continuing negotiations with Canada on transboundary pollution issues.

The system immediately above the Canadian border is complicated by the interaction of three major river systems (Figure 6). All three rivers have dams which are sources of TDG (Table 3). Canadian dam owners and government agencies have studied the transboundary area over the last ten years, in order to evaluate projects and operational measures to reduce TDG levels in the system. Some of these projects have been implemented, and some are still in the planning phase.

This document will use the information collected in Canada and at the international border to describe the generation of TDG that precipitated the listings at the border, as well as the anticipated reductions from planned and implemented improvements. Additional measures that may be needed to reduce TDG levels to the 110% standard at the international border will also be discussed.

Table 3: Canadian Dams on the Columbia, Kootenay, and Pend Oreille Rivers

Name	River Mile	Year Built	Normal Max Head (ft)	Hydro-electric Capacity (mw)	Hydraulic Capacity (cfs)	Average Annual River Q (cfs)	Owner	Drainage Area (sq.mi.)
Columbia River								
Hugh Keenleyside	780	1968	69	185	40,000	40,100	BC Hydro	14,100
Revelstoke	934	1983	425	1,740	56,000		BC Hydro	10,300
Mica	1018	1973	615	1,740	41,600	20,510	BC Hydro	8,100
Pend Oreille River								
Waneta	0.5	1954	205	420	28,300	27,820	Teck Cominco	26,000
Seven Mile	6	1979	197	605	39,000	26,800	BC Hydro	–
Kootenay River								
Brilliant	1.9	1944	98	109	18,000	30,650	CPC/CBT	18,996
South Slocan	13.4	1928	72	54	10,500	27,570	Fortis	–
Lower Bonnington	14.3	1897	66	41	9,500	27,570	Fortis	–
Upper Bonnington	14.8	1907	71	60	13,500	27,570	Fortis	–
Corra Linn	16.1	1932	58	41	12,600	27,570	Fortis	–
Kootenay Canal	–	1975	245	528	26,000	–	BC Hydro	–

mw – megawatts
cfs – cubic feet per second
Q – discharge (flow)
ft – feet
sq.mi. – square mile
BC – British Columbia
CPC – Columbia Power Corporation
CBT – Columbia Basin Trust

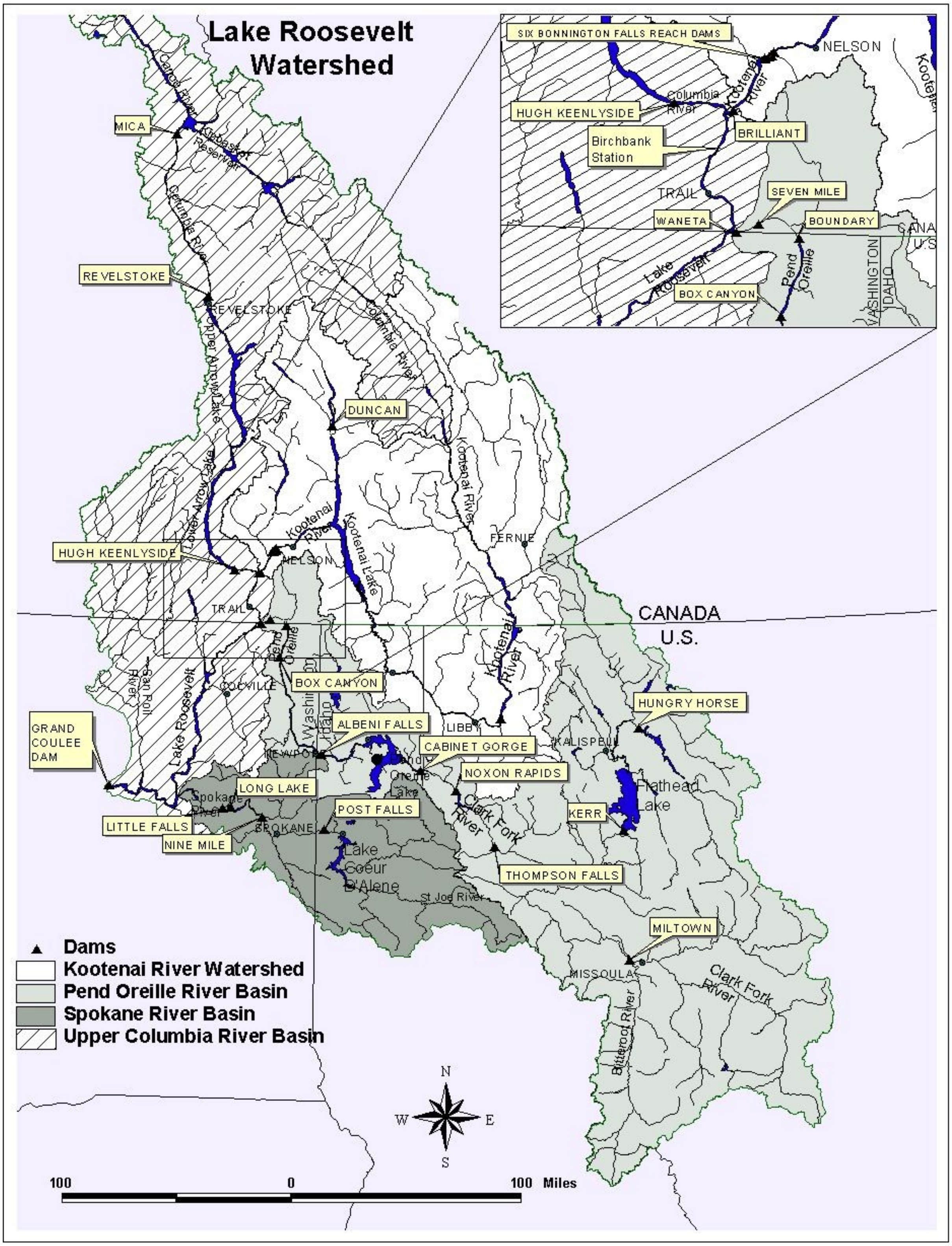

Figure 6: Lake Roosevelt Watershed

Canadian Modeling of TDG in Transboundary Columbia System

To assess the relative impacts of the sources of TDG and the effects of the river system's interaction on TDG levels and fish habitat, the Canadian dam owners and governmental agencies commissioned the creation of a model of the system. The model was created by Aspen Sciences Limited. It is a mass balance model that uses empirical data on dam operation in conjunction with data collected at a variety of TDG monitoring stations.

Canadian dam operators have used this model to predict the effects of operational changes in dam management and increases in power generation capacity on TDG levels. The model uses data that have been collected between 1991 and 2000 on the Columbia, Kootenay, and Pend Oreille rivers, in Canada and at the international border. The model is based on conservation of TDG and flow as described by the following equation:

$$\Delta P_{River} * Q_{River} = \Delta P_{Forebay} * Q_{Turbine} + \Delta P_{Spill} * Q_{Spill} + \Delta P_{Low\ Level\ Ports} * Q_{Low\ Level\ Ports}$$

where: ΔP = difference between TDG pressure and local barometric pressure

ΔP_{Spill} = Spillway ΔP

ΔP_{River} = ΔP at Monitoring Site(s) Downstream of Dam

Q_{River} = Total River Volumetric Flow

$\Delta P_{Forebay}$ = Forebay ΔP

$Q_{Turbine}$ = Total Turbine Volumetric Flow

Q_{Spill} = Total Spillway Volumetric Flow

$\Delta P_{Low\ Level\ Ports}$ = Low Level Ports ΔP

$Q_{Low\ Level\ Ports}$ = Total Volumetric Flow through Low Level Ports

Assumptions of the model:

Flow through turbines is not assumed to alter TDG levels.

The total flow of the river below a dam is equal to the sum of the flow over the spillway, the flow through the turbines, and the flow through the low-level ports.
($Q_{River} = Q_{Turbine} + Q_{Spill} + Q_{Low\ Level\ Ports}$)

TDG is not assumed to dissipate except in three locations, where field data indicate a reduction in TDG levels:

- Flow going over Seven Mile Dam on the Pend Oreille River
- Flow over the natural cascade spillway at South Slocan Dam on the Kootenay River
- The reach above Brilliant Dam forebay

Increases in TDG levels at each dam are estimated for spill and operational conditions using regressions on data collected in the dam forebays and tailraces between 1995 and 2000. For Hugh Keenleyside and Brilliant dams, there have been several years of data collected including near-field studies of TDG increases under controlled operational conditions.

Results of the Canadian modeling are summarized in Tables 4 and 5 and will be expanded on in the discussion on sources of impairment below.

Table 4. Canadian Model Results for Dams in Canada

River	Dam/ Monitoring Station	River Mile	Proposed Improvement	Scheduled Completion	Days per Year TDG Exceedence: Upstream (Forebay) TDG 110%	120%	130%	Pre-Project Downstream (Tailrace) TDG 110%	120%	130%	Post-Project Downstream (Tailrace) TDG 110%	120%	130%
Columbia	Hugh Keenleyside	780	Arrow Lake Generating Plant (ALGS)	Completed in February 2002	0**	0	0	146	47	29			
Kootenay	Corra Linn	16.1	None	None	0	0	0	33	0	0	N/A	N/A	N/A
	Upper Bonnington	14.8	None	None	33	0	0	44	4	0	N/A	N/A	N/A
	Lower Bonnington	14.3	None	None	44	4	0	69	40	26	N/A	N/A	N/A
	Kootenay Canal	13.4	None	None	33	0	0	73	0	0	N/A	N/A	N/A
	Brilliant	1.9	Brilliant Expansion Project (BEP)	2006	73	4	0	157	51	0	80	18	0
Pend Oreille	Seven Mile	6	None	None	58	44	40	62	44	7	N/A	N/A	N/A
	Waneta	0.5	Waneta Expansion	2011	62	44	7	135	62	0	*	*	*

* Data currently being gathered will be available in 2005.
** There are minor exceedances of 110% saturation for a couple days in most years.

Table 5. Canadian Model Results for the Columbia River International Border

Proposed Improvement	Scheduled Completion	Days per Year TDG Exceedence: Pre-Project TDG 110%	120%	130%	Post-Project TDG 110%	120%	130%
Arrow Lake Generating Plant (ALGS)	Completed in 2002	128	40	0	102	29	0
ALGS *and* Brilliant Expansion Project (BEP)	2006	102	29	0	84	22	0
Waneta Expansion Project *and* ALGS *and* BEP	2011	84	22	0	*	*	*
ALGS	Completed in 2002	150	51	0	102	15	0
ALGS *and* (BEP)	2006	102	15	0	88	4	0

* Data currently being gathered will be available in 2005.

Sources of Impairment

Kootenay River

Current Conditions

The Kootenay River confluence with the Columbia is 28 river miles upstream of the international border. Its flow accounts for approximately 30% of the Columbia River annual flow at the international border. The headwaters of the Kootenay are in the Canadian Rockies near the Columbia River headwaters. The river crosses the border into the U.S. (where it is spelled "Kootenai"), flowing about 200 miles through Montana and Idaho before re-crossing into Canada. Much of the lower portion of the river in Canada is a natural lake.

The seven hydroelectric projects located near the mouth of the river are all run-of-the-river dams. Six of the seven projects are located between river mile 16 and 13. In this reach, the river drops 270 feet through a series of natural cataracts called Bonnington Falls. Most of the power projects located on this reach take advantage of the natural falls for additional spillway capacity. One project is located on a canal that bypasses the falls.

TDG was monitored in the forebay of the uppermost of these six dams, Corra Linn, between April and November of 1999. TDG never exceeded the 110% criteria at this station. The next mainstem project upstream is Libby Dam, over 200 river miles away in Montana. Libby is the only storage dam on the Kootenai River.

Apart from the forebay station at Corra Linn, only short-term TDG data have been collected in this reach. These limited data show high gas levels during spring runoff in the tailraces of several of these dams. Values as high as 412 mm Hg delta pressure (155% saturation) have been recorded in this reach.

At the end of the Bonnington Falls section of the Kootenay River, TDG values are elevated in times of medium and high runoff. In the 11 miles between the South Slocan Dam tailrace at the lower portion of the Bonnington Falls area, and Brilliant Dam at river mile 1.9, TDG levels decline. This decline is assumed to be due to dilution from the Slocan River and dissipation in shallow riffle sections of the free flowing river. Nevertheless, TDG levels in the Brilliant forebay are often over 110% saturation (Figure 7). Brilliant Dam forebay and tailrace have been the sites of seasonal TDG monitoring for several years. The Canadian TDG model predicts that Brilliant Dam forebay TDG levels exceed 110% saturation 70 days each year, although the model does not show a high correlation with the available data at the Brilliant forebay.

Brilliant Dam has eight spillways and four turbines. Through the period of data collection (prior to 2001), the turbines had a total hydraulic capacity of 18,000 cfs. The turbines were upgraded in 2003 to a hydraulic capacity of 21,000 cfs. The average annual discharge at Brilliant is 30,650 cfs. Over 40% of the Kootenay River was spilled at Brilliant Dam in an average year. Increases in TDG in the Brilliant tailrace are high when spills over 7000 cfs occur at the dam (Figure 7).

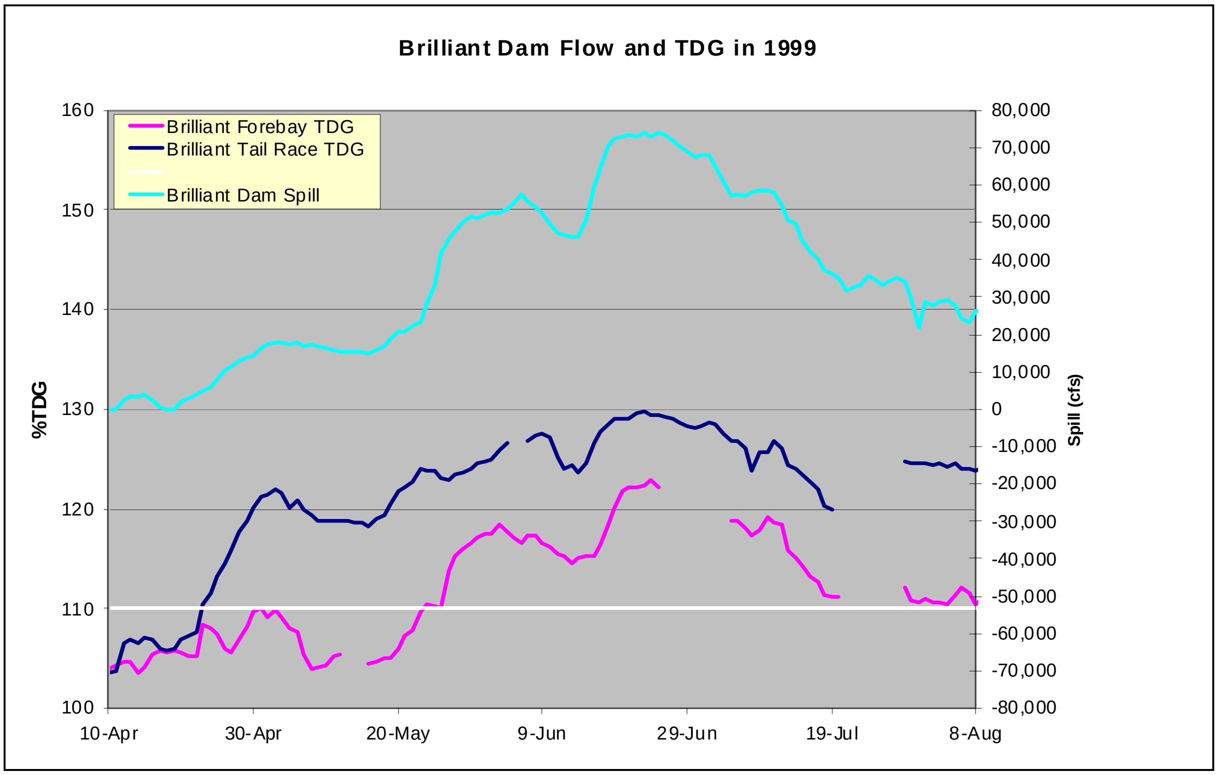

Figure 7: Brilliant Dam TDG Data from 1999

Improvements at Brilliant Dam

Near-field operational studies were conducted at Brilliant Dam, and in 2000 the dam owner agreed to use a spillgate operation plan that would reduce TDG levels downstream. In addition, projects to increase generating capacity by upgrading and increasing the capacity of the turbines were completed at Brilliant in 2003. A further improvement is currently under contract that will lead to construction of an additional power plant on the eastside of the river. This project, scheduled for completion in 2006, will reduce to a minimum the necessity of spilling at Brilliant Dam. TDG reductions anticipated from this project are shown in Tables 4 and 5 in the section on Canadian modeling.

Completed in 2002, upgrade of the four turbines at Brilliant Dam increased the hydraulic capacity through the power plant from 18,000 cfs to 21,560 cfs. Construction of an additional generating plant will further increase hydraulic capacity to 34,150 cfs. The Canadian model estimates that, when completed, these projects will reduce the number of days that the Brilliant tailrace is over 110% saturation criteria, nearly in half, from five months to two and a half months a year. This is slightly greater than the levels coming into Brilliant forebay. The Brilliant power plant expansion is also anticipated to reduce gas levels at the international border, reducing the number of days over 110% saturation by approximately three weeks a year.

Reducing TDG input at Brilliant Dam by additional power plant capacity will not address the problem of high TDG levels that are generated by dams in the Bonnington Falls reach. Flow through the power plants will pass elevated TDG water downstream without reduction. As illustrated by Figure 7, the water coming into the forebay of Brilliant Dam is typically over 110% saturation 70 days a year. TDG generated by dams in this reach remains an obstacle to meeting the standard at the international border.

Pend Oreille River

Current Conditions

The Pend Oreille River's confluence with the Columbia is immediately upstream of the international border. Its flow makes up approximately 28% of the Columbia River annual flow volume at the border and 10% of the total flow of the Columbia River. The headwaters of the Pend Oreille River are in the Rocky Mountains of Montana. The Bitterroot and Flathead rivers merge with the Clark Fork River in Montana. The Clark Fork flows north into Pend Oreille Lake in Idaho. At the lake's outlet, the river is renamed the Pend Oreille River. It flows north through Washington State and enters Canada 16 miles before its confluence with the Columbia River. The Pend Oreille River confluence with the Columbia River is immediately upstream of the Canada border.

There are two dams on the Canadian segment of the Pend Oreille River: Waneta (immediately upstream of the Columbia River confluence) and Seven Mile (at river mile 6). There are several major upstream dams on the Pend Oreille and its tributaries in the United States. The primary storage dam in the system is Hungry Horse, on the South Fork Flathead River, over 300 miles upstream of the Canada border.

Peak flow typically occurs in early to mid-June. The runoff season can begin anytime from mid-April to mid-May, often with a rapid increase in flow volume. The peak runoff season is typically over in early July, often with an equally precipitous decline in flow volume. Generally the peak of the Pend Oreille hydrograph coincides with the Kootenay River's peak flow in early to mid-June.

A smaller volume of TDG data has been collected in the Canadian Pend Oreille River system than in the Kootenay or the transboundary Columbia rivers. The aerated zone in the tailrace of Waneta Dam extends into the confluence with the Columbia River. Turbulence and mixing effects have deterred collection of TDG data that would quantify the increase in TDG from spill at Waneta Dam. It is generally acknowledged that the dam increases TDG levels during spill. This conclusion is based on information collected at dams with a similar configuration and the limited data collected in the Waneta tailrace.

From 1995 through 1998, data were collected at Seven Mile Dam, five miles upstream of Waneta, during the June high water season. These data indicate that Seven Mile Dam generally causes a reduction of TDG levels when it spills, and incoming TDG levels are often high during the peak flow season.

Seven Mile Dam has a hydraulic capacity significantly greater than the average annual flow of the river. Waneta Dam spills over 10% of the river flow in an average year. Data collected on the Pend Oreille River at the border from 1999 through 2003 indicate that TDG levels coming across the border into Canada during the spring high water season are often above 110% saturation. When Seven Mile Dam is spilling and the water coming in has TDG levels over 110% saturation, spill over the dam tends to reduce TDG. However, flow through the powerhouse at Seven Mile does not reduce gas levels, and spill at Seven Mile can cause a slight increase in TDG when incoming levels are below 115% saturation. Figure 8 shows the levels of TDG experienced in 1999 on the Pend Oreille and Columbia rivers at their international border crossings and the forebay of Waneta Dam.

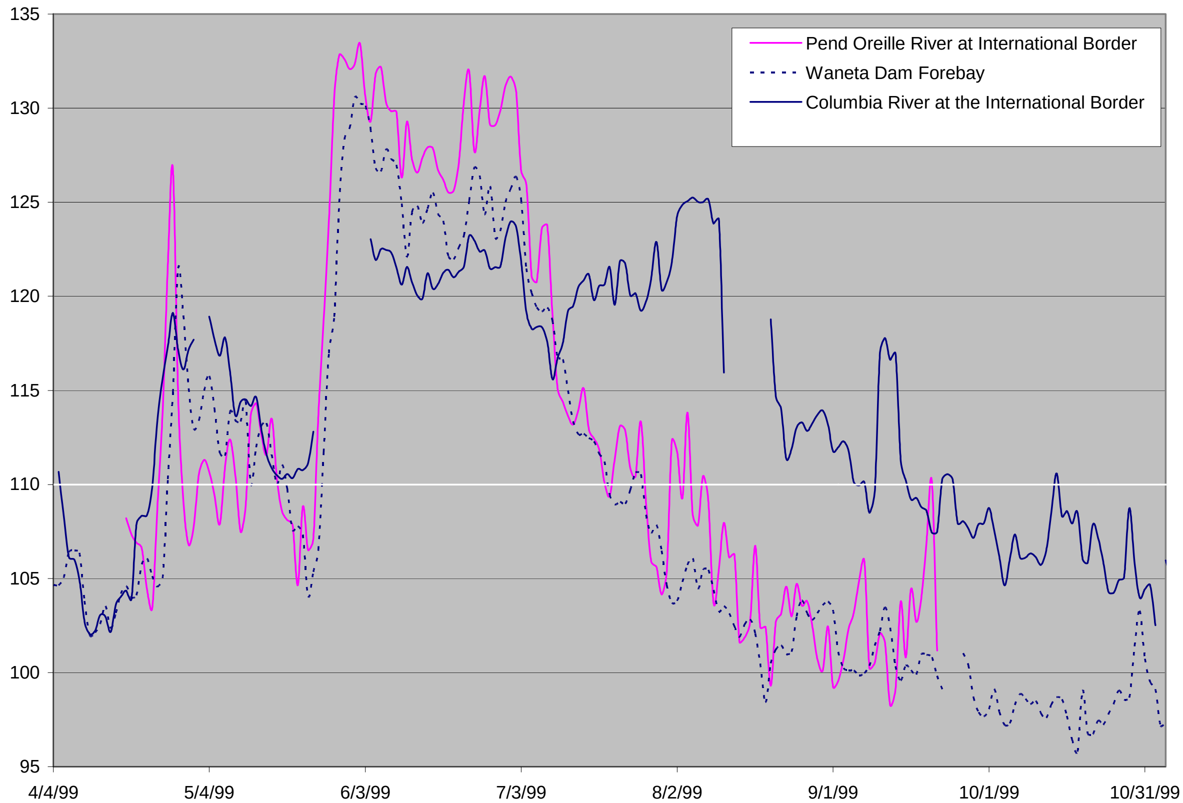

Figure 8: Pend Oreille and Columbia River TDG Data from 1999

Canadian modeling of the Pend Oreille River predicts that Seven Mile Dam will substantially reduce peak incoming TDG levels over 120% on the river. Seven Mile Dam is not predicted to cause any change in the number of days that TDG is above 110% saturation. The model indicates that spill at Waneta Dam causes substantial increases in TDG. Tables 4 and 5 give more detail on the modeling results. The modeling was based on data collected between 1995 and 1999. The correlation between the model and the empirical data is low for prediction of Waneta forebay TDG levels.

Planned Improvements

The upgrade of all four of the turbines at Waneta Dam is currently under construction. This would have the effect of reducing spill over the dam by increasing the hydraulic capacity from 25,000 cfs to 31,300 cfs, as well as increasing the power output of the dam. Canadian modeling of these upgrade proposals predicts a reduction in the days over 110% of three to four days a year and no change in days over 120% saturation. This low number is partially due to the high levels of TDG coming into the forebay of Waneta Dam. The addition of a second power plant at the Waneta site is currently in the planning stages. This project would yield a more substantial reduction in the amount of spill and TDG levels in the dam tailrace than the turbine upgrades.

Columbia River

The Pend Oreille River's confluence with the Columbia is immediately upstream of the international border, and the Kootenay River enters 28 river miles upstream. The Columbia, Pend Oreille, and Kootenay rivers have similar average annual flow volumes in this area (Figure 9). The complex interactions occurring in this reach, as well as the contribution of dams on the Columbia River in Canada to TDG levels, will be discussed in the following section.

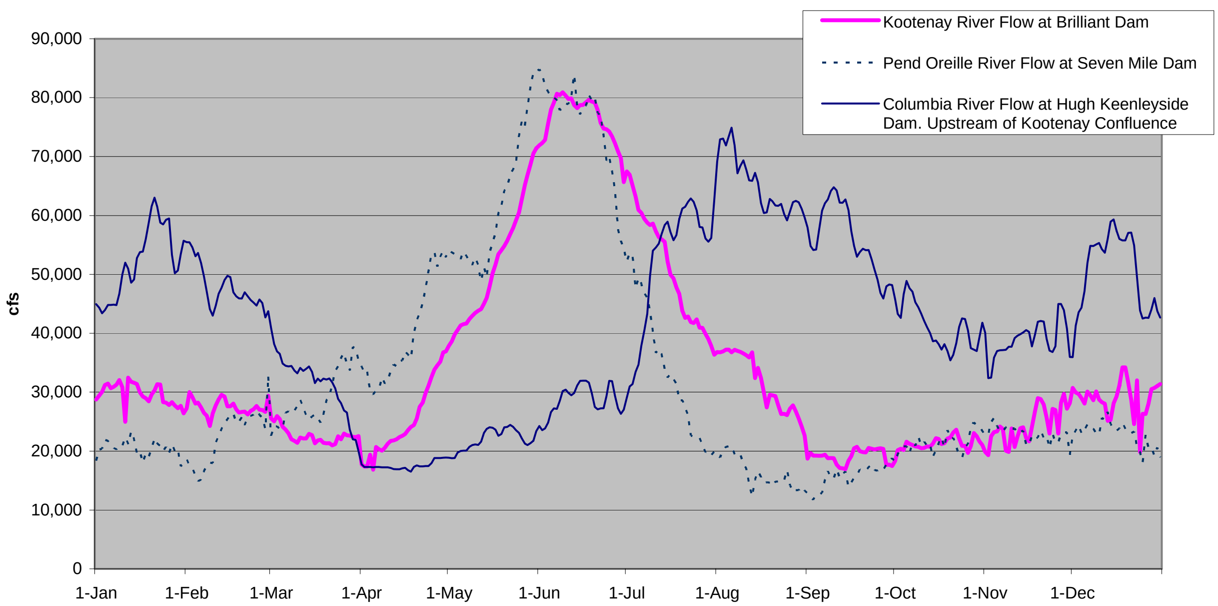

Figure 9: Average Flows in the Columbia, Pend Oreille, and Kootenay Rivers (1995-2000)

Hugh Keenleyside Dam

There are three dams on the Columbia River in Canada. Seven miles upstream of the Kootenay River confluence is Hugh Keenleyside Dam. Revelstoke Dam is 144 river miles upstream of Hugh Keenleyside. The intervening reach of the Columbia is a large natural lake called Arrow Lakes. Mica Dam is 84 miles upstream of Revelstoke. Hugh Keenleyside and Mica dams are major storage dams.

Hugh Keenleyside Dam was constructed in 1968 under the Columbia River Treaty as a storage dam to prevent flooding on the Columbia. Until 2002, Hugh Keenleyside had no power generation capacity. It has four spillways and eight low-level ports. The low-level ports are located four on either side of the central spillways. Data collected from 1995 through 1999 show that spill over Keenleyside Dam dramatically increases TDG levels downstream in the Columbia. Figure 10 illustrates this pattern using average levels of recorded TDG (averaging years vary by monitoring station). Flow through the north low-level ports increases TDG only slightly, but flow through the south ports can add noticeable TDG to the flow, although not as significant as levels from spillway releases.

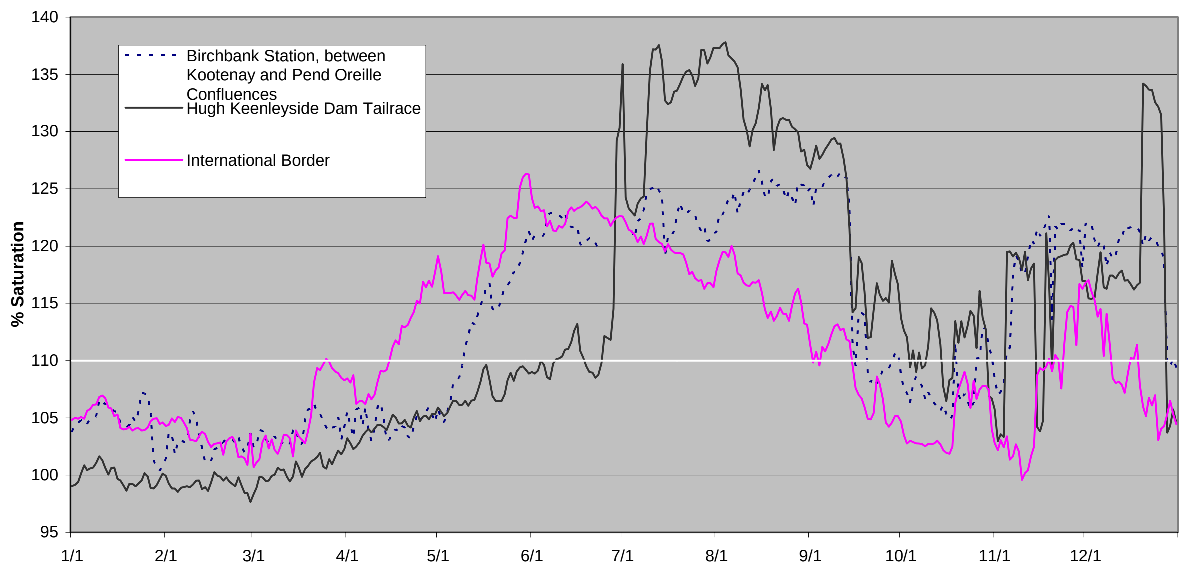

Figure 10: Average TDG Values in the Columbia River at and above the Canadian Border (Border 1995-2003; Birchbank 1995, 1999, 2000; Hugh Keenleyside 1995, 1997-2000)

The maximum capacity of flow through the low-level ports is a little over 88,000 cfs. But flow through the ports is constrained by a number of restrictions relating to the structural integrity of the dam. When high spill is occurring, usually at times of high head behind the dam, the flow through the low-level ports is limited to approximately 28,000 cfs. The average annual flow volume in the Columbia at Hugh Keenleyside is 40,100 cfs.

Water coming into the forebay of Hugh Keenleyside is occasionally over 110% saturation in the spring. The next dam upstream on the Columbia is Revelstoke, 144 miles upstream. Since Revelstoke is not a dam that elevates TDG significantly, the slightly elevated levels of TDG have been attributed to elevated temperatures in Arrow Lakes.

During spill over Hugh Keenleyside, TDG increases of 30% saturation are commonly measured at the station 1.5 miles below the dam. Values as high as 140% have frequently been recorded at this station. According to the Canadian TDG model, TDG levels exceed 110% saturation almost five months annually, on average, downstream of the dam. TDG saturation exceeds 130% saturation for nearly a month each year.

During the spill season, TDG levels caused by Hugh Keenleyside's spill are reduced downstream of the dam, primarily by dilution from the Kootenay and Pend Oreille rivers. Despite the downstream dilution, these high levels of TDG appear to be responsible for most TDG impairment at the international border from early July through the autumn.

Arrow Lakes Generating Station Improvement

The Arrow Lakes Generating Station (ALGS) was completed in February 2002. It is a power generation plant constructed immediately downstream of Hugh Keenleyside Dam, with its intake above the dam. The ALGS plant was constructed to use the Columbia River flow for power generation and, in doing so, reduce the necessity for spill at Hugh Keenleyside Dam, and thus reduce downstream TDG levels. The hydraulic capacity of the plant is approximately 40,000 cfs, roughly equivalent to the average annual river flow at this location.

The Canadian model predicts that the ALGS plant will lead to a reduction from 35% to 28% of the year (25 fewer days) when TDG would exceed 110% saturation at the international border, and a 3% reduction (11 fewer days) in the percent of the year over 120% saturation. Since the power plant has come into operation, there has been no TDG monitoring of TDG downstream of the dam in Canadian waters to compare to the model predictions, though the international border station appears to indicate lower TDG levels from late July into September.

Dynamics of the Columbia River System Upstream of Lake Roosevelt

In the 30 miles above the Canadian border, the Pend Oreille and Kootenay rivers flow into the mainstem Columbia River with flows similar to the Columbia at their confluence points. There are multiple TDG-producing dams, as well as projects aimed at reducing TDG levels at many of the dams, on all of these rivers. Unlike the lower reaches of the Columbia, the effects of these tributaries and the timing of runoff are important to understanding the levels of TDG downstream. This is the basic premise of the Canadian model of TDG.

The majority of the spill over Hugh Keenleyside Dam on the Columbia River begins in late June or early July and often continues through late September. There are often periods of spill in the winter as well. The runoff season on the Pend Oreille River begins anytime from mid-April to mid-May, often with a rapid increase in flow volume. The peak runoff season is typically over in early July, often with an equally precipitous decline in flow volume. The Kootenay River runoff season also begins in early to mid-May, with peak flows coinciding with the Pend Oreille's in early to mid-June. The Kootenay's hydrograph declines more slowly, although its season tends to be over by early August.

In the spring, when run off on the Kootenay and Pend Oreille rivers is highest, Hugh Keenleyside Dam is allowing its reservoir to fill and is generally not spilling. This staggering of flow has two effects on TDG impairment:

- A longer season of TDG levels exceeding the 110% standard.
- A reduction in TDG levels, due to dilution by unsaturated flows.

Attainment of 110% Saturation at the International Border

As discussed above, Canadian dam owners have completed a number of operational and structural improvements at many of the TDG-producing dams in the transboundary Columbia system. Other projects anticipated to yield reductions in TDG impairment are in the construction or planning stages. It is anticipated that these projects will have a significant beneficial effect on the TDG levels in the Columbia and Lake Roosevelt. Modeling done in Canada predicts that these projects will reduce, but not eliminate, exceedances of TDG levels above 110% saturation at the border.

Further reductions within Canada may also be possible on the Kootenay River upstream of Brilliant Dam in the Bonnington Falls reach and through additional reductions at Waneta, Brilliant, and Hugh Keenleyside dams as well as upstream dams on the Columbia.

Projects that could be undertaken in Canada to bring the river closer to 110% saturation are listed below. There has not been sufficient study of the dams in the system to determine the magnitude of reductions that could be expected from these measures.

- Installation of flow deflectors and flow dividers.
- Near-field studies of the major system dams that would evaluate the contribution of tailrace depth, entrainment of powerhouse/low-level port flows, and spill pattern to allow more precision in selecting effective retrofits and operation plans.
- Monitoring of improvements after installation to verify reduction in gas levels.

Spokane River

The only source of TDG into Lake Roosevelt below the international border is the Spokane River. The Spokane River flows into Lake Roosevelt approximately 45 miles above Grand Coulee Dam and makes up 9% of the Columbia's flow at the Spokane Arm confluence. There are seven dams on the Spokane River upstream of this TMDL area. Data collected from 1999 through 2001 by Avista indicate that TDG levels during the spring high-flow season often exceed the 110% criteria in the tailrace of Little Falls Dam, just above the Spokane Arm.

TDG levels measured below Little Falls Dam between 1999 and 2001 exceeded 110% saturation from mid- to late March until mid June or early July. For at least a month each year, TDG levels were above 120% saturation, and levels as high as 134% were measured. Although the average annual flow of the Spokane is small in comparison with the Columbia River, it peaks earlier than the Columbia and thus makes up over 22% of the Columbia flow in April (Figure 11).

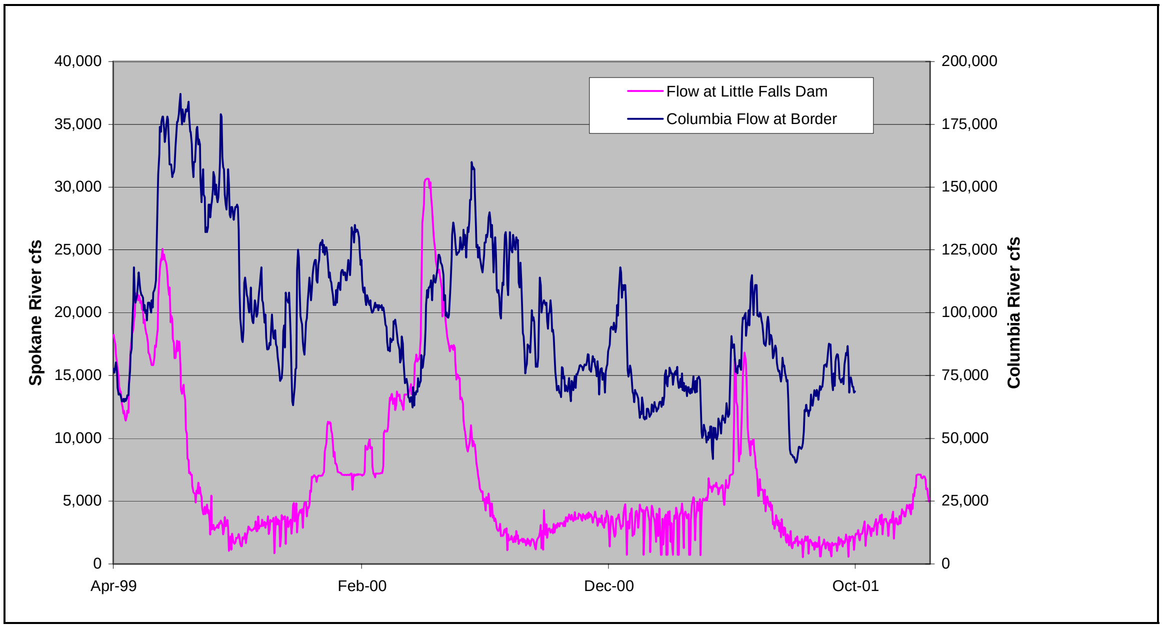

Figure 11: Flow in the Spokane River and Columbia River (International Border)

A comparison of data from the FMS sites at the international border and Grand Coulee Dam forebay, with data taken in the Little Falls tailrace does not indicate that TDG from the Spokane River significantly influences levels downstream in the Columbia. The exception to this may be from late March through early April, when TDG levels in the Grand Coulee forebay are slightly elevated above the levels at the international border and high TDG levels are recorded in the Little Falls tailrace (Figure 12). These increases at Grand Coulee Dam are very minor and do not lead to TDG levels above 110% saturation.

Although there are relatively little available data, elevated TDG levels below Little Falls Dam appear to have a significant effect on the Spokane Arm. During 2004-2005, Ecology and EPA are planning to develop a TMDL for TDG in the Spokane basin. The Spokane River TDG TMDL at its downstream end will address reductions necessary to attain the load allocation derived for the Spokane River as presented in this TMDL.

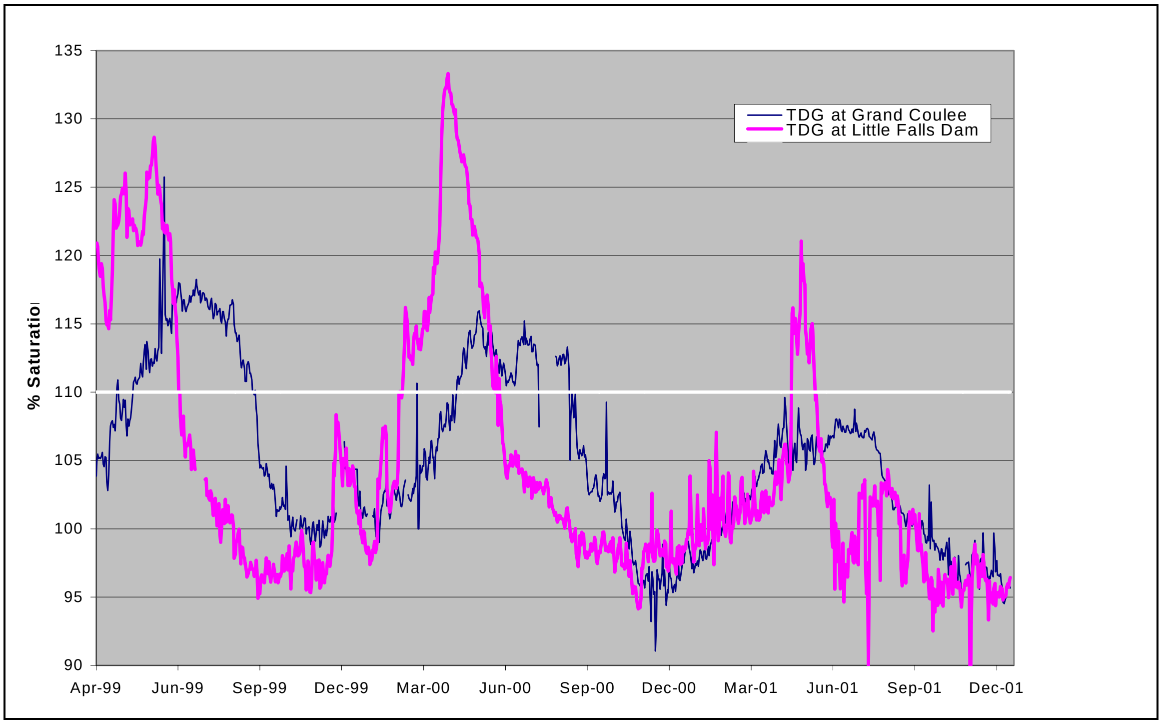

Figure 12: TDG at Little Falls Dam and Grand Coulee Dam Forebay

Influence of Ambient Conditions

Lake Roosevelt has a residence time of a week to several months. The median residence time is five weeks, with the 5^{th} and 95^{th} percentiles ranging from two to 10 weeks. Therefore, TDG entering from Canada has ample opportunity to be influenced by ambient influences such as turbulence and mixing, changes in water temperature and barometric pressure, and wind.

When dissolved gas is supersaturated compared to the atmosphere, the system seeks equilibrium by gas exchange from the water to the air. Since Lake Roosevelt is fairly deep, the surface-to-volume ratio is low and gas exchange is slow. Nonetheless, the general tendency will be for TDG levels to decrease. Wind can increase gas exchange by causing mixing in the surface layers and increased surface area from waves and "white-caps". A variety of empirical models have been developed to predict gas exchange as a function of wind speed (see Cole and Wells, [2001] for a review of these equations). However, the physical process is too variable and dependent on environmental conditions to be deterministically modeled. A wind-gas exchange curve usually must be calibrated to fit observed data through modeling.

An increase in water temperature or decrease in barometric pressure can cause an increase in TDG percent saturation without any change in the mass of dissolved gas. Therefore, for any given gas pressure crossing the border, TDG levels are likely to rise and fall as they move through Lake Roosevelt simply because of changes in these two parameters.

Another possible influence is primary productivity. In the late spring and early summer, algal oxygen production can raise TDG levels by several percentage points. Therefore hot, still, sunny conditions will optimize conditions that can result in increased TDG levels. Conversely, cool, windy, cloudy days will produce the greatest decreases in TDG.

The long residence time of Lake Roosevelt, and the complexity and variability of interactions between these parameters, make it very difficult to predict the magnitude and frequency of TDG increases from changing ambient conditions. An accurate and well-calibrated model would be the best way to assess changes in TDG in Lake Roosevelt away from the FMS sites. However, no existing model has been developed and calibrated for TDG in Lake Roosevelt, and such an effort is beyond the scope of this TMDL. The need for improved modeling of Lake Roosevelt may provide a future opportunity to evaluate TDG dynamics in the lake in greater detail.

1. Grand Coulee Dam

Project Description

Grand Coulee Dam, operated by the U.S. Bureau of Reclamation, is a complex project with multiple structures (Appendix E, Figure E-1). It has three powerhouses: the original two – right and left – are aligned with the spillway, while the third powerhouse, completed in 1980, sits at a slight angle on the east bank. The Pump-Generating Plant connected to Banks Lake is located on the west bank of the forebay.

The 1650-foot-wide spillway consists of 11 drum gates at the top of the dam, controlling spill from the crest at an elevation above mean sea level (El.) of 1260 feet to the maximum water surface of El. 1290. There are also 40 outlet works conduits (two rows of 20) that allow spill when the impoundment is below the spillway crest. The centerlines of the upper and middle outlets are El. 1137 and 1037 respectively. (Lower outlets were used for construction but are now sealed shut.) The outlet works can pass 192 kcfs at full pool, and the spillway has a capacity of 1000 kcfs. The outlet works discharge onto the face of the spillway, and both use a submerged roller-bucket energy dissipater at El. 874.4 that discharges onto the rock surface downstream. The total hydraulic height of the dam is 350 feet.

The three powerhouses have a combined capacity of 280 kcfs, which allows them to pass the entire river's flow up to and beyond the 7Q10 flood flow. The centerline for the right and left powerhouse intakes are at El. 1041, while the centerline for the third powerhouse intake is El. 1130. The power units may all be operated to pass flows up to 27 kcfs when not generating ("spin-no load") to assist with flow release during low power demand. The Pump-Generating Plant consists of six pumps and six pump-generators. The intake is at El. 1193. Water is pumped into Banks Lake, which is the upstream end of the Columbia Basin Irrigation Project. Water can be released from Banks Lake back through the pump-generators for peak power demand.

When Grand Coulee Dam was constructed, no fish passage facilities were provided so it blocked anadromous fish access to all spawning areas upstream. Anadromous fish passage has since been blocked about 50 miles downstream at Chief Joseph Dam.

Grand Coulee Dam is the furthest downstream storage reservoir on the Columbia River, and has a large capacity to store or release water. Grand Coulee Dam is operated for authorized project purposes, including irrigation water supply, power, flood control, and fish and wildlife. Once water is released from Grand Coulee, the ten downstream reservoirs can only make minor adjustments and must otherwise pass those flows through. System-wide effects of Grand Coulee operations, including intra-day fluctuations in downstream flows, are managed under the Mid-Columbia Hourly Coordination Agreement.

TDG Generation Processes

Frizell (1996) conducted an analysis of historical gas measurements to evaluate gas production from Grand Coulee Dam. Research in the 1970s evaluated total dissolved nitrogen, the primary constituent of TDG. When high TDG levels were observed entering Lake Roosevelt at the Canadian border, they showed up in the Grand Coulee forebay with very little change. Frizell (1998) notes that:

> "…only limited surface degassing occurs as water travels the 150 miles from the international border to Grand Coulee Dam. Although Grand Coulee power plant releases do not increase downstream dissolved gas levels, releases from the dam consistently exceed the 110% dissolved gas standard between May and August of most years, even with no spill, because of high gas levels in the Coulee forebay. Operation of Grand Coulee Dam further increases the already high forebay TDG levels during periods when spill releases, which bypass hydropower facilities, are discharged through the outlet works or the spillway drum gates."

In March 1997, the U.S. Bureau of Reclamation conducted testing of TDG generation from combinations of the powerhouse and outlet works (Frizell, 1997a; 1997b; Frizell and Vermeyen, 1997). Five tests were conducted that explored combinations of upper and lower outlet works conduits and powerhouse discharges. Three tests were run with upper outlet conduits discharging at around 32 kcfs and power plant flows of 0, 31, and 66 kcfs. Two tests looked at outlet works discharges from the lower conduits alone, and combined upper and lower conduits, both with no powerhouse flows. TDG measurements were taken downstream of the dam at 2.3 miles, 6.6 miles (FMS site), and 15 miles (fish pens). Initial reconnaissance showed that powerhouse and spill flows were mixed by the 2.3 mile station (at flows of roughly 100 kcfs), but were not fully mixed at locations closer to the dam.

Forebay TDG values were under 110% during the tests. TDG levels exceeded 140% saturation when either the upper or lower conduits were operated alone with no powerhouse flows. When the upper and lower conduits were operated together, TDG levels were relatively lower, but still exceeded 130% saturation. Increased powerhouse flows produced lower TDG levels, mostly through dilution. TDG levels were highest at 2.3 miles downstream and decreased with the downstream distance.

Interpretation of results from these tests is limited due to the narrow range of flows under which they were conducted and the limited number of measurements and sample locations. However the tests did demonstrate the high level of gas generated by use of the outlet works. The final report recommended operating paired high and low conduits if use of the outlet works was necessary.

Extremely high spring run-off in 1997 caused TDG levels in excess of 130%, resulting in high fish mortality both in wild resident fish and fish in aquaculture operations in Lake Rufus Woods (between Grand Coulee Dam and Chief Joseph Dam) (AquaTechnics, 1998). Researchers were able to document that the highest TDG levels resulted when the outlet works were opened to create storage in Lake Roosevelt for flood flows. Operation of the drum gate spillway produced relatively lower TDG levels.

The AquaTechnics report made a number of recommendations:

- Operations should be modified to minimize the use of outlet works for spills.
- Acutely lethal spikes of TDG were attributed to the rigid adherence to "rule curves" that produce rapid variations in outlet works releases. They recommended some modification of the rule curve to avoid high magnitude peaks and operate for steady spill rates.
- In general, operations should be reevaluated to include the minimization of TDG levels.
- Further evaluations were recommended of existing monitoring and of the TDG generation processes for various spill and power generation operations.

These recommendations have been addressed by U.S. Bureau of Reclamation through operations in accordance with spill caps and priorities in the Federal Columbia Power System Biological Opinion Total Dissolved Gas Monitoring Plan. Frizell (1998) outlined operational gas management measures currently in use at the dam, including:

- Use of turbines for power generation up to the limit of turbine availability and the power demand.
- Operation of turbines at speed-no-load when power loads are not available.
- Use of the spillway drum gates as the primary structure for spills that are not through the turbines, within their operating limits.
- Operation of the outlet works in a combined over/under spill pattern whenever possible to minimize gas production during involuntary spills when the lake elevation is below the level of the spillway crest.

In addition, the U.S. Bureau of Reclamation was an active participant in the Biological Opinion Water Quality Team investigation of Grand Coulee and Chief Joseph joint operations which culminated in a recommendation to trade power generation and spill to reduce TDG levels below both structures.

Schneider (1999) evaluated TDG production at Grand Coulee from previous studies and FMS data. Using data from 1996 and 1997, this study developed TDG exchange equations for outlet works and drum gate operations. The evaluation of outlet works releases assumed that TDG loading is a linear function of spillway discharge, and found a statistically significant relationship with the field data, especially when powerhouse flow entrainment was included. The analysis of drum gate spills assumed that TDG loading is an exponential function of unit spillway discharge (average discharge per spill bay), and found a moderate statistical relationship with field data with no entrainment. In general, for the same spill volume, TDG loading from drum gate releases was considerably less than TDG loading from outlet works releases. This study was limited in scope as it relied on existing data taken at the FMS six miles below the dam. Additional data collection, particularly when the spillway is operating, was recommended.

Both Frizell (1998) and Schneider (1999) raise concerns about the quality of forebay TDG data. The forebay monitor is located at a fixed depth about 100 feet below the maximum water surface. Evaluation of the data suggests that thermal stratification sometimes occurs in the forebay during June through August, which may produce different TDG levels at different depths. In addition, differences in turbine intake depth can selectively affect which depth TDG is drawn from and can pull in upstream TDG at that depth, possibly affecting both the vertical variability in TDG in the forebay and TDG pressures downstream. Additional research would help to better understand TDG patterns and processes under stratified conditions in the forebay.

2. Chief Joseph Dam

Project Description

Chief Joseph Dam, operated out of the U.S. Army Corps or Engineers (USACE) Seattle office, is the USACE's largest power-producing dam. The dam is over a mile long and spans the Columbia River near Bridgeport above the Okanogan River (Appendix E, Figure E-2). The powerhouse contains 27 turbines with a hydraulic capacity of 219 kcfs, and is angled at 90^o from the spillway structure. The spillway has a total length of 980 feet, with 19 radial gate-controlled bays each 36 feet in width. The elevation of the spillway crest is 901.5 feet, and the operating pool of Lake Rufus Woods (the impoundment behind the dam) ranges from 950 to 956 feet. The maximum total spillway design capacity is 1,200 kcfs. The spillway currently has no deflectors installed.

The tailwater elevation ranges from 780 to 790 feet, and typical depths on the stilling basin apron are 36-42 feet. The stilling basin is 167 feet long and ends with baffle blocks and stepped end sill about 11 feet in height. Downstream of the end sill, the channel bed elevation ranges from 725 to 755 feet elevation.

Chief Joseph Dam is the farthest downstream barrier to anadromous fish passage on the mainstem Columbia River. Due to the existing blockage at Grand Coulee Dam and the limited habitat available below Grand Coulee, fish passage facilities were deemed unnecessary.

TDG Generation Processes

The USACE conducted an intensive TDG field study at Chief Joseph Dam on June 6 through 11, 1999 (Schneider and Carroll, 1999). Twenty-five meters were deployed to record TDG, temperature, and other parameters at 15-minute intervals in the Chief Joseph forebay, tailrace, along several transects in the downstream pool (Lake Pateros), and in the Wells Dam forebay. TDG was also measured manually in the Methow and Okanogan rivers. Velocity was measured below the dam with Acoustic Doppler Current Profiling equipment. During the study, the dam operated under a series of varying spill volumes and configurations to evaluate different specific spill levels, percent spill conditions, tailwater elevations, and powerhouse operation configurations.

TDG levels were found to be fairly constant laterally across the forebay. TDG levels exiting the powerhouse were unchanged from forebay levels. At the meter in the powerhouse outlet closest to the spillway, higher TDG was observed, most likely from spill flows encroaching on turbine releases or from recirculation of high TDG from spills.

Measurements at Transect 1, closest to the spillway, showed TDG levels from 125 to 142%, with measurements as high at 175% from a single meter placed closest to the south spill bay. For a standard spill (similar spill from all bays), the highest TDG levels were found in the center of the channel. When spills occurred from the south half of the spillway, the highest levels were observed at the southern end. The spill using the south half tended to recirculate water to the north end of the spillway, shown by elevated TDG at that location.

The potential for powerhouse entrainment to add to TDG loading was evaluated both by direct measurement and by calculations. Powerhouse operations were varied by running alternately the west half of the powerhouse and the east half of the powerhouse under similar spill configurations. No significant difference in TDG levels downstream was observed. When observed TDG levels were predicted with a mass balance model, calculated values matched observed fairly well. Both analyses suggest that the entrainment of powerhouse flows into the aerated spill resulting in increased TDG loading is negligible.

Transect 2, crossing the channel at the FMS site, showed that spillway and powerhouse flows were not mixed at this location. TDG levels at the southwest side of the channel closely resembled forebay levels, indicating the presence of unmixed powerhouse flows. TDG at the northeast side, which includes the FMS site, were highest, indicating the presence of spillway flows unmixed or only partially mixed. Some TDG degassing below Transect 1 is also suggested by the lower levels at Transect 2.

A flow-weighted average of TDG at Transect 2 was calculated to determine an empirical model for the average TDG production from standard spillway releases. TDG generation was found to be an exponential function of unit spillway discharge. Partial spill patterns generated higher TDG levels for given unit spillway discharges as compared to a standard spill.

As TDG plumes from spill events moved downstream, they tended to mix across the channel but were also affected in the Brewster Flats area by channel variability and inflow of the Okanogan River. At the forebay of Wells Dam, TDG was fairly consistent across the channel. TDG generally took between 18 to 20 hours to reach Wells Dam from Chief Joseph Dam. Flow-weighted mass balance calculations of TDG indicated that very little degassing occurred in Lake Pateros below the Chief Joseph Dam tailrace during the study, which took place mostly during low wind conditions. However, cooler, low-TDG inflows from the Okanogan and Methow rivers were observed to moderate TDG saturation at Wells Dam.

3. Wells Dam

Project Description

Wells Dam, owned and operated by Douglas Public Utility District, is located between the Methow and Chelan rivers (Appendix E, Figure E-3). It is the only dam on the Columbia River with a "hydrocombine" structure. This design integrates the spillway and powerhouse into a single structure. Each spillway bay is stacked on top of and between each turbine bay. Turbines are contained in individual silos. As a result, the powerhouse draft tube discharges are directly below the foot of the spillway.

The Wells Dam hydrocombine structure is 1,130 feet wide and contains 10 generating units. The overall dam length is 4,460 feet and the maximum gross head is 78 feet. The total hydraulic capacity of the generators is 220 kcfs, and the maximum spillway design capacity is 1,180 kcfs. The spillway consists of 11 vertical gates with upper and lower leafs. The spillways crest is 5½ feet above normal tailwater, and is below the tailwater during high flows. Even-numbered spillway entrances have been modified to constrict flow for fish attraction. Because of its design, Wells Dam has been the most successful of Columbia and Snake River dams in meeting downstream fish passage goals.

TDG Generation Processes

Wells Dam has not been the subject of a detailed TDG generation study such as has occurred on most of the other Columbia River dams. Therefore little is know about its TDG generation processes. However, a general sense of its TDG generation characteristics can be inferred from the FMS record.

The TDG continuous monitoring record at Wells is relatively short and begins after the high TDG years of 1996 and 1997. For purposes of our analysis 2002 data were examined, since it was characterized both by periods of high flow and spills at Columbia River dams and by periods of low power demand. The daily average TDG value for the forebay monitoring station was subtracted from the tailwater value for the same day and the calculated increase plotted against the reported spill volume. Figure 13 shows that relationship.

This simple analysis shows a linear relationship of spill to TDG generation. Columbia River dams with separate spillways typically show an exponential relationship to unit spillway discharge. A detailed study would be needed to determine the effect of unit spillway discharge, powerhouse entrainment, tailwater depth, and other factors.

Ecology conducted two field surveys for TDG at Wells Dam in 2002 (Pickett, 2002). Only limited results were obtained, but slight lateral variation was observed in data across the channel. Possible causes include non-uniform spill configurations and velocity patterns which vary with depth and laterally across the channel. The lack of information on hydraulics in the Wells Dam tailrace limits the ability to understand the effect of flow characteristics on TDG levels.

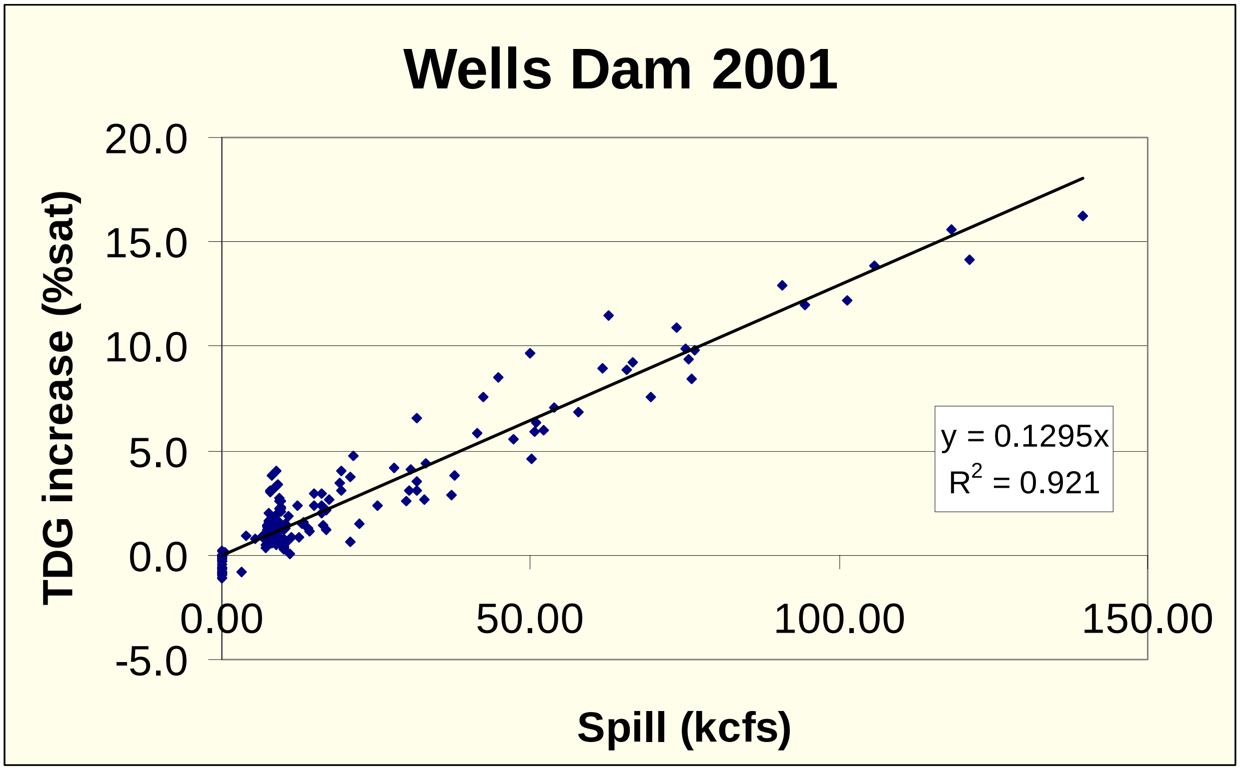

Figure 13: Wells Dam TDG Increases from Forebay to Tailwater Fixed Monitoring Stations

4. Rocky Reach Dam

Project Description

Rocky Reach Dam, owned and operated by Chelan Public Utility District, is located just north of Wenatchee (Appendix E, Figure E-4). The forebay elevation varies from 703 to 707 feet, while the tailwater elevation is normally 619 feet and varies with river flows. The spillway, which crosses the channel, has a crest elevation of 650 feet, a total length of 740 feet, and consists of 12 bays, each controlled by a 56 foot radial gate. The powerhouse sits at about a right angle to the spillway, parallel to the shore. It is 1,090 feet long, contains 11 turbines, and has a hydraulic capacity of 212 kcfs.

The spillways and tailrace at Rocky Reach Dam have several features not found at other Columbia River dams. Each spill bay (except number 1) has a notched nappe deflector which forces the edges of the flow together into the center. The stilling basin has several structures for energy dissipation, including aeration wedges, baffle blocks, and a notched sloping end sill. The purpose of these structures is to dissipate energy by creating very turbulent conditions in the shallow stilling basin.

The average stilling basin bottom elevation is around 595 feet. Tailrace bottom elevations mostly vary from 580 to 600 feet, with a few holes dropping to 570 feet elevation.

TDG Generation Processes

Typically the height of the spillway, the angle that the spill strikes the stilling basin, the depth of the tailwater, and the volume of spill will determine how much TDG spill will generate. Because of the configuration of Rocky Reach's spillway, it has been considered a relatively low generator of TDG.

Chelan PUD did a limited assessment of TDG production during the 1999 season (Perleberg and McDonald, 1999). A fairly weak relationship was found between the increase in TDG from forebay to tailrace at Rocky Reach Dam and spill volumes, both as total discharge and percent of river flow. The change in TDG from forebay to tailrace averaged around 2% saturation with maximum increases of 12 to 15% saturation. Transect measurements showed a trend towards decreasing TDG levels laterally from east to west across the channel.

To better understand TDG production processes and the fate of TDG below Rocky Reach Dam, Chelan PUD contracted with the USACE to conduct a detailed study (USACE, 2003a). Transects of meters were placed just below the stilling basin at 1600 feet, and 3700 feet below the dam and near the tailwater FMS site at the Highway 97 bridge about 4.4 miles downstream. Monitoring occurred from April 26 through May 3, 2002.

Spills were varied both in amount and configuration. Spillway discharge varied from 10.6 to 61.0 kcfs, while spill patterns included standard, uniform over 11 of 12 bays, and uniform over the four bays closest to the powerhouse, in the center, or farthest from the powerhouse.

Maximum TDG levels observed were over 128% saturation immediately downstream of the spillway and farthest from the powerhouse. Forebay levels at this time were around 108% saturation. The increase in average TDG from forebay levels ranged from 1.6 to 8.6% saturation. In general, TDG generation at Rocky Reach Dam, without spill deflectors or other gas abatement structures, was comparable to other Columbia and Snake river dams with deflectors.

TDG saturation exiting the spillway was found to be a function of spill pattern and discharge, while also being influenced by powerhouse operations. TDG generation followed a linear relationship to spillway discharge, with that relationship varying by spill pattern. The lowest TDG levels resulted from a uniform spill over 11 of 12 spill bays, both near the spillway and downstream. Spilling from four bays farthest from the powerhouse produced the highest TDG levels near the spillway, but average conditions downstream were similar to the standard spill. Spilling from the bays closest to the powerhouse produced higher average TDG downstream.

The hydraulics of the powerhouse flows and how they interacted with spill flows had a strong effect on TDG levels and spatial distribution below Rocky Reach. Throughout the river downstream, TDG remained highest on the east bank and lowest on the west bank closest to the powerhouse, reflecting incomplete mixing of powerhouse flows (with TDG at lower forebay levels) with spill flows.

Entrainment of powerhouse flows into spill flows was observed in the field and also identified through TDG mass balance calculations. Higher powerhouse flows appeared to decrease TDG generation, which could be related to tailwater elevation and depth of flow. Shifting power generation to the southern turbines (farthest from the spillway) also appears to help reduce TDG generation.

5. Rock Island Dam

Project Description

Rock Island Dam, owned and operated by Chelan Public Utility District, is located just south of Wenatchee (Appendix E, Figure E-5). It was the first dam constructed on the Columbia River. The minimum pool elevation is 609 feet above sea level, and normal tailwater elevation is 577 feet. Total head is relatively small (35-40 feet) in comparison to other Columbia River dams. The total dam structure is 3,800 feet long and consists of a spillway in the center flanked by two powerhouses. The structure as a whole is relatively complex, since it was constructed on natural basalt outcroppings and has been built in three separate construction phases.

The First Powerhouse extends 746 feet from the east bank, while the Second Powerhouse on the west side of the channel is 470 feet long. The combined hydraulic capacity of the powerhouses is 225 kcfs. The spillway is slightly curved on its west end, and consists of 32 vertical gates. The six east gates (1-6) and seven west gates (26-32) have deep sills with bottom elevations of 559 feet, well below the tailwater elevation, and are controlled with drop gates with three leaves. The 19 center gates have shallow sills with bottom elevations of 581.5 feet, slightly above normal tailwater elevation, and are controlled with two drop gate leaves. Gates 21-23 discharge to a very shallow concrete step. Nine gates have been retrofitted with notched upper leaves to optimize downstream fish passage. Historically the Columbia River has overtopped the dam during extreme floods.

The bathymetry of the tailwater channel is highly variable, and is composed of a complex array of spires, channels, and holes. Bottom elevations vary from 568 feet downstream of Bay 7 to a deep hole below Bay 30 with an elevation of less than 500 feet. A shallower channel below bays 5-23 ranges in elevation from 550-560 feet, while a deeper channel at the east and west ends of the spillway ranges from 530-540 feet. The river bed continues to be fairly complex until about 200 feet downstream.

TDG Generation Processes

Chelan PUD did a limited assessment of TDG production during in the 1999 season (Perleberg and McDonald, 1999). A moderate to strong relationship was found between the increase in TDG from forebay to tailrace at Rock Island Dam and spill volumes, both as total discharge and percent of river flow. The change in TDG from forebay to tailrace averaged around 6% saturation with maximum increases of 15 to 17% saturation. Transect measurements showed a slight trend towards decreasing TDG levels laterally from east to west across the channel.

An intensive TDG investigation was conducted at Rock Island Dam on June 17-22, 1999 (Schneider and Carroll, 2000). Meters were placed in transects in the forebay, immediately downstream of the spillways, about 600 feet downstream of the dam, and adjacent to the tailwater FMS sites about 6,000 feet downstream. Twelve spill events with varying volumes and patterns were scheduled, with total spillway discharges ranging from 11.0 to 94.4 kcfs. Unit spillway releases ranged from 1.7 to 40.3 kcfs per bay. Spill patterns varied widely, and included use of the notched weir, overflow discharge, and discharge under the gates; and use of deep sill gates, shallow sill gates, and the gates with concrete pads.

Results suggested that forebay TDG levels are transferred unchanged through the powerhouses, which is typical of other Columbia and Snake River dams. Spills to the concrete pad were observed to actually reduce forebay gas levels, but only at low total spill levels. Transect 2, located 600 feet below the spillway, measured the highest TDG levels with a maximum level of 137.5% saturation. Average TDG pressures downstream were found to be a linear relationship to total spillway discharge, which is a similar finding to the results of earlier studies.

Overall, underflow releases in deep spill bays showed the most promise for the lowest TDG generation. However, existing equipment is inadequate to pull all three leaves of most deep sill gates, so an upgrading of equipment would be necessary. Under standard spills (overflow), use of shallow sill gates produced the lowest TDG levels. For low unit spill discharges, the concrete bays also produced low TDG levels. Use of the deep spill bays for overflow spill releases produce higher TDG levels, and likely also entrain powerhouse flows producing higher levels of TDG loading. The notched fish passage gates tended to produce the highest levels of TDG, but the low spills associated with fish passage allowed lower TDG levels downstream due to dilution from powerhouse flows.

The representativeness of TDG readings at the tailwater FMS can vary according to spillway and powerhouse operations. Since spill flows tend to hug the east bank, the river is not fully mixed at the tailwater FMS. Operation of the Second Powerhouse will tend to push higher TDG flows into the east bank. However, First Powerhouse flows can have the opposite effect, pushing higher TDG flows towards the middle of the channel so that FMS readings reflect forebay TDG levels carried by powerhouse flows.

In September 2000, Chelan PUD installed a prototype flow deflector at Bay 29, a deep sill spillway at the west end of the spillway. An angled deflector was built on the endsill below the spillway to redirect spill flow slightly upward. Bay 29 is operated as a notched overflow weir for fish passage. The USACE conducted an evaluation of the deflector's TDG performance (Carroll et al., 2001). Pre- and post-deflector monitoring surveys were conducted below Bays 29 and 30 (the bay next to 29 used as a control). The study found comparable TDG levels below both bays during pre-deflector monitoring. Post-deflector monitoring found an average reduction in TDG of 4.5% saturation below Bay 29. The complexities introduced by the variability of river flow, tailrace elevation, powerhouse flows, upstream TDG levels, spill discharge rates, and spill pattern makes it difficult to extrapolate results to a wider range of conditions

In 2001, Chelan PUD had the USACE test a prototype deflector below Bay 16 for use with a notched weir overflow spill for fish passage (Carroll et al., 2002). Bay 16, a shallow bay with a flat concrete pad, was retrofitted with an angled deflector on the endsill to redirect spill flow slightly upward. The study paired Bay 16 with Bay 18, and monitoring was conducted before and after deflector installation. Despite extremely low flows that limited the ability to spill, the study showed that the deflector reduced TDG by as much as 6% saturation. TDG levels during this study never exceeded 110% saturation. As with the previous single-bay study, it is difficult to extrapolate these results to a wider range of conditions.

6. Wanapum Dam

Project Description

Wanapum Dam, owned and operated by Grant Public Utility District, is located downstream of Vantage (Appendix E, Figure E-6). The project information below is summarized from Grant PUD’s October 2003 License Application for FERC relicensing (Grant PUD, 2003).

The normal pool operating range is between 560 and 571.5 feet elevation. The entire structure is 8,637 feet, about two-thirds of which is embankment. The powerhouse and spillway are bent at an angle away from each other; the powerhouse is 1,000 feet long on a roughly north-south orientation, while the spillway run is 832 feet from the northeast to southwest. Fish ladders and space for future powerhouse units make up the balance of the structure.

The powerhouse contains 10 turbine units which operate at a design head of 80 feet and discharge of 178 kcfs. The spillway has a total design capacity of 1,400 kcfs, and includes 12 50-foot wide tainter gates and a 20-foot-wide, top-spilling sluice gate at the east end of the spillway. The 12 spillways have been retrofitted with deflectors for TDG abatement as part of Grant PUD’s Gas Abatement Plan approved by Ecology. Energy dissipation is provided by a stilling basin which consists of a level concrete apron extending 80 feet downstream. Grant PUD has proposed to install advanced turbines at Wanapum that could increase powerhouse capacity to 188 kcfs.

TDG Generation Processes

Wanapum Dam has gone through an extensive program of gas abatement. Several prototype spill deflectors were designed, installed in single bays, and tested in the late 1990s. In early 2000, spill deflectors were installed in all 12 spill bays. Installation of spill deflectors at Wanapum Dam has significantly reduced TDG generation during spill.

Post-deflector testing was conducted by USACE in spring 2000 (USACE, 2001c). Thirty meters were placed in five locations: one in each forebay of Wanapum and Priest Rapids dams and three transects 800 feet, 2100 feet, and 16,000 feet downstream of the Wanapum Dam spillway. The downstream transect was located near the tailwater fixed monitoring station (FMS) at the Beverly Railroad Bridge.

River flows during the study varied between 142 and 268 kcfs, resulting in tailwater elevations ranging from 492 to 497 feet. The dam used a variety of powerhouse flows and spill volumes and patterns during the study. Powerhouse flows were used to vary tailwater elevations. Spill patterns included uniform spill, fish migration spill, and fish spill with the sluice gate closed. The uniform pattern discharges relatively evenly from all bays, while the fish spill usually has higher spill from one to eight bays at the west end of the spillway. Spill volumes varied from 3.7 to 12 kcfs per bay. Maximum spills exceeded the 7Q10 levels specified in this TMDL (264 kcfs).

The highest TDG pressures during the study were measured along Transect 1, closest to the center of the spillway. The highest value observed was 136.5% saturation during a uniform spill event of 12 kcfs per bay (the highest spill in the study). TDG levels from meters at the east end of Transect 1 were strongly affected by powerhouse flow and resembled forebay levels.

Transect 2 (2100 feet downstream) measured conditions below the turbulent aerated zone and reflected a mix of spillway and powerhouse TDG conditions. The highest TDG levels were found near the west (spillway) side of the channel, with maximum TDG measured at 129.3% saturation during maximum spill. Twice when spillway discharges were below 50 kcfs, downstream TDG levels were observed to drop below forebay TDG levels. This suggests that some degassing or stripping of TDG is occurring under these conditions.

Transect 3, about three miles downstream from Wanapum Dam near the FMS, continued to show lateral variation with higher TDG levels near the west bank. The maximum TDG observed at this transect was 124.9% saturation, again during the maximum spill. Some stations on the east end of the transect showed evidence of degassing under certain conditions, perhaps related to a shallow channel section near the east bank. The FMS tended to measure a mid-range of TDG levels, with levels lower than meters to the west but higher than meters to the east.

Lateral gradients continued to be observed in the Priest Rapids Dam forebay, with levels again increasing from east to west. Conditions at the forebay FMS (located in the center of the dam) were variable, with levels sometimes higher and sometimes lower than either side of the channel. In general, the effects of spill releases from Wanapum Dam translated themselves downstream with some mixing and attenuation of peaks.

Pre-deflector and post-deflector TDG levels were compared to evaluate reductions in TDG due to the deflectors. Looking at the higher values on the west side of the channel, deflectors reduced TDG levels by approximately 11% saturation. TDG levels averaged over the cross section showed greater reductions for low river flows than for high river flows, with reductions of 3-4% saturation at flows of 60 kcfs or less and 1-2% at flows of 100 kcfs or more. A spill flow of 118 kcfs (slightly higher than a spill at 7Q10 with full powerhouse capacity) produced 128% saturation, which is a significant reduction from TDG levels of over 140% prior to deflector installation.

Juul (2003) used regression equations to compare pre- and post-deflector TDG generation at the Beverly Bridge FMS site. This analysis showed a 9% decrease in TDG at 120 kcfs spill and 6% decrease at 150 kcfs spill when 200-2001 data were compared to a 1996-1997 data set.

Spills of up to 85 kcfs are expected to remain below the tailwater fish passage TDG criteria of 120% saturation, as compared to a spill of 20 kcfs having this effect prior to deflector installation. A spill of up to 95 kcfs should meet the 120% saturation TDG criterion at the tailwater FMS, because TDG levels at the FMS are lower than the maximum level below the spill. Spills up to 60 kcfs should meet the Priest Rapids forebay fish passage TDG criterion of 115% saturation, as compared to the pre-deflector spill limit of 16 kcfs at this location.

TDG generation was found to be a linear function of unit spillway discharge. The study found a weak relationship of TDG levels to tailwater elevation, with data suggesting that TDG levels are slightly lower as tailwater levels rise. This result is contrary to what is usually observed at Columbia River dams.

Velocity measurement in the Wanapum Dam tailrace indicated flows sometimes moving from the powerhouse discharge into the spill. This suggested that powerhouse flows were being entrained into the spill and being aerated along with the spill. A mass balance calculation comparing TDG levels below the spillway to the average TDG levels at Transect 3 pointed towards possible entrainment of powerhouse flows under certain conditions. The calculations estimated that a partition wall to separate powerhouse flows from the aerated spill could possibly reduce average downstream TDG levels, but the variability of the estimates prevents any strong conclusions.

7. Priest Rapids Dam

Project Description

Priest Rapids Dam, owned and operated by Grant Public Utility District, is located upstream of the Vernita Bridge (Appendix E, Figure E-7). The project information below is summarized from Grant PUD's April 2003 draft License Application for FERC relicensing (Grant PUD, 2003). Priest Rapids Dam is the last dam on the Mid-Columbia River before the river enters the Hanford Reach and eventually meets the Snake River.

The normal pool operating range is between 481.5 and 488 feet elevation. The entire structure is 10,103 feet long, of which 7,385 feet are rock-filled embankment, and runs straight across the channel perpendicular to river flow. The powerhouse is 1,025 feet long and contains 10 turbine units which operate at a design head of about 80 feet and discharge of 178 kcfs. The spillway is 1,152 feet long with a total design capacity of 1,400 kcfs. The spillway consists of 22 tainter gates, each 40 feet wide.

Energy dissipation is provided by the stilling basin which consists of a level concrete apron extending 75 feet downstream at 387 feet elevation with a sloped end sill rising to 391 feet. Tailwater elevations are typically between 400 and 412 feet, resulting in stilling basin depths of 13-25 feet.

Downstream of the stilling basin, bottom elevations range from 390 to 404 feet. Areas shallower than 400 feet can become exposed when tailwater elevations are low. The river as it enters the free-flowing Hanford Reach moves through areas with shallow areas and islands, with deeper areas over 35 feet in depth.

TDG Generation Processes

An intensive study was conducted between July 21 and August 4, 2003 to characterize TDG production by spill at Priest Rapids Dam and transport into the Hanford Reach (USACE, 2003b). Total river flow was held constant, and standard spill varied over four spill discharge rates (from 27 to 100 kcfs), at two powerhouse flow rates (50 and 150 kcfs) and at constant total flow (150 kcfs) with variable powerhouse flows. A spill of 100 kcfs combined with a powerhouse flow of 150 kcfs approximates conditions just below a 7Q10 flood flow. Non-standard spill was also tested by spilling from only the west, central, and east sections of the spillway. Each test treatment was scheduled to last at least three hours to allow conditions to equilibrate.

Twenty-one meters were placed above and below the dam to evaluate TDG conditions. A transect of four meters were placed in the forebay; six meters were placed directly below the dam – four below the spillways, one at the powerhouse draft tube deck, and one at the entrance to the north fish ladder; a transect of six meters was placed at the USGS flow gaging station several miles downstream; and a transect of five meters were placed at the Vernita Bridge, which is also the site of the FMS.

The highest TDG levels during the study were measured just below the spillway and reached over 135% saturation. In general, TDG levels below the spillway were proportional to total spill (although the highest spill did not produce the highest TDG levels). During the lowest spill levels (specific discharges of less than 2 kcfs/bay), TDG levels below the spillway dropped from forebay levels, suggesting that the spill was causing degassing. Where the unit spill discharge varied between bays, higher TDG was seen below bays with higher unit spills per bay.

TDG was also proportional to tailwater elevations. TDG could be observed to rise and fall with tailwater elevation changes. Under one pair of spill events, when spill increased but the tailwater elevation decreased, TDG production decreased as well.

Spillway bays near the powerhouse showed evidence of dilution with powerhouse flows. Bay 22, which discharged with a fully aerated top spill during the entire study, tended to generate higher TDG levels than the other bays for the same specific discharge rates.

Lateral gradients in TDG were observed downstream at both the USGS and Vernita Bridge transects, corresponding to spillway and powerhouse flows. The FMS at Vernita is midchannel, and tended to represent the highest TDG levels in that transect.

Transect values were averaged and compared for forebay, spillway, and downstream. From the forebay to the USGS site, the change in average TDG ranged from a decrease of 1.1% saturation to an increase of 10.6% saturation. The average change over the study was 2.3% saturation. From the USGS transect to Vernita, TDG levels for the cross-sectional average decreased by about 1% saturation, which indicates a small amount of degassing was occurring.

During the highest river flows and spills (145 kcfs spill at 272 kcfs flow), average TDG reached its highest level of 129.4% below the spillway, 122.2% at the USGS transect, and 121.5% at the Vernita Bridge. Decreasing TDG at these flow levels was mostly due to mixing of powerhouse flows with lower TDG levels from the forebay. However, some degassing occurred, which was increased by higher wind velocities and shallower flow, which would be expected.

A non-linear regression was used to develop an equation to predict average TDG below the spillway. A good prediction was developed for TDG as a linear function of tailwater depth and an exponential function of specific discharge. TDG exchange tends to be controlled by the specific discharge at low levels of discharge, but at high specific discharges the tailwater depth becomes the dominant factor.

Using the non-linear regression and a simple mass-balance mixing model, TDG levels at the USGS transect were predicted from specific discharge, tailwater elevations, average forebay TDG, and powerhouse flows. A good prediction was obtained, thus indicating that entrainment of powerhouse flows into the aerated spill is negligible. The training wall between the powerhouse and stilling basin reduces the interaction of these flows.

In general, TDG exchange at Priest Rapids, which has no spill deflectors, resembled the TDG exchange rates at Lower Granite Dam which has been modified with deflectors. Priest Rapids Dam's moderate exchange rate is likely due to its shallow stilling basin, whose depths are similar to The Dalles Dam where TDG exchange rates are also relatively low.

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Loading Capacity

Linkage of TDG Loading to the Criteria

As discussed above, the fundamental process that elevates TDG is gas transfer between the air and water at the boundary of entrained bubbles, driven by differential gas pressures. For any given spill volume and tailwater depth, the excess pressure over ambient barometric pressure, ΔP, can be predicted. The mass loading of air that is associated with any given ΔP will depend on water temperature. However, this mass loading is of less importance than ΔP, since it is ΔP that drives whether gas bubble trauma will occur. For these reasons, using excess pressure rather than mass loading to express loading capacity is appropriate for this TMDL and is supported by the Clean Water Act's allowance for the use of *other appropriate measures* in the development of TMDLs.

The use of critical barometric pressure to set a value of ΔP to meet the criterion of 110% saturation is appropriate because of the need to meet the criteria throughout the river as conditions change downstream of the dams and away from compliance locations. However, the TDG criteria for fish passage are very specific for their location of application and are silent about the required levels away from the compliance locations. Therefore, loading capacities for fish passage will be set in terms of percent saturation, and are equal to the criteria.

To determine the TMDL loading capacity, ΔP can be directly related to the TDG water quality criteria as described in Equation 6:

$$S_{tdg} = \frac{(P_{atm} + \Delta P)}{P_{atm}} * 100$$

Where

S_{dtg} = TDG percent saturation
P_{atm} = barometric pressure
ΔP = excess pressure over ambient barometric pressure

If S_{tdg} is set at the criterion of 110% saturation, the equation can be rearranged to establish a ΔP loading capacity (ΔP_{lc}):

$$\Delta P_{lc} = P_{atm} * 0.1$$

To choose a critical barometric pressure P_{atm} for establishing the loading capacity, the 95th percentile low pressure was determined during the spring and summer spill season for each dam. This pressure varies from 748 mm Hg at the downstream boundary above the Snake River to 721 mm Hg in Lake Roosevelt. Therefore, loading capacities for the Mid-Columbia River and Lake Roosevelt are set to the values of ΔP shown in Table 6.

Table 6: Loading Capacities for TDG in the Mid-Columbia River and Lake Roosevelt

Reach of Columbia River	Loading Capacity
International border to Grand Coulee Dam, including Lake Roosevelt, Spokane Arm, Grand Coulee Dam forebay (all conditions)	72 mm Hg above saturation (ΔP)[1]
Grand Coulee Dam to Okanogan River (all conditions)	73 mm Hg above saturation (ΔP)[1]
Fish passage – Forebays of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	115% saturation[3]
Fish passage – Tailrace of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	120% saturation[3] 125% saturation[4]
Non-fish passage – Okanogan River to Wells Dam	73 mm Hg above saturation (ΔP)[1]
Non-fish passage – Wells Dam to Yakima River	74 mm Hg above saturation (ΔP)[1]
Non-fish passage – Yakima River to Snake River	75 mm Hg above saturation (ΔP)[1]

[1]Maximum instantaneous
[2]When authorized by Ecology after approval of a gas abatement plan
[3]Average of 12 highest hourly readings in a 24-hour period
[4]Maximum one hour average

Load Allocations

For the purpose of this TMDL, each dam will be included in a load allocation based on a river reach, because no NPDES permits will be issued to the dams to regulate TDG caused by spills[1]. This approach is also reasonable for several reasons:

- Spills entrain air to reach a polluted state, much like a high-energy release of water might erode a stream bank.
- Dams are essentially very large instream structures that will require modifications to achieve attainment of water quality standards.
- The level of improvement expected from any specific structural or operational modification is uncertain, and therefore a series of modifications may be needed to achieve the desired outcome, with effectiveness monitoring to assess results.

The wasteload allocation in this TMDL is zero because there are no NPDES-permitted point sources that contribute to elevated TDG in the Mid-Columbia River or Lake Roosevelt.

Table 7 shows the load allocations for forebays and tailraces of each of the seven dams on the Mid-Columbia River, the international border, and the Spokane River inflow. As noted previously, because of the unique nature of TDG, load allocations are not directly expressed in terms of mass loading.

Almost all dams on the Columbia and Snake rivers have been studied for TDG exchange processes. These studies have shown that under most conditions TDG concentrations created by spills are independent of upstream conditions. This is because the spilled water and entrained air rapidly reach a new equilibrium under the hydrostatic pressures of the stilling basin. The only exceptions appear to be when spill volumes are very low and the time for gas absorption short. Therefore, it is a fairly accurate generalization to say that each dam's spill "resets" the TDG levels for the water that passes over the spillway and for any entrained powerhouse water.

For this reason, the primary approach of this TMDL is that each dam is responsible for the TDG generated by its spill, and not for TDG levels upstream. Each dam has the obligation to meet the load allocation below the spillway where conditions are entirely or predominantly representative of the spill and downstream to the forebay of the next dam if possible. If upstream conditions prevent meeting allocations downstream, then each dam should manage its spill to at least make TDG conditions in the downstream pool no worse and ideally to improve TDG levels downstream.

Downstream levels are a simple mass balance of each dam's TDG generation from spill plus powerhouse flows that pass forebay levels from upstream. Therefore for non-fish passage, if TDG comes from Canada at 110%, and each dam does not increase the gas in its spill above 110%, the river will always meet 110%.

[1] The Courts have determined the characterization of dams as point sources for which NPDES permits will not be issued for certain parameters. The current policies of the state of Washington and EPA are to not issue NPDES permits for TDG.

Table 7: Load Allocations for TDG in the Mid-Columbia River and Lake Roosevelt

Location	Load Allocation
All Conditions – International border to Grand Coulee Dam, including Lake Roosevelt, Spokane Arm and Grand Coulee Dam forebay	72 mm Hg above saturation[1]
All Conditions - Grand Coulee Dam to Okanogan River	73 mm Hg above saturation[1]
Fish passage – Forebays of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	115% saturation[3]
Fish passage – Tailrace of Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids dams[2]	120% saturation[3] 125% saturation[4]
Non-fish passage – Okanogan River to Wells Dam	73 mm Hg above saturation[1]
Non-fish passage – Wells Dam to Yakima River	74 mm Hg above saturation[1,5]
Non-fish passage – Yakima River to Snake River	75 mm Hg above saturation[1,6]

[1]Maximum instantaneous. If the upstream forebay of a project exceeds the load allocation, then this allocation shall apply to the TDG pressures generated only by that project's spill.
[2]When authorized by Ecology after approval of a gas abatement plan; allocations only apply if spill is occurring
[3]Average of 12 highest hourly readings in a 24-hour period
[4]Maximum one hour average
[5]For Wells Dam and for dams with spills that are not independent of upstream levels, if upstream forebay levels exceed the load allocation, then TDG levels in the downstream compliance area shall not exceed upstream forebay levels.
[6]This load allocation meets the upstream load allocation set by the TMDL for Lower Columbia River TDG.

Like loading capacity, allocations are stated in terms of percent saturation for fish passage and in terms of ΔP at all other times and locations. Load allocations are equal to loading capacity throughout the TMDL area, including each dam's forebay and tailrace. The load allocation for the downstream boundary above the Snake River is equal to the allocation at the upstream boundary of the Lower Columbia River TDG TMDL (Pickett and Harding, 2002) thus ensuring consistency between the TMDLs.

One challenge to meeting the allocations in this TMDL is that, for any given dam, if TDG levels in the forebay exceed 115%, the forebay of the next dam downstream may also not meet 115%, no matter how the dam manages spill. In this situation, the goal of the TMDL is to continue spill for fish passage, but spill at a level that does not worsen TDG levels and hopefully improves them somewhat. Details of how this approach will be implemented are provided in Appendix A.

When this TMDL is fully implemented, spills from dams downstream of the international border must meet the allocations (except during flows above a 7Q10 flood). Increased hydropower generation capacity from expansion projects at Hugh Keenleyside Dam and Brilliant Dam in Canada are predicted to significantly reduce TDG levels (RL&L Environmental Services Ltd., 2002), while TDG reductions can also be expected from expansion of hydropower capacity at Waneta Dam in Canada. Implementation of TDG TMDLs and FERC license conditions at dams in the Pend Oreille and Clark Fork rivers in the United States should also reduce TDG levels entering the Columbia River. The combination of all these activities is expected to result in forebay levels of TDG from Wells Dam downstream that will only exceed 115% when flows are above 7Q10 flood levels.

Long-term Attainment of Water Quality Standards

Attainment of Standards for All Spills

Federal and state laws and rules require attainment of state water quality standards; therefore, the ultimate goal of this TMDL is to achieve attainment. Since special criteria have been established in Washington for "voluntary" spills for fish passage under an approved plan, this TMDL also includes allocations for that situation.

For a dam wholly within Washington's jurisdiction to be covered by the allocations for fish passage, the Department of Ecology must designate the fish passage period (beginning and ending dates) based on the recommendations of NOAA Fisheries and other decision-making bodies and approve the gas abatement plan for the dam. Spills in support of fish passage (such as for research or performance testing) can also be included under the fish passage load allocations with prior approval from Ecology.

Spills can occur at any time and at any volume due to flood control requirements, lack of power demand, or turbine maintenance or failure. Therefore, as allowed by Washington State and Colville Tribe water quality standards, this TMDL will be applicable for all spills below 7Q10 river flood flow conditions during the March through September season, regardless of the cause of the spill.

Operational versus Structural Solutions

The Mid-Columbia River dams, as currently designed, will not be able to meet TDG criteria for all spill discharge levels up to the 7Q10 flow. Table 8 illustrates three cases: a spill of the entire river at 7Q10 flow, a 50% spill at 7Q10 flow, and a spill at 7Q10 flow in excess of 95% powerhouse hydraulic capacity. TDG is estimated from regression equations developed for these dams using data from fixed monitoring stations or special studies (source cited in Table 8 footnotes). The estimates in Table 8 for each project are not exactly comparable, since the equations developed at each project are based on varying levels of analytical complexity and represent conditions at varying locations. Nonetheless, Table 8 provides a rough comparison of each project's TDG generation and ability to meet allocations.

None of the dams will likely meet even Washington's 125% TDG criterion if forced to spill the entire river at 7Q10 flows (an extremely unlikely event, but provided to illustrate a worst-case scenario). However, most of the dams can meet Washington's 120% criterion if they are able to use most of their powerhouse capacity. With the addition of flow deflectors and/or additional powerhouse capacity at several projects, it is likely that all dams could at least achieve 120% saturation.

Table 8: Predicted TDG for 7Q10 Spill

Dam	7Q10 (kcfs)	100% spill *TDG (%sat)*	50% spill *TDG (%sat)*	7Q10 less 95% PH[1] (kcfs)	%spill	*TDG (%sat)*
Grand Coulee[2]	222	*142*	*142*	0	0%	0
Chief Joseph[3]	222	*145*	*137*	14	6%	115
Wells[4]	246	*147*	*131*	37	15%	120
Rocky Reach[5]	252	*150*	*131*	43	17%	118
Rock Island[6]	264	*145*	*128*	55	21%	117
Wanapum[7]	264	*149*	*129*	95	36%	123
Priest Rapids[8]	264	*129*	*129*	95	36%	129

[1] PH = powerhouse capacity
[2] Schneider, 1999; Table 5 (total drum gate spill discharge with entrainment, maximum TDG level in spill below aerated zone)
[3] Schneider and Carroll, 1999; Figure 27 (unit uniform spill discharge, tailwater FMS TDG level)
[4] Figure 13 above (assumes 115% in forebay, tailwater FMS TDG level)
[5] USACE, 2003a; Figure 44 (total standard spill discharge, maximum TDG level in spill below aerated zone)
[6] Schneider and Carroll, 2000; Figure 56 (total spill discharge, downstream average TDG level)
[7] USACE, 2001c; Figure 26 (total spill discharge, maximum TDG level in spill below aerated zone)
[8] USACE, 2003b; Table 11 (unit spill discharge, tailwater elevation = 418 feet, BP = 742 mm Hg, average TDG level in spill below aerated zone)

Therefore, attainment of this TMDL's allocations may require structural changes. The state's and tribe's Summary Implementation Strategy (Appendix A) outlines a variety of alternatives for operational and structural changes which move in the direction of compliance under all spill levels. However, the effectiveness of many of these changes can only be estimated and must be assessed after implementation. Also, implementation of structural solutions is dependent on Congressional appropriations and the financing and budgeting limitations of the public utility districts. Therefore, attainment of the allocations set in this TMDL will take a significant length of time and must take into account a certain level of inherent uncertainty.

In addition, compliance with standards, especially with the 110% criterion where and when applicable, will depend on operational solutions. Management of river flows and spill patterns can help minimize spill. The ability to fully utilize powerhouse capacity during high flows could also help reduce periods when TDG criteria are exceeded if additional power use and marketing strategies were developed. Development and implementation of operational tools to minimize TDG generation is an ongoing process, and further research is likely to produce additional options for improvement.

Compliance Locations

In this TMDL, geographic locations are specified where the TMDL is in effect. Monitoring for TMDL compliance will occur at locations within or near compliance locations, as described in the TMDL Implementation Plan (Appendix A) and in future implementation and monitoring plans. The state and tribes will be responsible for evaluating monitoring results and progress towards attainment of these allocations. Any potential compliance actions are also the responsibility of the state and tribes.

Fish Passage Compliance Locations

For fish passage allocations, the compliance locations are at the fixed monitoring station (FMS) sites in the forebay and tailrace (or other downstream site) of each dam. These compliance locations have been established by collaboration between the fisheries agencies, state agencies, and dam operators, usually through the interagency Water Quality Team.

Non-Fish Passage Compliance Areas

For non-fish passage conditions, the TMDL will be in effect in eight reaches of the Columbia River, termed *compliance areas*. Compliance areas are defined in the pools behind each dam and in the reach from Priest Rapids Dam to the Snake River. From Grand Coulee to Priest Rapids dams, the compliance areas will begin in the tailrace below the upstream dam and extend to the forebay of the downstream dam. The compliance area of Lake Roosevelt will begin at the head of the lake below the Canadian border and extend to the forebay of Grand Coulee Dam. The compliance area downstream of Priest Rapids Dam extends from the tailrace to the confluence of the Snake River.

Load allocations for non-fish passage conditions apply at all locations throughout each compliance area. The TMDL does not apply from the dam structure to the beginning of the compliance area below each dam. Load allocations are by reach within the compliance areas, and although dam spills are the primary source of TDG in the compliance area, the TMDL recognizes that other natural and human influences may contribute to TDG levels in the compliance areas,

The compliance area boundaries for the tailrace of each dam were chosen from several options, illustrated in Figure 14:

1. By a strict interpretation of state and tribal water quality standards without any consideration of applying the mixing zone provisions of the water quality standards, the tailrace compliance area would be the entire river from the dam downstream. This includes the area of maximum TDG immediately below the spillway. However, this area is difficult to identify and monitor in real time and does not take into account the rapid degassing in the aerated zone.

2. If state and tribal mixing zone provisions were applied to the aerated zone (the area of bubble entrainment and dissipation), then the tailrace compliance area would begin at the end of the aerated zone. This location would be easier to identify for regulatory purposes.

3. The area of compliance could begin at the tailwater FMS sites, but mixing zone provisions would need to be applied to the entire river, including powerhouse flow. The locations of the tailwater FMS sites are clearly identified. However, they are inconsistent with respect to the amount of mixing they represent between water gassed by the spill and water unchanged from the forebay.

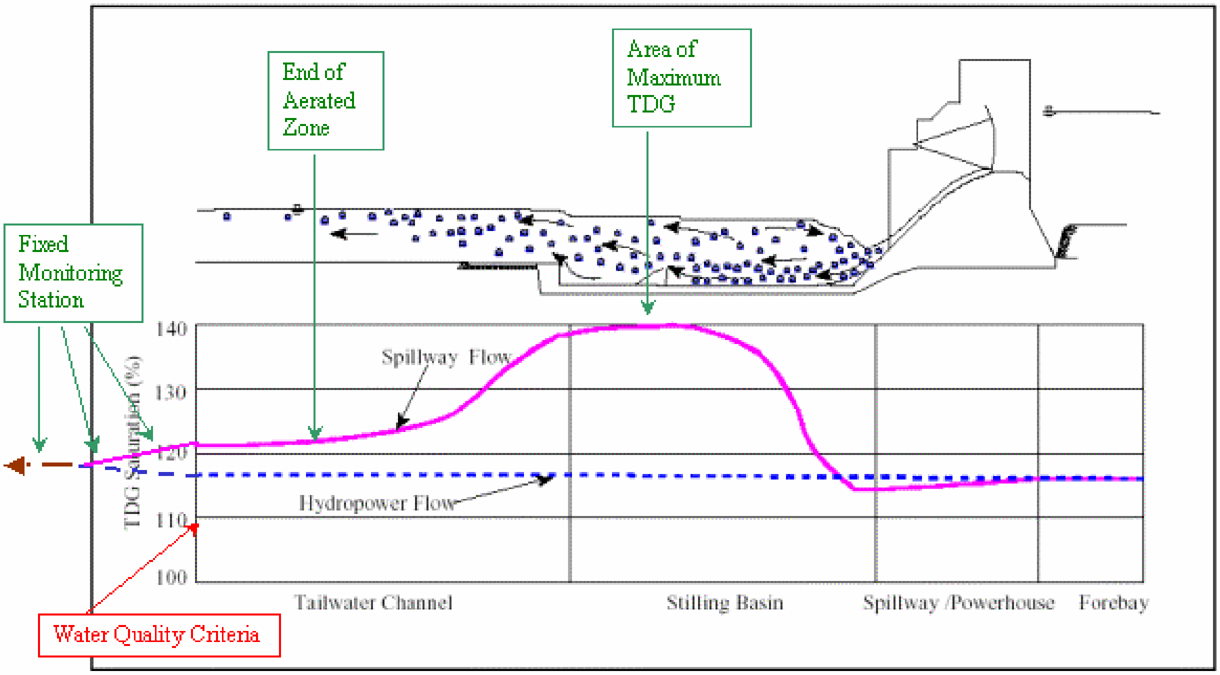

Figure 14: Key Features of Potential Tailwater Compliance Area Boundaries

The upstream boundaries of tailwater compliance areas will be based on application of the mixing zone provisions of the water quality standards to the aerated zone immediately below the spillways of the Mid-Columbia dams. The water quality standards for the state of Washington and the Colville Tribe provide an allowance for a mixing zone. Within a mixing zone, water quality can exceed standards, but compliance with standards is required at the boundary of the mixing zone. In this context, the area excluded from compliance with the standards is the aerated zone, and not literally a mixing zone.

There are several reasons that it is appropriate in this situation to exclude an area from compliance with the standards through use of the mixing zone provisions of the standards:

- TDG levels rise immediately below the spillway, but then degas for some distance downstream. The tailrace compliance area boundaries were determined from field observations or research which identified the location where degassing was mostly complete. This is a local area of impact with very dynamic conditions.
- Because the area below the spillway is highly turbulent and aerated, TDG levels are difficult to accurately assess.
- Extensive fisheries research has shown that most anadromous fish are able to pass through this area below the spillway quickly without ill effects.
- Because of the turbulent flow associated with the spill above the compensation depth (the depth where hydrostatic pressure equals ΔP), little or no resident fish habitat is available in

this area. (The zone below the compensation depth is by definition in compliance with standards.)

- Provision of a mixing zone and deviation from the size requirements are appropriate because of the public interest in ensuring that water quality standards are applied appropriately to the dam projects.

The upstream boundaries of compliance areas are determined on a case-by case basis for each dam. The compliance areas for load allocations will begin at the end of aeration zone in the tailrace. These distances will be estimated using the best available information based on:

- Measurements from a near-field study which show the location where rapid degassing has ceased.
- Visual field observations of where significant bubble rising has ceased.
- The "footprint" of the project, where the natural channel has been modified.

A table showing the distance below each dam where the compliance area begins, as determined by current information, is shown in the Implementation Plan (Appendix A). As additional information becomes available that improves or modifies the estimate of the end of the aerated zone, Ecology can modify how the location of a boundary is defined, through amendment of the Implementation Plan

Each dam will be responsible for managing its own spill to remain in compliance with the TMDL allocations but will not be responsible for high TDG levels produced upstream and passed through the powerhouse, nor for other human inputs or unpredictable natural influences downstream.

Compliance with the standards is required in all locations below Grand Coulee Dam for several reasons. Detailed studies have not been conducted to determine the extent of the aerated zone, so information is not available to allow quantification of that boundary. Also, since Grand Coulee Dam has the powerhouse capacity to pass flows greater than 7Q10 flows without spilling, compliance with the standards at all locations below the dam is achievable.

Monitoring of Attainment

For monitoring of attainment of non-fish passage allocations, it will be desirable to monitor the highest TDG levels within the load allocation compliance areas, especially at the boundaries. However, it is not expected that critical locations will lend themselves to a permanent remote monitoring setup. The TMDL also recognizes that although monitoring should be representative, it is neither feasible nor necessary to monitor all locations at all times.

Attainment of the allocations can be determined in two ways: (1) periodic synoptic surveys, especially after structural changes have been completed, and (2) continuous monitoring, possibly using a statistical relationship between the continuous monitor and conditions at the designated monitoring location. This allows long-term monitoring to be managed separately from monitoring for short-term operational needs.

For monitoring compliance with non-fish passage allocations in the short-term, the FMS sites can continue to be used or new FMS sites can be established. This will allow operational management that is linked to easily accessible data, based on overall environmental management needs and the realities imposed by structural characteristics. Thus, short-term compliance can remain adaptive and flexible while long-term targets remain fixed to firm goals.

Compliance with fish passage allocations will be assessed at the FMS sites. Ideally FMSs will be sited to assess the location where the highest time-averaged TDG values can be found.

Compliance with allocations in the pools under non-fish passage conditions will be assessed both by comparison of FMS tailrace and downstream forebay monitoring and by detailed synoptic surveys. Detailed monitoring may be appropriate following changes in temperature management procedures that alter typical temperature increases, such as through implementation of a temperature TMDL or Endangered Species Act requirements.

Margin of Safety

The margin of safety for this TMDL is implicit in the TMDL analysis through the use of conservative assumptions. A detailed analysis of how the margin of safety is included is provided below.

Critical Conditions

No specific high- or low-flow critical conditions exist for this TMDL. Spills that generate high gas levels can occur in any season, and load allocations are applicable to spills at all flow levels below the 7Q10 flood flow.

Certain parameters that are necessary to develop load allocations were established at levels equivalent to critical conditions. As described above, time of travel, temperature, and barometric pressure were all developed at critical levels. This approach introduces several conservative assumptions that provide a margin of safety to the TMDL.

Criteria versus Site-specific Conditions

Probably few river systems have been as extensively studied for the effects of TDG than the Columbia system. Extensive research has been conducted for over 40 years on TDG and aquatic life. The fish passage spill program includes monitoring of gas bubble trauma symptoms in juvenile fish, which has demonstrated a low rate of symptoms when fish passage TDG criteria are being met.

Currently federal, state, and tribal fishery agencies all support a more lenient standard than the 110% criterion currently in water quality standards. Review of EPA guidance also suggests the 110% criterion could be applied with an averaging period, rather than as an instantaneous value. The fish passage criteria are being closely monitored for biological effect. Therefore, the current standards include an implicit margin of safety when applied to this river system.

Data Quality and Quantity

A margin of safety is usually identified in a TMDL to recognize uncertainty in the data used to produce the TMDL. Due to the monitoring requirements imposed by the Washington State Department of Ecology as a part of the fish passage program over the past seven years, there is a very large record of hourly data of TDG levels, barometric pressure, water temperature, tailwater elevation, forebay elevation, total river flow, and spill quantity. Operators follow data quality procedures for monitoring at the sites they are responsible for. These data are available on the Technical Management Team homepage, hosted by the Northwest Division of the USACE at: http://www.nwd-wc.usace.army.mil/TMT/welcome.html.

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Seasonal Variations

TDG levels above 110% saturation historically occur most commonly during mid-April to the end of August, which is both the fish migration season and the high-flow season in conjunction with spring runoff. One of the determinants of TDG levels is total river flow. When river levels are particularly high, TDG levels rise more rapidly if there is any water spilled over the spillway. During low-flow periods, there is generally not a TDG problem, other than spill for fish passage, as long as all water is passed through the powerhouses.

Long-term daily average TDG data were evaluated from year-round TDG monitoring below Grand Coulee Dam and below Priest Rapids Dam. An upper 99th percentile of data was evaluated using both non-parametric and a Z-statistic. Based on this analysis, the risk of TDG exceeding 110% is negligible from October through February.

The same analysis was applied to long-term stations in the Grand Coulee Dam forebay and the international border station. Here spikes of high TDG were observed during the fall and winter. These observed high TDG levels are suspect however, since high values were not observed at downstream stations. Nonetheless, until a more detailed analysis of data quality provides some evidence to remove the high TDG values from the record, the record suggests that TDG above 110% saturation can occur in Lake Roosevelt year-round.

Occasionally turbine units will be out of service for maintenance, either scheduled or on an emergency basis. This may require water to be spilled because there are insufficient turbines available to handle the water in the river. This can occur due to Bonneville Power Administration power purchasing and the sequencing of water releases from upstream storage reservoirs.

Clearly, there is little control over emergency outages. Maintenance is generally scheduled (1) to coincide with low electricity demand periods and (2) when river flows are such that they will not cause TDG exceedances. Dam operators and the Bonneville Power Administration have financial incentives to keep spill as low as possible, and manage the system accordingly.

In summary, spills can occur at any time, but they are only likely from March through September downstream of Grand Coulee Dam. This TMDL has been written so that the limits could apply at any season, since they are based on spill and not on river conditions. The *Margin of Safety* section describes how seasonal critical conditions were evaluated in this TMDL. TMDL allocations apply year-round in Lake Roosevelt, but only apply from March through September below Grand Coulee Dam. In either case, they have taken season critical conditions into consideration.

7Q10 Flows

As discussed above, the Washington State and the Colville Tribal regulations for water quality only apply when river flows are below the 7Q10 flood flows and the Spokane Tribe's water quality standards apply at all flows. These flows, shown in Table 9, were calculated from flows measured and reported by USGS. Methodology followed the guidelines of the U.S. Water Resources Council (1981):

Table 9: Lake Roosevelt and Mid-Columbia River 7Q10 Flood Flows

Reach	Flow (kcfs)
International border to upstream end of Lake Roosevelt	227
Spokane Arm of Lake Roosevelt	33.4
Lake Roosevelt to Okanogan River (Grand Coulee and Chief Joseph dams)	222
Okanogan River to Chelan River (Wells Dam)	246
Chelan River to Wenatchee River (Rocky Reach Dam)	252
Wenatchee River to Snake River (Rock Island, Wanapum, and Priest Rapids dams)	264

Annual peak 7-day average flows were calculated (using the October-September Water Year from 1975 through 2000), and then the 10-year return flow was determined by the Log-Pearson Type 3 method. The skew coefficient used in the analysis was calculated from the data; the generalized and weighted skew was not determined or used, but the error introduced by this shortcut was probably small to nil.

USGS flow gaging stations were evaluated by comparison to upstream or downstream stations while adding or subtracting major tributaries. Several stations appear to have unreliable flow measurements at high flows. Discussions with USGS staff indicated that two factors appear to introduce this error: backwater from downstream pools (for instream measurements); and errors in estimating flow through the spillways (for measurements taken at dams). The USGS gaging stations below Priest Rapids Dam, below Wells Dam, at Bridgeport, and at the International Boundary appeared to provide the most reliable data, and were used as the basis for determining 7Q10.

Summary of Public Involvement

The Washington State Department of Ecology, the U.S. Environmental Protection Agency, and the Spokane Tribe developed and implemented the Public Involvement and Outreach strategy for this TMDL project.

The public comment period on this proposed TMDL began February 10, 2004 and ended March 18, 2004. A summary of comments and agency responses are provided in Appendix B.

Public hearings were held on:

- Wednesday, March 10, 2004 – 6:30 PM at Eastern Washington University, Spokane Campus, 705 W. 1st Ave., Room 432, Spokane
- Thursday, March 11, 2004 – 6:30 PM at Chelan County Auditorium, 400 Douglas, Wenatchee.

Individual outreach meetings were held with the appropriate watershed advisory groups and with primary stakeholders, which included:

- Spokane Tribe
- Confederated Tribes of the Colvilles
- U.S. Army Corps of Engineers (Portland, Walla Walla, and Seattle Districts, and Pacific Northwest Division)
- Grant, Chelan, and Douglas Public Utility Districts
- U.S. Bureau of Reclamation
- Bonneville Power Administration
- NOAA Fisheries

Public Involvement Actions

- U.S. Environmental Protection Agency and Department of Ecology websites
- Focus sheets
- News releases
- Monthly updates and discussions with the NOAA Fisheries Water Quality Team
- Periodic meetings with the Transboundary Gas Group
- Public hearings

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