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Total Dissolved Gas Characterization of the Lower Columbia River below Bonneville Dam

Prepared For

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INTRODUCTION

The hydrology and water quality of the lower Columbia River is governed largely by the Columbia River hydropower system. The hydropower system affects many aspects of ecosystem function such as habitat formation and maintenance, water quality, and the composition of biological communities. One water quality parameter of importance to aquatic habitat at the egg incubation, juvenile, and adult life stages is the total dissolved gas (TDG) levels. The presence of spillway operations at Bonneville Dam (Figure 1) and upstream projects in the Columbia River hydropower system are the primary source for the supersaturation of TDG in the lower Columbia River. The fate of TDG pressures in the lower Columbia River is to return to equilibrium levels established at the water surface. The habitat impacted by depth compensated TDG levels in the lower Columbia River is closely tied to the river stage and morphometry. A review of historic TDG levels in the lower Columbia River will be important for developing future habitat management policy.

BACKGROUND

In March of 1995, the National Marine Fisheries Service (NOAA Fisheries) reissued its 1994-1998 Biological Opinion (BiOp) which included several directives related to management of total dissolved gas levels in the Columbia River Basin. Three major provisions were outlined in this document to limit voluntary spill policy. The first provision states that "Spill will be reduced as necessary when the 12-hour average TDG concentration exceeds 115% of saturation at the forebay monitor of any Snake or lower Columbia river dam or at the Camas/Washougal station below Bonneville Dam or another suitable location to measure accurately chronic exposure levels." The second major provision was the following: "Spill will also be reduced when 12 hour average TDG levels exceed 120% of saturation at the tailrace monitor at any Snake or lower Columbia River dams." The third provision stated "Spill will also be reduced when instantaneous TDG levels exceed 125% of saturation for any two hours during the 12 highest hourly measurements per calendar day at any Snake or lower Columbia monitor." As to the location of TDG monitoring sites, the Biop stated that "Specific monitoring sites for the purposes of in-season dissolved gas management should be selected on the basis of data consistency and relationship to fish exposure." The intent of the above TDG criteria was to ensure that long-term exposure of adult and juvenile migrants to TDG levels does not exceed 115 percent. These directives provided the foundation of for the rules modifications put in place by the states of Washington and Oregon regarding the TDG variances supportive of spill to aid salmon migration.

The 2000 BiOp directed the Action agencies to develop a plan to conduct a systematic review and evaluation of the TDG fixed monitoring stations in the forebays of all the mainstam Columbia and Snake River dams including the Camas/Washougal gauge below Bonneville Dam and to make changes as appropriate. This reasonable and prudent alternative was introduced because of concerns over whether the forebay TDG gauges were accurately representing TDG conditions in the river.   This program was completed and forebay FMS at several dams were relocated to provide for a more representative sample of TDG levels in the Snake and Columbia Rivers. The performance of the Camas/Washougal gauge was evaluated and retained as an important monitoring station in the lower Columbia River.

The Camas/Washougal gauge has recently been a subject of debate regarding its role in managing voluntary spill at Bonneville Dam. Due to the inability of interested parties to reach a resolution to this issue, a Federal policy level group meeting was held in May 2005. This meeting included representatives from NOAA Fisheries, Bonneville Power Administration, the U.S. Fish & Wildlife Service, and the Corps of Engineers. The group made several determinations, including the need to revisit the issue of TDG management and monitoring in the lower Columbia River using a more holistic, ecosystem approach. Some of the key questions to consider in this assessment include: What are the main sources of TDG in the lower Columbia River? How much do Bonneville operations contribute to the TDG loading in this river reach? What are the biological benefits for fish passage derived from Bonneville operations? What river reaches may elevated levels of TDG supersaturation cause negative biological impacts? What are the impacts of TDG on critical habitats for fish and other aquatic species, especially shallow water habitats? What are the impacts of TDG to ESA-listed salmon, especially sensitive life history stages?

The answers to these questions will be used to determine the optimum balance between the operational benefits of spill at Bonneville Dam versus the risk of elevated TDG saturation generated by these actions and imposed on the lower Columbia River. A management and monitoring strategy can then be formulated to assure protection of important aquatic habitat and beneficial uses. This report is an effort to address the some of the key questions concerning the characterization of TDG properties in the Columbia River below Bonneville Dam.

OBJECTIVE

The primary objective of this investigation was to characterize the TDG levels and related habitat in the lower Columbia River. The production, mixing, and transport of the TDG load released from Bonneville Dam was summarized for data collected from 1993-2005. The TDG loading released from Bonneville Dam are related to the structural characteristics of the spillway, spill pattern, spill policy, spillway channel depth, and background TDG levels in the forebay. The rate TDG levels return to equilibrium conditions established at the water surface below Bonneville Dam is related to tributary inputs, thermal exchange, biological productivity, and TDG exchange at the water surface. The habitat associated with TDG pressures was also briefly summarized by coupling the river bathymetry and stage in the lower Columbia River with the ambient TDG pressure in a given river reach. The management of TDG levels in the lower Columbia River as shaped by biological and water quality criteria is also presented.

APPROACH

The data regarding the TDG pressures and saturations observed in the lower Columbia River were compiled, reviewed, and summarized. TDG pressure, barometric pressure, dissolved oxygen, and water temperature were compiled from water quality monitoring stations maintained by the US Army Corps of Engineers, Portland District from Bonneville Dam to the Columbia River at Wauna Mill (river mile 42) from 1993-2005. Data was also compiled and reviewed from a number of research studies designed to monitor the TDG exchange, mixing, and transport below Bonneville Dam. In addition, several hydrologic parameters were targeted including flow and stage in the Columbia River throughout the study area. The current lower Columbia River bathymetry was compiled and used to estimate the habitat impacted by TDG pressures for a given river reach and flow. A general discussion regarding TDG properties and processes is presented to support the summary of water quality data the follows. The water quality standards for TDG are also presented for the states of Oregon and Washington to provide the background for monitoring and management activities conducted by the US Army Corps of Engineers in the lower Columbia River.

TDG PROPERTIES

The TDG pressure in water is composed of the sum of the partial pressures of atmospheric gases dissolved in the water. The primary gases making up TDG pressure in water are oxygen, nitrogen, argon, and carbon dioxide. The atmospheric compositions of these gases are 20.95, 78.09, 0.93, and 0.03 percent, respectively. Henry's Law relates the solubility or mass concentration of a constituent gas to the partial pressure at equilibrium. The constant of proportionality is a function of barometric pressure, temperature, and salinity. The mass concentration of dissolved gases in water can be determined from estimates of the TDG pressure, water temperature, and barometric pressure assuming atmospheric composition of gases in solution. Thus, for constant temperature and pressure conditions, the TDG can be represented as either a concentration or pressure in conservation statements.

The solubility of a gas in water is dependent on the ambient pressure of the gas, water temperature, and salinity. The total pressure exerted at the point of exchange between water and air will determine the equilibrium conditions. In bubbly flow, the total pressure experienced by entrained air bubbles in the water column is composed of barometric pressure and hydrostatic pressure. Thus, the solubility of gas in water doubles at a depth of about 33 ft in response to a doubling of the total pressure. If the primary TDG exchange occurs at the water surface, the TDG exchange will be governed by the local atmospheric pressure.

The solubility of gas in water is inversely proportional to the temperature. If the total dissolved gas concentration of 30 mg/l (907 mm Hg, 110.0 percent) is held constant in a water sample at one-atmosphere of pressure, and the temperature is raised from 20^{o} to 21^{o} C, the TDG pressure will increase by 17 mm Hg (924 mm Hg, 112.0 percent). Under these conditions, an increase in temperature of one degree will result in an increase in the TDG saturation of 2 percent. The degree of change in the TDG pressure as a result of temperature change will be dependent on the initial temperature of the water.

Changes in the oxygen concentration in a natural water body maybe influenced by the biological productivity associated with photosynthesis and respiration. A change in the dissolved oxygen concentration of 0.5 mg/l will result in a corresponding change in the TDG pressure of about 7 mm Hg at a water temperature of 10 C. The degree of change in the TDG pressure as a result of a change in oxygen concentration will be dependent on the initial temperature of the water.

The TDG saturation is determined by dividing the TDG pressure by the local atmospheric pressure. The absolute TDG saturation or the depth specific TDG saturation is determined by dividing the TDG pressure by the total pressure (atmospheric pressure plus hydrostatic pressure) at a specific depth. The absolute TDG saturation and TDG saturation are equal only at the water surface.

The compensation depth is where the total pressure is equal to sum of the partial pressures of the dissolved gasses or when the absolute TDG saturation is equal to 100 percent. At this depth, the saturation concentration is equal to the ambient concentration in the water and the delta pressure, the difference between the total pressure and total dissolved gas pressure, is equal to zero. The potential for the development of gas bubble trauma in an aquatic organism presents itself when the internal gas tension in the organism exceeds the local total pressure. An organism that has had sufficient exposure to water supersaturated with TDG will remain protected from GBT while remaining at or below the compensation depth. The compensation depth in water with a TDG saturation of 110 percent is about 3.4 ft. The volume of habitat in this same water body experiencing an absolute TDG saturation of 110 percent relative to total pressure is essentially zero since only the conditions at the water surface (depth of zero) meet this criterion.

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General TDG Exchange Description

This section describes processes governing TDG exchange in aerated and non-aerated flows. The aerated flow conditions in discharges from Bonneville Dam will change the TDG levels in the Columbia River. The non-aerated discharge from Bonneville Dam will retain the TDG levels in the Columbia River observed in the forebay. This description is based on studies at main-stem dams on the Columbia and Snake Rivers. Similarities are drawn between these general processes and the existing TDG exchange properties at Bonneville Dam and throughout the lower Columbia River.

TDG Exchange at Bonneville Dam

The gas exchange characteristics at Bonneville Dam are closely coupled to the project hydrodynamics and entrainment of air. Without the entrainment of air bubbles, the exchange of atmospheric gases at a hydraulic structure is restricted to the water surface. During spillway operations where a large volume of air is entrained and transported throughout the water column, the gas exchange process quickly become dominated by the entrained bubbles (Wilhelms and Gulliver 1994). If bubbles are transported to depth, the hydrostatic pressure compresses the bubbles thereby increasing their gas concentrations above atmospheric. This allows the transfer between entrained air and the water column to levels above atmospheric pressure, causing TDG supersaturation. These elevated total dissolved gas pressures cannot be maintained in a non-aerated flow environment, where gas transfer at the water surface tends to reduce supersaturated conditions back to equilibrium at 100 percent saturation. However, at depth the gas remains in solution due to hydrostatic pressure, resulting in the retention of elevated TDG levels in the river.

The TDG properties in the immediate forebay of a dam are generally uniform, when no thermal stratification or surface warming is present, although they can change rapidly in response to operations of upstream projects, tributary inflows, and meteorological, and limnological conditions. A small vertical temperature gradient of 3 to 4 ^{o}F can limit the influence of gas exchange at the water surface to the near-surface layers of a pool by inhibiting vertical circulation. Additionally, heating of surface water can cause TDG pressure responses that result in changes to supersaturated conditions because the solubility of a gas in water decreases as water temperature increases. Biological activity involving the production or consumption of oxygen may also influence TDG pressure changes in the forebay.

The depth of flow and water velocities change rapidly as flow passes under the spillway gate onto the face of the spillway. The roughness of the spillway piers and gates may generate surface turbulence and water spray that entrains air. Flow on the spillway may become aerated for low specific discharges[1] as a consequence of the development of the turbulent boundary layer. However, the short time of travel down the spillway will limit the exposure of water to entrained air bubbles to only a few seconds and tend to limit the absorption or desorption of TDG (Rindels and Gulliver 1989, Wilhelms 1997).

[1] Discharge per unit width, cfs per foot

There is little opportunity for entrained air to be introduced into the confined flow path through a turbine, except during inefficient turbine settings, or when air is aspirated into the turbine. During normal turbine operation, there is essentially no change in TDG pressure as power generation flows pass through the powerhouse. Since turbine discharges typically do not entrain air, it has generally been observed that generation discharges pass forebay TDG pressures to the downstream pool and do not directly contribute to changes in TDG loading (USACE, 1997). Air may be aspirated into a turbine during startup of shut down, or during speed-no-load operation. Condensing operation of a turbine will also involve the presence of air and potential for TDG exchange.

The flow conditions in the stilling basin are highly three-dimensional and are shaped by tailwater elevation, project head, spillway geometry, and the presence of spillway piers, flow deflectors, sidewalls, baffle blocks, and end sill. The flow conditions downstream of a spillway are characterized by highly aerated turbulent flow introduced into the stilling basin and adjoining tailwater channel. The spillway flow deflectors transition the vertical momentum of spill into a horizontal jet. The characteristics of this jet are dependent upon the specific discharge and deflector submergence. In general four different discharge jet flow regimes are formed during spill at Bonneville Dam: plunging flow, skimming surface jet, undulating surface jet, and surface jump. From a dissolved gas transfer standpoint, the skimming flow region has been viewed as the optimal flow conditions minimizing the mean depth to which entrained bubbles are transported and the resultant TDG pressures generated. The plunging flow regime has been identified as producing the highest TDG pressures caused by the vertical transport of water and entrained air in the stilling basin and adjoining tailwater channel. The interpretation of the expected gas transfer associated with the undulating surface jump was thought to be less effective than a skimming flow but substantially better than plunging flow. In general, the gas abatement characteristics for a given flow were thought to drop off for increasing deflector submergence conditions outside of the skimming and plunging flow regimes. The deflector submergence at Bonneville will vary with tailwater stage, and the deflector design. The flow deflectors at spill bays 1-3, 16-18 are at an elevation of 7 ft while the spillway flow defector at the remaining bays are located at an elevation of 14 ft.

Because of the high air entrainment and the transport of air to depth, a rapid and substantial absorption of atmospheric gases takes place in the stilling basin and adjoining spillway exit channel below the spillway. These flow conditions result in the maximum TDG pressures experienced below the dam. The TDG saturation observed in aerated flow conditions just downstream of the stilling basin at Bonneville was observed to exceed 170 percent (Wilhelms and Schneider, 1997). The resultant TDG pressure in spill is independent of the initial forebay levels because of the rapid approach to equilibrium conditions established between the entrained air and water column. The surface oriented jets can generate both horizontal and vertical circulation patterns in the stilling basin resulting in longer stilling basin retention time and regions of concentrated flow.

A rapid and substantial desorption of supersaturated dissolved gas takes place in the tailwater channel downstream of the stilling basin (Schneider and Wilhelms 1996). As the entrained air bubbles are transported downstream, they rise above the compensation depth in the tailwater channel. While above the compensation depth, the air bubbles strip dissolved gas from the water column. The entrained air content decreases as the flow moves downstream, and the air bubbles rise and escape to the atmosphere.

Dissolved gas desorption appears to be quickly arrested by the loss of entrained air within 200 to 500 hundred feet of the stilling basin. The depth of the tailwater channel appears to be a key parameter in determining TDG levels entering the downstream pool (Schneider, 2003). If a large volume of air is entrained for a sufficient time period, the TDG saturation will approach equilibrium conditions dictated primarily by the depth of flow. Thus, mass exchange in the tailwater channel has a significant influence on TDG levels delivered to the downstream pool during high spill discharges. The rapid exchange of TDG pressures ceases downstream of the zone of bubbly flow. The exchange of atmospheric gasses continues at the air-water surface driving conditions toward 100 percent of saturation.

MIXING ZONE

The zone of interaction between water of different quality is called the mixing zone. An understanding of the development of the mixing zone is critical to the interpretation of point observations of TDG pressure in the river. The TDG characteristics of spillway and powerhouse flows exiting Bonneville Dam are often quite different resulting lateral gradients in TDG pressure that diminish as water is transported downstream. In regions where the mixing between powerhouse and spillway releases are incomplete, lateral gradients in TDG pressure will be present and point observations of TDG pressure will reflect some degree of mixing of project flows. The properties of the mixing zone will be dependent upon the tailwater channel features, the location of powerhouse and spillway structures, hydrodynamic conditions in the river, spillway and powerhouse operations, and the entrainment of powerhouse flows into the aerated spillway flows. The interpretation of observations of TDG pressure directly below the dam and extending through the Ives Island area will be a function of the rate of development of the mixing zone. The TDG pressure at any one point of sample will be a function of the ratio of spill to powerhouse flow, spill pattern, spill magnitude, and the TDG content of forebay waters. The observations from the 2001 TDG exchange study concluded that the average TDG saturation in the Columbia River at the Warrendale fixed monitoring station was about 30 mm Hg higher than the response on the Washington shore at Skamania (SKAW).

RIVERINE TDG EXCHANGE PROCESSES

Riverine TDG is affected by tributary inflows, heat exchange,hydraulic andd topographic features, wind and biological factors. The inflow from tributaries to the main-stem can change the water quality properties in the study area through transport and mixing processes. Shallow, steep gradient streams generally will have a TDG content approaching 100 percent of saturation and will dilute the higher TDG levels in the main-stem river generated from spillway releases.

The water temperature of tributaries can also be different from conditions in the main-stem influencing both average main-stem temperatures and TDG pressures.

The heat exchange within the river systems can result in rising and falling water temperatures that influence TDG pressures. The exchange of energy will be governed by meteorological conditions influencing long wave and short-wave radiation, evaporative, and conductive heat exchange processes. The hydraulic and topographic features of a pool will also influence the responsiveness of a river reach to external energy forcing processes. Shallow channel reaches of slowly flowing water will respond much more quickly to external energy inputs than deeper more swiftly flowing sections. Lateral gradients in TDG pressure can be generated from the differential heat exchange in a river reach fed by uniform water quality.

The mass exchange at the water surface can be greatly accelerated where surface waves increase the air-water interface, entrain bubbles, and promote the movement of water to the surface layer. The roughening of the water surface can be generated by surface winds or channel features such as rapids or falls.

The interaction of nutrients, algae, and dissolved oxygen can impact TDG concentrations in a river. The diurnal cycling of photosynthesis and respiration is chiefly responsible for fluctuations in DO concentrations. A 1 mg/l variation in DO will result in a variation of total dissolved gas pressure ranging from 12 to 17 mm Hg depending upon water temperature.

WATER QUALITY STANDARDS FOR TDG

The lower Columbia River is shared by the states of Oregon and Washington and therefore the water quality standards of both states must be met. The water quality standards required by Oregon and Washington are similar and limit the total dissolved gas saturation relative to atmospheric pressure to 110 percent except when river flows exceed the seven-day ten-year average flood. For Bonneville Dam the seven-day ten-year average flood has been estimated to be 467 kcfs. Both states have provided special allowances for total dissolved gas levels above 110 percent of saturation in the Snake and Columbia rivers when spilling water at dams is necessary to aid fish migration.

Oregon's Water Quality Standards are contained in Oregon Administrative Rules (OAR) 340, Division 41. The standards relevant to the total dissolved gas (TDG) TMDL [OAR 340-041-0205(2)(n)] are as follows:

(A) The concentration of total dissolved gas relative to atmospheric pressure at the point of sample collection shall not exceed 110 percent of saturation, except when stream flow exceeds the ten-year, seven-day average flood. However, for Hatchery receiving waters and waters of less than two feet in depth, the concentration of total dissolved gas relative to atmospheric pressure at the point of sample collection shall not exceed 105 percent of

saturation;

(B) The Commission may modify the total dissolved gas criteria in the Columbia River for the purpose of allowing increased spill for salmonid migration. The Commission must find that:

(i) Failure to act would result in greater harm to salmonid stock survival through inriver migration than would occur by increased spill;

(ii) The modified total dissolved gas criteria associated with the increased spill provides a reasonable balance of the risk of impairment due to elevated total dissolved gas to both resident biological communities and other migrating fish and to migrating adult and juvenile salmonids when compared to other options for in-river migration of salmon;

(iii) Adequate data will exist to determine compliance with the standards; and

(iv) Biological monitoring is occurring to document that the migratory salmonid and resident biological communities are being protected.

The rule modification to the total dissolved gas criteria for the state of Oregon to allow spill for salmonid migration is as follows:

The Environmental Quality Commission approves a modification to the Total Dissolved Gas standard for spill over McNary, John Day, The Dalles and Bonneville Dams on the Lower Columbia River, subject to the following conditions:

(i) A revised total dissolved gas standard for the Columbia River for the period from midnight on April1 to midnight on August 31

(ii) the revised criteria will apply for 2003,2004, 2005,2006 and 2007.

(iii) a total dissolved gas standard for the Columbia River for a daily (12 highest hours) average of 115 percent as measured in the forebays of McNary, John Day, The Dalles, and Bonneville Dams and at the Camas/Washougal monitoring stations;

(iv) a cap on total dissolved gas for the Columbia River during the spill program of 120 percent measured in the tailraces of McNary, John Day, The,Dalles, and Bonneville Dams' monitoring stations, based on thehighest 12 highest hourly measurements per calendar day;

(v) and a cap on total dissolved gas for the Columbia River during the spill program of 125 percent, based on the highest two hours during the 12 highest hourly measurements per calendar day during these times;

(vi) a requirement that if 15 percent of the juvenile fish examined show signs of gas bubble disease in their non-paired fins where more than 25 percent of the surface area of the fin is

occluded by gas bubbles or that contraindicatory evidence suggests that fish are being harmed., the Director will terminate the variance;

Washington's Water Quality Standards, Chapter 173-201A Washington Administrative Code (WAC), classify the reaches of the Columbia River as Class A. The following standards specifically apply to TDG saturation in this reach.
:

Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.

(4)(a) The water quality criteria herein established for total dissolved gas shall not apply when the stream flow exceeds the seven-day, ten-year frequency flood.

(b) The total dissolved gas criteria may be adjusted to aid fish passage over hydroelectric dams when consistent with a department approved gas abatement plan. This gas abatement plan must be accompanied by fisheries management and physical and biological monitoring plans. The elevated total dissolved gas levels are intended to allow increased fish passage without causing more harm to fish populations than caused by turbine fish passage. The specific allowances for total dissolved gas exceedances are listed as special conditions for sections of the Snake and Columbia rivers in WAC 173-201A-130 and as shown in the following exemption:

Special fish passage exemption for sections of the Snake and Columbia rivers: When spilling water at dams is necessary to aid fish passage, total dissolved gas must not exceed an average of one hundred fifteen percent as measured at Camas/Washougal below Bonneville dam or as measured in the forebays of the next downstream dams.

Total dissolved gas must also not exceed an average of one hundred twenty percent as measured in the tailraces of each dam. These averages are based on the twelve highest hourly readings in any one day of total dissolved gas.

In addition, there is a maximum total dissolved gas one hour average of one hundred twenty-five percent, relative to atmospheric pressure, during spillage for fish passage. These special conditions for total dissolved gas in the Snake and Columbia rivers are viewed as temporary and are to be reviewed by the year 2007.

(c) Nothing in these special conditions allows an impact to existing and characteristic uses.

The state of Washington has proposed an amendment to the modified rules for TDG saturation that would remove all reference to the Camas Washougal gauge. This amendment is currently being reviewed by the Environmental Protection Agency, Region 10.

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DATA COMPILATION

A number of sources of TDG data exist concerning the TDG properties in the Columbia River below Bonneville Dam. The most comprehensive temporal record of TDG conditions in the lower Columbia River are contained in the CROHMS database maintained by the Corps of Engineers, North Pacific Division. Data were retrieved from the USACE regional water management database (http://www.nwd-wc.usace.army.mil/perl/dataquery.pl) for 6 fixed monitoring stations as follows: WANO (Wauna Mill, river mile 42), KLAW (Kalama, river mile 77), CWMW (Camas/Washougal, river mile 122), SKAW (Skamania, river mile 140), WRNO (Warrendale, river mile 140), BON (Bonneville Forebay, river mile 145). The fixed monitoring station labels ending with an "O" were deployed near the Oregon shore and labels ending with a "W" were located adjacent to the Washington shore. The location of continuous sampling fixed monitoring stations of TDG pressure and tributaries of the lower Columbia River are shown in Figure 2. The parameters of interest were temperature, total dissolved gas pressure, barometric pressure, percent saturation, and dissolved oxygen (partial pressure). The data was typically collected during the fish passage season from April through August on an hourly frequency. The routine collection of TDG data was initiated in 1990 at Warrendale and in the forebay of Bonneville Dam and continues today. The TDG records at the CWMW station are available for the years 1993-2005. The two station located downstream of the confluence with the Willamette River, WANO and KLAW were active for the 1993-1998 fish passage seasons.

A series of three pool studies were conducted in the Columbia River downstream of Bonneville Dam during the Dissolved Gas Abatement Study (USACE, 2002). These studies involved the deployment of from 15 to 30 auxiliary TDG stations positioned throughout the Columbia River from Bonneville Dam to the Wauna Mill station. The length of deployment was from one to two weeks and included multiple stations at selected river transects. These studies provided information on the spatial and short-term temporal properties of water temperature, dissolved oxygen and total dissolved gas pressure throughout this study area. These instruments were deployed on the channel bottom in protective instrument housings. These studies were conducted in the spring and summer of 1996 and summer of 1997.

The first detailed field investigation of the TDG exchange in the Bonneville spillway exit channel was conducted during February 17-18, 1997 (Wilhelms and Schneider, 1997). A detailed array of 37 instruments was used to describe the TDG exchange associated with spill ranging from 40 to 245 kcfs for the standard spill pattern and a uniform pattern over bays 4-15. The standard spill pattern involved a flow distribution that was highly non-uniform with the highest unit discharges through spill bays without flow deflectors.

During the winter of 2001-2002, six new spillway flow deflectors were constructed at Bonneville Dam to reduce the production of total dissolved gas saturation during spillway releases. The new flow deflectors in spill bays 1-3, 16-18 were placed 7 feet deeper than the existing flow deflectors located in spill bays 4-15. A new spill pattern was also implemented in conjunction with the addition of the new flow deflectors. A study was conducted throughout the 2002 spill season to determine the TDG exchange characteristics of spill operations at Bonneville Dam. An array of five TDG instruments was deployed across the spillway exit channel during April-June of 2002 (Schneider, 2003). A more comprehensive array of x TDG instruments were deployed during August of 2002 to capture TDG exchange associated with standard and non-standard spill patterns involving spill bays with new and old flow deflectors.

An investigation of the TDG properties in the Columbia River near the Camas/Washougal fixed monitoring station was conducted during the low flow conditions in June of 2001 (Carroll et. al., 2002). The study period captured the impacts of 50 kcfs spill for 8 days followed by 6 days of no spill. A total of 20 auxiliary TDG stations were deployed both near Bonneville Dam, at the tailwater fixed monitoring station at WRNO, and throughout the river at the CWMW fixed monitoring station. The dissolved oxygen, total dissolved gas pressure and water temperature were collected on a 15-minute interval during this investigation.

The final water quality data set compiled for this review involved instruments deployed at the retired WANO and KLAW fixed monitoring stations during the month of August 2005. Again, the water temperature, total dissolved pressure and dissolved oxygen were recorded for the period of August 12 to 24. These data will supplement the observations from the active fixed monitoring stations located below Bonneville Dam during this period.

The Columbia River flow at Bonneville Dam and major tributaries was compiled for the period from 1990-2005. The hourly operations records at Bonneville Dam included total river flow, spillway flow, forebay elevation, and tailwater elevation. The daily average flow records from the Cowlitz, Kalama, Lewis, Willamette, Sandy, and Washougal Rivers were compiled to assess the general water budget of this study area.

The river stage data was compiled from six gauging stations located throughout this study area. The six stage gauging stations were the following: (1) the USGS station 14128870 located on the Columbia River below Bonneville Dam at river mile 144.5, (2) the USGS station 14144700 located on the Columbia River at Vancouver, WA, river mile 106.5, (3) the NOAA station SHNO, located on the Columbia River at St Helens, OR, river mile 86, (4) the USGS station 14245300 located on the Columbia River at Longview, WA, river mile 68, (5) the USGS station 14247295 located on the Columbia River at Wauna, river mile 42, (6) and the SKAW gauge located on the Columbia River at Skamakowa, OR, river mile 33.5. This information enabled the determination of the depth of flow throughout the river when combined with the Columbia River channel bathymetry and the relative importance of ocean tides on river stage and discharge.

The current hydrographic surveys of the Columbia River from the mouth to river mile 144 were obtained from the Portland District Corps of Engineers. Both cross sectional and longitudinal channel transects were compiled and imported into a GIS to allow the generation of a digital terrain map of the river. The river stage data was used in conjunction with the channel bathymetry to determine the physical features of the river such as average channel width and depth, cross sectional area, channel volume, average velocity, and time of travel.

RESULTS

The objective of this data compilation and review was to characterize the TDG levels in the lower Columbia River as it relates to aquatic habitat. Below are the results of the review of data collected at the direction and support of the Corps of Engineers. The types of data summarized include the river channel bathymetry, lower Columbia River hydrology, Bonneville Dam operations, river stage, TDG conditions, water temperature, and dissolved oxygen concentrations.

COLUMBIA RIVER CHANNEL

The Columbia River channel bathymetry near Bonneville Dam is highly varied. The channel width is less than 1000 ft in places and as wide at 4400 ft from bank to bank at Pierce Island. The tailwater channel elevation is as small as –60 ft just downstream of the stilling basin. A manmade plunge pool was excavated to an elevation of –70 ft at the Bonneville 2nd powerhouse corner collector outfall. The channel bed elevations from Bonneville Dam to river mile 140 are shown in Figure 3. As the channel widens the depth of flow becomes shallower. The channel behind Ives Island is shallow and susceptible to dewatering during low river flows.

The channel is defined by a series of riffle and pool segments where the channel thalweg migrates from the Washington to Oregon shore several times as the Columbia River emerges from the steep-walled Columbia Gorge. The channel is braided in several locations where the secondary channel is generally much shallower than the main channel. The bathymetry in the Columbia River near the towns of Camas and Washougal Washington is shown in Figure 4. A well defined main channel and point bar are clearly evident in this section of the river.

The Columbia River's floodplain expands near the confluence with the Willamette River, forming a series of sloughs and lakes of North Portland, Sauvie Island, and the Vancouver lowlands. The Columbia cuts through the Coastal Mountain Range downstream from the town of St. Helens and is characterized by steep-shouldered bluffs and broad alluvial floodplains. The river channel opens out as it approaches the Pacific Ocean and has many low islands of deposited sediments throughout its lower reaches.

LOWER COLUMBIA RIVER HYDROLOGY

There are six major tributaries that feed into the Columbia River within the 104 mile stretch investigated. These tributaries include the Washougal River, Sandy River, Willamette River, Lewis River, Kalama River, and Cowlitz River as shown in Figure 2. The Washougal River flows into the Columbia River from Washington at river mile 121. Just downstream the Sandy River flows into the Columbia from the Oregon side of the river at river mile 120.5. The Willamette River, the largest river out of all the tributaries mentioned, flows into the Columbia River at river mile 102.5. Approximately 15 miles downstream of the mouth of the Willamette, the Lewis River drains into the Columbia River (river mile 87.5). Both the Kalama River and the Cowlitz River flow into the Columbia River from the Washington side, with the Kalama River draining into the Columbia River at river mile 73, and the Cowlitz River emptying into the Columbia River at river mile 68.

The river flows in the lower Columbia River are an important determinant of the TDG levels in this reach. During the fish passage season, voluntary spill has been scheduled at main stem dams to aid fish migration and dam passage. Involuntary spill frequently is required when the river flows exceed the hydraulic capacity of the powerhouse or when electrical generation limits have been reached. The average monthly flows in the Columbia River at Bonneville Dam, Willamette River, Lewis River, Cowlitz River, and Sandy River are shown in Figure 5 for the period from 1993-2005. The months of May and June are typically when the highest river flows occur and the contributions from the tributaries represent 23.8 and 22.0 percent of the total river flow of the Columbia River at the lower end of the study reach. The reliable powerhouse hydraulic capacity is about 250 kcfs, which implies that involuntary spill is required during average flow conditions during the months of May-June. The lowest monthly flows are during September and October when the likelihood for spill is at its lowest. The months with the highest contribution of flow from tributaries is December and February where over 40 percent of the Columbia River flow is derived from tributary sources. A tabular summary of monthly average flows in the Columbia River at Bonneville Dam and major tributaries downstream of Bonneville Dam are listed in Table 1. The 7Q10 high flow (7 day consecutive high flow with a 10 year return period) average at Bonneville Dam has been estimated to be 467 kcfs. The compliance with state water quality standards for TDG saturation is not required when the river flow is larger than the 7Q10 high flow.

BONNEVILLE DAM OPERATIONS

Bonneville Dam operations have a significant impact on downstream TDG levels. The annual average total flow and spill flow from Bonneville Dam was compiled from flow records. The estimates of total flow and spill at Bonneville Dam were estimated from daily flow records below The Dalles Dam for the years 1938-1959 by assuming the hydraulic capacity of the first powerhouse at Bonneville was a constant 120 kcfs. It is likely that the spill rates during these years were higher than estimated because of unaccounted flow from tributaries between The Dalles and Bonneville Dam and realities of powerhouse hydraulic capacity. The flow conditions from 1960-2005 were based on Bonneville Daily flow records as shown in Figure 6. The completion of the 2nd powerhouse at Bonneville in 1982 resulted in a significant reduction in spill at Bonneville Dam. Prior to the expansion of powerhouse capacity, the average annual spill rate frequently exceeded 100 kcfs that was significantly higher than occurred during the flood of record in 1997. These early spill events would have occurred without the beneficial effects of spillway flow deflectors. Other factors influencing the spill rates at Bonneville Dam include the development of water control dams throughout the Columbia River Basin and the policy to spill for fish during the mid-1990's.

A detailed summary of Columbia River flows at Bonneville Dam since the initiation of a routine TDG monitoring program during the mid-1990's was conducted. The Bonneville total river flow, and spill discharge were summarized annually during the fish passage season from April 15-August 31 and outside of the fish passage season as listed in Tables 2 and 3. The highest flow years during the fish passage season occurred in 1996 and 1997 with average total river discharges of 301.3 kcfs and 356.7 kcfs respectively. During 1996 maximum total river flows reached 459.8 kcfs, while minimum flows were 115.4 kcfs. During 1997 maximum total river flows reached 575.2 kcfs, while minimum total river flows were 155.4 kcfs. In contrast the lowest flow year of 2001 saw average total river discharge conditions of 118.9 kcfs, which were lower than the minimum flows of 1997 and near the minimum flows observed in 1996. Maximum total river discharges during 2001 were 202.2 kcfs, while minimum flows were 65.7 kcfs. All other years were considered moderate to average flow years and as an example, the average total river flow in 1998 was 242.0 kcfs.

Bonneville Dam spill has accounted for about 40-50 percent of the total annual project discharge during the fish passage season with the exception of drought conditions during 2001. The highest annual average spill discharge occurred during 1997 where spill averaged 178.5 kcfs and maximum hourly spill of 448 kcfs was recorded. During the fish passage season average spill in 1996 was 137.0 kcfs while maximum spill was 322.6 kcfs. During the drought year of 2001 average spill was 19.9 kcfs while maximum spill was 51.1 kcfs. The moderate year of 1998 saw average spill conditions of 99.5 kcfs and maximum spill releases of 230.9 kcfs. Even though flow events were much greater in 1996 and 1997 than in 1998 the percent of river spilled during these years were similar. The percentage of river spilled in 1996 was 45.5%, in 1997 was 50.0% and in 1998 was 41.1%. Only 16.7% of the river was spilled in 2001 at Bonneville Dam.

Outside of the fish passage season, river flows infrequently exceed the powerhouse capacity. As summarized in Table 2, the average, minimum, maximum and standard deviation of total river discharge (kcfs) and total spill (kcfs) released at Bonneville Dam were calculated for the period of time outside of the fish passage season from 01 January-14 April and 01 September-30 December for the years 1994 to 2005. The highest off-season flow years occurred in 1995 and 1996 with total river flows of 223.5 kcfs and 222.9 kcfs respectively. During 1996 maximum total river flows reached 442.3 kcfs, while minimum flows were 80.2 kcfs. The 1997 maximum total river flows reached 434.3 kcfs, while minimum total river flows were 85.6 kcfs. The low flow year of 2001 saw average total river discharge conditions of 115.0 kcfs, similar to average flow conditions observed during the fish passage season (Table 2.).

Although the great majority of spill has occurred during the period from April-August at Bonneville Dam, runoff events have necessitated spill during the winter months. The average number of days where spill exceeded 10 kcfs is summarized in Figure 7 for Bonneville Dam for each year and month from 1990-2005. Bonneville has spilled significant amounts of water for the entire month of January during one year. The spill is nearly continuous during the fish passage season. Outside of the fish passage season, average spill in 1996 was 51.1 kcfs while maximum spill was 364.5 kcfs. Average spill during 1997 was 34.4 kcfs while maximum spill was 249.5 kcfs. During the drought year of 2001 average spill was 1.3 kcfs while maximum spill was 50.5 kcfs. During a typical flow year like 1998, the average spill flow was only 4.2 kcfs and the maximum spill releases was 129.2 kcfs (Table 2). Spill was frequency scheduled at

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Bonneville Dam to coincide with the release of juvenile from the Spring Creek Hatchery. The number of days during the non-fish passage season where spill was greater than 10 kcfs was determined. During the two high flow years a total of 98 days out of 226 of 10+ kcfs spill were observed in 1996 while 97 days of 10+ kcfs spill were observed in 1997. The 1998 year saw 18 days of 10+ kcfs spill while 2001 saw 3 days of 10+ kcfs. The spill observed in 1998 and 2001, in general, was associated with Spring Creek National Fish Hatchery releases and not forced spill like conditions, while 1996 and 1997 spill was associated with both situations. The percentage of river spilled outside of the fish passage season in 1996 was 22.8%, in 1997 was 15.4% in 1998 was 2.7% and in 2001 was 1.1%.

Total river flows during 1996, 1997, and 1998 peaked at various times of the year but in general were highest in late May through early June during the time of snowmelt and subsequent runoff. The duration of high total river discharge was longer during the high flow years of 1996 and 1997 compared to the flow conditions observed in 1998. Total river flows in both 1996 and 1997 were above 250 kcfs at the start of the spill season (April 15th) and continued at or above 250 kcfs well into the summer. Total river flows during both years did not begin to taper off until late July. Total river flows in 1998 did not exceed 250 kcfs until the end of April. High total river flows during 1998 lessened about a week to two weeks earlier than what was seen in 1996 and 1997. Flow conditions observed among all three years during the latter part of the summer were similar with 1997 flows remaining higher than flows observed in 1996 and 1998. The low flow year of 2001 never truly peaked and flow conditions stayed relatively flat throughout the fish passage season.

Lower Columbia River Stage

The river stage throughout the Lower Columbia River impacts the channel discharge, velocity, depth of flow, cross sectional area, habitat delineation as impacted by elevated TDG pressures, TDG exchange in spillway flows, and water circulation patterns**.** The river stage below Bonneville Dam is dominated by the total river discharge. A small tidal influence can be seen below Bonneville Dam when total river flow drops below 100 kcfs and the tailwater stage ranges from 6 to 8 ft as shown in Figure 8. The tailwater fluctuation below Bonneville on July 14-15, 2001 was caused by the propagation of a tidally driven wave during a discharge of 75 kcfs. The tailwater rating curve for the Columbia River at Bonneville Dam is shown in Figure 9 for stage data observed at the Tanner Creek gauge during April-August, 1974-1999. The tailwater stage changes about 1 ft in response to a discharge change of 12.5 kcfs for flows ranging from 100-200 kcfs. The change in river stage observed near Ives Island corresponds closely with the stage changes observed in the tailwater of Bonneville Dam. The correlation between hourly river flow and tailwater stage at Bonneville Dam is shown in Figures 10-13 for total Columbia River flows ranging from 150 to 441 kcfs. The tailwater elevation dropped from 17.5 ft to 13 ft on February 5-6 during a reduction in flow from 200 kcfs to 105 kcfs as shown in Figure 10.

The tailwater stage at Bonneville has been found to be an important determinant of TDG exchange in spillway flows. An evaluation of the average TDG pressure in the spillway exit channel generated during spill determined a direct linear relationship between the TDG pressure and tailwater stage (Schneider, 2003). A five-foot increase in tailwater stage typically resulted in an 8 mm Hg increase in TDG pressure (~1% saturation increase). The tailwater stage influence on TDG exchange is likely related to the available depth of flow in the stilling basin and tailwater channel and the hydraulic flow regime generated for difference spillway flow deflector submergences.

The stage in the Lower Columbia River is increasingly impacted by tidal influences as the mouth of the river is approached. The hourly Lower Columbia River stage was compiled at four gauging stations during four different flow conditions as shown in Figure 10-13. Stage information from the USGS gauge just below Bonneville Dam located at river mile 144.5, the USGS gauge at Vancouver, WA located at river mile 106.5, the NOAA gauge located at St Helens, OR, river mile 86, and the SKAW gauge located at river mile 33.5 near Skamakowa, OR was used in each of these figures for a range of river flows. The bimodal daily tidal variation is clearly evident when Bonneville Dam releases averaged 150 kcfs during the week of 2/1/2002-2/8/2002 at the Vancouver gauge (RM 106), St Helens gauge (RM 86), Skamakowa gauge (RM 33) as shown in Figure 10. Upstream of the Skamakowa gauge (RM 33) the stage in the Columbia River increases and daily tidal variation decreases for increasing river flows of 250, 348, and 441 kcfs as shown in Figures 11-13. The stage gauge closest to the mouth of the Columbia River, the Skamakowa gauge (river mile 33.5), was most influenced by tidal fluctuations and was minimally affected by high total river flows.

The tidally driven variation in river stage influences the local channel velocities, discharge, and at the lower end of the reach, the direction of flow. Flows affected by tide can cause reverse direction when mean daily flows are less than 250,000 ft^3/s on the Columbia River at Beaver Army Terminal (RM 53.8). The Columbia River stage at river mile 33 was greater than the stage at river miles 86 for short periods of time as shown in Figures 8 and 10, indicating an adverse water surface gradient and potential for flow reversal in the lower reach of the study area.

BONNEVILLE TDG LOADING

The TDG loading released from Bonneville Dam consists of the TDG pressures contained in powerhouse releases and the TDG exchange associated with the aerated releases from the spillway and auxiliary fish passageways. The background TDG levels monitored in the forebay of Bonneville Dam are transported past the project unaltered in powerhouse discharges. The TDG exchanges during spillway operations are directly related to the spill magnitude and pattern, structural spillway configuration, the tailwater stage and associated stilling basin and tailwater channel depth of flow. The interaction and mixing of these independent sources of TDG saturation at Bonneville Dam provide the basis for determining the distribution and fate of TDG loading throughout the Lower Columbia River.

The TDG saturation in the Columbia River in the forebay of Bonneville Dam generally remains below 115 percent except during forced spill conditions at upstream dams. The hourly TDG saturation observations in the forebay of Bonneville Dam (BON) were summarized for the years 1995-2005 during the period from April 15-August 31 as listed in Table 4. The average TDG saturation in the Bonneville forebay for the entire period was 110.3 percent with a maximum annual average of 118.2 percent during 1997 as shown in Figure 14. The hourly TDG saturation at BON exceeded 110 percent about 50 percent of the time, and 115 percent about 18.2 percent of the time. The relatively low TDG conditions in the forebay are conveyed past Bonneville Dam in powerhouse releases. The powerhouse releases generally contribute between 50-60 percent of the total river flow during the fish passage season at TDG levels well below conditions in spill and thereby significantly moderate the TDG saturation below Bonneville Dam. The TDG saturation in the forebay of Bonneville Dam typically peak during the high flow period in late May and early June and decline throughout the summer months as shown in Figure 15 for 1998. The TDG saturation can vary considerably from day to day in response to wind generated degassing events during passage from The Dalles Dam to Bonneville Dam. A significant portion of the elevated TDG levels in the forebay of Bonneville Dam originates from spill over the conventional spillway and stilling basin at The Dalles Dam.

There is no record of the TDG saturations generated during spill at Bonneville Dam prior to the installation of the original spillway flow deflectors in 1976. However, during the TDG exchange research studies conducted in 1999 (Schneider, 1999) four spill bays without deflectors were exercised and TDG pressures determined as shown by the blue line in Figure 16. The TDG exchange quickly increased from an average of 116 percent at 3 kcfs/bay to 135 percent at 6.7 kcfs/bay. The TDG saturation remained constant for higher spillway discharges over these spill bays without flow deflectors. The TDG response of the standard spillway was likely even greater than shown in Figure 16 when considering the tailwater influence on available depth.

The TDG production properties of the spillway in 1999 with deflectors on spill bays 4-15, and 18 were determined for the standard spill pattern (Schneider, 1999). The standard spill pattern prior to 2002 called for heavy usage of the outside bays without flow deflectors and lighter usage of the interior bays with flow deflectors at elevation 14 ft. The TDG saturation response curve for the standard spill pattern in 1999 as a function of the specific spill discharge is shown as a black curve in Figure 16. This curve begins at a specific discharge of 6.7 kcfs because only selected bays were used at small spill rates. The TDG response remains flat at about 125 percent up to 10.6 kcfs as additional spillbays were brought online to deliver the higher spillway releases. The TDG saturation increases linearly for specific discharges above 10.6 kcfs/bay reaching 132 percent at a specific discharge of about 18 kcfs/bay.

During the winter of 2001-2002, six new spillway flow deflectors were constructed at Bonneville Dam to reduce the production of total dissolved gas saturation during spillway releases. The new flow deflectors in spill bays 1-3, 16-18 were placed 7 feet deeper than the existing flow deflectors located in spill bays 4-15. A new spill pattern featuring a uniform spill distribution over all 18 bays was also implemented in conjunction with the addition of the new flow deflectors. A study was conducted throughout the 2002 spill season to determine the TDG exchange characteristics of spill operations at Bonneville Dam. The purpose of the study was to determine the impacts of spill on the total dissolved gas (TDG) pressures in the Columbia River downstream from Bonneville Dam. The relative TDG exchange performance of the new and old spillway flow deflectors was a secondary objective.

The addition of six new flow deflectors and the corresponding change in spill pattern resulted in a significant reduction in the TDG saturation when compared to similar spill rates prior to the 2002 spill season. The degree of improvement over pre-2002 conditions declined for increasing discharge. The estimated reduction in TDG saturation for a spill discharge of 75 kcfs was 10 percent of saturation.

The new flow deflectors generated considerably lower TDG pressures than the old deflectors for low tailwater conditions ranging from 10.2 to 13.7 ft. The difference in the mean TDG saturation (old deflector minus new deflector) for a specific discharge of 7 kcfs/bay was 6.1 percent. There is insufficient evidence to determine the TDG exchange performance of the different deflector designs at higher tailwater elevations or specific discharges.

The TDG exchange in spillway releases from Bonneville Dam were found to be directly related to the specific spillway discharge and weakly related to the tailwater stage. A family of multivariate linear regression equations was developed to predict the TDG exchange as a function of the specific discharge and tailwater elevation. The comparison of cross sectional average delta TDG pressures as function of the specific spillway discharge is shown in Figure 17 for data collected during the 2002 spill season. This equation was based on the 2002 spillway rating curve. The typical average cross sectional TDG saturation generated for spill of 50, 100, 150, 200, and 250 kcfs were 115, 120, 125, 130, and 135 percent of saturation as observed in 2002.

The lateral distribution of TDG pressure exiting the spillway exit channel was relatively uniform for spill up to 100 kcfs. For spill discharges much greater than 100 kcfs, the lateral distribution of TDG in the spillway channel is non-uniform with the maximum TDG levels positioned away from the channel banks. The maximum TDG saturation (ps-max green), cross sectional average TDG saturation (ps-avg blue), and TDG saturation near Cascade Island (BONTWP5 pink) for spill events during the 2002 spill season are shown in Figure 18. The location of the current tailwater fixed monitoring station on Cascade Island (CCIW) is located in the same location as the station labeled BONTWP5 in Figure 18. The average cross sectional TDG saturation estimates were based on the integration of observations from 5 sampling stations distributed across the exit of the spillway channel downstream of the highly aerated flow conditions. The linear regression line (blue line) fitted through the average cross sectional TDG saturation data intercepts the 120 percent saturation level at a discharge of about 105 kcfs. The linear regression line derived from the maximum TDG saturation and spill data intercepts the 120 percent saturation level at about 90 kcfs. The TDG response at Cascade Island as approximated by least squared linear regression with spill discharge intercepts the 120 percent saturation level at a discharge of 133 kcfs. The spill discharge used in Figure 18 reflects the updated spillway-rating curve presented in 2004. The TDG response near Cascade Island was also found to be dependent on tailwater stage.

The non-uniformity in TDG pressures exiting the spillway exit channel at discharges greater than 100 kcfs poses a challenge for both monitoring and managing TDG pressures below Bonneville Dam. The tailwater fixed monitoring station for Bonneville Dam was officially moved from the Warrendale gauge (WRNO RM 140) to a location in the spillway exit channel near Cascade Island labeled CCIW in 2005. The TDG pressures observed at the previous tailwater fixed monitoring station at the Warrendale gauge WRNO more closely approximate the flow-weighted average of both spillway and powerhouse releases from Bonneville Dam. The existing CCIW station is close to the BONTWP5 station used during the 2002 TDG exchange study at Bonneville and the TDG saturation response was also similar as shown in Figure 19 for TDG observations in 2005. During the 2005 fish passage season, voluntary spill of 160 kcfs were scheduled and TDG levels at CCIW were observed to remain below 120 percent saturation. A maximum TDG pressure of 128 percent likely occurred during this 160 kcfs event based on the 2002 findings shown in Figure 18. Similarly, the cross sectional average TDG saturation was likely about 125 percent of saturation for a 160 kcfs spill. Water management strategies to meet the TDG target of 115 percent downstream at the Camas/Washougal fixed monitoring station should take into account the sampling bias at CCIW in setting spill levels.

Other aerated discharges are evident at Bonneville Dam such as lock discharges, fish ladders and outfalls, ice and trash sluiceway releases, and collection water releases. These aerated flows involve small discharges with low entry velocities into the receiving waters and likely have minimal impact on the TDG loading released from Bonneville Dam with the exception of the Bonneville 2nd powerhouse corner collector (B2CC) outfall completed prior to the 2004 fish passage season. The B2CC outfall consists of a gated release from the forebay of the 2nd Bonneville Powerhouse over an ogee section and into a 15 ft wide rectangular chute that has an exit at an elevation of 16 ft near the tip of Cascade Island. The B2CC has a discharge operating range of 4.4 to 5.9 kcfs as determined by the forebay elevation. The B2CC discharges into a plunge pool with a minimum elevation of –70 ft and a maximum depth of 86 ft for a tailwater stage of 16 ft.

The TDG exchange associated with the B2CC outfall was evaluated during seven release events ranging from 4.5-6.0 kcfs during total river flows of 123-170 kcfs in February of 2004. The spillway was closed throughout this investigation that limited the TDG production to the B2CC flows. The operation of the Bonneville second powerhouse corner collector resulted in the elevation of average TDG pressures in the Columbia River 0.8 to 2.3% saturation for background TDG saturation ranging from 100.0-101.4 percent of saturation. The maximum TDG saturation was generally observed in the B2CC plunge pool and ranged from 103 percent to 118 percent during the testing period. The average effective TDG pressure of the B2CC outfall of 1063 mm Hg (140 percent) and was found to remain relatively constant for all flow conditions. A strong entrainment flow about 4 times the B2CC discharge was observed to interact with the releases from the B2CC in the plunge pool. These findings were determined for a limited number of operating conditions where the tailwater elevations ranged from 12.8-16.2 ft.

LONGITUDINAL TDG PATTERNS

The fate of the TDG load released from Bonneville Dam can be evaluated by comparing the TDG response across the fixed monitoring stations located throughout the Lower Columbia River. The monthly average TDG saturation was determined across the network of six fixed monitoring stations maintained throughout the lower Columbia River during five years running from 1994-1998. The comparison of monthly average TDG saturation filters out the high frequency fluctuations observed across the monitoring network and provides general trends in the change in the TDG saturation throughout the lower Columbia River. The hourly TDG saturation from the following six fixed monitoring stations are summarized on a monthly basis as listed in Table 4: BON (RM 146), WRNO (RM 140), SKAW (RM 140), CWMW (RM 122), KLAW (RM 77), and WANO (RM 42).

The operation of Bonneville Dam increases the TDG loading of the Lower Columbia by as much as 6 percent saturation on average. The increased TDG loading of the Columbia River is attributed to Bonneville spillway operations and the B2CC release. The monthly average TDG saturation for the month of June is shown in Figure 20 for the years 1994-1998, and 2005. The high flow conditions in 1996-1997 resulted in small increases in the TDG saturation during passage through Bonneville Dam based on TDG saturation observed between the forebay (BON) and tailwater (WRNO, SKAW) stations. The largest increase in the monthly average TDG saturation in June of 6 was observed during 1994 and 2005 when forebay TDG pressures averaged 107 and 108 percent, respectively. During the high flows of 1997, the monthly average TDG saturation in June increased only 1-2 percent in response to Bonneville Dam operations. These TDG uptake trends are consistent with observation that TDG exchange in spillway flows are driven to new equilibrium conditions established by the aerated flow conditions in the stilling basin and adjoining tailwater channel independent from the initial conditions in the forebay. The TDG levels in the forebay only contribute to the Bonneville TDG load through powerhouse flows.

The TDG saturation in the Lower Columbia River consistently declines with increasing distance from Bonneville Dam. The rate of decline is likely related to dilution from tributaries, time of travel, channel morphometry, degassing at the air/water interface, heat exchange, and biological productivity. The net reduction in the average monthly TDG saturation in June from the tailwater stations at WRNO/SKAW (RM 140) to WANO (RM 42) ranged from 4 to 8 percent saturation as shown in Figure 20. The rate of decline in TDG saturation varies from year to year and reach to reach. The TDG saturation remained above 110 percent throughout the entire study area for the month of June for all years except 1994. The average TDG saturation in June remained above 115% at the CWMW station for the years 1996-1998. The average TDG saturation in June remained above 125% at the tailwater stations WRNO and SKAW for the years 1996-1997.

The seasonal patterns of the longitudinal TDG saturation in the Lower Columbia River during spill at Bonneville Dam also reflect a gradual return to equilibrium conditions with the atmospheric at the water surface. The average monthly TDG saturation during the normal flow year of 1998 is shown in Figure 21. The net decline in monthly average TDG saturation from the tailwater FMS to WANO ranged from 7 to 10 percent saturation or 0.07 to 0.10 percent/mile for the months of May-August. The TDG saturation remained above 110% throughout the entire reach for the months of May and June.

The longitudinal TDG saturation throughout the Lower Columbia River during the high flow conditions in 1997 is shown in Figure 22. The TDG levels remained above 120% throughout the study area during the forced spill events in May and June of 1997. During the lower voluntary spill conditions in April, July, and August, the TDG levels remained above

110% throughout the study area. The TDG levels in September represent the river in equilibrium with the atmosphere as the TDG saturation remained constant at about 102-104 percent.

TDG pressures were monitored in the Lower Columbia River during the period of August 12-24, 2005 near the WANO and KLAW stations during the low flow releases from Bonneville Dam. This TDG saturation observed at these two stations were summarized and compared to the TDG conditions at upstream fixed monitoring station located at CWMW, WRNO, CCIW, and BON as shown in Figure 23. The operation of Bonneville Dam resulted in a significant increase in TDG saturation of about 10 percent saturation in the Lower Columbia River during this period. The mean TDG saturation in the spillway exit channel at CCIW was similar to the mean response observed at the WRNO station located six miles downstream. A very sharp decline in TDG pressures was observed in the Lower Columbia River during this sampling period. The mean response at the WANO station at river mile 42 was similar to the mean TDG saturation observed upstream of Bonneville Dam.

The observed TDG data throughout the Lower Columbia River below Bonneville Dam has demonstrated a consistent response to open river mass exchange processes. The TDG levels at neighboring fixed monitoring stations are highly correlated when comparing monthly average TDG saturation levels. The monthly average TDG saturation observed at the WRNO fixed monitoring station was compared to the response at the CWMW station for records from 1993-2005 as shown in Figure 24. The high correlation between the monthly average TDG saturation at WRNO and CWMW was determined by generating a linear regression equation between the two record sets. The slope of the regression equation of 0.886 quantifies the ordered reduction in TDG levels from WRNO to CWMW.

The monthly average TDG levels observed at CWMW are highly correlated to the downstream response at the KLAW for conditions monitored during the 1994-1998 sampling period. A linear regression equation was generated between the average monthly TDG saturation observed KLAW and CWMW as shown in Figure 25. The slope of this relationship was 0.80 indicating a greater reduction in TDG levels between these station as compared with the response between WRNO and CWMW. The greater distance between the KLAW and CWMW stations and the contributions from tributary flows including the Willamette River are likely the source for the different slope. This consistent and ordered TDG response demonstrates the utility in basing TDG management decisions on the observations provided at active fixed monitoring stations.

TDG SATURATION – FREQUENCY ANALYSES

Analyses were performed on TDG data to determine averages, frequency of exceedances and longitudinal TDG patterns. A statistical summary of observations of TDG saturation at the fixed monitoring stations in the Lower Columbia River was conducted on data collected from April 15-August 31 for the years 1994-2005. The general statistics for hourly TDG observations including mean, maximum, minimum, and standard deviation were determined by station and year as listed in Table 5. The frequency of hourly TDG records exceeding 110, 115, 120, 125, 130, and 135 percent were also determined. The daily water quality standards metric of the highest 12 hourly observation in a calendar day is not reported here.

The TDG levels in the lower Columbia River remained at very high levels greater than 120 percent throughout much of the 1997 fish passage season. The average TDG saturation in the Lower Columbia River during the high flow conditions of 1997 increased from 118.2 percent in the forebay of Bonneville Dam to 123.0 percent at the tailwater station at WRNO, a 4.8 percent increase. A maximum TDG saturation of 143.5 percent was observed at the SKAW gauge below Bonneville Dam. The hourly TDG saturation at WRNO was greater than 120 percent about 50 percent of the time or 76 days as shown in Figure 26. The average TDG levels decreased with increasing distance from Bonneville Dam. The average TDG saturation at CWMW (RM 122), KLAW (RM 77), and WANO (RM 42) were 121.6, 118.3, and 114.0 percent, respectively. The TDG saturation at CWMW (RM 122) exceeded the 115 percent criteria about 75 percent of the time or about 115 days. At the lower end of the study reach at WANO, the TDG saturation exceeded the 110% level about 57 percent of the time and the 120% level about 24 percent of the time.

The TDG levels in the lower Columbia River infrequently exceeded the 120 percent level during the average flow condition in 1998. The average TDG saturation in the Lower Columbia River during the average flow conditions of 1998 increased from 110.3 percent in the forebay of Bonneville Dam to 115.3 percent at the tailwater station at WRNO. The increase in TDG saturation resulting from Bonneville Dam operation of 5.0 percent saturation was equal to the increase observed during the forced spill conditions in 1997. A maximum TDG saturation of 127.3 percent was observed at the SKAW gauge below Bonneville Dam. The hourly TDG saturation at WRNO was greater than 120 percent about 2 percent of the time or 3 days as shown in Figure 26. The average TDG levels decreased with increasing distance from Bonneville Dam. The average TDG saturation at CWMW (RM 122), KLAW (RM 77), and WANO (RM 42) were 114.0, 111.2, and 107.7 percent, respectively. The TDG saturation at CWMW (RM 122) exceeded the 115 percent criteria about 40 percent of the time or about 61 days. At the lower end of the study reach at WANO, the TDG saturation exceeded the 110% level about 22 percent of the time and the 120% level about 0 percent of the time.

The TDG levels in the lower Columbia River during low flow conditions in 2005 were similar to conditions observed during normal flows in 1998. The consistency of voluntary spill policy resulted in the similar response between these two water years. The average TDG saturation in the Lower Columbia River during the low flow conditions of 1997 increased from 108.2 percent in the forebay of Bonneville Dam to 114.5 percent at the tailwater station at WRNO. A maximum TDG saturation of 121.6 percent was observed at the WRNO gauge below Bonneville Dam. The hourly TDG saturation at WRNO was greater than 120 percent about 1 percent of the time or 1.5 days as shown in Figure 26. The average TDG levels decreased with increasing distance from Bonneville Dam. The average TDG saturation at CWMW (RM 122) was 111.4. The TDG saturation at CWMW (RM 122) exceeded the 115 percent criteria about 8 percent of the time or about 12 days.

The TDG records clearly indicate that TDG levels increase during passage through Bonneville Dam when spill occurs. During the low flow years of 1994 and 2001 when spill was limited at Bonneville Dam, the frequency of TDG saturation above the 110 percent level was small. The frequency of TDG saturation greater than 110 percent in 2001 ranged from about 2 percent of the time in the forebay of Bonneville Dam at BON, to about 38 percent of the time at the WRNO gauge as shown in Figure 27. The TDG levels below Bonneville Dam were similar during average flow years. The frequency of TDG saturation greater than 120 percent was less than 10 percent for all the years except 1996-1998. The frequency of TDG levels above 115 percent at the CWMW has declined the previous four years from 2002-2005 due to improvements in spill management.

LATERAL TDG DISTRIBUTION

Lateral gradient in TDG saturation across the Columbia River can be large within the mixing zone of the releases from Bonneville Dam and tributary inflows. The mixing zone below Bonneville Dam can extend downstream of the Ives Island area or river mile 140. Outside of these mixing zones in the main channel, the lateral gradient in TDG saturation are generally small, on the order of several percent saturation. The lateral TDG sampling of the Columbia River has generally been restricted to the main channel or near shore regions where water is actively being exchanged. The TDG levels in sheltered side channels or embayments have not been sampled in the data compiled for this report.

The lateral distribution of TDG saturation was investigated throughout the Lower Columbia River during July of 1997. The study details can be found in the Phase II Dissolved Gas Abatement Report (USACE, 2002). This evaluation of lateral TDG gradients was based on a network of supplemental sampling stations located across the main conveyance channel and not in remote side channels or embayments. Supplemental TDG stations were deployed near fixed monitoring stations and at intermediate river locations to quantify the lateral and longitudinal TDG characteristics over a two-week period during July of 1997. The time history of Bonneville Dam operations and the hourly TDG saturation at featured transects at river mile 140, 122, 77, and 42 are shown in Figures 28-31, respectively. The Bonneville operations cycled between 75 kcfs spill during the day and 120 kcfs spill at night during July 14-25 followed by a constant spill of 120 beginning on July 26. The total river flow ranged from 200 to 300 kcfs during this study.

The TDG response six miles downstream of Bonneville Dam at river mile 140 reflects the increased TDG saturation associated with spill as moderated by the TDG saturation released from the 1st and 2nd powerhouse. Throughout most of the sampling period, the TDG saturation on the Oregon side of the channel was higher than observed on the Washington side of the channel as shown in Figure 28. However, this trend was reversed when the constant spill operation was implemented on July 26. The peak TDG pressures near the Washington shore were as much as 40 mm Hg (5.3 percent saturation) higher than the minimum TDG pressures observed closer to the Oregon shore. These data suggest that the dynamics of the mixing zone below Bonneville Dam are complex and influence the TDG characteristics throughout the Ives Island reach. The nature of the current mixing zone below Bonneville Dam involves the loading of the 1st and 2nd powerhouses, forebay TDG levels, and spill magnitude and pattern, Bonneville 2nd powerhouse corner collector outfall, and the hydraulic transport properties throughout this reach.

The TDG response near the Camas/Washougal fixed monitoring station reflects the lagged response of Bonneville releases as impacted by dispersion and mixing, off-gassing, heat exchange, and biological productivity. The elevated TDG conditions generated during nighttime operations at Bonneville Dam took about 12-16 hours to travel the 24 mile reach between the dam and sampling transect near Camas/Washougal as shown in Figure 29 for flows ranging from 200-340 kcfs. A net reduction in both the average and extreme levels of TDG saturation were observed during this time period. The arrival of the elevated TDG levels generated at Bonneville to CWMW sampling station was in phase with the period of peak heating during the afternoon hours causing a greater variation in daily pressures than observed at some upstream locations. The thermally induced TDG pressure response at CWMW is evident after July 25 when spill was held steady on a 24 hour schedule.

The TDG response in the Lower Columbia River at river mile 77 shows a strong influence from riverine processes but remained at levels well above 110 percent of saturation as a consequence of upstream TDG sources. The daily variations in TDG pressure are driven primarily by water temperature and secondarily by dissolved oxygen cycling as shown in Figure 30. The propagation of elevated TDG fronts observed at upstream stations are highly attenuated upon arrival at this sampling transect. The TDG response at station TID07701P was consistently smaller than observed at the other three stations. The source of the lower TDG levels at station TID07701P could be physically related to flows from the Multnomia channel entering the Columbia River at river mile 85 or incomplete mixing of the Willamette and Columbia Rivers. The highest TDG levels at river mile 77 were consistently observed near the Washington shore at the fixed monitoring station KLAW.

The TDG pressures in the Lower Columbia River at river mile 42 were the smallest observed during this study and averaged about 840 mm Hg (110.5 percent). The general TDG pressures trends released from Bonneville Dam are still discernable on this transect and indicate a mean travel time of about 2 days. The daily variation in TDG pressure on this transect are smaller than observed at upstream transects and are probably related primarily to thermal cycling. The TDG response at the fixed monitoring station WANO frequently involved a TDG pressure decline during the early morning hours not observed at nearby stations which could be related to a quiescent sampling environment. The TDG levels observed at WANO during this period likely underestimated the cross sectional average TDG levels in the Columbia River by several percent saturation.

A summary of the lateral gradients in TDG saturation in the lower Columbia River were estimated by determining the frequency distribution of TDG saturation at each sampling station during the period from July 15-29, 1997 as shown in the box plot in Figure 32. The statistical summary at each sampling station have been grouped by river transect and oriented from the Oregon to Washington side of the channel in Figure 32. The black line in the box represents the median observation while the red line reflects the average TDG pressure. The vertical range of the box identifies the 25th and 75th percentile while the 10th and 90th percentile defines the whiskers.

In general, the lateral gradients of the mean TDG saturation were small outside of the mixing zone below Bonneville Dam with a typical range less then 30 mm Hg. The TDG response at fixed monitoring stations located very near the Oregon or Washington shore were similar to TDG levels observed in the main channel. This data set did not identify a systematic bias for higher TDG pressures being located away from the river shoreline. Some of the lateral TDG gradients identified in this study were likely attributed to instrument malfunction (Bonneville forebay). The TDG response in the mixing zone of spillway and powerhouse releases at river mile 144 exhibit large lateral gradients and temporal variability associated with spillway operation.

The lateral gradients in TDG saturation in the lower Columbia River have been classified as small or on the order of several percent saturation outside of the mixing zone of Bonneville Dam releases and tributary inflows. These observations were based on study results sampling the main channel and don't include the habitat that resides in side channels or sheltered embayments. The small differences observed across a channel maybe critical when it comes to management of sensitive habitat for TDG exposure. The CE has not collected TDG data in regions of the lower Columbia River that are well outside of the main channel and may experience different exchange rates of mass and energy with the atmosphere. The close coupling of TDG pressures to water temperatures is likely to result in selected habitat in the lower Columbia River that experience thermally induced TDG pressure spikes on the order of several percent saturation or more.

DISSOLVED OXYGEN

Other aquatic sources and sinks that may impact TDG pressures in productive systems such as the Lower Columbia River below Bonneville Dam include aquatic community metabolism. This biological phenomenon affecting dissolved oxygen (DO) and carbon dioxide concentrations are well documented in the scientific literature.

The daily variation in dissolved oxygen concentration in the Columbia River below Bonneville Dam was documented during a research study addressing the performance of the CWMW fixed monitoring station (Carroll et. al., 2003). An array of 20 automated remote instruments were deployed for logging time histories of TDG pressure, water temperature, and dissolved oxygen concentrations from Bonneville Dam, river mile 145.7, downstream to just below the CWMW FMS at river mile 121.6. The water quality data was collected during the period from June 8-21, 2001. The first week of sampling corresponded with a constant spill of 50 kcfs. There was no spill at Bonneville during the second week of sampling. The weather conditions during this study were generally mixed with cool conditions on June 11-12 and generally warm sunny conditions during the final week of sampling.

The dissolved oxygen concentrations observed in the spillway exit channel during a spill of 50 kcfs ranged from 10–11 mg/l during spill and 8 – 9.5 mg/l with no spill. The dissolved oxygen was supersaturated during spill at about 107% compared to 119.7 % for total dissolved gas. The difference in levels of saturation between oxygen and total dissolved gas suggests that oxygen was under-represented in the exchange of atmospheric gases in aerated flow whereas Nitrogen was likely over represented. After spill-ceased, the oxygen concentration declined to a saturation of only 90% and the TDG saturation dropped to 106%. Clear diurnal cycles in oxygen were not evident in the spillway exit channel. The under representation of oxygen in the TDG pressures observed downstream of aerated spillway flows has also been observed at Ice Harbor Dam (Wilhelms and Schneider, 1998).

The variation in dissolved oxygen concentration in the Columbia River channel near the Camas/Washougal fixed monitoring station demonstrated a strong daily cycle with peak concentrations in phase with the thermal patterns. The variation in daily DO concentration typically ranged from 0.3 to 0.6 mg/l as shown in Figure 33. The sampling stations used in Figure 33 were scattered around the vicinity of the Camas/Washougal gauge and reflect both near shore and mid-channel conditions. The dissolved oxygen patterns followed the TDG pressure trends, with higher levels during spill and slightly lower concentration during the no-spill period. Diurnal cycles of as great as 1 mg/l were measured. Note that this reflects an actual change in mass that is distinguishable from the higher TDG pressures resulting from temperature fluctuations. A 1 mg/l variation in DO translates to a TDG saturation range of 1 percent. The reduction in daily average DO concentrations as a consequence of the stoppage of Bonneville spill was varied across the sampling array.

WATER TEMPERATURE

Water temperature plays an important role in determining the concentrations and pressure fluctuations of TDG's in the lower Columbia River. The resultant TDG pressures generated in aerated flow are primarily a function of the pressure time history of the air bubbles and weakly dependent on water temperature. However, the rate of heat exchange is generally considerable faster than mass exchange rates resulting in thermally induced pressure responses that exhibit a daily cycle. Water temperature is directly related to TDG pressure when the TDG concentration is held constant meaning that when a water body is warmed up the TDG pressure will also increase. The water temperature plays a secondary role in determining the mass exchange rate at the air/water interface and the rates of biological productivity.

Water temperatures in the lower Columbia River experience typical warming trends during the course of a year. The coldest water temperatures are generally measured during the month of January and gradually warm to the highest temperatures in the summer months of July and August. On average water temperatures range from about 40° F in the winter to about 70° F in the summer.

The longitudinal temperature trend in the lower Columbia River or temperature gradients from Bonneville Dam (river mile 146.1) to Wauna Mill (river mile 42) is relatively flat based on a review of monthly average temperatures at the FMS as shown in Figure 34. The amount of warming over this river reach is greatest during March and consistently declines in each successive month. During the summer month the average river temperatures are nearly constant over this 100 mile reach. For example, monthly averaged water temperatures recorded during July of 1998 were as follows: 68.9° F at BON, 69.0° F at SKAW, 69.0° F at WRNO, 69.3° F at CWMW, 69.1° F at KLAW, and 69.1° F at WANO. Within the reach from Bonneville Dam to Wauna Mill there was an average warming a 0.2° F.

Columbia River water temperatures can be affected by the influence of tributaries during periods of high flows when tributary contributions can be as much as 30-40% of total Columbia River flows. The tributary water temperatures were not investigated in this review.

When water temperatures change at a rate that is different from the mass exchange of atmospheric gasses, a temperature induced change in TDG pressure results. The differential exchange of heat in the Columbia River will cause gradients in TDG saturation. Differential heating can be prominent in channel reaches that are shallow, or have limited water exchange with the main channel. The sensitivity of TDG pressure to changes in water temperature can be illustrated by the following example. A water sample with a TDG pressure of 740 mm Hg at 11^{o} C will have a concentration of dissolved gasses of 29.4 mg/l (assuming atmospheric composition of gasses). If no mass is exchanged, and the water temperature rises 1^{o} C, the resultant pressure will equal 756 mm Hg or an increase of 16 mm Hg in total pressure.

The shallow river reach below Bonneville Dam is more responsive to daily heating and cooling cycles compared to upstream impounded reaches of the Columbia River. Typical diurnal temperature cycles were recorded during June 8-21, 2001 across an array of water quality sampling station near river mile 122 as shown in Figure 35. The daily variation in water temperature near the CWMW gauge was as high as 1.5 C. These daily temperature cycles were in phase with the observed TDG pressures observed across this sampling array as shown in Figure 36. The increase in TDG saturation between Bonneville Dam (BON) and the Camas/Washougal (CWMW) transect after June 17 is a consequence of heat exchange and biological productivity in this reach. The daily temperature variation was much weaker in the Bonneville forebay (BON) due to the ratio of channel volume to surface area.

The change in water temperature from the Bonneville Dam to downstream sampling stations provides an estimate of the size of the temperature influence on observed TDG pressure. The change in water temperature between Bonneville Dam and the CWMW gauge was estimated by calculating the time of travel for each hourly release during April-August, 2002. The change in water temperature was then determined by comparing the water temperature at the BON gauge with the appropriately lagged water temperature observed downstream at CWMW. The change in temperature was then used to estimate a change in TDG pressure based on the gas laws governing the temperature, total pressure, and mass concentration properties as presented by Colt (1983). The net change in TDG pressure was also determined using the travel time between sampling stations. The change in TDG pressure associated with temperature changes between Bonneville Dam and the CWMW gauge are summarized in Figure 37. The frequency distribution of TDG pressure change associated with temperature change between stations BON and CWMW was estimated from April-August, 2002 as shown by the blue line in Figure 37. Most of the time a net temperature increase is experienced over this reach resulting in a corresponding increase in

TDG pressure based on the gas laws. However, during the nighttime a small degree of cooling can take place resulting in a net decrease in TDG pressure. In general, most of the temperature changes resulted in TDG pressure increases of 7 mm Hg or less. During hot days, the temperature induced pressure influence can be a high as 15-25 mm Hg (2-3 percent saturation).

The net change in TDG pressure based on the difference between the estimated cross sectional TDG pressure released from Bonneville Dam and the TDG pressure observed at CWMW was also determined and shown in Figure 37 by the green line. The median change in TDG pressure between BON and CWMW was -16.8 mm Hg during the 2002 fish passage season. The variability in the change in TDG pressure over this river reach is considerable. The reduction in TDG pressure in this river reach was less than 6.4 mm Hg only 10 percent of the time and greater than 25.2 mm Hg 10 percent of the time during this study period.

The differential heating of the Columbia River is likely an important source for the variability of TDG pressures throughout this area. The habitat in secluded embayments, sheltered flats, and secondary channels are likely to experience a greater range in daily temperatures and TDG pressures than observed in the main channel. The data compiled for this report was primarily collected from the main channel and in regions of active water exchange and is not inclusive of shallow, lower velocity habitat.

TDG Monitoring

The monitoring of TDG pressures in the Lower Columbia River has undergone considerable change since the initiation of continuous monitoring in the early 1990's. As many as five fixed monitoring stations were maintained in the lower Columbia River downstream of Bonneville Dam during the 1994-1998 for a distance of over 100 miles. The stations at WANO (RM 42) and KLAW (RM 77) were retired in 1999. A summary of the TDG records during April 15-August 31, 1994-1998 at these stations indicated that hourly TDG observations exceeded the 110 percent of saturation 45 percent of the time at the WANO gauge and 78 percent of the time at the KLAW gauge. Both of these stations were located downstream of tributaries to the Columbia River and were generally representative of TDG levels in the lower Columbia River.

The tailwater station SKAW (RM 140) was retired in 2002. The SKAW station was paired with the WRNO station to capture any persistent lateral gradients in the Columbia River six miles below the dam. The SKAW station was retired because of the poor sampling environment at this station. The SKAW gauge was located in a large recirculation cell where the flow direction at the station was typically directed upstream and the TDG response was lagged several hours behind conditions at mid-channel.

The WRNO station remains active but was retired as the official tailwater station during the fish passage season in 2005 in lieu of the CCIW station located in the spillway exit channel. The tailwater station was moved for several reasons. The new station CCIW provides a direct measure of the TDG content in spillway releases undiluted from powerhouse flow. The CCIW station provides the most comprehensive description of the TDG loading in Columbia River

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below Bonneville Dam. The information gathered from this new station can be used to help manage spill operations at Bonneville to comply with both the Washington and Oregon water quality standards/waivers at the Camas/Washougal gauge. The spillway exit channel contains the highest TDG pressures released from Bonneville Dam for normal operations during the spill season. The location of the CCIW station is consistent with most of the other TDG tailwater stations operated by the Corps of Engineers. This new location is consistent with the recommendations in the Lower Columbia TMDL and will provide direct evidence of gas abatement activities. The CCIW station is located upstream of the B2CC outfall and only will detect this release when the spillway in inactive. The CCIW station will also be operational year round in place of the WRNO gauge. The WRNO station is currently scheduled for activation during the chum management season running from March 1 through May 31.

A major challenge for monitoring the TDG exchange associated with spillway operations at Bonneville Dam is the spatial variability of TDG pressures that develop in the exit channel at spill discharges greater than 100 kcfs. The sampling bias that develops in the Bonneville spillway exit channel was shown in Figure 18 (CCIW=BONTWP5). . At spill rates below 75 kcfs, the TDG level measured at CCIW is fairly representative of both the cross-sectional average TDG and the peak TDG levels in the spillway channel. However, as spill increases, the CCIW gauge consistently and predictively underestimates both the cross-sectional average and peak TDG levels. For example, at 100 kcfs spill, the CCIW gauge underestimates the cross-sectional average TDG by about 1.5 percentage points. It underestimates the peak TDG (at the center of the channel) by about 3%. At 150 kcfs spill, CCIW underestimates the cross-sectional average TDG by about 3% and underestimates peak TDG by about 5.5%. Because this sampling bias is both consistent and predictable, the observations at this station still provides reliable information to manage TDG loading to the lower Columbia River. These conditions do rise several concerns regarding habitat management and adherence to water quality standards in the Columbia River at Bonneville Dam.

The CWMW gauge is the only mixed river sampling site below Bonneville Dam on the Columbia River scheduled to remain active throughout the entire fish passage season. The TDG levels at CWMW based on the highest 12 hourly observation in a day, have been found to be representative of average river conditions. The time of travel in this 24 mile reach from Bonneville Dam to the CWMW gauge generally ranges from 12 to 24 hours. This gauge is located upstream of the significant tributaries to the Lower Columbia River. The TDG response at CWMW is influenced by riverine surface exchange processes, as are all other forebay gauges. The most prominent riverine process influencing the TDG loading in the Columbia River below Bonneville Dam is mass exchange at the water surface, which tends to restore the TDG pressures to 100% of saturation. The cross section average TDG levels in the river just below Bonneville Dam are considerably higher than those observed at the Camas/Washougal gauge (about 3% higher for 2004).

The use of the Camas/Washougal gauge to manage TDG levels in the lower Columbia River has not been embraced by ~~some~~ **all** regional management agencies. In a Joint Technical Staff Memorandum, several wildlife agencies requested cessation of the use of data from the Camas/Washougal gauge and provided technical arguments to support this proposal. Some of the concerns raised with this sampling location involve the variability of TDG pressure and concerns of a sampling bias. The variable TDG readings at CWMW are generated in large part because of the day/night spill policy at Bonneville Dam. The nighttime spill to capacity policy generates a large volume of water with high TDG pressures that is arrives at CWMW during the warmest part of the afternoon. The Camas/Washougal gauge was found to be representative of mixed river conditions based on the daily TDG standards metric (Carroll et. al.., 2003).

Another criticism of the CWMW gauge is the lack of a close relationship between spill and the TDG response at CWMW. The direct relationship between spillway discharge at any project and TDG response at a downstream mixed river station is always going to be a poor relationship because the TDG loading from powerhouse releases has not been considered. The impact the spillway TDG load is an integral component of the TDG pressures observed at the CWMW gauge. The development of a model to predict the TDG budgets in this river reach has been successful in supporting TDG management activities.

The impacts of environmental factors like heat exchange, degassing, and biologic productivity on the TDG response at CWMW have been listed as reasons to retire this station. However, the TDG response at all downstream forebay stations are influenced by these same processes. In most cases, the time of travel from the tailwater station to the downstream mixed river station is considerably longer than is the case below Bonneville. The longer travel time will increase the importance of these environmental factors on the TDG response at the mixed river station.

The short travel time in this reach has also been used as justification to remove the CWMW station. However, the exposure to elevated TDG pressure continues well downstream of river mile 122. The TDG saturation was observed to remain just below 115 percent at river mile 77 during the months of May and June of the normal flow year of 1998. The TDG saturation remained above 110 percent of saturation for over two months at river mile 42 during this same year. The removal of the CWMW gauge would also remove a safeguard against chronic exposure to TDG saturation greater than 115 percent in the lower Columbia River. This safeguard would remain in effect at all other impounded river reaches of the Columbia and lower Snake Rivers.

TDG MANAGEMENT

The current applicable state standards mandate management of TDG levels below Bonneville Dam to a level of 120 percent at the tailwater FMS and 115 percent at the Camas/Washougal gauge. The removal of the CWMW gauge would result in TDG management activities based only on conditions in the spillway exit channel near Cascade Island at CCIW. The TDG loading in powerhouse releases or in the B2CC outfall flow would not influence the TDG response at CCIW and may result in average TDG conditions in the lower Columbia River that frequently exceed 115 percent of saturation and potentially much higher. The time of travel, heat and gas exchange at the water surface would not be considered in managing TDG levels below Bonneville. During involuntary spill operations, spill management decisions become potentially more critical since TDG levels are maintained above 120 percent of saturation. The retirement of CWMW would force TDG management decisions to be based on estimates of current conditions in the lower Columbia River and not on current observed conditions throughout the impounded reaches of the Columbia River. The dual points of concern below Bonneville Dam are consistent with the management constraints for TDG at all other dams on the Columbia River. The TDG response at CWMW can be a limiting constraint on the spill capacity at Bonneville Dam. When the TDG levels in the forebay of Bonneville are high (> 113%) the additional loading caused by spillway operations can cause the mixed river TDG levels downstream at CWMW to exceed the daily 115 percent constraint. Spill management decisions governed at mixed river FMS are subject to many influences (time of travel, TDG load contributed by spill, heat exchange, degassing, powerhouse TDG load) which complicates developing management decisions. The TDG responses in spillway releases are generally consistent, stable, and often highly correlated with project operations (spill magnitude, pattern, tailwater stage). The tailwater FMS can define the spill capacity when spill policy requests the maximum allowable spill discharge as limited by state water quality allowances for TDG during the fish passage season and the TDG levels in the forebay are low (<110 percent). The limiting sampling point of TDG management typically shifts back and forth between the forebay and tailwater FMS's as river conditions change during the fish passage season.

The 2005 spill policy at Bonneville Dam of maintaining 75 kcfs during the daytime and spilling up to a capacity limited by TDG criteria in the Lower Columbia River at the tailwater (CCIW) and CWMW gauges, resulted in 15 days of excursions above the criteria at the CWMW gauge. During the 2005 spill season, the TDG saturation at CCIW never exceeded the 120 percent criteria (average of the 12 highest daily observations) and reached 119 percent saturation only once. The elevated nighttime spill with a duration of 7 hours or less allowed the TDG response at 75 kcfs to be factored into the daily water quality standards computation. However, if the cross sectional average TDG saturation relationship (Figure 18) is applied to the 2005 operations and used in determining adherence with the water quality standards, the conditions in the spillway exit channel would have exceeded 120 percent about 25 times during the 2005 spill season. The low tailwater elevations during 2005 caused the TDG response at CCIW to be somewhat less than observed during the 2002 spill season during much of the year as shown in Figure 19.

The TDG saturations in Bonneville releases at CCIW were generally greater than observed at WRNO. The TDG response to spill at WRNO was generally 3-5 hour behind the response observed in the spillway channel. The recirculation cell along the Oregon shore at the WRNO gauge further distorts the TDG response at this sampling location. There were several occasions when the peak daily TDG saturation at WRNO was larger than observed in the spillway channel at CCIW when forebay TDG levels were around 110 percent. The observation of the peak daily TDG saturation at WRNO supports the hypothesis that the observations at CCIW underestimate the TDG content in spillway releases for a range of operations. The TDG levels at WRNO generally correspond closely to the flow weighted average of the TDG content of all of Bonneville Dam releases. The TDG saturation observed at the WRNO gauge are likely a reasonable estimate of conditions experienced in the Ives Island area for many flow conditions.

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The weak lateral gradients observed during the 1997 field investigation near the WRNO gauge also support this conclusion.

The management of TDG saturation at CWMW is more complex because of the added influences that contribute to the TDG response at this site and the time lag between the spill decision and the observed response. During the 2005 spill season, the TDG levels at the CWMW gauge exceeded the criteria during 15 days. About one-third of the time the criteria was exceeded, the forebay levels were greater than 114 percent to begin with and even a minimum spill of 75 kcfs generating a TDG saturation of 117.5 percent will increase average conditions above 115 percent at CWMW. However, on 7 of the 15 days when the TDG standard was exceeded, the Bonneville forebay levels were less than 111 percent when greater flexibility existed in selecting spill operations to meet downstream criteria. The weather conditions during the day will determine how much heating occurs in this reach and how much degassing takes place at the water surface.

In general, when the forebay TDG levels are high (>114 percent), the amount of TDG saturation added during spillway operations must be limited because of the likelihood of TDG levels exceeding 115 percent at CWMW. On the other hand, when forebay TDG levels are low (<110 percent), there is an opportunity to spill additional water without exceeding the 115 percent criteria downstream at CWMW. The average degassing amount between Bonneville Dam and CWMW during the 2005 season was about 2.8 percent saturation. A conservation statement can be written to estimate the level of spill resulting in a release target TDG saturation from the Bonneville Dam. A target TDG saturation of 115+2.8=117.8 percent would have a 50 percent chance of resulting in an excursion above 115 percent at the CWMW gauge. The selection of the target TDG saturation contains an associated risk of TDG levels falling above the water quality standards threshold for TDG saturation at the CWMW gauge. In some cases, the forebay TDG levels are already above 115 percent and there is no opportunity to manage spill to prevent an excursion above 115 percent at CWMW. In this case, a spill level may be targeted that will result in a net reduction in the cross sectional average TDG pressure in the Columbia River (degassing) and therefore minimize the size of the excursion above the criteria. The corrective spill management directive during these circumstances must include reducing TDG sources upstream of Bonneville Dam. This risk based management strategy will ultimately require the identification of an acceptable risk of exceeding the daily TDG criteria.

The relationship between spill policy at Bonneville Dam and TDG levels observed at the downstream TDG monitoring stations can be explored using the SYSTDG model of the Columbia River. SYSTDG is a one-dimensional model of TDG pressure and saturation in the Columbia and Snake Rivers and has been developed to support spill management decisions at Bonneville and other main-stem dams. This model uses empirically derived TDG exchange relationships to estimate the TDG saturation in spillway and B2CC flows. The calculated or observed forebay TDG saturation is applied to powerhouse flows. The resultant flow weighted TDG pressure is routed from the dam at RM 146 to the CWMW sampling location at RM 122. The surface degassing is estimated by a first order exchange relationship where the exchange coefficient is a function of the wind speed. The wind data from the Troutdale weather station is used to estimate the exchange coefficient. The time of travel is determined from a hydrologic routing approximation with dispersion. The amount of heat exchange from Bonneville to CWMW is used to estimate the temperature induced pressure change in this river reach.

The 2005 TDG saturations in the lower Columbia River below Bonneville Dam were simulated based on hourly operations records at Bonneville Dam and the TDG saturation observed in the forebay at BON. The predictive error of the hourly TDG saturation during June at the Camas/Washougal FMS was –5.5 mm Hg (0.6 percent) with a standard error of 7.7 mm Hg (1.0 percent). The observed and calculated TDG saturation during the month of June is shown in Figure 38 for the CWMW station and in Figure 39 for the WRNO station. The TDG criteria of 115 percent saturation as determined from the highest 12 hourly observations in one day were exceeded 6 days during the month of June. The historic spillway operations and forebay TDG pressures were used as the base case to compare alternative spill policies at Bonneville Dam.

The sensitivity of alternative spill policies on the TDG response at CWMW was investigated using the SYSTDG model. The type of alternative spill policy was chosen only to demonstrate the sensitivity of TDG levels below Bonneville to spill activities while holding constant all other contributing processes. The first alternative spill policy involved increasing the daytime spill from 75 kcfs to 100 kcfs as shown in Figure 40. This increase in daytime spill resulted in an average increase in TDG pressure of 10 mm Hg at CWMW for the month of June compared to the base condition and resulted in a total of 10 days where the daily 115 percent standard was surpassed. The increase in daytime spill had a small impact on the daily peak TDG saturation observed at CWMW.

The second alternative spill policy investigated called for nighttime spill to be equal to 160 kcfs as constrained by a minimum powerhouse discharge of 30 kcfs. This operational spill policy maintained a daytime spill of 75 kcfs as shown in Figure 41. This spill policy increased the average TDG pressure by 5 mm Hg at CWMW for the month of June over the base condition. The number of days where the 115 percent standard was exceeded increased to 13. The ability to achieve suitable TDG conditions at the CWMW gauge is sensitive to the nighttime spill policy at Bonneville Dam.

A third alternative spill policy called for a constant 100 kcfs spill both night and day as shown in Figure 42. This spill policy decreased the nighttime spill and increased the daytime spill when compared to the 2005 spillway operations (base conditions). The constant spill policy resulted in hourly TDG saturation at CWMW remaining below 115 percent. There were no days when the 115 percent standard was exceeded for this spill policy at CWMW during June.

The fourth alternative spill policy investigated called for spilling 50 percent of the hourly total river flow at Bonneville Dam as shown in Figure 43. This policy resulted in spills ranging from 65 to 130 kcfs. The constant percent of river spilled also limited the TDG saturation at CWMW to 115 percent or less. There were no days when the 115 percent standard was exceeded for this spill policy at CWMW during June.

The influence of the powerhouse TDG loading on conditions at CWMW was investigated by assuming the forebay TDG levels were 2 percent saturation larger than observed during the

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month of June 2005 as shown in Figure 44. Using the spillway releases of the base condition, this 2 percent increase in forebay TDG saturation resulted in a 6.4 mm Hg increase in TDG pressure at CWMW. The number of days where the 115 percent standard could not be attained at CWMW during June was 10 for these conditions. In order to manage TDG levels at CWMW, the forebay conditions must be factored into setting spill levels.

This series of simulations demonstrates the sensitivity of spill policy at Bonneville Dam and upstream dams, on the TDG response at CWMW. Relatively small changes in spill policy can significantly change the frequency of excursions above the TDG criteria at the downstream mixed river gauge. The nighttime spill from Bonneville Dam arrives at CWMW in phase with the peak heating of river waters during the afternoon and evening hours resulting in maximum hourly TDG pressures in the lower Columbia River. Reducing the spill to capacity policy during the nighttime period will significantly lower the daily TDG response at CWMW. In addition, lower forebay TDG saturations will allow greater spill rates at Bonneville without TDG levels exceeding the 115 percent criteria at CWMW. The recognition of the sampling bias in the spillway exit channel will also significantly influence the management of spill at Bonneville Dam based on the tailwater TDG criteria of 120 percent.

TDG and Aquatic Habitat

TDG and river cross section data were analyzed to develop an aquatic hazard map of a limited section of the Columbia River near the Camus-Washougal monitoring site. Several factors help determine the hazard and the susceptibility of fish and other aquatic organisms to gas bubble trauma. The incidence of gas bubble trauma in fish depends on degree of TDG supersaturation, duration of exposure to the fish, water temperature, species, general physical condition of the fish, life stage, and swimming depth maintained by the fish. Shallow river reaches afford less protection for fish against the formation of GBT because of the compensating effects of depth (Weitkamp, 1980). The susceptibility of aquatic organisms to the harmful effect of water supersaturated with TDG in shallow water less than two feet of depth is recognized in the Oregon water quality standards.

One metric of the relative risk of a river reach to elevated TDG levels is the amount of habitat above the compensation depth. A volumetric estimate of habitat above the compensation depth can be calculated based on a typical channel cross-section, river stage, and the average TDG saturation.

A channel cross section was selected above and below Bonneville Dam to compare the percent habitat above and below the compensation depth in water with TDG saturation of 115 percent. The cross sectional area in the Columbia River about one mile upstream of Bonneville Dam was compared to conditions near the Camas/Washougal fixed monitoring station at river mile 122 for a stage of 10 ft as shown in Figure 45. Above Bonneville Dam, only 8.2 % of the total area of the cross-section (89 feet deep and 1800 feet wide) is above the compensation depth at 115% saturation, while 21.1% of the total area of the cross-section at river mile 122 (42 feet deep and 3000 feet wide) is above the compensation depth. The volumetric ratio of habitat will vary as a function of river stage, TDG pressure, and channel morphometry.

Another means of identifying potential risks to elevated TDG pressures is to determine the absolute TDG pressure or compensated TDG pressure on the channel bed. An absolute TDG saturation of 105 percent at the channel bed means that an organism residing on the channel bed would be exposed to a TDG pressure that is 5 percent greater than the compensating total pressure (atmospheric+hydrostatic pressure). If the organism is above the channel bed in the water column, the absolute TDG saturation will be even greater. This type of mapping may be particularly import to redds located below Bonneville Dam. The absolute TDG saturation on the channel bed is a function of river stage, channel geometry, and the TDG pressure. A TDG hazard map based on the absolute TDG saturation for the Columbia River channel bed was prepared for a reach of the Columbia River near Camas/Washougal for a uniform TDG saturation of 115 percent as shown in Figure 46. A water surface elevation of 10 feet NGVD with a compensation depth of 1.5 meters or approximately 5.1 feet was used to delineate this channel reach. The color contours represent the depth compensated absolute TDG saturation on the channel bed. The area shaded in pink represents regions where the absolute TDG saturation at the channel bed is less than 95 percent. The yellow shaded areas represent the regions of the channel where the absolute TDG saturation ranged from 105-110 percent. The region shaded in red represents locations where the absolute TDG saturation at the channel bed ranges from 110 to 115 percent. Figure 4 displays the bathymetry information at the same section of the Columbia River near Camas/Washougal. These bottom contours of absolute TDG saturation vary as a function to river stage and TDG saturation.

CONCLUSIONS

A summary of the TDG characteristics in the Lower Columbia River below Bonneville Dam (RM 42-146) was conducted by reviewing research and routine monitoring TDG data. Supplemental information involving channel bathymetry, stage, and river flow were also compiled to address related TDG properties. The availability of continuously monitored TDG data at selected locations in the study reach was initiated in 1990. The major findings from this investigation are listed below.

The spill at Bonneville Dam and at projects upstream on the Columbia River is the primary source of elevated TDG saturation in the Lower Columbia River. Bonneville Dam typically spilled from 40-50 percent of the Columbia River during the fish passage season during the period from 1995-2005. Prior to the completion of the Bonneville 2nd powerhouse in 1982, the average spill during the fish passage season was 160 kcfs or comparable to conditions experienced during the period of record flood in 1997. Spill at Bonneville Dam was continuous during the fish passage season with the exception of low flow conditions during 2001. Spill at Bonneville Dam was infrequent outside of the fish passage season. However, during 1995-1999 Bonneville Dam spilled on average 40 or more days outside of the fish passage season and spilled over 300 kcfs during February of 1996. The daily spill policy typically called for spilling higher rates during the nighttime hours resulting in significantly higher peak and average TDG levels in releases from Bonneville Dam during this period.

Bonneville powerhouse releases retain the TDG levels observed in the forebay generated in spill operations at upstream dams. During normal flow conditions where voluntary spill levels can be maintained in the system, the forebay TDG levels range from 108-111 percent and infrequently exceed 115 percent. During high flow conditions in 1996 and 1997, the forebay TDG levels averaged 117-118 percent and remained above the 115 percent level throughout most of the fish passage season. The TDG content in powerhouse releases is generally less than spill TDG levels and thereby moderate average TDG conditions in the lower Columbia River.

The TDG saturation generated in spillway releases at Bonneville Dam are a function of spill magnitude and pattern, tailwater channel stage, and structural configuration of the spillway and stilling basin. Spillway flow deflectors have been added to the Bonneville spillway to abate TDG exchange during spill. The original 13 flow deflectors constructed in 1976 at elevation 14 ft were designed to optimally function during forced spill events at high tailwater conditions. The 2002 spillway flow deflectors were placed at elevation 7 on the six exterior spill bays to function optimally for voluntary spill conditions that generally occur at lower tailwater levels. The TDG exchange during spill over just the elevation 7 ft flow deflectors was significantly less than a comparable spill over the elevation 14 ft flow deflectors for tailwater elevations less the 16 ft.

The peak TDG pressures observed in the Bonneville spillway exit channel have been observed within the aerated flow conditions just downstream of the stilling basin. The mass transfer between entrained air governs the TDG saturation generated in aerated spill at Bonneville Dam. The pressure time history of entrained air bubbles results in a region of net absorption of TDG pressure where the spill jet entrains and transports bubbles to depth in the stilling basin and adjoining tailrace channel, followed by a region of net desorption when bubbles rise out of the water column. The TDG pressures retained outside of this region of highly aerated flow contributes to the TDG loading in the Columbia River below Bonneville Dam. The TDG saturation in aerated flow below the spillway at Bonneville Dam has been observed to be as high as 170 percent. The TDG saturation in the spillway exit channel downstream of the bubbly flow has been observed to be as high as 142 percent of saturation.

The TDG exchange in spillway releases from Bonneville Dam with the current complement of 18 flow deflectors for the standard spill pattern was directly related to the specific spillway discharge and weakly related to the tailwater stage. A uniform spill pattern distributed across all 18 spill bays during low tailwater stages will minimize the TDG generated in spillway flows. The average cross sectional TDG saturation generated for spills of 50, 100, 150, 200, and 250 kcfs were 115, 120, 125, 130, and 135 percent of saturation as observed in 2002. The tailwater stage affects the deflector submergence and available maximum depth of flow in the spillway exit channel.

The lateral distribution of TDG pressures in the spillway exit channel becomes non-uniform for spillway flows greater than 100 kcfs. The TDG pressures monitored at the fixed monitoring station located at CCIW near the shore of Cascade Island consistently underestimated both the average and peak TDG pressures for higher spill discharges monitored during 2002.

A secondary source of TDG exchange at Bonneville Dam is the discharge associated with the Bonneville second powerhouse corner collector outfall. The plunge pool constructed at the outfall to aid fish passage likely impacts the TDG exchange properties. The TDG loading estimates associated with the outfall can be approximated by an effective TDG pressure greater than 1000 mm Hg. The B2CC outfall discharge jet mixes quickly with other project discharges and influences the local TDG pressures. The TDG saturation measured in B2CC flows at the tip of Bradford Island did not exceed 110 percent of saturation and increased the average cross sectional TDG saturation in the lower Columbia River by 1-2 percent as observed in 2004.

The mixing zone between spillway, B2CC, and powerhouses 1 and 2 discharges shapes the lateral distribution of TDG pressures in the Columbia River. Strong lateral gradients in TDG saturation are common downstream of the spillway exit channel. This mixing zone has been observed to extend through river mile 140 for certain flow conditions. In most cases, the mixing zone is well developed by RM 140, as the TDG response measured at WRNO is closely approximated by the flow weighted average of TDG levels from all Bonneville Dam discharges.

The mass exchange at the air/water surface results in a gradual loss of TDG pressures in the Lower Columbia River as water is transported downstream. The generation of breaking waves by winds can greatly increase the rate of degassing in this reach.

The heat exchange in the lower Columbia River can result in water temperature fluctuations that induce TDG pressure changes. The diurnal temperature variation is typically highly correlated with the daily variation in TDG pressure at sampling stations located downstream from the mixing zone below Bonneville Dam. The daily variation in temperature can be as large at 1.5 C at the CWMW gauge. This temperature change can result in a 3.5 percent change in TDG saturation at a base water temperature of 15° C.

The dissolved oxygen variation resulting from respiration and photosynthesis can influence the TDG pressures observed in the lower Columbia River. The daily DO variation in the lower Columbia River is typically 0.5 mg/l that will result in a 1 percent change in TDG saturation.

Tributary flows to the lower Columbia River contribute from 20 to 40 percent of the monthly average flow. The TDG data associated with tributaries to the Lower Columbia River is sparse but manual samples taken below Willamette Falls on the Willamette River have exceeded 120 percent of saturation during high flows.

The lateral variation in TDG pressure is generally small outside of the mixing zones of Bonneville Dam or tributary flows. In general, the mean TDG response at a point of sample is within 2 percent of the cross sectional average TDG saturation. Lateral gradients in TDG saturation can result from differential exchange of mass or energy.

A continuous reduction in the TDG saturation in the lower Columbia River is evident in data collected throughout this reach as TDG pressures are restored to equilibrium with the atmosphere. The rate of reduction in TDG saturation per mile of reach length will vary according to cross sectional average TDG saturation released from Bonneville Dam, river flow rate, channel geometry, tributary dilution, heat exchange, biological productivity, and mass exchange at the water surface. During the month of June for the high flow years of 1996-1997, the net reduction in TDG saturation from Bonneville Dam (WRNO) to WANO was only 4-5 percent saturation.

The Camas/Washougal fixed monitoring station provides a representative measure of the TDG saturation in the lower Columbia River approximately 24 miles downstream from Bonneville Dam. The TDG levels at CWMW are closely related to the cross sectional average TDG pressures released from Bonneville Dam. The TDG response at CWMW is from 0-4 percent less than the average TDG saturation released from Bonneville Dam as a consequence of in river processes. The limiting TDG criteria of 115 percent at CWMW are generally more restrictive for spill management than adhering to the 120 percent criteria at the tailwater station CCIW.

The TDG saturation during high flow years can exceed 120 percent of saturation for several months throughout the entire lower Columbia River reach from Bonneville Dam to RM 42. A peak TDG pressure greater than 140 percent was observed in the tailwater of Bonneville Dam during the 1996 and 1997 flood events.

The TDG saturation during normal to low flow years can exceed 110 percent of saturation for several months throughout the entire lower Columbia River reach from Bonneville Dam to RM 42. The peak TDG pressures during voluntary spill will be limited by the 120 percent criteria at the tailwater fixed monitoring station.

A model of the TDG exchange and transport processes has been developed in the lower Columbia River and is being applied to support spill level decisions and the resultant TDG conditions below Bonneville Dam. The adherence of TDG criteria at the Camas/Washougal fixed monitoring station is sensitive to the nighttime spill policy at Bonneville Dam. The entire TDG loading released from Bonneville Dam for alternative spill levels must be considered in effective management of TDG levels in the lower Columbia River. A risk based management approach that considers the stochastic nature of TDG exchange in the lower Columbia River must be considered in selecting spill levels at Bonneville Dam.

The habitat impacted by TDG supersaturation will be a function of river stage, geometry, and TDG levels. A larger percentage of the habitat downstream of Bonneville Dam will be above the compensation depth when compared to the impounded river upstream of the dam. The variation in river stage caused by tidal or river discharge changes will impact the absolute TDG saturation on the channel bed.

RECOMMENDATIONS

TDG monitoring of conditions in the Columbia River main channel have been well documented during spill operations at Bonneville Dam either through the routine fixed monitoring program or site-specific research studies. However, the TDG conditions in secondary channels, sheltered embayments, and shallow flats are not well known. The collection of additional TDG pressure, water temperature, and channel depth outside of the main conveyance channel would help support the management and monitoring policies and practices in the lower Columbia River channel.

Sensitive habitat areas have been identified within 6 miles of Bonneville Dam and fall within the mixing zone of project flows. The development of the TDG mixing zone involving powerhouse flows, spillway releases, and flows from the Bonneville 2nd powerhouse corner collector have not been rigorously sampled. The reliance on TDG data observed at the WRNO gauge located near the Oregon shore has been used to manage Bonneville operations assuming these conditions also apply to habitat located upstream and across the river in Washington. The collection of additional TDG pressure, water temperature, and channel depth data would support the development of a management plan to protect these sensitive areas. The effectiveness different load distributions between the 1st and 2nd powerhouse during spillway or B2CC operations could be measured and operational guidance developed. The utility of data collected at fixed monitoring station to other regions in the mix zone below Bonneville could be quantified

One operational safeguard for sensitive habitat below Bonneville Dam is the river stage afforded by project releases. Higher river flows translate to higher water surface elevations and a smaller absolute TDG saturation on the channel bed below Bonneville Dam. The stage in the Columbia River is also influenced by tidal fluctuations. A database of river stage, TDG pressure, and water temperature could be collected to support the development of a two dimensional hydrodynamic model of the lower Columbia River that could be used for management support. The results from this model could be used to predict the water surface elevation for different flow conditions that could provide safeguards up to certain TDG thresholds. Conversely, the river operation required to protect a specific habitat experiencing a given TDG saturation could be obtained. The model also could be used to identify other habitat attributes like local velocity, channel depth, and flow path that can be dynamic with changing river conditions

The TDG exchange properties associated with the new spillway flow deflectors (bays 1-3, 16-18) were found to be a significantly improvement over the old flow deflectors at tailwater elevations less than 16 ft and specific discharge up to 6 kcfs/bay. A TDG sampling program could be developed in the spillway exit channel to identify spill patterns that minimize TDG generation and also provide for suitable flow conditions to support fish passage. The optimal spill pattern may vary as a function of spill discharge and tailwater elevation. This information could identify operational alternatives to reduce the TDG load below Bonneville Dam.

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TABLES

Table 1. Monthly Averaged Flows measured at Bonneville Dam and Tributaries on the Lower Columbia River, 1995-2005							
RIVER MILE		146.1	120.5	102	87.5	68	
YEAR	MONTH	BONNEVILLE (kcfs)	SANDY (kcfs)	WILLAMETTE (kcfs)	LEWIS (kcfs)	COWLITZ (kcfs)	Q_{bon} /Q_{total} (%)
1995	1	150.24	3.71	98.79	8.03	14.23	54.6
1995	2	204.66	5.51	109.19	10.84	19.31	58.6
1995	3	189.43	2.22	67.59	7.38	11.92	68.0
1995	4	186.66	2.39	54.95	3.13	8.64	73.0
1995	5	266.43	2.41	68.39	3.65	8.59	76.2
1995	6	283.43	1.53	60.12	2.67	6.45	80.0
1995	7	202.05	0.69	45.25	1.57	4.58	79.5
1995	8	147.20	0.57	33.29	1.20	3.03	79.4
1995	9	104.82	0.47	26.36	2.00	2.75	76.8
1995	10	125.44	2.20	37.03	4.04	6.10	71.8
1995	11	167.38	7.84	77.89	12.58	22.24	58.1
1995	12	259.39	5.90	149.99	13.26	29.40	56.6
1996	1	257.28	5.19	134.83	10.44	18.51	60.4
1996	2	360.94	8.88	193.97	15.69	28.80	59.3
1996	3	321.96	2.83	86.44	6.74	8.09	75.6
1996	4	330.73	3.74	98.34	6.31	11.39	73.4
1996	5	351.24	2.91	96.66	5.81	9.78	75.3
1996	6	385.42	1.23	88.36	2.88	5.60	79.7
1996	7	247.93	0.65	51.23	1.89	4.24	81.0
1996	8	189.12	0.42	38.27	1.32	3.42	81.3
1996	9	130.13	0.39	29.01	2.08	3.49	78.8
1996	10	133.30	1.73	38.42	5.05	5.59	72.4
1996	11	140.66	4.78	95.13	8.05	14.53	53.5
1996	12	198.12	7.55	176.19	11.36	24.36	47.4
1997	1	293.29	5.58	157.14	12.63	27.04	59.2
1997	2	291.43	3.95	106.93	8.43	17.35	68.1
1997	3	296.44	5.23	119.11	9.87	19.44	65.9
1997	4	336.14	3.78	92.20	7.27	12.47	74.4
1997	5	456.31	2.46	121.66	5.55	13.19	76.2
1997	6	483.34	1.29	125.34	3.74	10.40	77.4
1997	7	277.11	1.00	58.88	2.27	14.48	78.3
1997	8	202.83	0.52	43.65	1.50	51.96	67.5
1997	9	152.61	0.54	40.36	3.35	4.63	75.7
1997	10	169.79	1.95	53.86	7.50	10.17	69.8
1997	11	153.90	2.08	67.20	8.93	15.97	62.0
1997	12	176.14	2.22	64.99	7.06	10.69	67.5

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RIVER MILE		146.1	120.5	102	87.5	68	
YEAR	MONTH	BONNEVILLE (kcfs)	SANDY (kcfs)	WILLAMETTE (kcfs)	LEWIS (kcfs)	COWLITZ (kcfs)	Q_{bon}/Q_{total} (%)
1998	1	178.29	4.39	115.98	9.89	15.41	55.0
1998	2	206.45	2.49	83.59	8.24	9.49	66.5
1998	3	196.42	3.02	75.04	6.49	7.98	68.0
1998	4	174.88	1.83	51.06	3.71	6.79	73.4
1998	5	335.17	2.62	84.64	3.58	6.66	77.5
1998	6	305.86	1.59	73.80	3.14	7.05	78.1
1998	7	205.52	0.81	40.04	1.93	5.33	81.0
1998	8	151.95	0.48	20.85	1.43	4.94	84.6
1998	9	116.61	0.42	29.44	2.38	4.72	75.9
1998	10	108.49	0.53	32.29	4.08	5.10	72.1
1998	11	125.01	3.04	73.59	7.98	11.79	56.5
1998	12	168.25	6.90	128.11	12.96	18.55	50.3
1999	1	223.26	4.63	141.85	11.50	19.73	55.7
1999	2	232.93	4.11	123.75	10.01	16.78	60.1
1999	3	265.13	2.91	103.08	9.39	12.66	67.4
1999	4	264.07	2.22	71.04	3.94	8.99	75.4
1999	5	301.18	3.42	82.43	4.98	8.90	75.1
1999	6	344.52	2.29	83.70	4.38	10.65	77.3
1999	7	256.26	1.11	55.12	3.24	9.19	78.9
1999	8	209.13	0.64	43.89	1.94	7.41	79.5
1999	9	142.20	0.43	33.79	2.47	6.31	76.8
1999	10	129.10	0.41	33.29	3.99	5.91	74.8
1999	11	155.36	4.05	64.27	7.18	12.50	63.8
1999	12	206.09	5.60	110.90	12.80	19.18	58.1
2000	1	204.62	2.98	102.14	7.51	12.72	62.0
2000	2	197.26	3.82	83.11	6.71	10.49	65.5
2000	3	195.14	2.52	70.06	4.12	9.60	69.3
2000	4	278.03	3.00	69.06	3.67	8.30	76.8
2000	5	270.43	2.62	68.80	5.23	8.69	76.0
2000	6	216.39	1.75	51.43	4.39	8.90	76.5
2000	7	173.83	0.68	37.59	1.90		81.2
2000	8	148.46	0.53	32.48	2.26		80.8
2000	9	119.03	0.44	29.95	2.65		78.3
2000	10	114.26	0.97	33.68	3.76	5.88	72.1
2000	11	131.77	1.28	36.34	3.27	8.44	72.8
2000	12	145.19	1.23	46.23	3.06	8.25	71.2
2001	1	133.23	1.46	36.95	2.71	6.40	73.7
2001	2	130.53	1.36	36.12	1.63	6.31	74.2
2001	3	125.57	2.06	36.70	1.13	4.73	73.8
2001	4	121.35	2.56	42.62	2.06	5.27	69.8
2001	5	144.02	2.29	42.68	4.71	5.22	72.4
2001	6	136.82	1.22	32.72	2.23	4.10	77.3
2001	7	90.28	0.59	22.96	1.60	3.55	75.9
2001	8	104.44	0.44	25.28	1.50	3.19	77.4

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RIVER MILE		146.1	120.5	102	87.5	68	
YEAR	MONTH	BONNEVILLE (kcfs)	SANDY (kcfs)	WILLAMETTE (kcfs)	LEWIS (kcfs)	COWLITZ (kcfs)	Q_{bon}/Q_{total} (%)
2001	9	86.78	0.34	23.11	2.50	3.06	74.9
2001	10	89.55	0.74	25.13	2.23	3.36	74.0
2001	11	112.20	2.74	48.41	6.22	9.58	62.6
2001	12	123.99	5.48	113.31	10.95	21.00	45.1
2002	1	143.41	3.41	97.19	9.12	18.15	52.9
2002	2	148.75	2.76	68.39	6.95	10.91	62.6
2002	3	132.19	2.87	66.45	6.11	11.40	60.4
2002	4	226.24	5.22	73.76	6.45	11.96	69.9
2002	5	244.22	2.64	57.05	4.93	9.98	76.6
2002	6	322.15	2.10	72.20	4.21	11.12	78.2
2002	7	233.06	0.87	47.62	2.17	6.26	80.4
2002	8	158.38	0.51	32.28	1.36	4.56	80.4
2002	9	105.02	0.38	27.24	1.35	4.74	75.7
2002	10	104.96	0.33	26.47	2.03	4.87	75.7
2002	11	126.84	0.46	34.13	2.97	3.89	75.4
2002	12	119.71	0.71	55.76	4.66	5.85	64.1
2003	1	124.95	3.70	85.97	9.31	11.43	53.1
2003	2	139.80	3.60	79.80	9.69	15.65	56.2
2003	3	165.87	5.00	91.02	9.10	14.91	58.0
2003	4	213.70	3.23	78.99	4.54	12.69	68.2
2003	5	258.55	1.93	59.13	3.24	7.15	78.3
2003	6	261.72	0.91	52.75	2.21	4.72	81.2
2003	7	166.09	0.53	31.73	1.33	3.70	81.7
2003	8	152.40	0.39	29.99	1.25	3.12	81.4
2003	9	95.49	0.39	25.08	1.72	3.21	75.9
2003	10	106.54	0.56	28.80	2.56	5.26	74.1
2003	11	125.84	1.45	35.10	4.73	8.12	71.8
2003	12	139.12	3.57	86.92	6.99	14.60	55.4
2004	1	142.57	4.40	98.82	6.72	12.96	53.7
2004	2	138.71	2.88	81.87	7.53	11.65	57.2
2004	3	149.84	2.72	51.18	4.95	9.29	68.7
2004	4	177.69	1.90	46.56	2.23	6.98	75.5
2004	5	244.07	2.13	52.74	2.65	5.52	79.5
2004	6	245.92	1.97	52.43	3.73	5.70	79.4
2004	7	167.88	0.66	30.26	1.59	4.20	82.1
2004	8	151.12	0.72	31.38	1.69	3.73	80.1
2004	9	113.27	1.18	32.36	3.83	6.07	72.3
2004	10	110.82	1.34	35.79	4.18	7.35	69.5
2004	11	124.79	1.94	39.91	4.72	8.75	69.3
2004	12	153.71	2.76	61.14	5.21	13.17	65.1
2005	1	147.63	1.83	46.05	5.93	9.77	69.9
2005	2	143.78	1.28	37.34	3.69	6.00	74.8
2005	3	132.13		42.30	3.89	6.64	71.4
2005	4	148.08	2.22	56.83	4.79	7.65	67.4

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Table 1. Monthly Averaged Flows measured at Bonneville Dam and Tributaries on the Lower Columbia River, 1995-2005							
RIVER MILE		146.1	120.5	102	87.5	68	
YEAR	MONTH	BONNEVILLE (kcfs)	SANDY (kcfs)	WILLAMETTE (kcfs)	LEWIS (kcfs)	COWLITZ (kcfs)	Q_{bon}/Q_{total} (%)
2005	5	236.34	2.20	65.64	3.83	6.95	75.0
2005	6	197.89	1.62	48.65	2.52	5.55	77.2
2005	7	176.56	0.64	39.43	1.89	3.53	79.5
2005	8	137.79	0.41	32.47	1.76	3.20	78.5
2005	9	91.00	0.35	27.02	1.66	3.78	73.5

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Table 2. Summary of Hourly Columbia River Flows at Bonneville Dam During Fish Passage Season, April 15-August 31										
Year	n	Total River Flow Q_t (kcfs)				Spill Discharge Q_s (kcfs)				Qs/Qt (%)
		Avg	Max	Min	Std	Avg	Max	Min	Std	
1994	3336	163.5	267.6	70.0	47.3	66.1	187.8	0.0	31.4	40.4
1995	3334	218.9	359.5	70.9	60.8	85.6	235.5	0.0	30.3	39.1
1996	3336	301.3	459.8	115.4	88.0	137.0	322.6	46.2	62.5	45.5
1997	3336	356.7	575.2	155.4	121.2	178.5	448.0	0.0	93.1	50.0
1998	3336	242.0	453.7	96.0	84.2	99.5	230.9	0.0	43.8	41.1
1999	3336	277.5	400.5	150.4	58.9	97.7	174.0	49.5	28.6	35.2
2000	3332	216.6	393.8	96.2	64.7	91.6	177.7	46.9	19.7	42.3
2001	3336	118.9	202.2	65.7	29.9	19.9	51.1	0.0	24.2	16.7
2002	3336	242.8	404.1	109.7	66.5	117.7	248.7	0.0	35.5	48.5
2003	3336	212.0	369.4	103.3	59.5	106.9	170.1	65.9	32.8	50.4
2004	3336	201.6	332.7	105.4	50.4	86.4	180.0	48.7	29.7	42.9
2005	3336	183.2	325.1	100.9	45.2	85.1	163.9	0.0	24.0	46.5
95-05	40026	227.9	575.2	65.7	23.9	97.7	448.0	0.0	20.6	42.8

N = number of observation.
Avg = Average
Max = maximum
Min = minimum
Std = standard deviation

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Table 3. Summary of Hourly Columbia River Flows at Bonneville Dam Outside of the Fish Passage Season, Sept 1 – April 14											
Year	n	Total River Flow Q_t (kcfs)				Spill Discharge Q_s (kcfs)					
		avg	max	min	std	avg	max	min	std	Qs/Qt	Days Q_s>10
1994	5423	117.3	194.0	69.9	32.0	2.5	119.1	0.0	14.3	2.1	7
1995	5309	170.9	337.6	70.6	58.2	11.9	294.2	0.0	33.3	6.9	40
1996	5415	223.5	442.3	80.2	92.8	51.1	364.5	0.0	72.8	22.8	98
1997	5422	222.9	434.3	85.6	75.0	34.4	249.5	0.0	50.3	15.4	97
1998	5422	157.0	327.8	72.0	43.1	4.2	129.2	0.0	16.5	2.7	18
1999	5422	196.6	343.5	82.0	54.3	11.2	266.7	0.0	33.2	5.7	41
2000	5445	162.8	319.8	75.8	46.0	4.9	146.6	0.0	21.5	3.0	16
2001	5423	115.0	221.8	68.8	26.4	1.3	50.5	0.0	4.0	1.1	3
2002	5423	128.5	266.8	69.7	29.8	3.0	139.4	0.0	12.6	2.4	9
2003	5423	132.1	256.4	68.4	37.4	2.2	134.2	0.0	6.8	1.7	4
2004	5447	134.7	247.8	70.1	30.7	2.9	115.6	0.0	8.3	2.2	7
2005	5423	126.8	228.4	69.7	27.7	1.1	9.0	0.0	1.1	0.9	0
95-05	64997	157.4	442.3	68.4	20.8	10.9	364.5	0.0	21.2	6.9	

N = number of observation.
Avg = Average
Max = maximum
Min = minimum
Std = standard deviation

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Table 4. Monthly Averaged Total Dissolved Gas Saturations (%) at Lower Columbia River Water Quality Gauges, 1995-2005							
RIVER MILE		146.1	140	140	122	77	42
YEAR	MONTH	BON	SKAW	WRNO	CWMW	KLAW	WANO
1995	3	107.8	108.7	106.7	106.4	106.1	100.5
1995	4	107.4	113.2	111.9	108.2	108.7	103.4
1995	5	112.3	117.7	117.9	115.7	115.1	109.1
1995	6	111.2	116.7	115.9	114.7	113.6	111.0
1995	7	109.1	115.7	115.8	114.4	112.6	109.5
1995	8	107.8	116.4	114.4	115.0	111.5	108.2
1995	9	103.1	102.5	100.9	101.0	103.5	102.4
1995	10	99.5	100.0	99.8	101.2		100.6
1995	11	100.1		101.0	101.5		102.1
1995	12	102.6		112.0	108.3		109.5
1996	1	100.9		101.4	102.5		105.5
1996	3	117.2		119.9	120.7		113.8
1996	4	117.7		119.1	120.5		113.1
1996	5	119.0	121.5	122.8	122.3	121.1	115.5
1996	6	121.1	125.1	125.7	124.5	121.7	118.4
1996	7	115.5	118.6	117.3	116.4	114.2	113.4
1996	8	110.7	117.1	116.0	113.7	111.4	108.9
1996	9	103.3	104.2	104.4	102.9	104.3	104.1
1996	12	98.1		98.6			
1997	1	111.0		115.7			
1997	2	113.2		116.3			
1997	3	111.1	114.0	114.8	114.5	111.5	110.6
1997	4	114.5	116.8	118.0	116.6	114.1	112.1
1997	5	124.4	127.7	129.2	127.1	124.1	120.3
1997	6	124.7	125.7	126.5	125.8	126.2	122.2
1997	7	114.4	116.8	117.4	115.4	113.5	110.4
1997	8	112.0	119.5	115.8	116.7	112.7	108.1
1997	9	102.0	103.8	102.7	102.2	104.1	103.4

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Table 4. Monthly Averaged Total Dissolved Gas Saturations (%) at Lower Columbia River Water Quality Gauges, 1995-2005							
RIVER MILE		146.1	140	140	122	77	42
YEAR	MONTH	BON	SKAW	WRNO	CWMW	KLAW	WANO
1997	10	99.6		101.4			
1997	11	99.1		100.8			
1997	12	99.3		100.4			
1998	1	99.0		100.1			
1998	2	101.0		102.5	101.9		
1998	3	104.4	106.1	107.2	106.1	106.6	106.3
1998	4	106.7	108.8	107.7	108.0	106.8	105.9
1998	5	113.8	118.3	118.9	116.9	114.6	111.0
1998	6	113.3	118.1	118.7	116.8	114.5	110.4
1998	7	109.4	116.1	115.4	114.0	110.6	107.8
1998	8	106.7	117.8	114.1	113.4	109.3	105.4
1998	9	100.3	103.3	103.1	103.8	103.6	102.4
1998	10	97.9		98.9			
1998	11	97.8		98.6			
1998	12	97.6		99.2			
1999	1	99.5		101.0			
1999	2	101.1	102.5	102.8			
1999	3	104.4	108.7	109.0	109.7		
1999	4	109.6	111.7	113.0	111.2		
1999	5	114.6	116.1	117.7	116.1		
1999	6	113.6	116.7	118.3	117.5		
1999	7	112.0	114.6	113.9	114.3		
1999	8	110.9	116.2	113.5	113.4		
1999	9	101.9	102.8	102.3	103.3		
1999	10	98.5		100.7			
1999	11	98.9		99.7			
1999	12	99.5		100.4			
2000	1	99.9		100.4			
2000	2	102.5	102.2	102.5	102.1		
2000	3	102.6	104.9	106.6	105.2		
2000	4	108.7	111.7	112.1	111.9		

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Table 4. Monthly Averaged Total Dissolved Gas Saturations (%) at Lower Columbia River Water Quality Gauges, 1995-2005							
RIVER MILE		146.1	140	140	122	77	42
YEAR	MONTH	BON	SKAW	WRNO	CWMW	KLAW	WANO
2000	5	112.5	116.5	116.0	115.6		
2000	6	111.3	117.3	116.6	115.1		
2000	7	107.3	118.4	116.1	114.6		
2000	8	104.6	116.7	114.1	113.0		
2000	9	100.1	97.0	101.7	102.7		
2000	10	99.1		100.6			
2000	11	98.6		99.8			
2000	12	98.7		99.6			
2001	1	99.8		100.6			
2001	2	102.5	103.9	102.6	103.8		
2001	3	104.8	105.4	105.3	105.4		
2001	4	103.8	104.2	104.8	105.1		
2001	5	106.0	107.6	109.9	108.8		
2001	6	104.2	106.3	108.5	107.5		
2001	7	100.4	101.8	102.1	102.7		
2001	8	102.9	108.1	110.6	107.5		
2001	9	100.2	100.8	101.5	101.8		
2001	10	99.3		100.6			
2001	11	99.2		100.8			
2001	12	98.9		99.4			
2002	1	99.7		100.2			
2002	2	101.6	103.7	102.0	104.6		
2002	3	102.8	102.8	104.0	103.5		
2002	4	109.5		112.2	110.7		
2002	5	113.0		116.7	114.6		
2002	6	114.9		118.6	116.7		
2002	7	110.8		116.0	113.8		
2002	8	107.1		115.5	111.7		
2002	9	100.2		101.8	101.9		
2002	10	99.6		101.1	99.5		
2002	11	99.1		100.5			

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Table 4. Monthly Averaged Total Dissolved Gas Saturations (%) at Lower Columbia River Water Quality Gauges, 1995-2005

RIVER MILE		146.1	140	140	122	77	42
YEAR	MONTH	BON	SKAW	WRNO	CWMW	KLAW	WANO
2002	12	97.9		99.2			
2003	1	99.7		100.8			
2003	2	100.9		101.8			
2003	3	101.9		103.2	103.1		
2003	4	107.4		110.9	108.9		
2003	5	113.4		116.8	114.1		
2003	6	111.8		116.0	113.2		
2003	7	107.2		112.6	109.5		
2003	8	105.3		111.7	109.0		
2003	9	100.5		101.5	103.2		
2003	10	99.2		100.3			
2003	11	98.5		99.3			
2003	12	98.5		98.8			
2004	1	98.7		98.8			
2004	2	101.7		101.8	103.1		
2004	3	104.2		105.2	105.2		
2004	4	108.4		110.2	109.2		
2004	5	111.4		114.1	112.2		
2004	6	110.7		113.0	111.2		
2004	7	106.2		112.1	110.0		
2004	8	104.7		114.2	112.5		
2004	9	100.3		102.2	101.9		
2004	10	99.1		101.3			
2004	11	98.6		100.3			
2004	12	98.5		99.3			
2005	1	98.8		99.2			
2005	2	101.5		101.9	103.4		
2005	3	105.0		106.0	105.8		
2005	4	108.1		110.5	109.3		
2005	5	112.0		114.4	112.3		
2005	6	107.9		114.5	111.2		

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Table 4. Monthly Averaged Total Dissolved Gas Saturations (%) at Lower Columbia River Water Quality Gauges, 1995-2005							
RIVER MILE		146.1	140	140	122	77	42
YEAR	MONTH	BON	SKAW	WRNO	CWMW	KLAW	WANO
2005	7	107.4		115.2	111.8		
2005	8	105.1		115.1	111.3		
2005	9	100.8		103.2	103.6		

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Table 5. Statistical Summary of Total Dissolved Gas Saturation at Fixed Monitoring Stations in the Lower Columbia River during the Fish Passage Season, April 15-August 31, 1994-2005

Station	year	n	TDG Saturation (%)				Frequency of Exceeding TDG Saturation (fraction)								
			avg	max	min	std	100	105	110	115	120	125	130	135	140
BON	1994	2461	105.4	118.6	97.5	4.5	0.89	0.51	0.16	0.02	0.00	0.00	0.00	0.00	0.00
BON	1995	3004	109.2	119.0	103.1	3.1	1.00	0.94	0.37	0.05	0.00	0.00	0.00	0.00	0.00
BON	1996	3326	117.0	127.4	103.5	4.8	1.00	0.99	0.89	0.72	0.29	0.03	0.00	0.00	0.00
BON	1997	3262	118.2	130.6	105.9	6.2	1.00	1.00	0.93	0.58	0.44	0.18	0.00	0.00	0.00
BON	1998	3325	110.3	122.4	102.1	4.3	1.00	0.89	0.52	0.15	0.02	0.00	0.00	0.00	0.00
BON	1999	3297	110.2	119.6	99.0	4.4	0.98	0.85	0.62	0.12	0.00	0.00	0.00	0.00	0.00
BON	2000	3224	108.9	118.2	101.0	4.1	1.00	0.81	0.39	0.08	0.00	0.00	0.00	0.00	0.00
BON	2001	3321	103.0	112.8	97.9	2.8	0.89	0.22	0.02	0.00	0.00	0.00	0.00	0.00	0.00
BON	2002	3329	111.2	119.0	102.7	3.7	1.00	0.95	0.66	0.17	0.00	0.00	0.00	0.00	0.00
BON	2003	3322	109.2	118.7	102.5	4.0	1.00	0.82	0.43	0.09	0.00	0.00	0.00	0.00	0.00
BON	2004	3334	108.3	117.3	101.4	3.4	1.00	0.79	0.37	0.01	0.00	0.00	0.00	0.00	0.00
BON	2005	3336	108.2	117.0	101.8	3.1	1.00	0.87	0.28	0.02	0.00	0.00	0.00	0.00	0.00
BON	95-05	36080	110.3	130.6	97.9	5.7	0.99	0.83	0.50	0.18	0.07	0.02	0.00	0.00	0.00
CCIW	2004	47	114.0	116.0	112.6	1.3	1.00	1.00	1.00	0.29	0.00	0.00	0.00	0.00	0.00
CCIW	2005	3327	115.6	121.1	97.4	2.1	1.00	1.00	1.00	0.45	0.03	0.00	0.00	0.00	0.00
WRNO	1994	3325	110.2	121.9	100.1	3.7	1.00	0.93	0.53	0.08	0.01	0.00	0.00	0.00	0.00
WRNO	1995	3013	115.1	120.7	107.8	2.5	1.00	1.00	0.97	0.53	0.01	0.00	0.00	0.00	0.00
WRNO	1996	3332	120.5	138.0	110.4	4.9	1.00	1.00	1.00	0.88	0.49	0.19	0.04	0.01	0.00
WRNO	1997	3318	123.0	143.0	108.1	8.1	1.00	1.00	1.00	0.85	0.51	0.45	0.24	0.09	0.01
WRNO	1998	3295	115.3	127.2	101.3	4.3	1.00	0.96	0.96	0.50	0.13	0.02	0.00	0.00	0.00
WRNO	1999	3256	115.2	121.4	108.1	2.8	1.00	1.00	0.98	0.51	0.04	0.00	0.00	0.00	0.00
WRNO	2000	3304	114.9	124.2	108.2	2.8	1.00	1.00	0.97	0.52	0.03	0.00	0.00	0.00	0.00
WRNO	2001	3313	106.7	116.9	90.7	5.2	0.96	0.50	0.38	0.04	0.00	0.00	0.00	0.00	0.00
WRNO	2002	3305	115.9	128.9	105.9	3.3	1.00	1.00	0.98	0.61	0.08	0.01	0.00	0.00	0.00
WRNO	2003	3316	113.8	129.0	107.1	3.3	1.00	1.00	0.86	0.41	0.00	0.00	0.00	0.00	0.00
WRNO	2004	3310	112.8	120.4	98.4	2.6	1.00	1.00	0.86	0.20	0.00	0.00	0.00	0.00	0.00
WRNO	2005	3324	114.5	121.6	109.4	2.0	1.00	1.00	1.00	0.38	0.01	0.00	0.00	0.00	0.00
WRNO	95-05	36086	115.3	143.0	90.7	5.8	1.00	0.95	0.90	0.49	0.12	0.06	0.03	0.01	0.00
SKAW	1994	2479	113.0	122.6	100.9	2.7	1.00	0.99	0.89	0.19	0.01	0.00	0.00	0.00	0.00

Table 5. Statistical Summary of Total Dissolved Gas Saturation at Fixed Monitoring Stations in the Lower Columbia River during the Fish Passage Season, April 15-August 31, 1994-2005

Station	year	n	TDG Saturation (%)				Frequency of Exceeding TDG Saturation (fraction)								
			avg	max	min	std	100	105	110	115	120	125	130	135	140
SKAW	1995	2899	115.6	126.2	108.0	3.2	1.00	1.00	0.97	0.57	0.08	0.00	0.00	0.00	0.00
SKAW	1996	2886	120.7	140.7	109.6	5.1	1.00	1.00	1.00	0.89	0.50	0.19	0.05	0.02	0.00
SKAW	1997	3299	122.8	143.5	106.5	7.3	1.00	1.00	0.98	0.86	0.59	0.39	0.19	0.07	0.01
SKAW	1998	3318	116.5	127.3	101.4	4.3	1.00	0.96	0.96	0.68	0.19	0.01	0.00	0.00	0.00
SKAW	1999	3324	115.1	121.5	106.2	2.4	1.00	1.00	0.99	0.52	0.02	0.00	0.00	0.00	0.00
SKAW	2000	3316	116.2	141.2	107.0	2.8	1.00	1.00	0.98	0.67	0.07	0.00	0.00	0.00	0.00
SKAW	2001	3330	104.9	123.0	97.9	3.7	0.94	0.46	0.11	0.00	0.00	0.00	0.00	0.00	0.00
SKAW	95-02	22372	115.9	143.5	97.9	6.9	0.99	0.92	0.85	0.59	0.20	0.08	0.03	0.01	0.00
CWMW	1994	1835	108.8	117.4	98.9	2.7	1.00	0.96	0.29	0.02	0.00	0.00	0.00	0.00	0.00
CWMW	1995	3013	113.2	121.6	90.4	3.0	1.00	1.00	0.87	0.27	0.01	0.00	0.00	0.00	0.00
CWMW	1996	3235	119.5	139.1	107.5	5.6	1.00	1.00	0.97	0.77	0.46	0.17	0.04	0.01	0.00
CWMW	1997	3193	121.6	140.2	106.6	7.4	1.00	1.00	0.99	0.76	0.51	0.39	0.16	0.03	0.00
CWMW	1998	3328	114.0	125.7	100.5	4.2	1.00	0.96	0.87	0.40	0.08	0.01	0.00	0.00	0.00
CWMW	1999	3289	114.4	121.8	104.3	2.8	1.00	1.00	0.96	0.43	0.02	0.00	0.00	0.00	0.00
CWMW	2000	3262	113.6	122.4	106.6	2.8	1.00	1.00	0.89	0.31	0.01	0.00	0.00	0.00	0.00
CWMW	2001	3326	105.6	117.2	97.9	3.7	0.98	0.51	0.13	0.01	0.00	0.00	0.00	0.00	0.00
CWMW	2002	3332	113.5	125.1	104.0	3.3	1.00	1.00	0.86	0.34	0.03	0.00	0.00	0.00	0.00
CWMW	2003	3327	110.9	127.8	102.9	3.8	1.00	0.96	0.60	0.15	0.01	0.00	0.00	0.00	0.00
CWMW	2004	3336	110.9	125.7	104.0	3.7	1.00	0.99	0.55	0.08	0.03	0.03	0.00	0.00	0.00
CWMW	2005	3319	111.4	118.9	105.6	2.5	1.00	1.00	0.67	0.08	0.00	0.00	0.00	0.00	0.00
CWMW	95-05	35960	113.5	140.2	90.4	5.8	1.00	0.95	0.76	0.33	0.11	0.05	0.02	0.00	0.00
KLAW	1994	3309	108.4	118.5	100.8	3.3	1.00	0.88	0.33	0.03	0.00	0.00	0.00	0.00	0.00
KLAW	1995	3329	111.3	117.0	103.5	2.3	1.00	0.99	0.70	0.04	0.00	0.00	0.00	0.00	0.00
KLAW	1996	2262	115.6	128.2	107.5	4.6	1.00	1.00	0.94	0.47	0.24	0.02	0.00	0.00	0.00
KLAW	1997	3242	118.3	132.8	105.9	6.7	1.00	1.00	0.95	0.54	0.45	0.20	0.05	0.00	0.00
KLAW	1998	3330	111.2	121.9	101.8	3.7	1.00	0.95	0.58	0.15	0.01	0.00	0.00	0.00	0.00
KLAW	95-98	12163	113.9	132.8	101.8	5.5	1.00	0.99	0.78	0.28	0.17	0.06	0.01	0.00	0.00
WANO	1994	3120	104.9	112.5	97.1	3.4	0.93	0.44	0.07	0.00	0.00	0.00	0.00	0.00	0.00
WANO	1995	2921	107.0	113.0	99.1	2.5	0.99	0.82	0.11	0.00	0.00	0.00	0.00	0.00	0.00
WANO	1996	3305	113.8	124.4	103.6	3.6	1.00	0.99	0.84	0.40	0.04	0.00	0.00	0.00	0.00

Table 5. Statistical Summary of Total Dissolved Gas Saturation at Fixed Monitoring Stations in the Lower Columbia River during the Fish Passage Season, April 15-August 31, 1994-2005																
Station	year	n	TDG Saturation (%)				Frequency of Exceeding TDG Saturation (fraction)									
			avg	max	min	std	100	105	110	115	120	125	130	135	140
WANO	1997	3324	114.0	127.5	102.7	6.3	1.00	0.99	0.57	0.47	0.24	0.02	0.00	0.00	0.00
WANO	1998	3324	107.7	115.9	100.9	3.1	1.00	0.79	0.24	0.01	0.00	0.00	0.00	0.00	0.00
WANO	95-98	12874	110.7	127.5	99.1	5.3	1.00	0.90	0.45	0.23	0.07	0.01	0.00	0.00	0.00

N = number of observation.
Avg = Average
Max = maximum
Min = minimum
Std = standard deviation

Figure 1. Bonneville Dam and the Columbia River during spillway releases.

Figure 2. Lower Columbia River and TDG fixed monitoring stations.

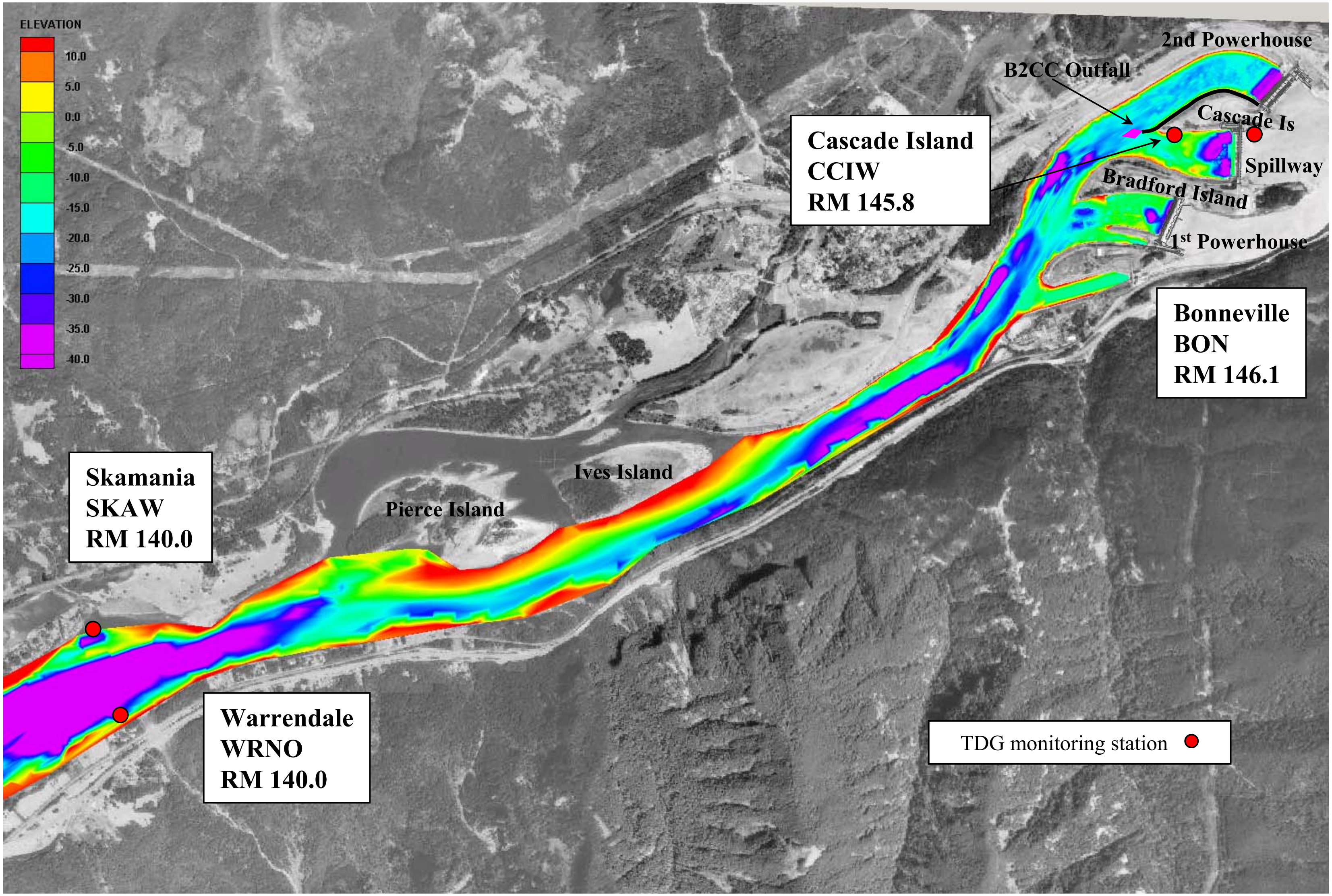


Figure 3. Columbia River Channel Elevations and TDG Fixed Monitoring Stations near Bonneville Dam.

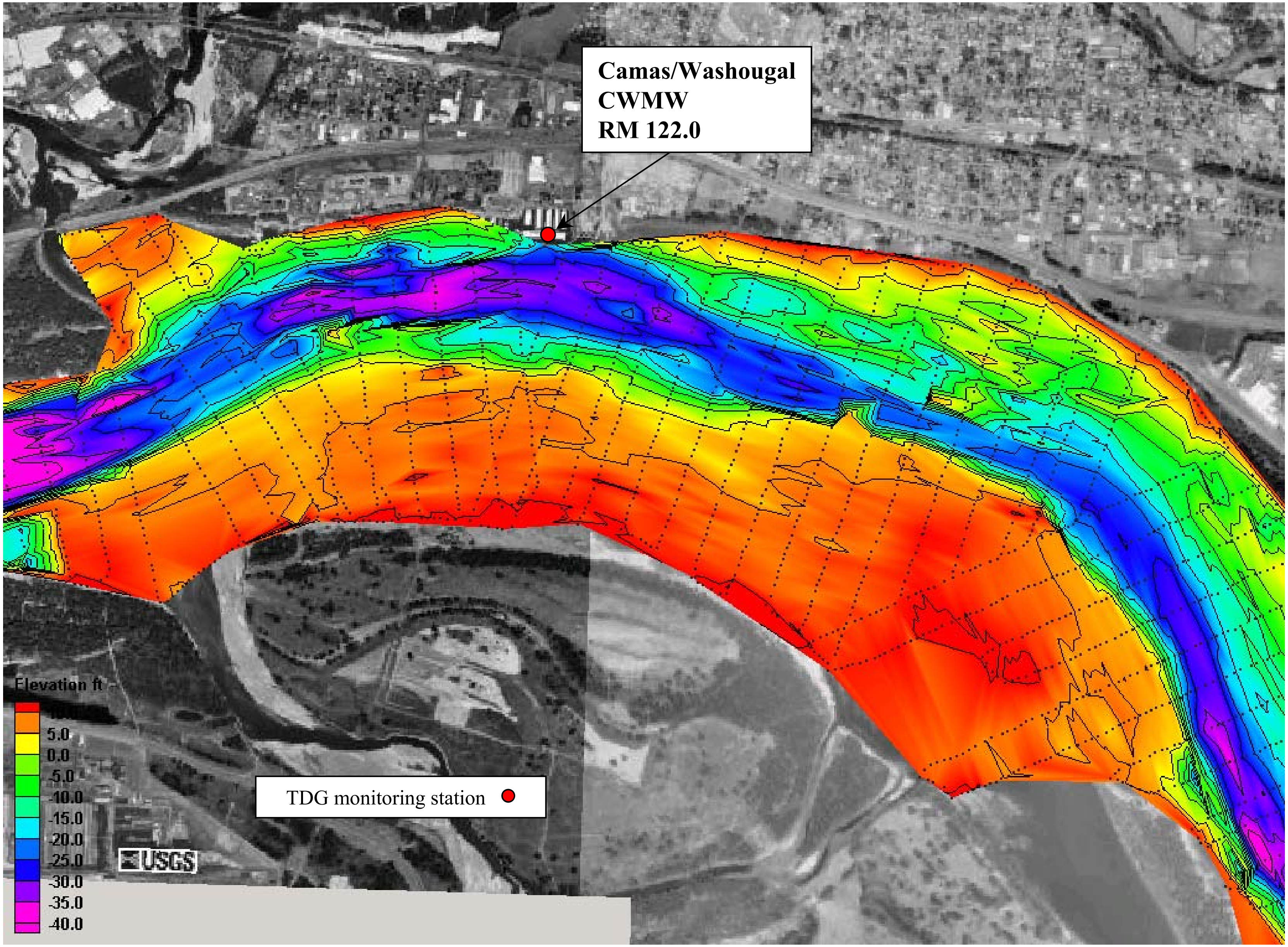


Figure 4. Columbia River Channel Elevations and TDG Fixed Monitoring Station near Camas/Washougal Washington.

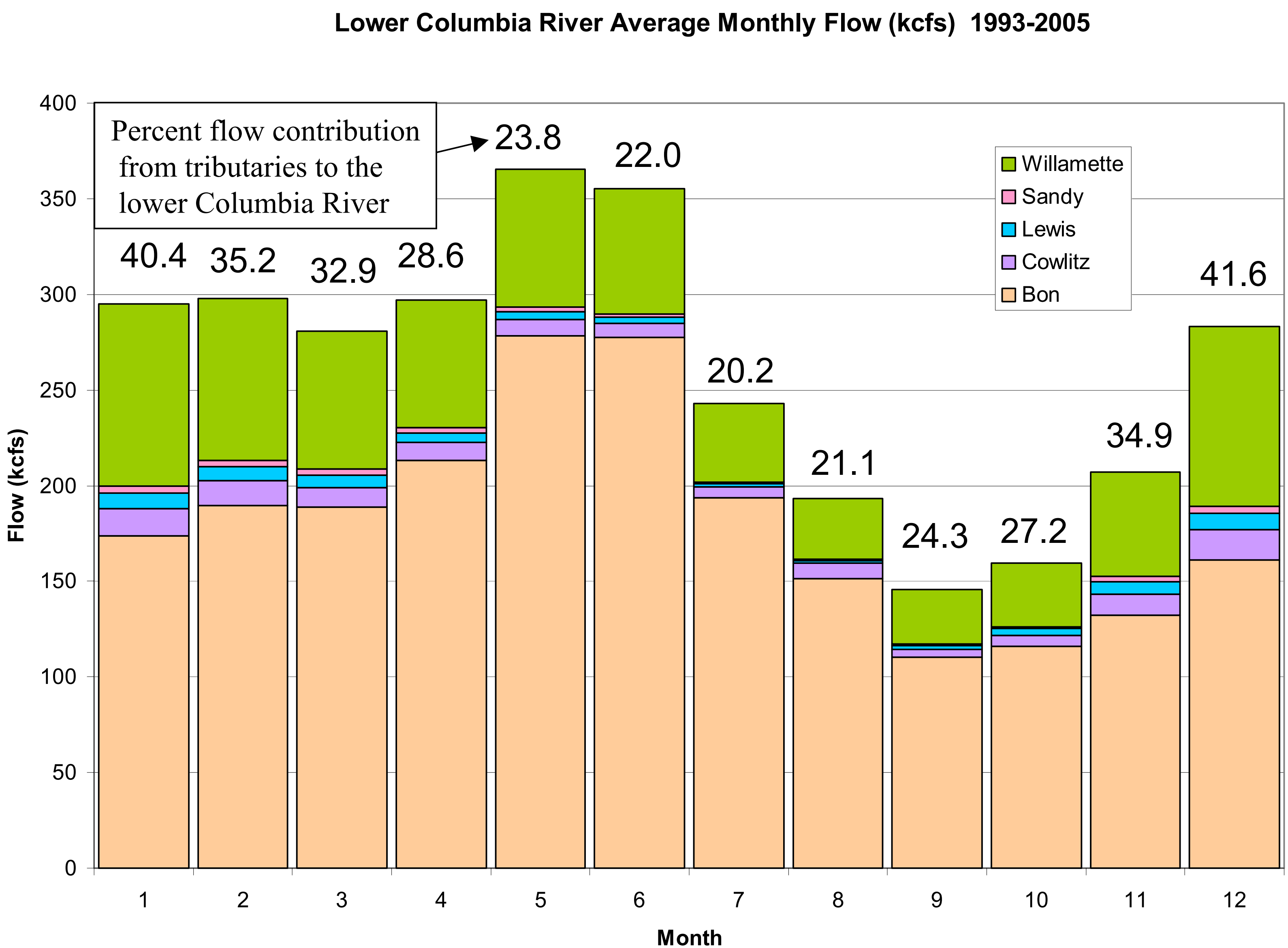


Figure 5. Lower Columbia River Average Monthly Flow Composition, 1993-2005

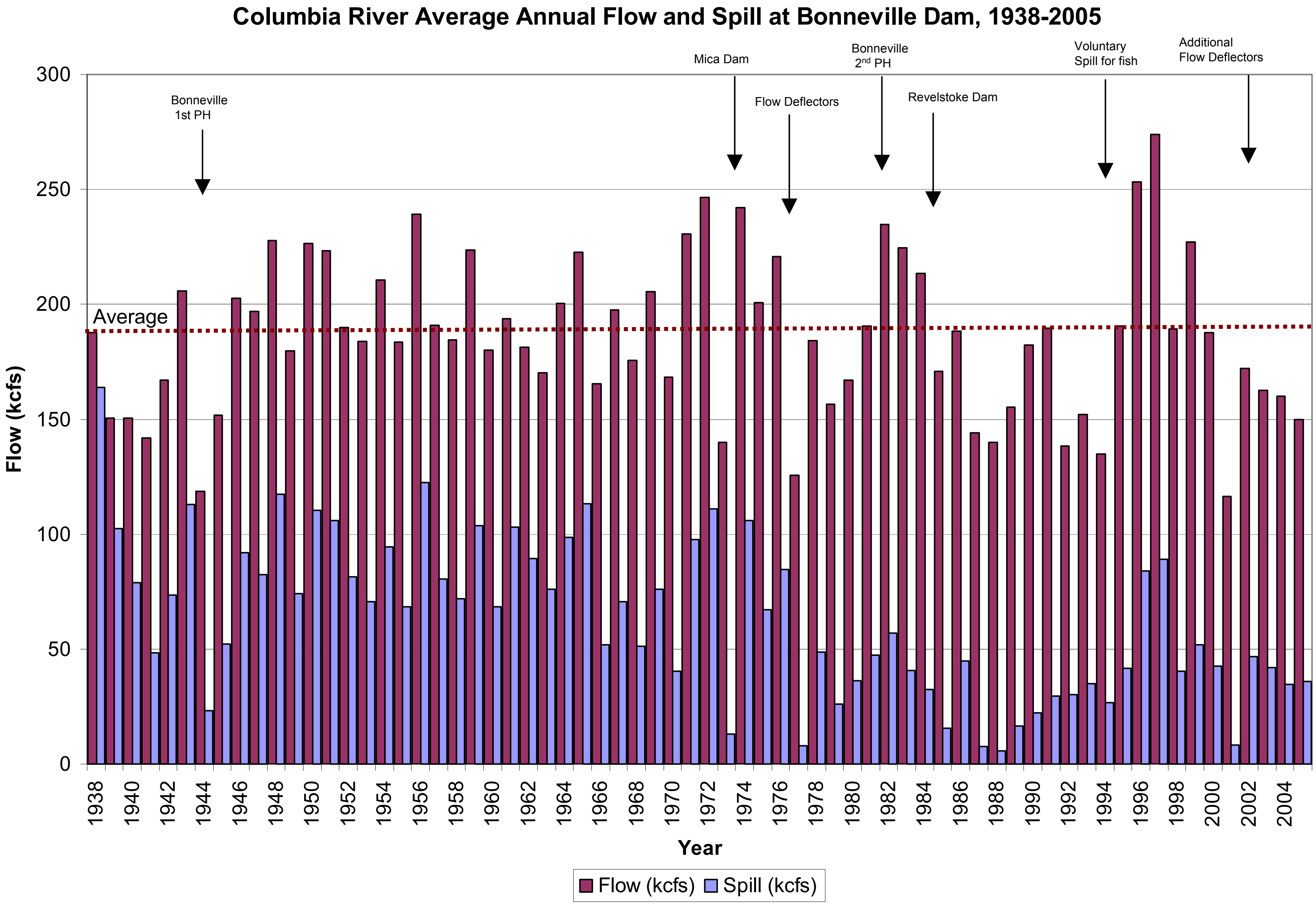


Figure 6. Average annual Columbia River Flow and spill at Bonneville Dam 1938-2005

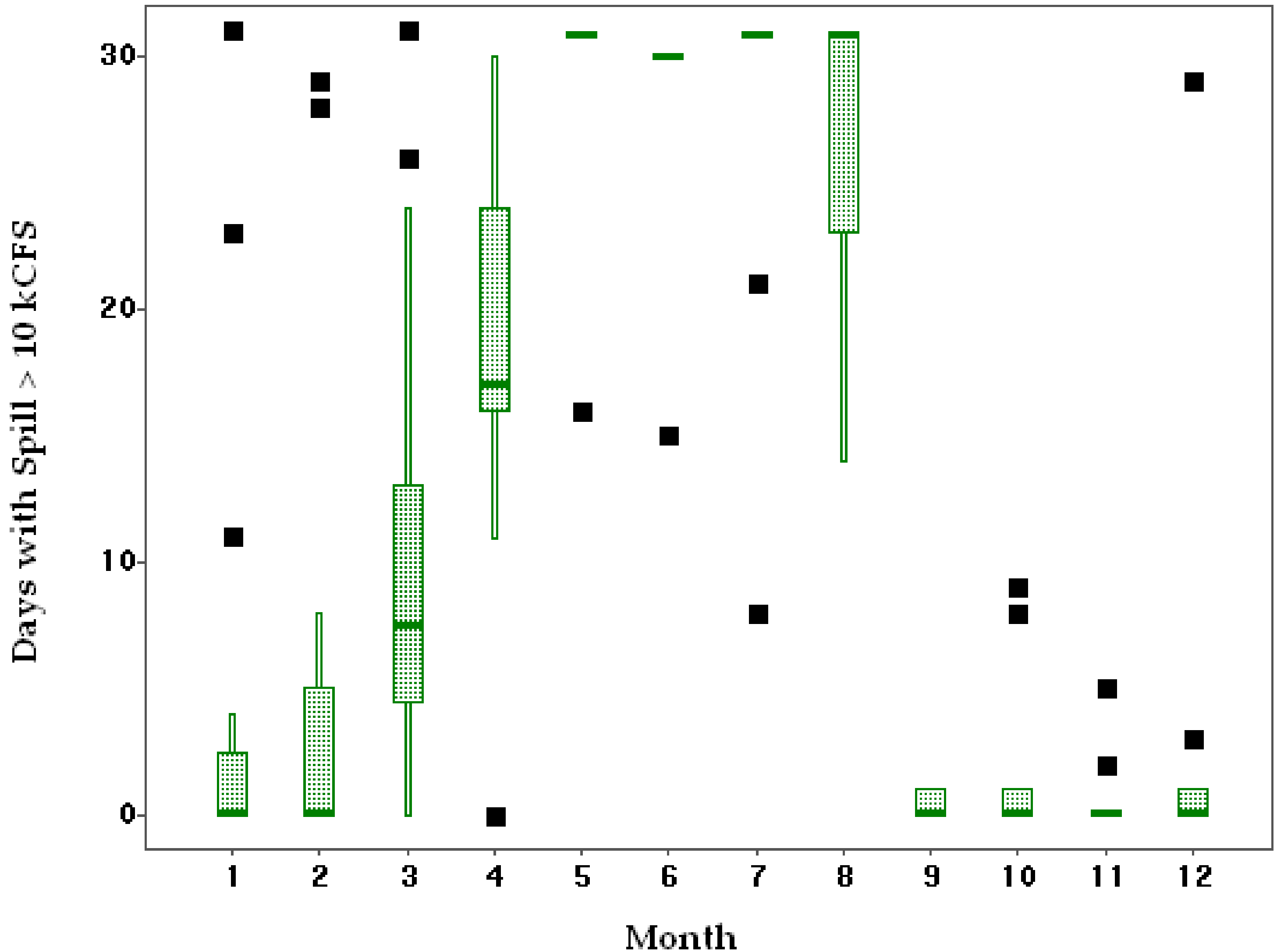


Figure 7. Number of days in a month where Bonneville spill was greater than 10 kcfs , 1990-2005.
(Grouped by year and month, percentiles 5, 25, 50, 75, 95 are shown)

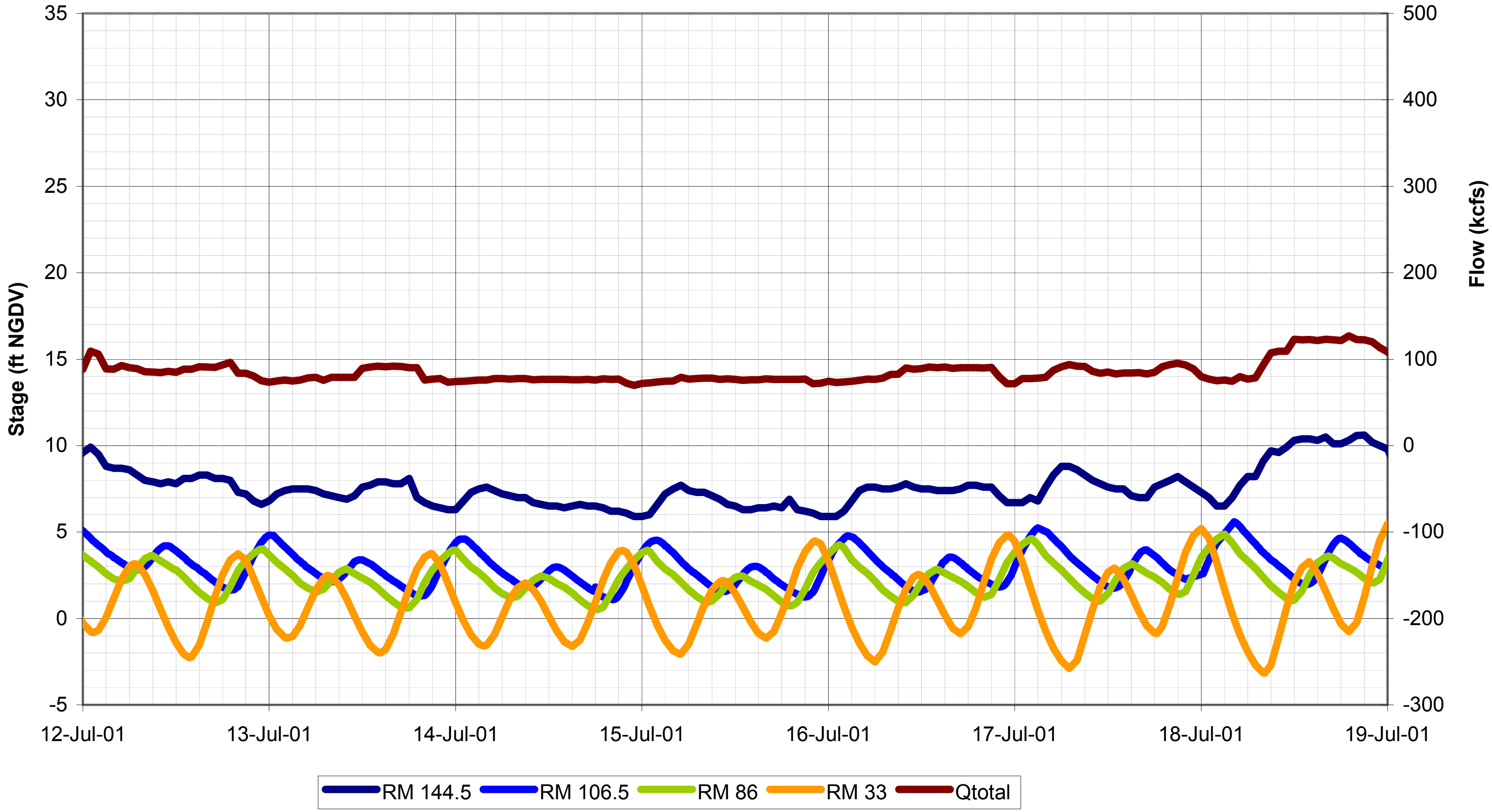


Figure 8. Bonneville Dam Flow and Columbia River Water Surface Elevation for July 12-18, 2001, Average Bonneville Flow = 85 kcfs.

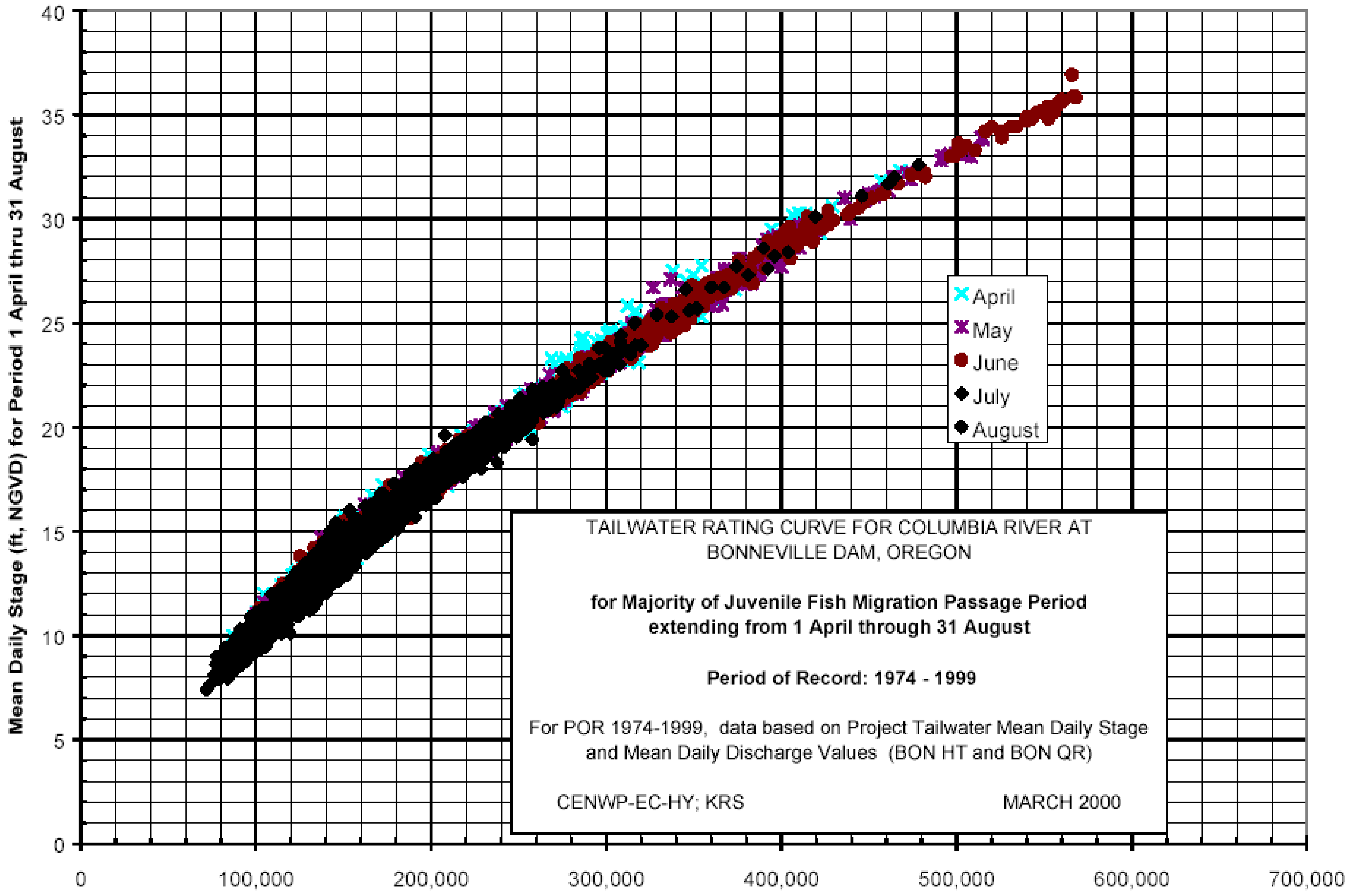


Figure 9. Tailwater Stage Rating Curve for Columbia River at Bonneville Dam 1 April-31 August

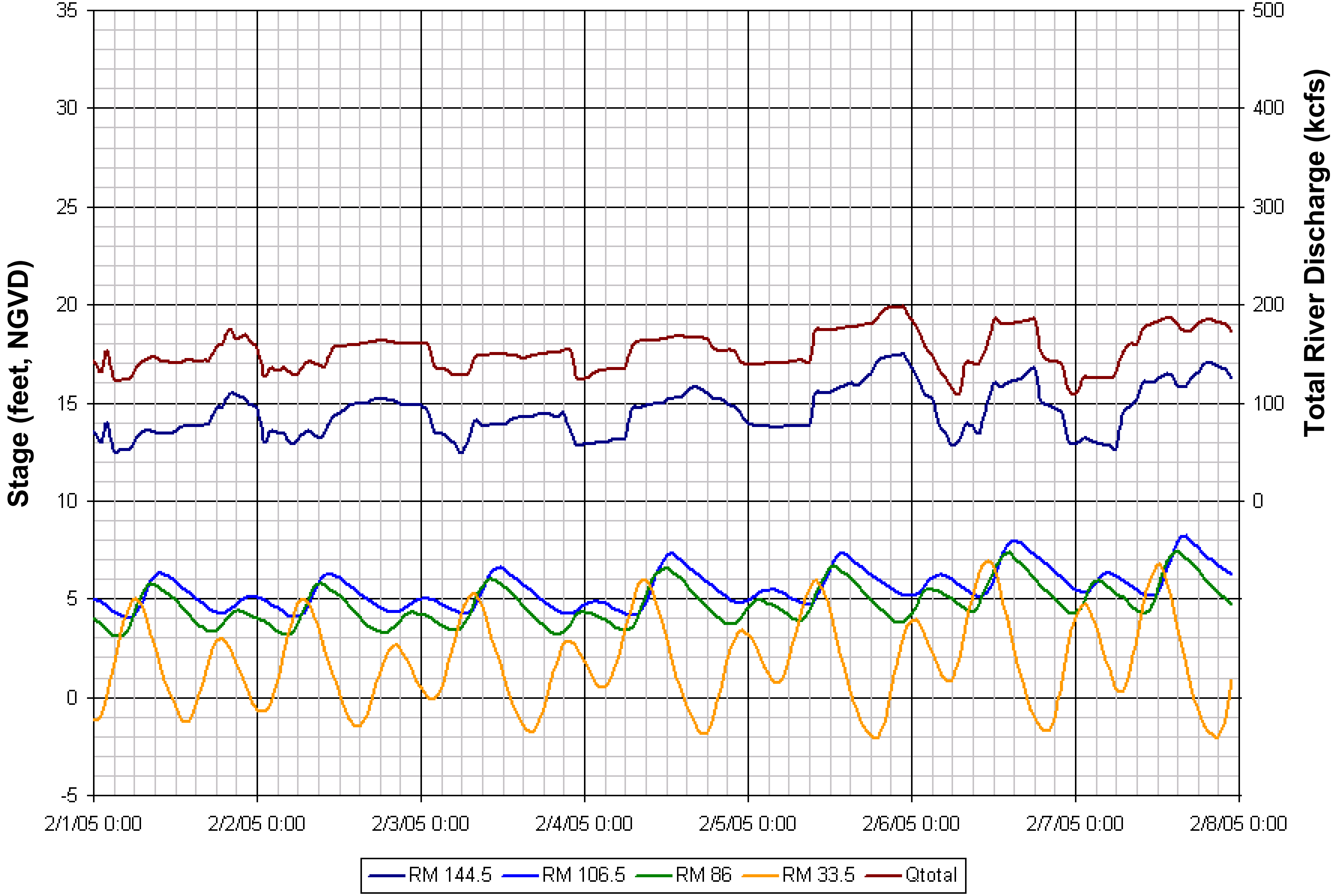


Figure 10. Bonneville Dam Flow and Columbia River Water Surface Elevation for February 1-7, 2005 Average Bonneville Flow = 150 kcfs.

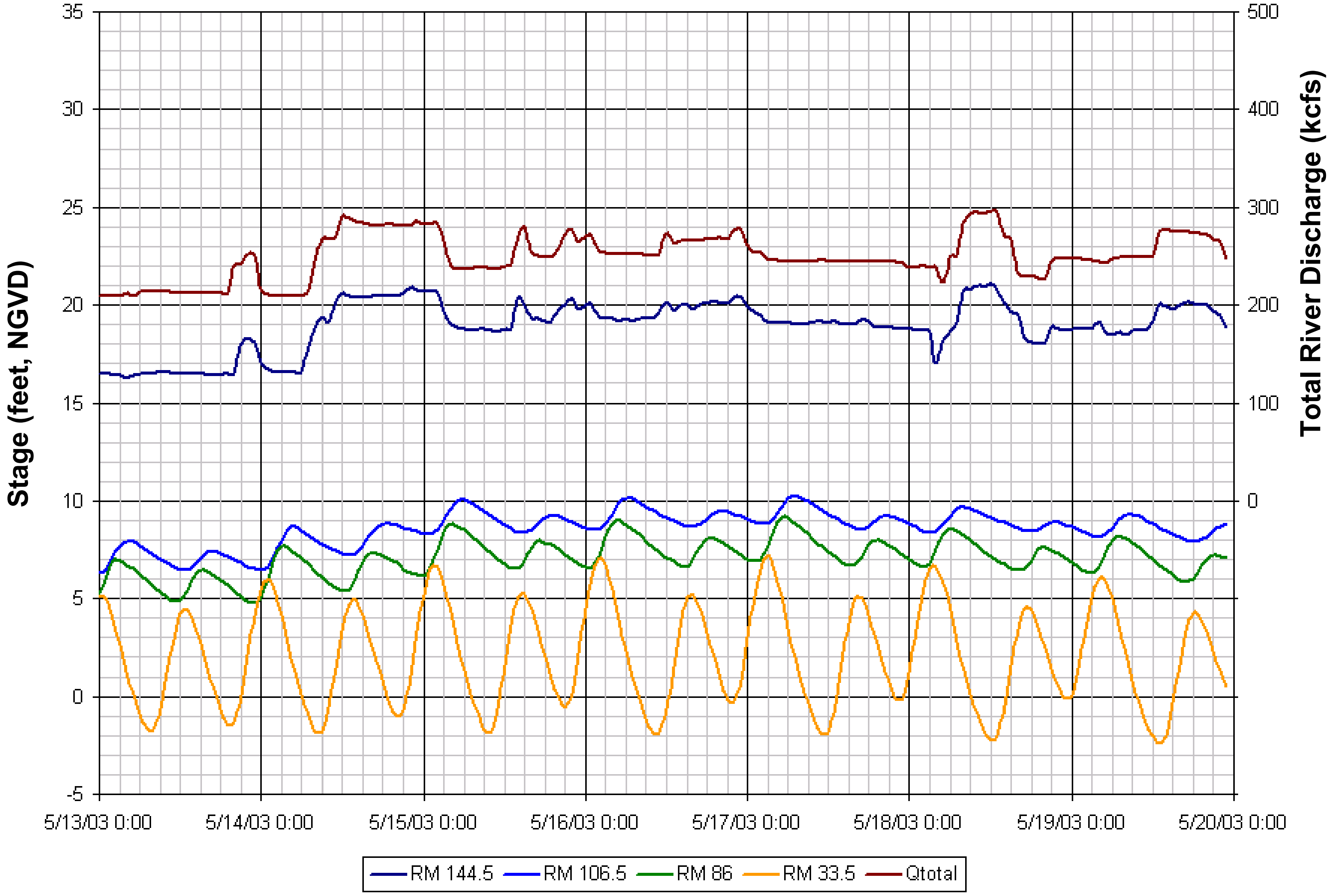


Figure 11. Bonneville Dam Flow and Columbia River Water Surface Elevation for May 13-19, 2003, Average Bonneville Flow = 250 kcfs

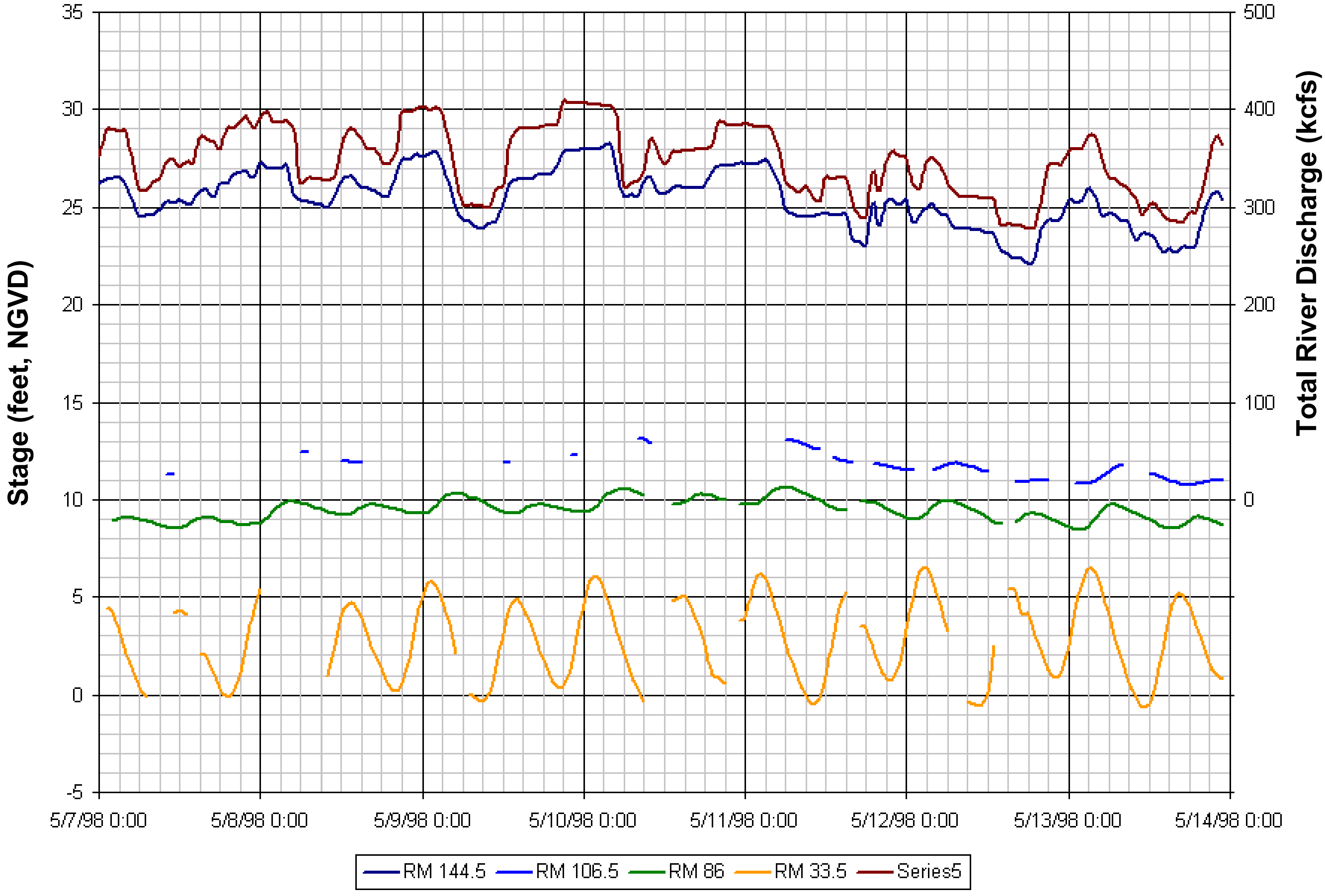


Figure 12. Bonneville Dam Flow and Columbia River Water Surface Elevation for May 7-13, 1996, Average Bonneville Flow = 348 kcfs

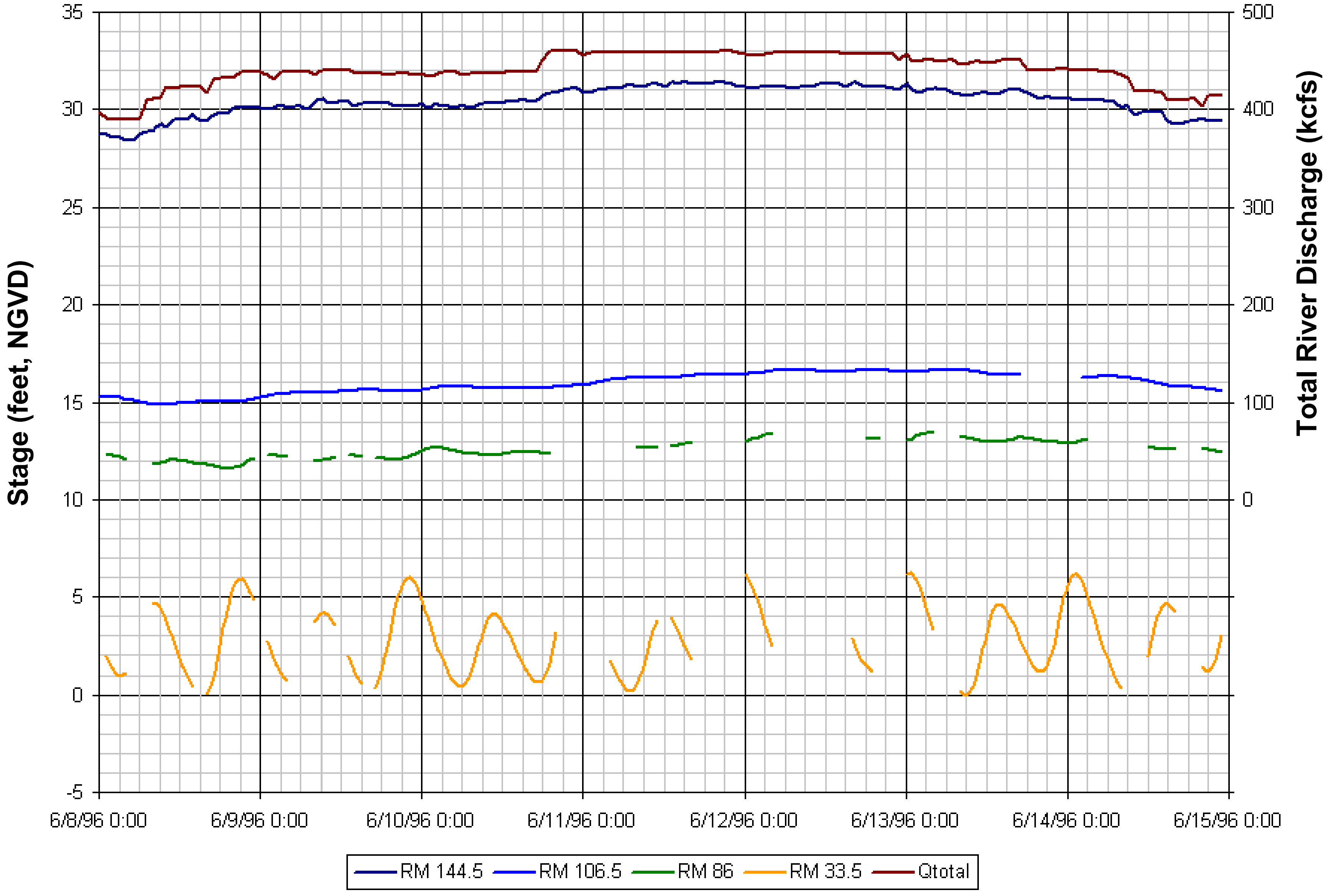


Figure 13. Bonneville Dam Flow and Columbia River Water Surface Elevation
for June 8-14, 1996 (Average Bonneville Flow = 441 kcfs)

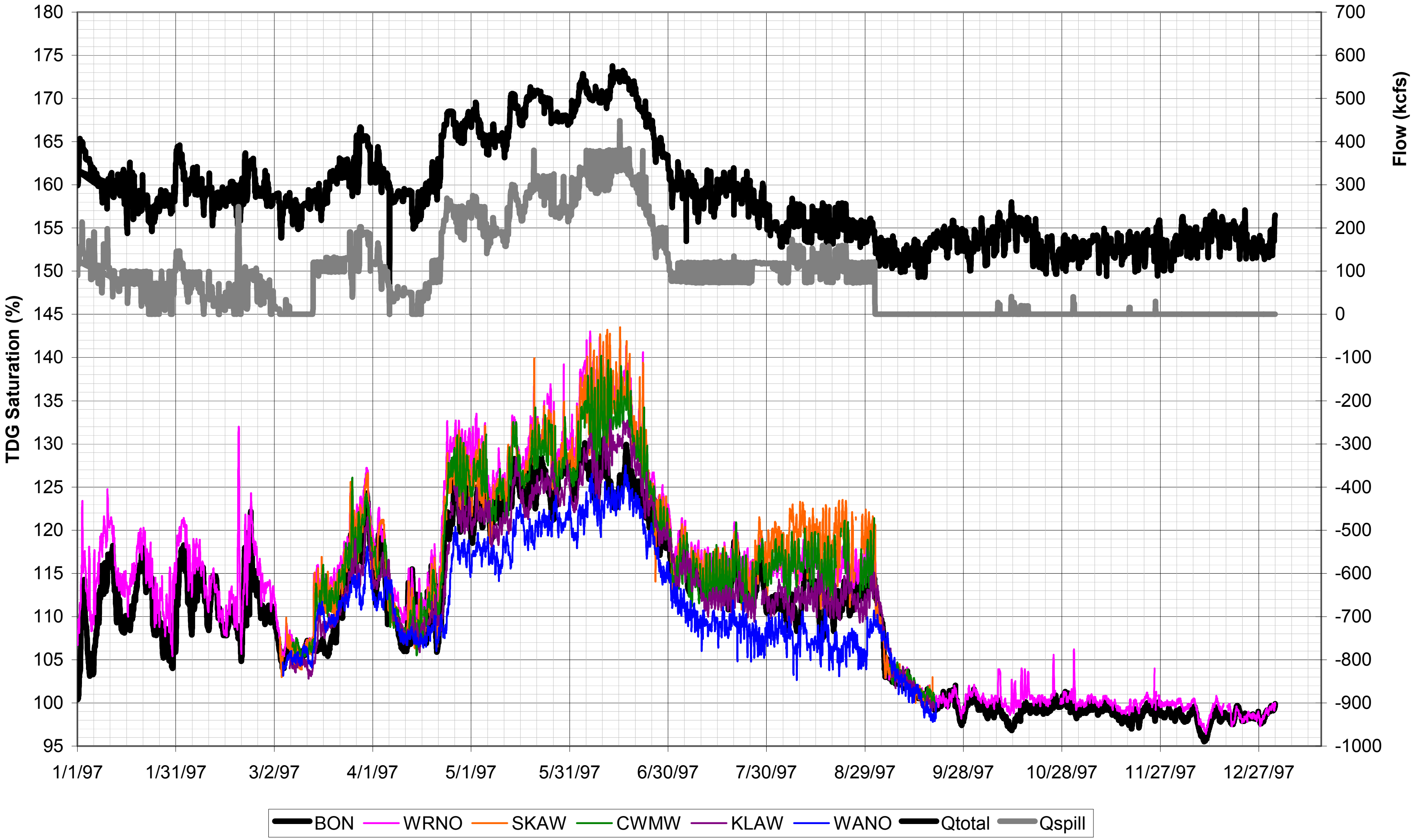


Figure 14. Bonneville Dam Flow and Columbia River Total Dissolved Gas Saturation, 1997.

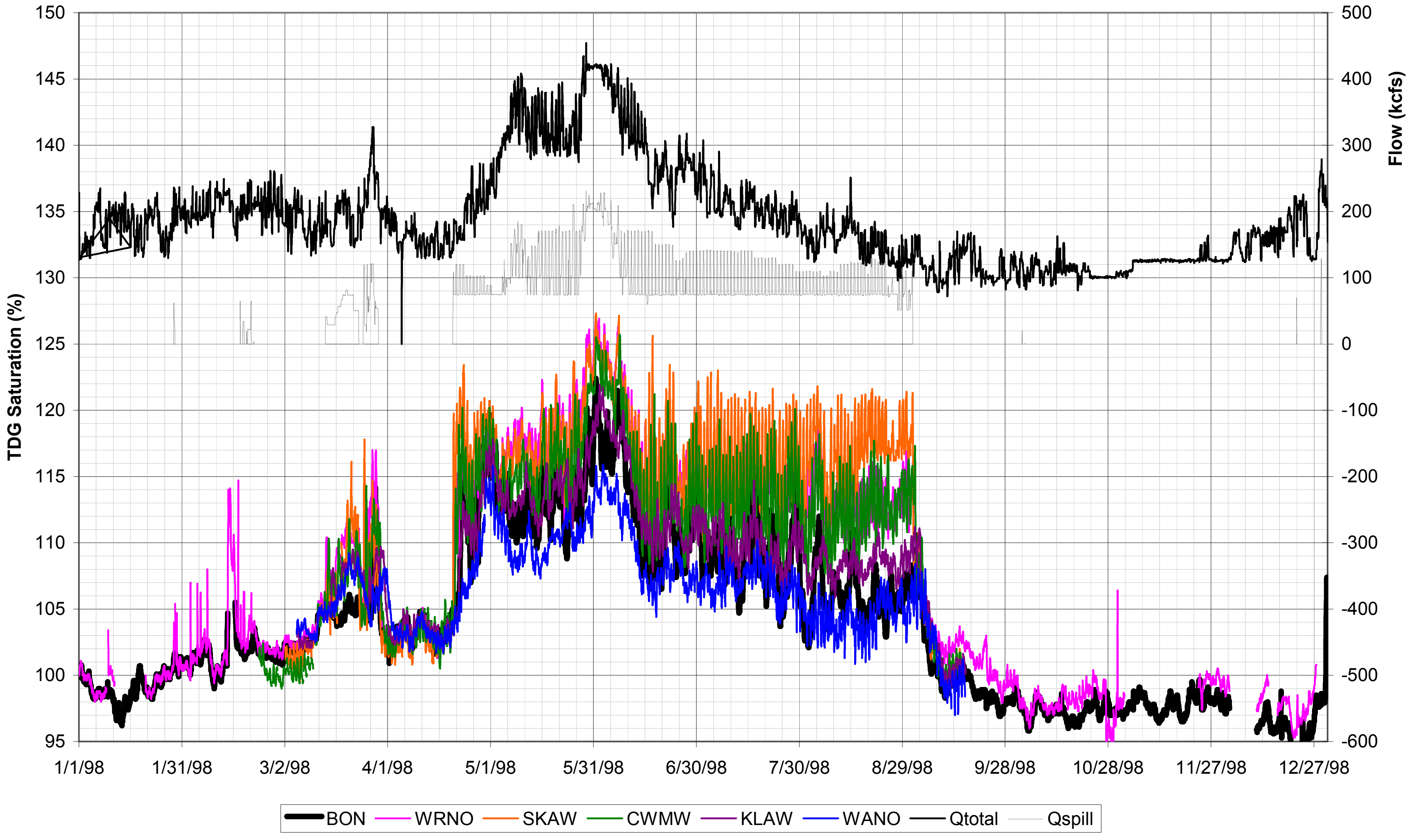


Figure 15. Bonneville Dam Flow and Columbia River Total Dissolved Gas Saturation, 1998.

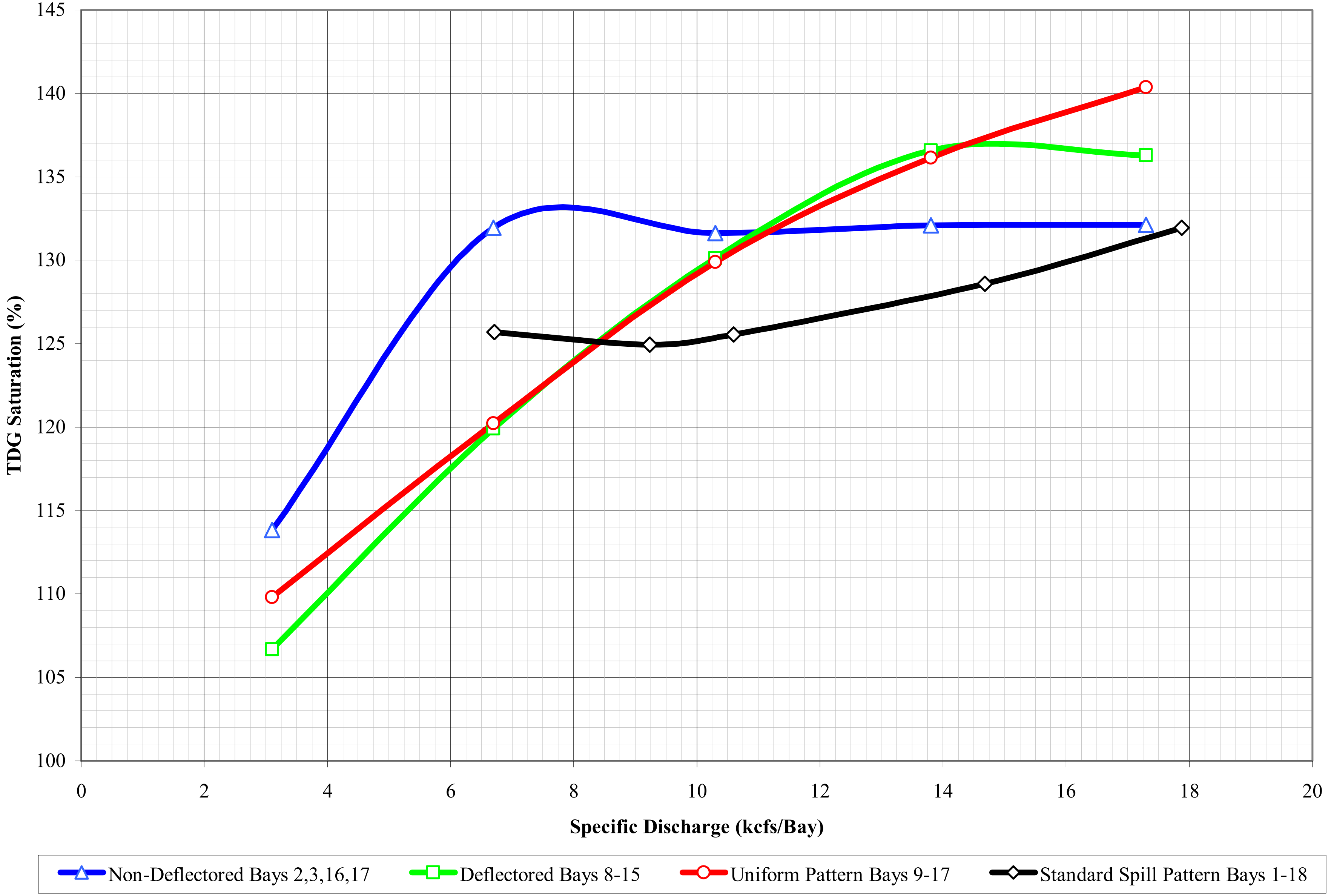


Figure 16. Average Total Dissolved Gas Saturation below Bonneville Spillway as a Function of Spill Pattern and Specific Discharge, February 1-4, 1999.

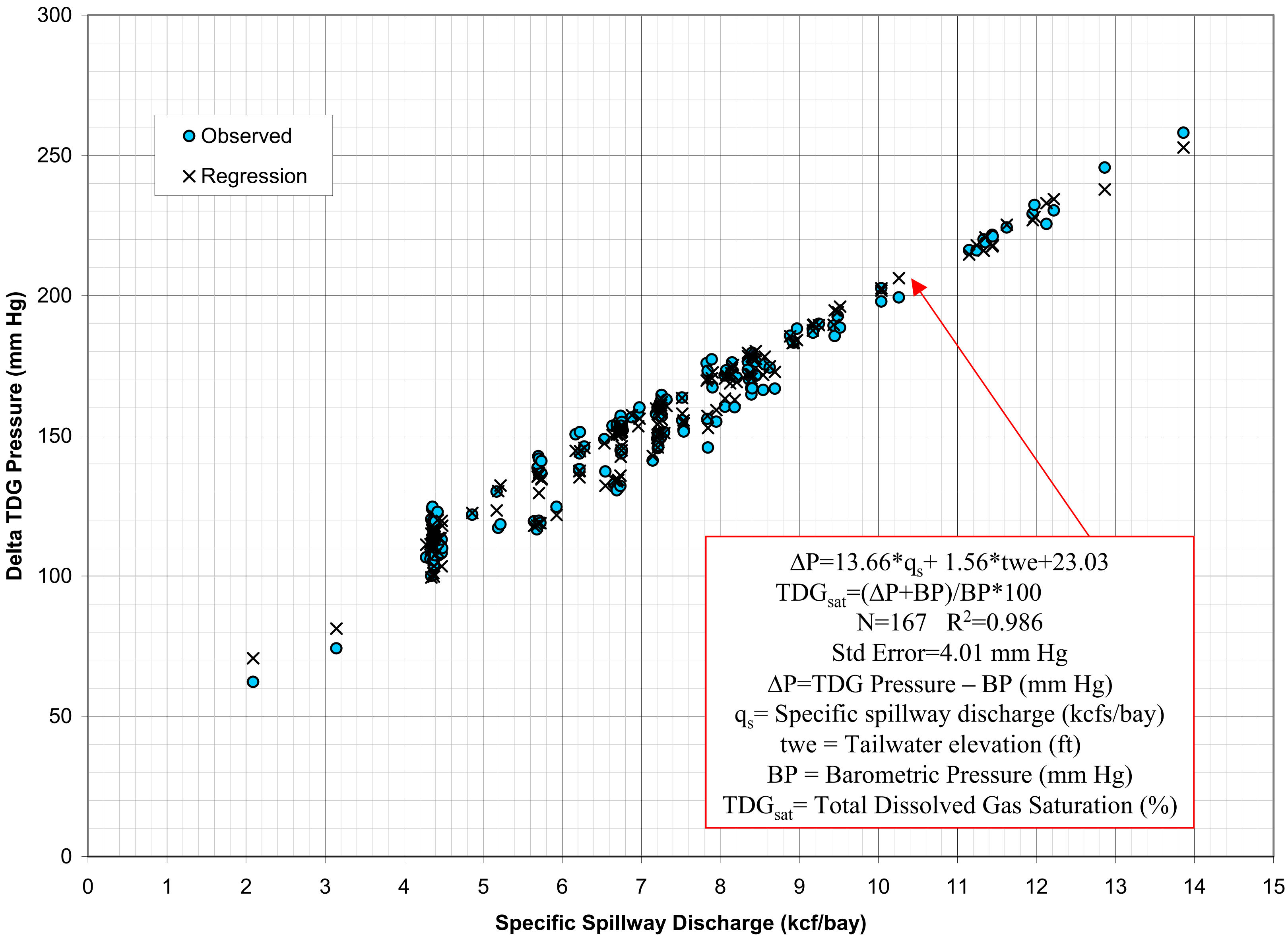


Figure 17. Observed and calculated average cross-sectional delta total dissolved gas pressure in the Bonneville spillway exit channel as a function of tailwater elevation and unit spillway discharge by event

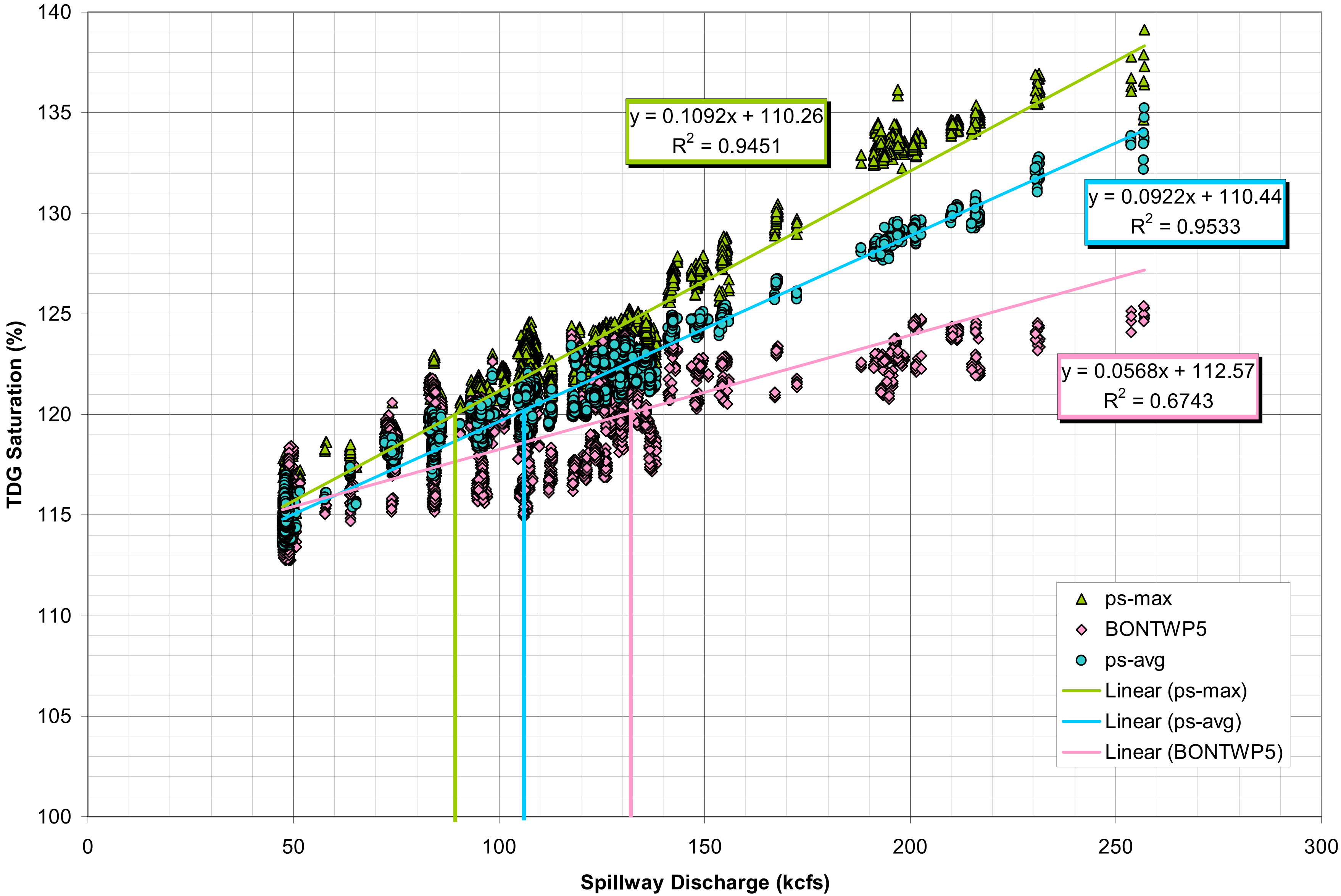


Figure 18. Total Dissolved Gas Saturation in the Bonneville spillway exit channel as a function of spillway discharge, April- July, 2002 (ps-max=maximum cross sectional, ps-avg=average cross sectional, BONTWP5-Cascade Island station)

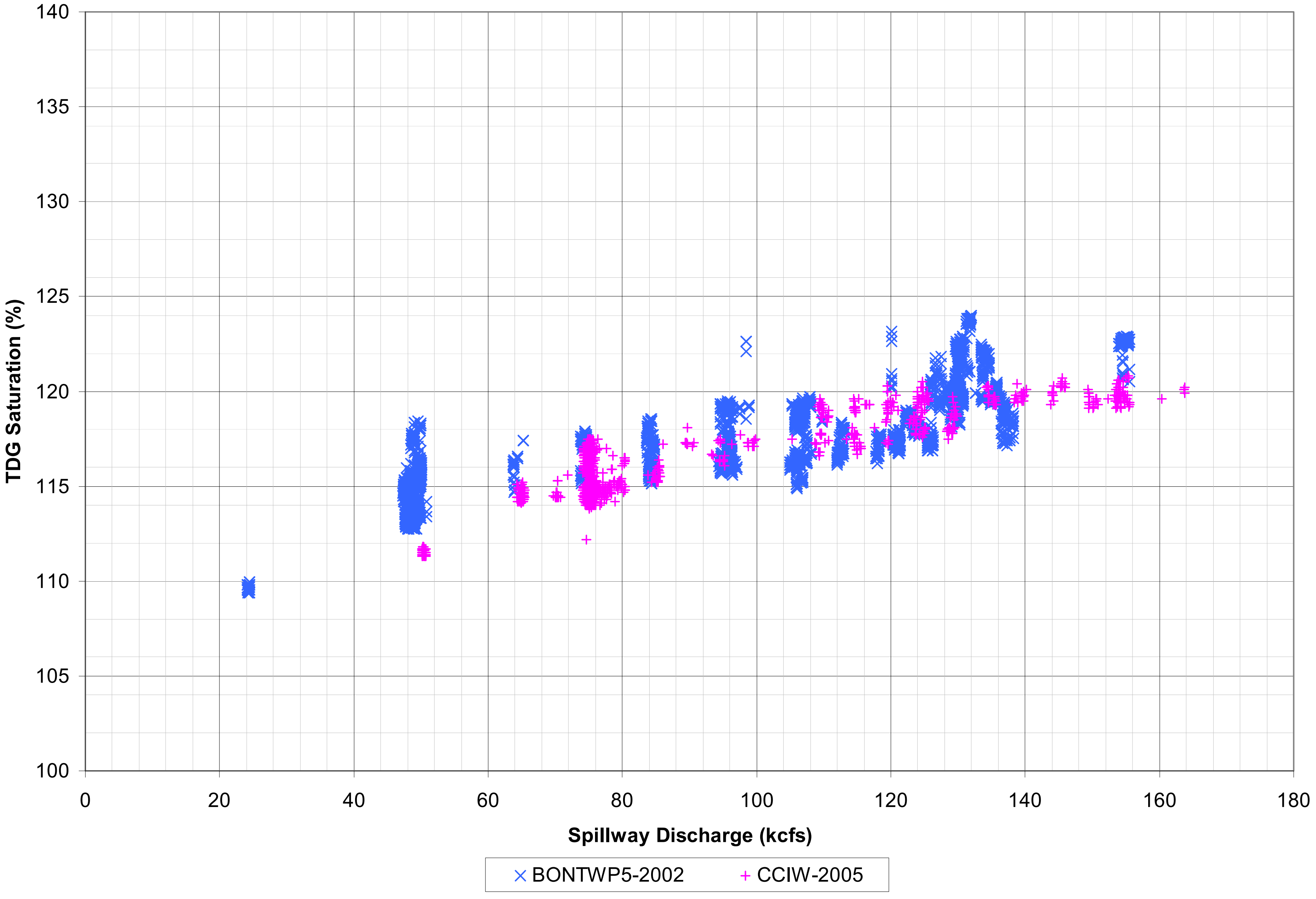


Figure 19. Total Dissolved Gas Saturation as a function of Spillway Discharge at stations BONTWP5 and CCIW.

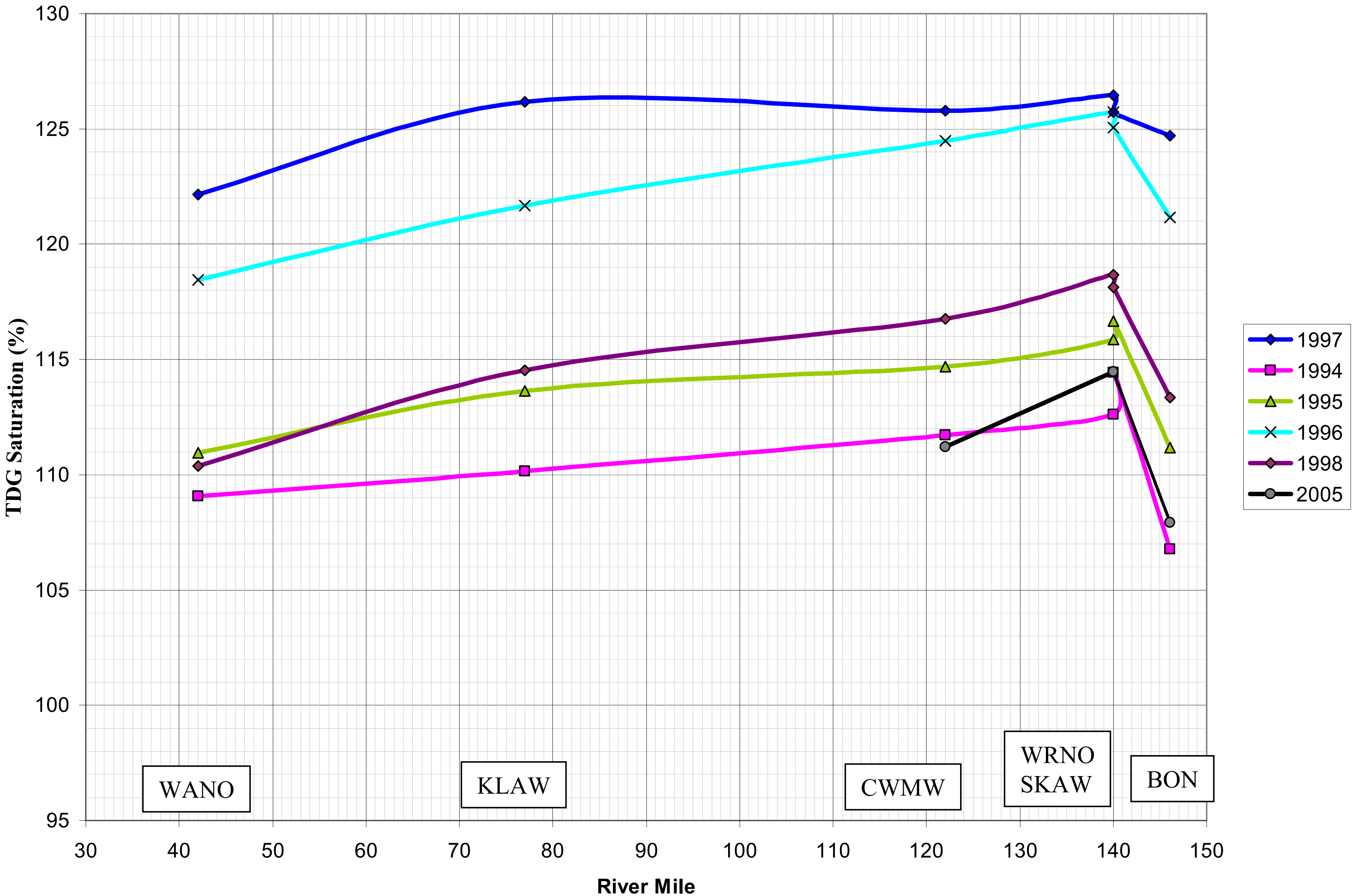


Figure 20. Monthly Average of TDG Saturation for June 1994-1998, 2005 in the Lower Columbia River.

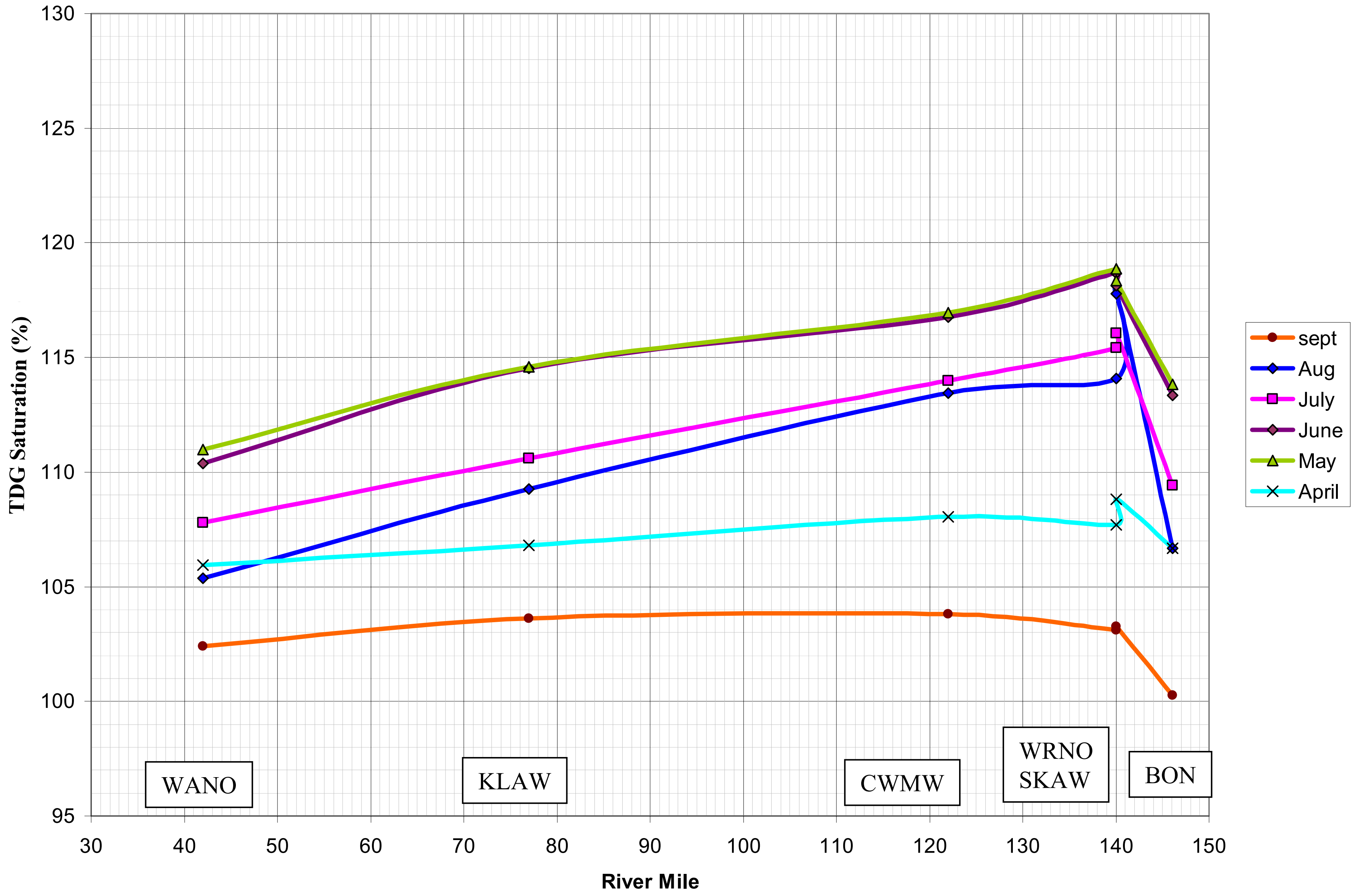


Figure 21. Monthly Average of TDG Saturation for 1998 in the Lower Columbia River.

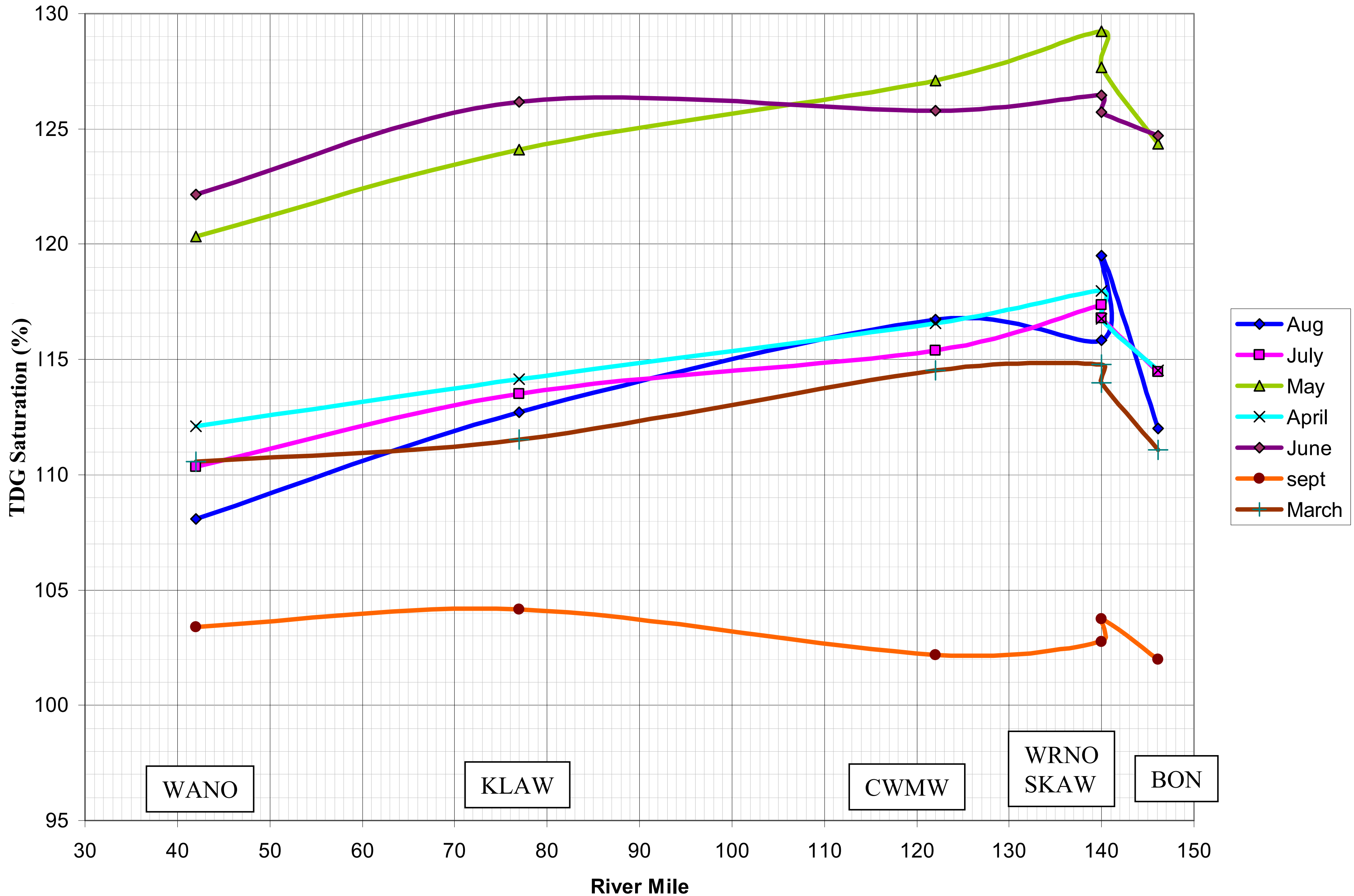


Figure 22. Monthly Average of TDG Saturation for 1997 in the Lower Columbia River.

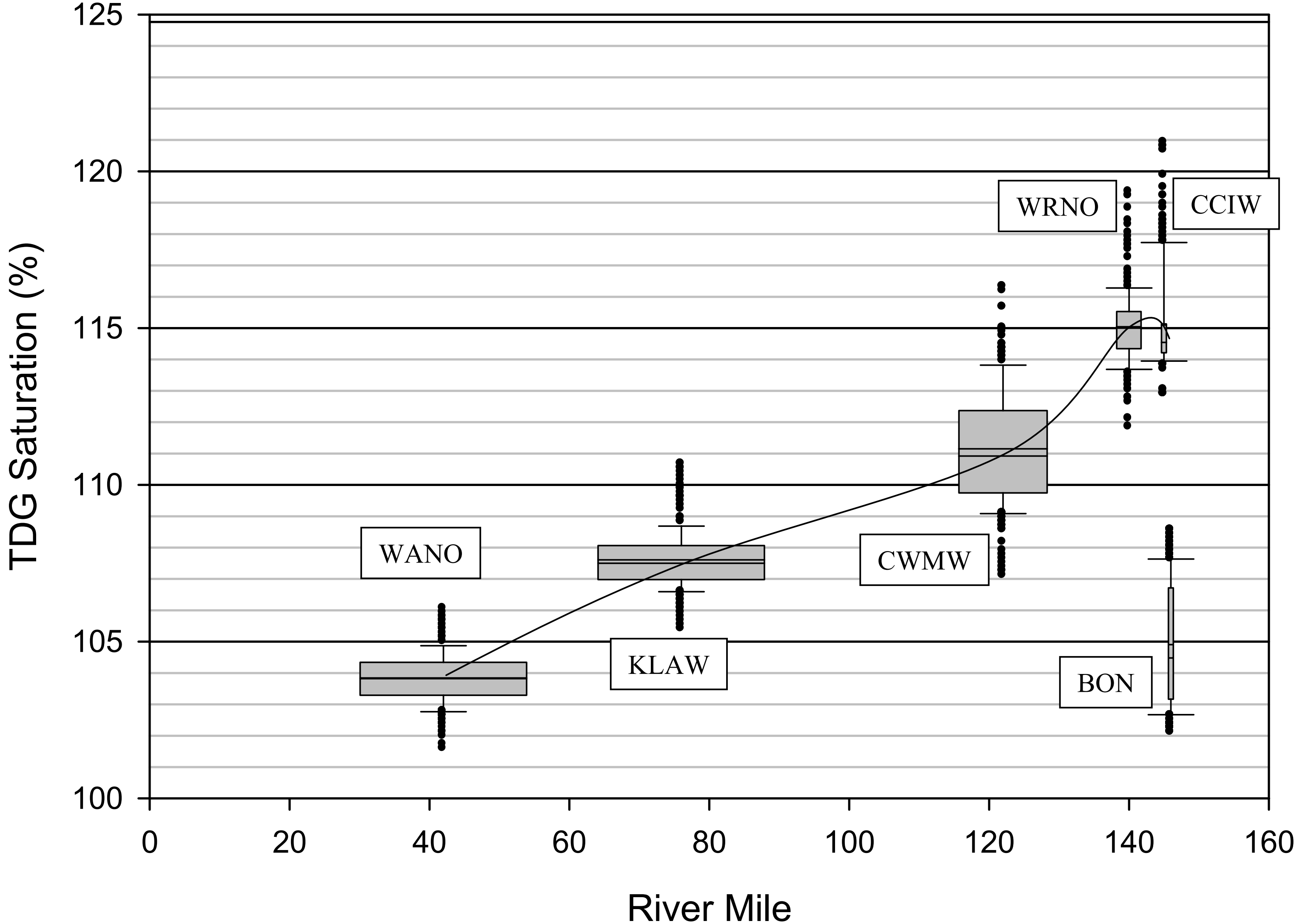


Figure 23. Average of TDG Saturation in the Lower Columbia River, August 12-24, 2005.

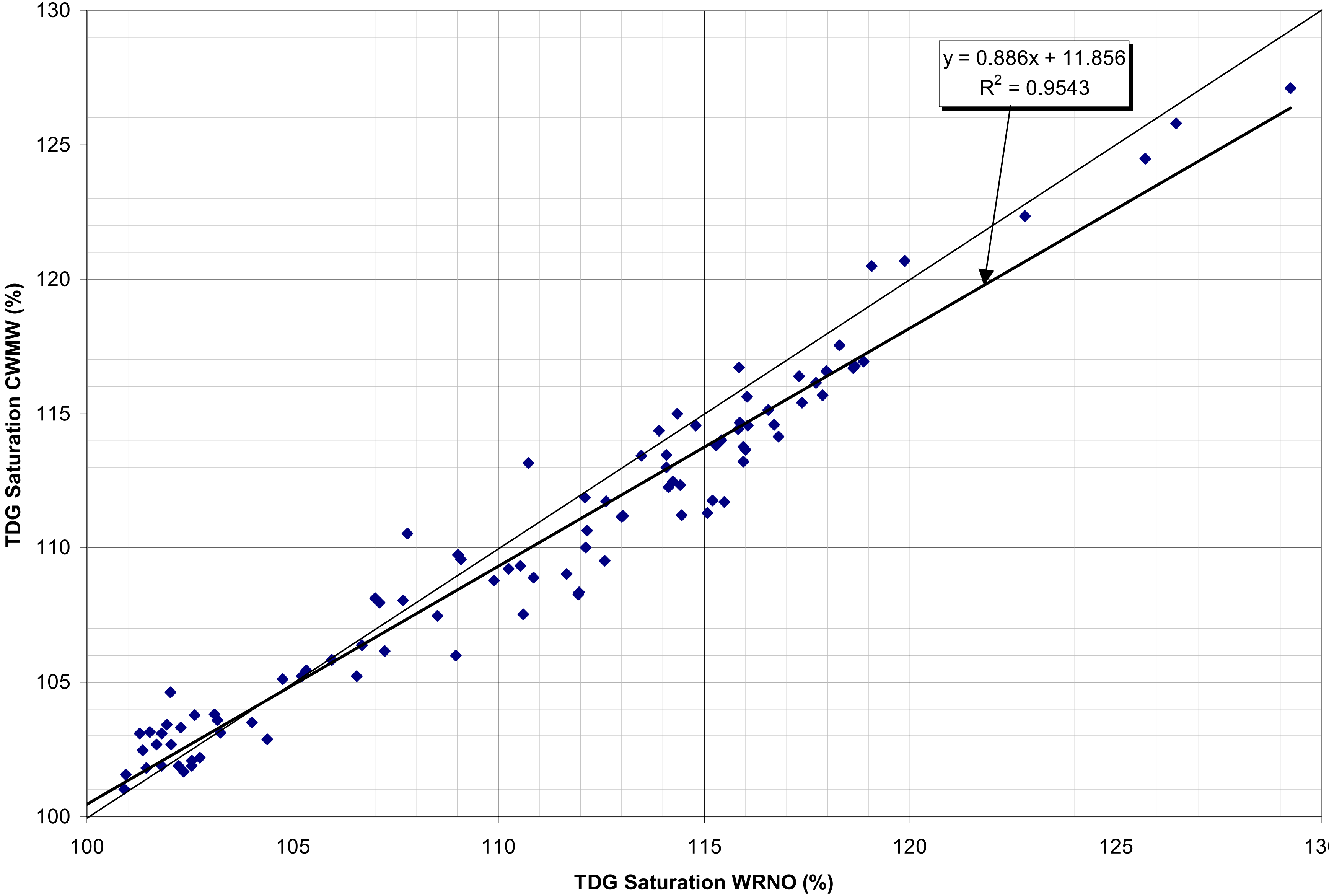


Figure 24. Monthly Average TDG Saturation in the Lower Columbia River at stations CWMW and WRNO, 1994-2005

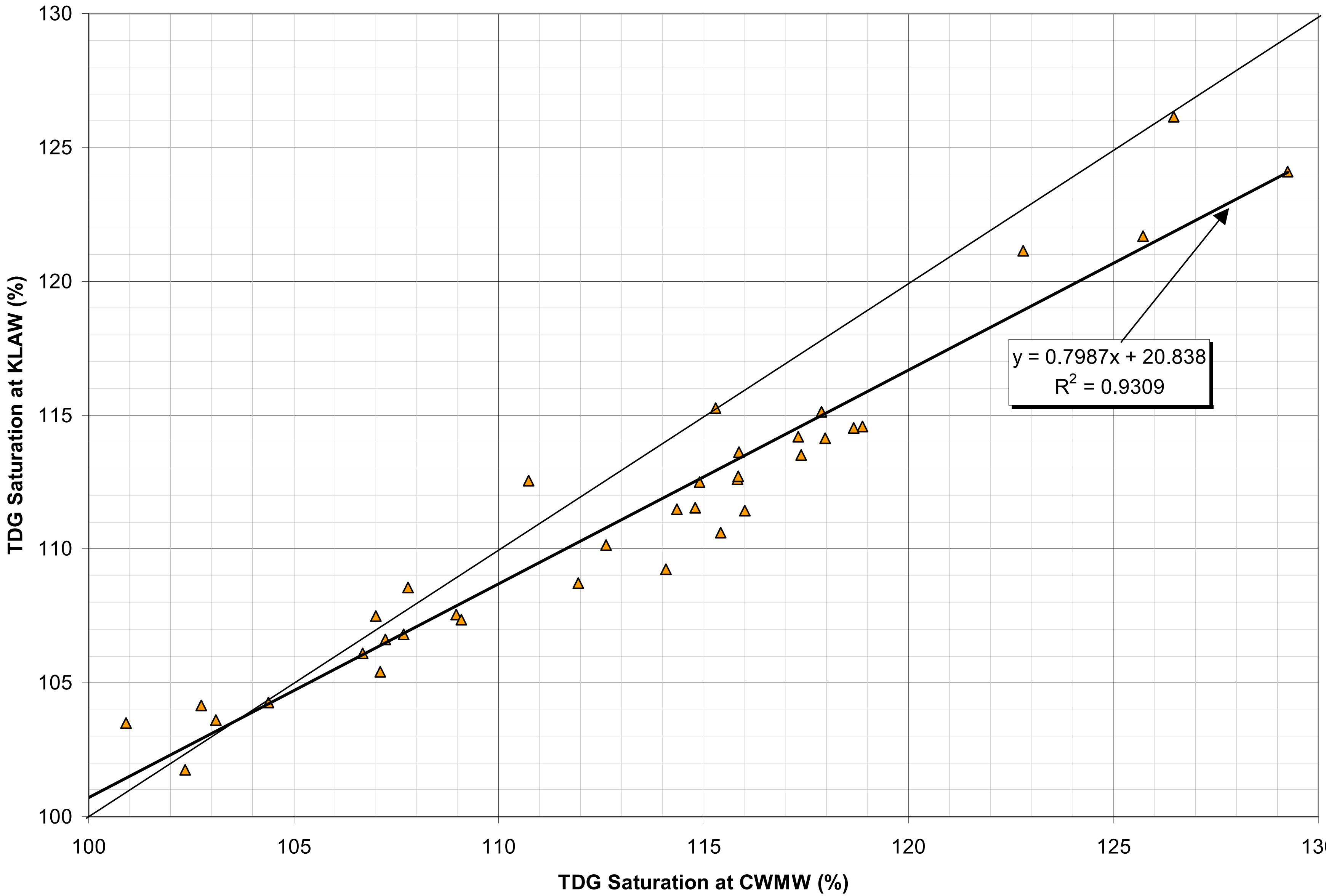


Figure 25. Monthly Average TDG Saturation in the Lower Columbia River at stations CWMW and KLAW, 1994-1998

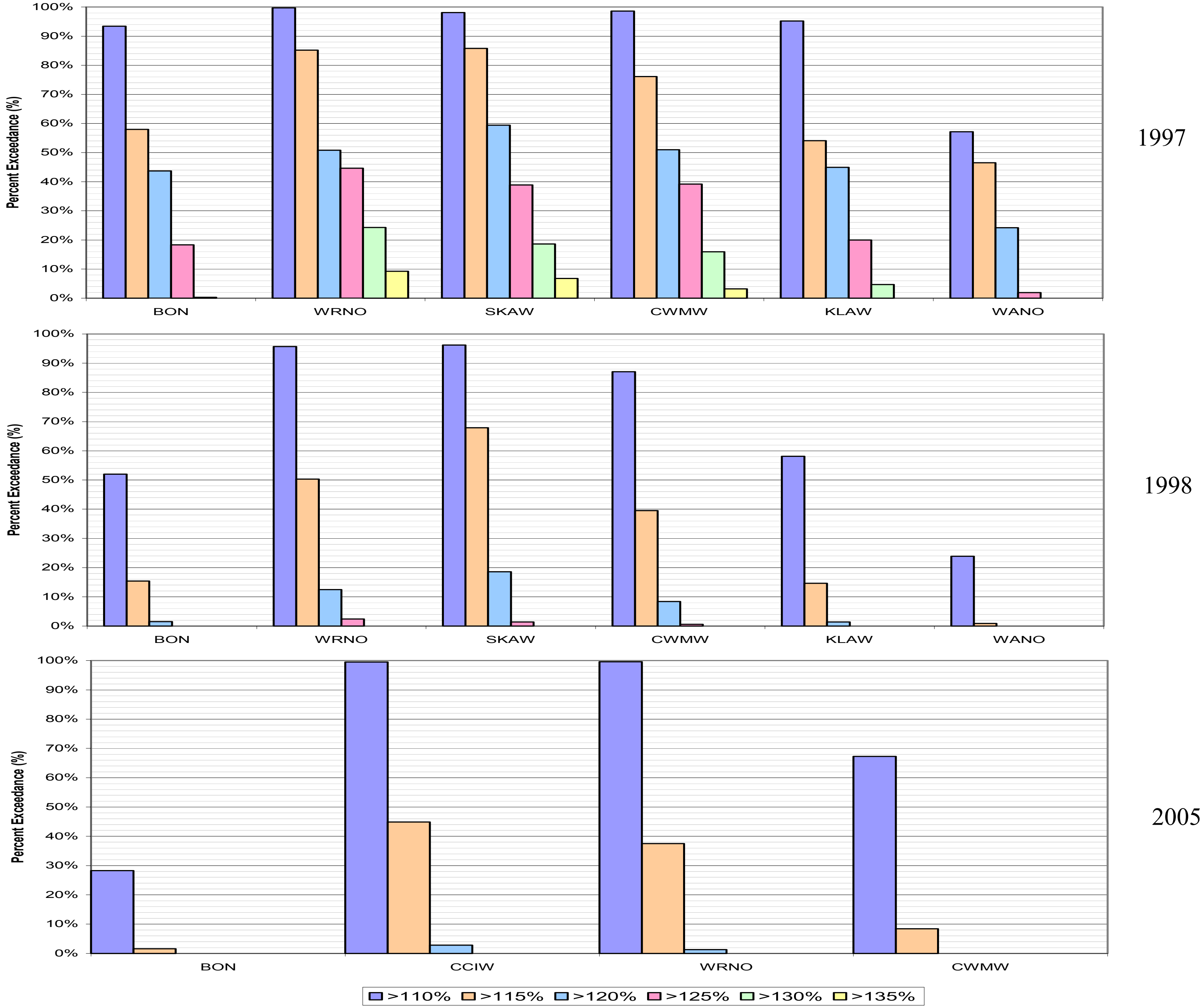


Figure 26. Frequency of Total Dissolved Gas Saturation levels in the Columbia River RM 42-146, 1997, 1998, 2005 (April 15-August 31)

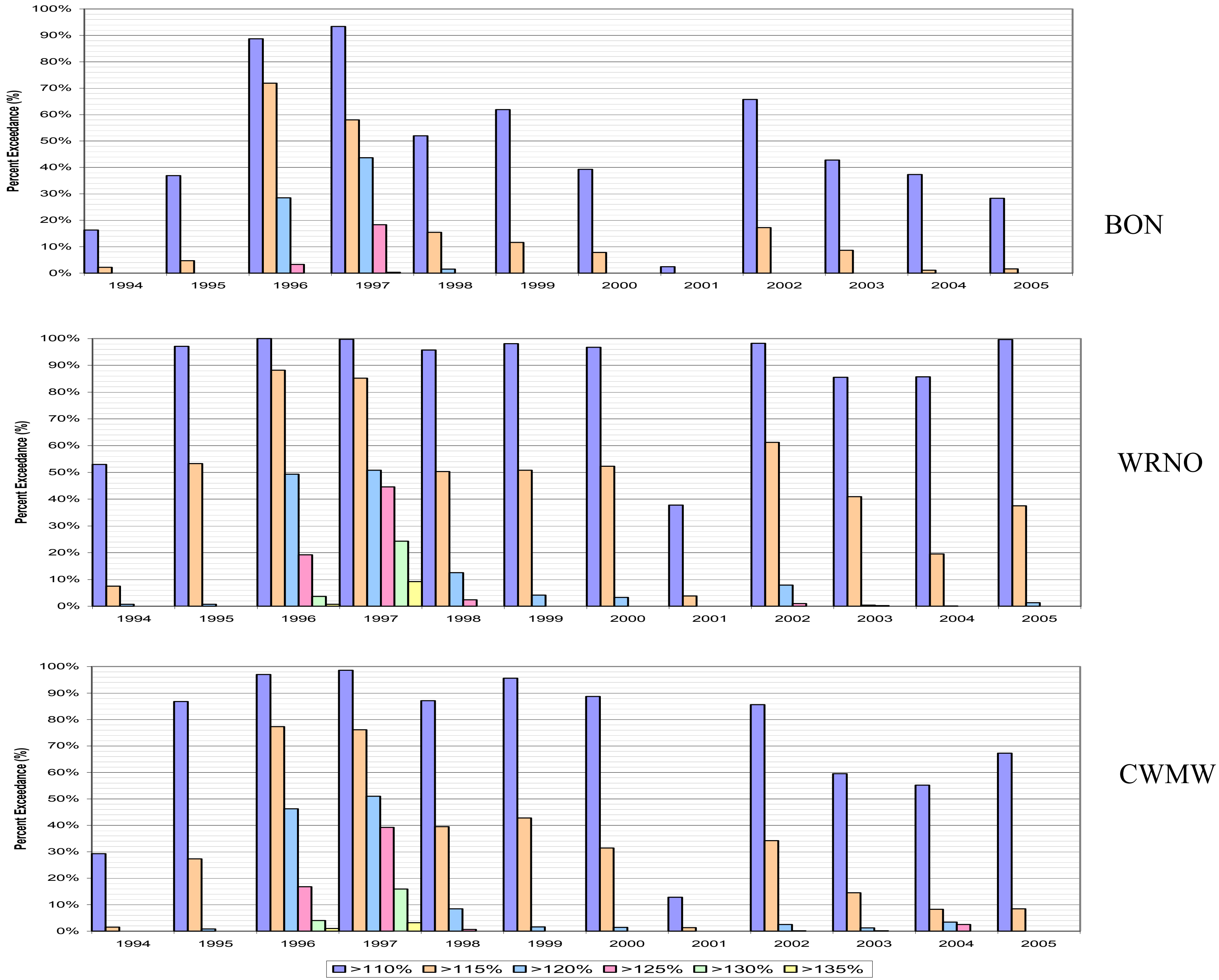


Figure 27. Frequency of hourly TDG Saturation in the Columbia River exceeding 110, 115, 120, 125, 130, and 135 percent at fixed monitoring stations, BON, WRNO, CWMW 1994-2005 (April 15-August 31)

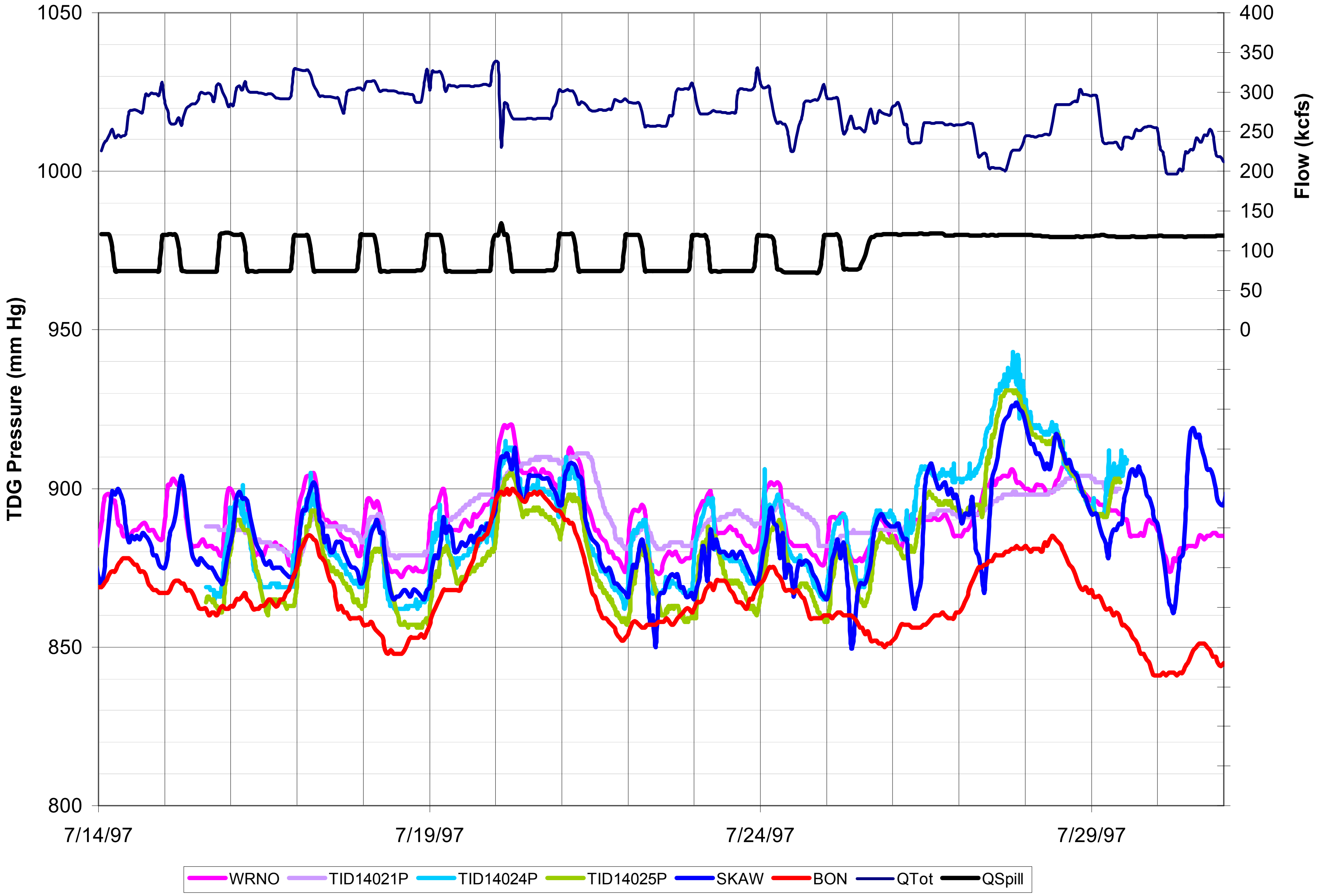


Figure 28. Time history of Total Dissolved Gas Pressure in the Lower Columbia River, July 14-20, 1997
(Featured Transect at RM 140.2, station 1P near Oregon shore and 5P near Washington shore)

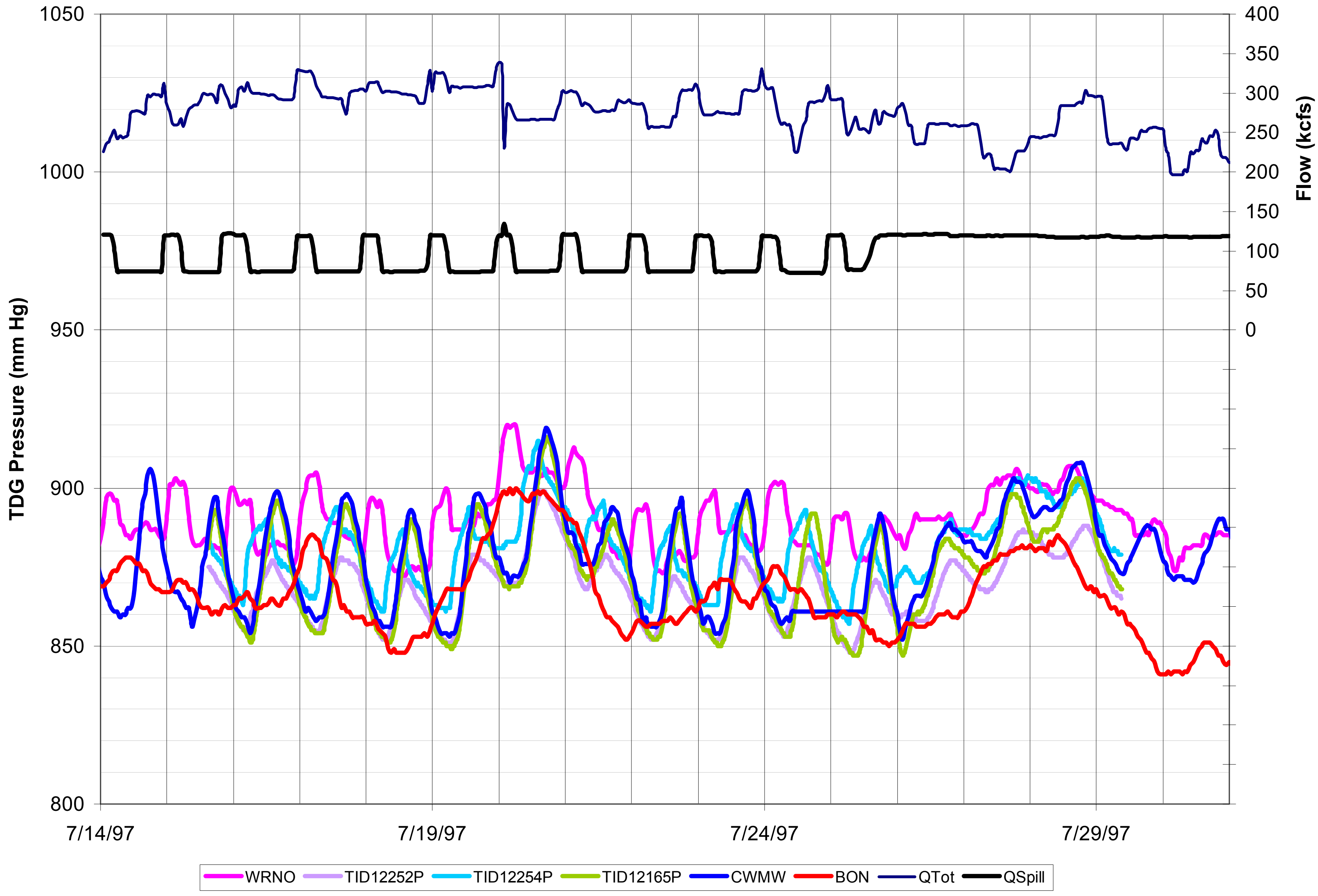


Figure 29. Time history of Total Dissolved Gas Pressure in the Lower Columbia River, July 14-20, 1997
(Featured Transect at RM 122.5, station 1P near Oregon shore and 5P near Washington shore)

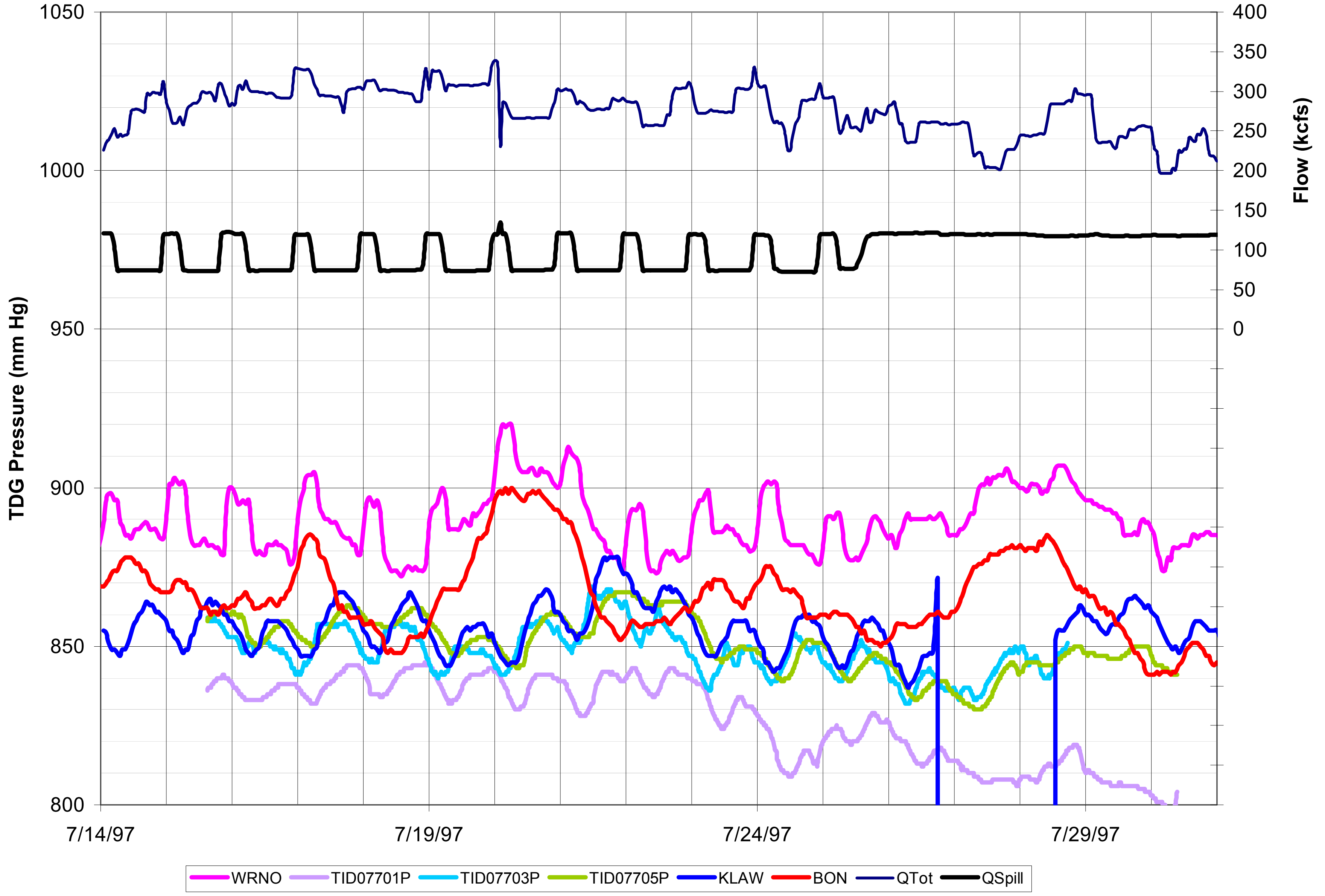


Figure 30. Time history of Total Dissolved Gas Pressure in the Lower Columbia River, July 14-20, 1997 (Featured Transect at RM 77.0, station 1P near Oregon shore and 5P near Washington shore)

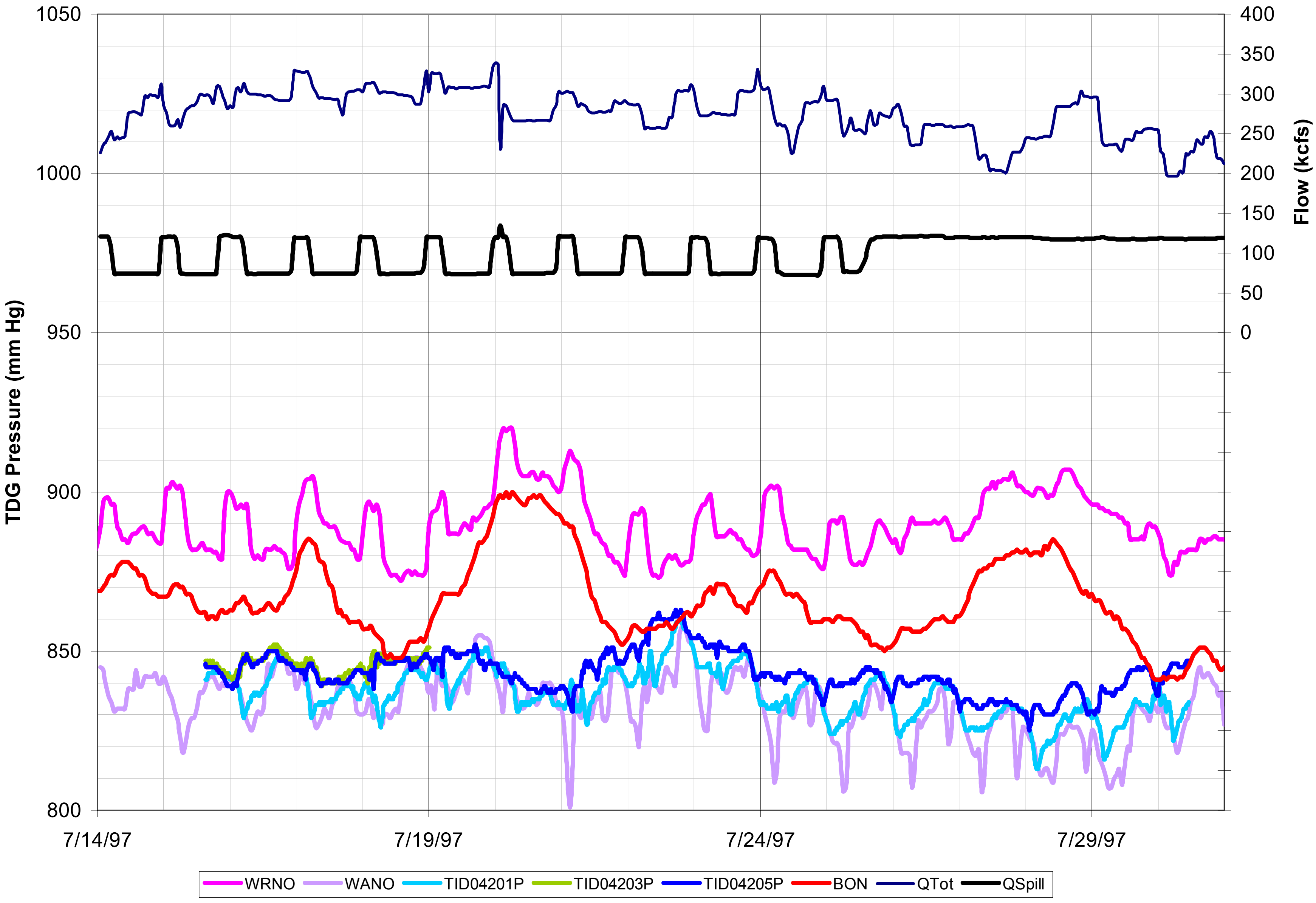


Figure 31. Time history of Total Dissolved Gas Pressure in the Lower Columbia River, July 14-20, 1997
(Featured Transect at RM 42.0, station 1P near Oregon shore and 5P near Washington shore)

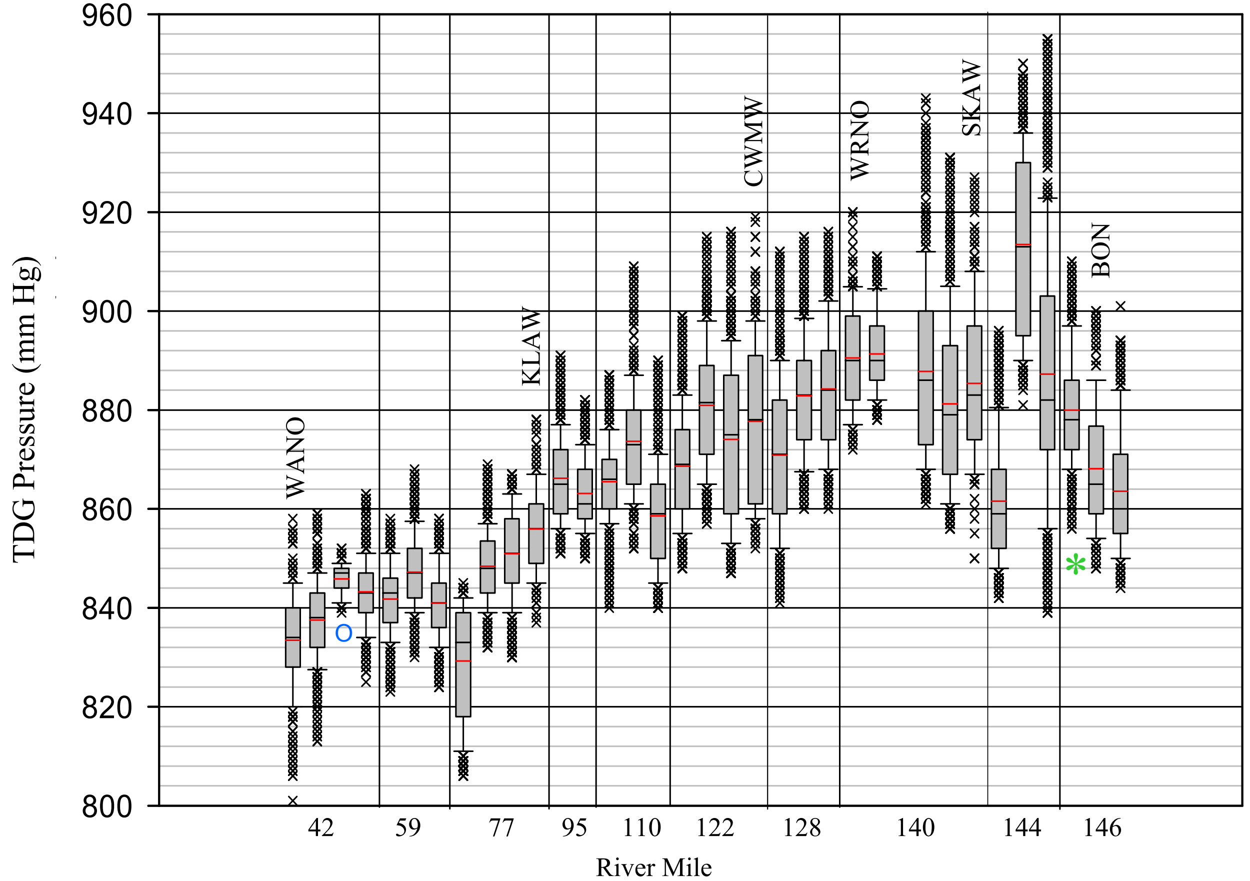


Figure 32. Statistical Summary of Total Dissolved Gas Saturation in the Lower Columbia River, July 15-28 1997
(Lateral sampling transects oriented from Oregon to Washington shore)
(TDG saturation mean-red, * Atypical TDG response, O partial record)

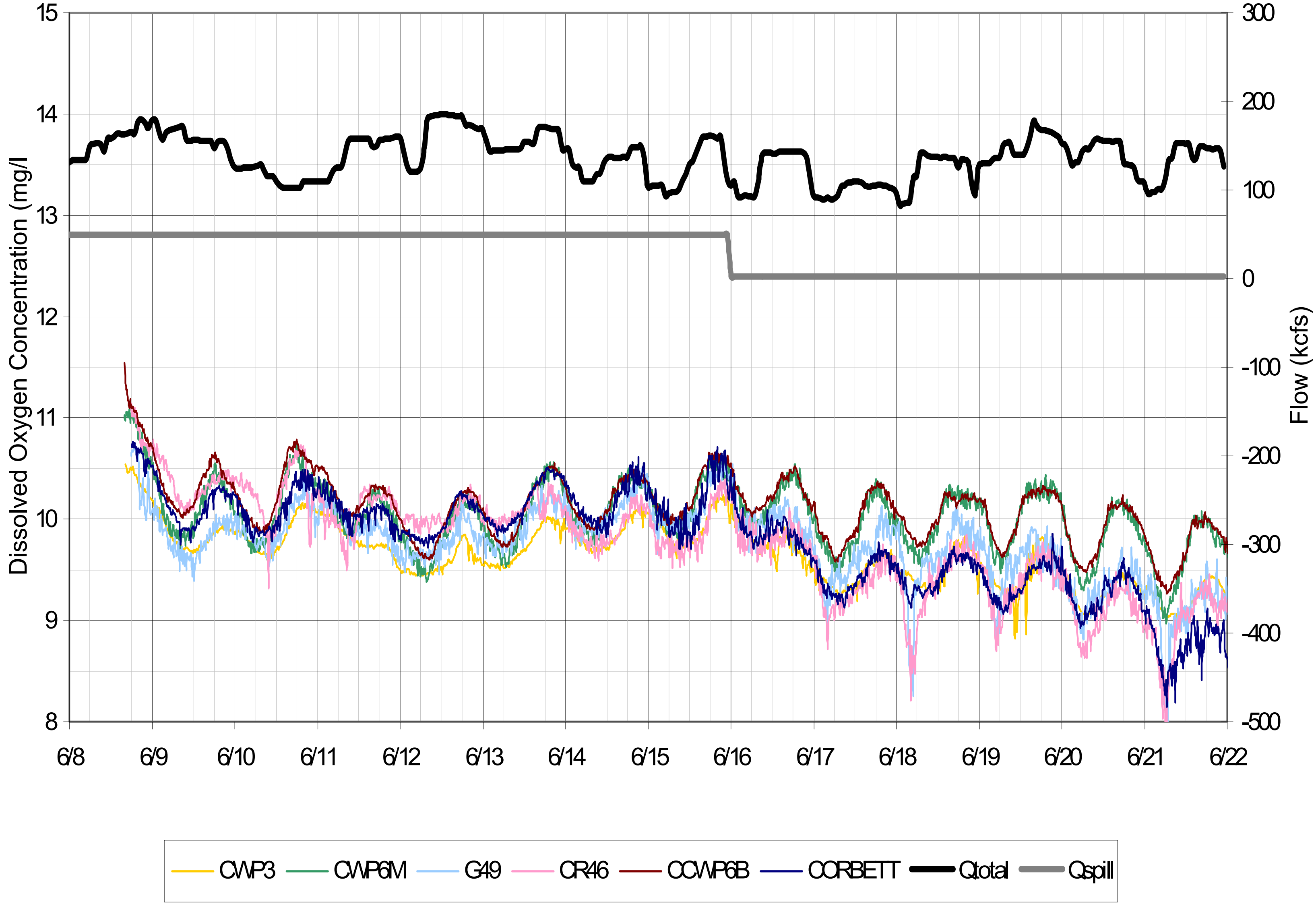


Figure 33. Hourly Columbia River Dissolved Oxygen concentrations at river mile 122, June 2001.
(lateral transect CWP1-CWP6 oriented Oregon to Washington shore)

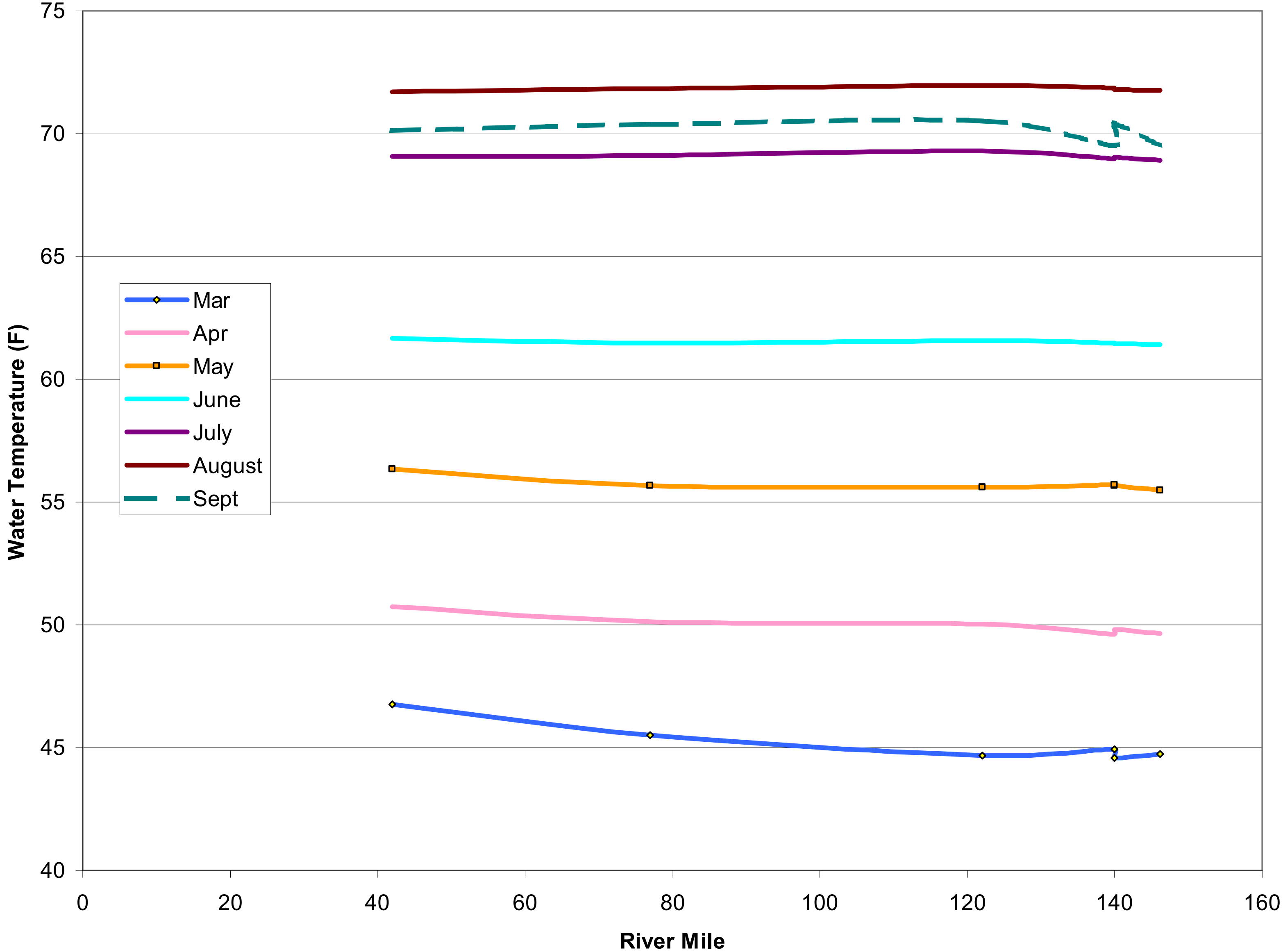


Figure 34. Columbia River Mile 42-145 monthly average temperatures from March-September 1998.

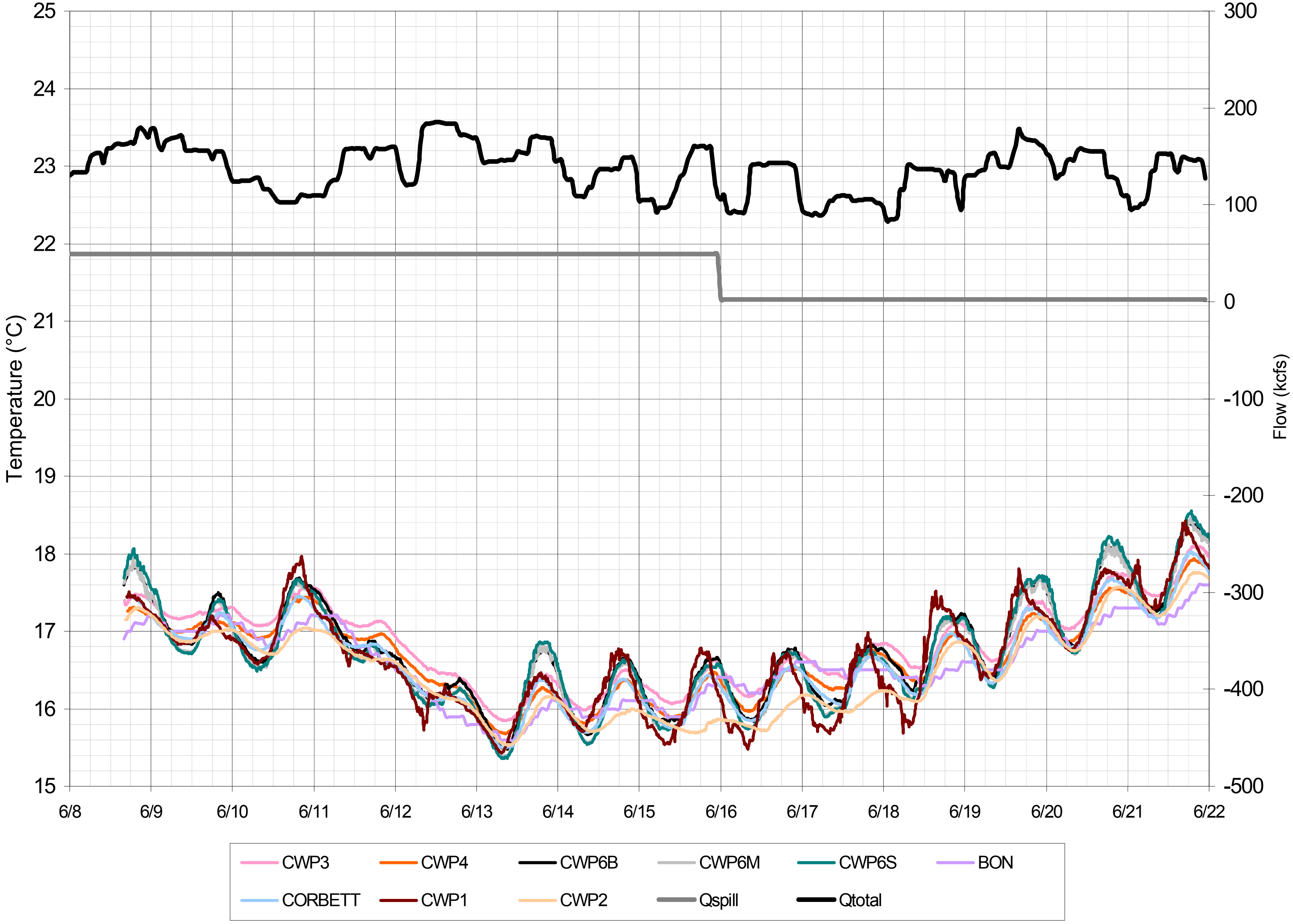


Figure 35. Hourly Columbia River water temperatures at river mile 122, June 2001.
(lateral transect CWP1-CWP6 oriented Oregon to Washington shore)

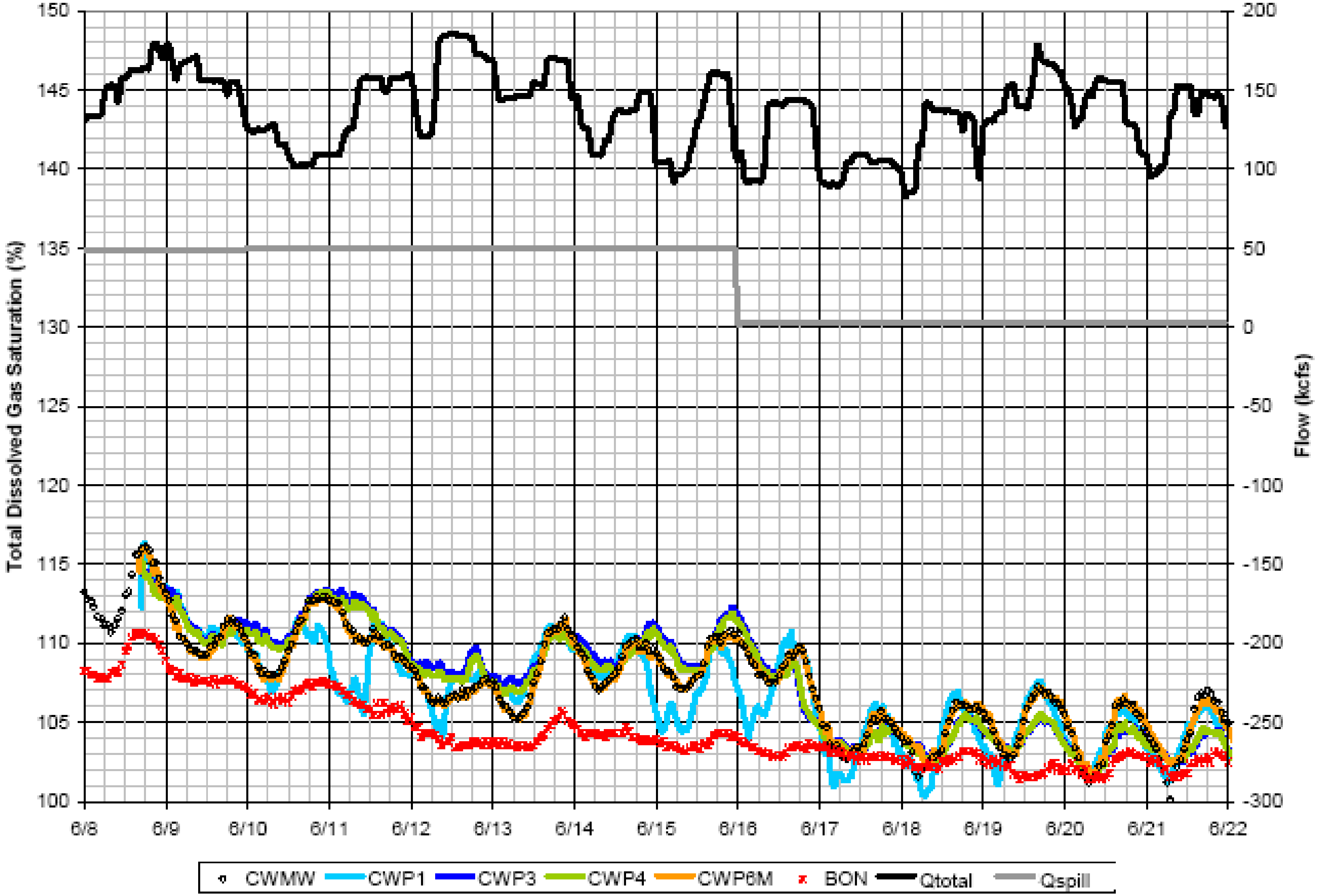


Figure 36. Hourly Columbia River Total Dissolved Gas Saturation at river mile 122, June 2001.
(lateral transect CWP1-CWP6 oriented from the Oregon to Washington shore)

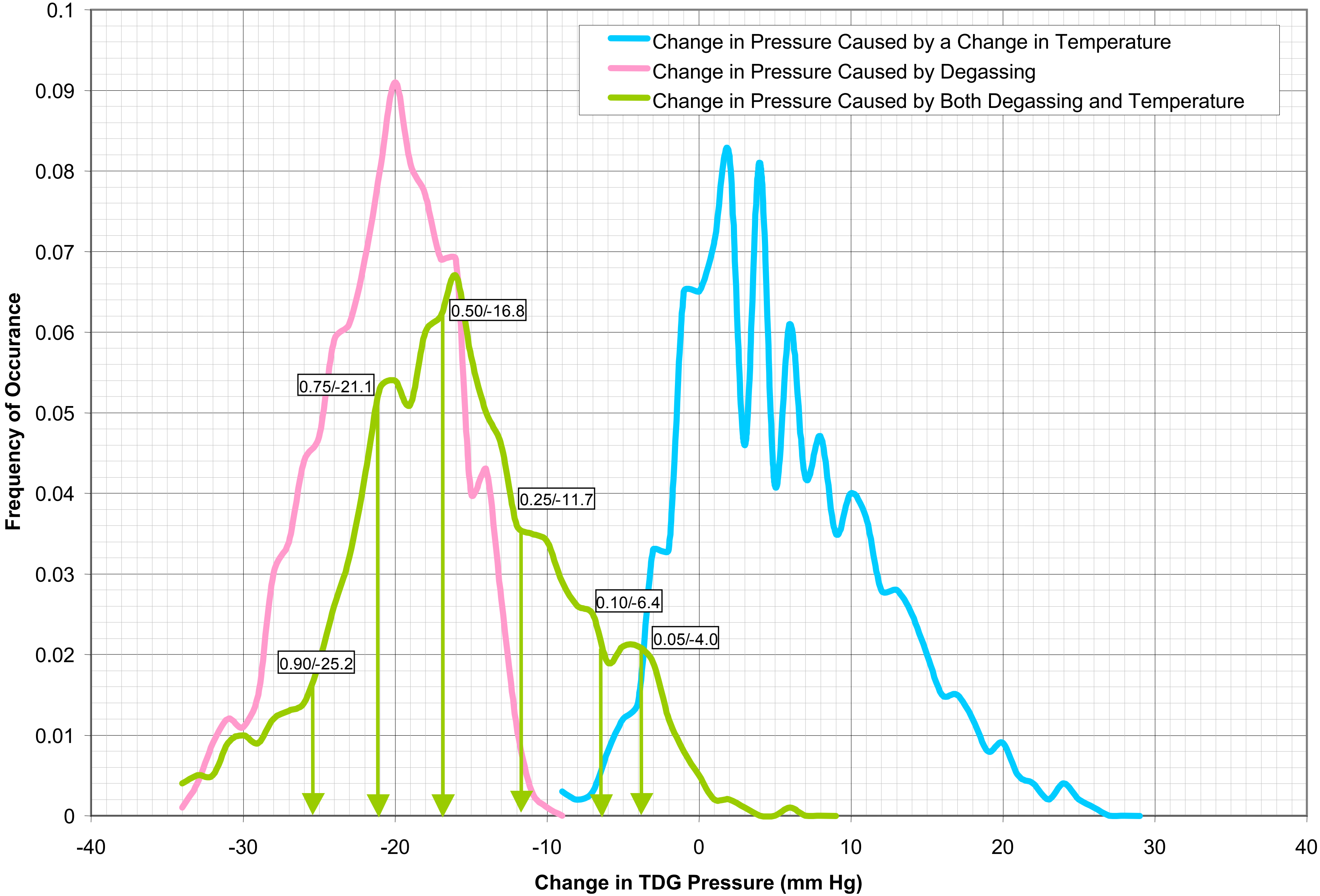


Figure 37. Fate of TDG Pressure in the Columbia River from Bonneville Dam to Camas/Washougal, April-August 2002

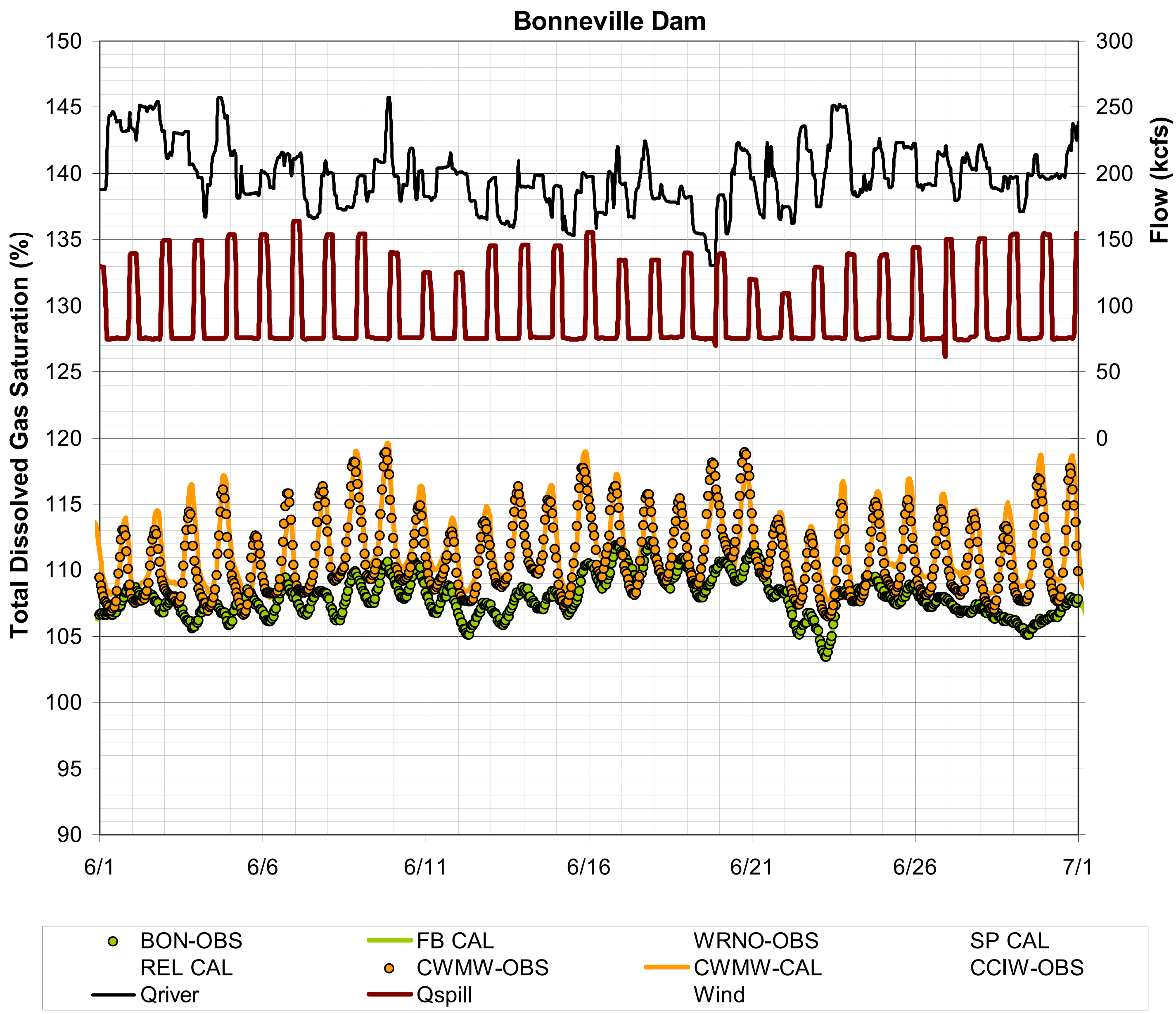


Figure 38. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005.
(Base Condition – Hourly Historic Flows)

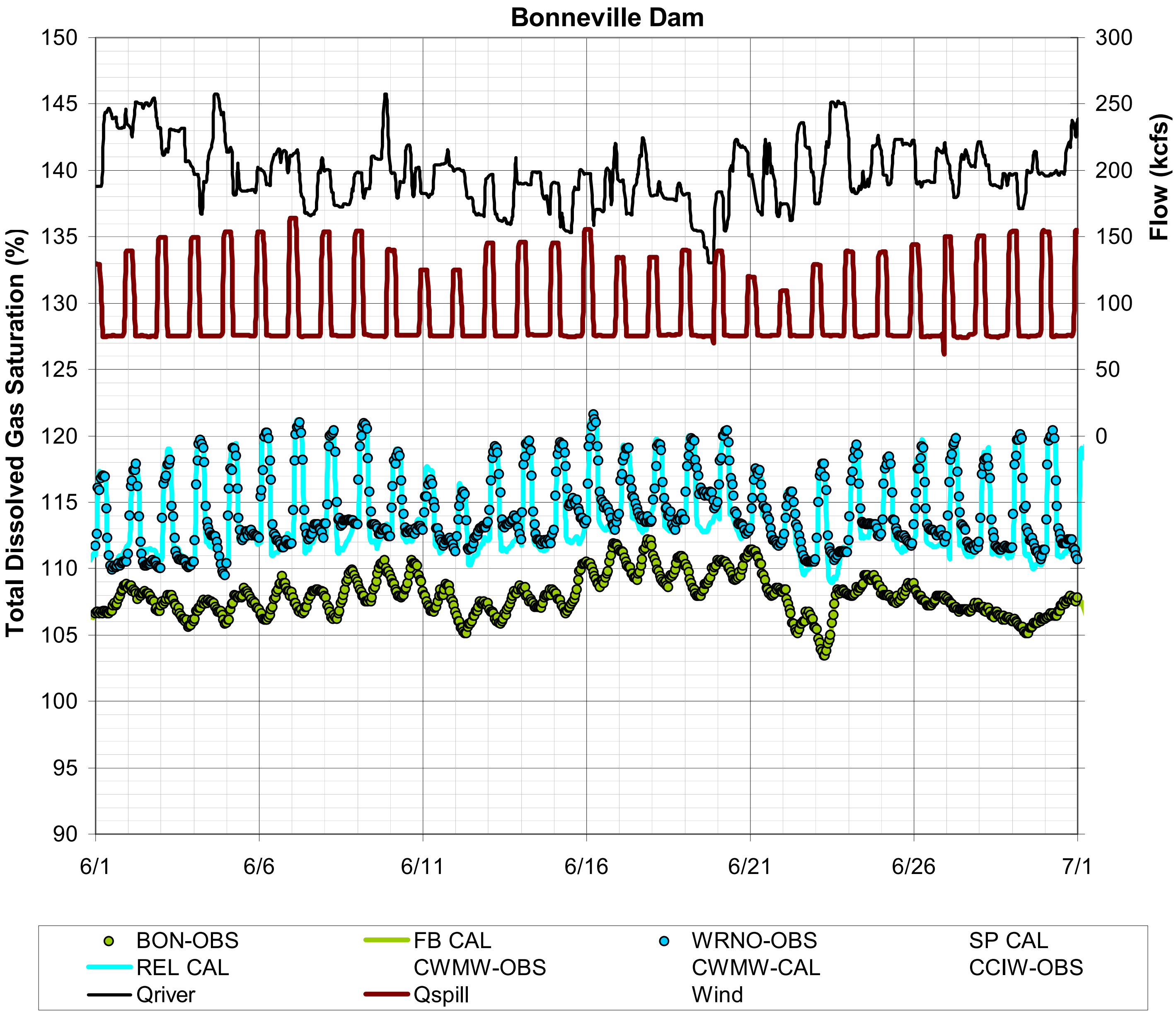


Figure 39. Observed and Calculated TDG Saturation in the Columbia River at Warrendale (WRNO) and in the forebay of Bonneville Dam (BON) during June 2005.
(Base Condition – Hourly Historic Flows)

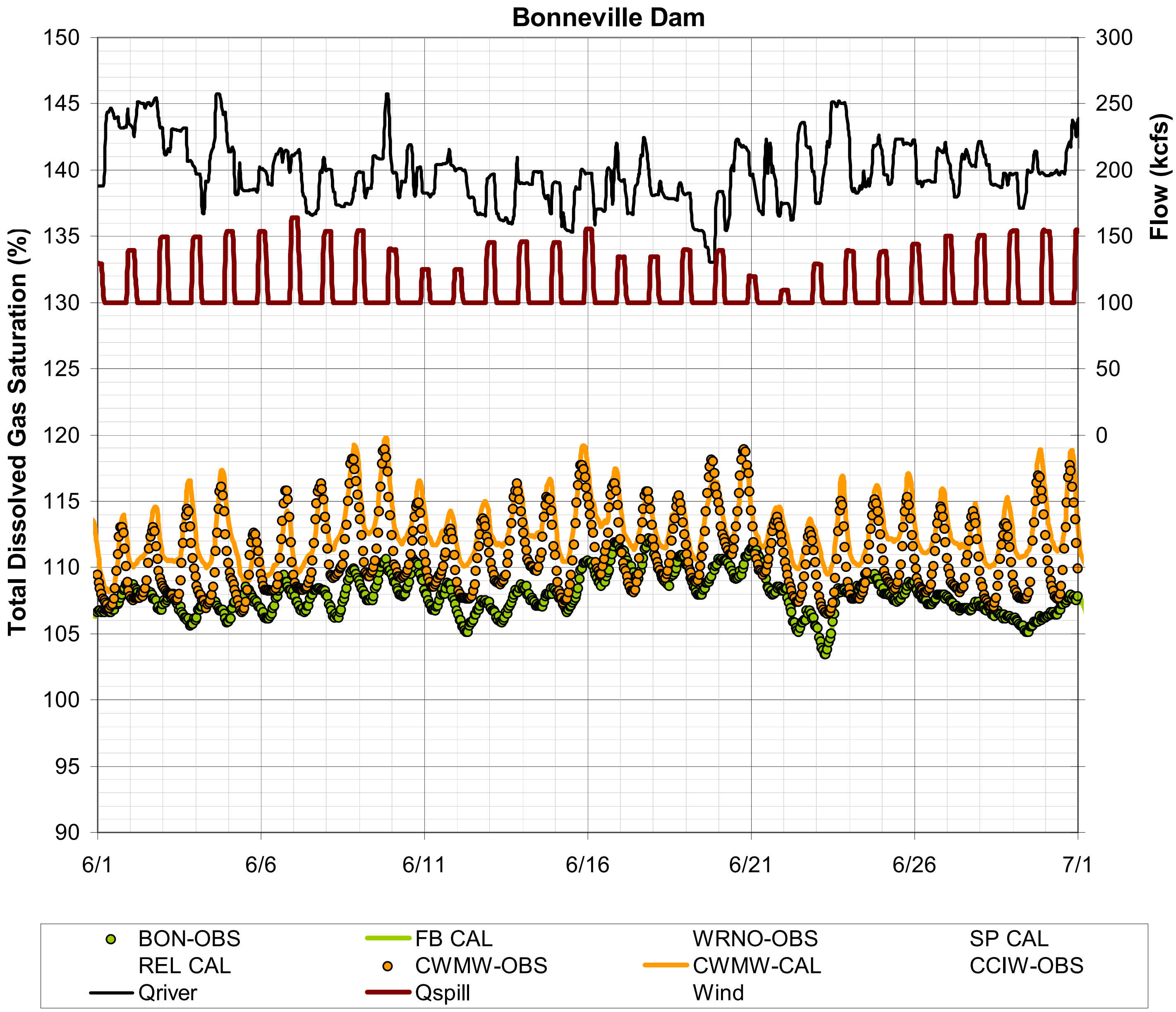


Figure 40. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005
(Observed – Base condition; Calculated - daytime spill = 100 kcfs, nighttime spill unaltered from base condition)

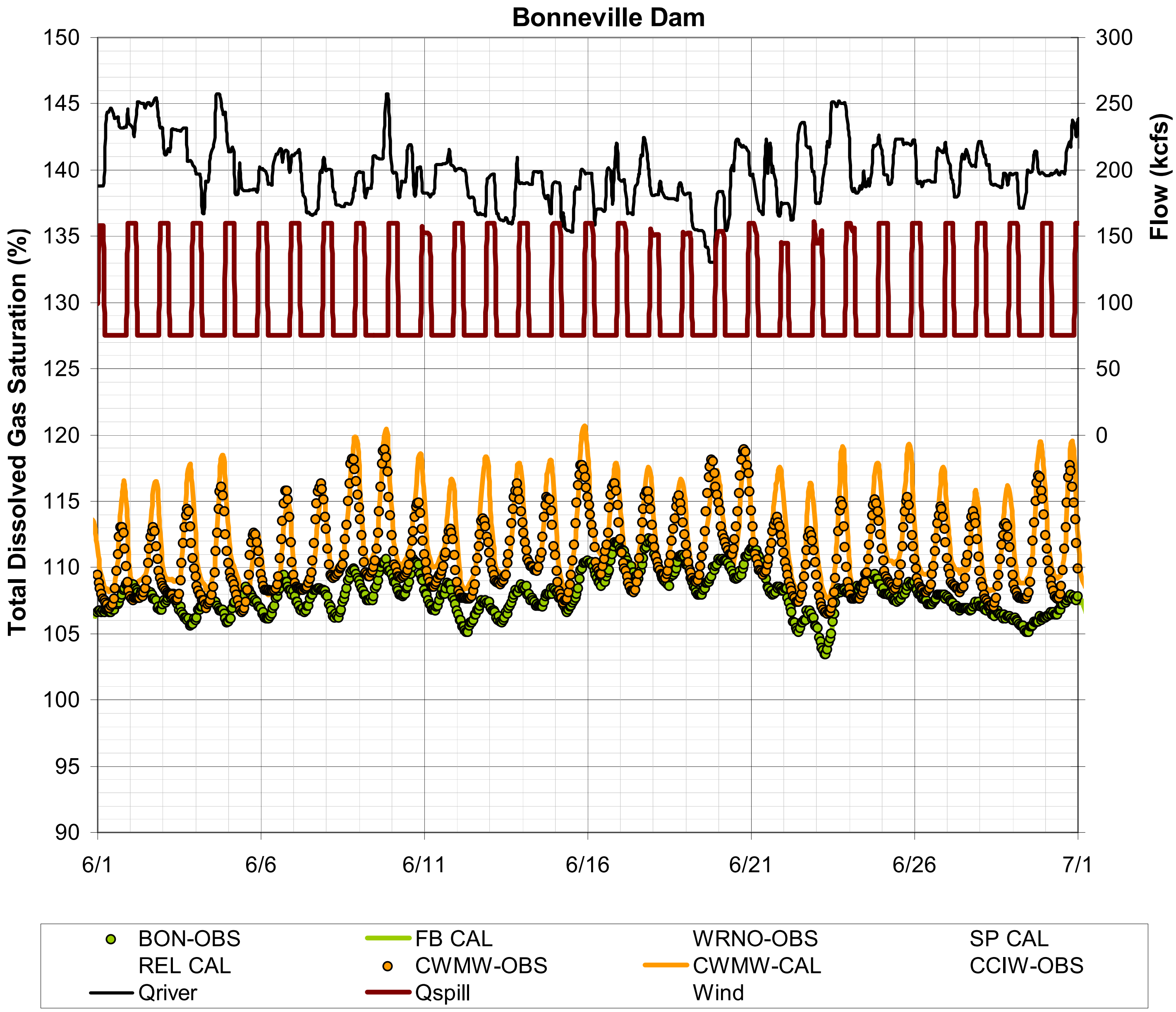


Figure 41. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005
(Observed – Base condition; Calculated nighttime spill = 160 kcfs, daytime spill unaltered from base condition

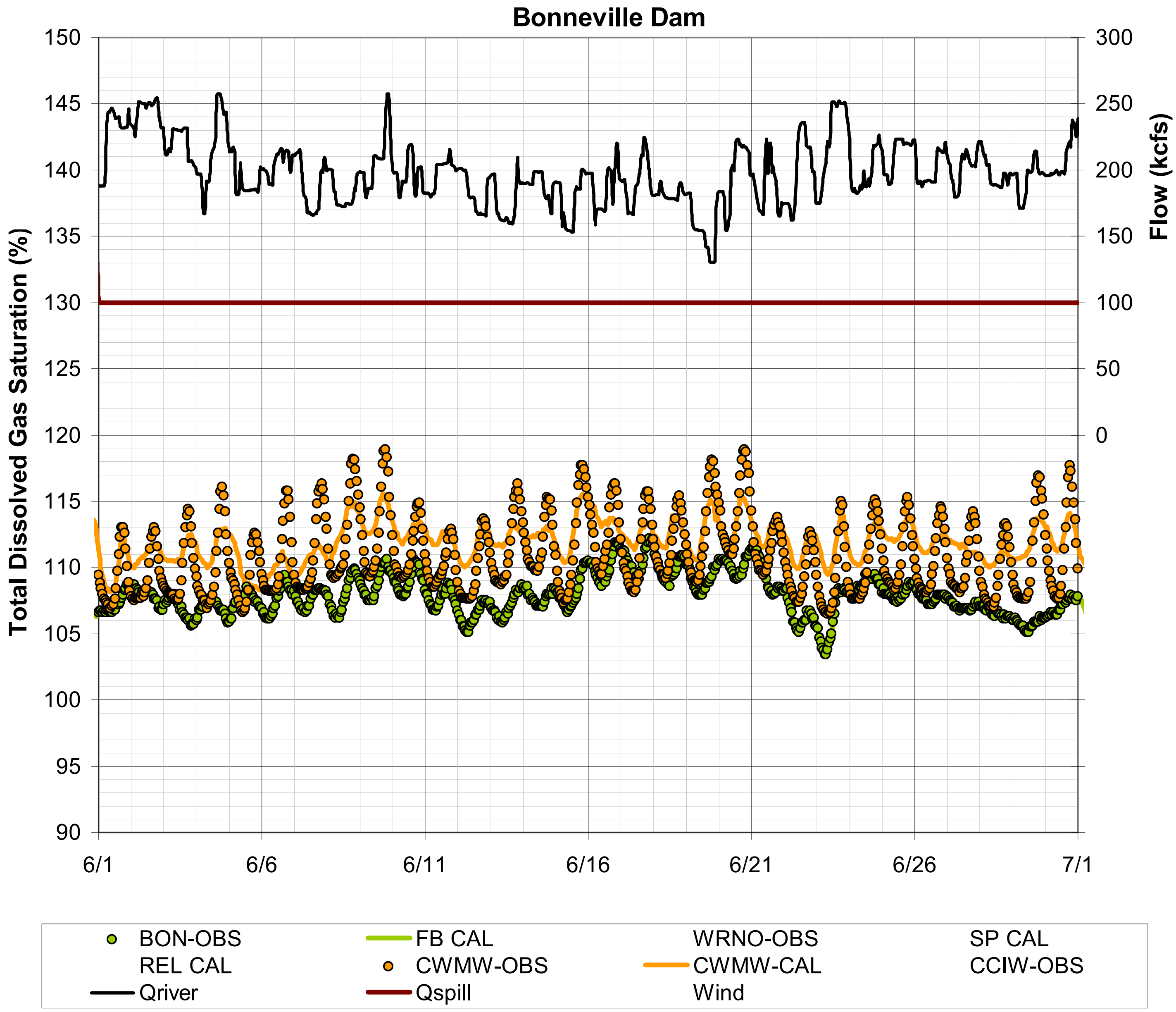


Figure 42. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005
(Observed – Base condition, Calculated – continuous 100 kcfs spill)

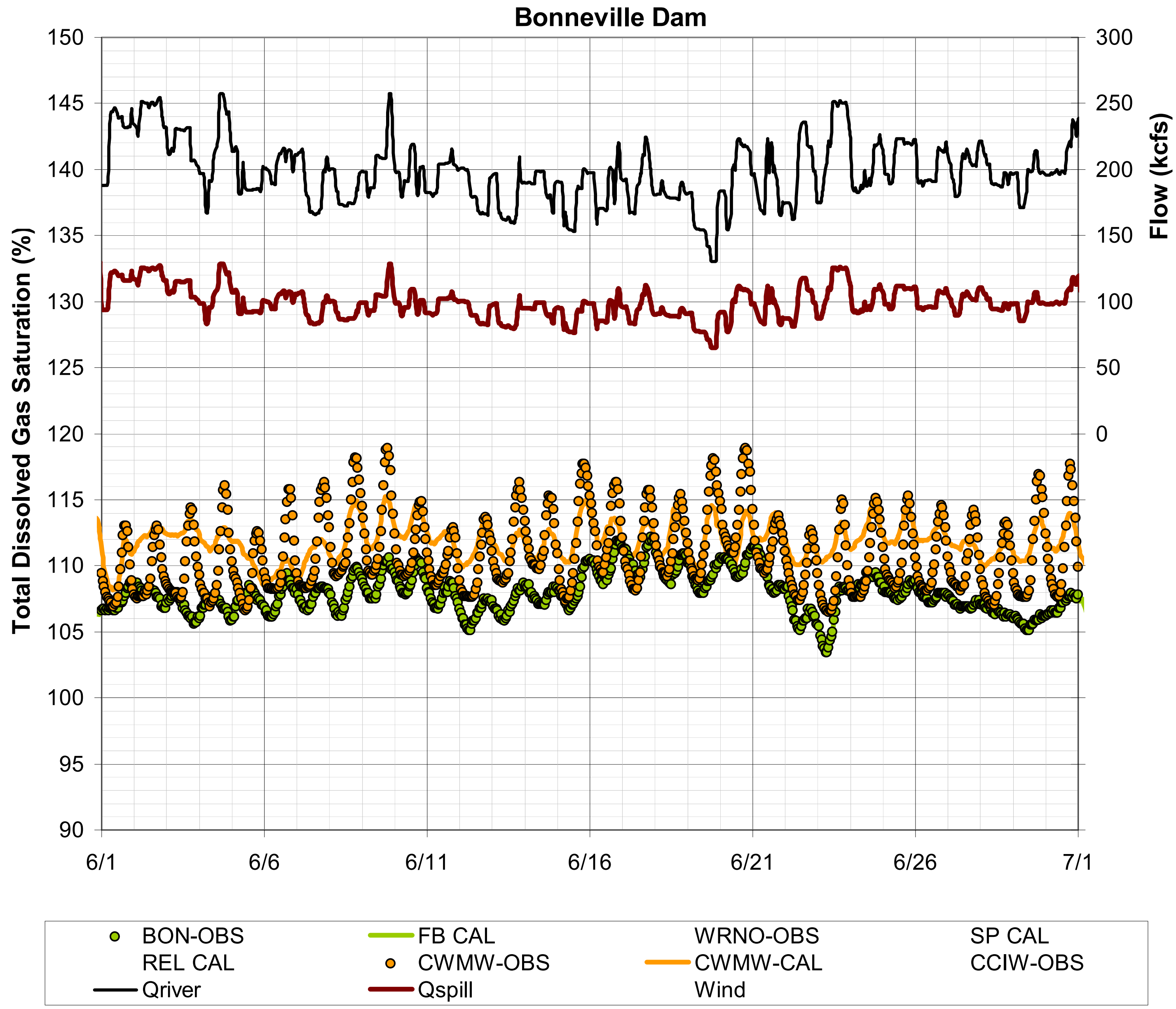


Figure 43. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005
(Observed – Base condition, Calculated – spill half of the instantaneous river flow)

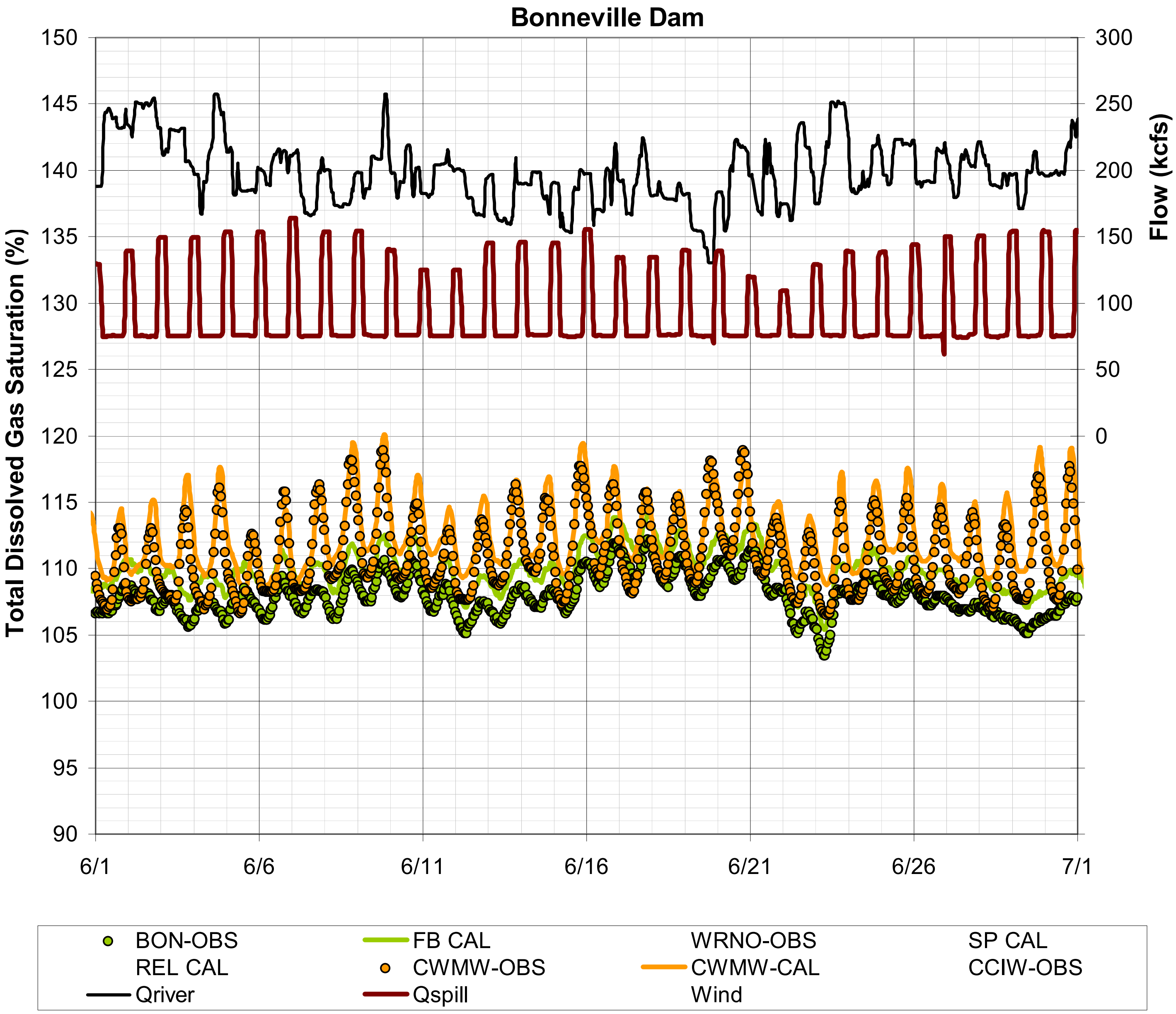
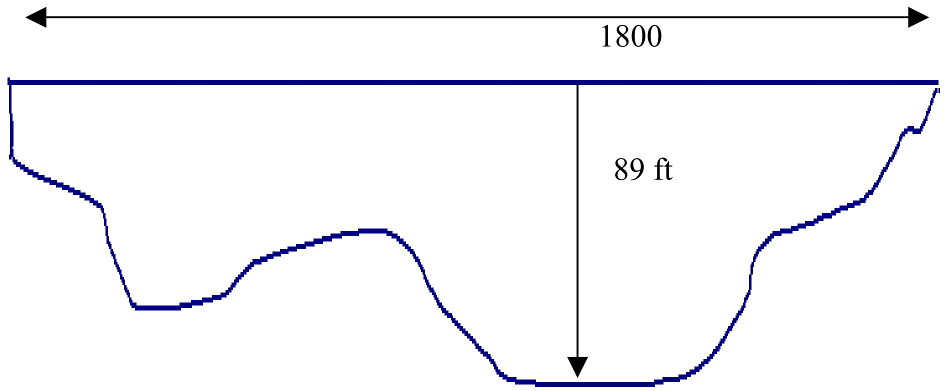
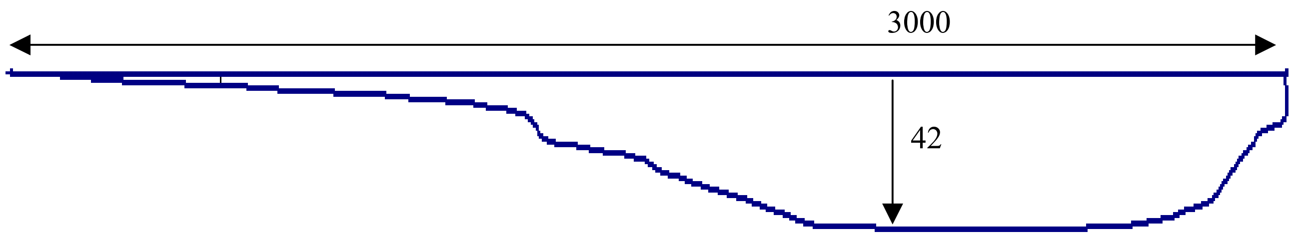


Figure 44. Observed and Calculated TDG Saturation in the Columbia River at Camas/Washougal (CWMW) and in the forebay of Bonneville Dam (BON) during June 2005
(Observed – Base condition, Calculated – spill unchanged from base condition with forebay TDG saturation 2 percent higher than base condition)



a. Columbia River Channel upstream of Bonneville Dam, 8.2% x-section area is above compensation depth at 115%.



b. Columbia River Channel downstream of Bonneville Dam, 21.1 % x-section area is above compensation depth at 115%.

Figure 45. Estimation of the percentage of cross sectional area in the Columbia River above the compensation depth.

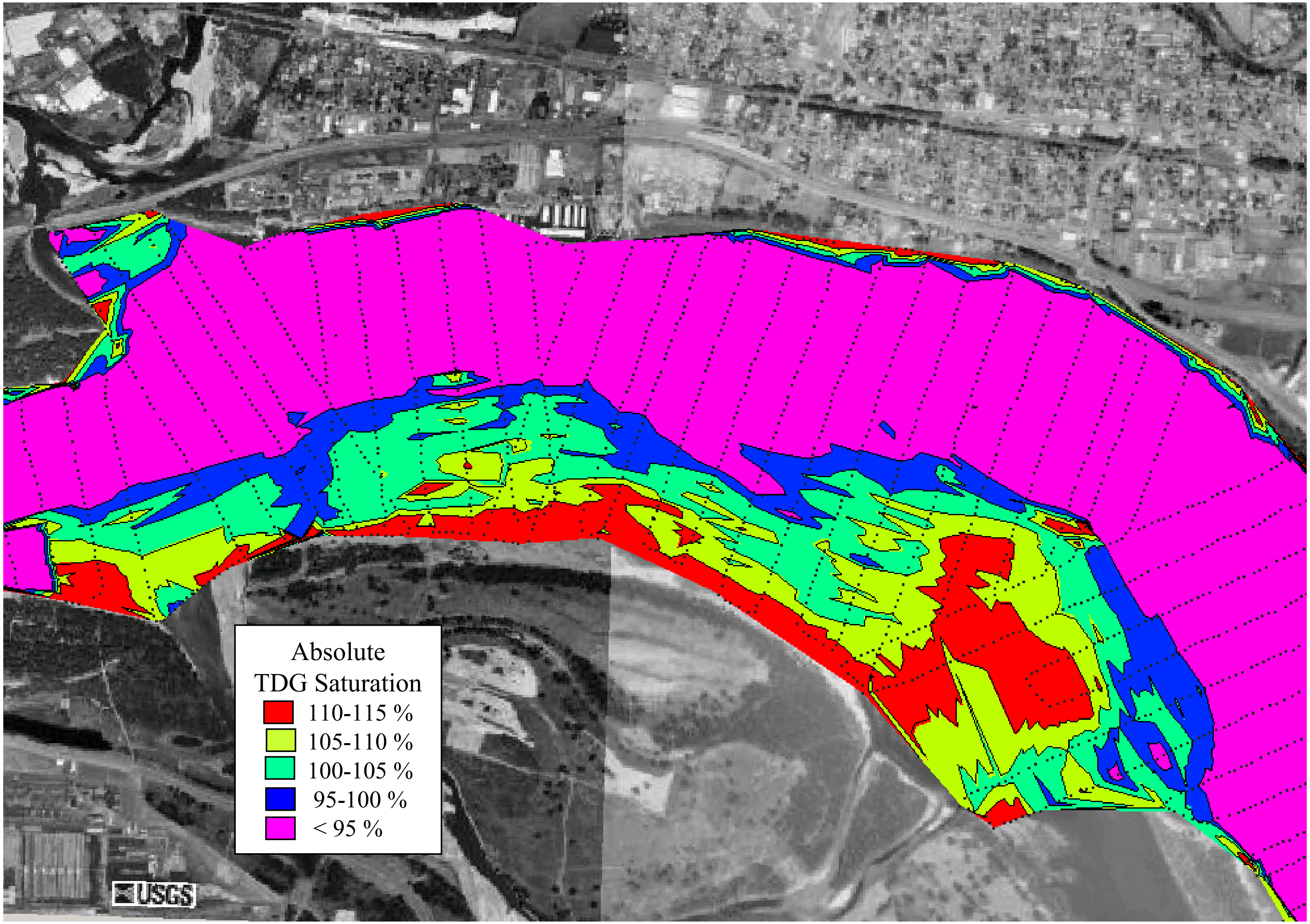


Figure 46. Absolute TDG Saturation at the channel bed of the Columbia River
(Stage 10 ft NGVD, TDG Saturation 115%,)