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Total Dissolved Gas Exchange at Albeni Falls Dam, 2003

Prepared for US Army Engineer District, Seattle; Seattle, Washington

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Executive Summary

The total dissolved gas (TDG) exchange properties at Albeni Falls Dam were investigated during May-June 2003. The TDG pressures were continuously sampled above and below Albeni Falls Dam during standard and alternative project operations to determine the change in the TDG levels in the Pend Oreille River, to identify TDG abatement operations, and to support the location of permanent fixed monitoring stations. The alternative project operations called for variations in the number and location of spill bays used to pass scheduled Pend Oreille River flows. The prominent findings from this study are as follows.

- The TDG levels in the forebay of Albeni Falls Dam were supersaturated throughout the study period from upstream natural and anthropogenic sources. The forebay TDG saturation frequently exceeded the Idaho water quality standards of 110 percent.

- The lateral distribution of TDG saturation in the forebay of Albeni Falls Dam was non-uniform for a portion of the study period. The TDG levels on the powerhouse side of the forebay experienced lower TDG conditions when compared to the spillway side of the forebay because of the influence of Priest River flows.

- The TDG pressures observed in Albeni Falls powerhouse releases were similar to the TDG pressures observed upstream of the powerhouse during the study period in 2003.

- Spillway operations at Albeni Falls Dam during the 2003 spill season increased the TDG loading in the Pend Oreille River by an average of 1.1 percent of saturation. The small increase in TDG pressure during spill is attributable to the low project head, shallow stilling basin channel, and wide spillway.

- Spillway releases using a gate opening of one foot resulted in no measurable change in TDG saturation from forebay levels. The maximum spillway capacity without changing the TDG saturation in the Pend Oreille River could be achieved by setting all ten spill bays to a one foot opening.

- The elevated TDG pressures observed below the spillway prior to dilution from powerhouse flows were a function of the initial forebay TDG pressure, spill pattern, total project head, aerated depth of flow below the

spillway, and downstream submergence of the spill gate lip. The TDG exchange associated with spillway operation at Albeni Falls Dam is best described by determining the increase in TDG pressure above forebay levels.

- The mixing zone between powerhouse and spillway flows extended over 1.6 miles downstream of the dam causing the TDG saturation to vary laterally across the Pend Oreille River. The maximum TDG saturation was consistently observed directly below the spillway and along the left channel bank (spillway side) while the lowest TDG saturations were associated with powerhouse releases along the right channel bank (powerhouse side).

- The establishment of routine fixed monitoring stations above and downstream of Albeni Falls Dam will enable the assessment of project impacts on the TDG loading in the Pend Oreille River, help determine compliance with state water quality standards for total dissolved gas saturation, and allow further evaluation of alternative spill patterns to minimize the generation of TDG supersaturation.

- The application of free flow conditions through several bays does hold promise to minimize the TDG production at Albeni Falls Dam particularly during low head conditions. Further experimentation with alternative spill patterns should be scheduled in the future to evaluate the effectiveness of alternative spill patterns on TDG management.

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Preface

The U.S. Army Engineer District, Seattle (NWS) funded the work described in this report. The authors would like to thank the following NWS personnel for their assistance in implementing the project: Joe Summers, Robert Schloss, Marian Valentine, and Kent Easthouse.

The report was prepared by Mr. Mike Schneider, U.S. Army Engineer Research and Development Center (ERDC)-Coastal and Hydraulics Laboratory (CHL), Ms. Laurin Yates, CHL, and Ms. Kathryn Barko, (contractor). Dr. Steve Wilhelms (CHL) provided technical review of this work.

The following document represents a summary of the total dissolved gas exchange study conducted at Albeni Falls Dam on the Pend Oreille River during May-June 2003. The document contains references to several digital video clips of flow conditions observed during the study period. An animation of project operations and changes in total dissolved gas (TDG) saturation has also been produced and is referenced in this report. All of these moving pictures are best viewed with the QuickTime media player, which provides greater flexibility during playback and can be downloaded from http://www.apple.com. Any questions or comments regarding this document can be addressed to Mike Schneider 541-298-6872.

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Background

The Albeni Falls Dam was built at the site of a natural falls called Albeni Falls. Prior to construction of the Dam, Albeni Falls impeded the spring runoff causing frequent flooding along the Pend Oreille River and Lake Pend Oreille. Congress authorized the construction of Albeni Falls dam in 1950 under the Flood Control Act of 1950. Construction began at the falls in 1951 and by 1952 the dam was operational for flood control. The Albeni Falls dam was completed in December of 1955 and produces over 200 million kilowatt hours of electrical energy each year with three Kaplan turbines and has significantly reduced the frequency of spring flooding.

The presence of aerated flow in a river caused by a natural water fall or water passing over a manmade spillway will promote the exchange of atmospheric gasses with the water. If a sufficient volume of air bubbles are entrained and exposed to pressures above the local atmospheric pressure, the transfer of atmospheric gasses into solution can result in waters becoming supersaturated. This excessive amount of total dissolved gas pressure in the river can expose fish and other aquatic organisms to gas bubble trauma (GBT). The signs of GBT in fish include bubbles in the lateral line, fins, external body surface, and gills. These symptoms can cause sub-lethal and indirect physiological consequences or in extreme cases, mortality.

The US Army Corps of Engineers, Seattle District (NWS) is responsible for the operation of Albeni Falls Dam and related water quality impacts to the Pend Oreille River. The state of Idaho's water quality standards for total dissolved gas saturation are 110 percent. The US Fish and Wildlife Service's (USFWS) 2000 Biological Opinion reasonable and prudent measure (RPM) 11.A.1.3.c recommended the NWS to evaluate and report to the service on TDG concentrations downstream of Albeni Falls Dam in the Pend Oreille River which may occur within the full range of operations of the facility, including forced spills. To meet the USFWS requirements, the NWS proposed monitoring TDG saturations in the Pend Oreille River above and below Albeni Falls Dam during a portion of the spring and summer of 2003. To quantify TDG exchange during spillway operations at Albeni Falls Dam, NWS tasked the ERDC CHL to conduct a comprehensive evaluation of TDG exchange.

Objectives

The proposed TDG monitoring study at Albeni Falls Dam was directed at describing spatial and temporal TDG exchange and transport characteristics both near the dam and downstream in the Pend Oreille River for a range of project operations. The TDG exchange characteristics of both powerhouse and spillway releases were determined by measuring the TDG levels upstream and downstream of the dam. The variation in TDG exchange was investigated for both standard and alternative spill patterns. The influence of other potential casual factors on TDG exchange, such as total project head, tailwater depth of flow, spill gate submergence, percent of river spilled, forebay TDG saturation, and water temperature were also explored during this investigation.

The specific objectives of the field study were:

- Quantify the background total dissolved gas pressures and water temperatures in the Albeni Falls Dam forebay throughout the study period.
- Describe the TDG pressures in both powerhouse and spillway flows downstream of Albeni Falls Dam associated with a range of operating conditions.
- Quantify the extent of the mixed zone between powerhouse and spillway releases and the resultant TDG loading of the Pend Oreille River for a range of operating and TDG background conditions.
- Provide guidance for future water quality (WQ) monitoring plans.
- Provide recommendations for TDG management alternatives associated with Albeni Falls Dam spillway operations.

The information obtained from this study at Albeni Falls Dam will help determine compliance with state and federal water quality standards, develop TDG management alternatives, establish an effective TDG monitoring program, and quantify project impacts on the TDG loading and habitat in the Pend Oreille River.

Approach

A TDG monitoring study was conducted to address the objectives stated above by deploying an array of automated remote logging water quality instruments that were capable of sampling the complete time histories of TDG pressures and water temperatures in the river system. The water quality instruments were deployed in the Pend Oreille River during May and June of 2003 during peak river flows resulting in a wide range of forced spill conditions at Albeni Falls Dam.

The TDG sampling array was deployed both above and below the dam in order to document the lateral and longitudinal TDG characteristics in the Pend Oreille River during the study period. The lateral array below the dam was designed to capture the different TDG conditions associated with powerhouse and spillway releases and the net TDG loading to the Pend Oreille River. The data collected by the water quality instrumentation during the study included the date, time, instrument depth, water temperature, TDG pressure, and internal battery voltage. The geographic location of each sampling station was also recorded. The water quality parameter of primary interest was the TDG pressure. These data were collected on a fifteen-minute interval during the deployment period. In addition, barometric pressure and air temperature were monitored near Albeni Falls Dam at a similar interval to allow the calculation of TDG percent saturation. Manual sampling was used where and when necessary to supplement observations collected from the fixed position instrument array.

The flow field at the downstream TDG sampling transect as determined by the United States Geological Survey (USGS), was used to estimate the average cross sectional TDG pressure in the Pend Oreille River. This computation allowed the estimation of the net change in TDG pressure in the Pend Oreille River associated with specific Albeni Falls Dam operations.

Total Dissolved Gas Properties and Processes

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 and the atmospheric composition of these gases are 20.95, 78.087, 0.93, and 0.03 percent, respectively. Henry's Law relates the solubility or mass concentration of a given gas to the partial pressure. The constant of proportionality, called Henry's constant or the Bunsen coefficient, is a function of barometric pressure, temperature, and salinity. The mass 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. For constant temperature and atmospheric pressure conditions, the total dissolved gas pressure can be represented as either a concentration or pressure in conservation statements.

The solubility of a gas in water is dependent on the total pressure, water temperature, and salinity. The total pressure in the water column is composed of the barometric pressure and hydrostatic pressure. The solubility of gas in water doubles at a depth of about 33 ft in response to a doubling of the total pressure. The compensation depth is where the saturation concentration is equal to the ambient concentration in the water. The solubility of gas in water is inversely proportional to the water temperature. As a consequence, any change in water temperature will induce a change in the total dissolved gas pressure and associated saturation. For example, if the total concentration of dissolved gases in a constant mass sample is 30 mg/l, an increase in temperature of 1^{o} C will result in a reduction in the saturation concentration and an increase in the TDG saturation of 2.2 percent.

TDG Exchange Processes

The TDG exchange characteristics at a hydraulic structure are closely coupled to the system hydrodynamics. As the flow conditions are altered by structural or operational means, the total dissolved gas exchange is also modified.

The following general description of processes governing TDG exchange at hydropower dams has been formulated based in part upon the theory of mass exchange, laboratory studies, and near-field TDG studies conducted as part of the Dissolved Gas Abatement Study (USACE, 1997). This discussion focuses upon the hydrodynamic and mass exchange characteristics in four regions: forebay, spillway/turbine passage, stilling basin, and tailwater channel.

Forebay

The TDG properties in the immediate forebay of a dam have generally been found to be well mixed when no thermal stratification is present. Thermal stratification can limit the influence of air/water exchange of gasses to the near surface layers of a pool. The heating or cooling of an impoundment can cause total gas pressure responses that result in supersaturated conditions. Biological activity involving the production or consumption of oxygen will influence the total dissolved gas pressure. Therefore, under stratified conditions, the initial TDG pressure of spillway releases may be different from those associated with hydropower releases. TDG levels in the forebay can change rapidly in response to operations of upstream projects, tributary inflows, and meteorological conditions. The flow under a spillway gate or into a turbine intake may spawn air-entraining vortices that provide a vehicle for air entrainment and mass transfer. In general, the TDG concentrations are not significantly altered by near-field flow conditions in the forebay.

The TDG properties in the forebay of Albeni Falls Dam are influenced by upstream operations at Cabinet Gorge Dam and tributary inflows from the Priest River. Lateral gradients in TDG saturation are evident in the forebay of Albeni Falls Dam due to the incomplete mixing between the flows of Priest River and the Pend Oreille River.

Spillway

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 sufficient surface turbulence and water spray to entrain air. Flow on the spillway may become aerated for smaller specific discharges 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 thereby limit the amount of gas exchange. The entrained air and shallow flow on the spillway may cause desorption of dissolved gases if forebay levels are elevated.

At a low head project like Albeni Falls, the spillway release is typically submerged limiting the formation of self aerating conditions on the spillway.

Turbine Passage

There is little opportunity for entrained air to be introduced into the confined flow path through a turbine, except during turbine startup or shutdown, when air may be aspirated into the turbine. Under some conditions it may be advantageous to introduce air into a turbine to prevent cavitation or smooth operation. When air is introduced into a turbine, the opportunity exists for mass transfer to occur resulting in TDG supersaturation. The extent of TDG transfer in a turbine will be dependent upon the amount of air introduced and the total pressures encountered. In most cases where no air is introduced, there is no appreciable change in TDG pressure as flows pass through the penstock, turbine, and draft tube. The powerhouse simply conveys the TDG properties withdrawn from the forebay pool to the tailwater and does not directly contribute to higher TDG loading.

The powerhouse operation at Albeni Falls Dam during low head conditions can actuate the vacuum breaker system and introduce air into turbine releases. This type of operation may result in a measurable change in TDG levels in the Pend Oreille River.

Entrainment of Powerhouse Releases

The high energy content and dissipation rate of spillway flows has the potential to entrain large volumes of water into highly aerated flow contributing to the TDG loading of project releases. Powerhouse discharge may either be entrained into spillway flows in the stilling basin, or mixed with spillway releases in the river channel downstream. When the spillway is adjacent to the powerhouse, a portion of this entrainment flow is supplied directly from powerhouse releases. This entrained flow is exposed to entrapped air bubbles causing some degree of uptake of dissolved gas. The fate of powerhouse discharges varies from project to project and depends upon operating conditions, structural features such as training walls and energy dissipation features, and tailwater channel properties. The findings from the Little Goose spillway performance test (Schneider and Wilhelms, 1998) showed that during some operations nearly all of the powerhouse flow was entrained into spillway releases and gassed to comparable pressures.

The interaction of powerhouse and spillway flows at Albeni Falls Dam is influenced by the natural island separating the powerhouse from the spillway. However, an upstream flow was observed during some spill patterns near this island conveying water originating from the powerhouse into the region of highly aerated flow below the spillway.

Stilling Basin

The flow conditions in the stilling basin are often highly three-dimensional and are shaped by the presence of nappe deflectors, spill pattern, spillway piers, training walls, baffle blocks, end sill, tailwater pool elevation, project head, and spillway geometry. In general, however, the flow conditions downstream of a standard spillway are characterized by highly aerated flow plunging to the bottom of the stilling basin. The baffle blocks and end sill redistribute the bottom-oriented discharge jet throughout the water column. 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 below the spillway. These flow conditions result in a local peak in TDG pressures experienced below the dam.

There is no formal stilling basin below the spillway at Albeni Falls Dam. The spill is discharged directly onto the natural channel bed with a range of channel elevations. The small project head and submergence of the spill discharge under the spillway control gates can limit the entrainment of air into spillway releases at Albeni Falls Dam.

Tailwater Channel

A rapid and substantial desorption of supersaturated dissolved gas takes place in the tailwater channel immediately downstream of the stilling basin. As the entrained air bubbles are transported downstream, they rise above the compensation depth in the shallow tailwater channel. 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 as the air bubbles rise and escape to the atmosphere. The desorption of dissolved gas appears to be quickly arrested by the loss of entrained air within 200-500 hundred feet of the stilling basin. The reduction of TDG pressures downstream from the aerated flow regime are generally the result of dilution, temperature change, surface exchange, and chemical/biological processes.

The depth of the tailwater channel appears to be a key parameter in determining TDG levels entering the downstream pool. 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 the greatest influence on TDG levels delivered downstream during high spill discharges. This process may account for the upper limit on TDG exchange observed at many Corps projects at high spillway discharges.

Mixing Zone Development

The TDG content of powerhouse and spillway releases often contain quite different TDG pressure characteristics. The interaction of project powerhouse and spillway flows can be characterized by the development of the mixing zone. The mixing zone refers to the properties that develop downstream of the highly aerated flow regime and can be thought of as the redistribution of TDG concentrations that are established during the aerated flow conditions associated with spillway operations. Hydropower releases entrained into the aerated spillway flows will often be exposed to similar levels of TDG exchange as experienced by spillway releases. The entrained hydropower releases can be thought of as adding to the effective spillway discharge from a project. These processes will also effectively reduce the amount of hydropower flows available for dilution of spillway releases in the mixing zone.

The development of the mixing zone below a project will influence the spatial distribution of TDG properties in the downstream pool. The understanding of the development of the mixing zone is critical to the interpretation of observed downstream TDG pressures. In regions where the mixing zone between powerhouse and spillway releases are not fully developed, lateral gradients in TDG pressure are present and point observations of TDG pressure will be biased by local project releases. 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 operational history, and the entrainment of powerhouse flows into the aerated spillway flows.

Riverine TDG Exchange Processes

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 longwave and shortwave radiation and 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 development of vertical gradients in water temperature can also develop on a diurnal basis in pools or near-dam areas where vertical mixing is limited by slack water and calm winds. These vertical gradients in temperature can also develop in areas where tributary inflows contain water temperatures that are significantly different from the primary river. These processes can result in forebay water temperatures that are significantly higher than tailwater water temperatures and as a consequence, significantly influence TDG pressures.

The TDG levels generally increase during spillway operations at main-stem dams due to the entrainment of bubbles in the stilling basin. Once most of the air bubbles are vented back to the atmosphere, exchange of total dissolved gas pressure at the air-water interface is driven towards equilibrium with atmospheric conditions. 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.

Site Characterization

Albeni Falls Dam is located in Bonner County, ID near the Washington - Idaho border on the Pend Oreille River at river mile 90.1 (RM 90.1), about 2.5 miles upstream and east of the city of Newport, Washington, 26 miles west of Sandpoint, Idaho, and 29 miles downstream from Lake Pend Oreille. Project location and vicinity are shown in Figure 1. The project is authorized for regulation of Lake Pend Oreille and associated purposes of flood control, navigation, fish and wildlife conservation, recreation and power generation. Box Canyon Dam owned by Pend Oreille County PUD No. 1 is located on the Pend Oreille River 55.7 miles downstream from Albeni Falls Dam at river mile 34.4. Cabinet Gorge Dam is located on the Clark Fork River upstream of Lake Pend Oreille at river mile 150.

Albeni Falls Dam is formed by two separate concrete gravity structures, a 10-bay spillway on the left or southwest side of the river and a powerhouse on the right or northeast side of the river (Figure 2). The spillway and powerhouse structures are separated by a non-overflow natural rock island near mid-channel. The total dam length is approximately 1,080 ft, which includes the 300-ft powerhouse, and the 472-ft spillway structure. The rock island section connecting the spillway and powerhouse structures is about 240 ft long.

The spillway structure contains 10 bays and 10 roller train, vertical lift, span-type gates, 32 ft high and 40 ft wide. Spillway crest elevation is at El 2033 ft[1]. Each gate has an upper and lower leaf, 19 ft high and 13 ft high, respectively, which are latched together for normal operation (Figure 3). All gate changes are made with an overhead rail-mounted gantry crane that travels on the spillway top deck. A typical cross sectional view of the spillway, gates, and sill are shown in Figure 4.

The downstream spillway gate slots for each of the ten spillway bays have 18 dogging steps to provide openings for normal regulation purposes. The first step is 1 ft, the next 14 steps are at l ½ ft increments, and the top 3 steps are at 6 ft increments. Spillway capacity is 420,000 cfs at El 2097 ft, the top-of-dam elevation. The structurally-safe spillway discharge is estimated to be about 500,000 cfs at forebay El 2106 ft. There are no sluiceways.

[1] All elevations cite herein are in feet and referenced to the NGVD Datum. To convert to meters, multiply number of feet by 0.3048 meters per foot.

The stilling basin below the spillway at Albeni Falls Dam consists of the natural bedrock. A coarse map of the channel bed below the spillway was constructed by merging the as built topography at the toe of the spillway (Figure 5) with depth sounding on three lateral transects located below the structure. The channel bed elevation downstream from bays 4-10 is 2022 ft resulting in a typical depth of flow of 15-20 ft. A natural plunge pool is located downstream from spill bays 1-3 with a minimum elevation of about 1994 ft and typical depth of flow of 43-48 ft as shown in Figure 6. The tailwater channel remains relatively shallow downstream from the middle section of the spillway (bays 4-6). A second major plunge pool in the tailwater channel is located downstream from the spill bays 8 and 9 with a minimum elevation of about 2000 ft and a typical depth of flow of 37–42 ft (Figure 6).

The powerhouse at Albeni Falls Dam is 300 ft long and 164 ft wide, indoor type, housing three Kaplan-type turbines, each rated 14,622 kilowatts (kW). During the spring runoff when high powerhouse tailwater reduces the hydraulic head to less than 8 ft, hydroelectric operation is curtailed.

Water control measures are applied at Albeni Falls Dam to control the level of Lake Pend Oreille according to the season. The lake is maintained in its normal range of between 2,062.0 and 2062.5 ft above sea level during the summer months as shown in Figure 7. In the fall, normally after Labor Day, the lake is drafted to its winter level of 2051.0 ft. to provide room for flood storage. The lake is maintained in its low range until the spring snowmelt again refills the lake during April-June. The tailwater stage at Albeni Falls Dam is a function of river flow and to a limited extent, the stage maintained in the Box Canyon Pool. During typical operations the tailwater stage ranges from 2028-2030 ft for flows less than 10 kcfs, to 2041ft at a flow of 50 kcfs, to 2049.5 ft at 100 kcfs discharge. At high river discharges the total head becomes small and hydropower operations cease, and free flow conditions are provided through the spillway.

Study Design

A total of thirteen instruments were deployed in the Pend Oreille River on May 6, 2003, at eleven different stations on three transects as shown in Figure 8. The purpose of this sampling scheme was to determine the change in the TDG levels in the Pend Oreille River caused by the operation of Albeni Falls Dam. The ambient TDG levels approaching the dam were determined by sampling in the forebay on Transect FB. The resultant TDG levels exiting the spillway undiluted from powerhouse flows were determined by sampling on Transect T2. The average cross-sectional TDG loading in the Pend Oreille River was established by sampling TDG levels on Transect T3. The Hydrolab Corporation DS4 and Minisonde 4 water quality sondes were used during this study. The TDG pressure, water temperature, instrument depth, and instrument voltages were measured at the sampling stations during the study period on a 15-minute frequency. The detailed description of the study design for TDG exchange at Albeni Falls Dam during the 2003 spill season is found in Appendix A.

Three instruments were deployed in the forebay of the Albeni Falls Dam. The station FBP3 was deployed from the platform on the right bank above the powerhouse. The station FBP2 was located in the middle of the river at the cofferdam spur between the spillway and powerhouse. The station FBP1 was suspended from the abutment for the railroad bridge on the left bank. The locations of these sampling stations are shown in a photograph taken from the left bank in Figure 9 and on an aerial photograph in Figure 10. These instruments were set at fixed elevations in the forebay and the depth of the sample varied as the forebay pool was raised during the study period.

Four instruments were positioned immediately below the dam on a second sampling Transect (T2) as shown in Figure 10. Three stations were sited approximately 480 to 595 ft below the spillway on the channel bottom in steel housings. The average depth of deployment for Stations T2P1, T2P2, and T2P3 were 28.4, 20.5, and 14.7 ft, respectively. The three stations (T2P1, T2P2, and T2P3) were located approximately 175, 320, and 516 ft, respectively, from the left channel bank. A fourth station (DTD) was suspended from the railing on the afterdeck of the powerhouse in the discharge from turbine 1. The spillway was shut down prior to the deployment of Transect T2 instruments at 1000 hrs on May 6, 2003. Several mobile transects were run with the sampling boat near the base of the spillway to gather channel bed depth information.

The third sampling transect, T3, was positioned about 1.6 miles below the dam at the site of a USGS gauging station and city water supply intake (Figure 11). Five stations were deployed at regular intervals across the channel with the depth of flow ranging from 8 to 14 ft (T3P1, T3P2, T3P3, T3P4, and T3P5). A duplicate instrument ($T3P1_{Dup}$) was deployed adjacent to T3P1 near the left channel bank. All the instruments with the exception of Stations FBP3, FBP1, and DTD were deployed on the channel bottom. The channel width at Transect T3 was 1064 ft with station distances from the left bank established at the following distances: T3P1-119 ft, T3P2-329 ft., T3P3-492 ft., T3P4-606 ft., and T3P5-830 ft.

The automated logging TDG instruments were deployed in the river for a period of up to two months to monitor the full range of Albeni Falls Dam operations. During the study period, the instruments in the forebay and below the powerhouse (DTD) were serviced on June 6. Instruments were removed once spillway operations were no longer needed at Albeni Falls Dam. The data were downloaded from the instruments and subjected to a quality assurance/quality control (QA/QC) post deployment calibration. The quality assurance and control summary for this study are found in Appendix B of this report.

Project Operation

The TDG exchange associated with project operations at Albeni Falls Dam were monitored during May 6–June 27, 2003. The hourly operations were dictated by water control measures on the Pend Oreille River, which required continuous spillway operations from May 6 to June 27. The flows in the Pend Oreille River were below normal in May and June of 2003. The daily average discharges at Albeni Falls Dam in 2003 are shown in comparison to the 10th, 50^{th}, and 90^{th} percentile flows in Figure 12. In 2003, the peak daily flows of about 68 kcfs approached the mean historical flows at Albeni Falls Dam during the first week in June. The inflow hydrograph during the 2003 spring runoff dictated a rapid increase and decrease in project flows from Albeni Falls Dam.

Lake Pend Oreille. Albeni Falls Dam controls the level of Lake Pend Oreille as dictated by the water regulation curve. During the study period, the forebay elevation ranged from 2,052 ft during the beginning of May to a maximum elevation of 2,062 by the end of June. The hourly forebay and tailwater elevation at Albeni Falls Dam are shown in Figure 13. The increase in storage in Lake Pend Oreille of about 10 ft resulted in a significant increase in total head at the project during the study period. The available head at Albeni Falls Dam ranged from a minimum of 11.2 ft to over 23.1 ft near the end of the study period. The smaller head conditions corresponded with the higher flow events when the Lake Pend Oreille was not filled and the tailwater elevation was at its maximum levels.

Powerhouse Operation. The powerhouse discharge ranged from 20.2 kcfs to over 33.5 kcfs as a function of the total project head. The minimum powerhouse discharge (20.2 kcfs) occurred during the highest river discharge of 67.8 kcfs resulting in only about 30 percent of the river passing through the powerhouse. The powerhouse discharge increased as the level in Lake Pend Oreille approached full pool in June. The three turbines were generally delivering similar electrical output. The hourly total project and spill discharge are shown in Figure 13 during the study period.

Spill Discharge/Pattern. The spillway operations at Albeni Falls Dam were initiated on May 6, 2003, and continued through June 27, 2004. The highest spill discharge of 47.4 kcfs occurred from June 3-5 for almost 46 hours. The standard spillway operation called for the opening of middle spillbays (4, 5, and 6) at low discharges followed by successively opening lower and higher numbered bays as the spill discharge increased. The standard spill pattern is not formally documented. Alternative spill patterns were recommended during the course of the study calling for a uniform spill discharge over 10, 6, and 3 spillbays for a duration of at least 4 hours. These alternative spill patterns were periodically scheduled during the 2003 spill season as listed in Table 1.

Study Events. A series of 30 operational events were defined to help quantify the study finding. An independent event was identified when a constant spill discharge and spill pattern was maintained for a duration of 4 hours or longer. The information pertaining to the first two hours of an event were not used in summary statistics because of the transitional state of observed TDG properties. A summary of the 30 spill events monitored during the 2003 spill season at Albeni Falls Dam are listed in Table 1 and shown in Figure 13. The spill events ranged in duration from about 8 hrs to 8 days. The spill discharge ranged from 1.9 kcfs to a maximum of 47.4 kcfs or about 70 percent of the total flow in the Pend Oreille River. Some of the important project attributes contributing to the TDG exchange at Albeni Falls Dam did vary during events defined only by maintaining a constant spill pattern. The project head, water temperature, and the TDG pressure just upstream of the dam were not used to further group observations into independent operational events. Other project properties such as gate submergence (S=gate elevation-tailwater elevation ft), total head (H=forebay elevation – tailwater elevation, ft), and specific discharge (q_s=spill discharge divided by number of active spill bays, kcfs/bay) were also calculated for each event as listed in Table 1. A summary of spill bay discharge and pattern for each event number is listed in Table 2.

Results

Hydrodynamics

The surface flows and entrained air conditions were observed and recorded on video and still photography during many of the daylight hours of testing during May 6-7 and June 5. The following observations pertain to several notable characteristics of those flow conditions.

Turbulent aerated flow developed on the downstream side of the vertical spillway gates when the gate opening was greater than 1 ft. At the lowest gate setting of 1 ft, the spillway release remained free of air entrainment due to the low exit velocity and submergence over the gate opening. A photograph (Figure 14) taken on May 7, 2003 at 1700 hrs during event 2, shows the flow conditions exiting a 1 ft gate opening on Bay 2 versus a 2.5 ft gate opening on spill bay 3. The larger gate opening resulted in highly aerated flow conditions in the tailwater channel while the flow exiting the 1 ft gate opening was relatively free of entrained air bubbles.

The aerated flow plunged into the tailwater channel below the stilling basin at the base of the spillway. The plunging jet generated a roller and surface return current to the base of the spillway. A zone of highly turbulent aerated flow was dependent upon the discharge through the spill bay. The stilling basin flow conditions for a 13.2-kcfs spill are shown in Figures 14 and 15 for a 4 and 8 bay spill patterns. The plume of highly aerated flow conditions extends much further downstream during the 4 bay spill pattern compared to the 8 bay spill patterns.

The white water and surface foam provided a means to visualize the movement of spillway flow downstream of the spillway as shown in the video clip in Figure 16. The spill of 7.8 kcfs through three bays on May 5 generates an aerated plume that extends several hundred feet downstream before most of the air is vented back to the atmosphere. The turbulent intensity of bubbly flow in a spill of 35.9 kcfs during Event 20 is shown in Figure 17. The plunging jet and resultant boil associated with each spill bay is clearly seen in this video. The highly aerated spillway discharge extends well downstream of the spillway.

The mixing zone between powerhouse and spillway releases develops downstream of the island separating these structures. In some cases, where the spill pattern is limited to several bays, a return current develops along the north (right) side of the spillway. When the spill discharge is concentrated in several interior bays (3-6), higher velocities were observed near the south shore. In contrast, when spill was distributed among all 10 bays, lower velocities were observed near the south shore (or left bank).

The flow conditions below the powerhouse were characterized by a series of boils associated with flow exiting the draft tubes of the three active turbines. The surface flow conditions below the powerhouse are shown in Figure 18. The entrainment of air into powerhouse flows was minimal in this region of the exit channel when observed during the study period.

The flow distribution in the Pend Oreille River below the dam was generally well behaved with velocities near Transect T3 being nearly uniform. A quantitative description of the velocity field at Transect T3 was obtained from USGS records for flows ranging from 16 to 96 kcfs. The channel bathymetry and velocity distribution for a total river flow of 54 kcfs is shown in Figure 19. The velocity magnitude ranged from 2.6 to 3.7 fps in water with a depth of 15 ft or greater with lower velocities located in the shallower channel bank regions. The normalized cumulative flow distribution was determined for the T3 transect for five flow conditions: 15.6, 41.8, 53.8, 87.5, and 95.9 kcfs. The detailed velocity records are listed in Appendix C. The normalized flow distribution was found to be similar for all five flow conditions as shown in Figure 20. This summary of the flow distribution was used to flow-weight the TDG pressures observed on Transect T3.

Study Database

Data collected and compiled for this study can be found in the Microsoft Access file called "Albeni Falls TDG 2003.mdb". This database is made up of three tables: "data-all", "data-ops", and "data-deployment". The table "data-all" contains 15-minute water quality data and includes the parameters: Station, DateTime, Date, Time, Temp (temperature, °C), Depth (ft), TDG (total dissolved gas, mmHg), IBatt (battery life, volts), and Check. A Check value of 0 represents unreliable or erroneous data while a Check value of 1 represents reliable or good data. For this report, only data with a Check value of 1 was analyzed. The table "data-ops" contain hourly project operations data collected at Albeni Falls Dam. The parameters that make up this table include DateTime, Date, Time, S1-S10 (discharge through each spill bay, kcfs), T1-T3 (discharge through each turbine, cfs), Qtotal (total river flow, kcfs and cfs), Qspill (total spill flow, cfs), Qgen (total generation flow, cfs), FBE (forebay elevation, ft), TWE (tailwater elevation, ft), Head (difference between FBE and TWE, ft), #Bays (number of active spill bays), q_s (average spill per bay, kcfs), and Open (average amount of gate opening, ft). The last table found in the "Albeni Falls TDG 2003" database is called data-deployment which includes a list of each water quality sampling station, the serial number of the instrument at that station, and the geographic coordinates in latitude and longitude (NAD83) collected at that station using a Garmin GPS76.

Albeni Falls Dam Forebay

The water temperature and TDG pressures in the Pend Oreille River just upstream of Albeni Falls Dam were recorded at three stations located adjacent to the left channel bank (FBP1), between the spillway and powerhouse (FBP2), and adjacent to the right channel bank just upstream of the powerhouse (FBP3) as shown in Figure 10. The TDG pressure and water temperature were also monitored in the turbine discharge below the powerhouse from an instrument deployed from the turbine deck at Station DTD.

Water Temperature

The water temperatures in the forebay of Albeni Falls Dam experienced a general warming trend during the course of the study period ranging from 8^o C on May 6 to 18.5^o C on June 27, 2003. Cold fronts lasting for several days caused water temperatures to decline on four occasions; 5/16-18, 5/29-6/1, 6/12-14, and 6/20-23 as shown in Figure 21. A daily temperature cycle was typically observed during sunny days where the daily maximum temperatures were typically about 1° C warmer than the daily minimum temperatures.

The lateral temperature gradients in the forebay were generally small, less than 0.5^o C. On several occasions the temperatures measured near the right channel bank at Station FBP3 were over 1^o C colder than temperatures observed at Station FBP1. This temperature gradient is likely caused by the influence of Priest River inflows 1.5 miles upstream of Albeni Falls Dam. The aerial photograph of turbid inflows from Priest River to the Pend Oreille River shown in Figure 22 clearly shows a distinct turbidity plume extending from the confluence of the Priest River to the forebay of Albeni Falls Dam.

The presence of prominent vertical thermal gradients in the forebay of Albeni Falls Dam were not evident in the water quality sampling array for this study. The forebay instruments were sited at various elevations in the forebay and the depth varied as the forebay elevation changed and with redeployment of instrumentation after equipment servicing as shown in Figure 23. The temperatures at Stations FBP1 and FBP2 were nearly identical from May 6-June 5 (Figure 21) where the sample depth at Station FBP1 ranged from 0.4 to 3.4 meters compared to a depth range of 2.2 to 7.2 meters at Station FBP2.

Total Dissolved Gas

The TDG levels reported herein are expressed as pressure in mm of mercury or as TDG saturation (%). TDG saturation was determined by dividing the TDG pressure by the local atmospheric pressure observed at the office complex located near the powerhouse below the dam. This normalization of TDG pressure will introduce a small degree of error at stations located at different elevations, such as in the forebay or at larger distances from the dam. However, the small elevation difference between forebay and tailwater stations will result in a less than 1 mm Hg change in atmospheric pressure that falls within the measurement accuracy of the sensor.

The TDG saturations at the forebay stations (FB) were consistently supersaturated throughout the study period. The TDG pressures ranged from a low of 720 mm Hg on May 7 and peaked at 810 mm Hg on June 9th as shown in Figure 24. The local atmospheric pressure was found to range from 692 to 720 mm Hg (BP in Figure 24). The highest forebay TDG levels lagged the peak river discharges by about 5 days and are likely related to operations at Cabinet Gorge Dam.

This study was not structured to identify the source of the forebay TDG pressures in the Pend Oreille River. However, the hourly flow records from Cabinet Gorge Dam during the spring of 2003 indicate that spillway releases were not initiated until May 26. This source of TDG pressure was probably responsible for the increase in TDG pressures in the forebay of Albeni Falls Dam one week later beginning on June 2 reaching peak levels around 800 mm Hg from June 5-10. The cessation of spill at Cabinet Gorge Dam was on June 15 followed by a marked decline in forebay pressures at Albeni Falls dam one week later. The hourly total dissolved gas saturations recorded at the forebay sampling stations are shown in Figure 25. The TDG saturation of 112 % on May 24 resulted from natural conditions on the Pend Oreille River independent from spilled related sourcing at upstream dams. The heating of Pend Oreille River water at a rate greater than the surface exchange at the water surface was likely one source for the elevated TDG pressures on May 24. The biological productivity associated with dissolved oxygen exchange in the Pend Oreille River is a secondary source of supersaturated TDG levels in the forebay.

The forebay TDG pressures at Albeni Falls Dam are closely related to the meteorological conditions and resultant water temperature fluctuations in the Pend Oreille River. The general decline in TDG pressures on May 15-18, May 30-June 1, and June 20-23 were, in part, caused by the reduction in water temperatures of 1-3^{o} C (Figure 21). The gas laws can be used to estimate the change in TDG pressure as a function of changes in temperature for a constant concentration. 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 is dropped by 1^{o} C, the resultant pressure will equal 724 mm Hg or a 16 mm Hg reduction in total pressure.

The diurnal variation in total pressure is also caused by the temperature fluctuations in the Pend Oreille River. It was common for Pend Oreille water temperatures to increase over 1^{o} C during the solar cycle during the day resulting in a corresponding pressure gain on the order of 16 mm Hg, as shown in Figure 24. On cloudy days where the thermal cycling is weak, the variation in the TDG pressures is also small such as on June 20-23, 2003.

A small lateral gradient in TDG pressure was observed in the forebay of Albeni Falls Dam during the study period. The TDG pressures at Stations FBP1 and FBP2 were 15 mm Hg higher than observations near the right bank (FBP3) and below the powerhouse (DTD) during the period of highest forebay TDG pressure from June 5-10. On June 6 a series of manual samples were taken to investigate the presence of TDG gradients in the forebay of Albeni Falls Dam. A lateral TDG gradient was indicated across the forebay of Albeni Falls Dam where the right bank station (Station FBP3) was about 20 mm Hg lower than the levels observed between the spillway and powerhouse (Station FBP2) and on the left channel bank (Station FBP1). Manual TDG samples were also taken upstream in the Priest River and just upstream of the confluence of the Priest and Pend Oreille Rivers on the right bank. The TDG pressure on June 6 at 1900 hrs in the Priest River was 729 mm Hg compared to 808 mm Hg just upstream in the Pend Oreille River. The lateral gradient in TDG pressure in the forebay of Albeni Falls was likely caused by the incomplete mixing of Priest River and Pend Oreille River waters.

The passage of water through the powerhouse caused no change in TDG pressure as observed at Stations FBP3 and DTD during the study period in 2003. The variation in TDG pressures between the forebay and tailwater observations at the powerhouse were within several mm Hg when the TDG pressure gradients in the forebay were small. The average TDG saturation by event and station are listed in Table 3 for the forebay and DTD stations. The TDG pressure at the DTD station was as much as 10 mm Hg higher than the forebay station (FBP3) when a lateral TDG pressure gradient was present in the forebay as listed in Table 4. When forebay TDG pressure gradients are present at Albeni Falls, the TDG pressure properties of powerhouse releases are best represented by some combination of pressures observed at the stations bounding the powerhouse (FBP2 and FBP3). It could be possible for turbine flow to change the TDG levels in the Pend Oreille River if air is introduced into the turbines at inefficient gate settings or during low head conditions.

Spillway Flow

The three stations (T2P1, T2P2, and T2P3), located approximately 530 ft downstream of the spillway, were located in a position to sample the characteristics of spillway releases downstream from the zone of highly aerated flow prior to mixing with releases from the powerhouse. These sampling stations were in an area of high velocities and turbulence. The circulation patterns in this area were often complex and dependent upon the spill pattern and discharge. The instrumentation was enclosed in a steel housing and deployed on the channel bed. The initial attempts to recover this equipment after the spill season, failed due to a fouled deployment cable. A team of divers were required to recover the instrumentation on August 28, 2003. The divers observed large deposits of gravel and sand (several feet) that had accumulated on the deployment cable. River bed gravel had also accumulated in the instrument housings.

A review of the TDG pressures observed at these three stations strongly suggests that the deposition of river sand and gravel over this equipment influenced the data collected at these three stations. The influence of river bed material deposits on TDG instruments can reduce the observed TDG pressures through restricting water movement past the sensor, pinching the membrane, or reducing the membrane surface area in contact with water. The data collected on this transect was closely reviewed and suspect data flagged. The presence of TDG pressures well below ambient forebay pressures or experiencing abrupt fluctuations were two key indicators of unreliable observations.

Water Temperature

The water temperatures at the T2 stations were nearly identical to the temperatures measured just upstream of the spillway at stations FBP1 and FBP2 as shown in Figure 26. There is one interesting departure from this observation at station T2P1 from May 29 to June 2. The temperature at Station T2P1 abruptly dropped 0.5 ^{o}C on May 29 and abruptly returned to the group temperature on June 2. This departure in water temperature at Station T2P1 could be associated with the deposition of bed material on the instrument followed by material being scoured away from the instrument triggered by an increase in spillway discharge. The colder water temperatures could be related to hyporheic exchange with groundwater.

Total Dissolved Gas

The TDG pressures observed on Transect T2 should be used with caution due to the inconsistent response of the observations. The reliability of this data declines as a function of the length of deployment. In general, the highest TDG pressures were observed on Transect T2 during the first half of the study period when station response appears to be more trustworthy as shown in Figure 27. The TDG observations on Transect T2 that fell below forebay pressures or below the response at nearby stations were removed from Figure 27 (Filtered TDG Data). The TDG pressures at station T2P3 were about 20 mm Hg lower than observed at stations T2P1 and T2P2 during the first two weeks of the study period. These lower pressures could have resulted from dilution with powerhouse flows or faulty instrument response. The post calibration of the instruments at these stations did not indicate a problem. TDG pressures observed on stations T2P1 and T2P2 during the first half of the study period were in general agreement with the TDG pressures observed downstream at station T3P1.

The detailed time history in TDG pressures observed below the spillway on Transect T2 are shown in Figures 27a-h. The response across this sampling array appears to be consistent during May 6-17 (Figure 27a). The TDG pressure drops slightly across the sampling array as a result of the spill pattern change between Events 1 and 2 when the active spill bays changed from four bays (4-7) to eight bays (2-9). The diurnal variation in TDG pressures apparent in the forebay was also evident in TDG pressures fluctuations observed below the spillway. The uptake in TDG pressure in spillway discharge ranged from 30-60 mm Hg during May 6-16.

The TDG pressures observed below the spillway from May 17-28 indicate a transition from a small uptake in TDG pressure during Events 3-5 to no uptake during Events 6-10 as shown in Figure 27b. During Events 6-10, the specific discharge was 0.9 kcfs/bay corresponding with a gate opening of 1 ft, which resulted in no change in the TDG pressure on Transect T2 when compared to forebay TDG pressure levels. Visual observations of the flow conditions associated with a gate opening of 1 ft indicated little or no entrainment of air occurred in the release discharge. A maximum spillway capacity of 9 kcfs could be established at a 1 ft opening without resulting in a change in TDG loading in the Pend Oreille River. The TDG response at station T2P3 was highly correlated with the observations at stations T2P2 and T2P1 during May 17-28 but with a pressure that was 15-20 mm Hg less than these nearby observations (Figure 27c).

The inconsistent TDG response at sampling stations below the spillway were first evident during the higher spill events during May 28-June 8 as shown in Figure 27d. An abrupt reduction in TDG pressures was observed in several instances resulting in TDG pressures below both the forebay TDG levels and the local atmospheric pressure raising questions as to the reliability of these observations. An example of the spurious change in TDG pressure observations for Station T2P1 is shown in Figures 27d. On May 29 the spill pattern was changed in order to pass 25.4 kcfs through 3 spill bays during Event 14. The TDG pressure response at Station T2P1 during this event began to decline, falling to levels below 750 mm Hg. A corresponding decline in TDG pressure was not observed at the downstream station T3P1. The TDG pressure at station T2P1 continued to decline during May 29 and reached an equilibrium pressure of 615 mm Hg the next day. The TDG pressure response at Station T2P1 was not consistent with nearby stations in the sampling array and the very low TDG pressure levels recorded do not reflect physically realistic condition in the Pend Oreille River. These low TDG pressures could be generated in the sand/gravel substrate of the river where water is not freely exchanged with the river. The observations at stations T2P2 and T2P3 also experienced similar abrupt changes in TDG pressure during this time period. The TDG pressure dropout and recovery are often associated with a change in spillway discharge. The spurious TDG observations below the spillway were identified and filtered out of the statistical summary of this data listed in Table 5 and 6. The time history of the filtered TDG saturations on Transect T2 along with project operations are shown in Figure 28 and Figures28a-e.

The response in TDG pressure on Transect T2 during Events 12, 13, and 14 demonstrates the influence of reducing the number of active spill bays from 10 to 6 to 3 bays for a discharge of about 25 to 27.9 kcfs. Of the three events, the 6 bay pattern (Event 13) resulted in the greatest increase in TDG pressure above forebay levels at station T2P1 as shown in Table 6 while the TDG pressure observed at Station T2P2 consistently declined as the number of spill bays was reduced (Figures 27a-h and Figures 28a-e). The six bay pattern may have generated the highest TDG pressures because of the transport of bubbles into the deeper sections of the tailwater channel. The open channel conditions associated with the 3 bay spill pattern may have reduced the air to water ratio and lessened the net uptake of TDG pressures.

The influence of the specific discharge on TDG exchange was not consistently evident in the data observed on Transect T2. The specific discharge has been a reliable indicator of the net TDG exchange at mainstem dams in the Columbia River basin. Numerous studies have found that if the specific discharge increases, the TDG exchange will also increase. In some events sampled during this study, the higher specific discharges associated with 3 spillbay patterns resulted in significantly lower TDG pressures on Transect T2 when compared to patterns with more active spill bays. The spill events 16, 17, and 18 shown in Figure 27e employed 10, 3, and 6 spill bays, respectively. The six bay pattern again resulted in a larger TDG saturation when compared to the 10 and 3 bay patterns.

The daily cycling of TDG pressure in the forebay caused by thermal exchange, is weakly evident during some of the events at the T2 transect. The correlation of this daily TDG pressure variation between the forebay and T2 stations during some events suggests that the resultant TDG pressure downstream of the aerated flow below the spillway does not completely reach a new equilibrium that is independent of forebay levels. This observation would become more prominent when the ratio of entrained air to spillway discharge becomes small. If free flow conditions entrain small volumes of air, the net exchange of TDG pressure could approach zero.

The highest spill discharge of 47.7 kcfs during Event 19 resulted in a very small increase in the TDG loading of the Pend Oreille River as shown in Figure 27e. The TDG pressures below the spillway ranged from 770-805 mm Hg and were only 10-20 mm Hg higher than observed in the forebay near the left channel bank. The TDG saturation ranged from 111-115 percent during Event 19 and experienced a daily TDG fluctuation similar to conditions in the forebay.

The peak TDG saturations (105-120 percent) observed below the Albeni Falls spillway were small compared to similar measurement made at other Columbia River Basin projects within the Corps of Engineers Seattle District. The TDG saturations generated in spill at Libby Dam (Schneider, 2002) located on the Kootenai River were similar to the response measured at Chief Joseph Dam (Schneider and Carroll 1999). At both projects, the TDG pressure in spillway flows approached an upper limit for spillway discharges above 5 kcfs/bay. This upper TDG limit was likely an indication that the depth of the stilling basin and tailwater channel effectively limited the mean bubble depth in the aerated spillway flow. The upper TDG limit at Libby Dam of about 133 percent was similar to the upper limit observed at Chief Joseph Dam of 134 percent. The magnitude of the upper TDG limit in spillway flows at Libby Dam was unexpected given the stilling basin depth at Chief Joseph Dam was 39 ft compared to 53 ft at Libby Dam.

Pend Oreille River – (mixing zone development)

The water quality properties released by the powerhouse and spillway interact downstream of the barrier island separating these two structures. Since the TDG properties of powerhouse and spillway releases can be significantly different, a mixing zone is established in the Pend Oreille River from this point downstream. The water quality properties as observed at Transect T3 were used to estimate the lateral water quality characteristics in the Pend Oreille River and integrated to determine the cross sectional average TDG pressures or TDG loading associated with Albeni Falls Dam releases.

Water Temperature

The water temperature on Transect T3 was nearly identical to the general trends observed at upstream stations. The presence of a significant change in Pend Oreille River temperatures from the dam to the downstream sampling Transect T3 was not evident in the observed temperature data collected during the study period. The instantaneous water temperatures near the left channel bank at Stations FBP1 and T3P1 were nearly identical throughout the study period as shown in Figure 29. A similar comparison of water temperatures near the right channel bank at Stations FBP3 and T3P5 (Figure 29) does show some variation during the study period. The different temperatures are likely caused by the influence of Priest River inflows on lateral temperatures in the forebay and the lateral mixing of Pend Oreille river water throughout the 1.6 mile reach from the dam to Transect T3.

Total Dissolved Gas

The TDG pressures across the Pend Oreille River downstream of Albeni Falls Dam were sampled at five different stations on Transect T3. This sampling design allowed the determination of the average cross-sectional TDG pressure downstream of the dam in response to both powerhouse and spillway releases. A continuous record of reliable TDG pressure observations was not maintained at sampling Stations T3P3, T3P4, and T3P5 throughout the study period. The Station T3P5 responded reliably only during the first two events as listed in the events averaged TDG pressure and saturation summary in Tables 7 and 8. The cause of the erroneous response in TDG pressures was likely the deposition of sediment on the instrument. The accumulation of sediment in the instrument housing was observed during the recovery of the equipment.

The TDG pressures on Transect T3 generally exhibited a prominent lateral gradient throughout most of the study period indicating a moderate elevation of TDG pressure above conditions in the forebay as shown in Figures 30a-e. TDG saturations are shown in Figures 31a-e for Transect T3 and selected stations. The TDG pressures generally were the highest near the left bank at Station T3P1 which was aligned with spillway releases, and decreased continuously across the river to the lowest levels at Stations T3P4 and T3P5 which was aligned with powerhouse releases. The TDG levels registered at Stations T3P4 and T3P5 were generally similar to the levels recorded below the powerhouse at station DTD. The change in TDG levels across transect T3 took about 2 hours to register after an operational change occurred at Albeni Falls Dam. This two hour lag in response to an operation change was accounted for in the statistical summary of the event based TDG average pressures and saturations listed in Tables 7 and 8.

The TDG pressures observed at Station T3P1 were similar to the TDG pressures observed at Station T2P1 and T2P2 located directly below the spillway. The TDG pressure observations at stations associated with waters discharged over the spillway are shown in Figure 32 and as TDG saturations in Figure 33 for the entire study period. The TDG pressures at Station T3P1 were typically greater than conditions in the forebay with the exception of Events 6-10, and similar to the observed TDG pressures at Stations T2P1 and T2P2. The highest TDG pressures observed at Station T3P1 of about 835 mm Hg observed during Events 20-23, were about 30 mm Hg higher than background conditions in the forebay at Station FBP1 and about 60 mm Hg higher than at Station DTD. These peak TDG pressures were also higher than conditions observed at Station T2P1 during these events probably due to the location of Station T2P1 to the spillway discharge release associated with spill patterns with 4-6 active bays. The period of peak TDG pressures on Transect T3 also corresponded to the highest TDG pressures in the forebay of Albeni Falls Dam. The largest increase in TDG pressures as determined from the difference of the events averaged conditions on Stations T3P1 and FBP1 was 62.4 mm Hg during Event 1, a 13 kcfs discharge through 4 spillbays. In contrast, the increase in TDG pressures from FBP1 to T3P1 during Event 19, a 47 kcfs spill over 10 bays was only 18.2 mm Hg. The TDG response at Station T3P1 provided the most comprehensive and reliable record of the change in TDG levels in the Pend Oreille River associated with spillway releases at Albeni Falls Dam during the study period because of the uneven length and reliability of TDG pressures observed across Station T2 and the availability of nearby TDG records on Transect T3.

The diurnal variation in the TDG pressures related to thermal cycling was evident across the Transect T3 stations. The TDG pressure cycling in response to this temperature variation at Station T3P1 implies that the resultant TDG pressure in spillway releases was a function of the initial TDG pressure observed in the forebay. The dependence between forebay TDG pressures and the response at Station T3P1 is clearly shown in Figure 30c (and as TDG saturation in Figure 31c) during Events 15 and 16 where the net change in TDG pressures between Stations FBP1 and T3P1 remains nearly constant at about 18 mm Hg while the TDG pressure time history varies considerably during each event.

The back to back operational changes sampled during the 2003 spill season demonstrate the changes in TDG response to changing forebay TDG levels, spill magnitude, spill pattern, and tailwater depth. An abrupt reduction in the TDG pressures across Transect T3 was observed during the transition from Event 1 to 2 where the spill pattern was changed from 4 to 8 active spill bays for a spill discharge of about 13.4 kcfs. The immediate reduction in TDG pressures at Station T3P1 and T3P2 was about 17 mm Hg. The change in TDG pressures was much smaller for the remaining stations on transect T3. In terms of event averaged properties at station T3P1 and FBP1, Event 1 created an increase in TDG pressure from 727.6 to 790.2 or a 62.6 mm Hg gain. Event 2 resulted in only a 33.3 mm Hg gain from upstream to downstream of the dam or about one-half the net increase in TDG pressure as measured at the selected sampling stations.

The change in TDG pressure on Transect T3 associated with Events 5 and 6 were noteworthy because of the significantly different TDG production properties of these events. Event 6 involved a gate opening of 1 ft for all 8 spillbays passing a total discharge of 7.2 kcfs while Event 5 included two bays with a gate opening of 2.5 ft and five bays with a one ft opening passing a total discharge of 8.8 kcfs. The TDG pressure increase above forebay levels as observed at Stations FBP1 and T3P1 during Event 5 was 27.9 mm Hg as compared to a 2.1 mm Hg increase during Event 6 as shown in Figure 30b. This same information is shown in TDG saturation in Figure 31b. Events 7-10 also exhibited no change in TDG pressures on Transect T3 in comparison to forebay levels. These events also involved spillway gates settings of 1 ft or less. Spill gate settings of 1 ft or less with an associated discharge of .9 kcfs/bay at a forebay elevation of about 2054 ft does not entrain air or change the TDG loading in the Pend Oreille River. Spillway discharges up to 9 kcfs could be scheduled using a 10 bay-1 ft gate opening at Albeni Falls Dam without impacting the TDG levels in the Pend Oreille River. A 1-ft gate opening at a higher heads and discharges may not provide the same TDG result.

The comparison of the TDG response on Transect T3 during Events 12, 13, and 14 are of interest because of the change in the number of active spillbays ranged from 10 to 6 to 3 while holding the spillway discharge nearly constant (25.0, 27.9, and 25.4, respectively). The time history of project operations and TDG pressures in the Pend Oreille River during May 27-29 are shown in Figure 30c. The average forebay TDG pressures remained nearly constant for these three events ranging from 758.1, 761.6, and 758.8 mm Hg for Events 12, 13, and 14, respectively as listed in Table 4. The TDG response on Transect T3 was varied with levels ranging from 782.2, 802.4, and 784.4 mm Hg at station T3P1 for Events 12, 13, and 14, respectively. At another point in the river at Station T3P4 the TDG pressure ranged from 757.2, 783.3, and 775.3 mm Hg for Events 12, 13, and 14, respectively. The change in operation from 10 to 6 spillbays (Events 12 to 13) resulted in a marked increase in the TDG pressures in the Pend Oreille River on Transect T3. However, the subsequent change in spill pattern from 6 to 3 bays (Events 13 to 14) resulted in a net decrease in the TDG pressure loading but not as low as observed during the 10 bay pattern (Event 12). Event 14 required free-flow conditions over the three active spill bays created by pulling the spill gates completely out of the water. It is likely that when this free-flow condition is set up at Albeni Falls Dam the amount of air entrained relative to the volume of water spilled changes significantly and the resultant TDG exchange is impacted. In this particular instance, the 3-bay free flow setting produced lower TDG pressures than the 6-bay pattern but higher TDG pressures than the 10-bay pattern.

A second series of events (16, 17, and 18) involving 10, 3 and 6 spillbays were scheduled for spill discharges of 36.1, 38.8, and 40.4 kcfs, respectively. These events are more complex to compare because of the range in spill discharge and the forebay TDG pressures ranged from 748.3, 762.1, and 764.8 mm Hg for events 16, 17, and 18, respectively. The time history of TDG pressures on Transect T3 shows increasing TDG pressures at all stations when the spill pattern is changed between Event 16 and 17 (Figure 30c). This information is shown as TDG saturation in Figure 31c. The operational change between Events 17 and 18 (opening up three more spill bays) also triggers an increase in TDG pressure across all T3 sampling stations. The TDG response on

Transect T3 ranged from 766.3, 780.6, and 804.8 mm Hg at station T3P1 for Events 16, 17, and 18, respectively. These average event conditions resulted in a net increase in TDG pressure above forebay levels of 18.0, 18.5, and 40.0 mm Hg.

Lateral TDG Distribution

The lateral distribution of TDG saturation varied widely during the study period as a function of spill pattern, spill discharge, powerhouse flow, and forebay TDG pressure. The TDG pressures and saturations from all 12 sampling stations together with project operations are shown in Figures 32 and 33 respectively. In the forebay, the influence of incomplete mixing of the Priest and Pend Oreille Rivers were likely responsible for a small degree of lateral variation on TDG pressures. The TDG production during spillway operations was the primary source of lateral variation in TDG pressure downstream of the Dam. The spill pattern was found to be an important determinant of TDG production at Albeni Falls Dam. The abrupt increase in TDG saturation below the dam on June 5 corresponded with a net reduction in spill discharge while using fewer (bays 3-8) spill bays.

The lateral distribution of TDG saturation is shown in Figures 34a-c for Transects FB, T2, and T3. The spill pattern and turbine discharge by unit is shown in the panel located in the lower left-hand side of these figures. The lateral distribution of TDG saturation in the Pend Oreille River on Transects FB, T2, and T3 is shown in the upper left-hand panel of Figure 34a-c. The left bank is adjacent to the Albeni Falls spillway while the right bank adjoins the powerhouse. The time history of TDG saturations and Albeni Falls operations are displayed in the right hand panel.

The time-dependent correlation between the project operations and the resultant TDG production and transport in the Pend Oreille River at Albeni Falls Dam has been represented in a data animation in Figure 34. A data animation of project operations and TDG saturation can be viewed in Figure 34 by clicking on the figure in the digital version of this document (requires file alftdgv6.avi). The influence of changing project operations such as the spill pattern, spill discharge, and powerhouse discharge can be seen in the magnitude and distribution of TDG saturation on Transect T2 and T3. Notable features of the lateral TDG distribution was the uniformity in elevated TDG saturation across the channel during relatively low percent spill conditions. The highest TDG pressures below the dam were often present at Stations T2P1, T2P2, and T3P1 and the lowest TDG pressures were located on the right side of the channel below the powerhouse. The correlations between forebay and tailwater TDG levels are readily apparent in this presentation of the data.

Selected frames from the data animation contained in Figure 34 have been reproduced in Figures 34a-c for Events 12-14. On May 28 at 900 hours Albeni Falls was spilling 25.1 kcfs over all ten spill bays with spill bays 5-7 set at a higher gate opening than the rest of the spillway as shown in Figure 34a. The TDG saturation in the forebay ranged from 108 percent at the left channel bank to 106 percent at the right channel bank upstream of the powerhouse (red symbols). The data collected below the dam indicated increased TDG saturation below the spillway (110.5 percent at T3P1) in the left side of the channel and no change in the TDG saturation below the powerhouse. The time-history of TDG saturation in this figure indicates a relatively constant TDG response over the previous 3 hours.

The spill discharge during Event 13 of 28.1 kcfs was only about 3 kcfs greater than Event 12 but only 6 of the 10 spill bays were used as shown in Figure 34b. The change in the spatial distribution of TDG below the dam as a consequence of this operation change was significant. The peak TDG saturation on Transect T3 increased from 111 percent to 114 percent. The higher TDG levels were felt across most of the stations on Transect T3 (T3P4 increased from 107-111 percent). The TDG distribution on Transect T3 was a linear function with distance for this operation. The highest TDG saturation of 116 percent was observed below the spillway on Transect T2. The forebay TDG conditions during Event 13 were similar to the previous event.

The following Event 14 resulted in a slight reduction in total spillway discharge of 25.5 kcfs using only spill bays 4-6 as shown in Figure 34c. The specific discharge for this Event was 8.5 kcfs/bay or about 3 times the specific discharge of Event 12. The TDG saturation at station T3P1 was 112 percent dropping off linearly to 111 percent at T3P4. The peak TDG saturation on Transect T3 was similar to Event 12 while the average TDG saturation was considerably larger due in part to the higher forebay TDG levels.

Data Analyses

TDG Loading

The determination of the flow weighted TDG pressures on Transect T3 were determined by applying the flow distribution observed from USGS records to the instantaneous observations of TDG pressure at each of the 5 TDG monitoring stations. The flow distribution for 5 different discharge conditions in the Pend Oreille River were assembled and normalized by the total river discharge. The lateral velocity distribution and channel depth are shown in Figure 19 for a discharge of 87.5 kcfs observed on June 7, 1976. The velocity distribution is relatively uniform with the exception of lower velocities in the shallow sections near the channel banks. This normalized flow distribution was then plotted against the normalized distance from shore (left bank-0, right bank-1) and the TDG sampling stations were located on Figure 20. The flow distribution was similar across the range of river flows and a least squared third order polynomial was determined to fit these data. The river was divided into 5 regions, each region associated with a TDG station, and the corresponding normalized discharge was determined for each region and used as the weighting coefficient in estimating the average TDG pressure in the Pend Oreille River. The weighting coefficients (C_n) determined from this analysis and applied to stations T3P1, T3P2, T3P3, T3P4, and T3P5 were 0.1735, 0.2051, 0.1655, 0.1937, and 0.2622, respectively.

$$P_{T3avg} = \sum_{n=1}^{5} P_n C_n \qquad (1)$$

The flow weighted TDG pressure in the Pend Oreille River at Transect T3 was determined by applying Equation 1. The determination of the flow-weighted average TDG saturation for the Pend Oreille River required an observation for each sampling station in the T3 transect. Data was generated for instances when there was missing data at a given sampling station. The methodology and order of application for generating TDG pressure estimates was as follows: interpolation between bounding stations; extrapolation from a neighboring station. The largest uncertainty involved in determining the flow weighted TDG pressure in the Pend Oreille River involved the loss of reliable data at station T3P5 for events 3-30. The weighting coefficient for Station T3P5 of 0.26 corresponds to over one-quarter of the flow in the river and was assigned to TDG pressure observations at this station. It is reasonable to assume that the responses at Station T3P5 would be bounded by TDG levels observed at Station FBP2 and FBP3 at the low end (Average TDG pressure of powerhouse releases) and T3P4 at the upper end. Information at station DTD was not used in this analysis because it was biased by lower TDG pressures associated with Priest River. Therefore, two sets of estimates were generated for determining the flow weighted average TDG pressure and TDG saturation in the Pend Oreille river corresponding with the high and low estimation of TDG pressure at Station T3P5. The average of the low and high estimate of the flow weighted TDG pressure in the Pend Oreille River were used to summarize the water quality impacts of project operations at Albeni Falls Dam.

The difference between the event and flow weighted TDG pressure average for the low and high estimates were generally within 2 mm Hg. In only 6 cases were the average TDG pressure estimates greater than 2 mm Hg as shown in Table 8. The largest difference between these estimates occurred during Event 18, a spill discharge of 40.4 kcfs through 6 bays, where the difference ranged from 793.1 (112.5 percent) to 785.4 (111.4 percent).

The spillway operations at Albeni Falls Dam during May 6-June 27, 2003, resulted in a small increase in the average TDG levels in the Pend Oreille River on the order of 1.1 percent saturation. The average forebay TDG level was 107.7 percent and ranged from a high of 114.9 percent to a low of 100.9 percent. The cross sectional average tailwater TDG level as measured on Transect T3 was 108.8 percent and ranged from 116.4 percent to a low of 102.5 percent. The percent of time the forebay TDG saturation was above the 110 percent standard was about 26 percent as shown in the cumulative frequency distribution for forebay TDG saturation in Figure 35. The average TDG saturation downstream of Albeni Falls Dam exceeded 110 percent about 38 percent of the time (Figure 35) and exceeded 115 percent about 8 percent of the time.

The peak TDG saturations in the Pend Oreille River downstream of Albeni Falls Dam were generally reflected at station T3P1 throughout the spill season. There were times when the TDG pressure observed at Station T2P1 or T2P2 were slightly higher than that observed downstream on Station T3P1. However, the TDG response at Station T3P1 was used for this summary because of the similarity of response to stations on Transect T2 and the duration of reliable observations. The average TDG saturation at Station T3P1 was 111.8 percent and ranged from a peak of 120.1 percent to a low of 104.5 percent. The TDG saturation at Station T3P1 exceeded 110 percent about 56 percent of the time (Figure 35) and exceeded 115 percent about 25 percent of the time.

The influence of operations at Albeni Falls Dam on the TDG loading of the Pend Oreille River was determined by comparing the event averaged TDG saturation in the forebay with the corresponding response across Transect T3. The event based change in TDG saturation are listed in Table 9 in the column labeled "Uptake". On average during the 2003 spill season, the spillway operations at Albeni Falls Dam resulted in a small increase in the TDG saturation in the Pend Oreille River ranging from no change during Events 6-10 to a maximum increase of 4.1 percent saturation during Event 20. Events 6-10 all involved spill bay gate settings of 0 or 1 stop with gate submergence ranging from 3.7 to 4.5 ft for a total head of 14.8 to 16 ft. The degree of increase in TDG loading was a function of the forebay TDG saturation, spill magnitude and pattern, and project head. During Event 19 when 70 percent of the river was being spilled, a spill discharge of 47.4 kcfs through all ten spill bays, the increase in the average TDG saturation of the Pend Oreille River was only 0.7 percent saturation: 111.2 percent in the forebay to 111.9 percent on Transect T3. The following Event 20, a spill of 35.9 kcfs over 6 spill bays, resulted in the average TDG saturation increasing from 111.2 percent in the forebay to 115.3 percent on Transect T3, or a net increase of 4.1 percent saturation while spilling 60 percent of the river. This comparison of net TDG loading illustrates the importance of spill pattern on TDG exchange at Albeni Falls Dam.

The net TDG uptake tended to increase as spillway discharge increased as shown in Figure 36. The spill pattern was found to influence the net TDG exchange observed at Albeni Falls Dam. For spill events equal to or greater than 25 kcfs, the 6 bay pattern resulting in the highest increase in both the peak and average TDG saturation on Transect T3 when compared to the 3 and 10 bay spill patterns. The increase in average flow weighted TDG saturation on Transect T3 in the Pend Oreille River during the 6 bay spill patterns (Events 13, 18, 20, and 21) were 3.5, 3.5, 4.1 and 2.4 percent, respectively. In contrast, the average flow weighted TDG saturation increase on Transect T3 during the 10 bay spill patterns (Events 12, 15, 16, and 19) were 1.3, 0.8, 1.2, and 0.7 percent, respectively. The TDG increase during the 3 bay patterns (free flow) fell below the 6 bay responses and slightly above the 10 bay responses. The increase in average flow weighted TDG saturation on Transect T3 in the Pend Oreille River during the 3 bay spill patterns (Events 14, 17) were 2.4 and 1.5 percent, respectively.

A similar trend between spill patterns and increases in TDG saturation above forebay levels as observed at Station T3P1 was observed for spill events greater than 25 kcfs as listed in Table 9. The 6 bay patterns resulted in TDG saturation increases at Station T3P1 ranging from 5.0 to 5.8 percent compared to only 2.1 to 3.4 percent for the 10 bay events. The 3 bay patterns were slightly higher than the 10 bay events with TDG saturation increase at Station T3P1 ranging from 2.6 to 3.6 percent saturation.

For spill flows less than 25 kcfs there also appears to be a smaller uptake in TDG pressures for events using more spill bays. The TDG uptake can be eliminated for spill discharges less the 10 kcfs by using only 1 ft gate openings.

A separate analysis of the fate of the TDG loading in the Pend Oreille River between Albeni Falls and Box Canyon Dam can be found in Appendix D. The evaluation applies the average cross sectional TDG pressures observed below Albeni Falls Dam with the TDG pressures observed in the forebay of Box Canyon Dam during the 2003 spill season.

Location of Fixed Monitoring Stations

The TDG saturation observed at Station T3P1 is representative of the properties of spillway releases undiluted from powerhouse flows for operations where the percent river spilled is 10 percent and greater. The close correspondence between the TDG levels observed at stations located directly below the spillway (T2P1, T2P2) and the lagged response at station T3P1 as shown in Figures 32-33, supports this hypothesis. The calculation of the average TDG saturation in the Pend Oreille River downstream of Albeni Falls Dam based on average forebay conditions and the response measured at the tailwater station T3P1 was performed for each of the 30 spill events sampled during the 2003 season. The average TDG saturation on Transect T3 was estimated using mass conservation principles as shown in Equation 2.

$$P_{T3avg} = \frac{(P_{sp}Q_{sp} + P_{ph}Q_{ph})}{(Q_{sp} + Q_{ph})} \qquad (2)$$

Where

Psp = PT3P1

Pph=Pfb

The events based flow weighted average on Transect T3 was closely approximated by the calculated TDG saturation using Equation 2 as listed in Table 9. The column labeled T3avg-est reflects the application of Equation 2 using the observations at Station T3P1 to represent the content of spillway releases. The observed (T3avg) and estimated (T3avg-est) TDG saturations were plotted as shown in Figure 37 and a least squares linear regression was generated with a r^2 coefficient of 0.99 and a standard error of 0.4 percent saturation.

Two sampling station at Albeni Falls Dam, one in the forebay and a second station located near the left bank of transect T3, could be used to effectively characterize the TDG exchange and peak TDG levels associated with spillway releases. The forebay station should be located away from the right channel bank because of the bias caused by Priest River inflow, in actively moving water at an elevation below 2037 ft. The tailwater station should also be sited at a distance away from the left bank to assure a depth of 15 ft. The instrument should be located above the channel bottom to avoid being covered by the gravel and sand bedload in the Pend Oreille River.

TDG Exchange Formulation

In previous studies at Chief Joseph and Libby Dams, the TDG exchange has been characterized by relating the delta pressure (ΔP) defined as the difference between TDG pressure in undiluted spillway flows and local atmospheric pressure, versus the tailwater depth and specific spillway discharge (kcfs/bay). The form of the regression equation used in these relationships is shown in Equation 3.

$$\Delta P = c_1 D_{tw}(1 - e^{-c_2 q_s}) \qquad (3)$$

where c1 and c2 are regression coefficients, qs is the specific spillway discharge in kcfs/ft and Dtw is the effective tailwater depth of flow (ft). For higher head projects like Libby or Chief Joseph Dams, the TDG exchange was found to be independent of the initial forebay TDG conditions. The highly aerated flow conditions in the stilling basin for these projects, coupled with large depths of flow and turbulence levels, result in high rates of mass exchange causing the result TDG levels to be independent from the initial conditions.

The formulation found to best estimate the TDG exchange at Albeni Falls Dam was quite different from those used at projects with moderate to high total head. The TDG saturation observed at Station T3P1 was found to be a weak function of spill discharge and unit spill discharge as shown in Figures 38-39. The TDG saturation at T3P1 generally increased for higher spill discharges but the range in TDG response for a given spill discharge was large. The TDG saturation as a function of unit spill discharge consolidated some of the variance in TDG response to project spill operations. The 3 bay spill events with high specific discharge fall outside the general trend identified by the remaining events.

The event averaged delta pressure at Station T3P1 was also found to be loosely correlated with total spillway discharge, specific spillway discharge, and tailwater depth of flow for spill events contributing over 10 percent of flow to the Pend Oreille River. The delta pressure or pressure above local atmospheric pressure at T3P1 as a function of total spill discharge and unit spill discharge are shown in Figures 40 and 41.

The dependency of the TDG saturation in spillway flow on the initial TDG saturation in the forebay requires a different formulation for describing the TDG exchange process at Albeni Falls Dam than presented in Equation 3. An alternative formulation can be developed by assuming TDG exchange to be considered a first order process where the rate of change of atmospheric gases is directly proportional to the ambient concentration. The driving force in the transfer process is the difference between the TDG concentration in the water and the saturation concentration in water in contact with air. The saturation concentration in bubbly flow will be greater than that generated for non-bubbly flow where the saturation concentration is determined at the air-water interface. The local saturation concentration associated with entrained air bubbles is a linear function of the total pressure at the point of exchange. Therefore, an aerated environment kept at 2 atmospheres (depth of 10 meters) of pressure will produce a TDG saturation of 200% at equilibrium. The flux of atmospheric gasses J across the air-water interface is typically described by Equation 4.

$$J = k_l(C_s - C) \qquad (4)$$

Where k_l is the composite liquid film coefficient, C_s is the saturation concentration, and C is the ambient concentration in water.

The rate of change of concentration in a well-mixed control volume can be estimated by multiplying the mass flux by the surface area of air and dividing by the volume over which transfer occurs as shown by the Equation 5:

$$\frac{dC}{dt} = k_l \frac{A}{V}(C_s - C) \qquad (5)$$

where A is the surface area associated with the control volume and V is the volume of the water body over which transfer occurs.

This relationship shows the general dependencies of the mass transfer process. In cases where large volumes of air are entrained, the time rate of change of TDG concentrations can be quite large as the ratio of surface area to volume becomes large. The entrainment of air will also result in a significant increase in the saturation concentration of atmospheric gases thereby increasing the driving potential over which mass transfer takes place. Outside of the region of aerated flow during transport through the pools, the contact area is limited to the water surface and the ratio of the surface area to the water volume becomes small thereby limiting the change in TDG concentration. The turbulent mixing will influence the surface renewal rate and hence the magnitude of the exchange coefficient k_l.

The Equation 5 can be integrated provided the exchange coefficient, area, and volume are held constant over the time of flow. The initial TDG concentration at time=0 is defined as C_i and the final TDG concentration at time=t_f is defined as C_f as shown in Equation 6. The resultant concentration C_f exponentially approaches the saturation concentration for conditions where the term $k_t At/V$ is large. The final concentration becomes independent of the initial concentration under these conditions.

$$C_f = C_s(1 - e^{-k_l \frac{A}{V} t}) + C_i e^{-k_l \frac{A}{V} t} \qquad (6)$$

Equation 6 can be rearranged in terms of a transfer efficiency where the observed gradient in TDG concentration is divided by the potential TDG concentration gradient as shown in Equation 7. The transfer efficiency ranges from zero, no exchange of TDG concentration, to unity where the final TDG concentration is driven to the effective saturation concentration associated with the bubbly flow regime established below the spillway.

$$\frac{(C_f - C_i)}{(C_s - C_i)} = (1 - e^{-k_l \frac{A}{V} t}) \qquad (7)$$

The TDG pressures can be substituted for concentrations in Equation 7 resulting in Equation 8 for the TDG pressure in spill water as a function of the initial TDG pressure in the forebay.

$$\frac{(P_{sp} - P_{fb})}{(P_s - P_{fb})} = (1 - e^{-k_l \frac{A}{V} t}) \qquad (8)$$

The two unknowns that need to be determined through an empirical evaluation of data collected at Albeni Falls Dam are the effective saturation TDG pressure P_s and the exchange coefficient $k_l At/V$. The effective saturation pressure was assumed to be a linear function of the tailwater depth D_{tw} that varied with changes in the tailwater elevation. There are alternative formulations for the functional form for the effective TDG saturation involving other parameters such as specific discharge or total head. However, the findings from the TDG exchange study at The Dalles Dam (Schneider, 2000), which has a shallow stilling basin and adjoining tailrace channel, found that the resultant effective TDG pressure was highly correlated to the tailwater channel depth of flow. The transfer efficiency at The Dalles Dam was found to equal unity removing the dependency of TDG pressures in spillway releases from the initial TDG pressures in the forebay.

The formulation for the exchange coefficient ($k_l At/V$) was found to be a function of the specific spillway discharge q_s, total head H, and gate submergence (S) as shown in Figure 4. The reaeration at low-head structures was investigated by Wilhelms and Smith (1981) where the transfer efficiency was found to be a function of the specific discharge, total head, and gate submergence. The transfer efficiency was thought to increase as the specific spillway discharge and total head are increased and decrease as the gate submergence increases. This formulation was also recommended in Gulliver et al. (1998) who evaluated predictive equations for oxygen transfer at hydraulic structures.

The effective TDG saturation P_s was assumed to be a function of the depth of flow in the receiving channel below the spillway. The larger the tailwater channel depth of flow, the greater the potential for bubbles to be transported to greater depths resulting in higher rates of mass transfer. The maximum amount of TDG exchange will occur when sufficient energy is available to entrain and transport bubbles throughout the entire depth of the receiving channel. The transfer efficiency is defined as the change in TDG pressure from the forebay to tailwater over the potential change (P_s-P_{fb}) .

A non-linear least squares regression was used to determine the form and coefficients to be applied to Equation 9 listed below. A subset of the events based TDG summary (Table 9) was used in this regression analyses. Events 6-10 were excluded from these analyses because the transfer efficiency was zero. A zero transfer efficiency requires the TDG pressure in spillway flows to be equal to the TDG pressure in the forebay. The two free flow events (Events 8 and 14) were not included in these analyses because no gate submergence was imposed under these operations. Events 27 and 30 were also excluded from this evaluation because of the small percentage of total river spilled. The observed TDG pressure response at Station T3P1 was used to estimate the spillway release properties undiluted from powerhouse flows. The assumption does not hold when the percent river spilled is small (<10%) because of the encroachment of the mixing zone at Station T3P1. The final data set used in this analyses involved 21 observations where the specific discharge ranged from 0.9 to 6.7 kcfs/bay, gate submergence ranged from 1.5 to 5.3 ft, and total head ranged from 11.4 to 22.1 ft.

$$\frac{(P_{sp} - P_{fb})}{(P_s - P_{fb})} = (1 - e^{-(c_2 q_s + c_3)H/S}) \qquad (9)$$

$P_s = c_1 D_{tw}$

$D_{tw=} El_{tw}$-2000

where $q_s > 1.0$

$S > 0.0$

$P_{sp} = P_{fb}$

where $q_s < 1.0$

A non-linear least squares regression solution was used to determine the three unknown coefficients in Equation 9. The effective TDG saturation pressure was assumed to be a linear function of the tailwater depth of flow which was equal to the tailwater elevation less the tailwater channel elevation of 2000 ft. The transfer efficiency was equal to the exponential function of the specific discharge, total project head, and gate submergence. The specific discharge was modified by coefficients C_2 and C_3. A nonlinear least squares regression was performed using Equation 9 for 21 observations (events) and the resultant equation was found to have a coefficient of correlation r^2=0.93 and a standard error of 7.30 mm Hg. The coefficients were determined to be significantly different from zero at the 95 percent confidence interval with the following values: c_1=22.59, c_2=0.0105, c_3=-0.0999. The observed and estimated TDG pressures in spillway releases using Equation 9 are shown in Figure 42.

Equation 9 was applied to the hourly operations data to hind cast the instantaneous TDG pressures in spill and average cross sectional TDG pressure in the Pend Oreille River. The calculated TDG pressures in spill were labeled $T3P1_{cal}$ in Figure 43 and the calculated average TDG pressures in the Pend Oreille River were based on Equation 2 where $P_{sp}=P_{T3P1cal}$. The calculated TDG pressure in spill closely estimated the observed conditions during the first 30 days of the study period. Both the magnitude and daily variation in the forebay TDG pressure were evident in the estimated TDG pressures associated with spillway flows. The change in spill pattern and discharge were also found to cause distinct changes in the TDG exchange. Equation 9 was less successful in estimating the TDG exchange during the 6 bay spill on June 5-8. The calculated TDG pressure under-estimated the observed pressures by about 20 mm Hg during this event. The TDG pressure during the small spill events on June 18-23 where over-estimated because of the encroachment of the mixing zone at station T3P1.

The average predictive error of the TDG pressure at T3P1 during selected events using Equation 9 excluding the free flow events (3 bay spill pattern) and events having a percent spill less than 10 percent was 2.22 mm Hg and the standard deviation of the predictive error was equal to 7.35 mm Hg based on 3873 observations. The estimate of the average cross sectional TDG pressure in the Pend Oreille River using Equations 9 and 2 was generally small with the average predictive error equal to –0.33 mm Hg and the standard error of 3.94 mm Hg. The observed (T3P1) and calculated (T3P1cal) TDG pressure in spill and average observed (T3avg) and calculated (T3avg-cal) cross sectional TDG pressure are shown in Figures 43a-e.

Conclusions

A field study was conducted at Albeni Falls Dam from May-June 2003 to more clearly understand total dissolved gas exchange processes associated with the operation of Albeni Falls Dam and the resultant transport and mixing in the Pend Oreille River immediately below the project. A total of thirteen instruments were deployed in the Pend Oreille River on May 6 at twelve different stations on three transects. The purpose of this sampling scheme was to determine the change in the TDG levels in the Pend Oreille River caused by the operation of Albeni Falls Dam and to support the location of permanent fixed monitoring stations. The ambient TDG levels approaching the dam were determined by sampling in the forebay. The resultant TDG levels exiting the spillway undiluted from powerhouse flows were determined by sampling below the spillway. The average cross-sectional TDG loadings in the Pend Oreille River were established by sampling TDG levels on Transect T3 located 1.6 miles downstream from the dam. The prominent findings from this study are as follows.

- The TDG levels in the forebay of Albeni Falls Dam were supersaturated throughout the study period from upstream sources. The average TDG saturation was 107.7 percent and ranged from a high of 114.9 percent to a low of 100.9

- The TDG saturation approaching Albeni Falls Dam was not uniform. The TDG levels on the powerhouse side of the forebay experienced lower TDG conditions when compared to the spillway side of the forebay. The incomplete mixing of the Priest River with the Pend Oreille River was the primary source for the lower TDG pressures approaching the powerhouse. The water temperatures were also slightly cooler on the powerhouse side of the forebay compared to the spillway side.

- The estimated time of travel of elevated TDG pressures from Cabinet Gorge Dam to Albeni Falls Dam was about one week during the 2003 study period. This estimate of travel time is considerably shorter than plug flow estimates based on the theoretical residence time through the Pend Oreille River and Lake Pend Oreille.

- The TDG pressures observed in Albeni Falls powerhouse releases were equal to the TDG pressures observed in the forebay during the study period in 2003. The change in the TDG pressures in the Pend Oreille

River during passage through Albeni Falls Dam approach zero when spill levels approach zero.

- Spillway operations at Albeni Falls Dam during the 2003 spill season increased the TDG loading in the Pend Oreille River by a small amount. The increase in the average TDG saturation in the Pend Oreille River during spillway operations in 2003 was only 1.1 percent of saturation. The small average increase in TDG pressure is attributable to the low project head, shallow stilling basin channel, and wide spillway. A project operation spilling 60 percent of the river over 6 spill bays resulted in the largest increase in the average TDG saturation in the Pend Oreille River of 4.1 percent of saturation. During this event, the average forebay TDG saturation was 111.2 percent and the resultant average tailwater TDG saturation was 115.3 percent.

- Spill gate setting of 1 ft did not cause a measurable change in TDG saturation from forebay levels. The maximum spill capacity without changing the TDG saturation in the Pend Oreille River could be achieved by setting all ten spill bays to a 1 ft opening.

- The elevated TDG pressures observed below the spillway prior to dilution from powerhouse flows were a function of the initial forebay TDG pressure. The highest TDG saturation observed during the study was 120 percent and was located below the spillway near the left channel bank. This functional relationship has not been apparent at higher head project with deeper stilling basins. The TDG exchange associated with spillway operation at Albeni Falls Dam is best described by determining the increase in TDG pressure above the forebay levels.

- The TDG exchange was found to be sensitive to the spill pattern employed. In general, the distribution of spill across all ten spill bays resulted in the smallest amount of TDG uptake in the Pend Oreille River. For instance, the highest spill during the study period of 47.4 kcfs or 70 percent of the total river flow, occurred when the forebay TDG saturation was 111.2 percent. The 47.4 kcfs was spilled through all 10 bays in nearly a uniform distribution and resulted in an average tailwater TDG saturation of 111.7 percent (0.7 percent saturation increase over forebay levels). The spill rate was subsequently dropped to 35.9 kcfs through only 6 spill bays while the forebay TDG saturation remained at 111.2 percent. This lesser spill discharge through 6 bays increased the average TDG saturation downstream from Albeni Falls Dam to 115.3 percent or a 4.1 percent saturation increase over forebay conditions.

- The direct relationship between specific discharge (discharge/width) and TDG exchange was not consistently observed. A spill pattern using three bays (bay 4-6) consistently resulted in a TDG uptake smaller than the six bay pattern (bays 3-8). The shallow stilling basin channel below the central portion of the spillway and the ratio of entrained air to water flow rate may account for these observations.

- A predictive model (Equation 9) of TDG exchange at Albeni Falls Dam was developed based on the TDG pressure in the forebay, total project head, submergence of the spill gate, specific discharge, and effective tailwater depth of flow. This equation should be used with caution outside of the range of dependent variables for which it was derived. This formulation does not apply to free flow conditions where the spillway gate is not submerged.

- The mixing zone between powerhouse and spillway flows extended over 3 miles downstream of the dam. The TDG saturation was found to vary laterally on Transect T3 during much of the study period. The maximum TDG saturation was consistently observed directly below the spillway and along the left channel bank (spillway side) while the lowest TDG saturations were associated with powerhouse releases along the right channel bank (powerhouse side). The TDG pressures observed near the left channel bank on Transect T3 were similar to conditions observed below the spillway on Transect T2.

The water temperature fluctuations in the Pend Oreille River caused corresponding changes to the TDG pressures observed throughout the study. An increase in water temperature resulted in a corresponding increase in the TDG pressure in the river at both upstream and downstream stations. The heat exchange in the Pend Oreille River will be an important determinant of the fate of TDG pressures from one project to another.

Recommendations

The establishment of routine fixed monitoring stations above and downstream of Albeni Falls Dam will enable the assessment of project impacts on the TDG loading in the Pend Oreille River, help determine compliance with state water quality standards for total dissolved gas saturation, and allow further testing of alternative spill patterns to minimize the generation of TDG supersaturation.

The forebay fixed monitoring station should be located away from the right bank which is influenced from flows from the Priest River at an elevation less than 2036 ft. The sampling location should be in active flow and secured from public access to prevent vandalism.

The tailwater fixed monitoring station should be located downstream of the spillway (near the left channel bank) and outside of the zone of highly aerated flow. The site should also be in active flow and located above the channel bottom with a minimum depth of 15 ft. One possible sampling site is at the USGS gage located 1.6 miles downstream from the dam near Station T3P1. When spill discharges contribute over 10 percent of the river flow, the TDG response at this location should reflect levels in spillway flow undiluted with powerhouse waters. The tailwater and forebay information can be used to estimate the average TDG loading released from Albeni Falls Dam.

Gate setting of one-stop or one-foot of opening did not contribute to higher TDG pressures in the Pend Oreille River. This type of spill simply transported TDG levels in the forebay past the dam unaltered. Spillway releases up to about 9 kcfs can be discharged without raising TDG levels by setting the appropriate number of spill gates to a one-stop setting.

For spillway releases in excess of 9 kcfs, the spillway flow should be distributed uniformly over all 10 spill bays taking into account the gate position constraints. The spill bays 4-6 should take on the highest flows when required because of the shallower tailwater depths downstream from these bays.

The findings from this study have contributed to the understanding of TDG exchange associated with spillway operations at Albeni Falls Dam. However, this description is limited to the range of operations encountered during this study period. In the future, the operational and environmental conditions will fall outside of the range of experience observed during the 2003 spill season. Future analyses should be conducted pooling all data collected at Albeni Falls Dam to improve the predictive model of TDG exchange and further refine operational guidance to abate TDG production.

The application of free flow conditions through several bays does hold promise to minimize the TDG production at Albeni Falls dam particularly during low head conditions. Further experimentation with alternative spill patterns should be scheduled in the future to evaluate the effectiveness of uniform spill patterns versus free flow spills.

The spillway gate operation could be refined to provide for 0.5 or 1.0 ft opening increments. Currently, a gate opening of one foot does not result in an increase in the TDG saturation while the next highest gate opening of 2.5 feet does result in a significant elevation of TDG saturation. It is likely that gate openings between 1.0 and 2.5 feet will result in intermediate or modest changes in TDG saturation. At higher discharges, the need to open a single or multiple gates by 1.5 ft could be replaced by opening the appropriate number of gates at 0.5 ft.

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Tables

Table 1 Statistical Summary of Albeni Falls Operations as grouped by Spill Events, 2003													
Event	**Start**	**End**	**Duration (hrs)**	**Q_{total} (kcfs)**	**Q_{spill} (kcfs)**	**Q_{ph} (kcfs)**	**Q_{spill}/Q_{total} *100 (%)**	**q_s (kcfs/bay)**	**Spillbays Active**	**FBE (ft)**	**TWE (ft)**	**Head (ft)**	**Gate Submergence (ft)**
1	5/6/03 17:00	5/7/03 12:45	21.8	38.3	13.2	25.1	34.5	3.3	4.0	2053.1	2039.2	13.9	2.2
2	5/7/03 14:00	5/15/03 10:45	190.8	39.2	13.5	25.7	34.4	1.7	8.0	2053.0	2039.5	13.5	4.6
3	5/15/03 11:00	5/19/03 9:45	96.8	37.7	12.1	25.6	32.1	1.5	8.0	2052.8	2039.3	13.5	4.6
4	5/19/03 10:00	5/20/03 11:45	27.8	35.8	10.0	25.8	27.9	1.4	7.0	2052.9	2039.0	13.9	4.4
5	5/20/03 12:00	5/21/03 7:45	21.8	35.1	8.8	26.3	25.1	1.2	7.0	2053.1	2038.8	14.3	4.4
6	5/21/03 8:00	5/22/03 7:45	25.8	34.0	7.2	26.8	21.2	0.9	8.0	2053.3	2038.5	14.8	4.5
7	5/22/03 8:00	5/22/03 13:45	7.8	29.5	4.6	24.9	15.6	0.9	5.0	2053.9	2038.0	16.1	4.0
8	5/22/03 14:00	5/23/03 9:45	21.8	30.5	2.8	27.8	9.2	0.9	3.0	2053.9	2037.9	15.9	3.9
9	5/23/03 11:00	5/25/03 8:45	47.8	29.9	1.9	28.1	6.4	0.9	2.0	2054.2	2037.7	16.5	3.7
10	5/25/03 9:00	5/26/03 10:45	27.8	32.2	4.6	27.6	14.3	0.9	5.0	2054.3	2038.0	16.3	4.0
11	5/26/03 13:00	5/27/03 11:45	24.8	39.1	11.9	27.2	30.4	1.2	10.0	2054.1	2039.0	15.2	4.7
12	5/27/03 15:00	5/28/03 9:45	20.8	48.7	25.0	23.7	51.3	2.5	10.0	2053.0	2040.8	12.2	4.8
13	5/28/03 13:00	5/29/03 8:45	21.8	49.7	27.9	21.9	56.1	4.6	6.0	2052.7	2041.4	11.4	2.4
14	5/29/03 10:00	5/29/03 16:45	8.8	47.4	25.4	21.9	53.6	8.5	3.0	2053.0	2041.5	11.6	-4.5
15	5/29/03 19:00	5/31/03 22:45	53.8	56.4	34.7	21.7	61.5	3.5	10.0	2053.7	2042.2	11.6	5.0
16	6/1/03 0:00	6/2/03 7:45	33.8	58.4	36.1	22.3	61.8	3.6	10.0	2055.1	2042.4	12.8	5.3
17	6/2/03 10:00	6/2/03 16:45	8.8	59.8	38.8	21.0	64.9	12.9	3.0	2055.1	2042.4	12.7	-3.2
18	6/2/03 17:00	6/3/03 9:45	18.8	60.6	40.4	20.2	66.7	6.7	6.0	2055.1	2043.0	12.1	1.5
19	6/3/03 13:00	6/5/03 8:45	45.8	67.8	47.4	20.3	69.9	4.7	10.0	2055.1	2044.0	11.2	5.3
20	6/5/03 15:00	6/7/03 9:45	44.8	59.8	35.9	23.9	60.0	6.0	6.0	2056.4	2043.2	13.2	3.2
21	6/7/03 11:00	6/8/03 8:45	23.8	55.9	31.5	24.4	56.4	5.3	6.0	2056.8	2042.8	14.1	3.8
22	6/8/03 11:00	6/9/03 8:45	23.8	46.4	21.4	25.0	46.1	5.3	4.0	2058.1	2041.3	16.9	2.4
23	6/9/03 10:00	6/10/03 13:45	29.8	44.2	19.0	25.2	43.0	4.8	4.0	2058.6	2040.6	18.0	2.5
24	6/10/03 15:00	6/11/03 9:45	20.8	44.2	16.5	27.7	37.3	4.1	4.0	2058.8	2040.5	18.3	3.2
25	6/11/03 11:00	6/12/03 9:45	24.8	39.7	11.4	28.3	28.7	2.8	4.0	2059.3	2040.0	19.3	4.1
26	6/12/03 11:00	6/18/03 8:45	143.8	35.9	7.6	28.3	21.2	2.5	3.0	2060.1	2039.1	21.0	3.6
27	6/18/03 13:00	6/23/03 14:45	123.8	36.1	2.6	33.5	7.2	2.6	1.0	2061.0	2038.5	22.5	3.0
28	6/23/03 15:00	6/24/03 15:45	26.8	39.8	6.5	33.3	16.3	3.2	2.0	2061.1	2039.1	22.0	2.9
29	6/24/03 16:00	6/25/03 9:45	19.8	38.6	5.2	33.4	13.5	2.6	2.0	2061.1	2039.0	22.1	3.5
30	6/25/03 10:00	6/27/03 9:45	49.8	33.3	2.6	30.7	7.8	2.6	1.0	2061.3	2038.2	23.1	2.7

Table 2 Spill Pattern by Event at Albeni Falls Dam, 2003

Event	Spill Bay Discharge (kcfs)									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0.0	0.0	0.0	3.3	3.3	3.3	3.3	0.0	0.0	0.0
2	0.0	0.9	2.2	2.2	2.2	2.2	2.2	0.9	0.9	0.0
3	0.0	0.9	0.9	2.2	2.2	2.2	2.2	0.9	0.9	0.0
4	0.0	0.9	0.9	0.0	2.2	2.2	2.2	0.9	0.9	0.0
5	0.0	0.9	0.9	0.0	0.9	2.2	2.2	0.9	0.9	0.0
6	0.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.0
7	0.0	0.0	0.0	0.9	0.9	0.9	0.9	0.9	0.0	0.0
8	0.0	0.0	0.0	0.9	0.9	0.9	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.9	0.9	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.9	0.9	0.9	0.9	0.9	0.0	0.0
11	0.9	0.9	0.9	0.9	2.3	2.3	0.9	0.9	0.9	0.9
12	2.2	2.2	2.2	2.2	3.3	3.3	3.3	2.2	2.2	2.2
13	0.0	0.0	4.3	4.3	5.3	5.3	4.3	4.3	0.0	0.0
14	0.0	0.0	0.0	8.5	8.5	8.5	0.0	0.0	0.0	0.0
15	3.3	3.3	3.3	3.3	4.4	3.3	3.3	3.3	3.3	3.3
16	3.5	3.5	3.5	3.5	4.6	3.5	3.5	3.5	3.5	3.5
17	0.0	0.0	0.0	12.9	12.9	12.9	0.0	0.0	0.0	0.0
18	0.0	0.0	6.7	6.7	6.7	6.7	6.7	6.7	0.0	0.0
19	4.6	4.6	4.6	4.6	5.7	4.6	4.6	4.6	4.6	4.6
20	0.0	0.0	5.9	5.9	5.9	5.9	5.9	5.9	0.0	0.0
21	0.0	0.0	4.9	4.9	6.0	6.0	4.9	4.9	0.0	0.0
22	0.0	0.0	0.0	5.0	5.0	6.2	5.0	0.0	0.0	0.0
23	0.0	0.0	0.0	3.7	5.1	5.1	5.1	0.0	0.0	0.0
24	0.0	0.0	0.0	3.7	5.1	3.7	3.7	0.0	0.0	0.0
25	0.0	0.0	0.0	2.5	2.5	3.7	2.5	0.0	0.0	0.0
26	0.0	0.0	0.0	2.5	2.5	2.5	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	2.5	3.6	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	2.5	2.5	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0

Table 3 Statistical Summary by Event of the TDG Saturation in the Forebay at Albeni Falls Dam, 2003

Event	Q_{total} (kcfs)	Q_{spill} (kcfs)	q_s (kcfs/bay)	Bays	BP (mm Hg)	FBP1 (% Sat)	FBP2 (% Sat)	FBP3 (% Sat)	FB_{avg} (% Sat)	DTD (% Sat)
1	38.3	13.2	3.3	4.0	700.9	104.4	104.4	103.3	103.8	103.7
2	39.2	13.5	1.7	8.0	702.6	105.4	105.4	104.1	105.0	104.7
3	37.7	12.1	1.5	8.0	709.5	103.2	103.0	102.5	102.9	102.7
4	35.8	10.0	1.4	7.0	712.2	103.3	103.1	103.0	103.1	103.1
5	35.1	8.8	1.2	7.1	708.6	104.7	104.5	103.9	104.3	104.2
6	34.0	7.2	0.9	8.0	708.3	105.2	105.1	104.5	104.8	104.8
7	29.5	4.6	0.9	5.0	707.2	105.4	105.3	104.7	105.1	105.0
8	30.5	2.8	0.9	3.0	706.5	105.5	105.4	104.9	105.1	105.2
9	29.9	1.9	0.9	2.0	700.1	108.5	108.2	107.8	108.0	108.0
10	32.2	4.6	0.9	5.0	700.4	108.6	108.5	107.1	107.9	107.9
11	39.1	11.9	1.2	10.0	706.5	107.7	107.2	106.1	106.9	106.6
12	48.7	25.0	2.5	10.0	705.2	108.0	107.6	106.7	107.5	107.0
13	49.7	27.9	4.6	6.0	700.7	109.3	108.9	107.5	108.7	107.8
14	47.4	25.4	8.5	3.0	700.6	109.6	108.0	107.6	108.3	107.6
15	56.4	34.7	3.5	10.0	701.4	108.1	107.6	106.2	107.5	106.4
16	58.4	36.1	3.6	10.0	704.6	106.8	106.2	105.2	106.2	105.1
17	59.8	38.8	12.9	3.0	704.8	109.1	107.9	107.0	108.1	106.7
18	60.6	40.4	6.7	6.0	705.2	109.1	108.5	106.9	108.4	107.0
19	67.8	47.4	4.7	10.0	705.9	111.8	111.4	108.9	111.2	108.9
20	59.8	35.9	6.0	6.0	704.2	109.4	113.4	108.6	111.2	110.2
21	55.9	31.5	5.3	6.0	699.6	114.6	114.2	110.6	113.5	111.5
22	46.4	21.4	5.3	4.0	697.1	115.1	115.0	110.8	113.9	112.2
23	44.2	19.0	4.8	4.0	697.5	114.8	114.5	110.1	113.3	111.5
24	44.2	16.5	4.1	4.0	700.0	111.4	111.2	107.4	110.0	108.7
25	39.7	11.4	2.8	4.0	699.5	111.7	111.7	108.2	110.4	109.6
26	35.9	7.6	2.5	3.0	703.6	111.4	111.2	109.4	110.5	110.0
27	36.1	2.6	2.6	1.0	698.8	109.4	109.4	108.6	109.0	108.7
28	39.8	6.5	3.2	2.0	704.9	106.1	105.4	105.4	105.5	105.5
29	38.6	5.2	2.6	2.0	707.5	104.8	104.1	104.4	104.3	104.5
30	33.3	2.6	2.6	1.0	706.2	105.6	105.3	105.3	105.3	105.4

Table 4 Statistical Summary of the Total Dissolved Gas Pressure in the Forebay of Albeni Falls Dam, 2003

Event	Q_{total} (kcfs)	Q_{spill} (kcfs)	Q_s (kcfs/bay)	Bays	BP (mm Hg)	FBP1 (mm Hg)	FBP2 (mm Hg)	FBP3 (mm Hg)	FB_{avg} (mm Hg)	DTD (mm Hg)
1	38.3	13.2	3.3	4.0	700.9	732.1	731.7	724.1	727.6	726.9
2	39.2	13.5	1.7	8.0	702.6	741.5	740.3	732.8	737.5	735.6
3	37.7	12.1	1.5	8.0	709.5	731.8	730.8	727.3	729.8	728.7
4	35.8	10.0	1.4	7.0	712.2	735.7	734.2	733.8	734.3	734.1
5	35.1	8.8	1.2	7.1	708.6	741.7	740.7	736.5	739.2	738.3
6	34.0	7.2	0.9	8.0	708.3	744.9	744.1	740.0	742.6	742.2
7	29.5	4.6	0.9	5.0	707.2	745.7	744.8	740.6	743.1	742.3
8	30.5	2.8	0.9	3.0	706.5	745.1	744.3	740.8	742.7	742.9
9	29.9	1.9	0.9	2.0	700.1	759.3	757.6	754.3	756.1	755.8
10	32.2	4.6	0.9	5.0	700.4	760.9	760.0	750.0	755.8	755.7
11	39.1	11.9	1.2	10.0	706.5	760.5	757.6	749.6	755.3	753.2
12	48.7	25.0	2.5	10.0	705.2	761.8	759.1	752.3	758.1	754.7
13	49.7	27.9	4.6	6.0	700.7	765.6	762.9	753.3	761.6	755.1
14	47.4	25.4	8.5	3.0	700.6	768.2	756.3	753.7	758.8	753.9
15	56.4	34.7	3.5	10.0	701.4	758.5	754.8	744.7	754.0	746.2
16	58.4	36.1	3.6	10.0	704.6	752.2	748.6	741.5	748.3	740.8
17	59.8	38.8	12.9	3.0	704.8	769.1	760.4	754.4	762.1	752.4
18	60.6	40.4	6.7	6.0	705.2	769.5	765.2	753.9	764.8	754.9
19	67.8	47.4	4.7	10.0	705.9	789.2	786.6	768.8	784.9	768.4
20	59.8	35.9	6.0	6.0	704.2	799.7	798.5	774.5	783.4	776.3
21	55.9	31.5	5.3	6.0	699.6	802.1	799.0	773.9	794.4	780.3
22	46.4	21.4	5.3	4.0	697.1	802.1	801.8	772.4	793.9	781.9
23	44.2	19.0	4.8	4.0	697.5	800.7	798.7	767.9	790.3	777.5
24	44.2	16.5	4.1	4.0	700.0	779.9	778.4	751.6	770.3	760.8
25	39.7	11.4	2.8	4.0	699.5	781.3	781.0	756.7	772.3	766.9
26	35.9	7.6	2.5	3.0	703.6	783.6	782.7	769.8	777.7	775.1
27	36.1	2.6	2.6	1.0	698.8	764.4	764.5	758.6	761.8	761.3
28	39.8	6.5	3.2	2.0	704.9	748.0	743.3	742.8	743.5	743.6
29	38.6	5.2	2.6	2.0	707.5	741.6	736.3	738.4	737.5	739.2
30	33.3	2.6	2.6	1.0	706.2	745.5	743.6	743.6	743.7	744.2

Table 5 Statistical Summary by Event of the TDG Saturation on Transect T2 Below Albeni Falls Dam, 2003

Event	Q_{total} (kcfs)	Q_{spill} (kcfs)	q_s (kcfs/bay)	Bays	BP (mm Hg)	FB_{avg} (% Sat)	T3P1 (% Sat)	T2P1 (% Sat)	T2P2 (% Sat)	T2P3 (% Sat)
1	38.3	13.2	3.3	4.0	700.9	103.8	112.7	112.0	109.8	104.5
2	39.2	13.5	1.7	8.0	702.6	105.0	109.7	110.5	108.7	106.7
3	37.7	12.1	1.5	8.0	709.5	102.9	108.9	109.5	108.6	105.1
4	35.8	10.0	1.4	7.0	712.2	103.1	108.8	109.7	110.6	106.6
5	35.1	8.8	1.2	7.1	708.6	104.3	108.3	109.1	110.2	107.2
6	34.0	7.2	0.9	8.0	708.3	104.8	105.1	105.0	104.5	
7	29.5	4.6	0.9	5.0	707.2	105.1	105.3	105.4	106.3	
8	30.5	2.8	0.9	3.0	706.5	105.1	105.2	105.1	105.0	
9	29.9	1.9	0.9	2.0	700.1	108.0	107.9	107.6	107.3	
10	32.2	4.6	0.9	5.0	700.4	107.9	108.1	107.8	108.7	
11	39.1	11.9	1.2	10.0	706.5	106.9	110.1	110.0	110.0	107.7
12	48.7	25.0	2.5	10.0	705.2	107.5	110.9	110.8	112.8	107.8
13	49.7	27.9	4.6	6.0	700.7	108.7	114.5	116.5	111.2	107.6
14	47.4	25.4	8.5	3.0	700.6	108.3	112.0	110.8		
15	56.4	34.7	3.5	10.0	701.4	107.5	109.6		109.9	
16	58.4	36.1	3.6	10.0	704.6	106.2	108.8		108.7	
17	59.8	38.8	12.9	3.0	704.8	108.1	110.7	111.3		
18	60.6	40.4	6.7	6.0	705.2	108.4	114.1	115.4		
19	67.8	47.4	4.7	10.0	705.9	111.2	113.8	112.2	113.6	
20	59.8	35.9	6.0	6.0	704.2	111.2	118.0	116.8		
21	55.9	31.5	5.3	6.0	699.6	113.5	118.8	117.0		
22	46.4	21.4	5.3	4.0	697.1	113.9	118.9	116.6		
23	44.2	19.0	4.8	4.0	697.5	113.3	119.1	116.6		
24	44.2	16.5	4.1	4.0	700.0	110.0	118.3			
25	39.7	11.4	2.8	4.0	699.5	110.4	117.3			
26	35.9	7.6	2.5	3.0	703.6	110.5	116.4			
27	36.1	2.6	2.6	1.0	698.8	109.0	110.5			
28	39.8	6.5	3.2	2.0	704.9	105.5	112.8			
29	38.6	5.2	2.6	2.0	707.5	104.3	111.0			
30	33.3	2.6	2.6	1.0	706.2	105.3	108.2			

Table 6 Statistical Summary by Event of the TDG Pressure on Transect 2 at Albeni Falls Dam, 2003								
Event	**Q_{total} (kcfs)**	**Q_{spill} (kcfs)**	**Q_s (kcfs/bay)**	**Bays**	**FB_{avg} (mm Hg)**	**T2P1 (mm Hg)**	**T2P2 (mm Hg)**	**T2P3 (mm Hg)**
1	38.3	13.2	3.3	4.0	727.6	785.4	769.5	732.8
2	39.2	13.5	1.7	8.0	737.5	776.1	763.6	749.5
3	37.7	12.1	1.5	8.0	729.8	776.7	770.6	745.9
4	35.8	10.0	1.4	7.0	734.3	781.4	787.6	758.9
5	35.1	8.8	1.2	7.1	739.2	773.2	781.2	759.3
6	34.0	7.2	0.9	8.0	742.6	743.9	740.3	
7	29.5	4.6	0.9	5.0	743.1	745.6	752.1	
8	30.5	2.8	0.9	3.0	742.7	742.8	742.0	
9	29.9	1.9	0.9	2.0	756.1	753.0	751.0	
10	32.2	4.6	0.9	5.0	755.8	754.7	761.2	
11	39.1	11.9	1.2	10.0	755.3	776.8	777.5	761.7
12	48.7	25.0	2.5	10.0	758.1	781.6	795.8	759.9
13	49.7	27.9	4.6	6.0	761.6	816.3	779.5	752.2
14	47.4	25.4	8.5	3.0	758.8	776.7		
15	56.4	34.7	3.5	10.0	754.0		771.2	
16	58.4	36.1	3.6	10.0	748.3		766.2	
17	59.8	38.8	12.9	3.0	762.1	784.8		
18	60.6	40.4	6.7	6.0	764.8	813.7		
19	67.8	47.4	4.7	10.0	784.9	792.2	801.6	
20	59.8	35.9	6.0	6.0	783.4	822.4		
21	55.9	31.5	5.3	6.0	794.4	818.5		
22	46.4	21.4	5.3	4.0	793.9	812.7		
23	44.2	19.0	4.8	4.0	790.3	812.3		
24	44.2	16.5	4.1	4.0	770.3			
25	39.7	11.4	2.8	4.0	772.3			
26	35.9	7.6	2.5	3.0	777.7			
27	36.1	2.6	2.6	1.0	761.8			
28	39.8	6.5	3.2	2.0	743.5			
29	38.6	5.2	2.6	2.0	737.5			
30	33.3	2.6	2.6	1.0	743.7			

Table 7 Statistical Summary by Event of the TDG Saturation on Transect T3 Below Albeni Falls Dam, 2003

Event	Q_{total} (kcfs)	Q_{spill} (kcfs)	q_s (kcfs/bay)	Bays	BP (mm Hg)	FB_{avg} (% Sat)	T3P1 (% Sat)	T3P1dup (% Sat)	T3P2 (% Sat)	T3P3 (% Sat)	T3P4 (% Sat)	T3P5 (% Sat)	$T3_{avg-low}$ (% Sat)	$T3_{avg-high}$ (% Sat)
1	38.3	13.2	3.3	4.0	700.9	103.8	112.7	113.0	109.3	105.7	104.5	103.8	106.7	106.7
2	39.2	13.5	1.7	8.0	702.6	105.0	109.7	109.9	107.0	105.5	104.8	103.9	106.2	106.2
3	37.7	12.1	1.5	8.0	709.5	102.9	108.9	108.8	105.1	103.4	102.7		104.4	104.4
4	35.8	10.0	1.4	7.0	712.2	103.1	108.8	108.7	104.9	103.5	102.9		104.5	104.4
5	35.1	8.8	1.2	7.1	708.6	104.3	108.3	108.3	105.4	104.5	104.2		105.2	105.2
6	34.0	7.2	0.9	8.0	708.3	104.8	105.1	105.3	104.6	104.5	104.7		104.7	104.7
7	29.5	4.6	0.9	5.0	707.2	105.1	105.3	104.9	104.5	104.8	104.9		104.9	104.8
8	30.5	2.8	0.9	3.0	706.5	105.1	105.2	105.3	104.8	104.8	105.0		105.0	104.9
9	29.9	1.9	0.9	2.0	700.1	108.0	107.9	107.8	107.5	107.5	107.8		107.8	107.7
10	32.2	4.6	0.9	5.0	700.4	107.9	108.1	108.3	107.7	107.5	108.0		107.8	107.9
11	39.1	11.9	1.2	10.0	706.5	106.9	110.1	110.2	108.1	106.5	106.9		107.6	107.6
12	48.7	25.0	2.5	10.0	705.2	107.5	110.9	111.4	110.9	108.1	107.4		108.8	108.8
13	49.7	27.9	4.6	6.0	700.7	108.7	114.5	115.1	113.4	112.5	111.8		111.8	112.7
14	47.4	25.4	8.5	3.0	700.6	108.3	112.0	112.3	111.4	111.2	110.7		110.4	111.1
15	56.4	34.7	3.5	10.0	701.4	107.5	109.6	109.9	109.5	108.6	107.3		108.3	108.4
16	58.4	36.1	3.6	10.0	704.6	106.2	108.8	109.5	108.9	107.4	106.4		107.3	107.5
17	59.8	38.8	12.9	3.0	704.8	108.1	110.7	111.3	110.6	108.9	109.4		109.3	109.8
18	60.6	40.4	6.7	6.0	705.2	108.4	114.1	114.7	113.8	110.8	111.9		111.4	112.5
19	67.8	47.4	4.7	10.0	705.9	111.2	113.8	113.8	113.4	111.9	110.7		111.8	111.9
20	59.8	35.9	6.0	6.0	704.2	111.2	118.0	118.1	116.9	115.4	114.1		114.9	115.6
21	55.9	31.5	5.3	6.0	699.6	113.5	118.8	118.8	117.4	117.1	114.2		115.6	116.1
22	46.4	21.4	5.3	4.0	697.1	113.9	118.9	118.5	117.9	116.3	113.7		115.7	115.9
23	44.2	19.0	4.8	4.0	697.5	113.3	119.1	118.5	117.5	115.5	112.8		115.2	115.3
24	44.2	16.5	4.1	4.0	700.0	110.0	118.3	117.6	115.7	111.0			112.4	
25	39.7	11.4	2.8	4.0	699.5	110.4	117.3	117.0	112.8				111.8	
26	35.9	7.6	2.5	3.0	703.6	110.5	116.4	116.1	111.6				111.6	
27	36.1	2.6	2.6	1.0	698.8	109.0	110.5	109.5	108.7	105.7			109.2	
28	39.8	6.5	3.2	2.0	704.9	105.5	112.8	112.1	107.4	105.6			107.1	
29	38.6	5.2	2.6	2.0	707.5	104.3	111.0	109.9	105.2	104.3			105.6	
30	33.3	2.6	2.6	1.0	706.2	105.3	108.2	106.7	105.0	105.2			105.7	

Table 8 Statistical Summary by Event of the TDG Pressure on Transect 3 at Albeni Falls Dam, 2003													
Event	**Q_{total} (kcfs)**	**Q_{spill} (kcfs)**	**q_s (kcfs/bay)**	**Bays**	**FB_{avg} (mm Hg)**	**T3P1 (mm Hg)**	**T3P1 dup (mm Hg)**	**T3P2 (mm Hg)**	**T3P3 (mm Hg)**	**T3P4 (mm Hg)**	**T3P5 (mm Hg)**	**$T3_{avg-low}$ (mm Hg)**	**$T3_{avg-high}$ (mm Hg)**
1	38.3	13.2	3.3	4.0	727.6	790.2	792.0	766.2	741.2	732.7	727.4	747.6	747.6
2	39.2	13.5	1.7	8.0	737.5	770.9	771.9	751.6	741.0	736.5	727.3	746.1	746.1
3	37.7	12.1	1.5	8.0	729.8	772.6	772.0	745.8	733.4	728.6		740.6	740.5
4	35.8	10.0	1.4	7.0	734.3	775.1	774.5	747.1	737.2	733.1		744.1	743.9
5	35.1	8.8	1.2	7.1	739.2	767.1	767.4	747.2	740.1	738.4		745.5	745.4
6	34.0	7.2	0.9	8.0	742.6	744.7	745.5	741.1	740.0	741.3		741.8	741.6
7	29.5	4.6	0.9	5.0	743.1	744.9	741.6	739.1	740.8	741.6		741.7	741.4
8	30.5	2.8	0.9	3.0	742.7	743.6	743.8	740.1	740.2	741.7		741.6	741.4
9	29.9	1.9	0.9	2.0	756.1	755.1	754.3	752.5	752.7	754.9		754.3	754.0
10	32.2	4.6	0.9	5.0	755.8	757.4	758.2	754.4	753.0	756.7		755.2	755.7
11	39.1	11.9	1.2	10.0	755.3	777.6	778.6	763.7	752.5	755.0		759.9	760.2
12	48.7	25.0	2.5	10.0	758.1	782.2	785.5	782.0	762.6	757.2		767.1	767.5
13	49.7	27.9	4.6	6.0	761.6	802.4	806.3	794.9	788.3	783.3		783.2	789.8
14	47.4	25.4	8.5	3.0	758.8	784.4	786.4	780.7	778.7	775.3		773.1	778.5
15	56.4	34.7	3.5	10.0	754.0	768.8	770.6	768.2	761.6	753.0		759.4	760.2
16	58.4	36.1	3.6	10.0	748.3	766.3	771.4	767.4	756.6	749.4		756.0	757.1
17	59.8	38.8	12.9	3.0	762.1	780.6	784.7	779.6	767.8	771.3		770.3	774.0
18	60.6	40.4	6.7	6.0	764.8	804.8	808.6	802.5	781.2	789.0		785.4	793.1
19	67.8	47.4	4.7	10.0	784.9	803.1	803.4	800.2	789.3	781.4		789.2	790.2
20	59.8	35.9	6.0	6.0	783.4	831.1	831.5	823.0	812.9	803.6		809.4	813.9
21	55.9	31.5	5.3	6.0	794.4	831.0	830.8	821.6	818.9	798.8		809.1	812.3
22	46.4	21.4	5.3	4.0	793.9	829.1	825.8	821.7	810.6	792.5		806.4	807.8
23	44.2	19.0	4.8	4.0	790.3	830.8	826.8	819.4	805.3	786.7		803.2	804.1
24	44.2	16.5	4.1	4.0	770.3	827.9	823.1	810.0	776.7			787.0	
25	39.7	11.4	2.8	4.0	772.3	820.4	818.1	788.9				781.8	
26	35.9	7.6	2.5	3.0	777.7	818.8	817.2	785.4				785.5	
27	36.1	2.6	2.6	1.0	761.8	772.3	765.1	759.4	742.7			762.9	
28	39.8	6.5	3.2	2.0	743.5	794.9	790.6	756.8	744.4			755.0	
29	38.6	5.2	2.6	2.0	737.5	784.9	777.5	744.3	738.1			747.1	
30	33.3	2.6	2.6	1.0	743.7	764.0	753.4	741.4	743.2			746.6	

Table 9 Statistical Summary by Event of the TDG Saturation on Transect T3 Below Albeni Falls Dam, 2003

Event	Q_{tot} (kcfs)	Q_{spill} (kcfs)	$\%_{spill}$	Bays	q_s (kcfs/bay)	Spill Gate Submergence (ft)	Forebay Elevation (ft)	Tailwater Elevation (ft)	Project Head (ft)	FB_{avg} (% Sat)	$T3_{avg*}$ (% Sat)	Uptake+ (% Sat)	T3P1 (% Sat)	$T3_{avg}$-est# (% Sat)	Gradient@ T3P1 (% Sat)
1	38.3	13.2	34.5	4.0	3.3	2.2	53.1	39.2	13.9	103.8	106.7	2.9	113.0	107.0	8.9
2	39.2	13.5	34.4	8.0	1.7	4.6	53.0	39.5	13.5	105.0	106.2	1.2	109.9	106.7	4.8
3	37.7	12.1	32.2	8.0	1.5	4.6	52.8	39.3	13.5	102.9	104.4	1.5	108.9	104.8	6.0
4	35.8	10.0	27.9	7.0	1.4	4.4	52.9	39.0	13.9	103.1	104.5	1.4	108.8	104.7	5.7
5	35.1	8.8	25.1	7.1	1.2	4.4	53.1	38.8	14.3	104.3	105.2	0.9	108.3	105.3	3.9
6	34.0	7.2	21.1	8.0	0.9	4.5	53.3	38.5	14.8	104.8	104.7	-0.1	105.3	104.9	0.3
7	29.5	4.6	15.6	5.0	0.9	4.0	53.9	38.0	16.1	105.1	104.9	-0.2	105.3	105.1	0.2
8	30.5	2.8	9.1	3.0	0.9	3.9	53.9	37.9	15.9	105.1	105.0	-0.1	105.3	105.1	0.1
9	29.9	1.9	6.2	2.0	0.9	3.7	54.2	37.7	16.5	108.0	107.7	-0.3	107.9	108.0	-0.1
10	32.2	4.6	14.3	5.0	0.9	4.0	54.3	38.0	16.3	107.9	107.9	0.0	108.3	108.0	0.2
11	39.1	11.9	30.4	10.0	1.2	4.7	54.1	39.0	15.2	106.9	107.6	0.7	110.2	107.9	3.2
12	48.7	25.0	51.3	10.0	2.5	4.8	53.0	40.8	12.2	107.5	108.8	1.3	111.4	109.5	3.4
13	49.7	27.9	56.0	6.0	4.6	2.4	52.7	41.4	11.4	108.7	112.2	3.5	115.1	112.3	5.8
14	47.4	25.4	53.7	3.0	8.5	-4.5	53.0	41.5	11.6	108.3	110.7	2.4	112.3	110.4	3.6
15	56.4	34.7	61.5	10.0	3.5	5.0	53.7	42.2	11.6	107.5	108.3	0.8	109.9	109.0	2.1
16	58.4	36.1	61.9	10.0	3.6	5.3	55.1	42.4	12.8	106.2	107.4	1.2	109.5	108.2	2.5
17	59.8	38.8	64.9	3.0	12.9	-3.2	55.1	42.4	12.7	108.1	109.6	1.5	111.3	110.2	2.6
18	60.6	40.4	66.6	6.0	6.7	1.5	55.1	43.0	12.1	108.4	111.9	3.5	114.7	112.6	5.7
19	67.8	47.4	70.0	10.0	4.7	5.3	55.1	44.0	11.2	111.2	111.9	0.7	113.8	113.0	2.6
20	59.8	35.9	60.0	6.0	6.0	3.2	56.4	43.2	13.2	111.2	115.3	4.1	118.1	115.3	6.8
21	55.9	31.5	56.3	6.0	5.3	3.8	56.8	42.8	14.1	113.5	115.9	2.4	118.8	116.5	5.2
22	46.4	21.4	46.1	4.0	5.3	2.4	58.1	41.3	16.9	113.9	115.8	1.9	118.9	116.2	5.0
23	44.2	19.0	43.0	4.0	4.8	2.5	58.6	40.6	18.0	113.3	115.2	1.9	119.1	115.8	5.8
24	44.2	16.5	37.3	4.0	4.1	3.2	58.8	40.5	18.3	110.0	112.4	2.4	118.3	113.1	8.2
25	39.7	11.4	28.6	4.0	2.8	4.1	59.3	40.0	19.3	110.4	111.8	1.4	117.3	112.4	6.9
26	35.9	7.6	21.3	3.0	2.5	3.6	60.1	39.1	21.0	110.5	111.6	1.1	116.4	111.7	5.8
27	36.1	2.6	7.2	1.0	2.6	3.0	61.0	38.5	22.5	109.0	109.2	0.2	110.5	109.1	1.5
28	39.8	6.5	16.3	2.0	3.2	2.9	61.1	39.1	22.0	105.5	107.1	1.6	112.8	106.7	7.3
29	38.6	5.2	13.5	2.0	2.6	3.5	61.1	39.0	22.1	104.3	105.6	1.3	111.0	105.2	6.7
30	33.3	2.6	7.8	1.0	2.6	2.7	61.3	38.2	23.1	105.3	105.7	0.4	108.2	105.5	2.9

* $T3_{avg}$ – Average TDG saturation on Transect T3 based on the flow weighted average at stations T3P1-T3P5
\+ Uptake – Change in cross sectional average TDG saturation: $T3_{avg} - FB_{avg}$
@ Gradient – Change in TDG levels in spillway releases as measured at station T3P1: T3P1-FB_{avg}
\# $T3_{avg}$-est - Flow weighted average using $(Q_{ph}TP_{ph}+Q_{sp}TP_{sp})/(Q_{ph}+Q_{sp})$ where $TP_{ph}=TP_{fb\text{-}avg}$ and $TP_{sp}=TP_{T3P1}$

Figures

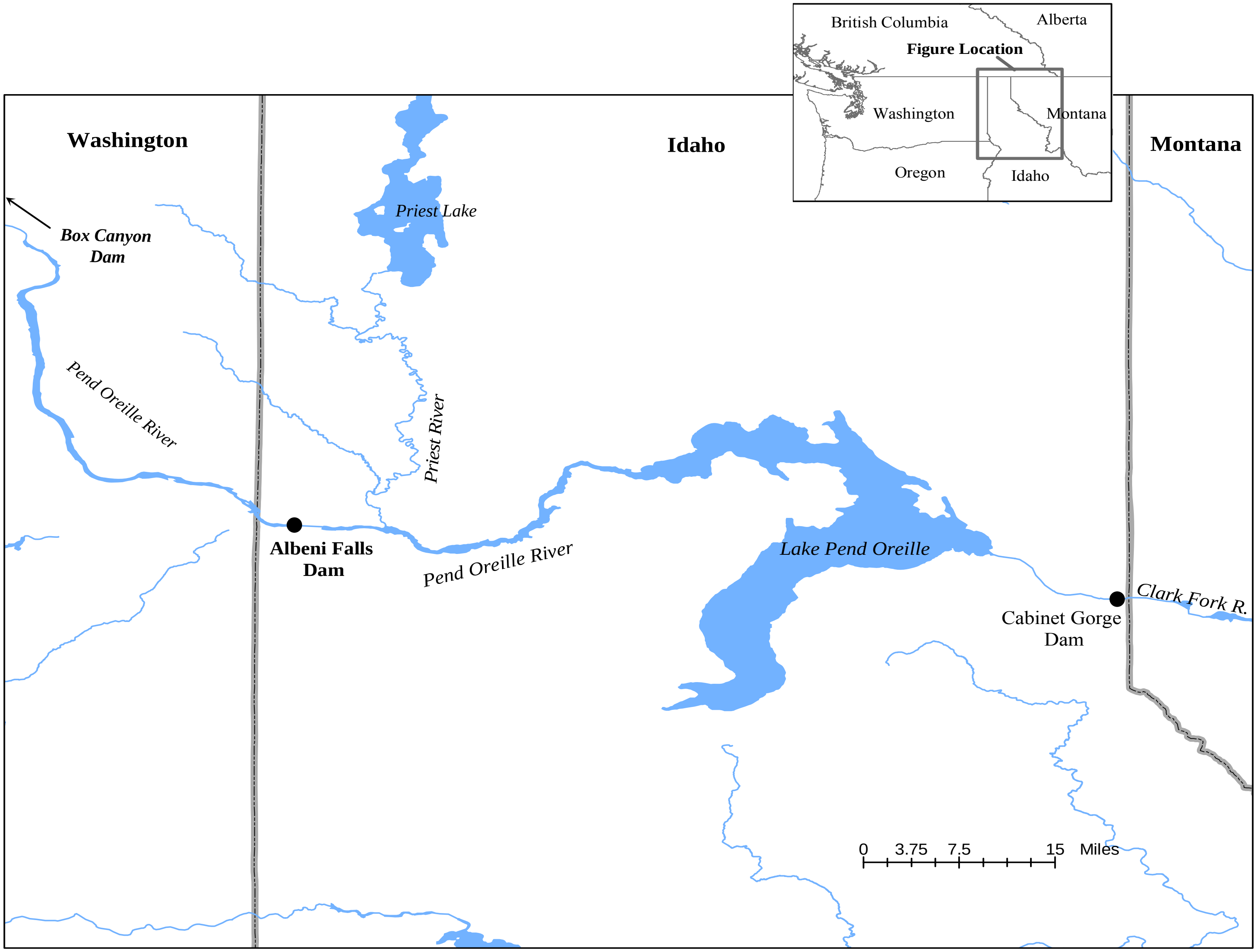

Figure 1. Location of Albeni Falls Dam and the Pend Oreille River.

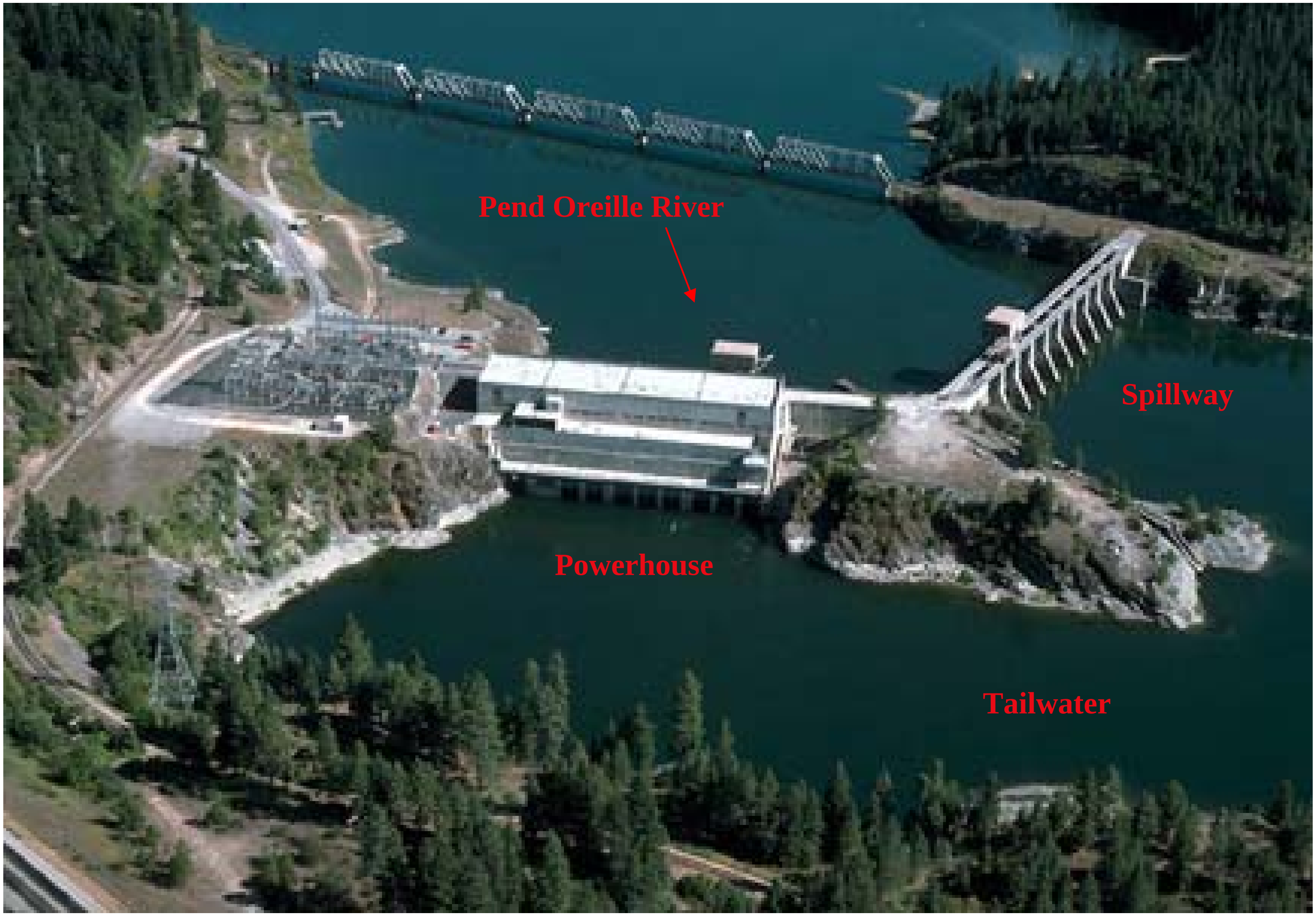

Figure 2. Aerial Photo of Albeni Falls Dam and the Pend Oreille River.

Figure 3 Photograph of Albeni Falls Spillway Vertical Split Leaf Lift Gates

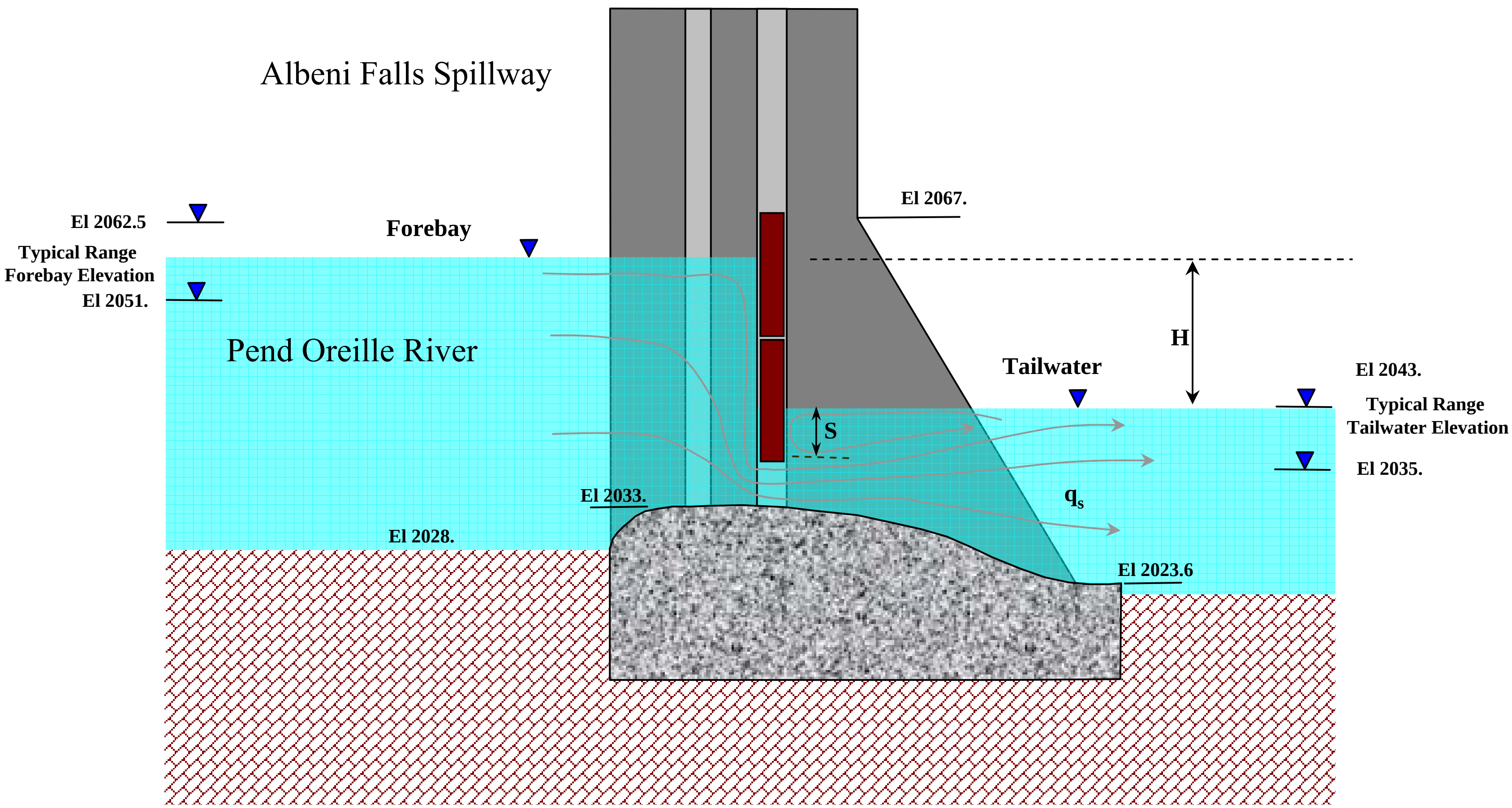

Figure 4. Profile view of the Albeni Falls Spillway and Tailrace Channel.

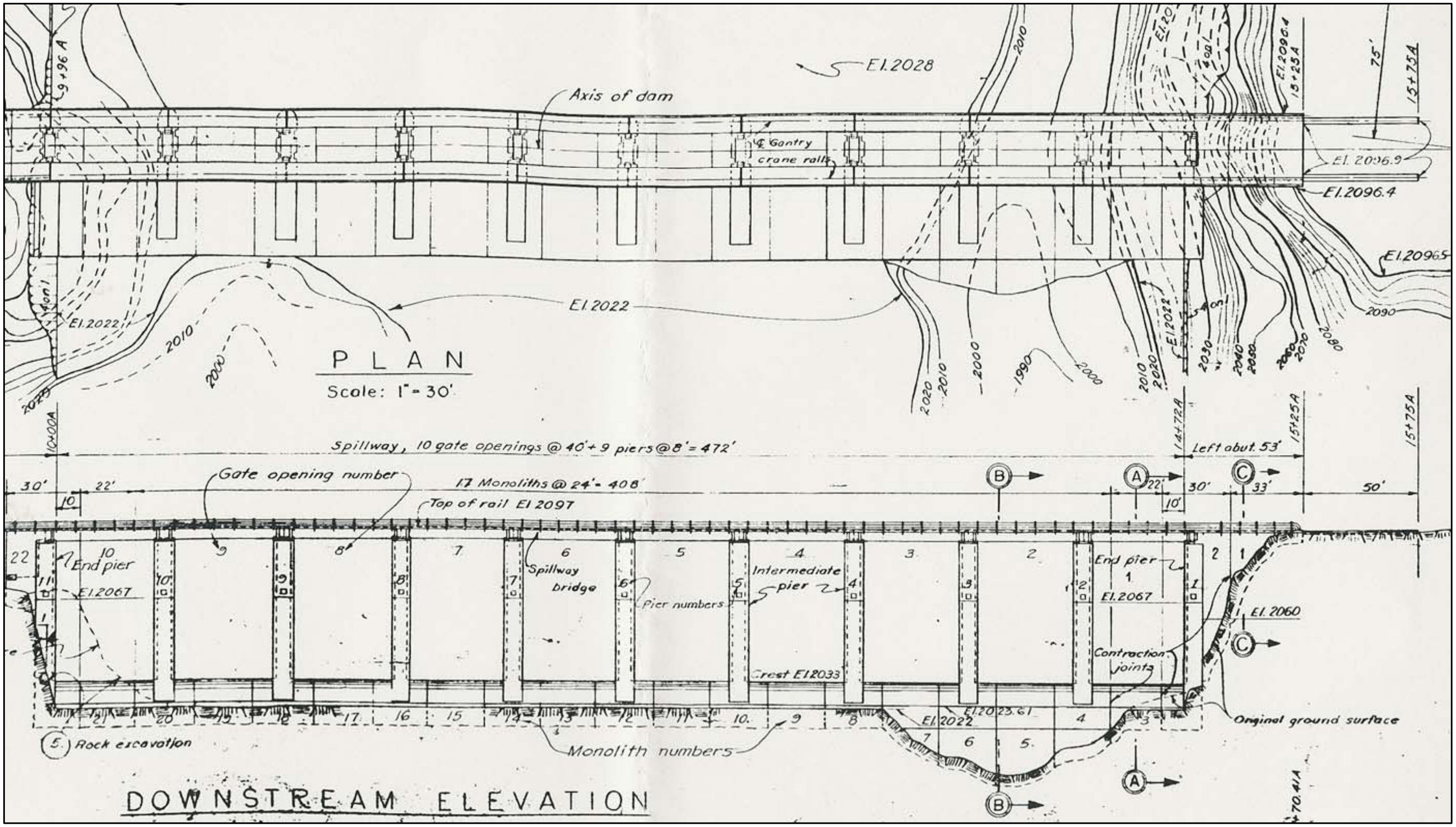

Figure 5 Plan and Elevation View of Albeni Falls Spillway.

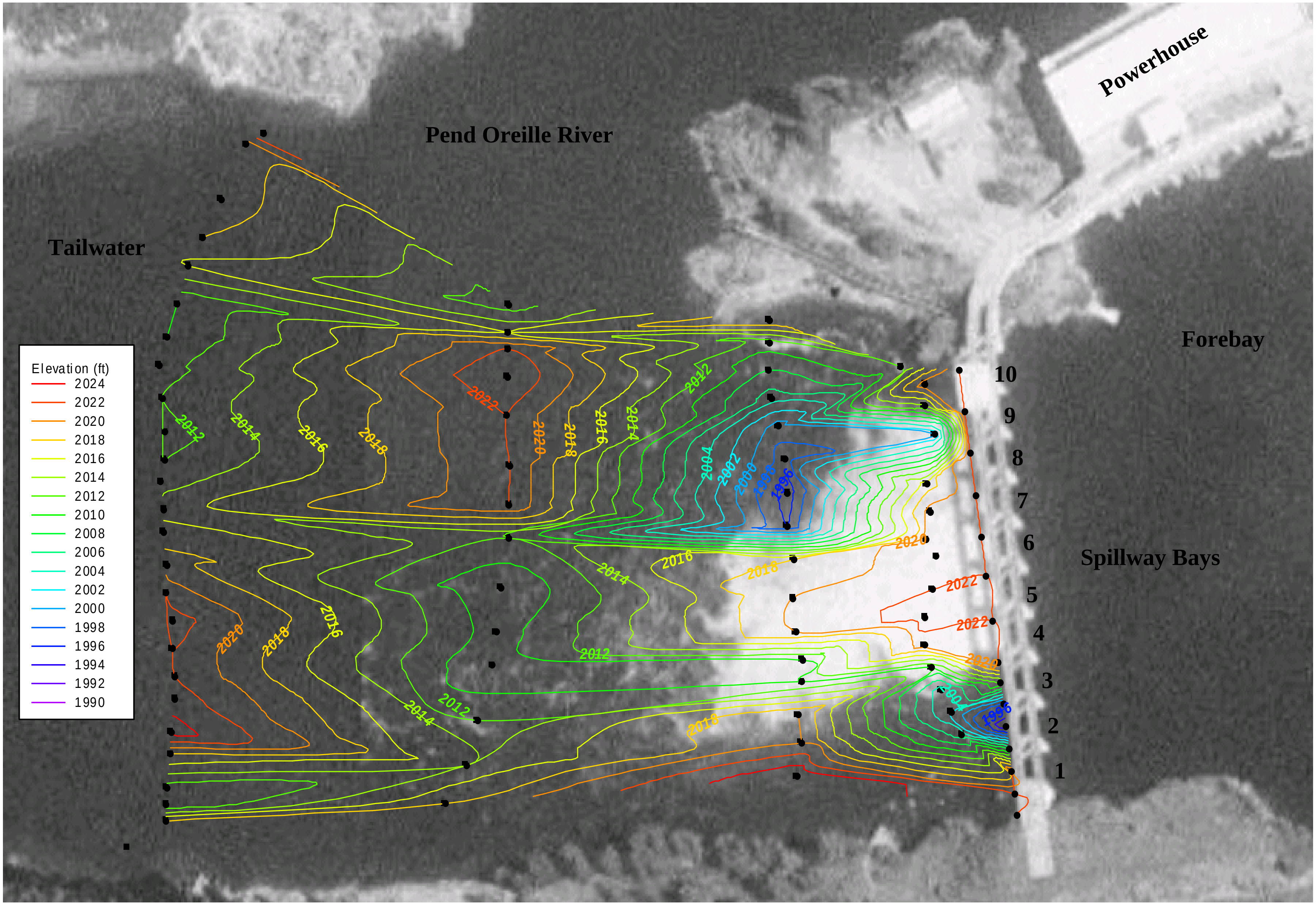

Figure 6. Pend Oreille River Exit Spillway Channel Bathymetry.

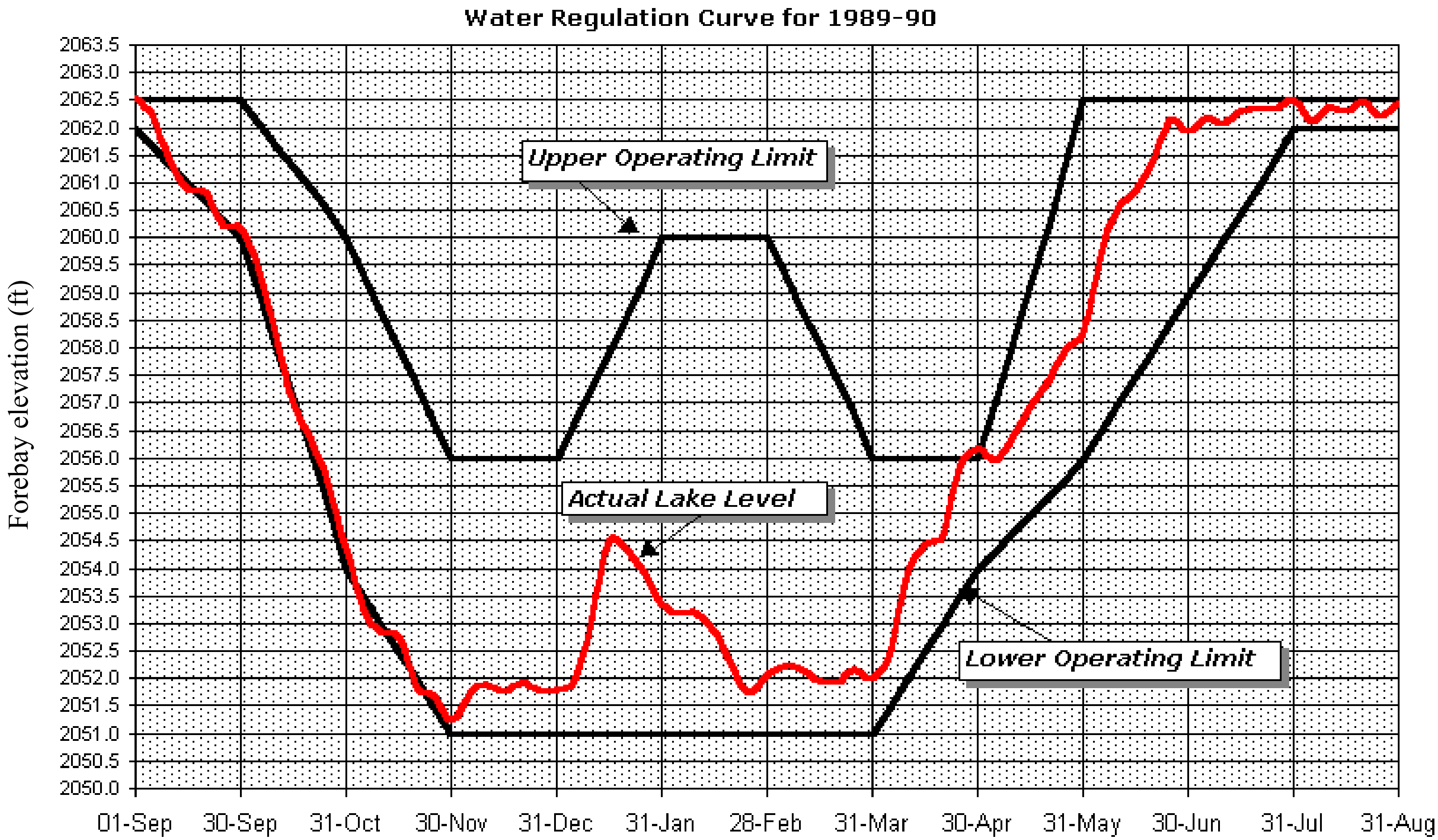

Figure 7. Water Regulation Curve for the Pend Oreille River at Albeni Falls Dam.

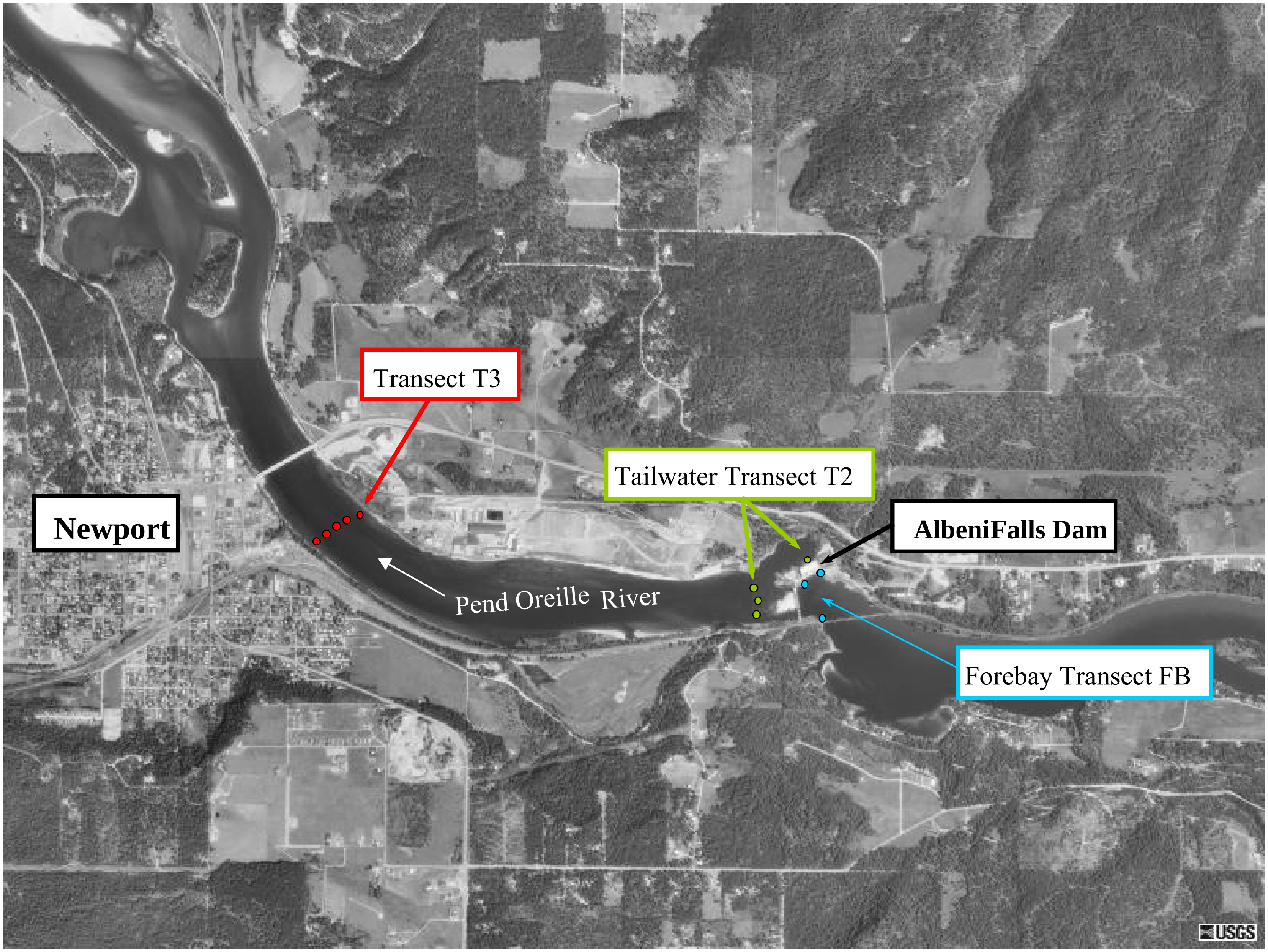

Figure 8. Total Dissolved Gas Sampling Transects and Locations in the Pend Oreille River Above and Below Albeni Falls Dam.

Figure 9 Photograph of Forebay of Albeni Falls Dam and TDG Sampling Stations FBP2 and FBP3.

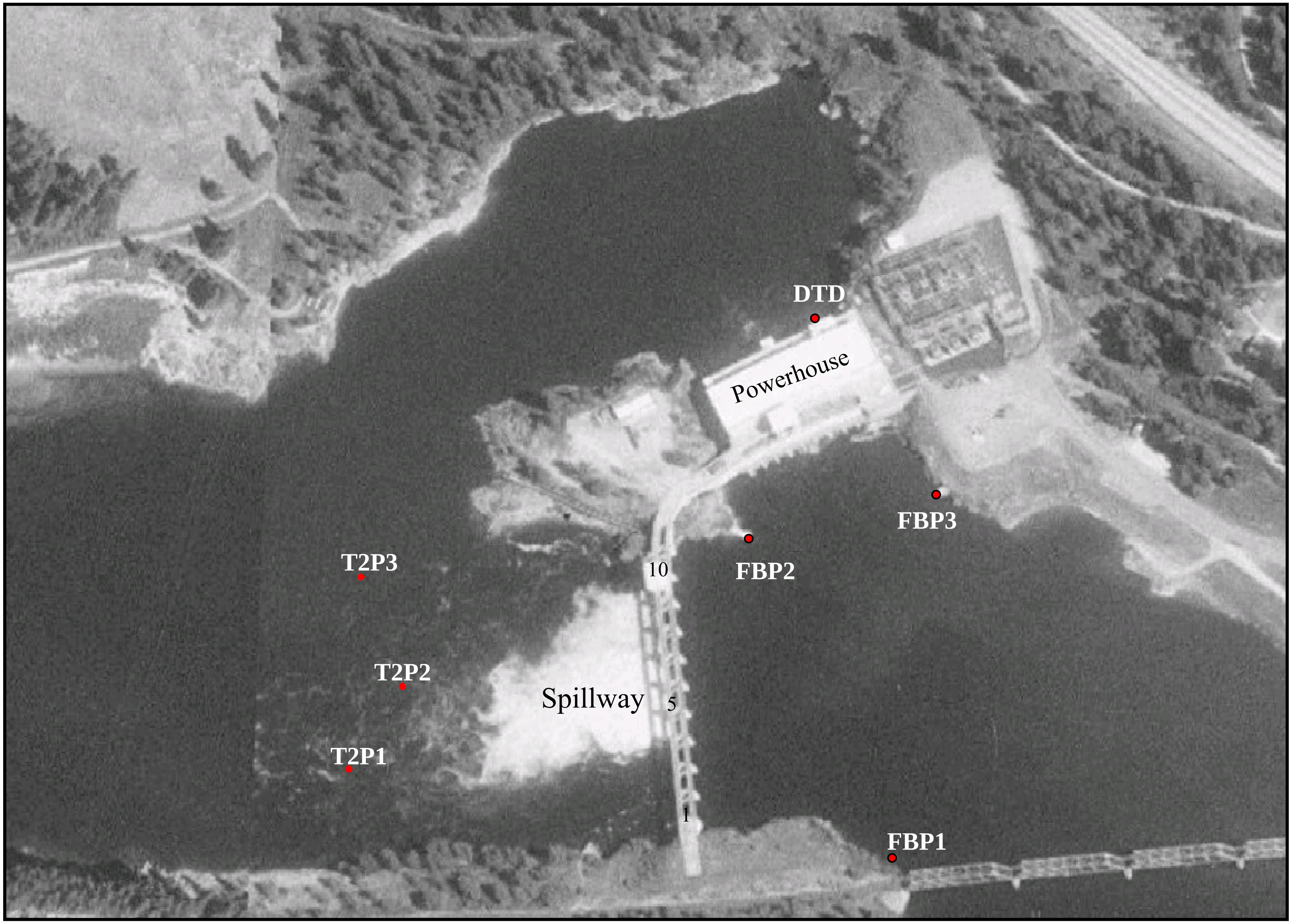

Figure 10. Total Dissolved Gas sampling stations near Albeni Falls Dam, forebay and tailwater transects.

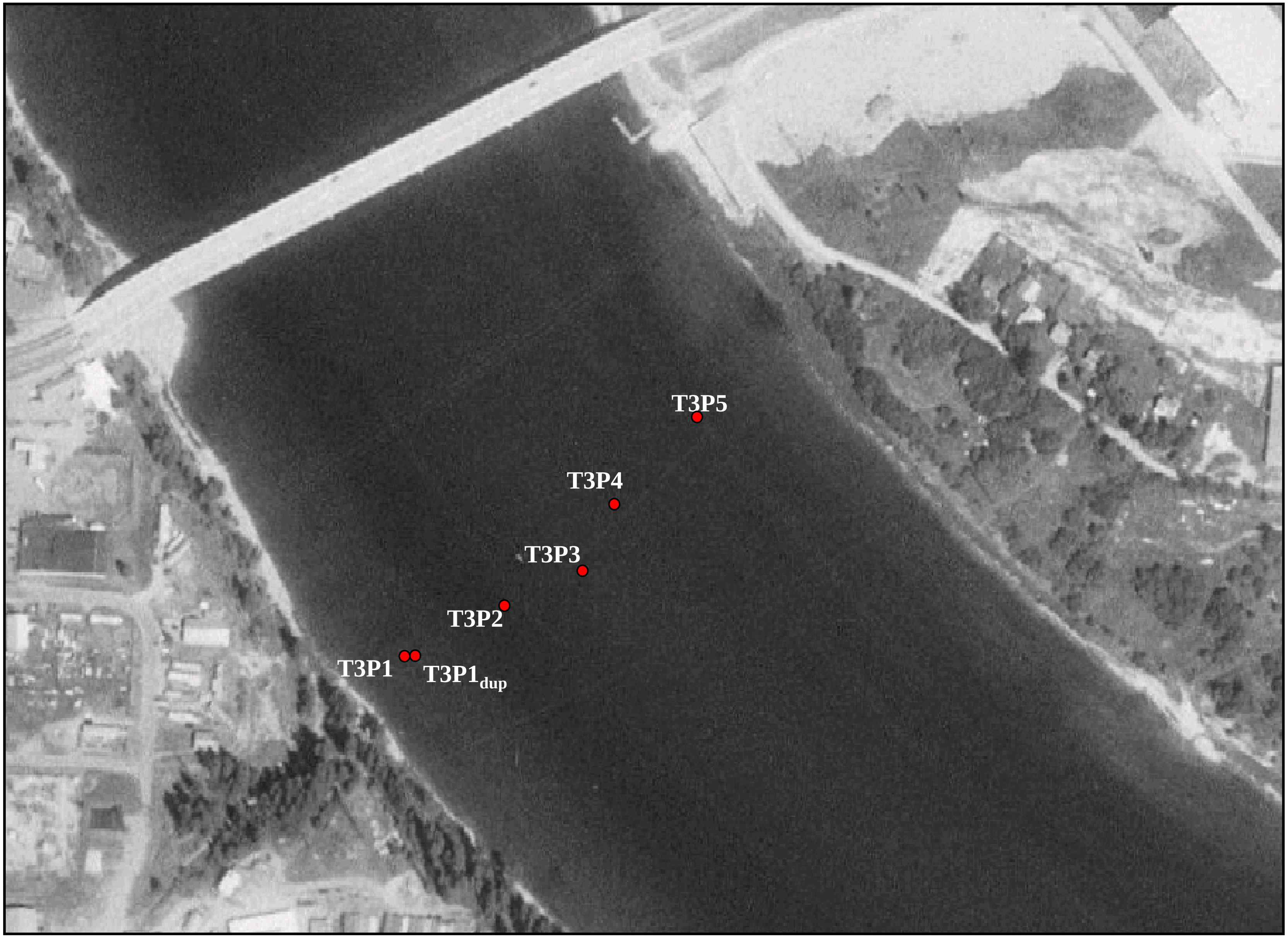

Figure 11. Total Dissolved Gas sampling station in the Pend Oreille River below Albeni Falls Dam, Transect T3.

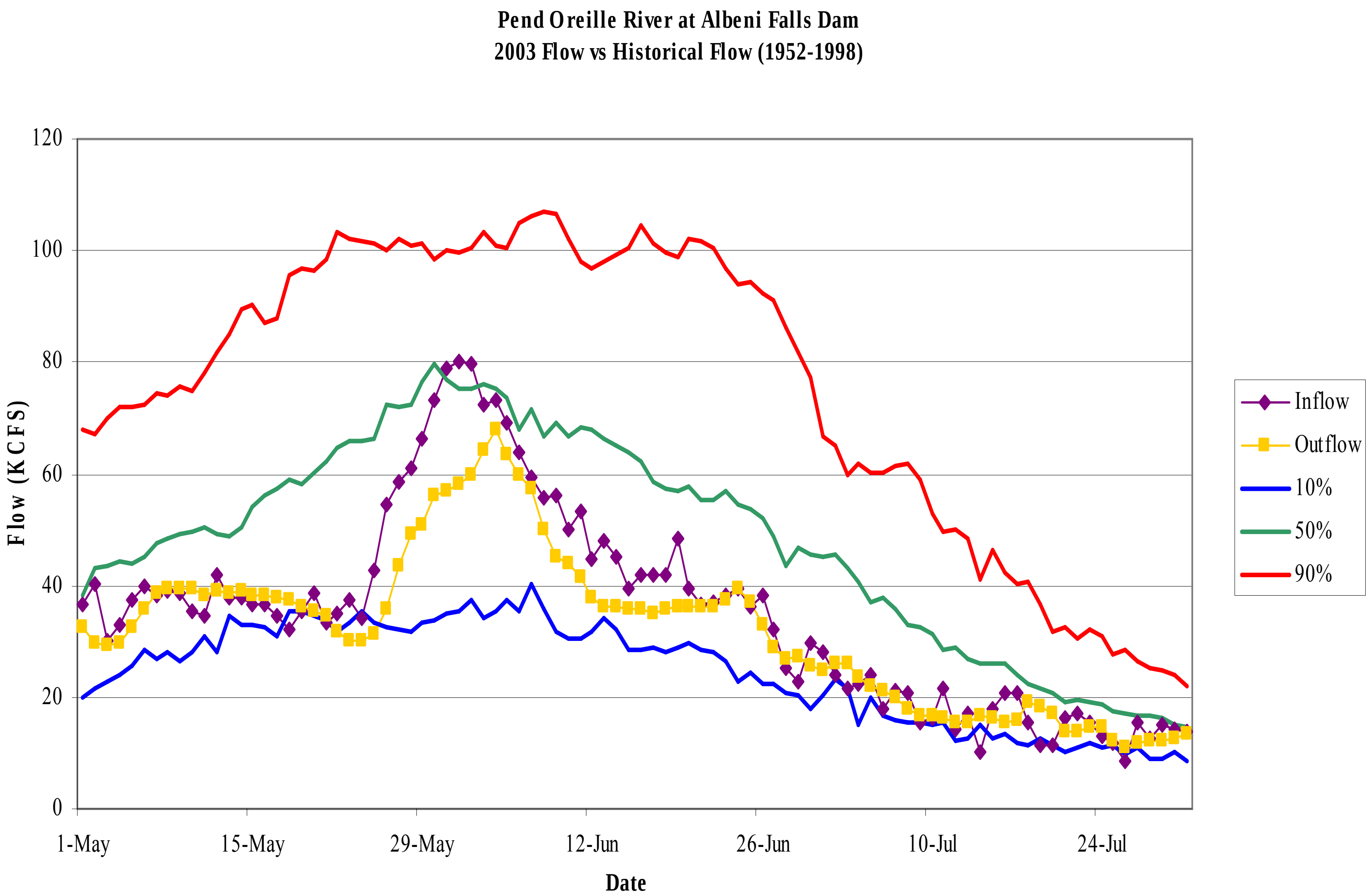

Figure 12. Pend Oreille River daily 2003 flows versus historical flows at Albeni Falls Dam.

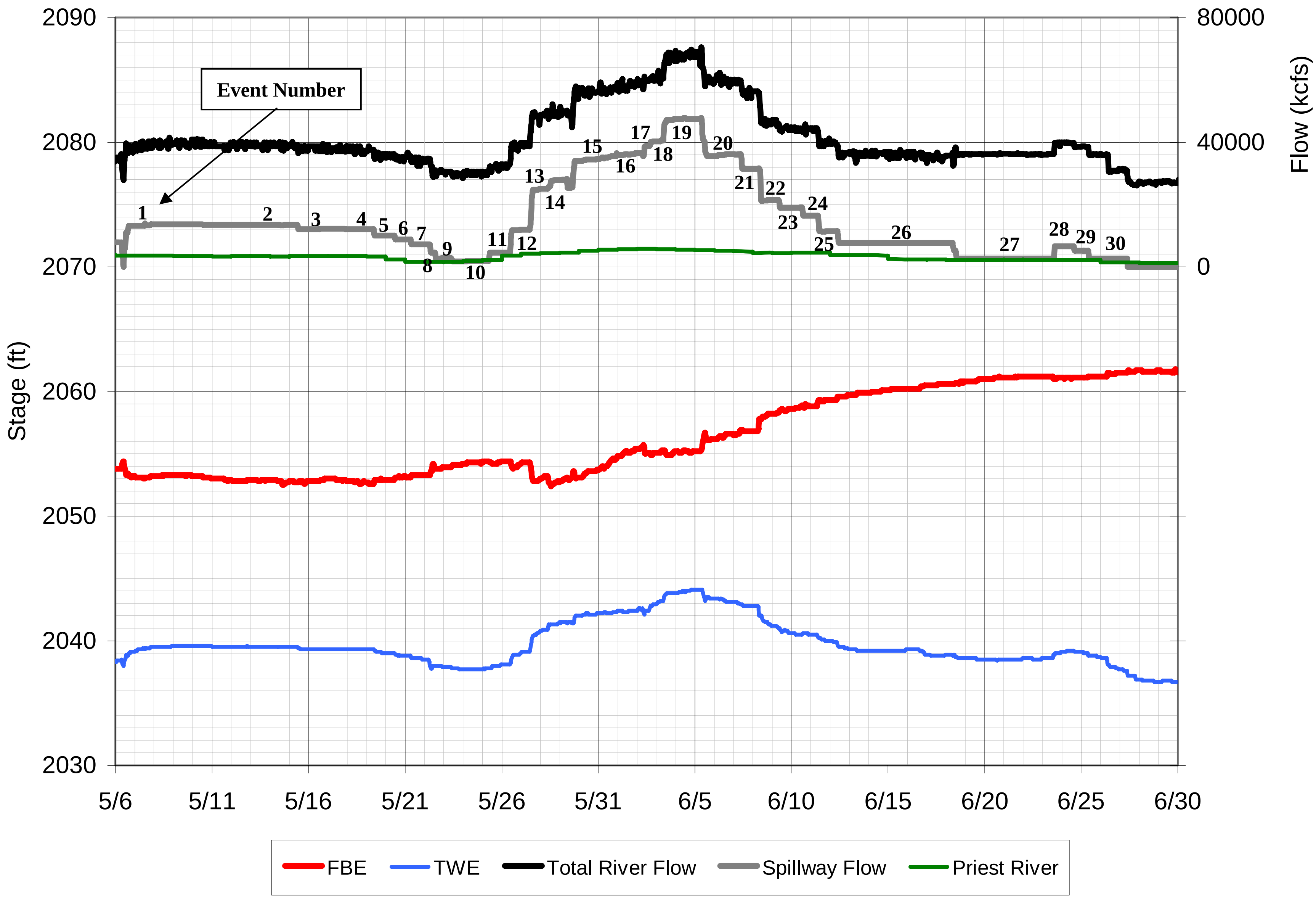

Figure 13. Albeni Falls Dam operation and Priest River flow, 5/6/2003-6/30/2003
(FBE-Forebay Elevation, TWE-Tailwater Elevation)

Figure 14. Flow conditions in the spillway exit channel during Event 2 on May 7, 2003 at 1700 hrs
(Qtotal= 38.3 kcfs, Qsp=13.2 kcfs, TWE=2039.2 ft, 8 bay spill pattern)

Figure 15. Flow conditions in the spillway exit channel during Event 1, May 6, 2003 1800 hrs
(Qtotal= 38.8 kcfs, Qsp=13.2 kcfs, TWE=2039 ft, 4 bay spill pattern)

Figure 16. Video Clip of Albeni Falls Spillway Discharges, May 5, 2003.
(Qtotal=33.2 kcfs, Qspill=7.8 kcfs, TWE=2038.1 ft, Requires filename alfc4.avi)

Figure 17. Video clip of flow conditions in the spillway exit channel during Event 20, June 5, 2003 at 13:33 hrs
(Qtotal= 59.8 kcfs, Qsp=35.9 kcfs, bays 3-8, requires file albf01.avi)

Figure 18. Tailrace channel flow conditions downstream of the Albeni Falls Powerhouse.

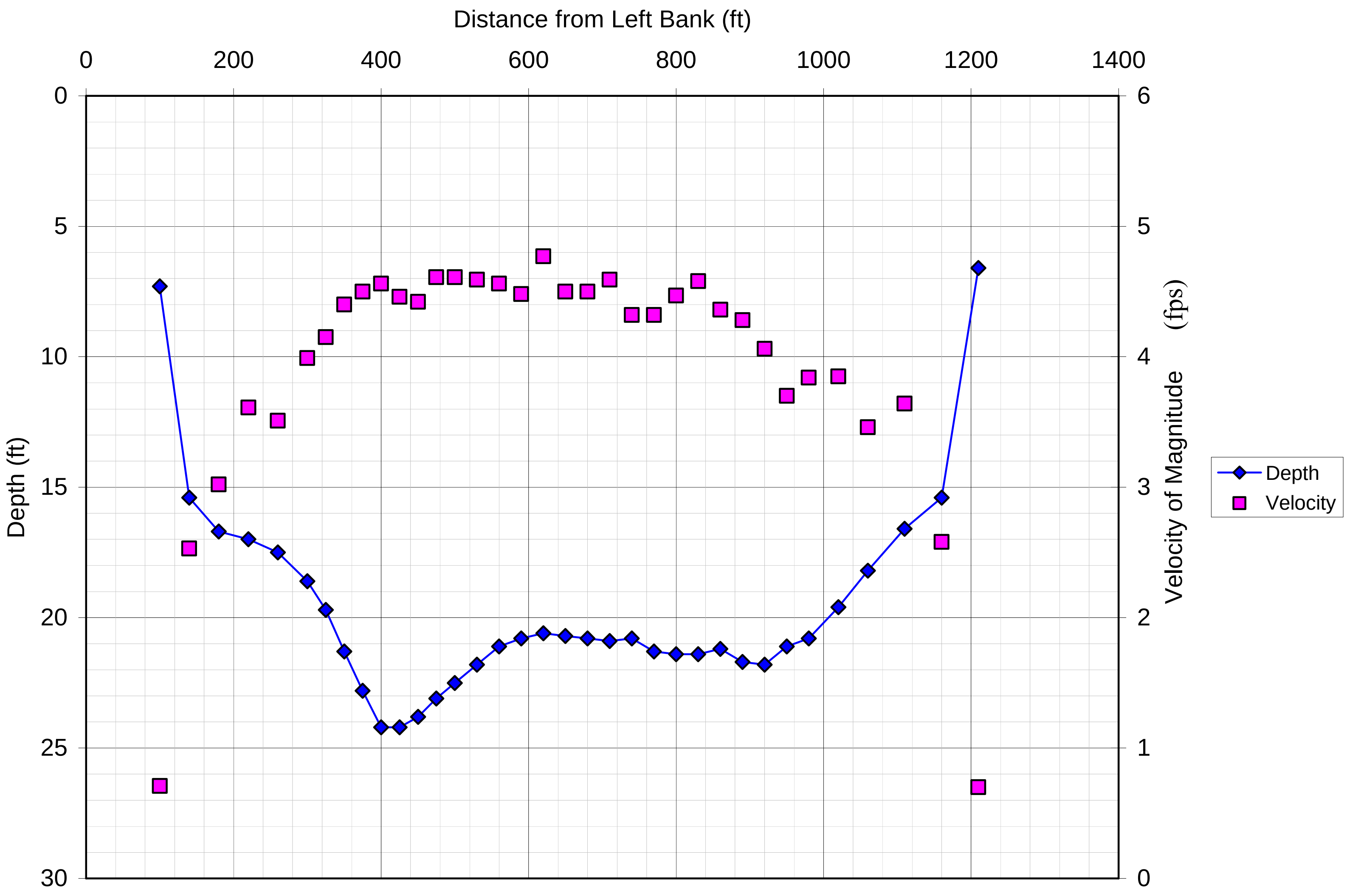

Figure 19. The channel bathymetry and velocity distribution on Transect T3 for a total river flow of 54 kcfs (Depth (ft) vs. Distance from left bank (ft))

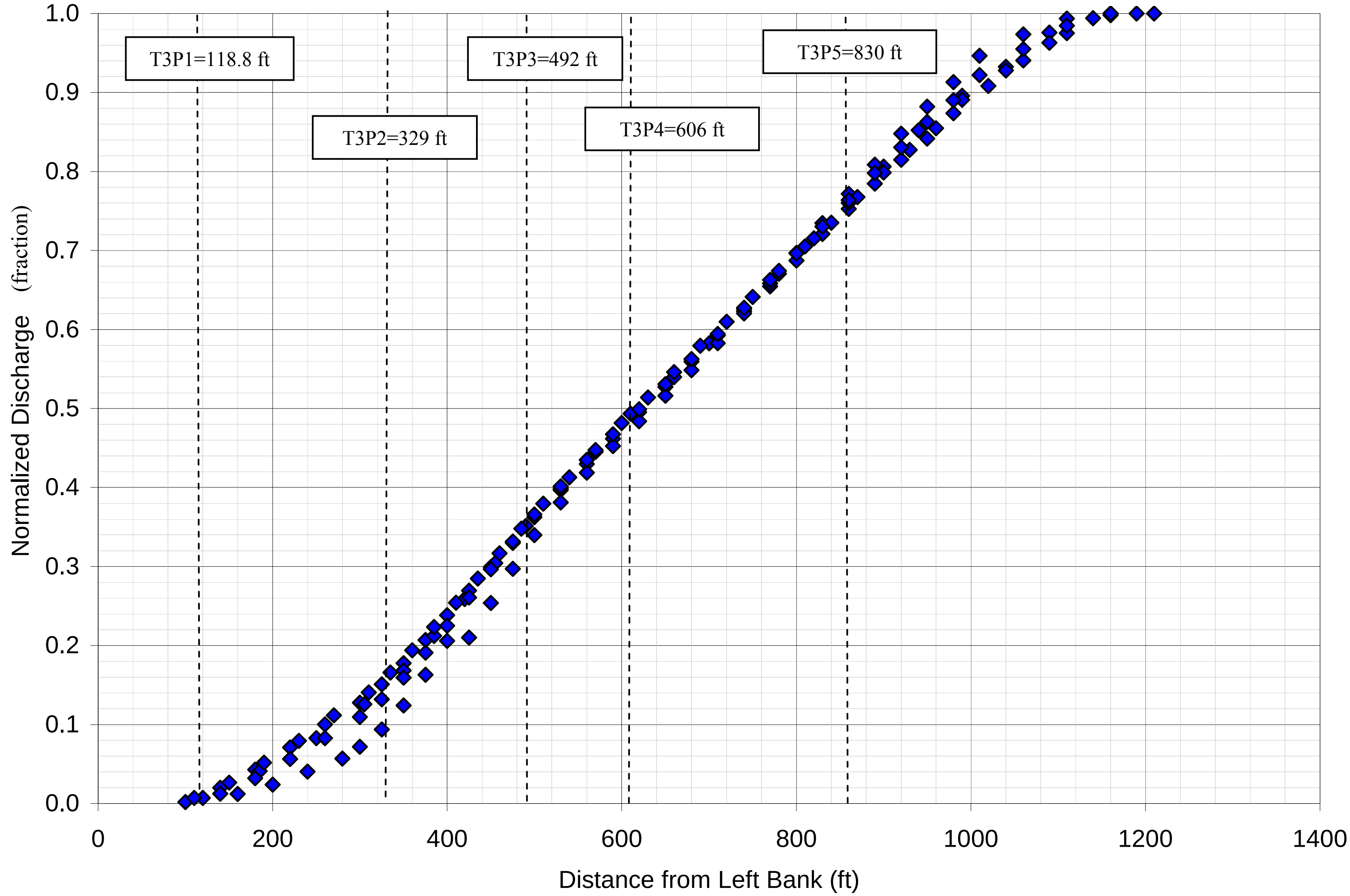

Figure 20. Normalized discharge (cfs/cfs) vs. distance from left bank (ft)

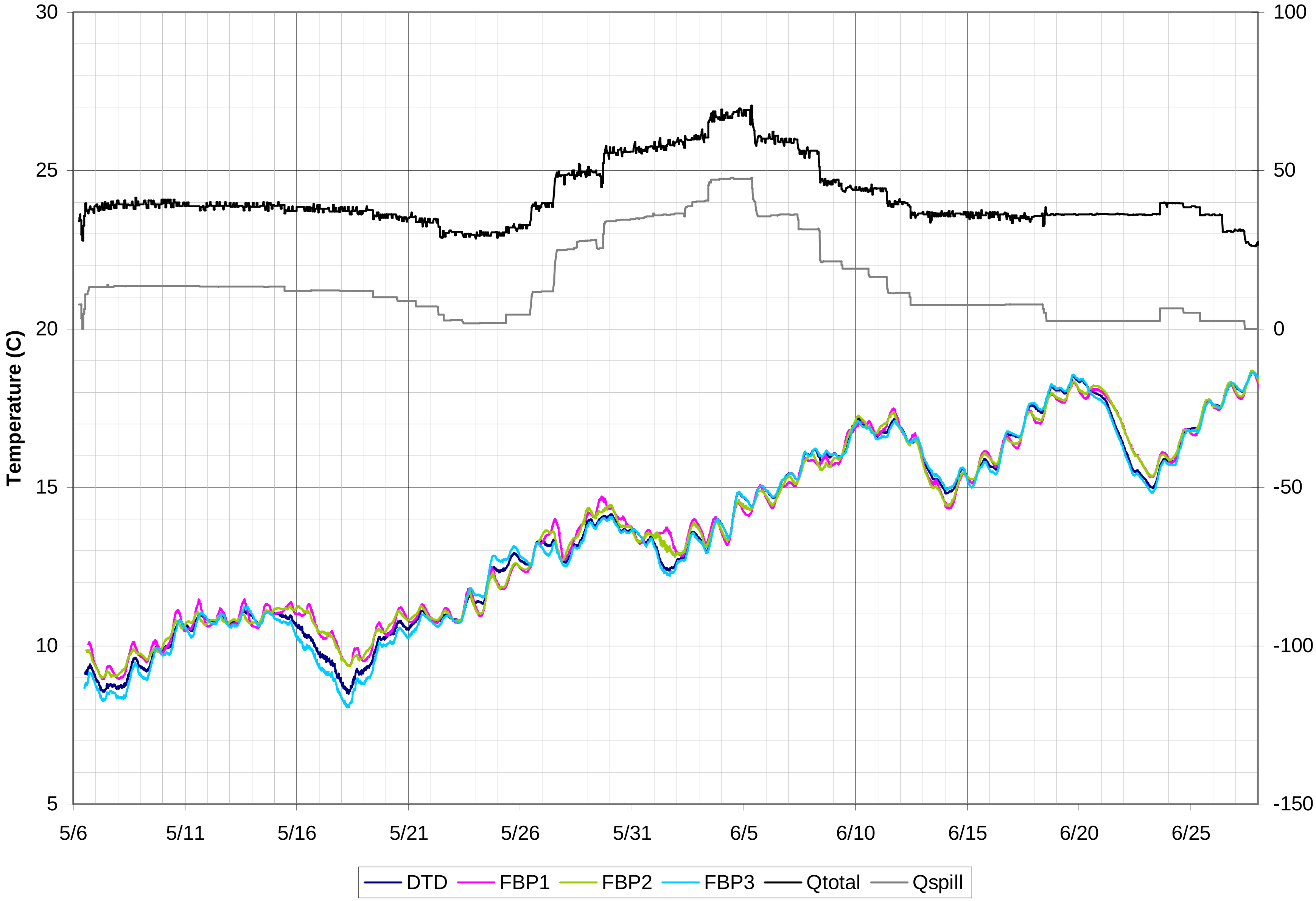

Figure 21. Water Temperatures in the Pend Oreille River at upstream and downstream of Albeni Falls Dam, May 6-June27, 2003.

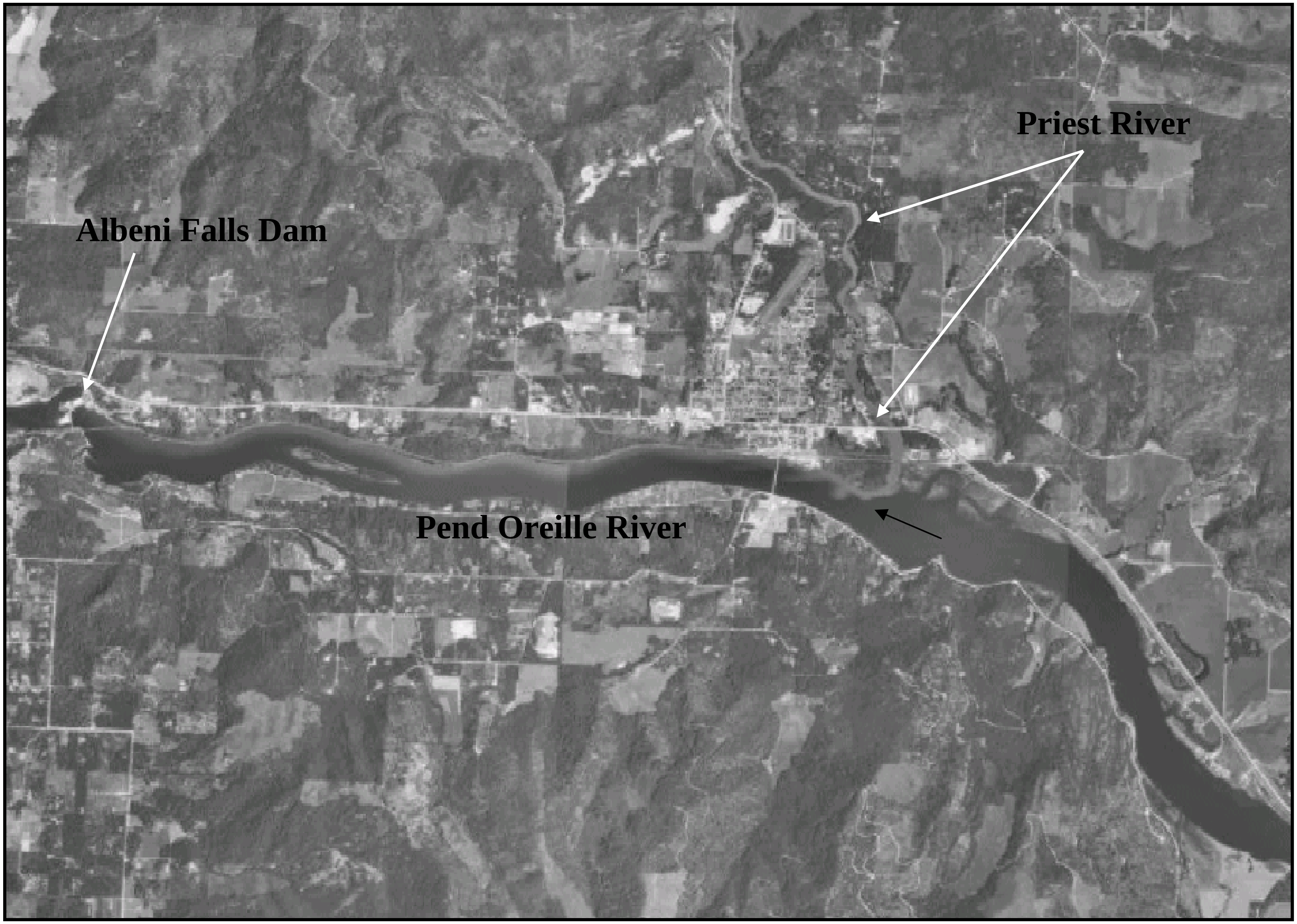

Figure 22. Albeni Falls Dam, Pend Oreille and Priest Rivers, Aerial Photo

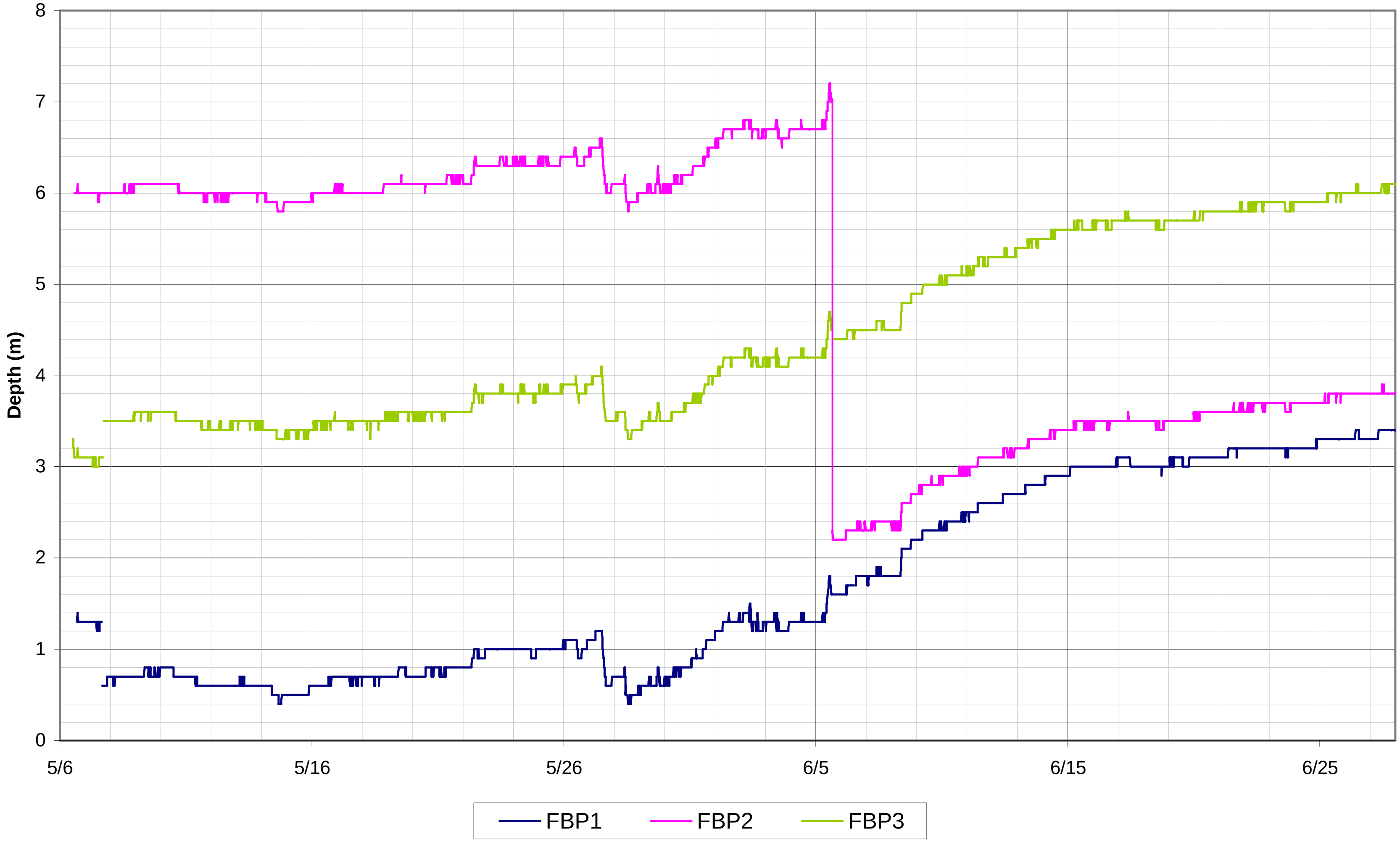

Figure 23. Instrument Depth in the Forebay of Albeni Falls Dam, May 6-June 28, 2003.

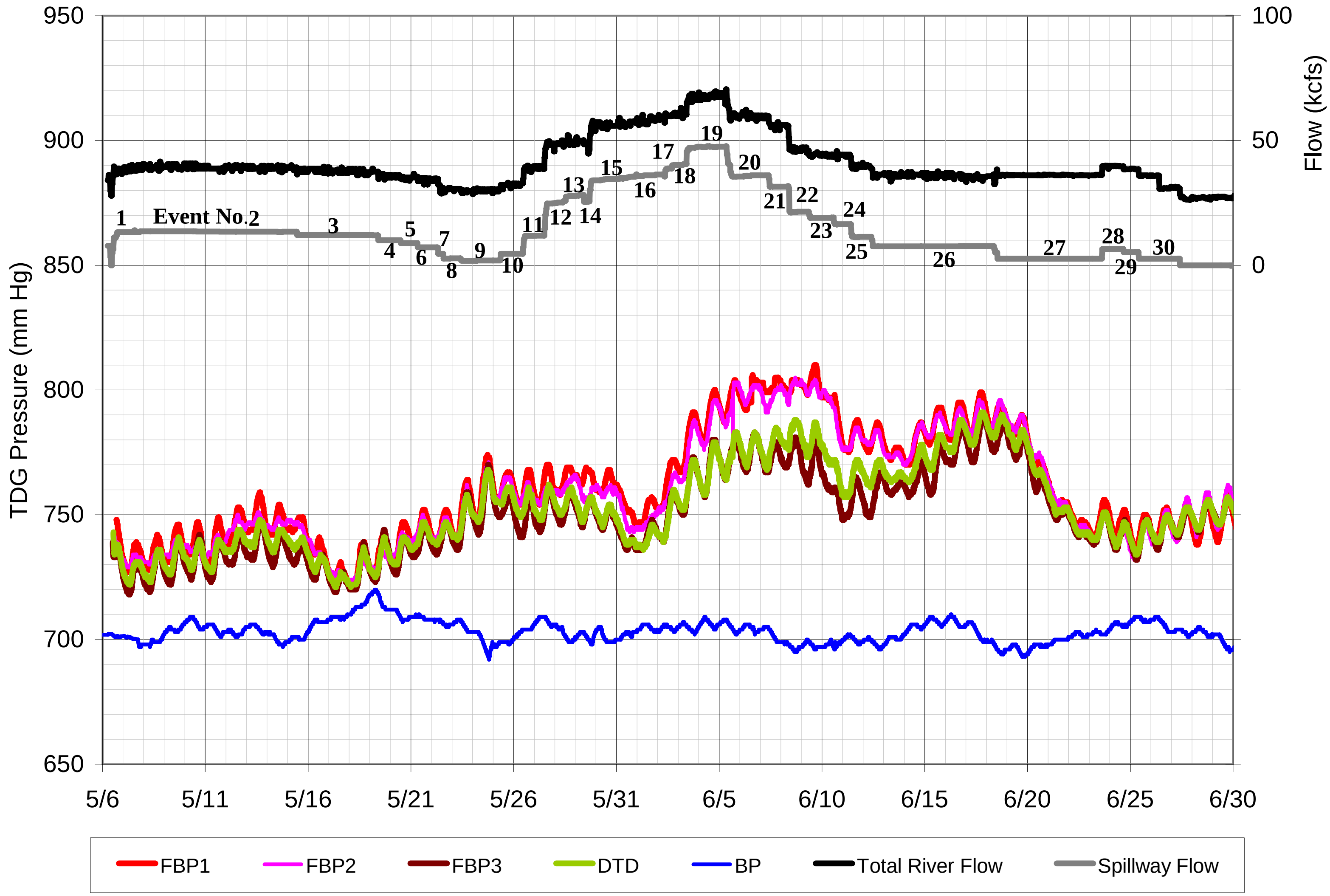

Figure 24. Forebay TDG pressure and Albeni Falls Dam Operations, 2003

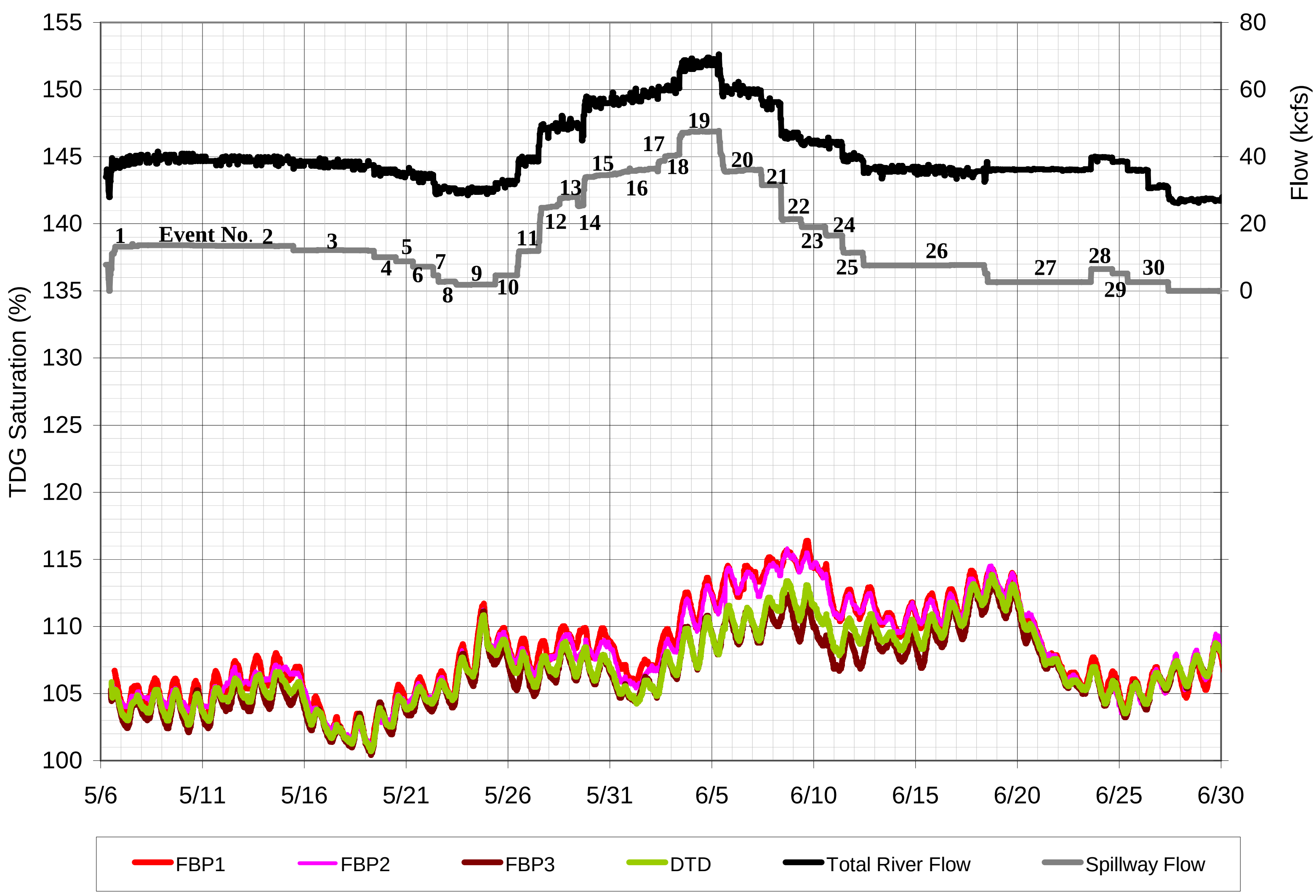

Figure 25. Forebay TDG Saturation and Albeni Falls Dam Operations, 2003

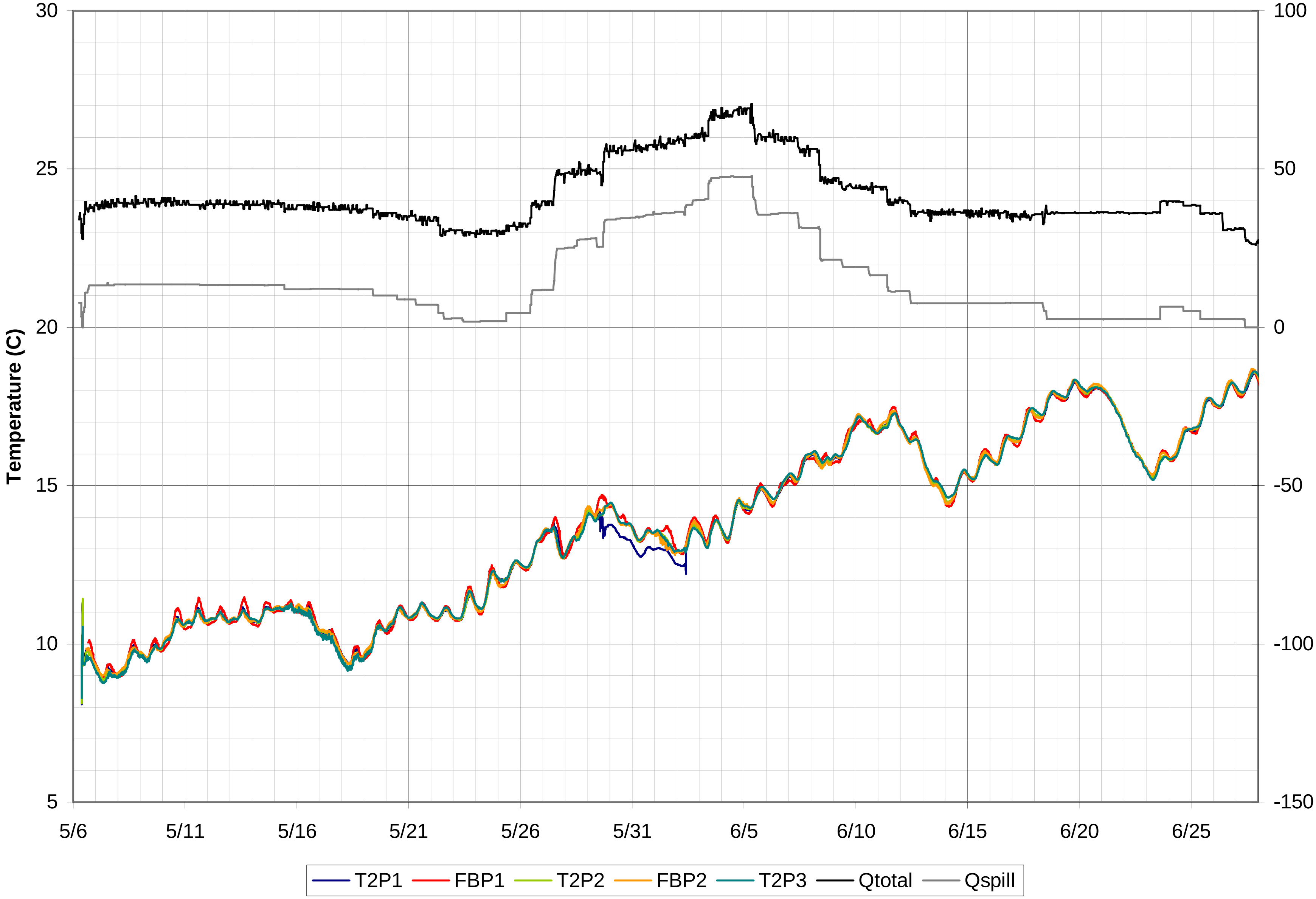

Figure 26. Water Temperatures in the Pend Oreille River at upstream and downstream of Albeni Falls Dam, May 6-June 27, 2003.

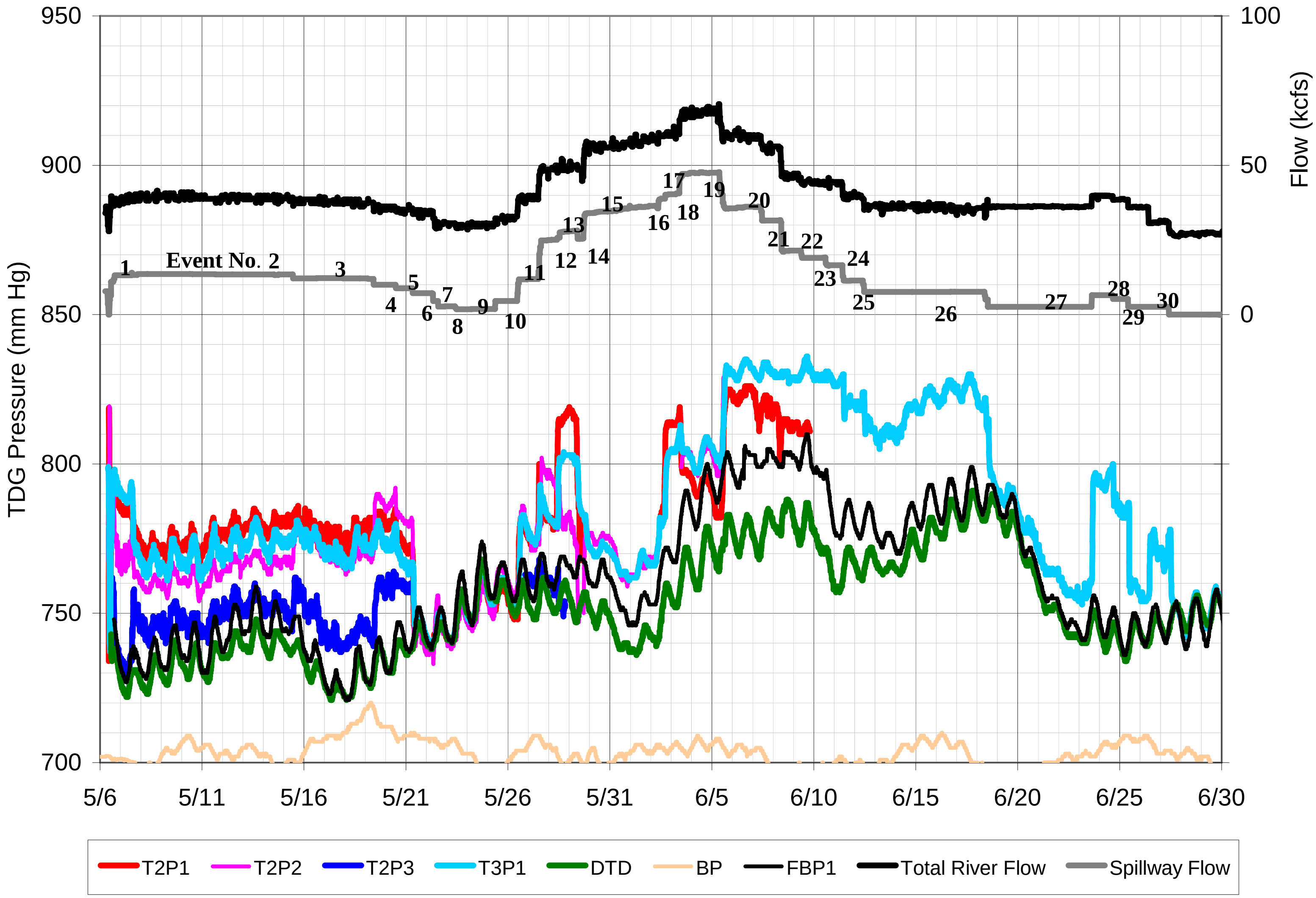

Figure 27. Transect 2 TDG Pressure and Albeni Falls Dam Operations, 2003
(Filtered TDG Data)

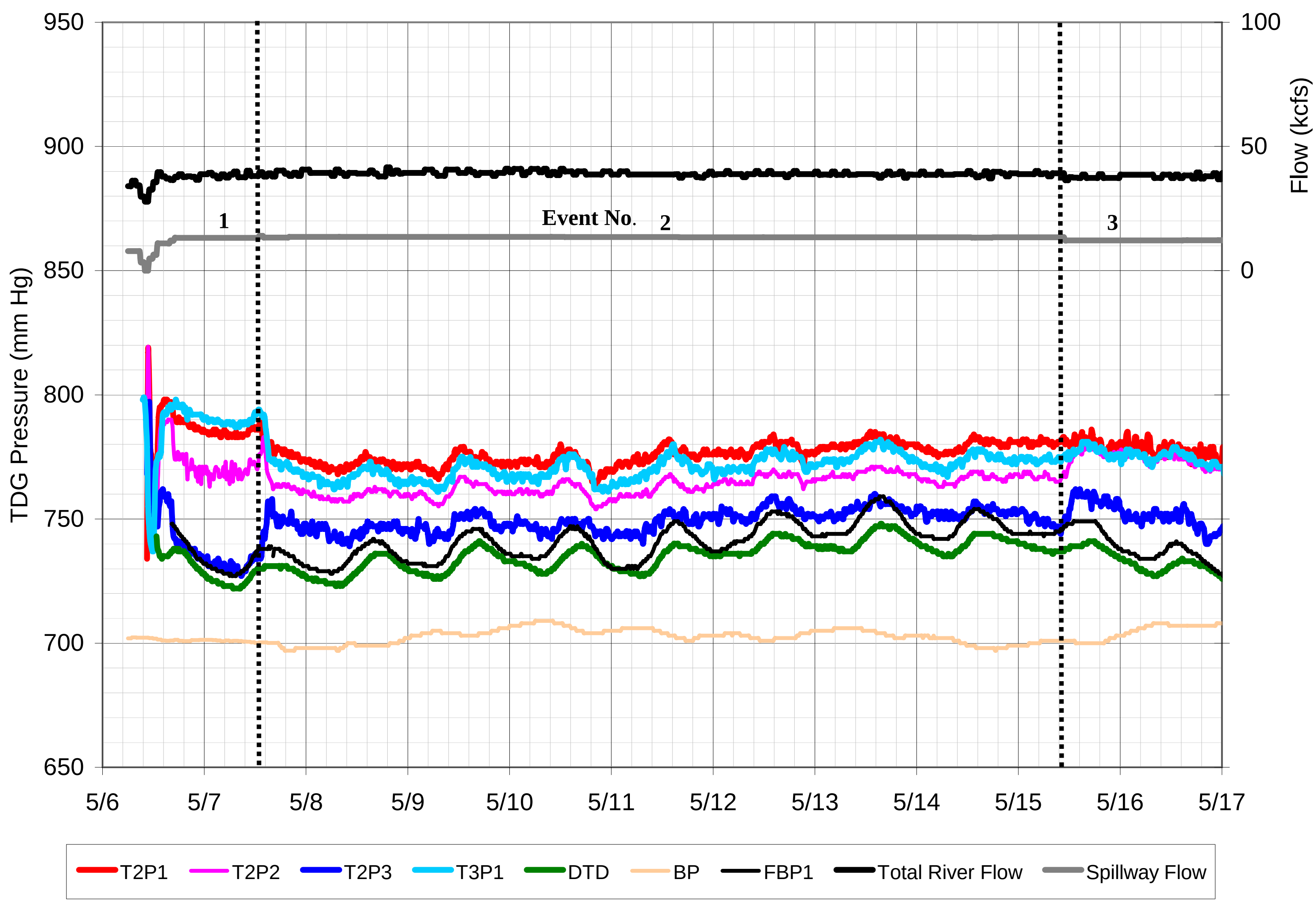

Figure 27a. Transect 2 TDG Pressure 6-17 May 2003 and Albeni Falls Dam Operations, 2003
(Raw TDG Data)

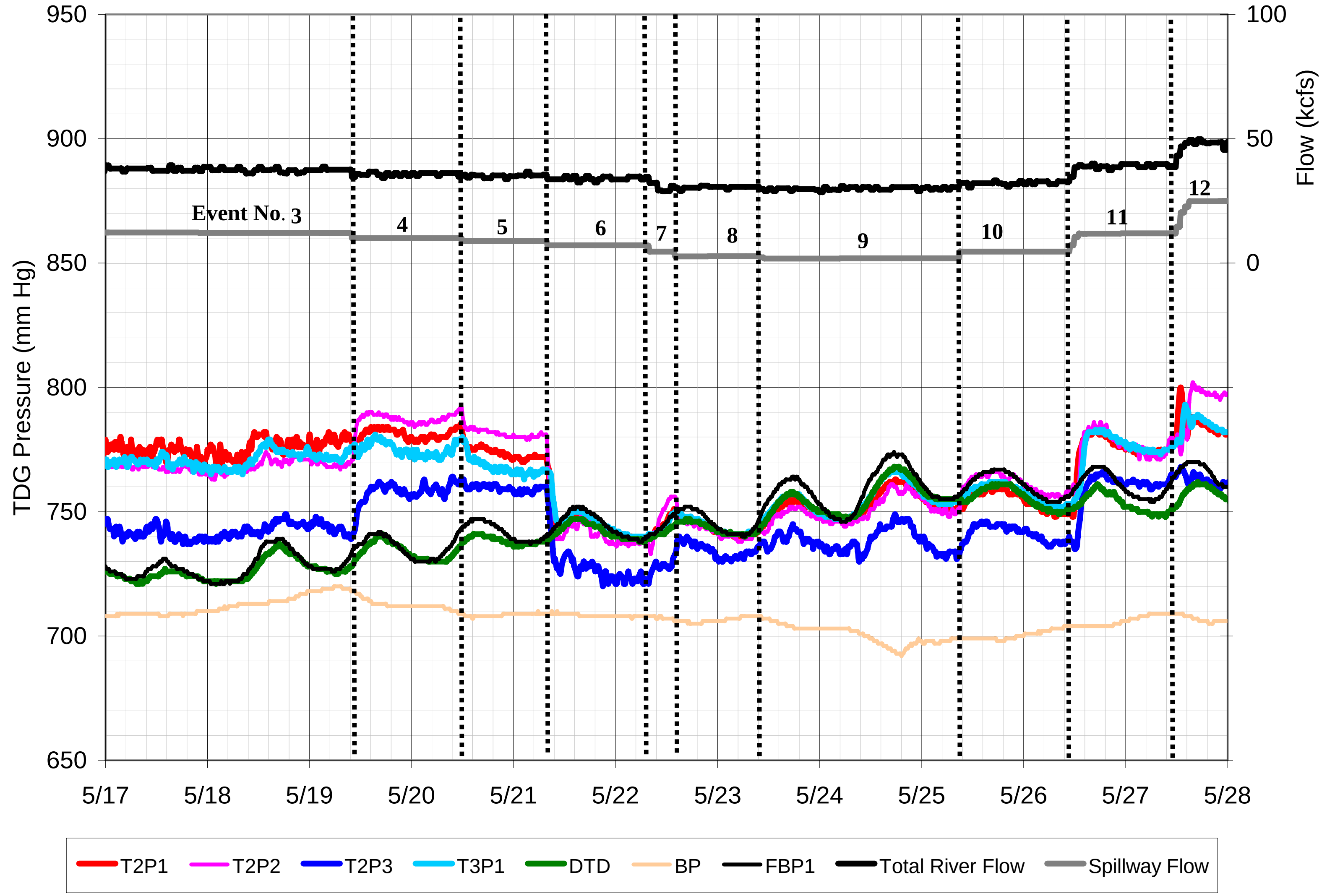

Figure 27b. Transect 2 TDG Pressure 17-28 May 2003 and Albeni Falls Dam Operations, 2003
(Raw TDG Data)

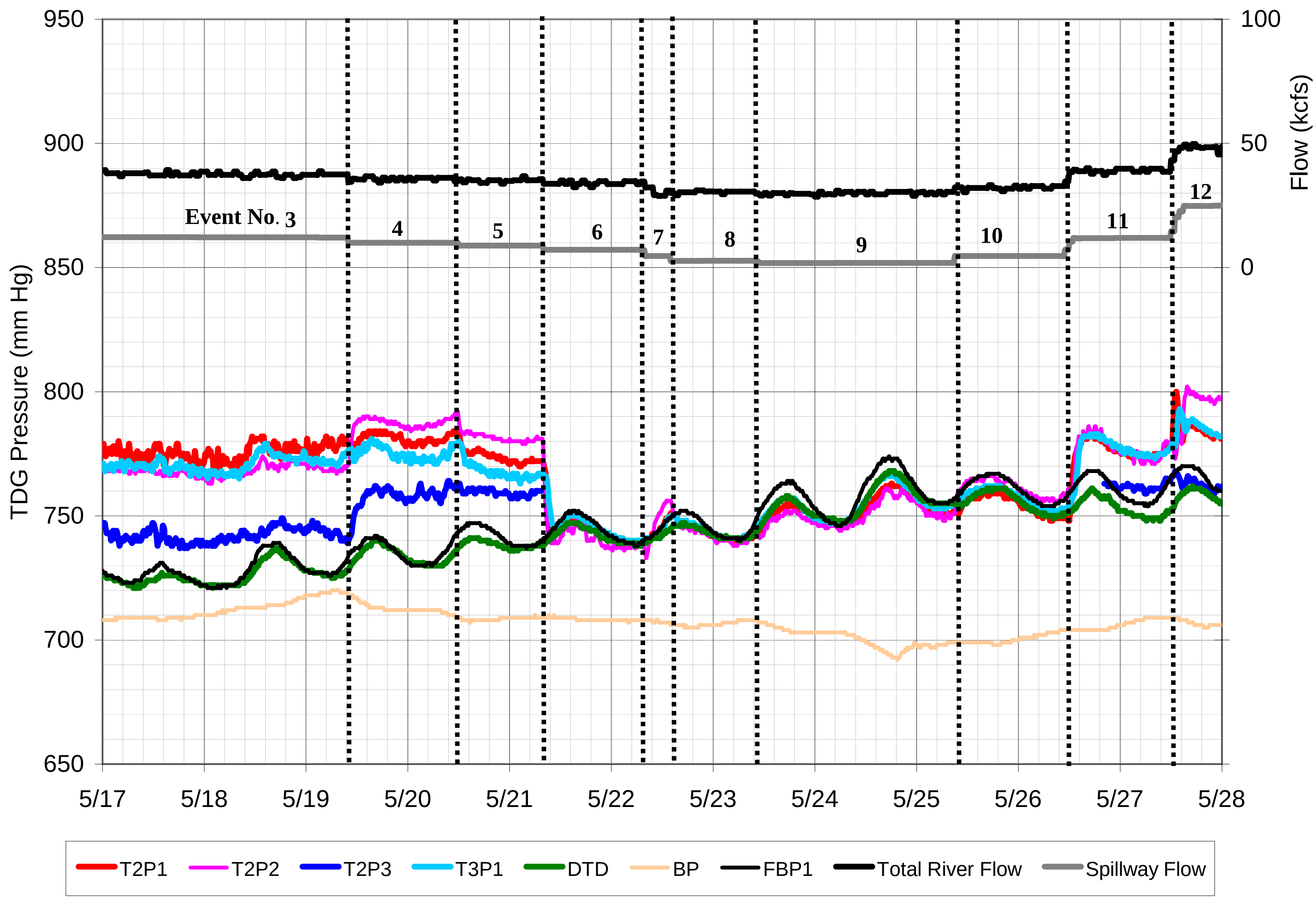

Figure 27c. Transect 2 TDG Pressure 17-28 May 2003 and Albeni Falls Dam Operations, 2003
(Filtered TDG Data)

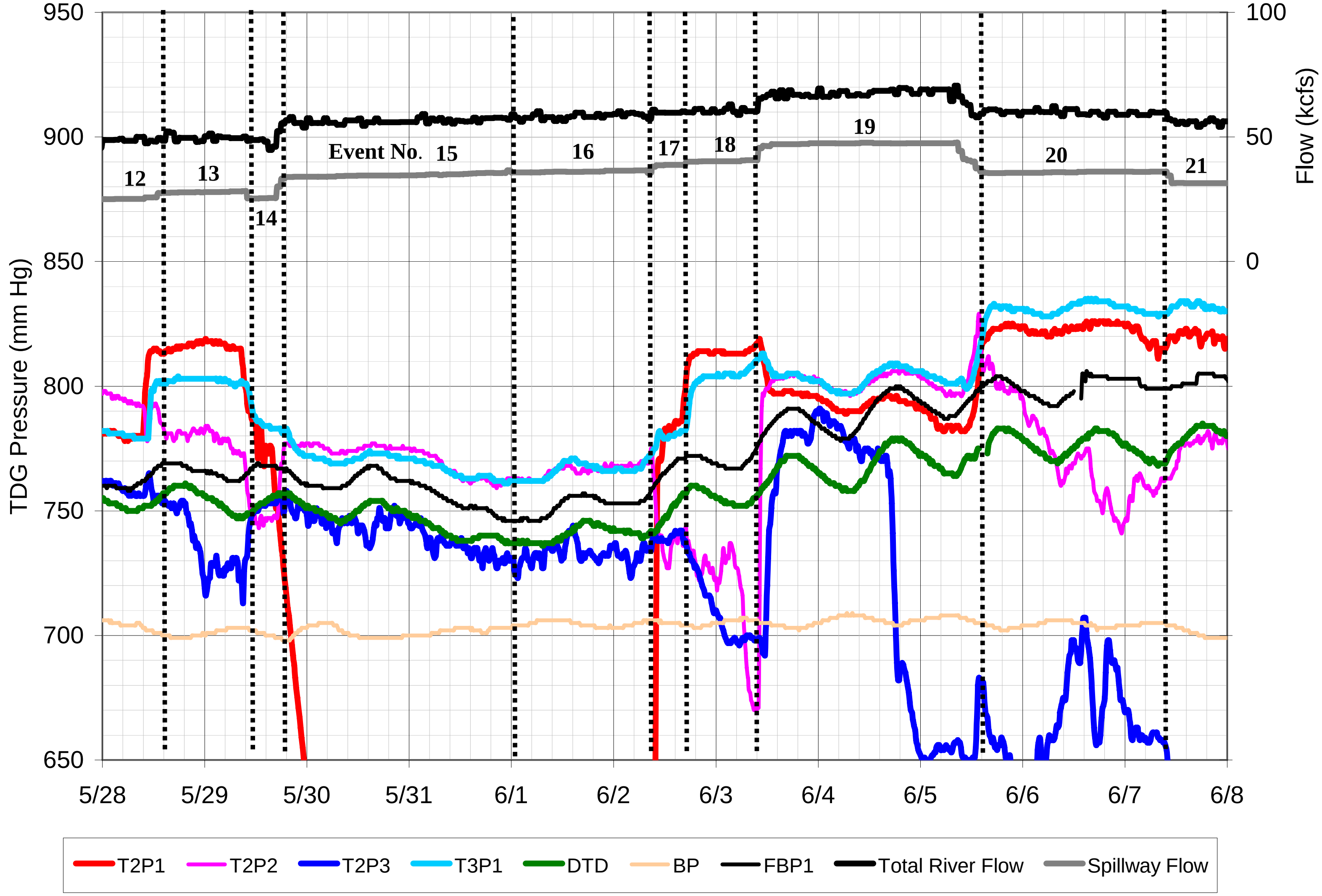

Figure 27d. Transect 2 TDG Pressure 28 May-8 June 2003 and Albeni Falls Dam Operations, 2003
(Raw TDG Data)

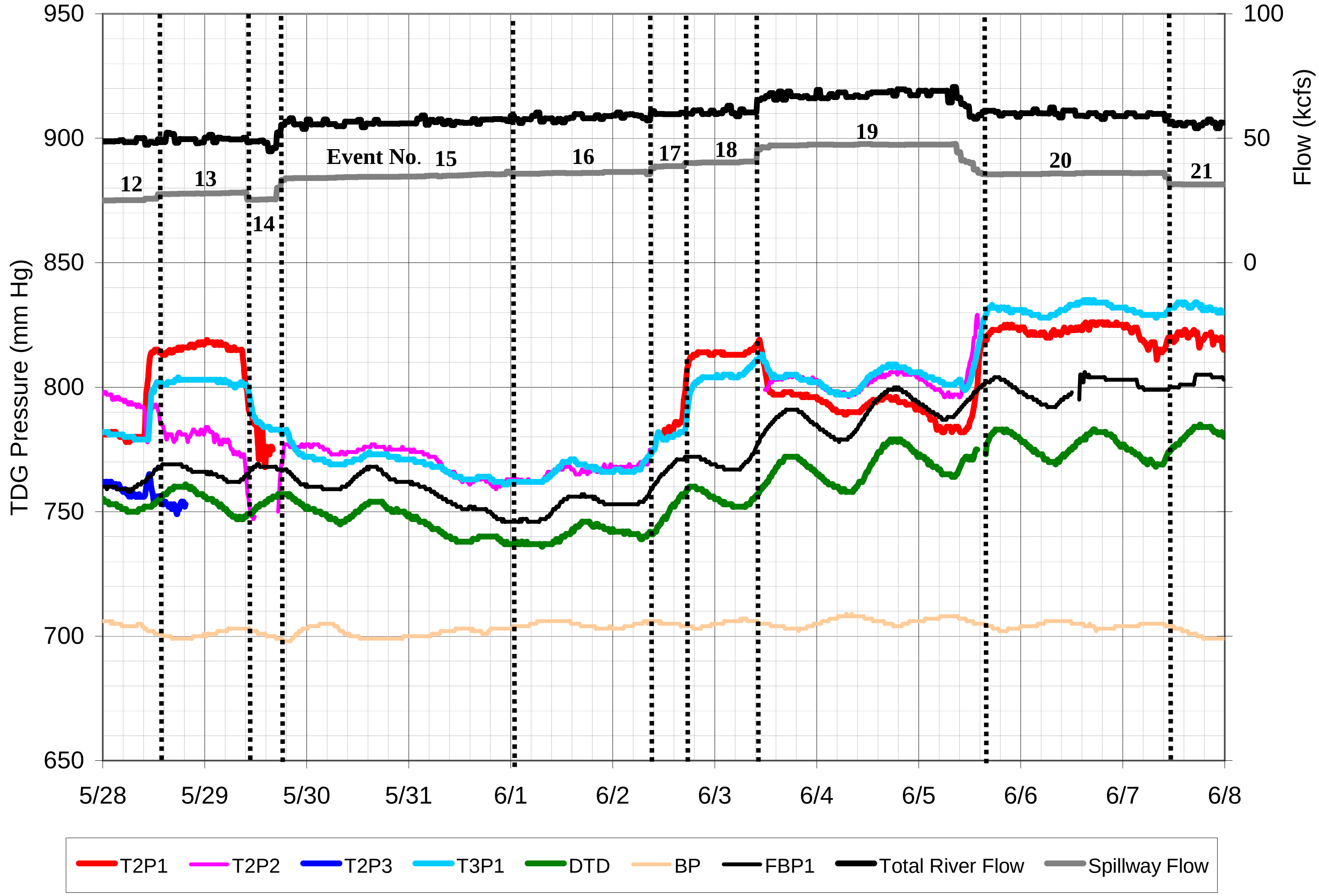

Figure 27e. Transect 2 TDG Pressure 28 May-8 June 2003 and Albeni Falls Dam Operations, 2003
(Filtered TDG Data)

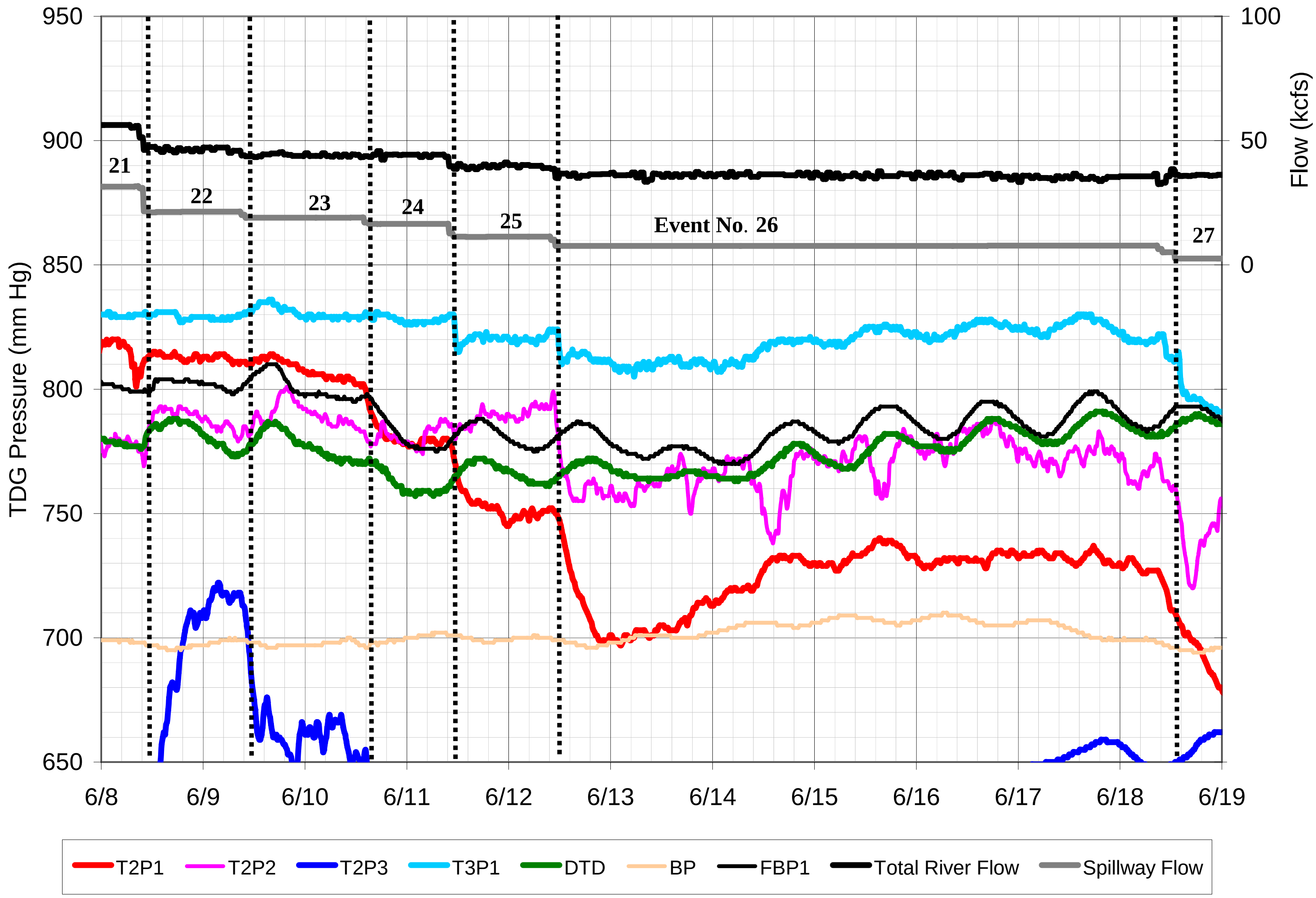

Figure 27f. Transect 2 TDG Pressure 8-19 June 2003 and Albeni Falls Dam Operations, 2003
(Raw TDG Data)

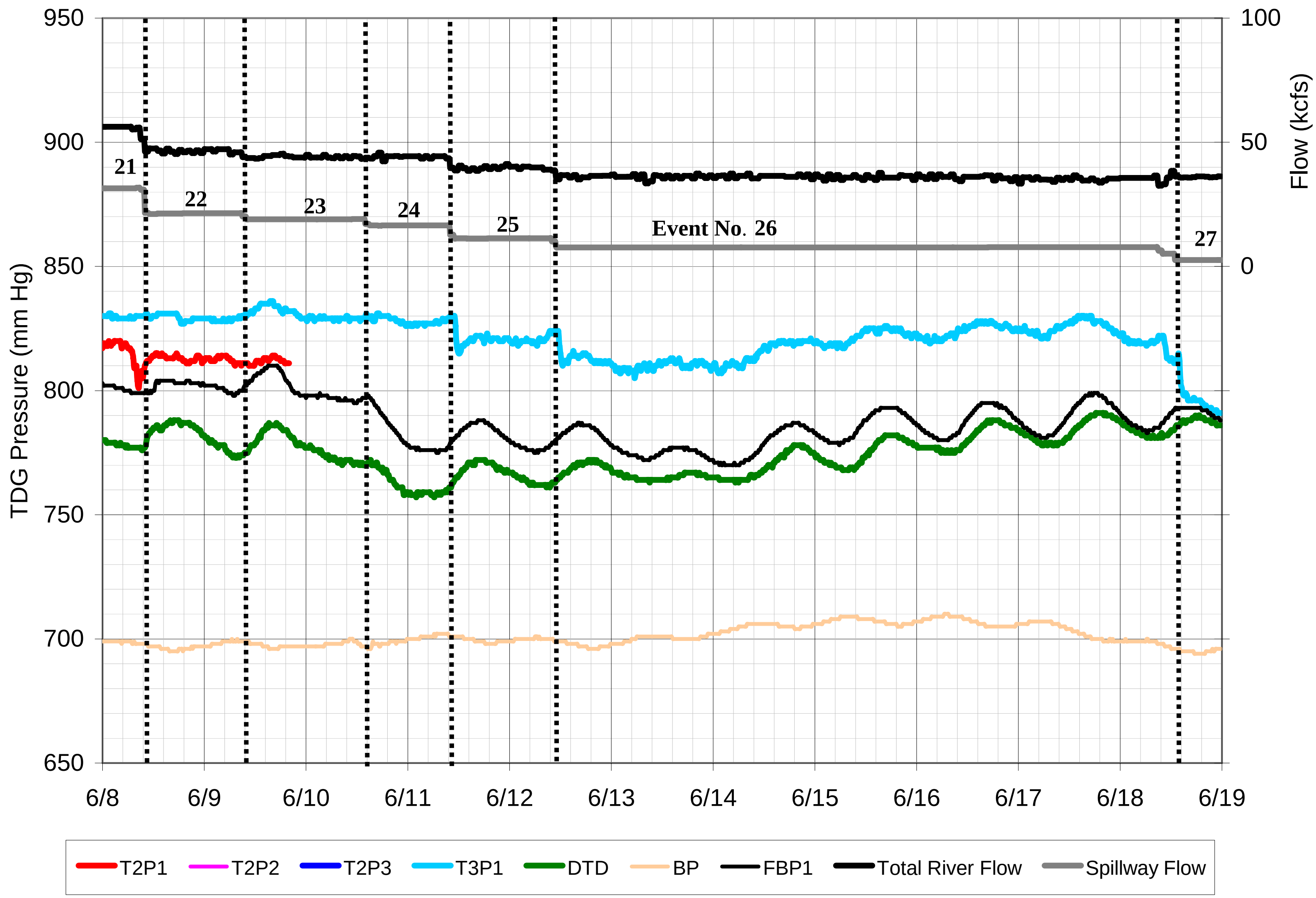

Figure 27g. Transect 2 TDG Pressure 8-19 June 2003 and Albeni Falls Dam Operations, 2003
(Filtered TDG Data)

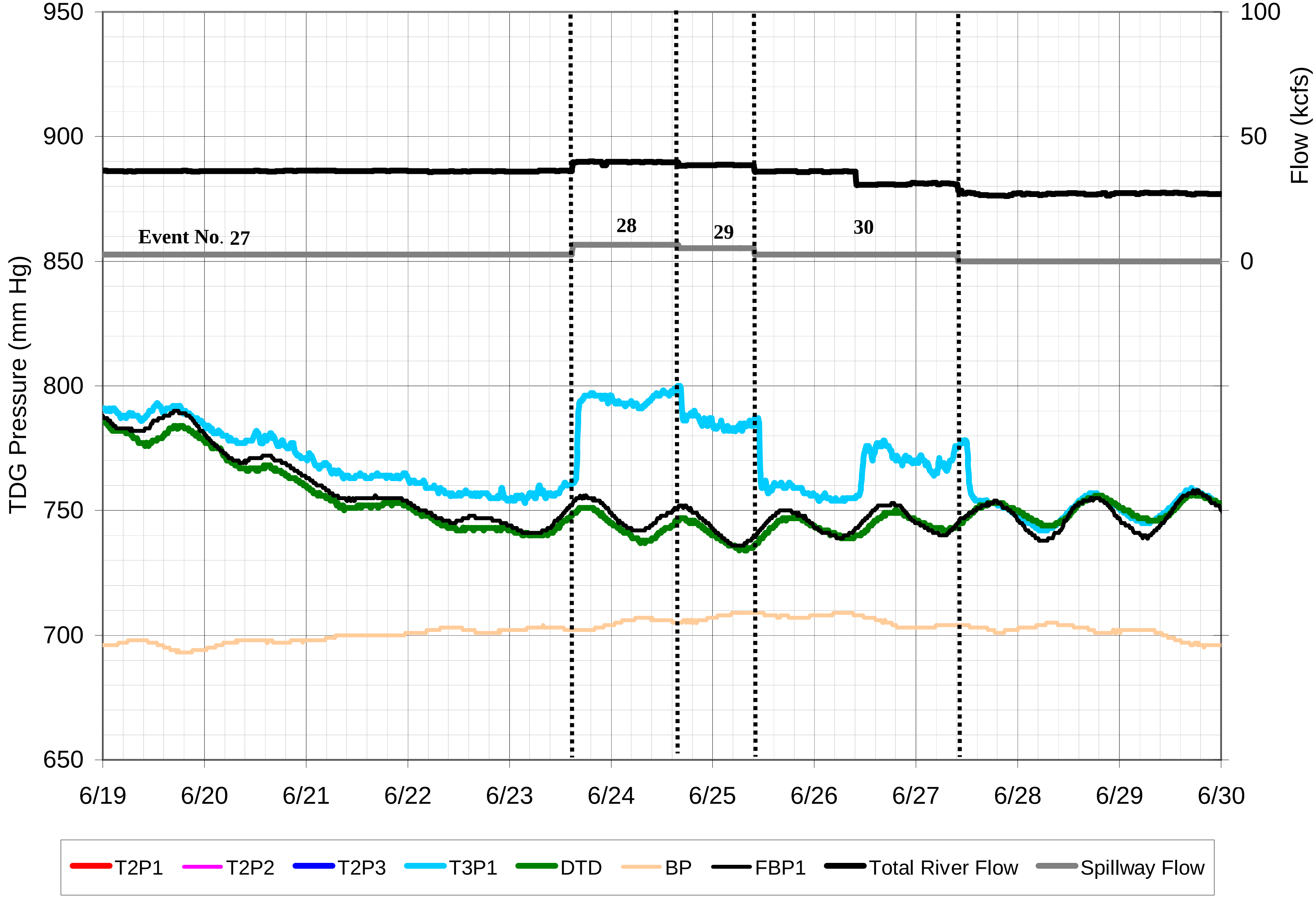

Figure 27h. Transect 2 TDG Pressure June 19-30 2003 and Albeni Falls Dam Operations, 2003
(Filtered TDG Data)

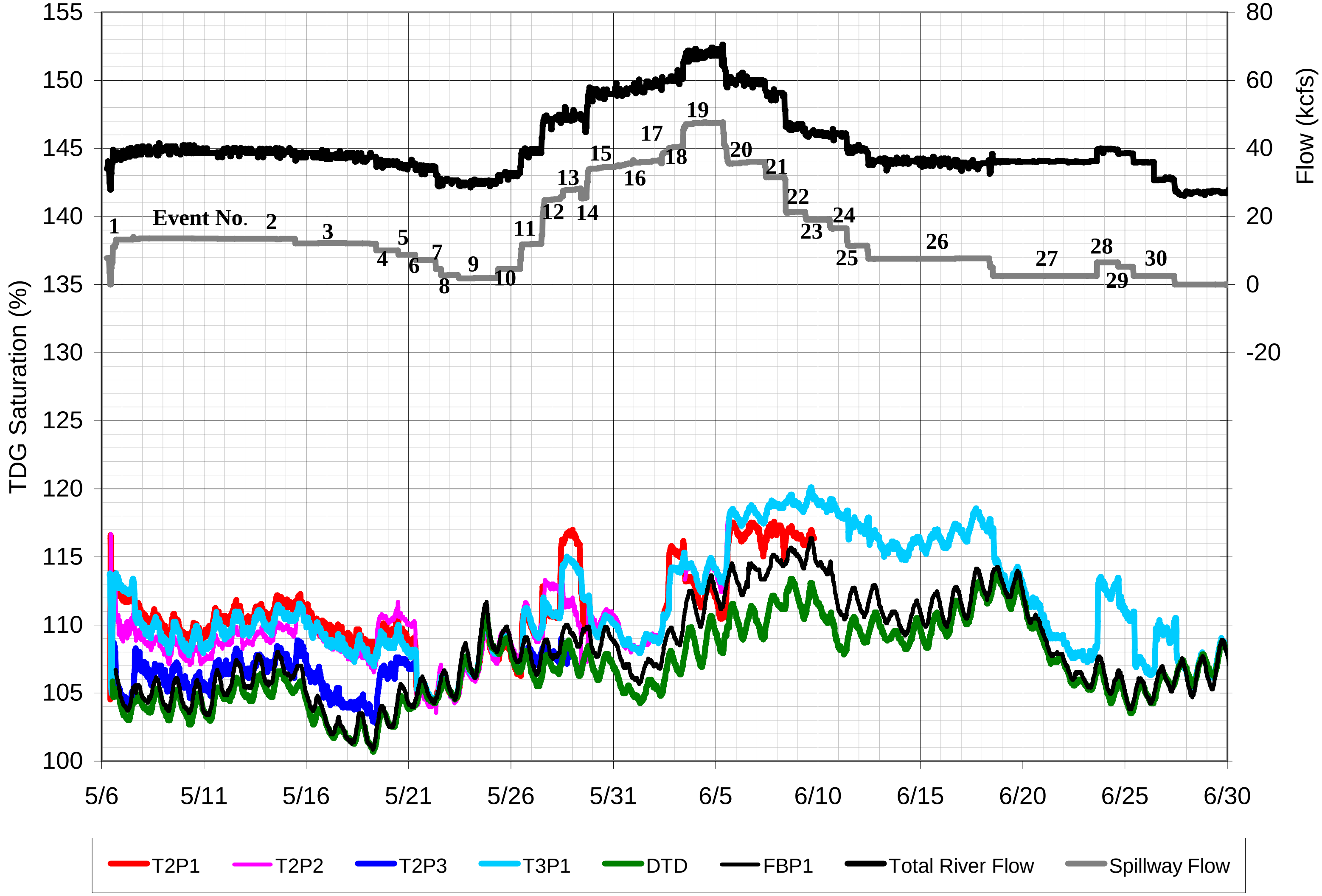

Figure 28. Transect 2 TDG saturation and Albeni Falls Dam Operations, 2003

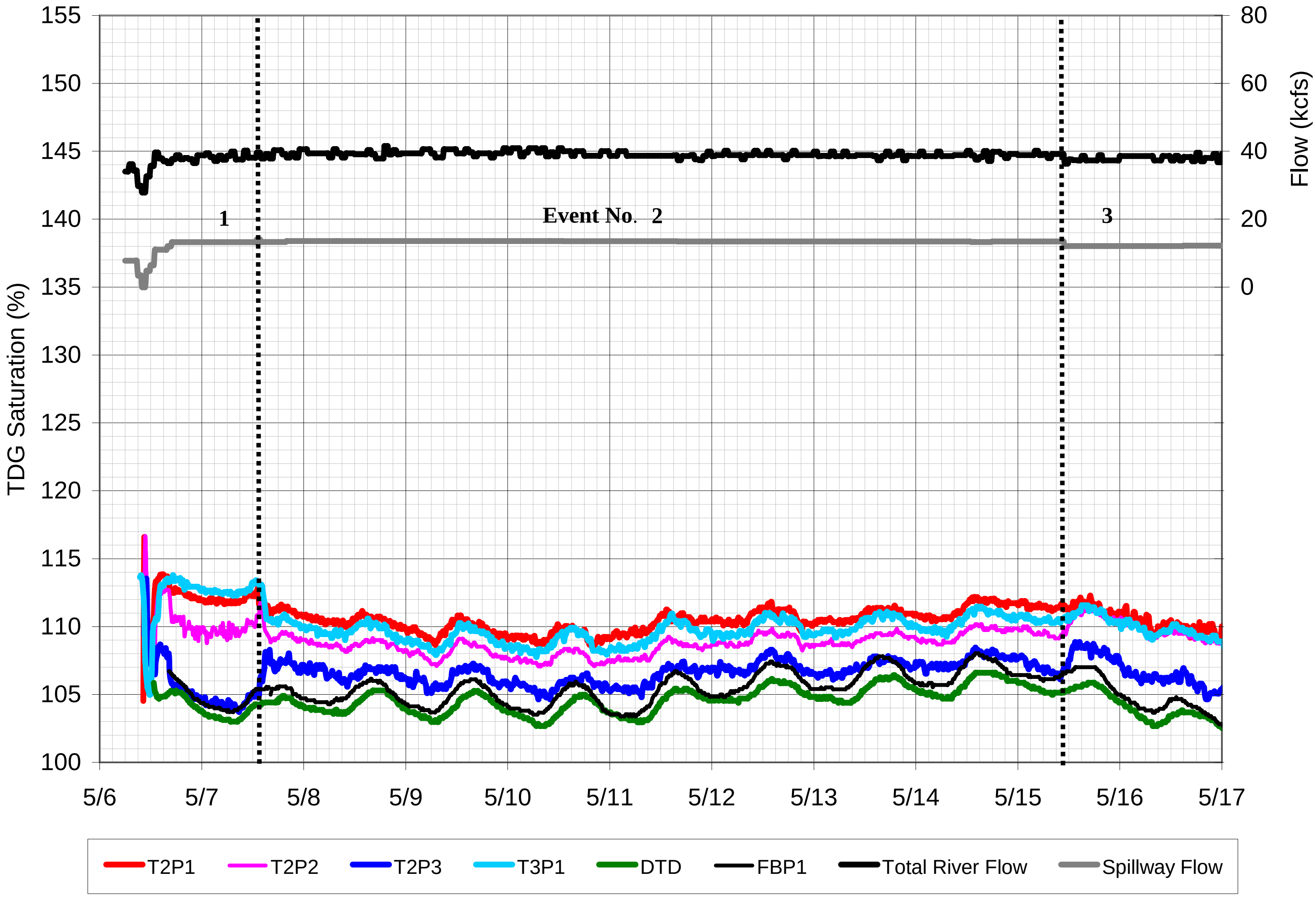

Figure 28a. Transect 2 TDG Saturation 6-17 May 2003 and Albeni Falls Dam Operations, 2003

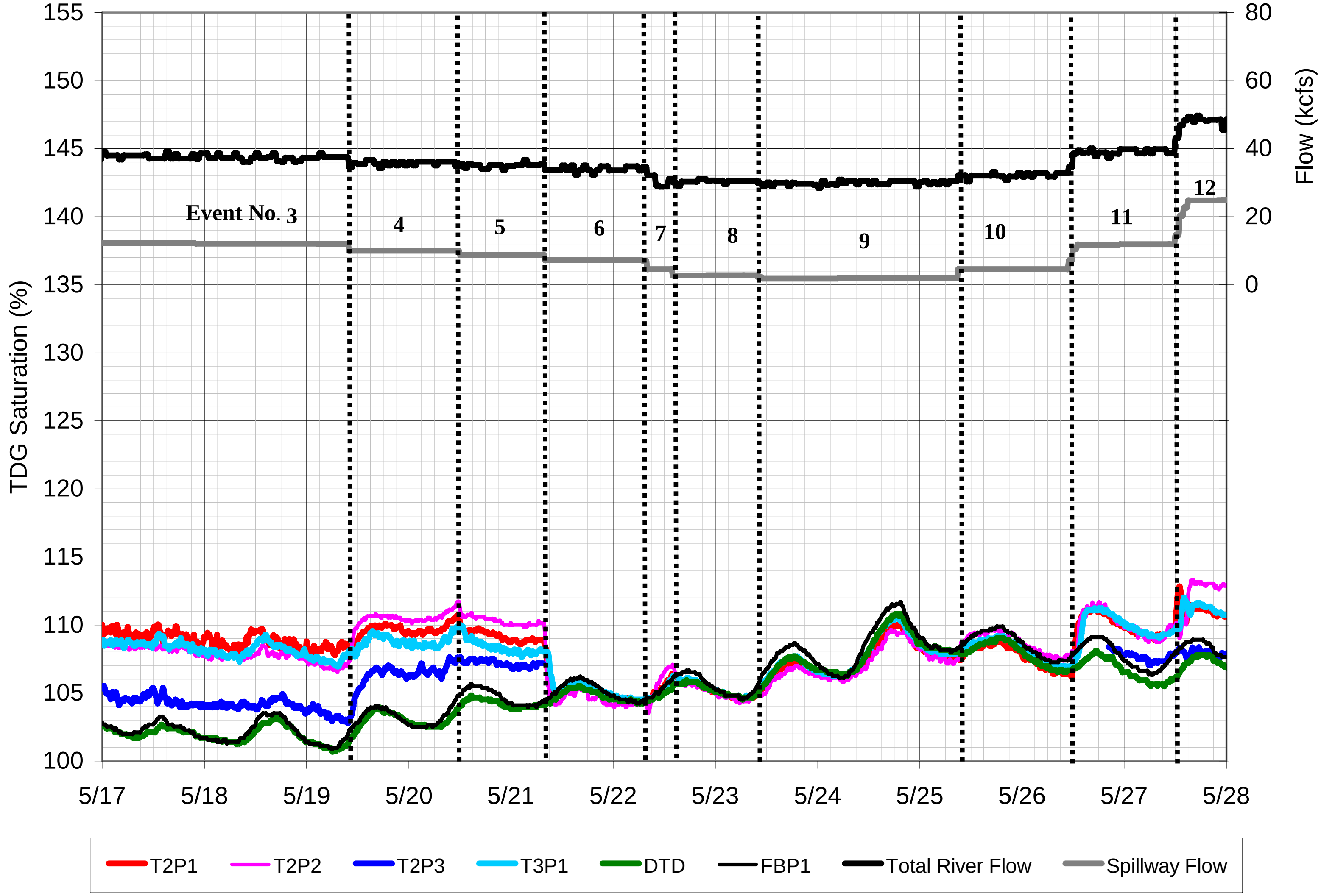

Figure 28b. Transect 2 TDG Saturation 17-28 May 2003 and Albeni Falls Dam Operations, 2003

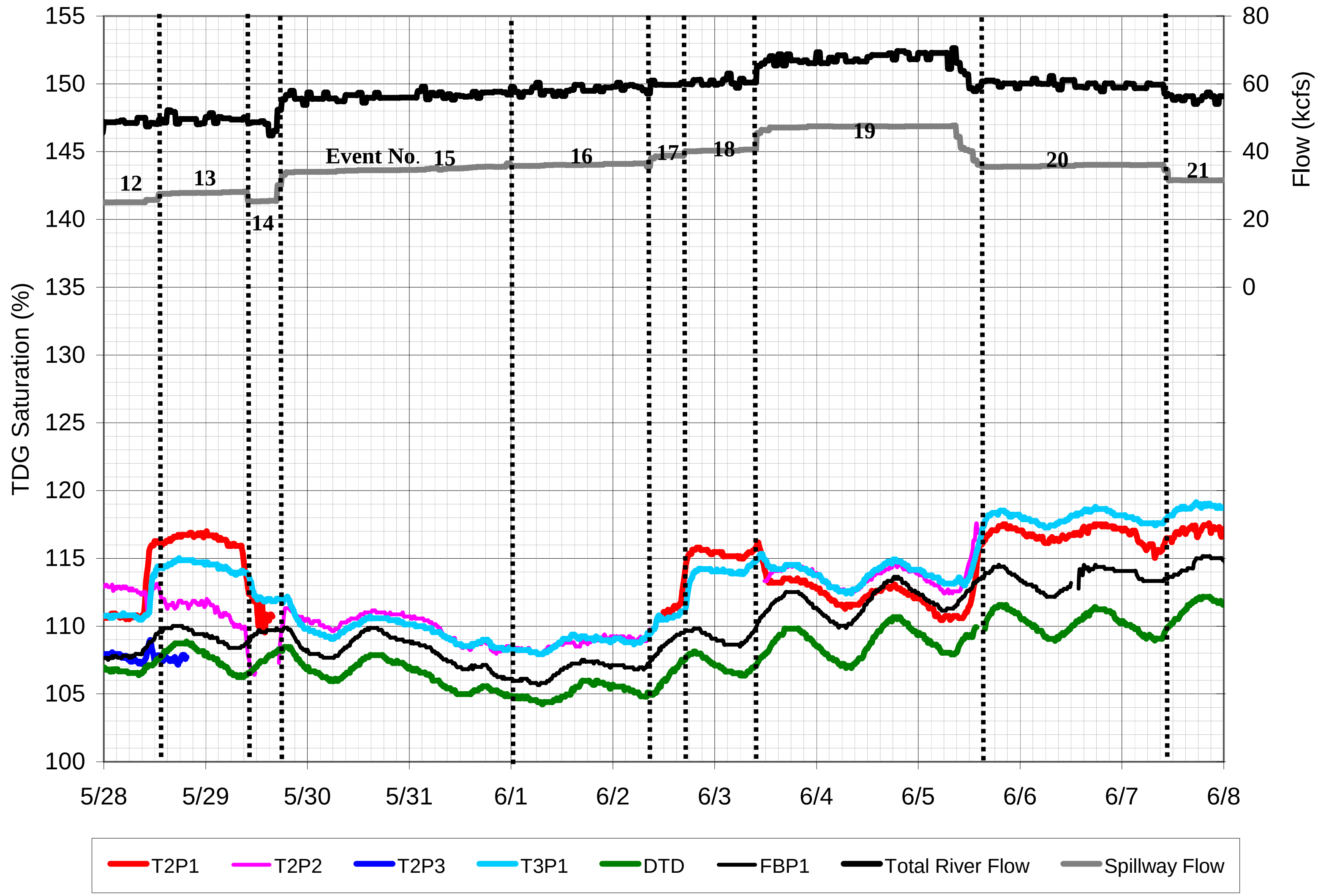

Figure 28c. Transect 2 TDG Saturation 28 May-8 June 2003 and Albeni Falls Dam Operations, 2003

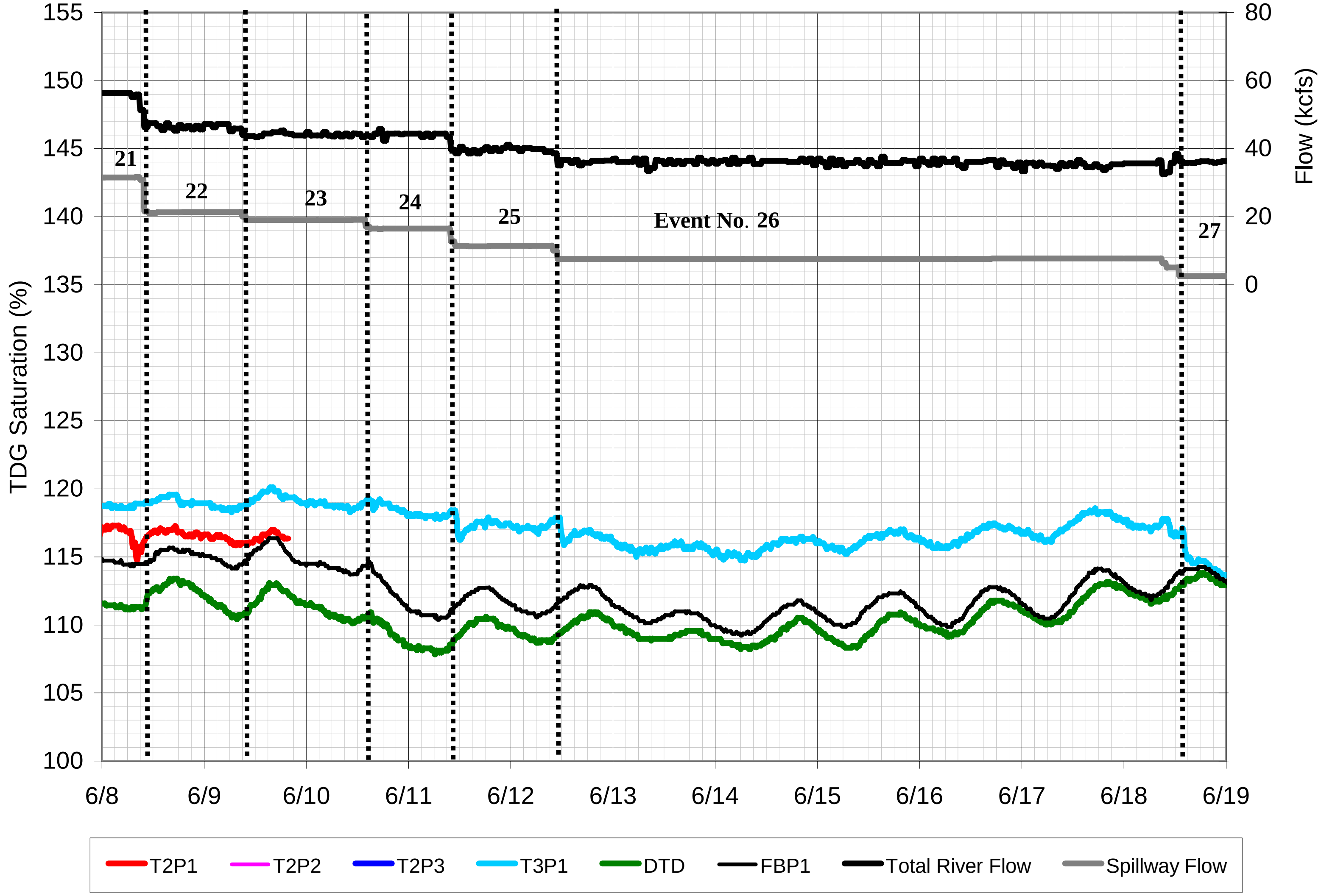

Figure 28d. Transect 2 TDG Saturation 8-19 June 2003 and Albeni Falls Dam Operations, 2003

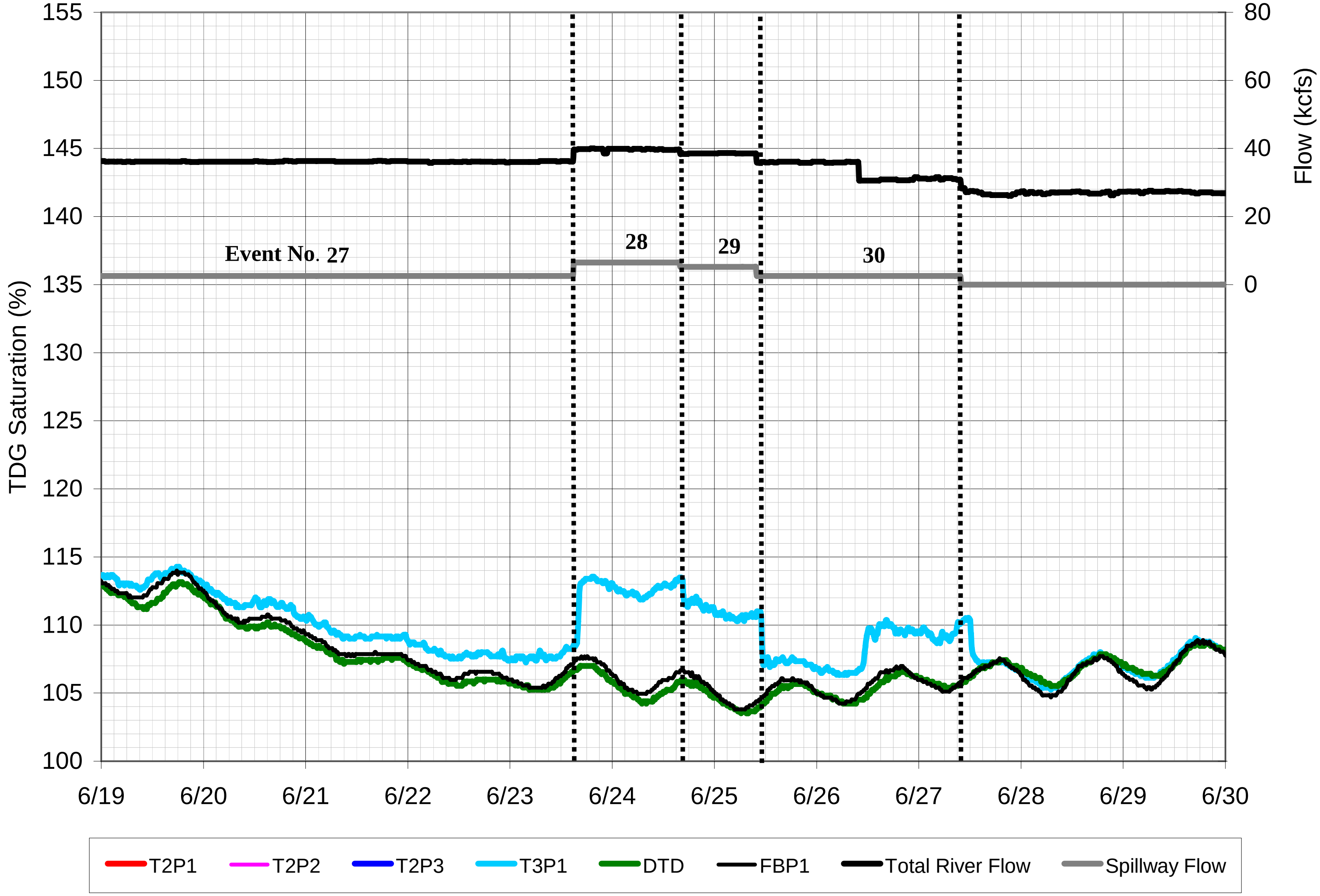

Figure 28e. Transect 2 TDG Pressure 19-29 June 2003 and Albeni Falls Dam Operations, 2003

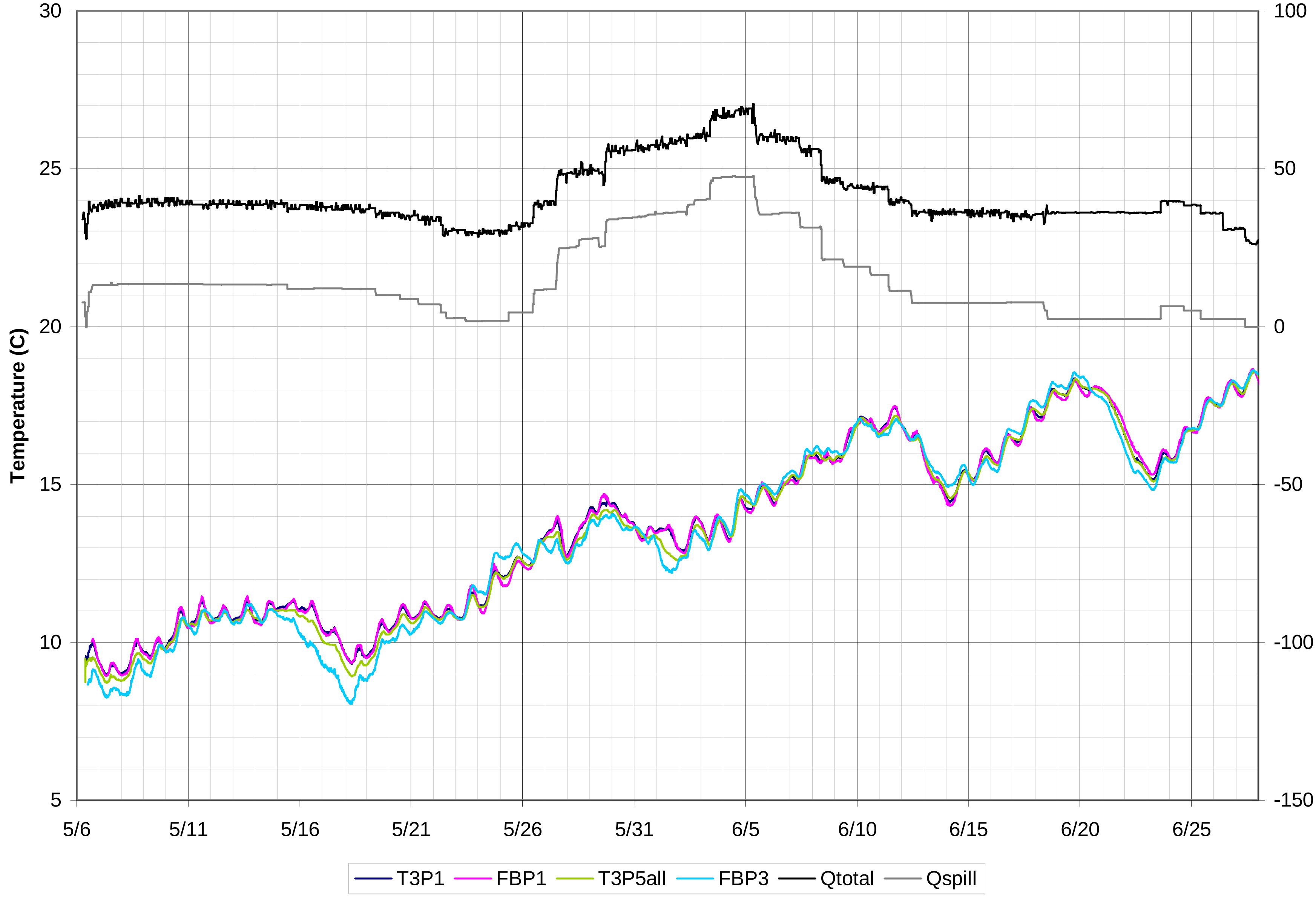

Figure 29. Water Temperatures in the Pend Oreille River at upstream and downstream of Albeni Falls Dam, May 6-June 27, 2003.

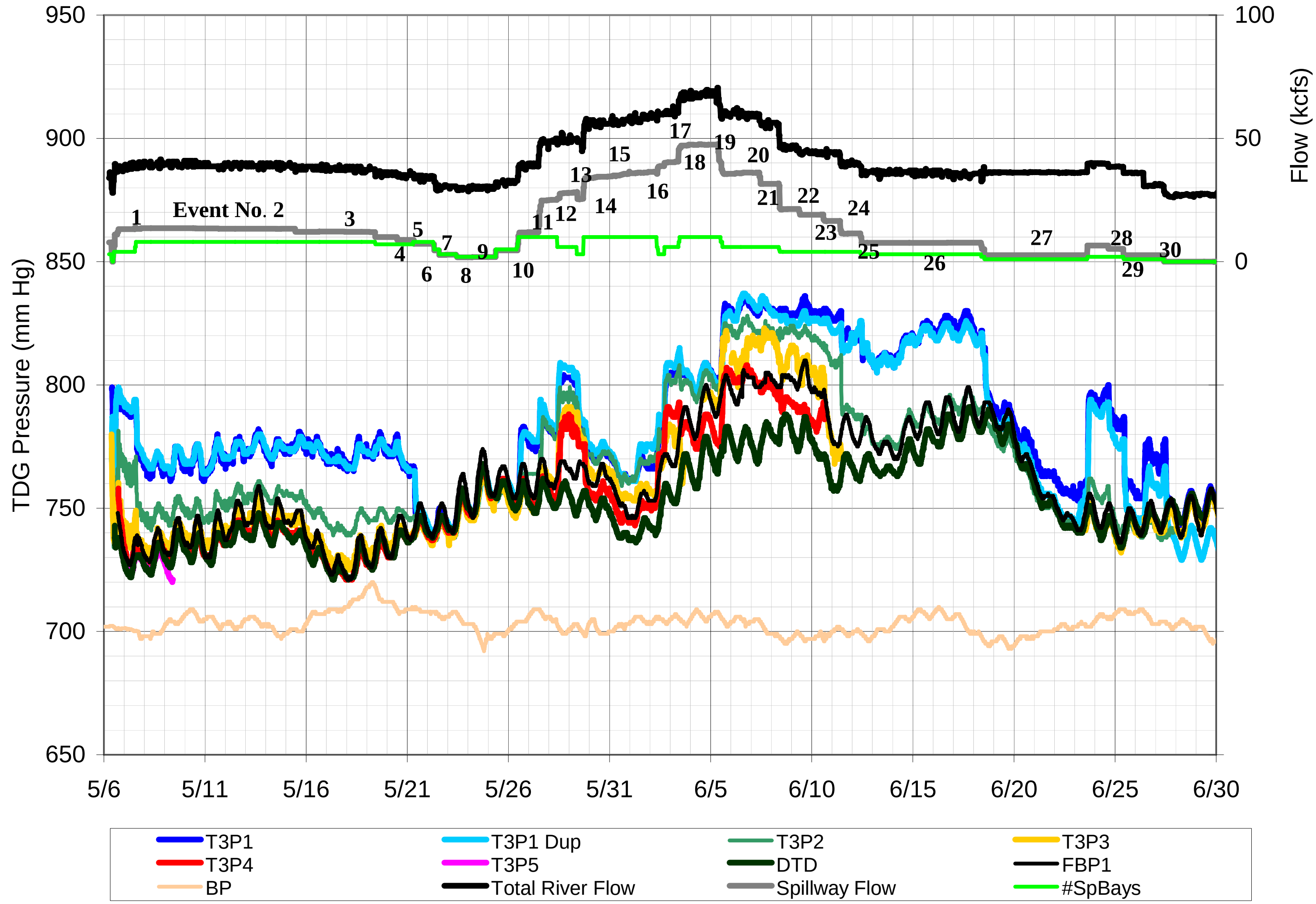

Figure 30. Transect 3 TDG Pressure and Albeni Falls Dam Operations, 2003

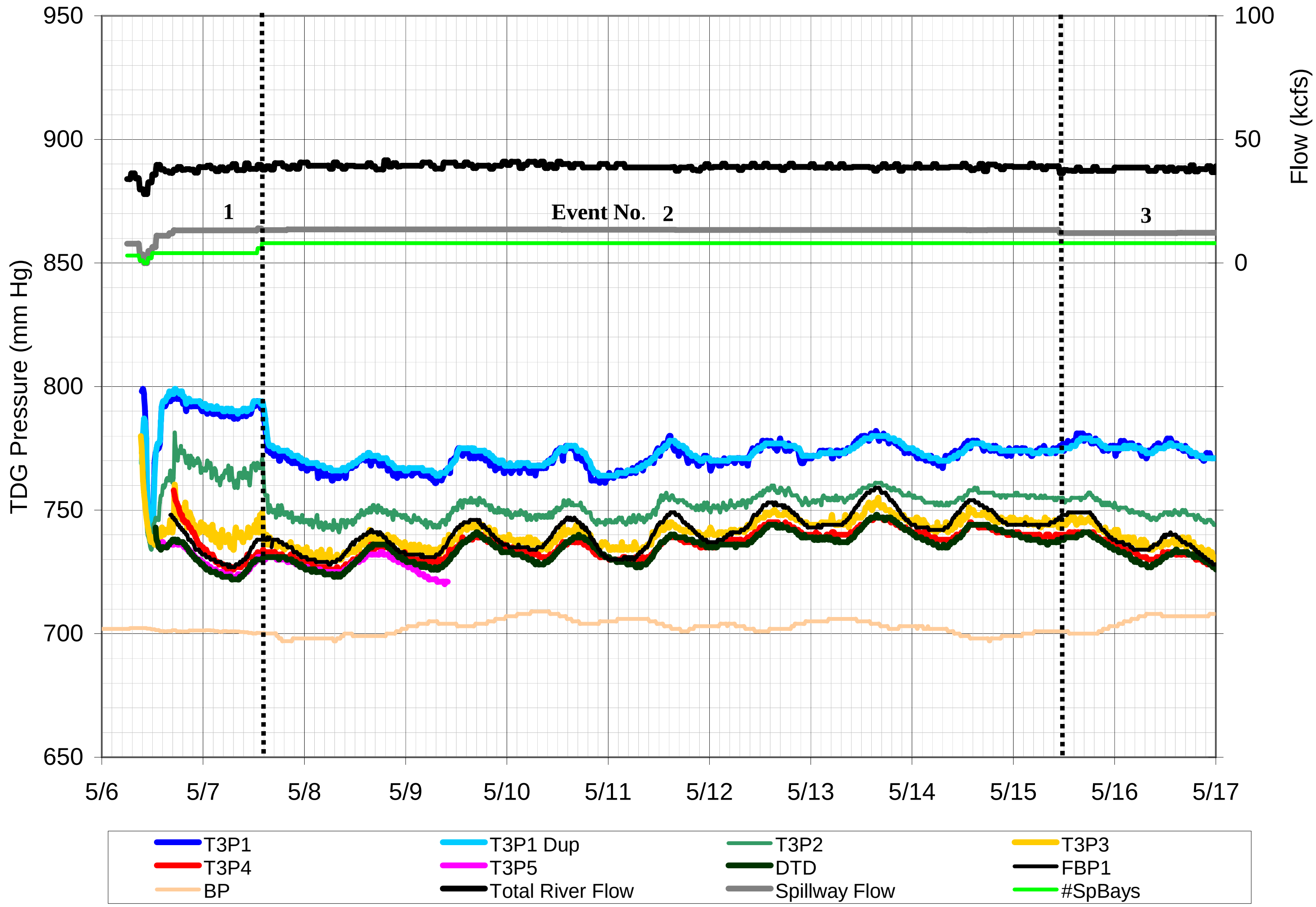

Figure 30a. Transect 3 TDG Pressure 6-17 May 2003 and Albeni Falls Dam Operations, 2003

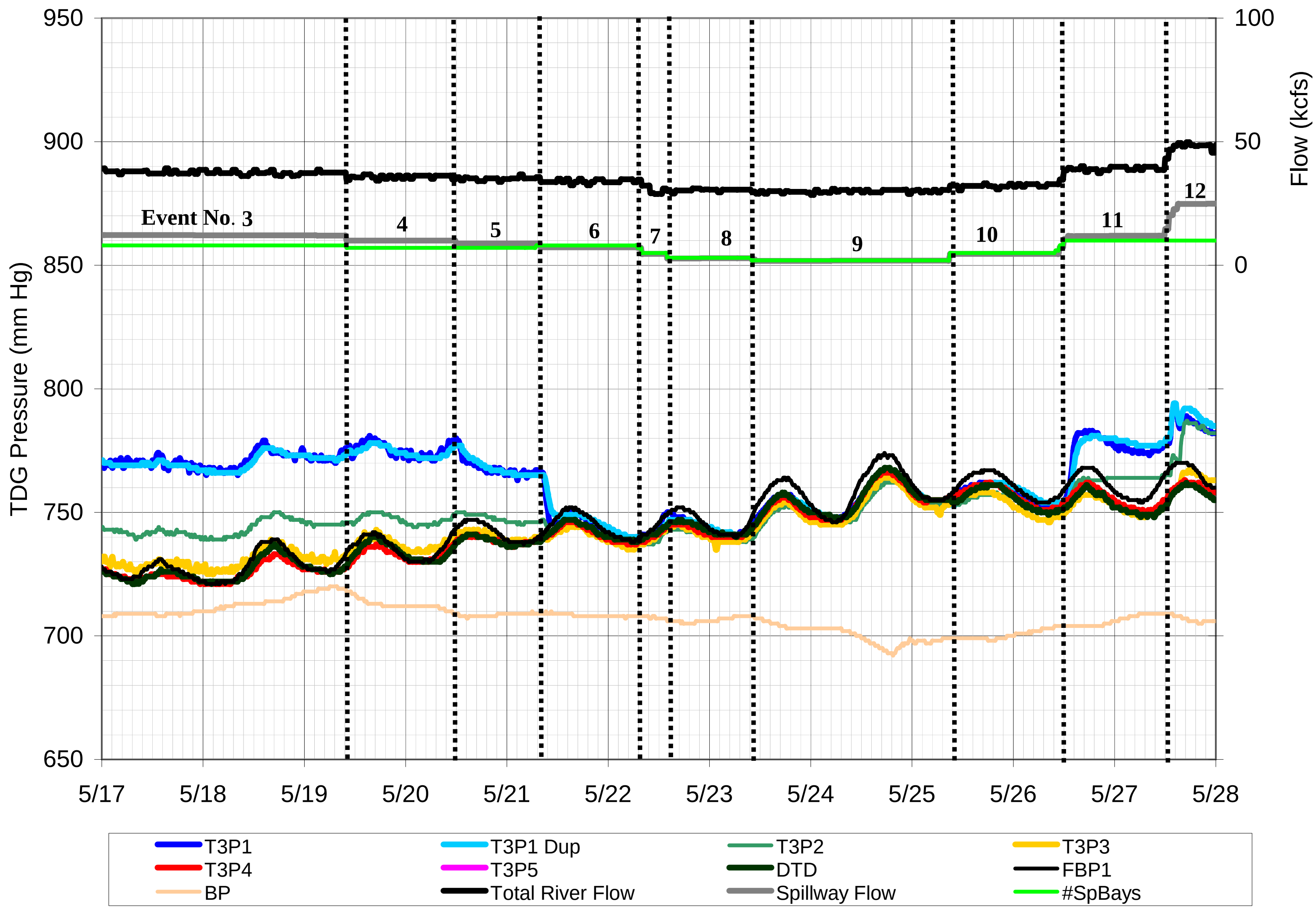

Figure 30b. Transect 3 TDG Pressure 17-28 May 2003 and Albeni Falls Dam Operations, 2003

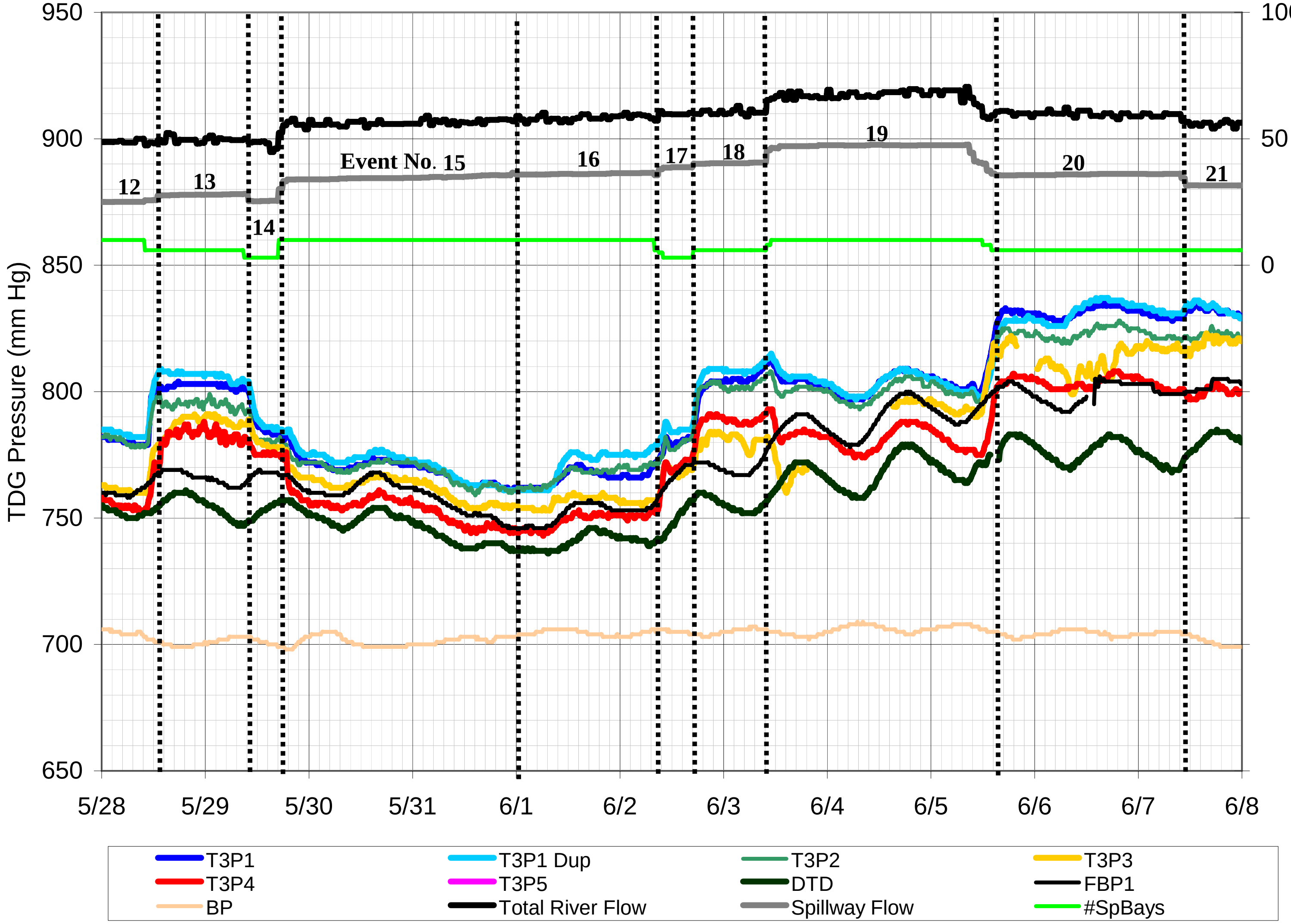

Figure 30c. Transect 3 TDG Pressure 28 May-8 June 2003 and Albeni Falls Dam Operations, 2003

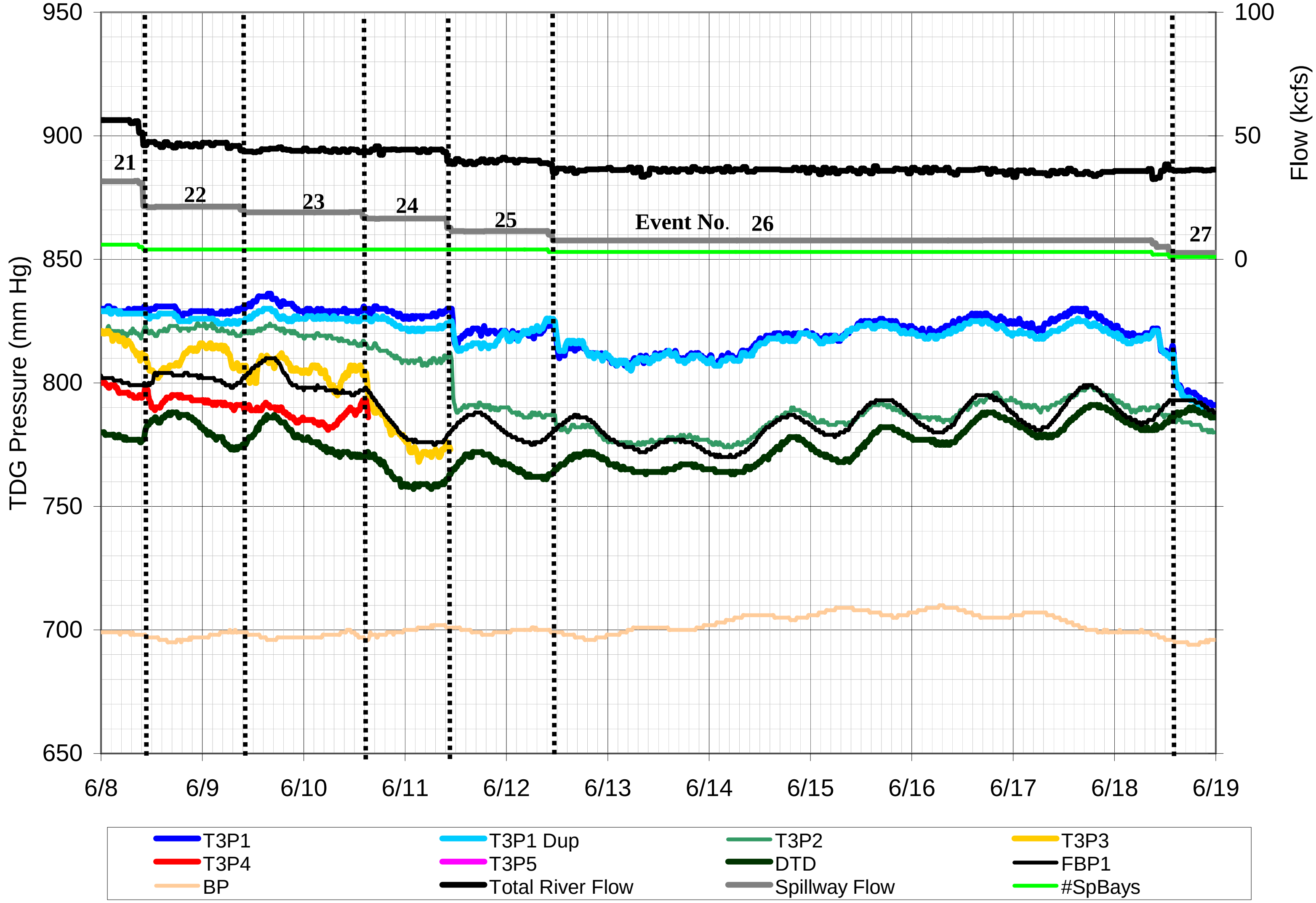

Figure 30d. Transect 3 TDG Pressure 8-19 June 2003 and Albeni Falls Dam Operations, 2003

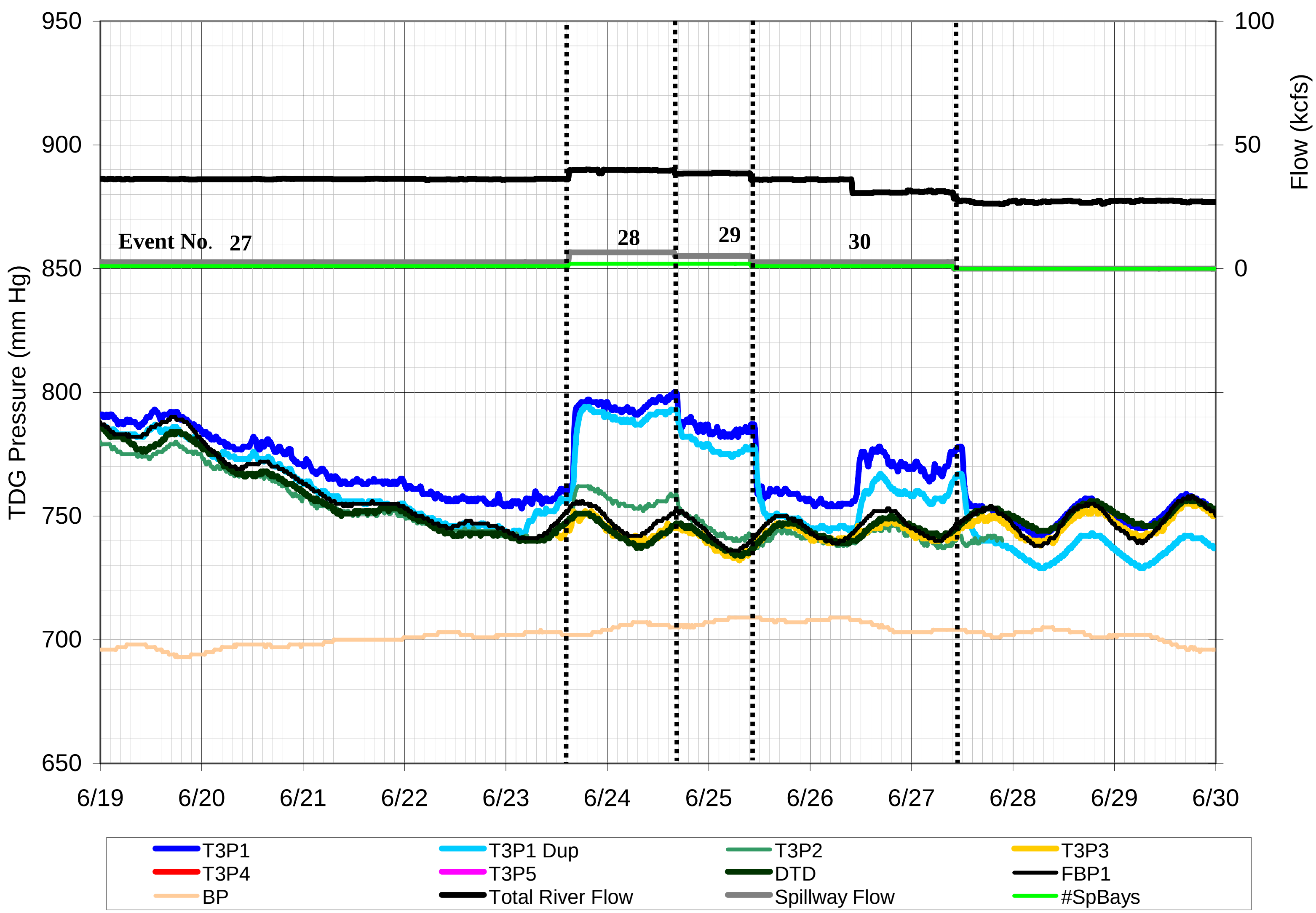

Figure 30e. Transect 3 TDG Pressure 19-30 June 2003 and Albeni Falls Dam Operations, 2003

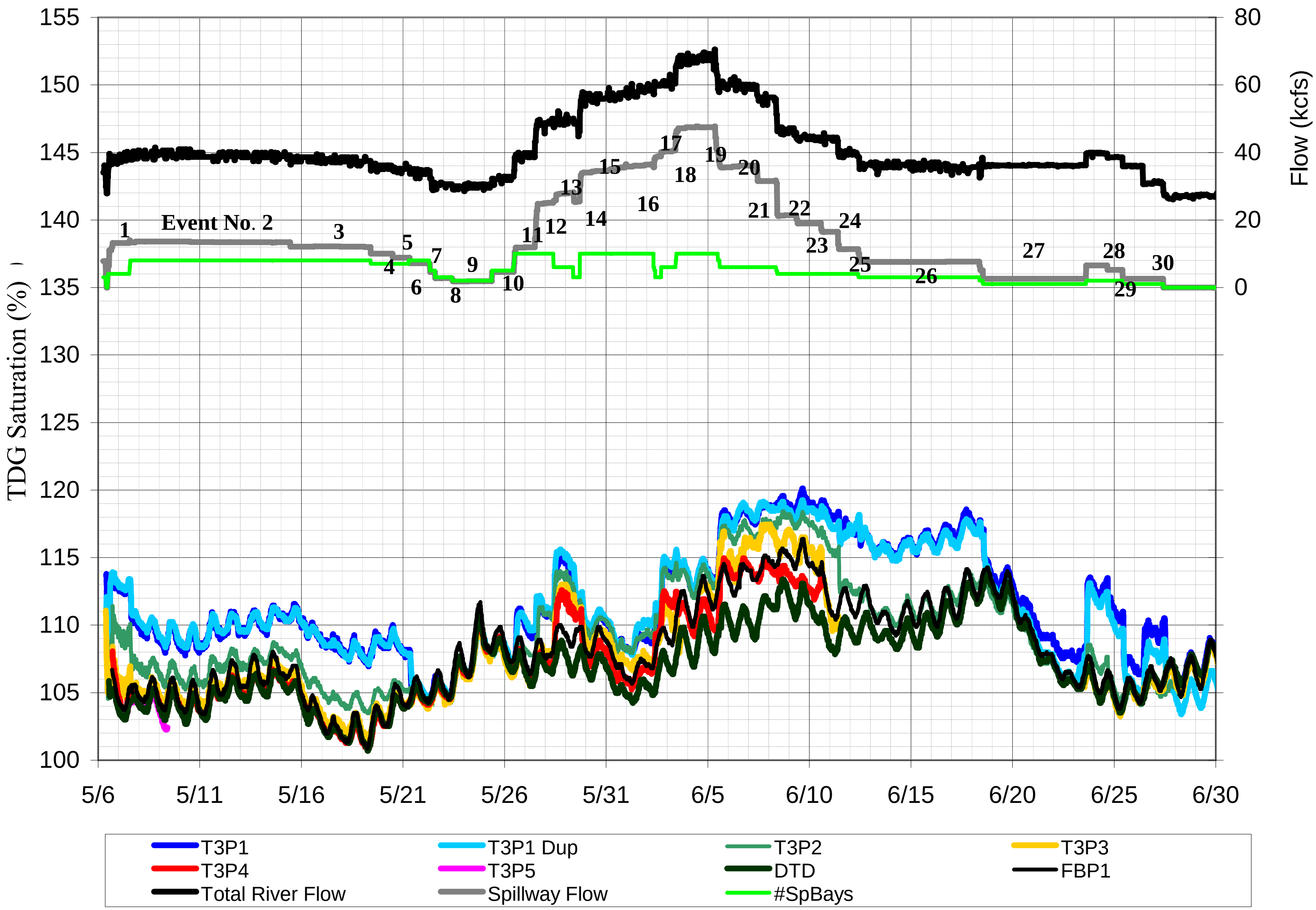

Figure 31 Transect 3 TDG Saturation and Albeni Falls Dam Operations, 2003

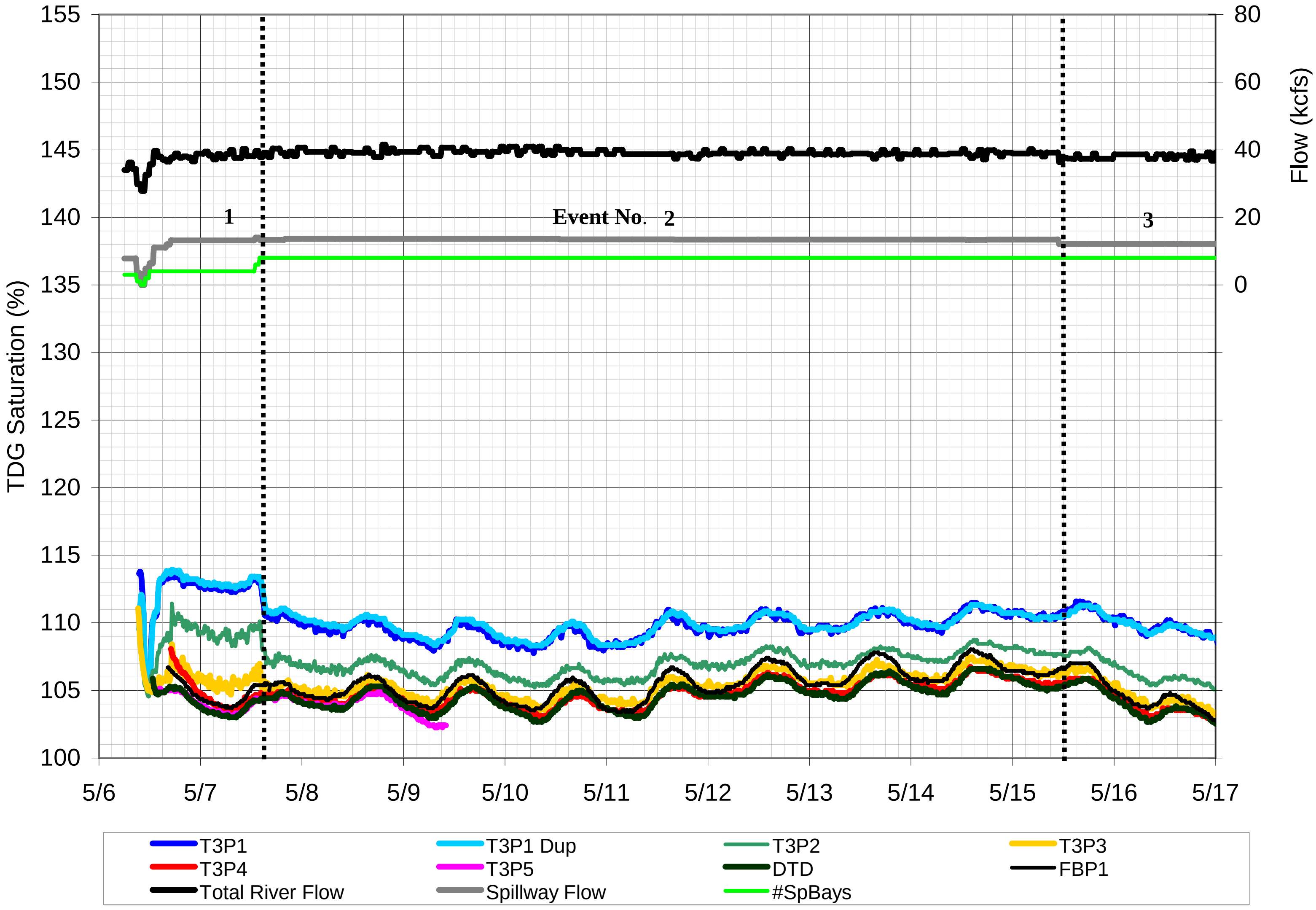

Figure 31a. Transect 3 TDG Saturation 06 – 17 May 2003 and Albeni Falls Dam Operations, 2003

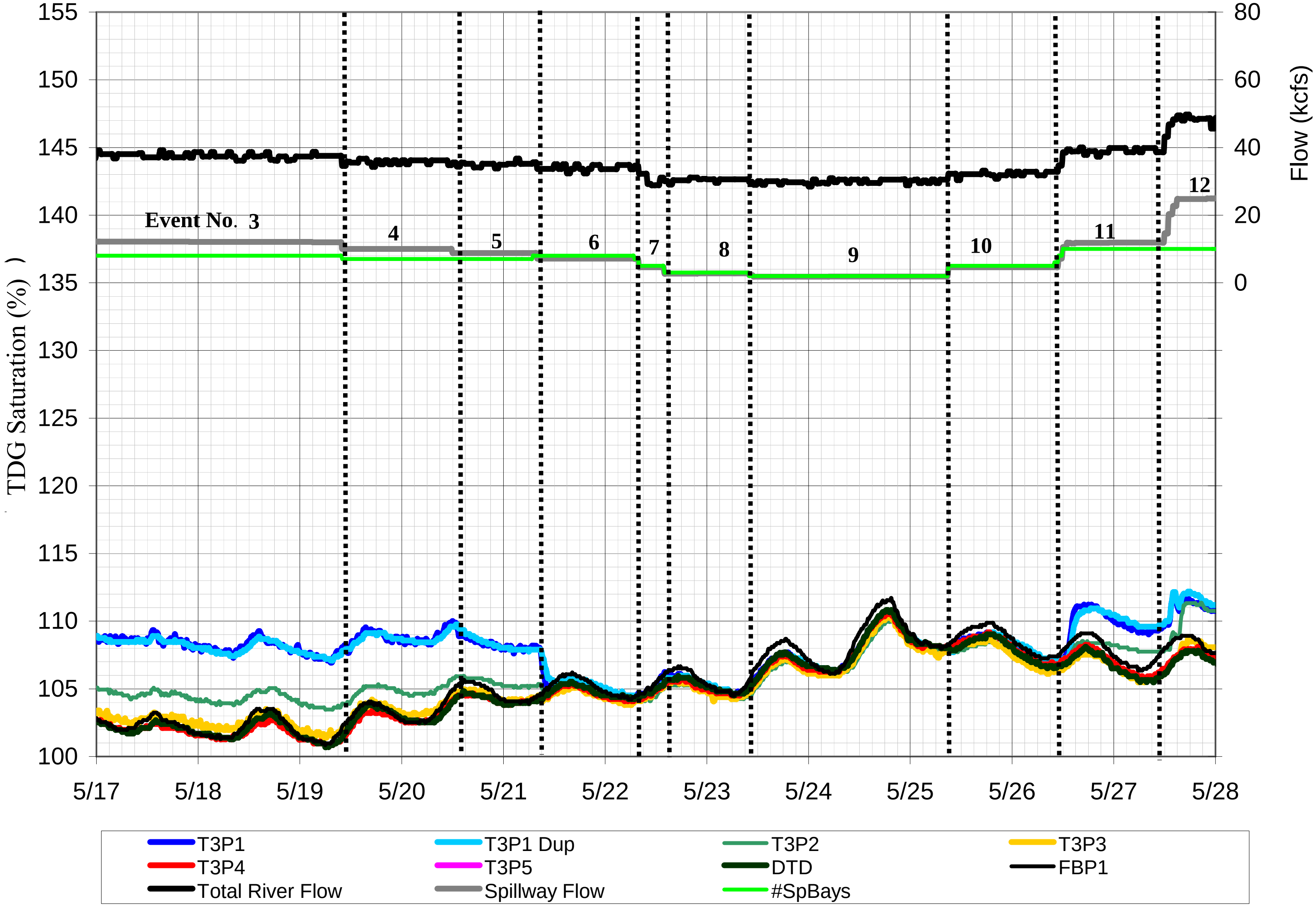

Figure 31b. Transect 3 TDG Saturation 17 – 28 May 2003 and Albeni Falls Dam Operations, 2003

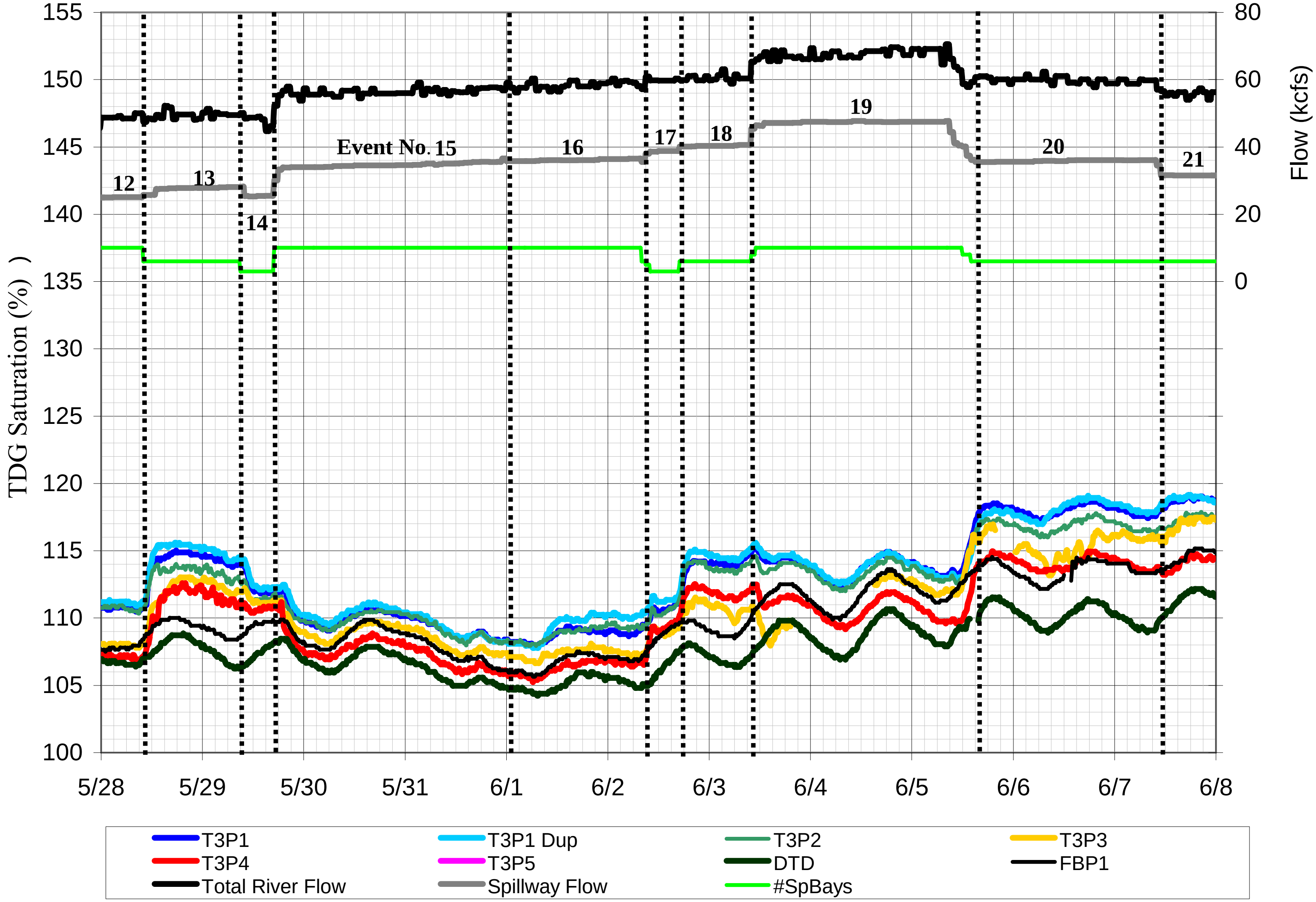

Figure 31c. Transect 3 TDG Saturation 28 May – 8 June, 2003 and Albeni Falls Dam Operations, 2003

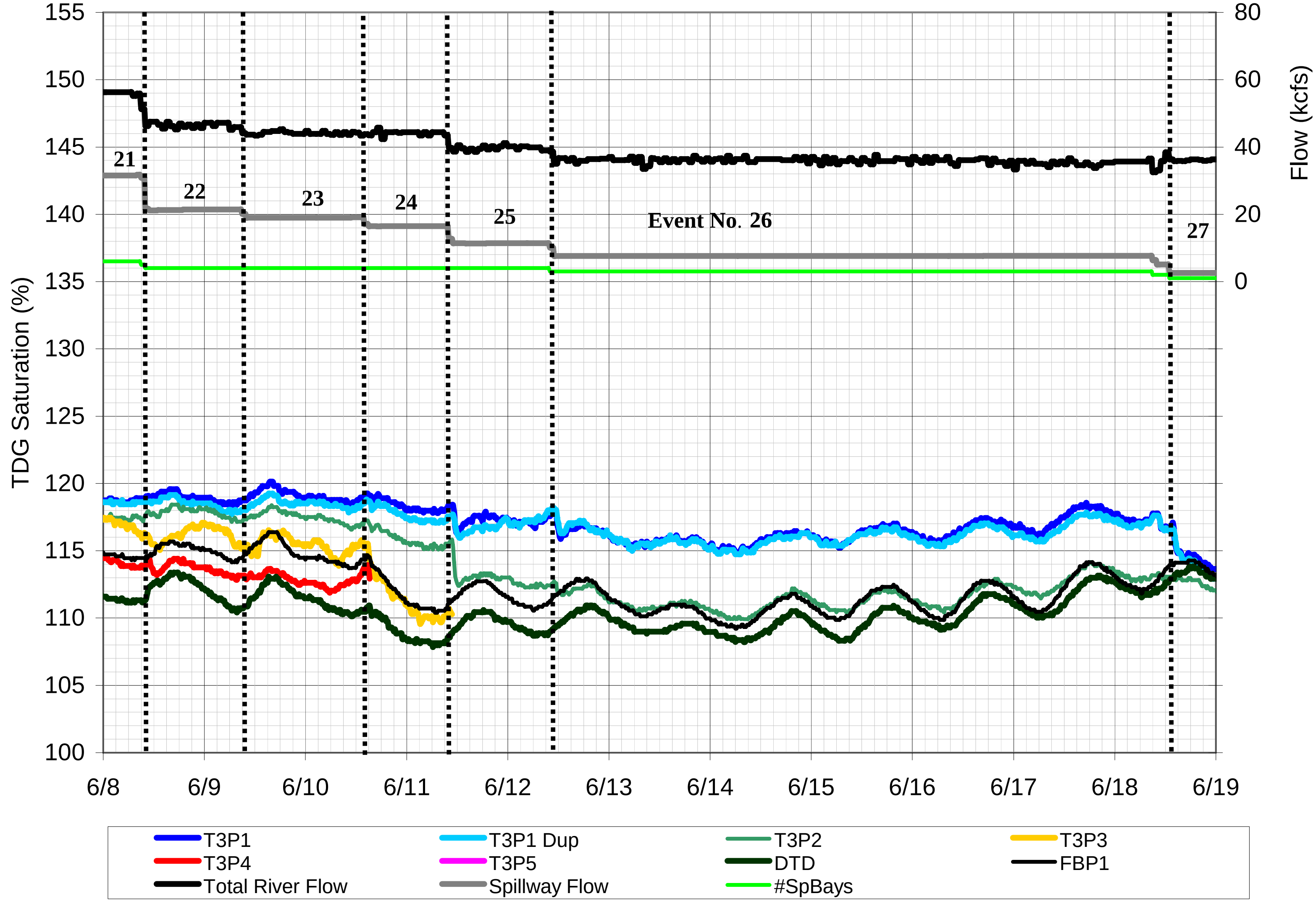

Figure 31d. Transect 3 TDG Saturation 8-19 June 2003 , 2003 and Albeni Falls Dam Operations, 2003

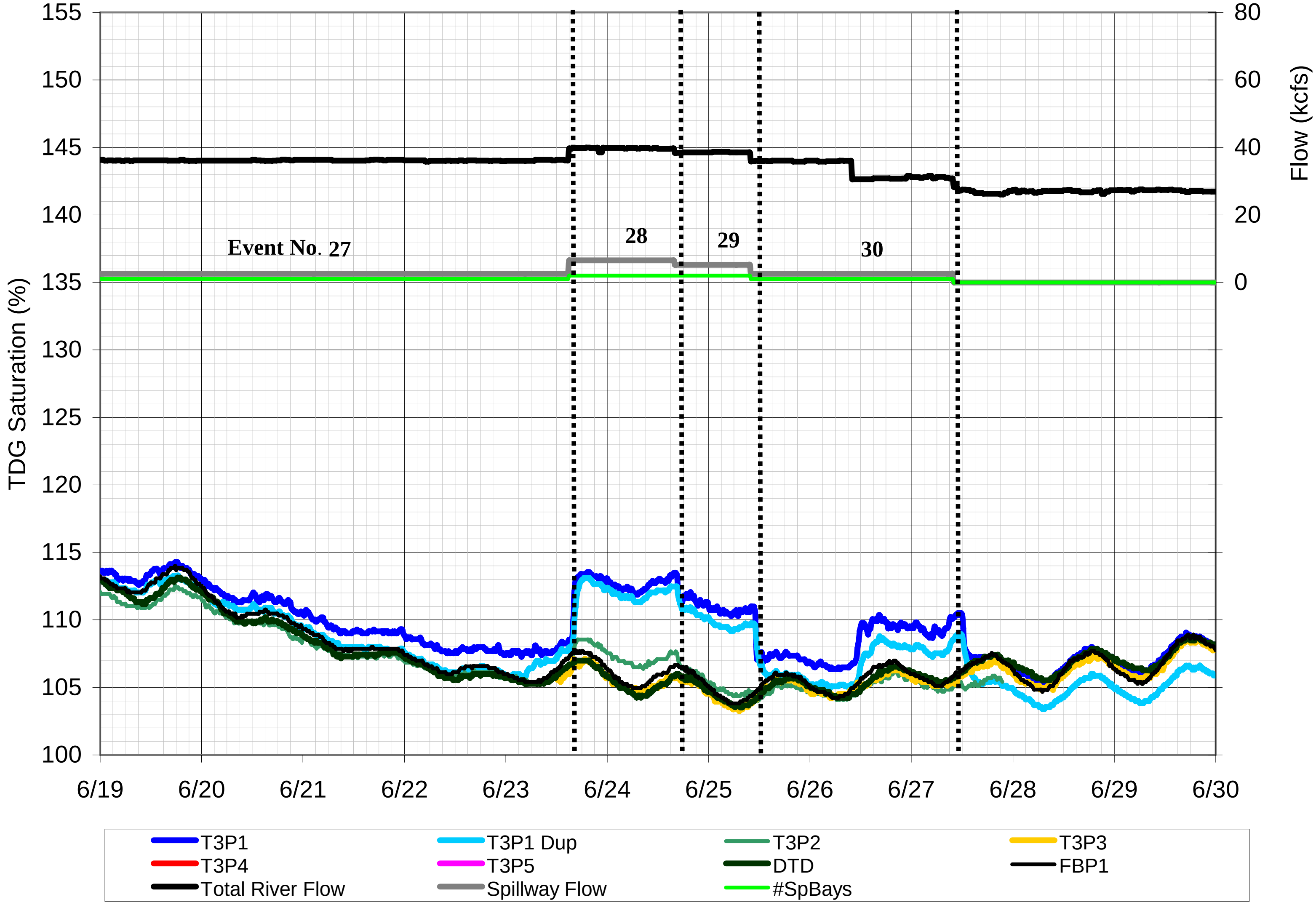

Figure 31e. Transect 3 TDG Saturation 19-30 June 2003 , 2003 and Albeni Falls Dam Operations, 2003

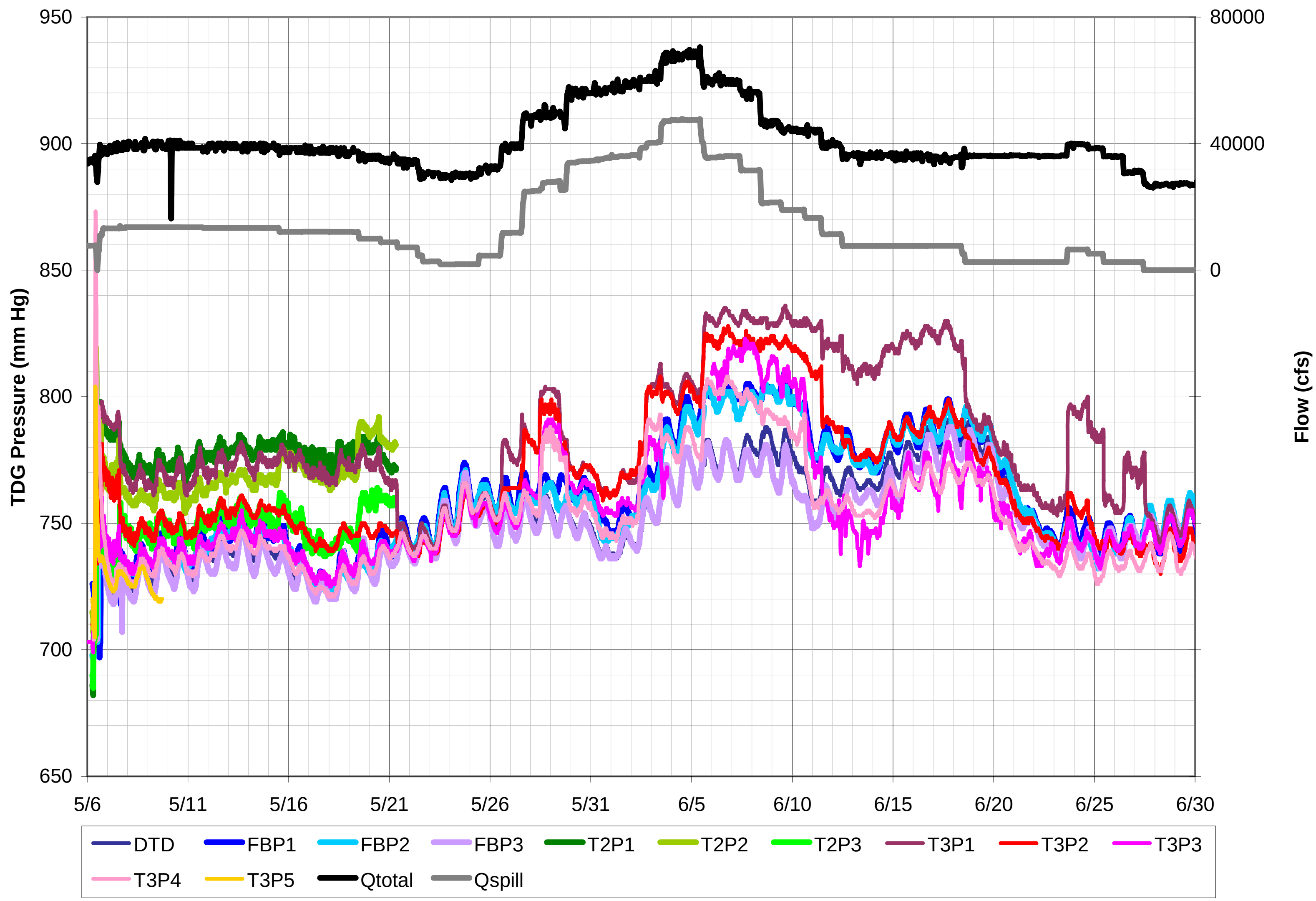

Figure 32. TDG Pressure with Project Operations Data.

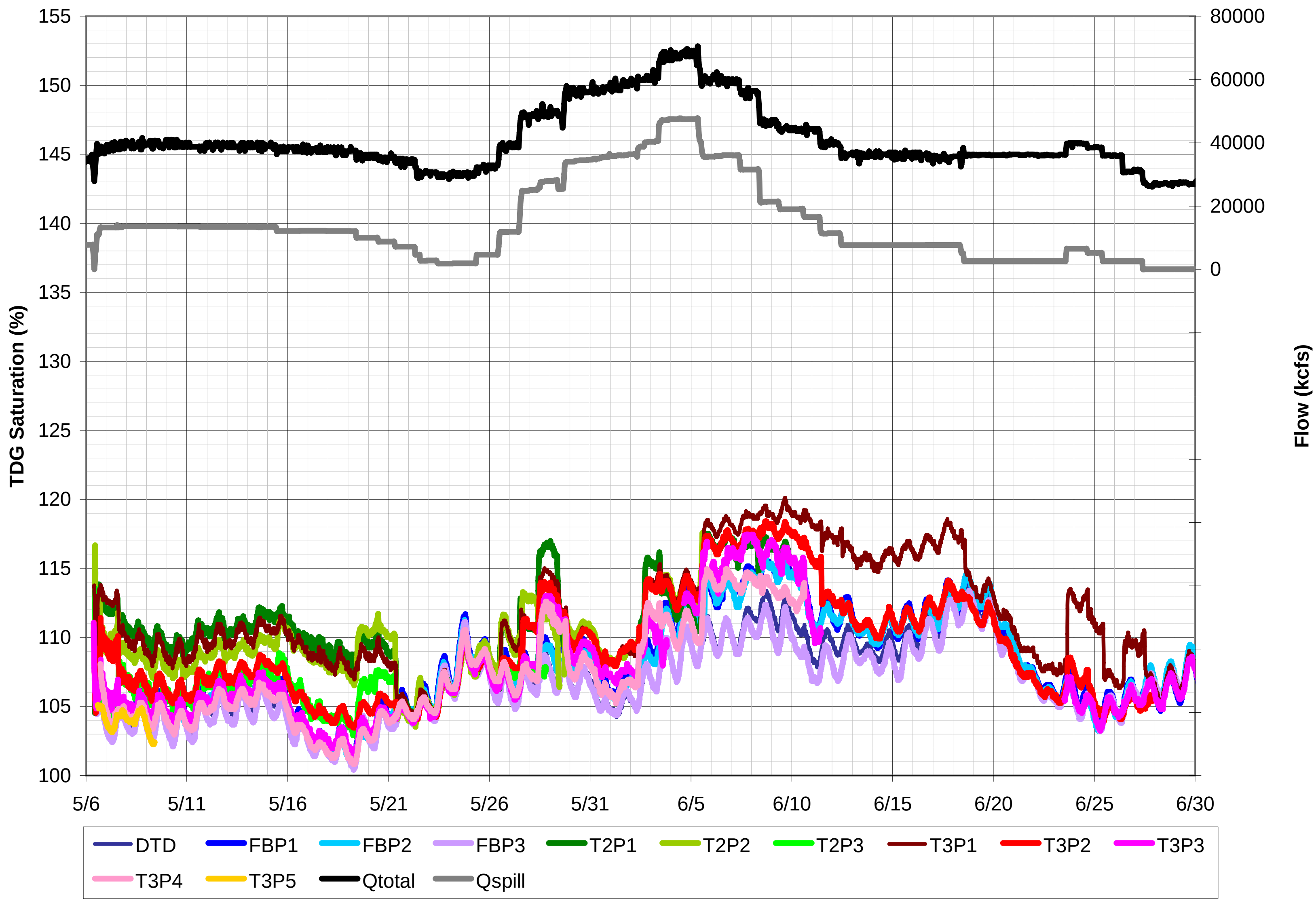

Figure 33. TDG Saturation with Project Operations Data.

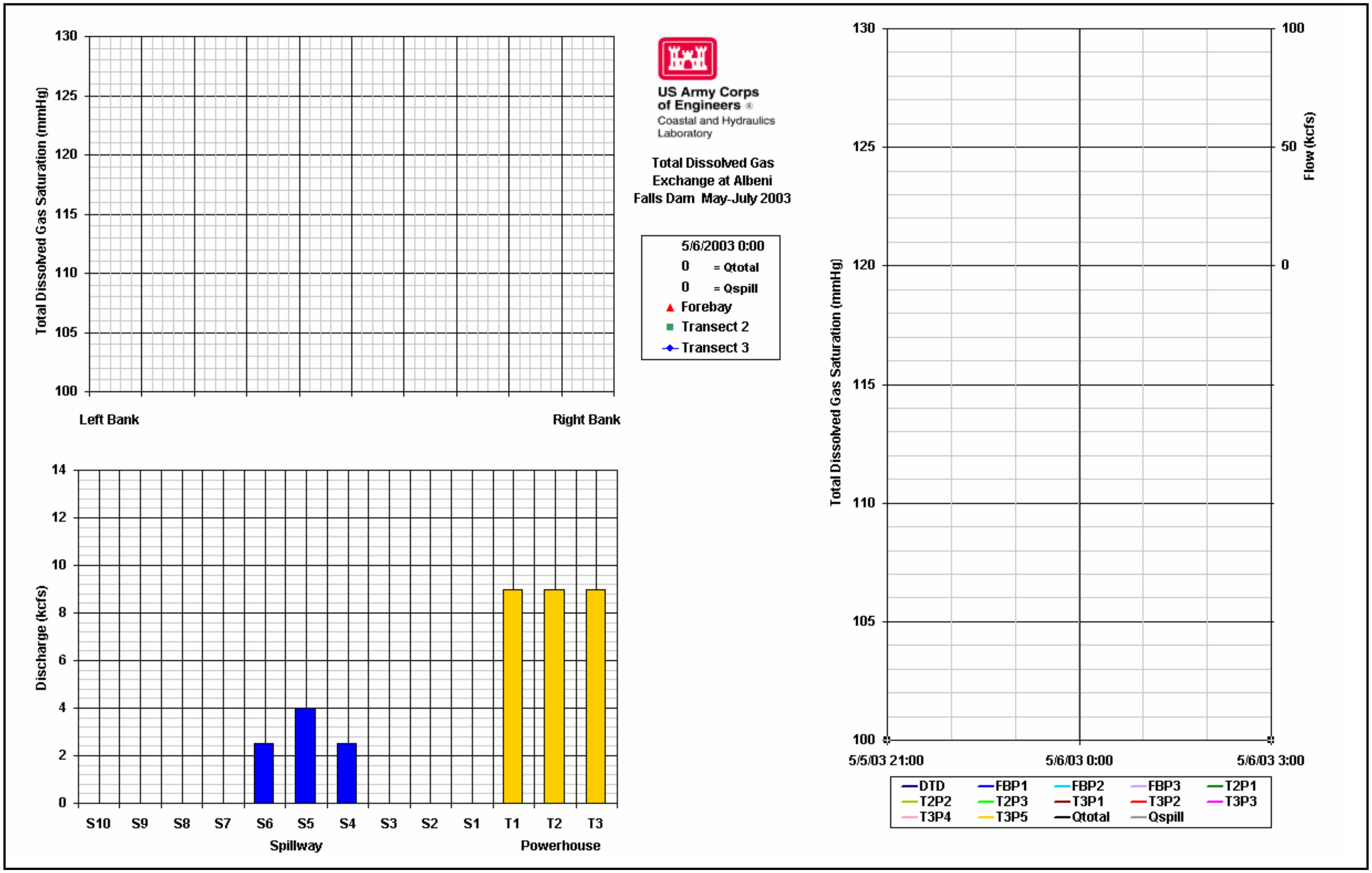

Figure 34. TDG Saturation and Project Operations Data.
(Requires file alftdgv6.avi)

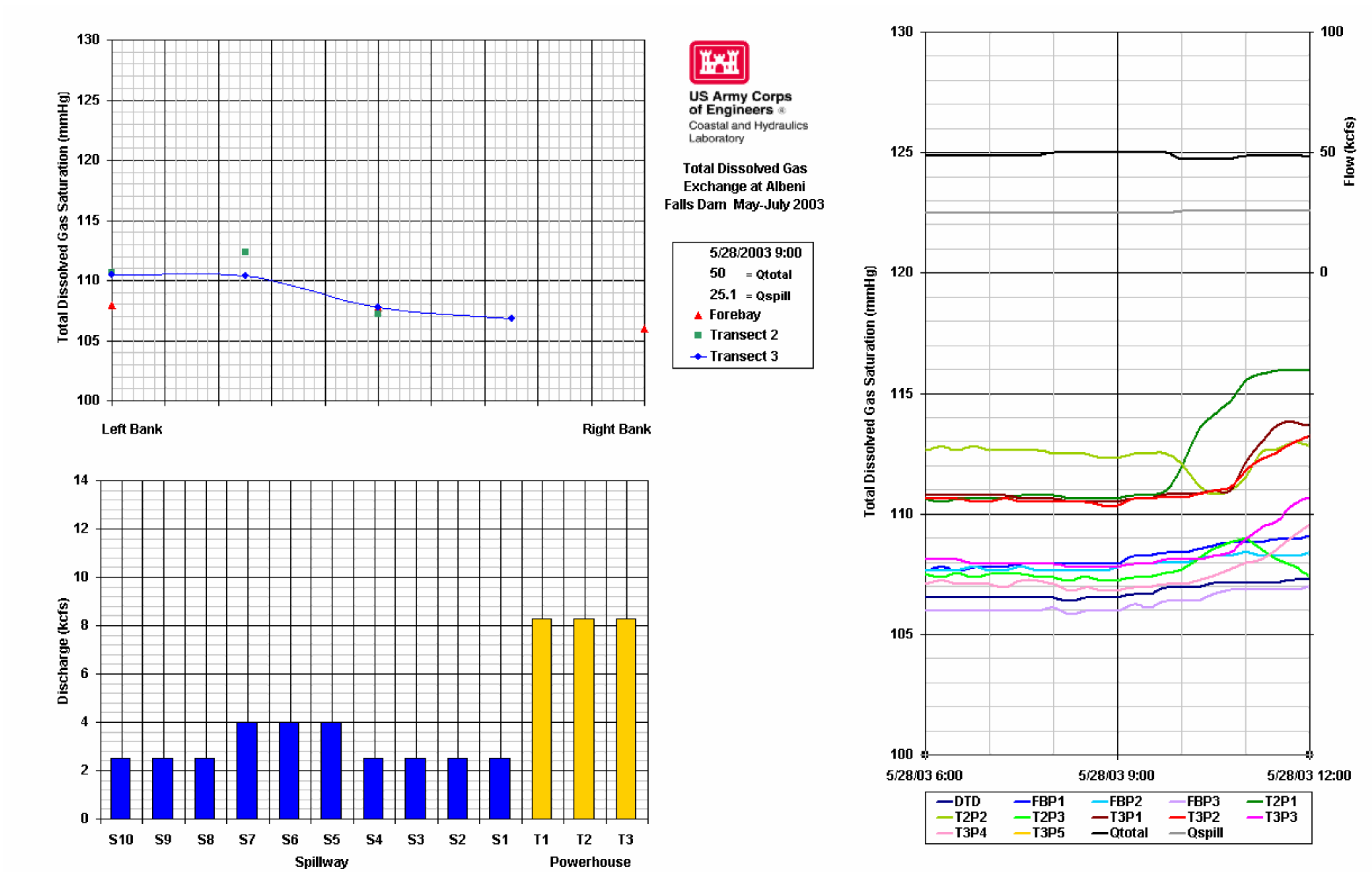

Figure 34a. TDG Saturation and Project Operations Data,
(Event 12, 28 May 0900 hrs, Qspill=25.1 kcfs)

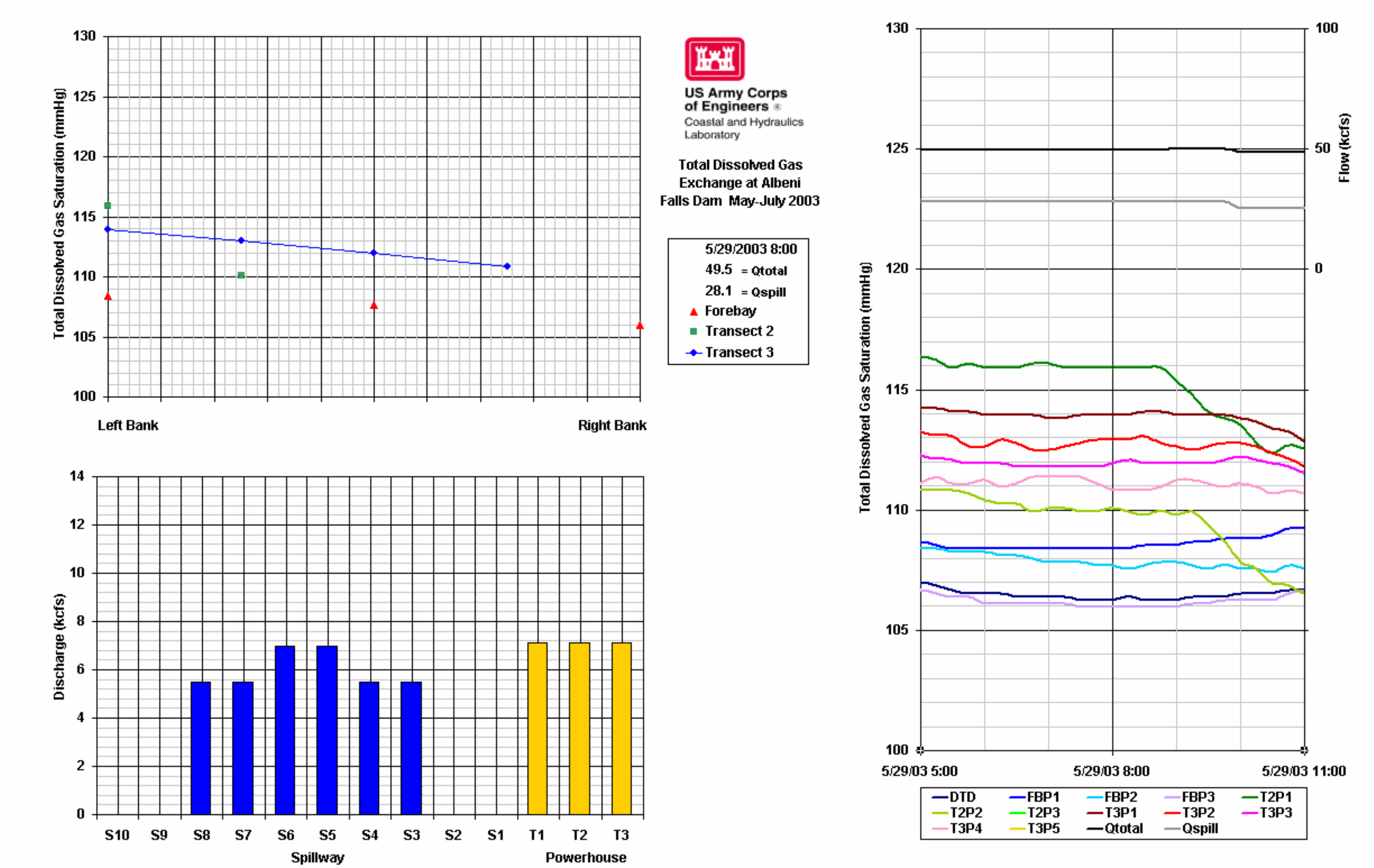

Figure 34b. TDG Saturation and Project Operations Data.
(Event 13, 29 May 0800 hrs, Qspill=28.1 kcfs)

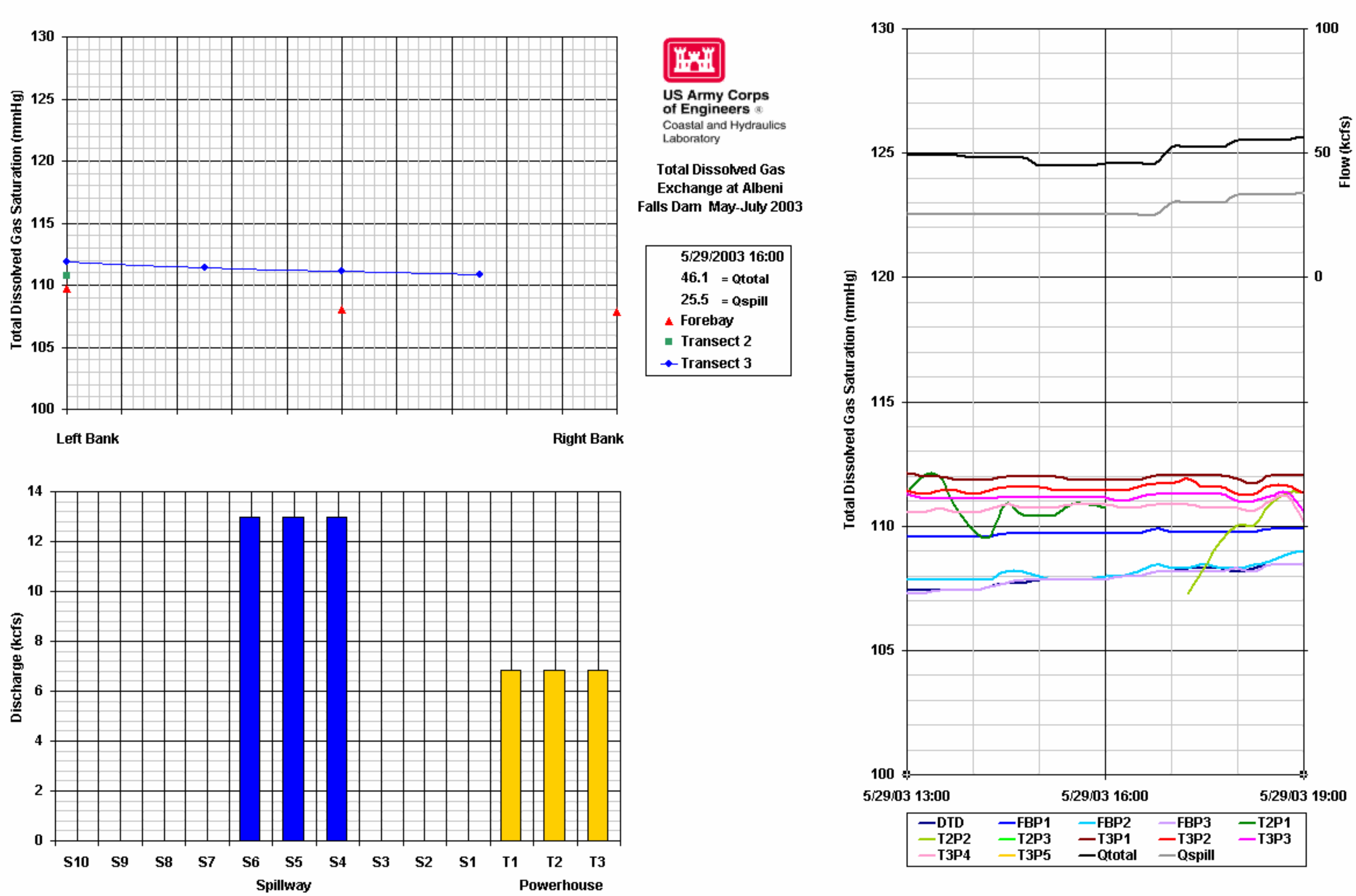

Figure 34c. TDG Saturation and Project Operations Data.
(Event 14, 29 May 1600 hrs, Qspill=25.5 kcfs)

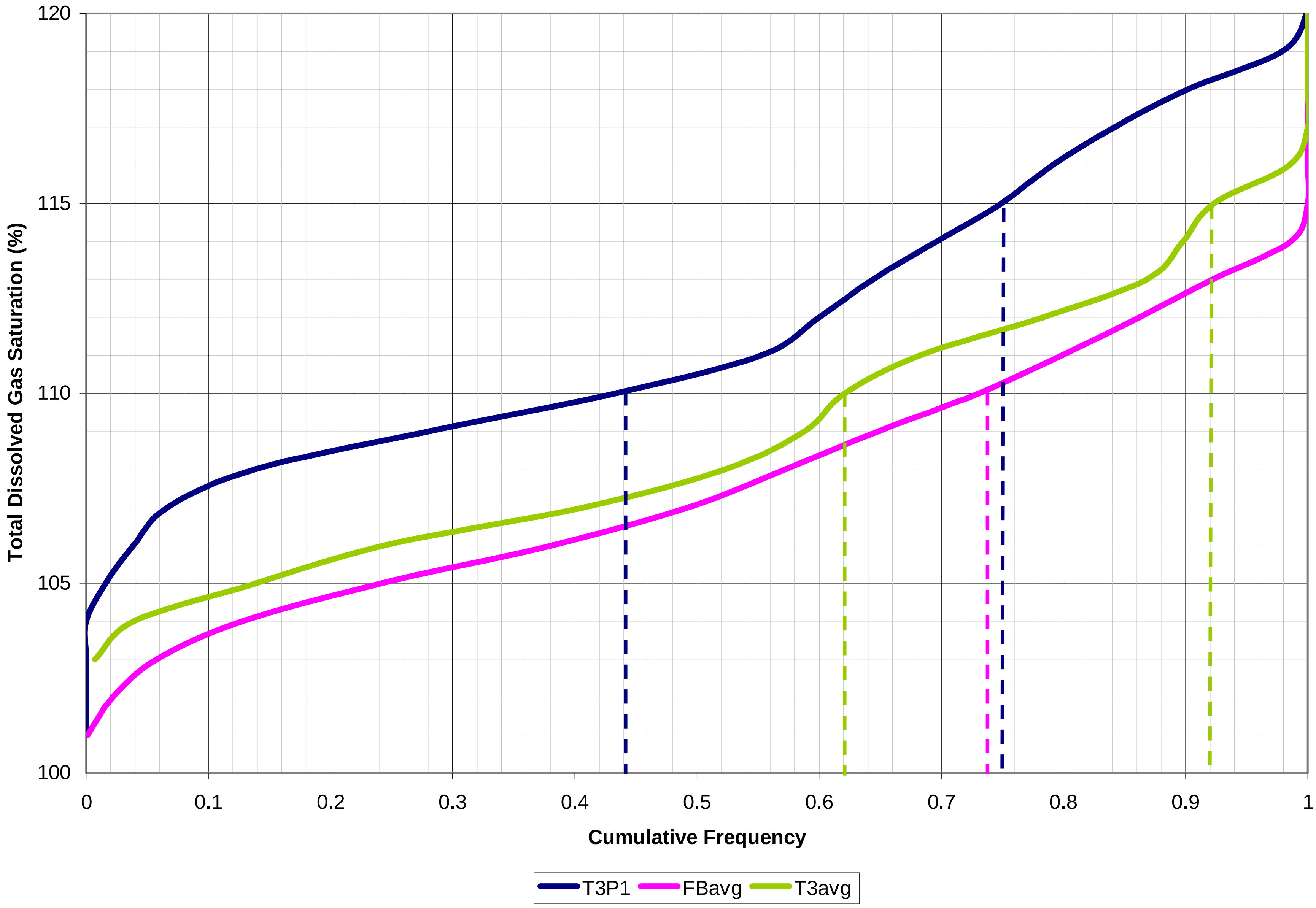

Figure 35. Cumulative Frequency Distribution of Forebay and Transect 3 Instruments at Albeni Falls Dam, 2003.

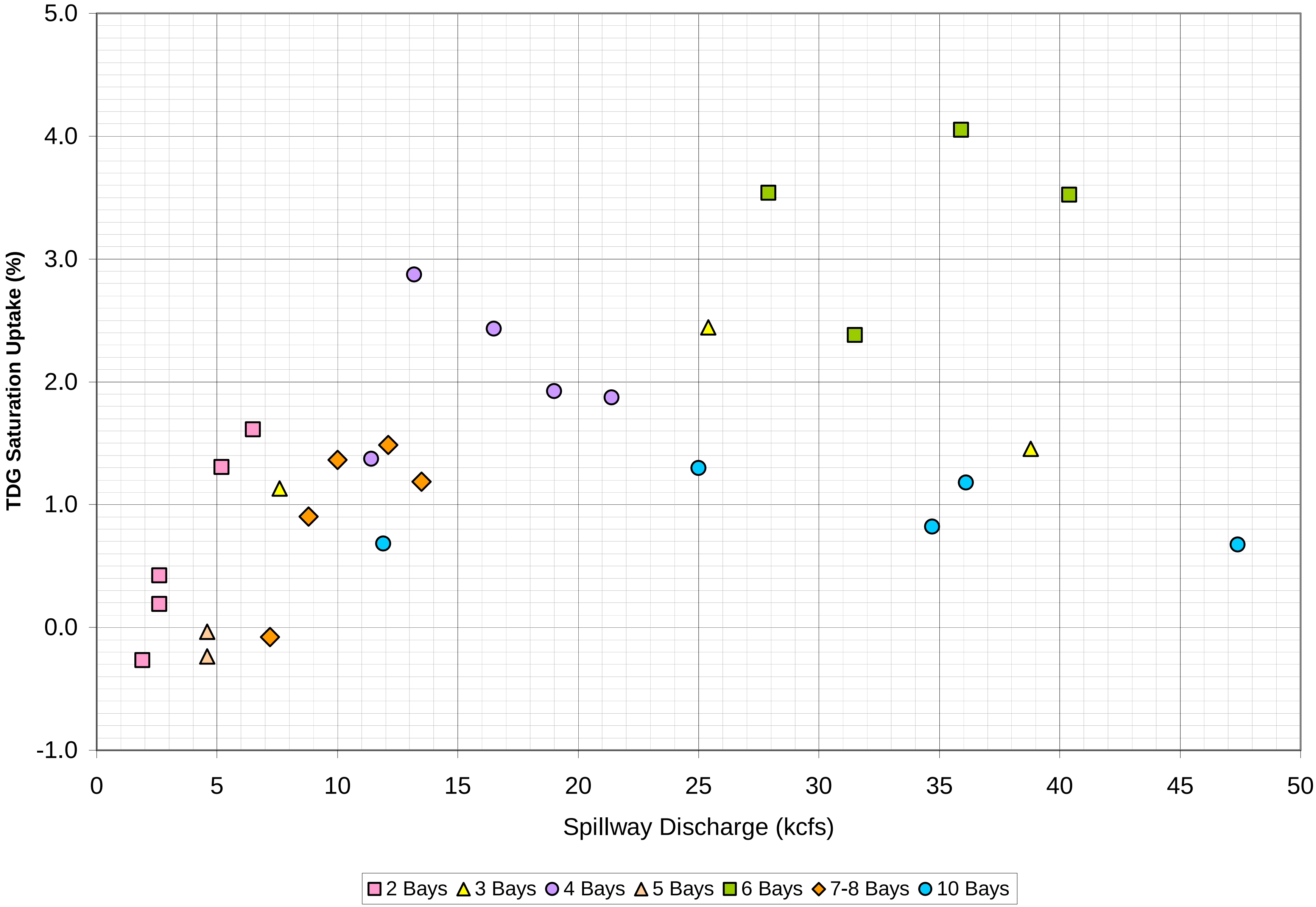

Figure 36. TDG Uptake as a function of spillway discharge at Albeni Falls Dam, 2003.
(TDG uptake = TDG_{t3avg}-TDG_{fbavg})

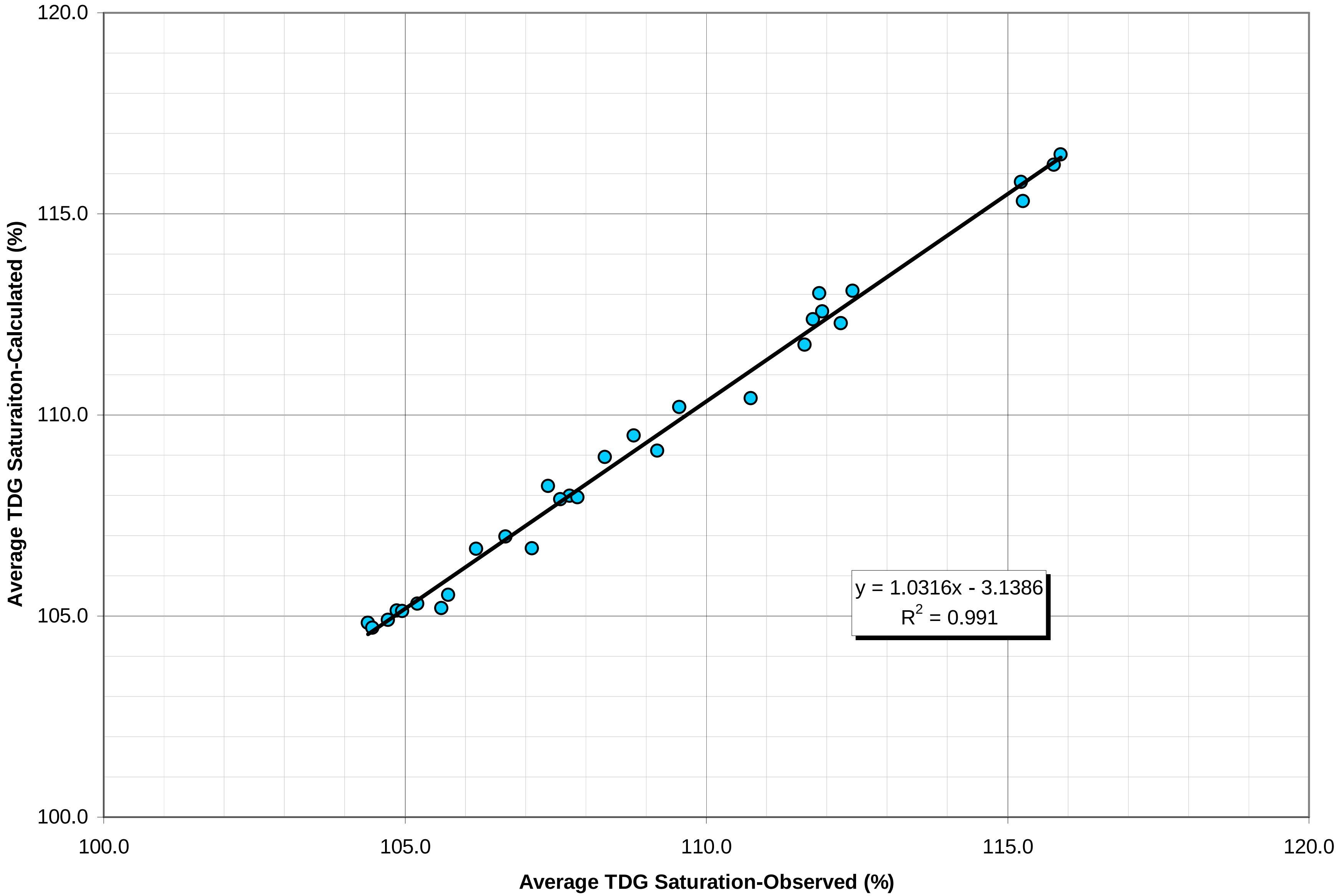

Figure 37. Calculated and Observed Cross sectional Average TDG Saturation in the Pend Oreille River on Transect T3

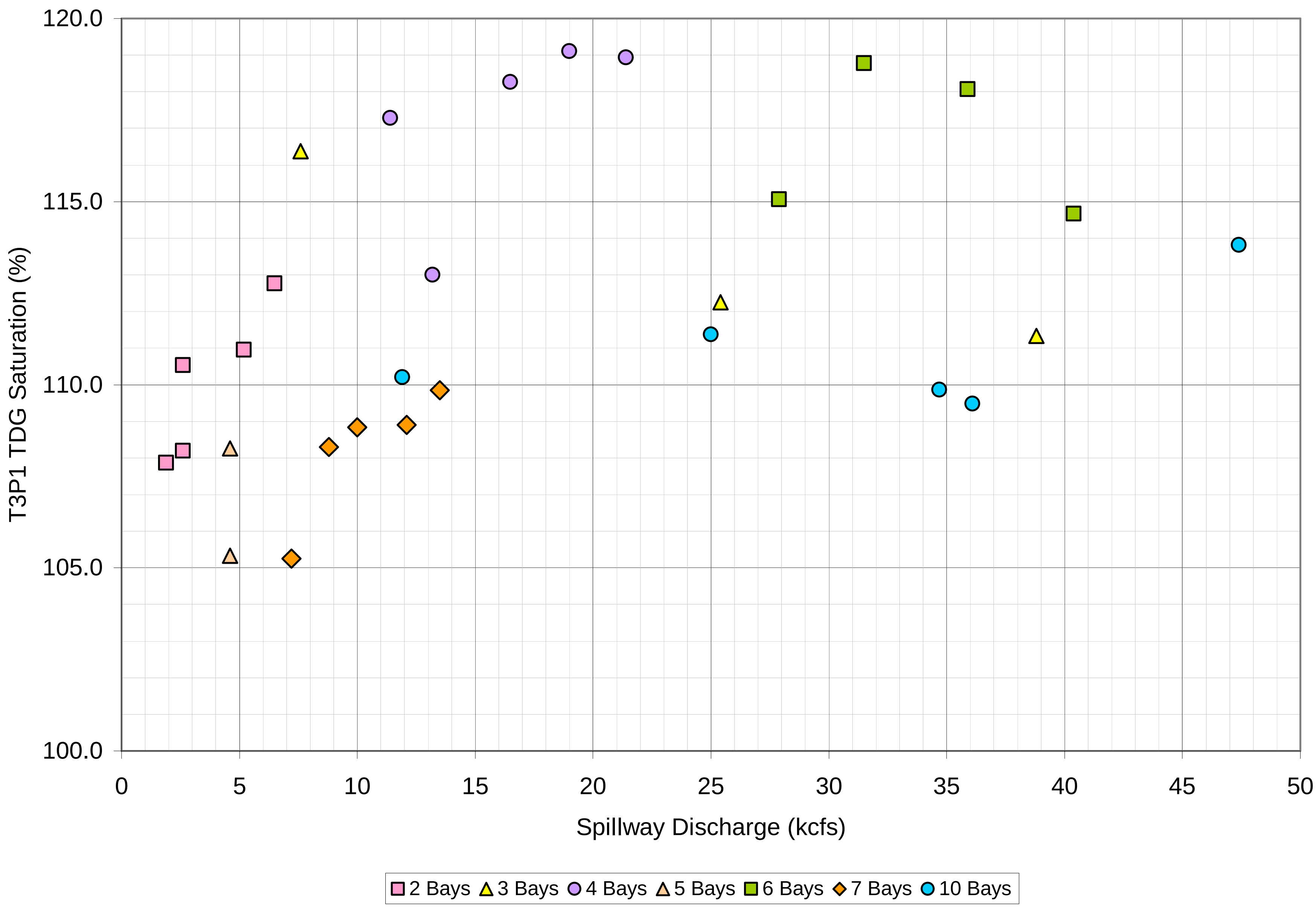

Figure 38. Total Dissolved Gas Saturation at T3P1 as a function of total spillway discharge at Albeni Falls Dam.

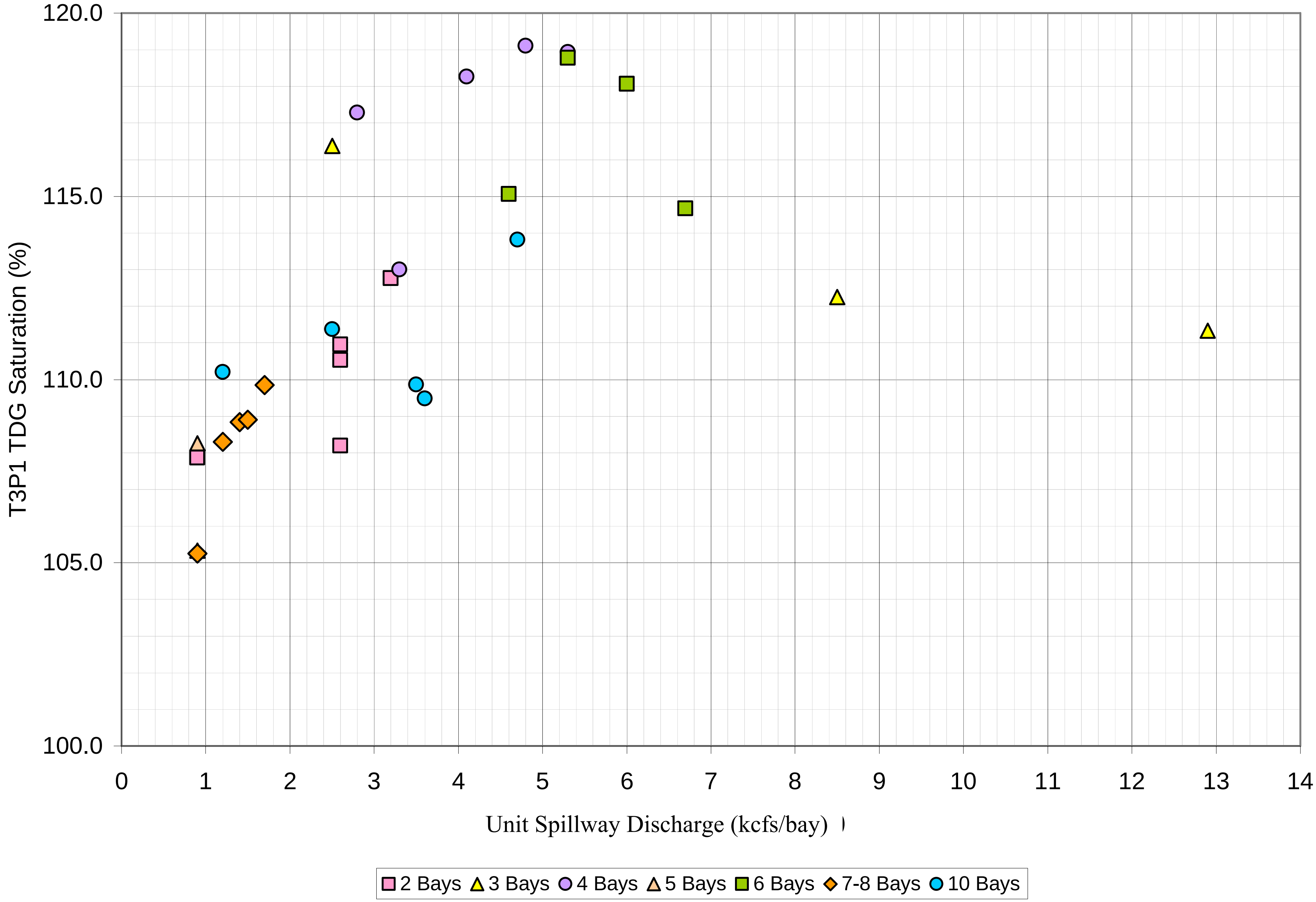

Figure 39. Total Dissolved Gas Saturation at T3P1 as a function of unit spillway discharge at Albeni Falls Dam.

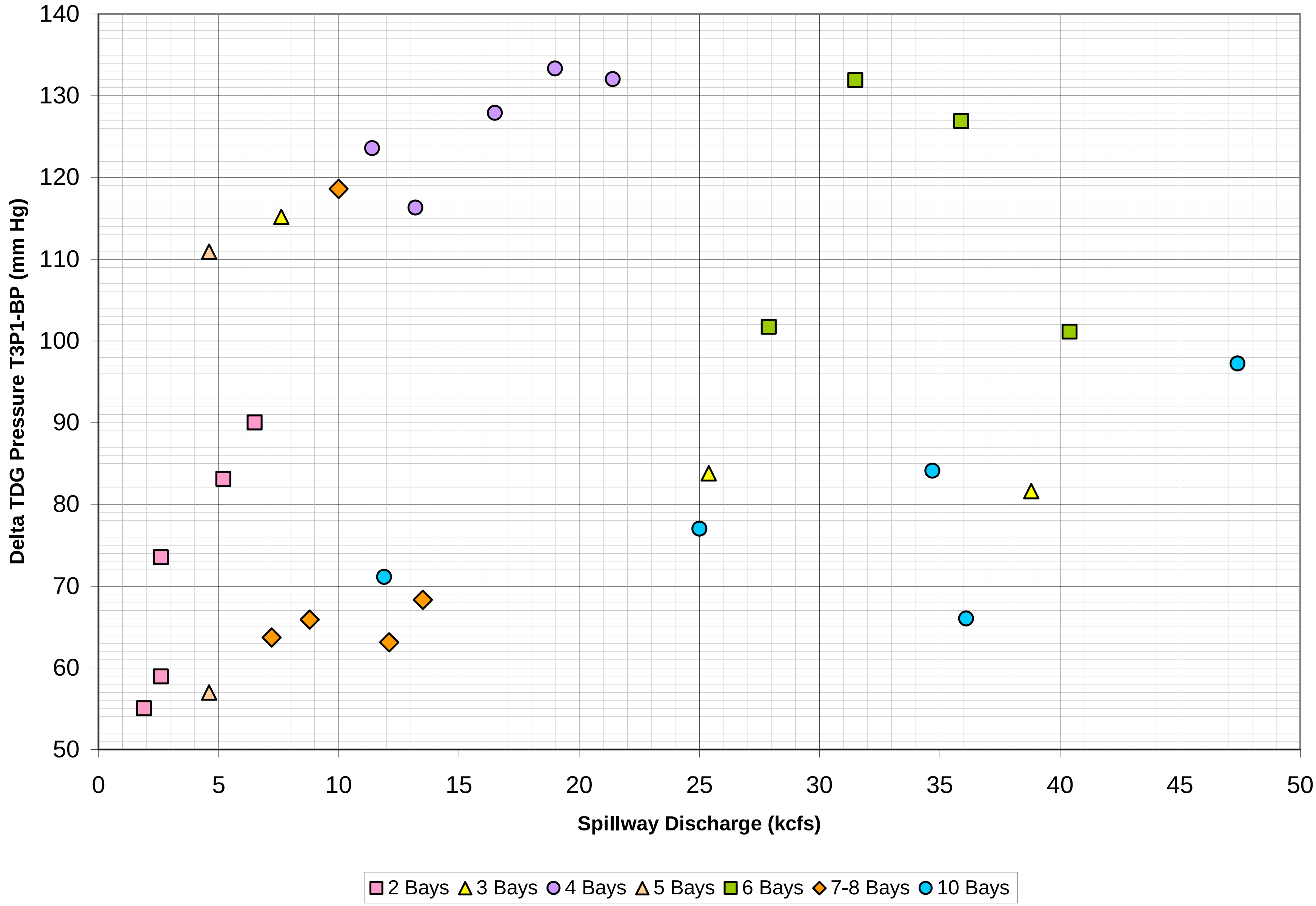

Figure 40. Delta TDG pressure in spill as a function of total spill discharge at Albeni Falls Dam, 2003

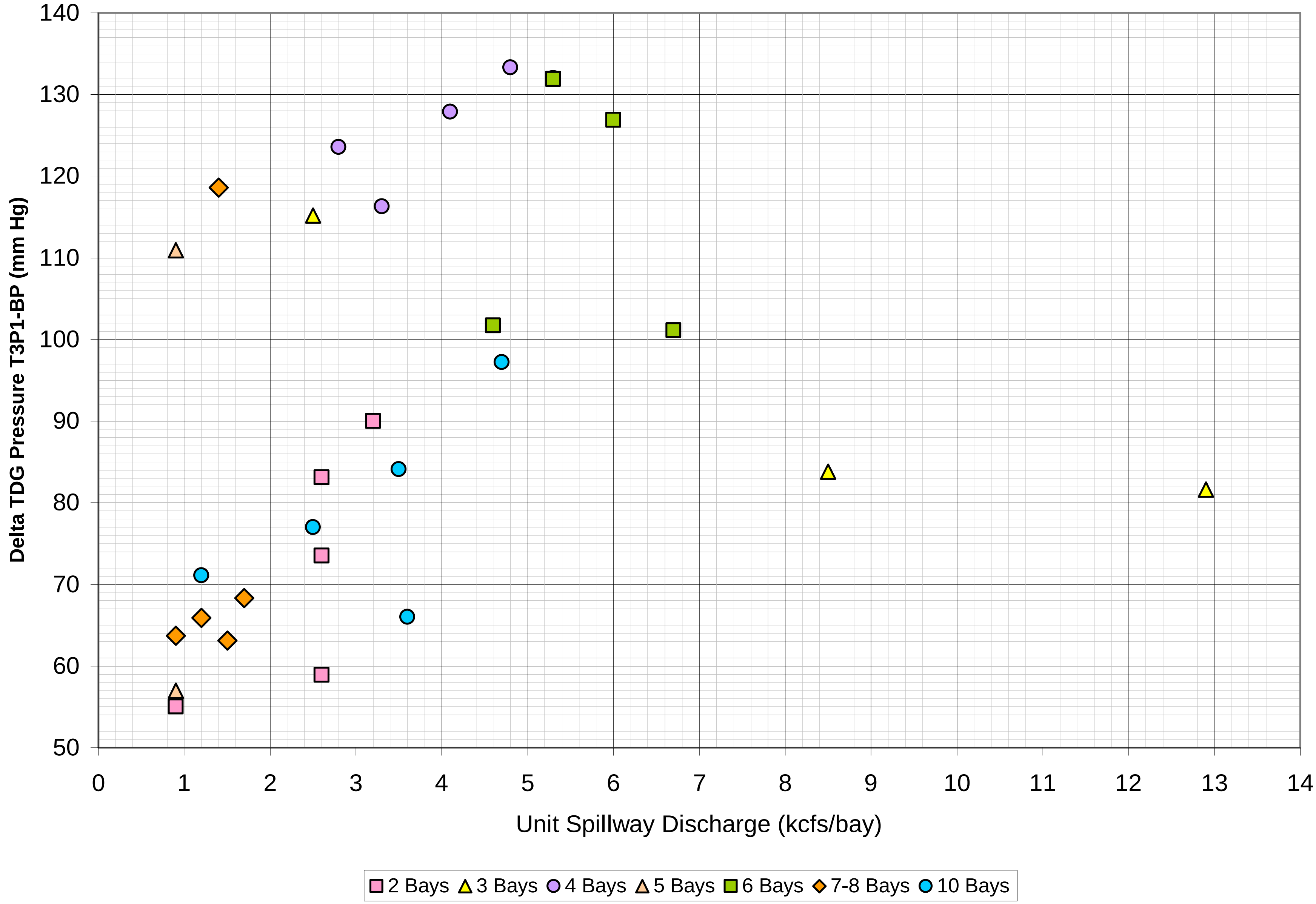

Figure 41. Delta TDG Pressure in spill as a function of unit spillway discharge at Albeni Falls Dam, 2003

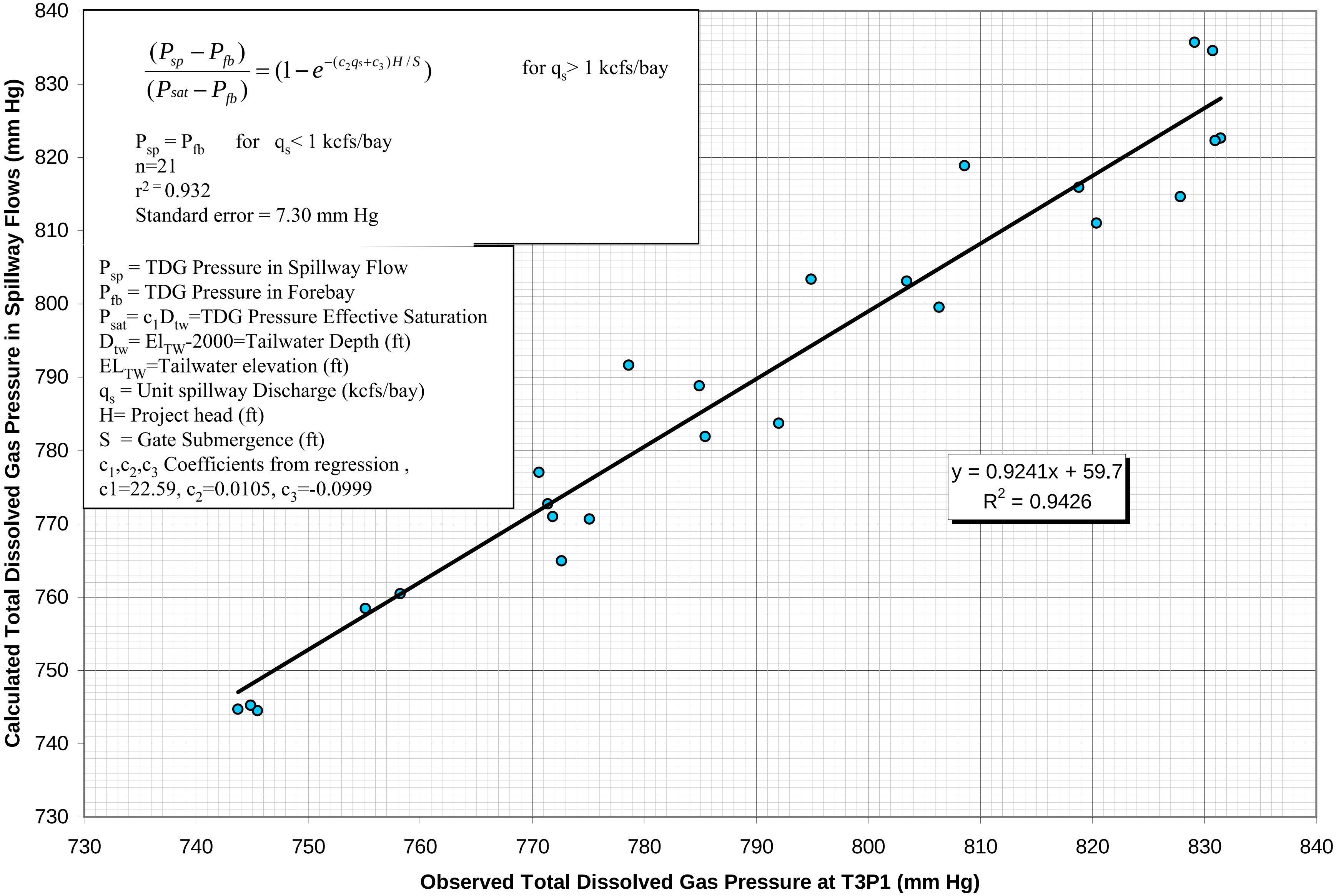

Figure 42. Observed and calculated total dissolved gas pressure in spill at Albeni Falls Dam
(Equation 9 used to calculate TDG pressure, excludes open river spill and small percent spill events)

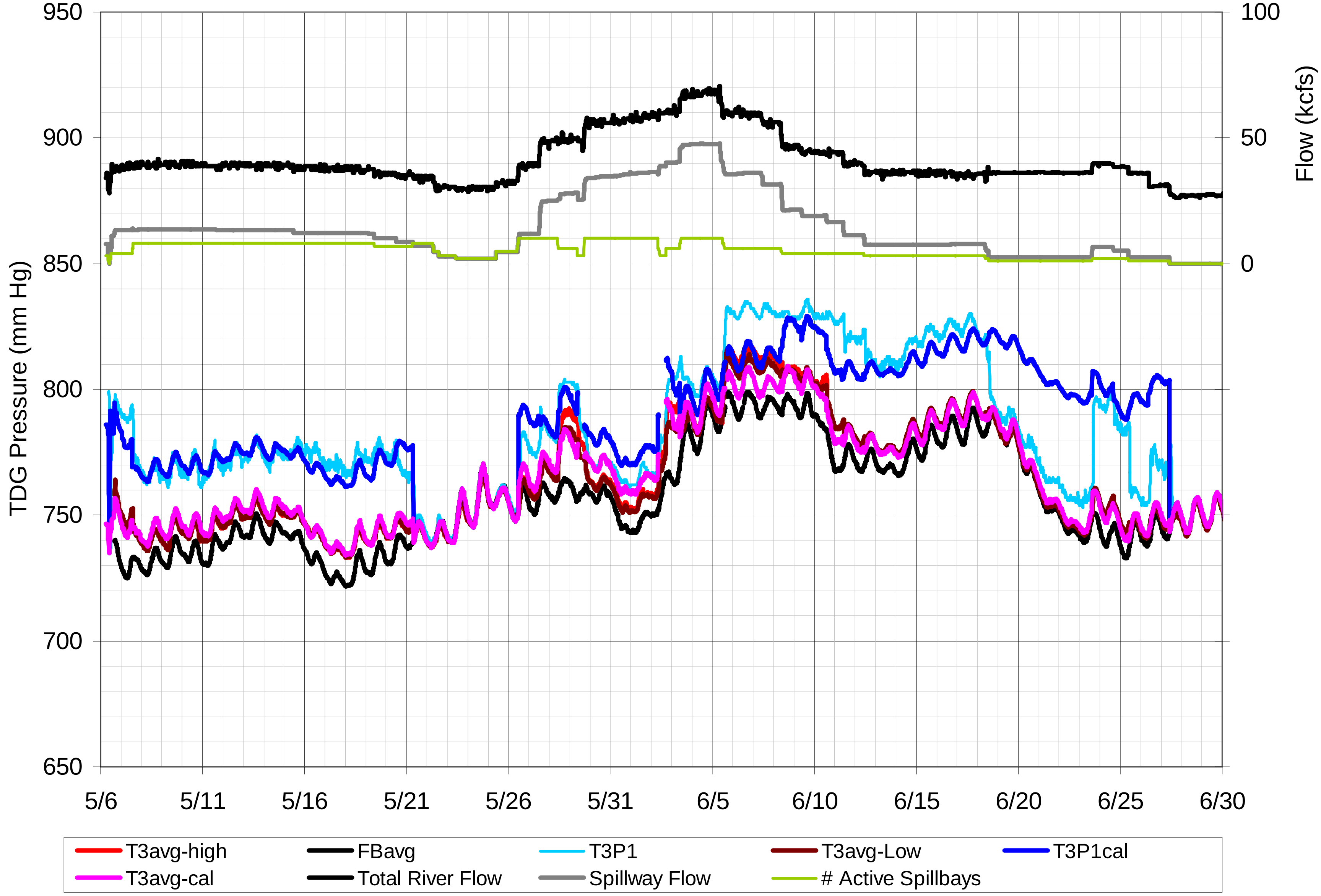

Figure 43. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, May-June 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

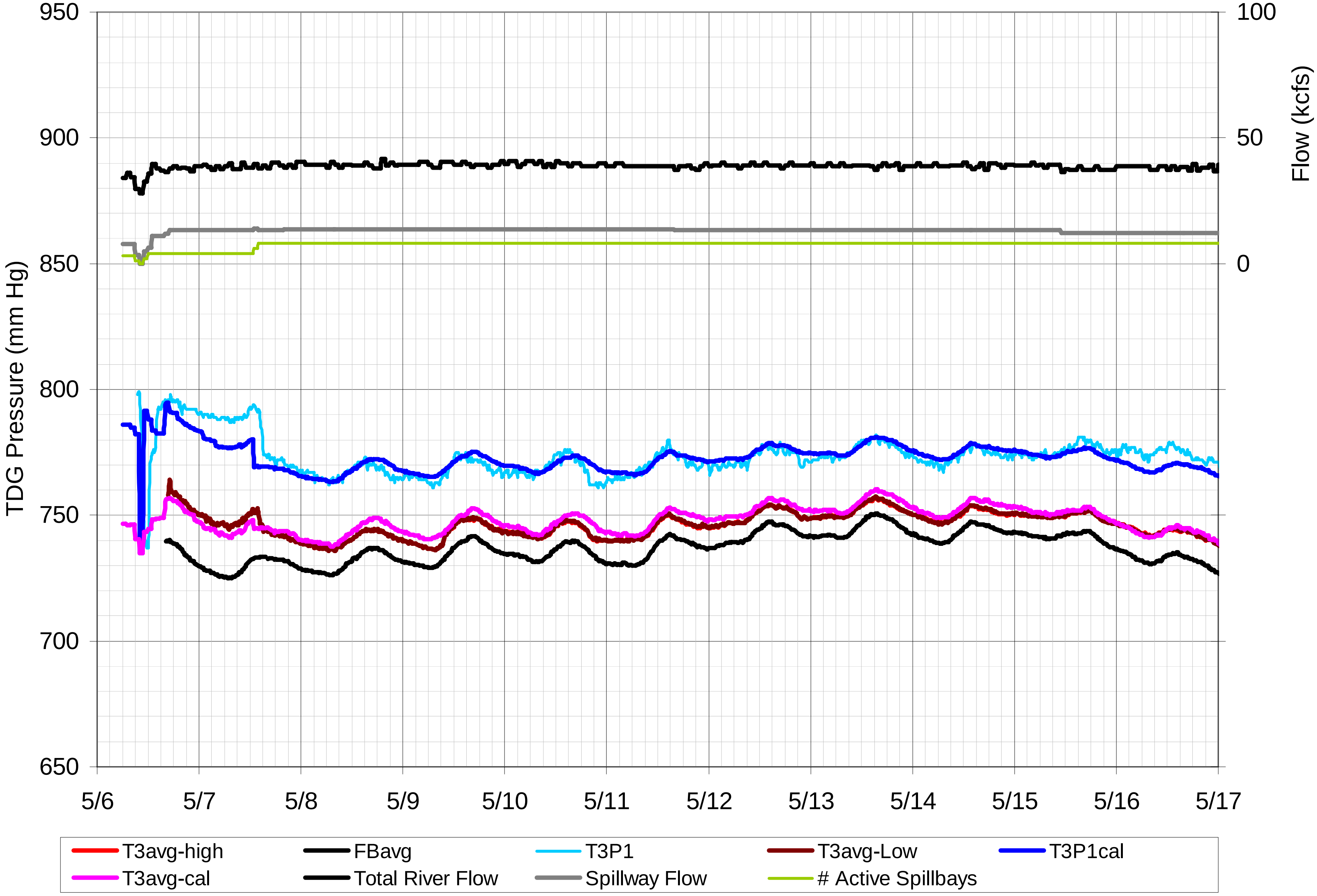

Figure 43a. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, May 6-16, 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

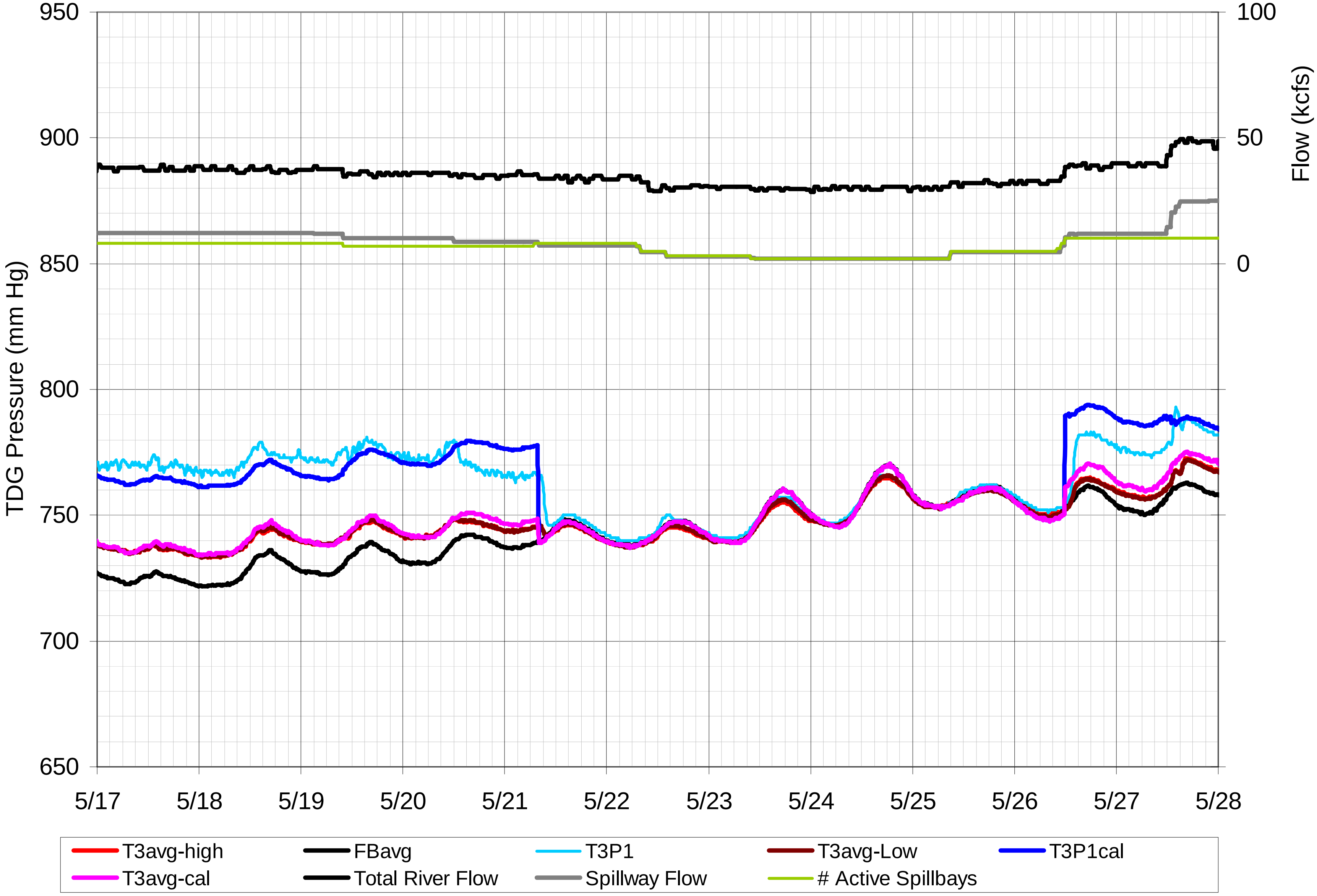

Figure 43b. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, May17-27 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

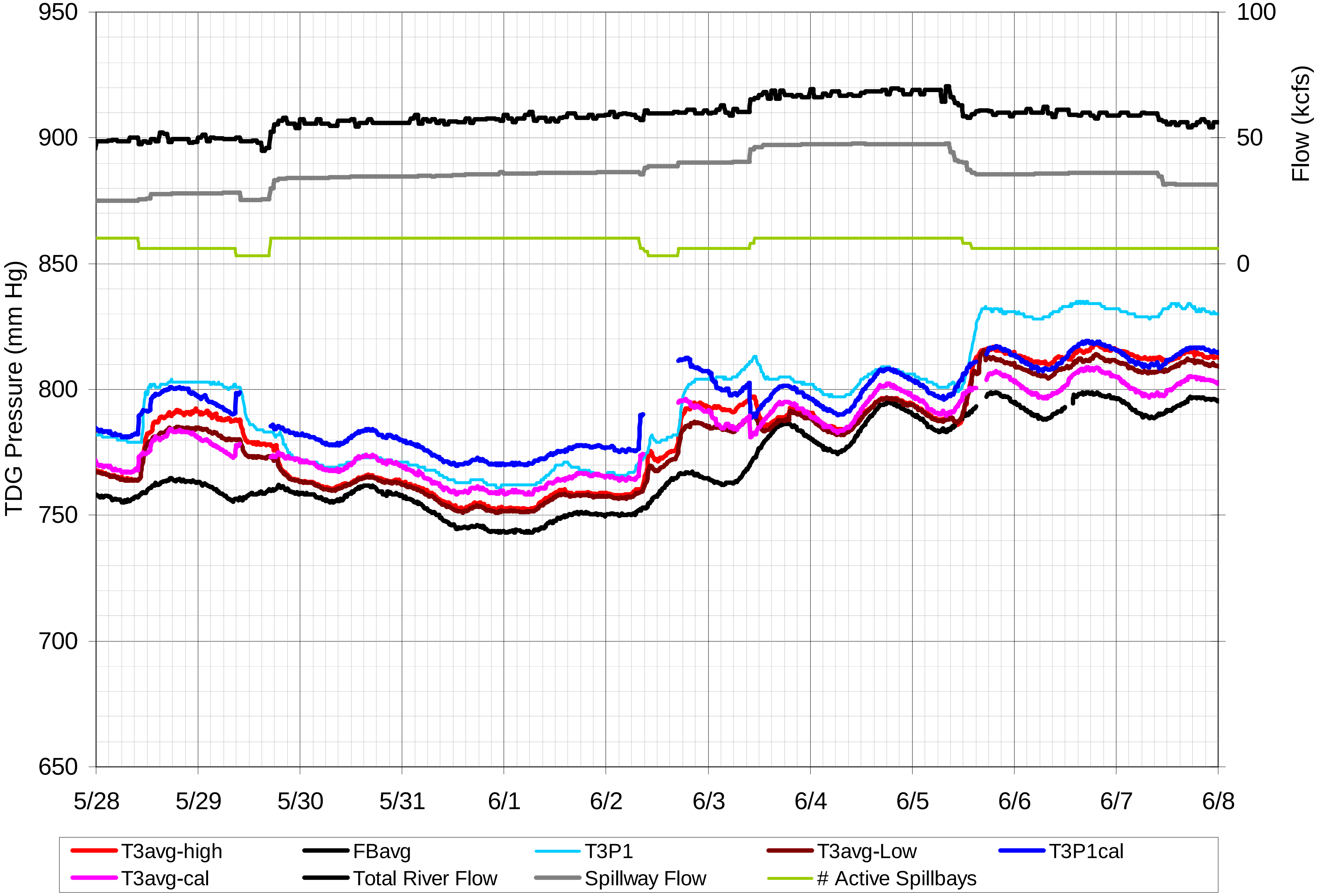

Figure 43c. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, May 28-June 7 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

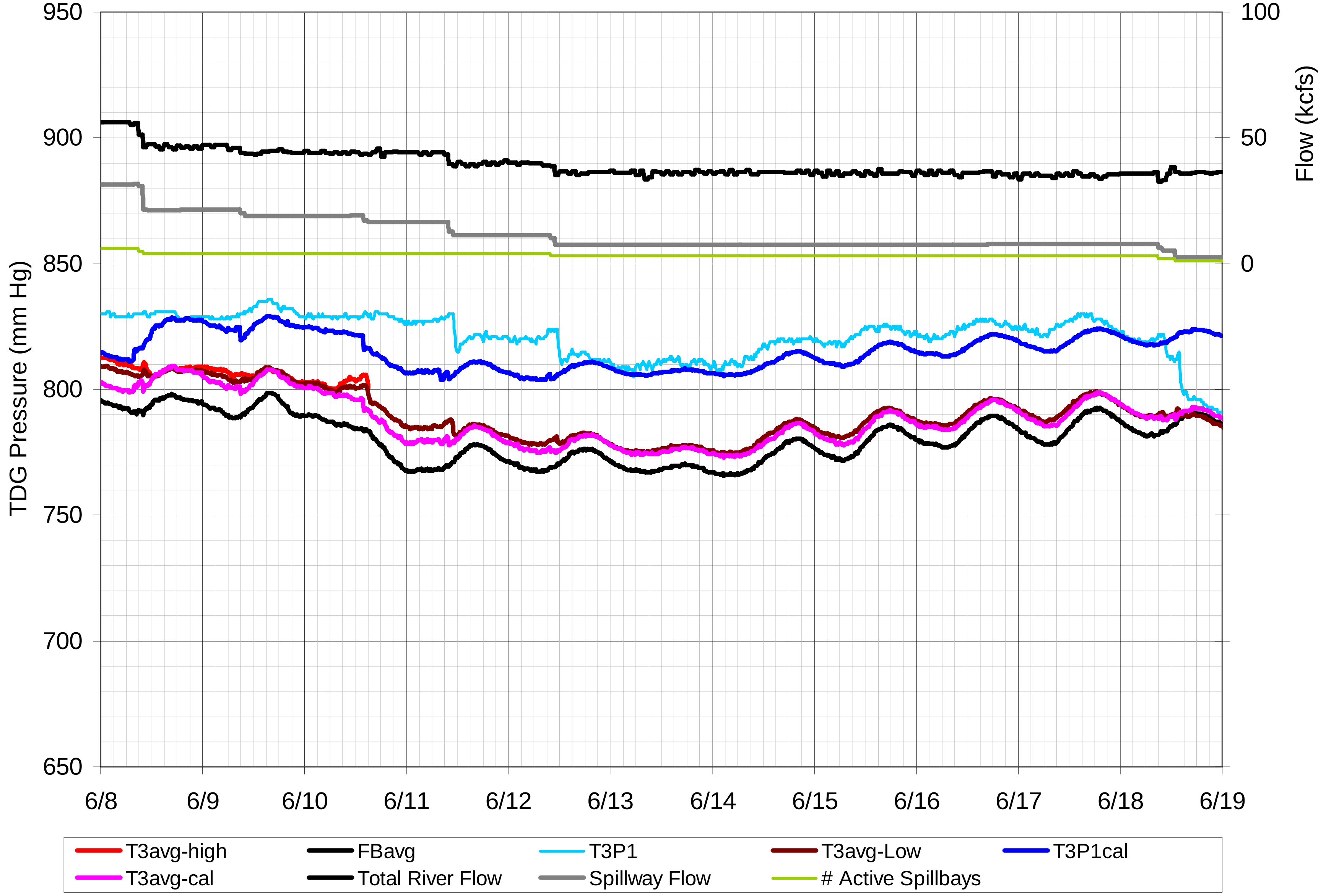

Figure 43d. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, June 8-18, 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

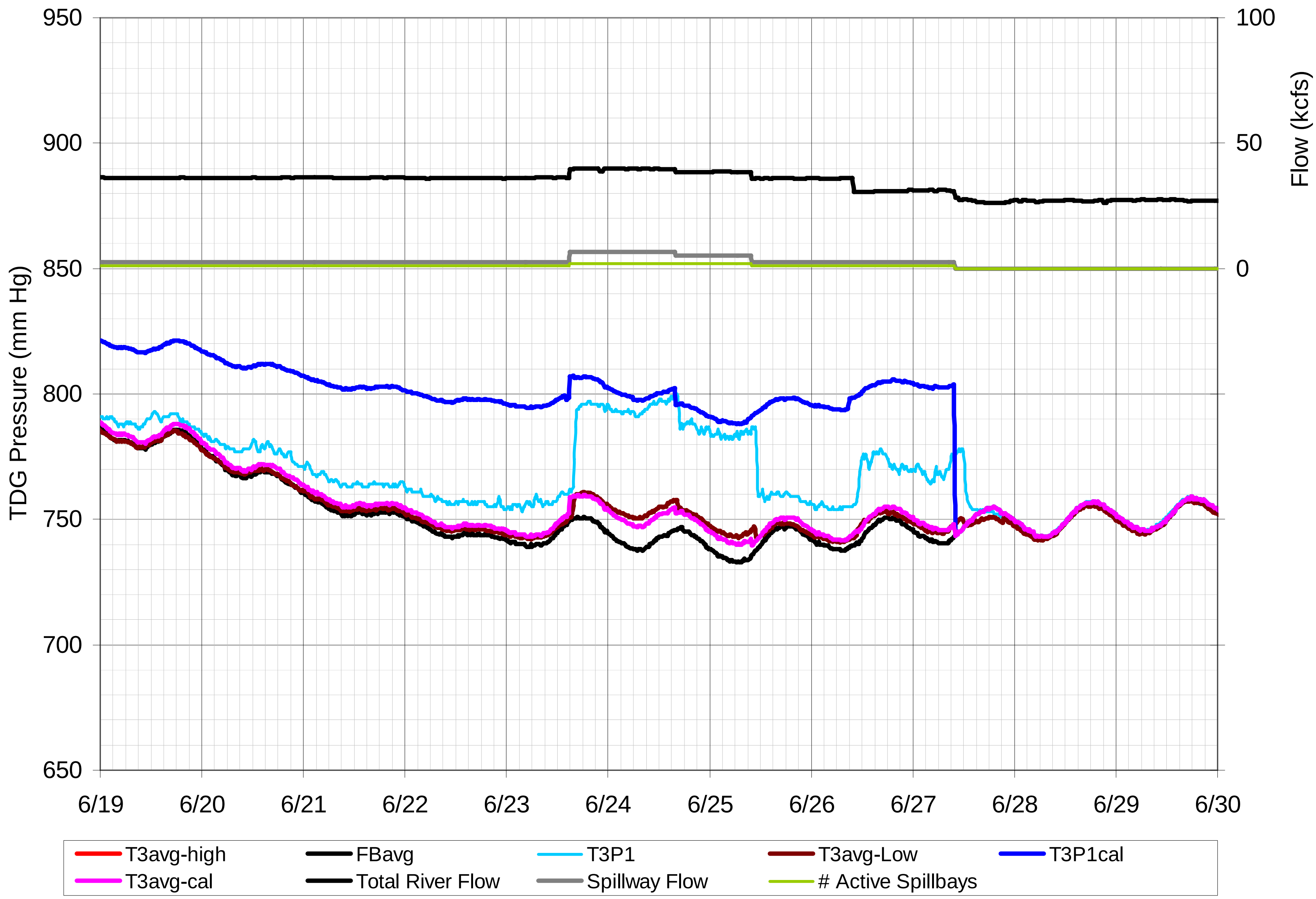

Figure 43e. Observed and Calculated Total Dissolved Gas Pressure in Spill and on Transect T3 in the Pend Oreille River at Albeni Falls Dam, June 8-18, 2003.
(Observed Spill=T3P1, Calculated Spill=T3P1cal, Observed Transect T3=T3avg, Calculated=T3avg-cal)

Appendix A: Albeni Falls Dam Total Dissolved Gas Study Sampling and Analysis Plan

Introduction

Total dissolved gas (TDG) supersaturation generated by aerated releases from dams increases the potential for gas bubble trauma (GBT) in downstream aquatic biota. Past TDG tests conducted by the Seattle District Corps of Engineers (CENWS) have shown the potential of high TDG saturation resulting from spill at Chief Joseph Dam on the Columbia River and Libby Dam on the Kootenai River. However, CENWS knowledge of TDG exchange at Albeni Falls Dam on the Pend Oreille River and TDG pressures downstream of the dam in the Pend Oreille River is limited. The US Fish and Wildlife Service's (USFWS) 2000 Biological Opinion reasonable and prudent measure (RPM) 11.A.1.3.c requires the CENWS to evaluate and report to the service on TDG concentrations downstream of Albeni Falls Dam in the Pend Oreille River which may occur within the full range of operations of the facility, including forced spills. To meet the USFWS requirements, the CENWS proposes to monitor TDG saturations in the Pend Oreille River above and below Albeni Falls dam during a portion of the spring and summer of 2003.

The proposed monitoring study will be directed at describing spatial and temporal TDG saturation characteristics both near the dam and downstream in the Pend Oreille River for about 2 months. The information gained can be used in better understanding the total dissolved gas exchange processes, particularly dissolved gas production during forced spill conditions, and dissolved gas transport and mixing downstream from the project. Results from this study will provide information on the impacts, if any, of Albeni Falls Dam on TDG concentrations in the Pend Oreille River, and will meet the letter of intent of the USFWS 2000 Biological Opinion. In addition, results will provide valuable information on existing water quality conditions in the Pend Oreille River at Albeni Falls Dam.

Objectives

The purpose of the TDG study is to more clearly understand total dissolved gas exchange processes associated with the operation of Albeni Falls Dam and the resultant transport and mixing in the Pend Oreille River immediately below the project. In particular, this study will sample TDG saturations in the Pend Oreille River above and below Albeni Falls Dam during May and June of 2003 and will be used to estimate the change in TDG loading associated with project operations. The study will focus on resolving questions regarding accurate source and sink descriptions of mass conservation of dissolved gases in the Pend Oreille River above and below the dam. TDG time history information as related to project operations is of particular interest. The data will be analyzed to provide estimates of the relative importance of background TDG concentrations in the Pend Oreille River and of dam operations on the downstream gas exchange processes. The conclusions drawn from this study will aid in the evaluation of the impacts of Albeni Falls Dam operations on the TDG concentrations downstream in the Pend Oreille River and potential TDG abatement measures.

Study Approach

A TDG monitoring study will be conducted to address the objectives stated above by deploying an array of automated remote logging water quality instruments, which are capable of sampling the complete time histories of TDG pressures in the river system. The water quality instruments will be deployed in the Pend Oreille River during May and June of 2003, a time period projected to experience a wide range of forced spill conditions at Albeni Falls Dam.

The TDG sampling array will be deployed both above and below the dam in order to document the lateral and longitudinal TDG characteristics in the Pend Oreille River during the study period. The lateral array below the dam will be designed to capture the different TDG conditions associated with powerhouse and spillway releases and the net TDG loading to the Pend Oreille River. The data collected by the water quality instrumentation during the study will included the date, time, instrument depth, water temperature, TDG pressure, dissolved oxygen concentration, and internal battery voltage. The geographic location of each sampling station will also be recorded. The water quality parameter of primary interest will be TDG pressure. These data will be collected at fifteen-minute intervals during the deployment period. In addition, barometric pressure and air temperature will be monitored near Albeni Falls at a similar interval to allow the calculation of TDG percent saturation. Manual sampling will be used where and when necessary to supplement the automated approach.

Study Design

The sampling design for TDG saturation will allow the determination of the TDG loading approaching and leaving the Albeni Falls dam and the peak TDG saturation generated during various spillway releases. TDG instruments will be deployed on 3 major transects in the Pend Oreille River near Albeni Falls Dam. The first transect will include three stations in the forebay of Albeni Falls measuring the TDG pressures approaching the powerhouse and spillway. The second transect will be positioned approximately 1800 feet below the spillway and consist of 5 sampling stations. The second sampling transect will capture the TDG levels in powerhouse and spillway flow prior to complete mixing and the resultant TDG loading associated with Albeni Falls operations. The third transect will be located just downstream from the Newport Bridge, about 1.8 miles below the dam and consists of 4 sampling stations. The third transect will provide a secondary estimate of the resultant TDG loading and a measure of the transport and mixing properties in the Pend Oreille River. Auxiliary stations will be located below the powerhouse and spillway (800 ft) to validate the TDG response in spillway flows at downstream transects.

The TDG instruments will be left in the river for a period of up to two months to monitor the full range of Albeni Falls Dam operations. During the study period, selected instruments will be maintained and calibrated on a three-week cycle. Instruments will be removed once it has been determined that Albeni Falls Dam has cycled through a normal range of operations, including forced spill conditions. The data will be downloaded from the instruments and subjected to a rigorous quality assurance/quality check (QA/QC) review.

Deliverables

A water quality monitoring report will be generated from the data gathered during the study. The report will provide the following information.

- Study review and description including background information

- Study goals and objectives
- Study design and methods
- Quality assurance review of data
- Documentation of the field study results, including text, tabular data, graphical presentation of the data, and other pertinent information
- Conclusions and recommendations.

Schedule of Study

The goal of the TDG study is to monitor dissolved gas in the Pend Oreille River above and below Albeni Falls dam under normal operating conditions, including forced spills. Because spill events are largely a factor of runoff conditions, the TDG study schedule will be flexible. A tentative TDG study schedule is presented below.

Instrument deployment and data collection	May 1–June 30, 2003
Data analysis	July 1–August 31, 2003
Draft report	October 15, 2003
Final report	December 15, 2003.

Appendix B

The Total Dissolved Gas Field Studies: Methodology Water Quality Instrument Calibration, Maintenance, and Precision

Hydrolab Corp. model DS4A® and minisonde 4A® were used exclusively for water quality monitoring in the Albeni Falls Dam TDG Field Studies of 2003. These instruments are wireless and capable of remotely logging temperature, depth, specific conductance, dissolved oxygen (DO), and TDG for a one-week to two-month deployment period depending on logging interval and water temperature. Colder waters have a major impact on battery life and can cut the periods to four day or less on a 15-minute sampling interval. Programming, calibration, and maintenance procedures of the instruments followed manufacturers' recommendations per instrument manuals. Any changes or modifications in instrument handling were implemented only after consulting with factory technicians. Calibration checks and adjustments were performed on all instruments within two days prior to each deployment. Post deployment checks on calibration were completed as soon after retrieval as possible for evaluation of instrument drift and accuracy. An evaluation of instrument performance based on calibration drift was conducted to verify proper equipment operation and define the confidence intervals (CI) for collected data. The inundation of the instruments by sediment creates another source of sampling bias that is not identified by the standard pre- and post-calibration protocol. This type of sampling bias was identified through comparison with neighboring stations and with stations located at upstream and downstream transects.

Calibration of Total Dissolved Gas

The Hydrolab tensionometers used for measuring TDG pressures employ semi-permeable membranes connected to pressure transducers with associated electronics to directly measure *in situ* total dissolved gas pressure. Air calibrations for TDG were performed using either a NIST certified mercury column barometer or portable field barometers that have been calibrated to a certified mercury column barometer. TDG was calibrated by comparing the instrument readings (in mm Hg) to those of the standard barometer at atmospheric conditions. TDG response slope checks were performed by adding known amounts of pressure, usually 100 and 300 mm Hg, directly to the transducer, and then adjusting the instrument reading accordingly to properly span the range of interest. The membrane is bypassed during these calibrations so that the probe itself is calibrated, rather than the probe/membrane combination. Direct comparisons of membrane off vs. membrane on vs. membrane on and wet have been made in past DGAS work and resulted in no appreciable difference in the calibrated measures. The condition of the membrane and any condensation trapped inside it can influence readings and result in erroneous data or instrument calibration.

An inspection for leaks is performed on the membrane itself before completing the calibration routine. One of the checks employed involves immersing the membrane in seltzer water (super saturated with carbon dioxide). The expected result of a properly functioning membrane is an immediate jump in the TDG reading of at least 300mm Hg. Membranes are also visually inspected for leaks and condensation moisture trapped inside the membrane. The leaks will usually appear as large darker spots in the membrane and indicate that water has entered the silastic tubing. This can occur from either leaks through a tear in the membrane or water vapor diffusion and then condensation inside the membrane. Defective membranes are replaced before use.

Calibration of Dissolved Oxygen

DO calibration followed procedures developed in the COE DGAS field sampling program. A water bath was employed to rapidly calibrate more than one instrument at a time. The water bath serves as a calibration chamber. After equilibration in this water bath, multiple instruments can then be calibrated to a standardized instrument. By adding a motor-driven propeller sleeved in a ported cylinder to the 50-gallon batch tank, it is possible to achieve a steady state, homogeneous mixture of water approximately 97 percent saturated with air at a constant temperature. One instrument is designated as the standard for comparison and calibrated for specific conductance, depth, and DO (in air). Once the standard instrument and tank are prepared, several Winkler titration analyses are run to further verify the dissolved oxygen concentration in mg/l of the calibration tank. Adjustments are made to agree with the Winkler titration of DO at this point. The remaining instruments are then adjusted to read the same as the standard instrument for DO, specific conductance, and depth. Additional Winkler DO titrations are performed throughout the calibration procedure to ensure consistency for the rest of the instruments.

Water Quality Calibration Data from COE Total Dissolved Gas Field Studies

Calibration checks and necessary adjustments performed on the Hydrolab instruments have been documented during the 1996, 1997, 1998, 1999, 2000, 2001, and 2002 field sampling for the COE dissolved gas field study program on the Columbia, Pend Oreille, and Lower Snake Rivers. The status of each of the parameters before and after each calibration check and adjustment is kept in a calibration log. Data gathered from logs kept on calibration activities were examined as a group, reflecting a pooled data set of all instruments for all deployments. The data assessed in this evaluation reflect only the calibrations performed on instruments before and after deployments that resulted in readings that are included in the study database. Logs for instruments requiring large-scale adjustments exceeding factory recommendations are not included in the data set. In addition, data logs resulting from instruments determined to be malfunctioning based on quality assurance criteria established by the manufacturer are not incorporated into the study database.

An analysis was completed to provide summary statistics defining the variability about the mean of the instrument drift and calibration error (Table B1). The individual data points comprising the population analyzed were the difference between the post-deployment reading of the parameter and a standard calibration value. DO and TDG were the only parameters evaluated in this assessment because they were the primary parameters in this study.

The mean ±2 standard deviations (SD) post operation calibration shifts in DO over all years and instrument types was 0.05 mg/l ± 1.08 mg/l. The mean ±2 SD post deployment calibration shift in TDG pressure over all years and instrument types was 0.44 mm Hg ± 6.5 mm Hg. The variation in DO has remained fairly constant over all years at an approximate SD of 0.5 mg/l. Improved quality assurance and control measures for conducting the TDG calibrations and handling has apparently resulted in reduced variability in the overall accuracy of the instruments used. The TDG calibration checks have gone from an average SD of 5.8 mm Hg in the 1996 sampling year to a low of 0.71 mm Hg SD average for the TDG field studies conducted during the 2001 sampling year. The 13 instruments used in the Albeni Falls TDG study during 2003 had a mean drift in the TDG calibration of 0.13 mm Hg ± 1.26 m Hg. This indicates that 95 percent of the individual measures for TDG pressure were within 2.52 mm Hg of the measured value.

Table B1. DGAS post deployment calibration check for drift in DO (mg/l) and TDG (mm Hg).						
YEAR	**Parameter**	**N**	**Min.**	**Max.**	**Mean**	**Std. Deviation**
1996	DO	253	-2.2	2.1	0.13	0.56
	TDG	233	-21.0	19.0	0.14	5.8
1997	DO	459	-2.4	1.5	0.04	0.42
	TDG	494	-16.0	18.0	0.43	3.5
1998	DO	295	-2.3	2.0	0.04	0.68
	TDG	316	-7.0	8.0	0.67	2.1
1999	DO	183	-1.5	1.27	-0.03	0.42
	TDG	244	-8.0	13.0	0.71	1.69
2000	DO	30	-1.0	0.8	-0.1	0.47
	TDG	73	-4.0	3.0	0.29	1.21
2001	DO	28	-0.4	1.2	0.24	0.35
	TDG	44	-2.0	1.0	0.09	0.71
2002	DO	0	-	-	-	-
	TDG	93	-2.0	3.0	0.0	0.99
Albeni Falls Dam	DO	0	-	-	-	-
	TDG	26	-3.0	3.0	0.13	1.26
Combined Years	DO	1248	-2.4	2.12	0.05	0.52
	TDG	1487	-21.00	19.0	0.43	3.31

Though these numbers do not necessarily reflect the number of times the instruments were serviced by field personnel or by factory technicians, they do suggest that there is a very low frequency of deployments resulting in erroneous measurements. Barring any unforeseen complications or errors associated with deployment and post-calibration handling, the instruments used in TDG field sampling produced accurate data. Most calibrations revealed that the instruments' measurement error generally fell within what could be considered an acceptable range of drift. The overall range in drift observed was a bit wider than that defined by the manufacturers (± .2 mg/l DO and ± 1 mm Hg TDG pressure). It should be noted, however, that manufacturer-defined expected error is based on optimal lab conditions, not the field conditions and time intervals in which the instruments were required to function. An additional consideration is the fact that calibration conditions and methods were modified and refined during the DGAS program so that the most accurate and efficient calibrations possible were maintained. It is likely that more experience resulted in the culmination of techniques that could afford tighter calibration data. The instruments accuracy or drift (± 0.77 mm Hg TDG) demonstrated during the Rocky Reach study was within manufacturers specifications of ± 1 mm Hg TDG pressure.

Water Quality Instrument Precision for COE Total Dissolved Gas Field Studies

In addition to the calibration accuracy described above the precision of the water quality instruments have been evaluated using three other approaches. These include the computation of SD's for individual instruments sampling in a time series in similar waters under near steady state conditions (both laminar flow and turbulent aerated flow below spill ways). The second approach has been to collect paired data using two like instruments deployed together in the same river conditions. The third method of evaluation has been to summarize data from collections of similar instruments located in close proximity for short periods when water conditions especially TDG pressures remained constant (steady state conditions).

During the near field TDG study conducted at the John Day Dam during 2000, a representative set of instruments was evaluated for precision of TDG measures. The analysis was conducted on 30 separate instruments for up to 10 different time periods of one to two hours each. Each time period was selected to meet the requirement of near steady state regarding flow and expected TDG conditions. The objective was to limit the variability of TDG to just that associated with or inherit in the individual instruments and not due to changing water conditions. The measures were taken and logged on a 15-minute time interval for all instruments producing 4 to 8 readings per instrument per selected time period. This design resulted in a grand total of 279 samples of 4 to 8 readings each. The analysis resulted in a mean standard deviation of 0.59 mm Hg ± 0.88 SD for the TDG pressure readings and a mean standard deviation of 0.08 percent ± 0.12 SD for the associated TDG saturation readings. The TDG saturation analysis also incorporated the error associated with barometric pressure measures collected during the studies. This would allow the calculation of mean TDG pressures for different periods during the John Day testing to have 95 percent CI of ± 1.18 mm Hg. If this variance were applied to all instruments then paired sample means for separate treatments using the same instrument with differences of more than 2.36 mm Hg would be significantly different

The same data set has been analyzed by grouping all water quality instruments on a sampling transect. This varied from 2 to 8 instruments on each of 6 transects. Again time series measures for TDG pressure and saturation were selected for up to 10 separate periods of testing or flow. These time cases were selected for steady state conditions in flow and TDG to represent variability within groups of gas instrument for the same waters. The outcome produced 57 different samples having a mean standard deviation of 1.89 mmHg ±1.04 SD for the pressure readings and a mean standard deviation 0.25 ±0.14 SD for the associated TDG saturation readings. This analysis of grouped instruments results in 95 percent CI for sample means of ±3.8 mm Hg.

The third approach in examining variation of field gas measures incorporated a paired instrument approach where two instruments were tied together and deployed at river sampling stations. The data collection was conducted during the 2000 John Day Near Field study and past river sampling studies conducted by the DGAS field sampling team in 1998 and 1999. Reading differences in TDG pressure was calculated for entire deployment logs of 11 pairs of readings. Under the above conditions the resulting differences are due to uncertainty or bias introduced in the calibration of the individual instruments. The pressure readings were logged on 15-minute time intervals in each case. Since the rate of gas diffusion through the membranes used by the TDG instruments is highly variable readings collected during times of rapid change were eliminated from the analysis. Table B2 depicts the results of one sample paired T-test applied to the 11 paired instrument sampling logs. The analysis was conducted for both TDG pressure and saturation readings. The gross mean standard deviation for the 11 paired samples is 1.89 ±1.25 mm Hg pressure and 0.23 ±0.16 percent saturation. As would be expected the overall mean of the differences for both TDG pressure, 0.18 mm Hg (95 percent CI = -3.86 to 4.22 mm Hg) and saturation, 0.03 percent (95 percent CI = –0.59 to 0.65) were not significantly different from 0.

In light of the above described quality assurance methods and uncertainty evaluation of the TDG procedures it appears that with a minimal replication of measures it is possible to significantly discriminate between sample means differing by only a few mm Hg or fractions of a percent TDG saturation. This general conclusion should apply in the application of either paired or multiple instrument sampling. Also, under the current practices for calibration, the average instrument accuracy falls into the same range of about ± ½ percent TDG saturation.

Table B2. Paired TDG sample log analysis, calculations made on paired reading differences.

Pair		N	Mean Difference	Standard Deviation
CWFMS	mm Hg	631	1.14	2.78
	Percent Saturation	582	0.16	0.37
LMO6954P	mm Hg	614	-2.94	3.33
	Percent Saturation	581	-0.41	0.23
LW13974P	mm Hg	998	-0.57	0.53
	Percent Saturation	909	-0.07	0.07
MN00614P	mm Hg	929	-0.45	1.09
	Percent Saturation	868	-0.06	0.13
RIST3P3	mm Hg	459	1.01	1.08
	Percent Saturation	459	0.14	0.14
RIST3P5	mm Hg	481	0.32	0.76
	percent Saturation	481	0.04	0.10
T1P3	mm Hg	835	-3.26	3.70
	percent Saturation	688	-0.51	0.54
T1P5	mm Hg	857	3.71	2.82
	percent Saturation	708	0.62	0.34
T5P4	mm Hg	1058	1.35	0.94
	percent Saturation	788	0.24	0.07
T5P6	mm Hg	739	1.89	3.18
	percent Saturation	755	0.25	0.43
T6P5	mm Hg	937	-0.27	0.63
	Percent Saturation	786	-0.05	0.08
Means	mm Hg		0.18 ± 2.03	1.89 ± 1.25
	Percent Saturation		0.03 ± 0.31	0.23 ± 0.17

Appendix C:

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam

Date	Distance (ft)	Depth (ft)	Velocity (ft/sec)	Discharge (cfs)	Q_{total} (cfs)	$q_{fraction}$
6/7/1976	100	7.3	0.71	171	87515	0.0020
6/7/1976	140	15.4	2.53	1560	87515	0.0198
6/7/1976	180	16.7	3.02	2020	87515	0.0429
6/7/1976	220	17.0	3.61	2450	87515	0.0709
6/7/1976	260	17.5	3.51	2560	87515	0.1001
6/7/1976	300	18.6	3.99	2410	87515	0.1276
6/7/1976	325	19.7	4.15	2040	87515	0.1510
6/7/1976	350	21.3	4.40	2340	87515	0.1777
6/7/1976	375	22.8	4.50	2560	87515	0.2069
6/7/1976	400	24.2	4.56	2760	87515	0.2385
6/7/1976	425	24.2	4.46	2700	87515	0.2693
6/7/1976	450	23.8	4.42	2630	87515	0.2994
6/7/1976	475	23.1	4.61	2660	87515	0.3298
6/7/1976	500	22.5	4.61	2850	87515	0.3623
6/7/1976	530	21.8	4.59	3000	87515	0.3966
6/7/1976	560	21.1	4.56	2890	87515	0.4297
6/7/1976	590	20.8	4.48	2800	87515	0.4616
6/7/1976	620	20.6	4.77	2950	87515	0.4954
6/7/1976	650	20.7	4.50	2790	87515	0.5272
6/7/1976	680	20.8	4.50	2810	87515	0.5593
6/7/1976	710	20.9	4.59	2880	87515	0.5923

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam						
Date	Distance (ft)	Depth (ft)	Velocity (ft/sec)	Discharge (cfs)	Q_{total} (cfs)	$q_{fraction}$
6/7/1976	740	20.8	4.32	2700	87515	0.6231
6/7/1976	770	21.3	4.32	2760	87515	0.6546
6/7/1976	800	21.4	4.47	2870	87515	0.6874
6/7/1976	830	21.4	4.58	2940	87515	0.7210
6/7/1976	860	21.2	4.36	2770	87515	0.7527
6/7/1976	890	21.7	4.28	2790	87515	0.7846
6/7/1976	920	21.8	4.06	2660	87515	0.8150
6/7/1976	950	21.1	3.70	2340	87515	0.8417
6/7/1976	980	20.8	3.84	2800	87515	0.8737
6/7/1976	1020	19.6	3.85	3020	87515	0.9082
6/7/1976	1060	18.2	3.46	2830	87515	0.9405
6/7/1976	1110	16.6	3.64	3020	87515	0.9750
6/7/1976	1160	15.4	2.58	1990	87515	0.9978
6/7/1976	1210	6.6	0.70	194	87515	1.0000
6/4/1998	120	8.4	1.00	378	53778	0.0070
6/4/1998	185	12.8	2.20	1830	53778	0.0411
6/4/1998	250	13.7	2.72	2240	53778	0.0827
6/4/1998	305	14.8	3.12	2310	53778	0.1257
6/4/1998	350	17.3	3.32	2300	53778	0.1684
6/4/1998	385	19.6	3.42	2350	53778	0.2121
6/4/1998	420	20.8	3.45	2510	53778	0.2588
6/4/1998	455	19.9	3.52	2450	53778	0.3044
6/4/1998	490	18.9	3.56	2520	53778	0.3512
6/4/1998	530	18.0	3.56	2560	53778	0.3988
6/4/1998	570	17.0	3.68	2500	53778	0.4453

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam

Date	Distance (ft)	Depth (ft)	Velocity (ft/sec)	Discharge (cfs)	Q_{total} (cfs)	$q_{fraction}$
6/4/1998	610	16.8	3.42	2590	53778	0.4935
6/4/1998	660	16.9	3.29	2500	53778	0.5400
6/4/1998	700	17.0	3.36	2280	53778	0.5824
6/4/1998	740	17.2	3.42	2350	53778	0.6261
6/4/1998	780	17.6	3.39	2390	53778	0.6705
6/4/1998	820	17.6	3.42	2410	53778	0.7153
6/4/1998	860	17.4	3.46	2410	53778	0.7601
6/4/1998	900	17.9	3.39	2480	53778	0.8062
6/4/1998	940	17.7	3.12	2480	53778	0.8524
6/4/1998	990	17.0	2.74	2330	53778	0.8957
6/4/1998	1040	15.3	2.59	1980	53778	0.9325
6/4/1998	1090	13.8	2.80	2320	53778	0.9756
6/4/1998	1160	11.6	2.06	1310	53778	1.0000
2/19/2002	160	4.3	1.00	192	15624	0.0123
2/19/2002	200	4.4	1.02	180	15624	0.0238
2/19/2002	240	4.6	1.40	258	15624	0.0403
2/19/2002	280	5.6	1.56	262	15624	0.0571
2/19/2002	300	6.1	1.70	233	15624	0.0720
2/19/2002	325	7.4	1.82	337	15624	0.0936
2/19/2002	350	9.0	2.12	477	15624	0.1241
2/19/2002	375	10.5	2.33	610	15624	0.1631
2/19/2002	400	11.4	2.35	670	15624	0.2060
2/19/2002	425	12.0	2.18	64	15624	0.2101
2/19/2002	450	11.6	2.35	682	15624	0.2538
2/19/2002	475	10.8	2.51	678	15624	0.2972

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam						
Date	**Distance (ft)**	**Depth (ft)**	**Velocity (ft/sec)**	**Discharge (cfs)**	**Q_{total} (cfs)**	**$q_{fraction}$**
2/19/2002	500	10.2	2.36	666	15624	0.3398
2/19/2002	530	9.3	2.32	647	15624	0.3812
2/19/2002	560	8.7	2.24	585	15624	0.4187
2/19/2002	590	8.3	2.12	528	15624	0.4524
2/19/2002	620	8.2	2.00	492	15624	0.4839
2/19/2002	650	8.2	2.04	502	15624	0.5161
2/19/2002	680	8.2	2.07	509	15624	0.5486
2/19/2002	710	8.4	2.12	534	15624	0.5828
2/19/2002	740	8.7	2.24	585	15624	0.6203
2/19/2002	770	8.9	2.22	593	15624	0.6582
2/19/2002	800	9.0	2.24	605	15624	0.6969
2/19/2002	830	8.8	2.22	586	15624	0.7344
2/19/2002	860	9.0	2.15	580	15624	0.7716
2/19/2002	890	9.3	2.08	580	15624	0.8087
2/19/2002	920	9.5	2.15	613	15624	0.8479
2/19/2002	950	8.8	2.02	533	15624	0.8820
2/19/2002	980	8.3	1.95	486	15624	0.9131
2/19/2002	1010	7.6	1.72	523	15624	0.9466
2/19/2002	1060	5.9	1.42	419	15624	0.9734
2/19/2002	1110	4.5	1.40	315	15624	0.9936
2/19/2002	1160	3.0	1.07	100	15624	1.0000
6/7/2002	110	11.2	1.50	672	95945	0.0070
6/7/2002	150	16.8	2.78	1868	95945	0.0265
6/7/2002	190	17.3	3.51	2429	95945	0.0518
6/7/2002	230	17.5	3.78	2646	95945	0.0794

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam

Date	Distance (ft)	Depth (ft)	Velocity (ft/sec)	Discharge (cfs)	Q_{total} (cfs)	$q_{fraction}$
6/7/2002	270	18.4	4.23	3110	95945	0.1118
6/7/2002	310	19.7	4.32	2765	95945	0.1406
6/7/2002	335	20.9	4.62	2412	95945	0.1657
6/7/2002	360	23.0	4.70	2702	95945	0.1939
6/7/2002	385	24.2	4.70	2844	95945	0.2235
6/7/2002	410	24.2	4.86	2940	95945	0.2542
6/7/2002	435	25.0	4.70	2938	95945	0.2848
6/7/2002	460	24.5	5.02	3072	95945	0.3168
6/7/2002	485	23.6	5.07	2990	95945	0.3480
6/7/2002	510	23.0	4.81	3040	95945	0.3797
6/7/2002	540	22.1	4.81	3189	95945	0.4129
6/7/2002	570	21.7	5.07	3301	95945	0.4473
6/7/2002	600	21.3	5.17	3304	95945	0.4818
6/7/2002	630	21.1	4.87	3083	95945	0.5139
6/7/2002	660	21.3	4.82	3080	95945	0.5460
6/7/2002	690	21.5	4.96	3199	95945	0.5793
6/7/2002	720	21.6	4.52	2929	95945	0.6099
6/7/2002	750	21.8	4.60	3008	95945	0.6412
6/7/2002	780	22.0	4.79	3161	95945	0.6742
6/7/2002	810	22.1	4.48	2970	95945	0.7051
6/7/2002	840	21.9	4.38	2878	95945	0.7351
6/7/2002	870	22.4	4.62	3105	95945	0.7675
6/7/2002	900	22.5	4.42	2984	95945	0.7986
6/7/2002	930	22.5	4.10	2768	95945	0.8274
6/7/2002	960	21.8	3.99	2609	95945	0.8546

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam						
Date	**Distance (ft)**	**Depth (ft)**	**Velocity (ft/sec)**	**Discharge (cfs)**	**Q_{total} (cfs)**	**$q_{fraction}$**
6/7/2002	990	21.4	4.06	3475	95945	0.8908
6/7/2002	1040	19.7	3.60	3546	95945	0.9278
6/7/2002	1090	18.1	3.72	3367	95945	0.9629
6/7/2002	1140	16.4	3.64	2985	95945	0.9940
6/7/2002	1190	8.3	1.54	576	95945	1.0000
5/19/2003	140	8.7	1.46	521	41826	0.0125
5/19/2003	180	9.8	2.08	815	41826	0.0319
5/19/2003	220	10.0	2.54	1020	41826	0.0563
5/19/2003	260	10.7	2.60	1110	41826	0.0829
5/19/2003	300	11.5	2.96	1110	41826	0.1094
5/19/2003	325	12.9	2.91	937	41826	0.1318
5/19/2003	350	14.3	3.20	1150	41826	0.1593
5/19/2003	375	16.0	3.32	1330	41826	0.1911
5/19/2003	400	17.3	3.27	1410	41826	0.2248
5/19/2003	425	17.5	3.43	1500	41826	0.2607
5/19/2003	450	17.0	3.54	1500	41826	0.2965
5/19/2003	475	16.2	3.64	1470	41826	0.3317
5/19/2003	500	15.5	3.36	1430	41826	0.3659
5/19/2003	530	14.7	3.36	1480	41826	0.4013
5/19/2003	560	14.0	3.36	1410	41826	0.4350
5/19/2003	590	13.7	3.29	1350	41826	0.4672
5/19/2003	620	13.7	3.23	1330	41826	0.4990
5/19/2003	650	13.7	3.23	1330	41826	0.5308
5/19/2003	680	13.8	3.20	1320	41826	0.5624
5/19/2003	710	14.0	3.16	1330	41826	0.5942

Table C1. Velocity Measurements at the USGS Gaging Station in the Pend Oreille River Below Albeni Falls Dam

Date	Distance (ft)	Depth (ft)	Velocity (ft/sec)	Discharge (cfs)	Q_{total} (cfs)	$q_{fraction}$
5/19/2003	740	14.2	3.29	1400	41826	0.6277
5/19/2003	770	14.5	3.36	1460	41826	0.6626
5/19/2003	800	14.3	3.29	1410	41826	0.6963
5/19/2003	830	14.4	3.29	1420	41826	0.7302
5/19/2003	1110	10.0	2.46	1230	41826	0.9844
5/19/2003	1160	8.5	1.92	653	41826	1.0000
5/19/2003	860	14.5	3.21	1400	41826	0.7637
5/19/2003	890	14.8	3.25	1440	41826	0.7981
5/19/2003	920	14.9	3.02	1350	41826	0.8304
5/19/2003	950	14.5	3.13	1360	41826	0.8629
5/19/2003	980	13.7	2.77	1140	41826	0.8902
5/19/2003	1010	13.0	2.56	1330	41826	0.9220
5/19/2003	1060	11.2	2.46	1380	41826	0.9550

Appendix D

TDG Exchange (Albeni Falls Dam to Box Canyon Dam)

The TDG exchange in the Pend Oreille River from Albeni Falls Dam (RM 90.1) to Box Canyon Dam (RM 34.4) was estimated by comparing the cross-sectional average TDG levels measured on Transect T3 with the forebay TDG levels measured at Box Canyon Dam as shown in Figures D1 and D2. In order to determine the amount of off-gassing that occurred between Albeni Falls Dam and Box Canyon Dam, a time offset was applied to the total dissolved gas pressures leaving Albeni Falls Dam. This time of travel offset ranged from 1.2 to 3.5 days, depending on Pend Oreille's total river flows, and was used to synchronize responses occurring at each dam in time. TDG pressures measured at the Box Canyon forebay FMS were on average about 11 mm Hg less than the flow weighted average TDG pressures observed on Transect 3 from May 6 through June 30, 2003. In some cases, the TDG pressure at Box Canyon Dam was greater than the lagged TDG pressure on Transect 3 (Figure D1 May 24-25) because of the influence of changing water temperatures throughout this reach.

As water flowed from Albeni Falls to Box Canyon Dam temperatures increased by approximately 1°C (Figure D3). This warming caused pressures to increase, biasing the amount of off-gassing determined by comparing the TDG pressures at the upstream and downstream boundaries of this reach. Therefore the change in TDG pressures in this river reach is composed of a net loss of mass associated with degassing at the water surface and a temperature induced pressure component.

The mass concentration corresponding with the observed TDG pressure and temperature on Transect T3 and in the forebay of Box Canyon Dam were determined throughout the study period assuming atmospheric composition of gases. The mass concentration estimates were lagged in time to synchronize observations at the ends of this river reach. An average concentration reduction of approximately 0.5 mg/L which corresponds to about 25 mm Hg in total dissolved gas pressure was estimated to have occurred in route from Albeni Falls Dam to Box Canyon Dam (Figure D4). The TDG concentration reduction may be slightly greater than 0.5 mg/l because the influence of tributary inflows were lumped onto this estimate. The discharges from Box Canyon Dam were about 6 percent higher than the releases from Albeni Falls Dam during this same time period. The net change in TDG pressure between Albeni Falls Dam and Box Canyon Dam was about 11 mm Hg consisting of a 25 mm Hg loss in mass and a 14 mm Hg gain due to increased temperatures.

During the spill season of 2002 Framatome ANP DE&S, Inc. calculated off-gassing by comparing data collected from the Newport and Box Canyon monitoring stations. According to their *Total Dissolved Gas Monitoring Final Report 2002 Box Canyon Hydroelectric Project (No. 2042)* the mean reduction in TDG saturation was 3.0% or 21.5 mmHg TDG pressure. This estimate is likely on the high side because the Newport station generally overestimates the average TDG pressures in the Pend Oreille River based on the comparison of TDG levels during the 2003 spill season shown in Figure D5. (TDG saturations are shown in Figure D6.)

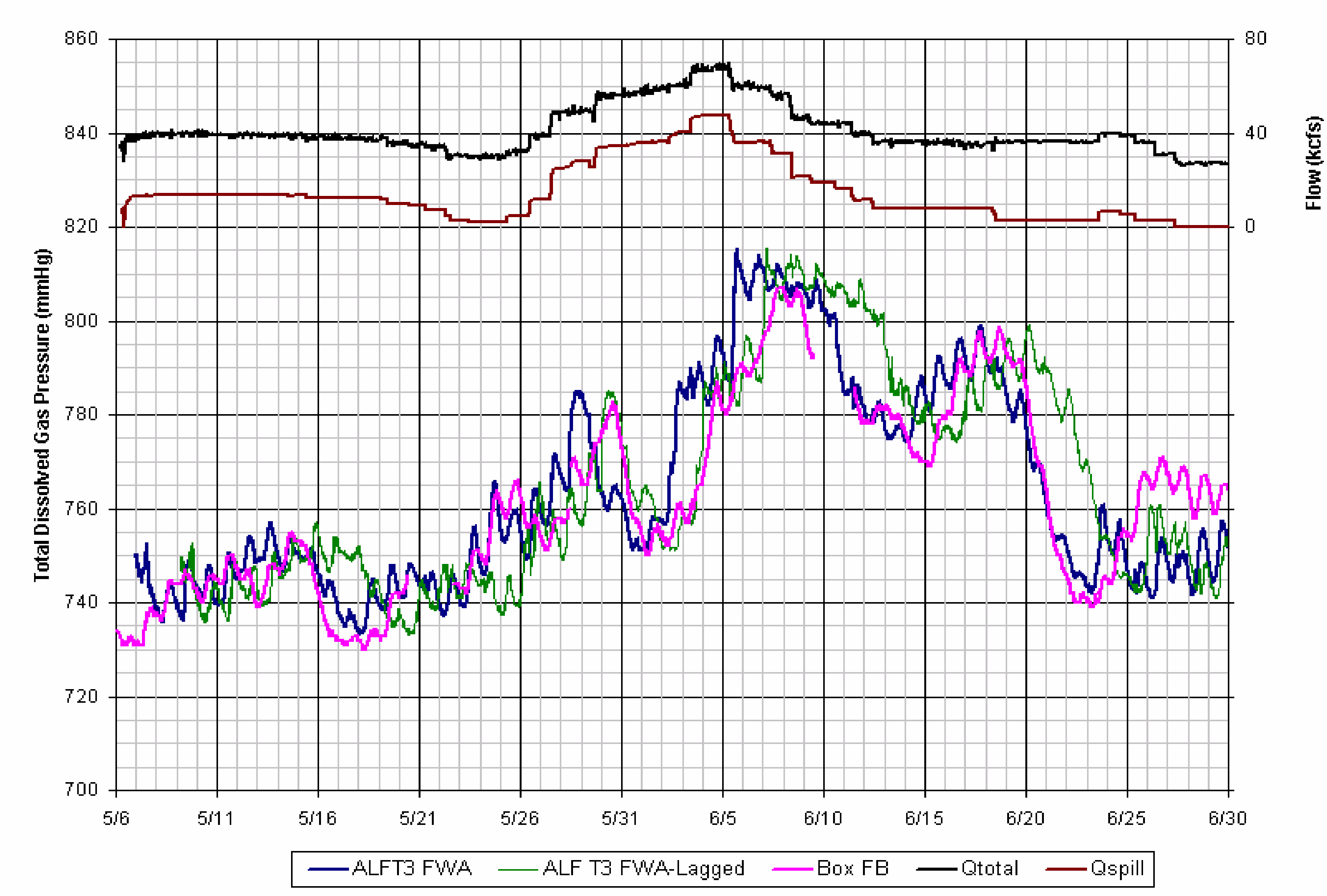

Figure D1. Total Dissolved Gas Pressures measured at Albeni Falls Dam Transect 3 and Box Canyon Forebay monitoring station

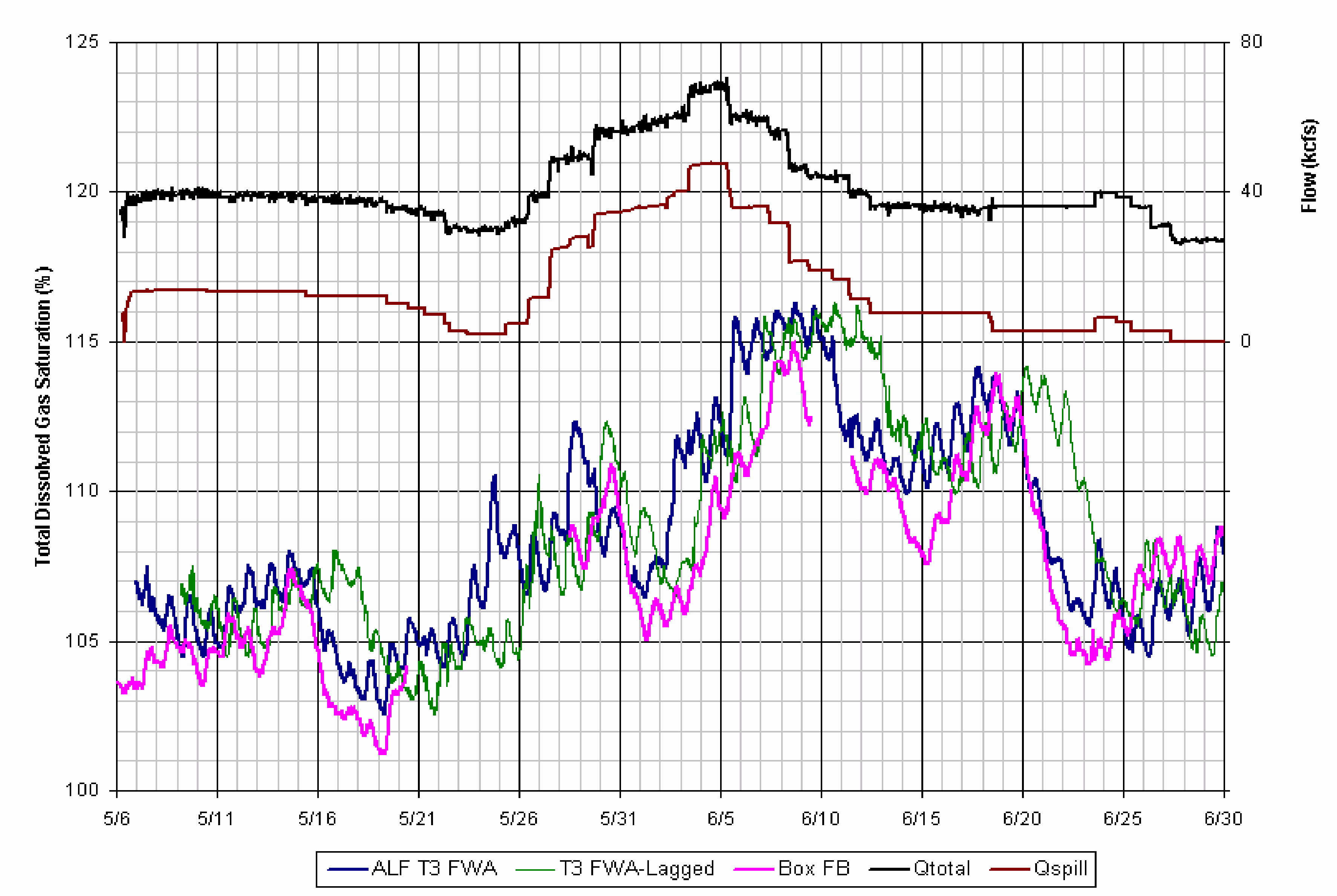

Figure D2. Total Dissolved Gas Saturations measured at Albeni Falls Dam Transect T3 and Box Canyon Forebay monitoring station

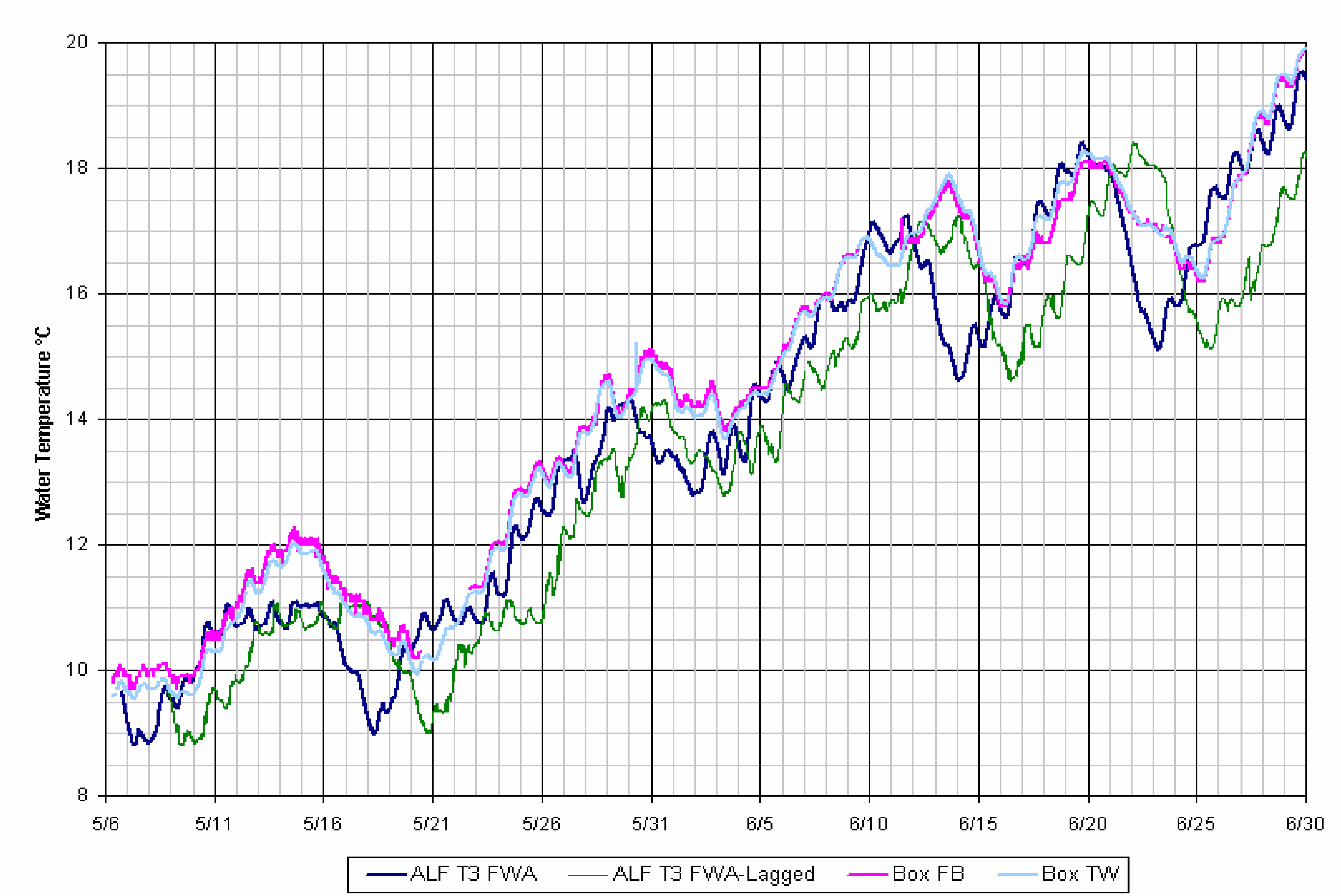

Figure D3. Temperatures measured at Albeni Falls Dam Transect T3 and Box Canyon Forebay Station

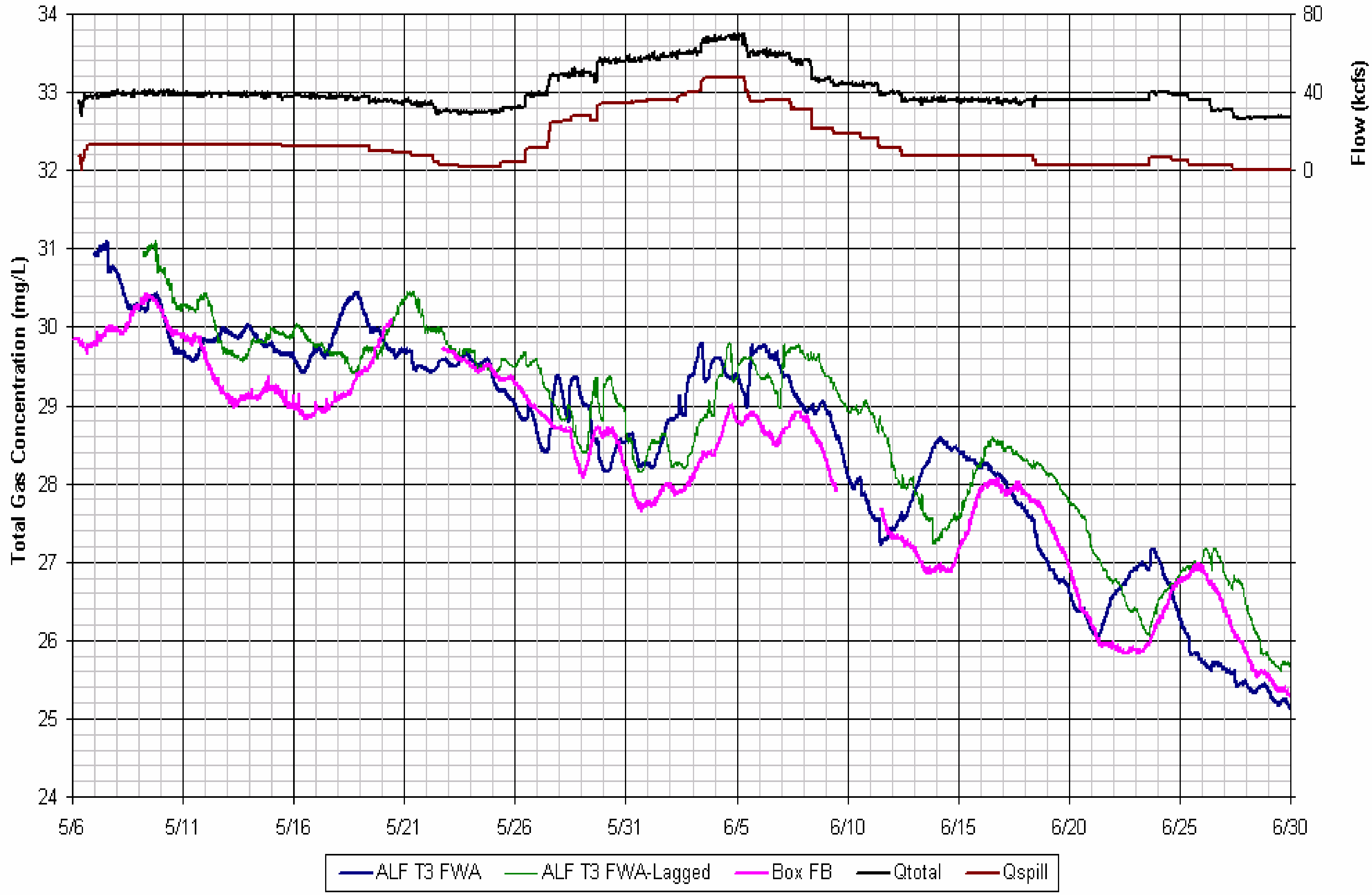

Figure D4. Gas Concentrations measured at Albeni Falls Transect T3 and Box Canyon Forebay Station

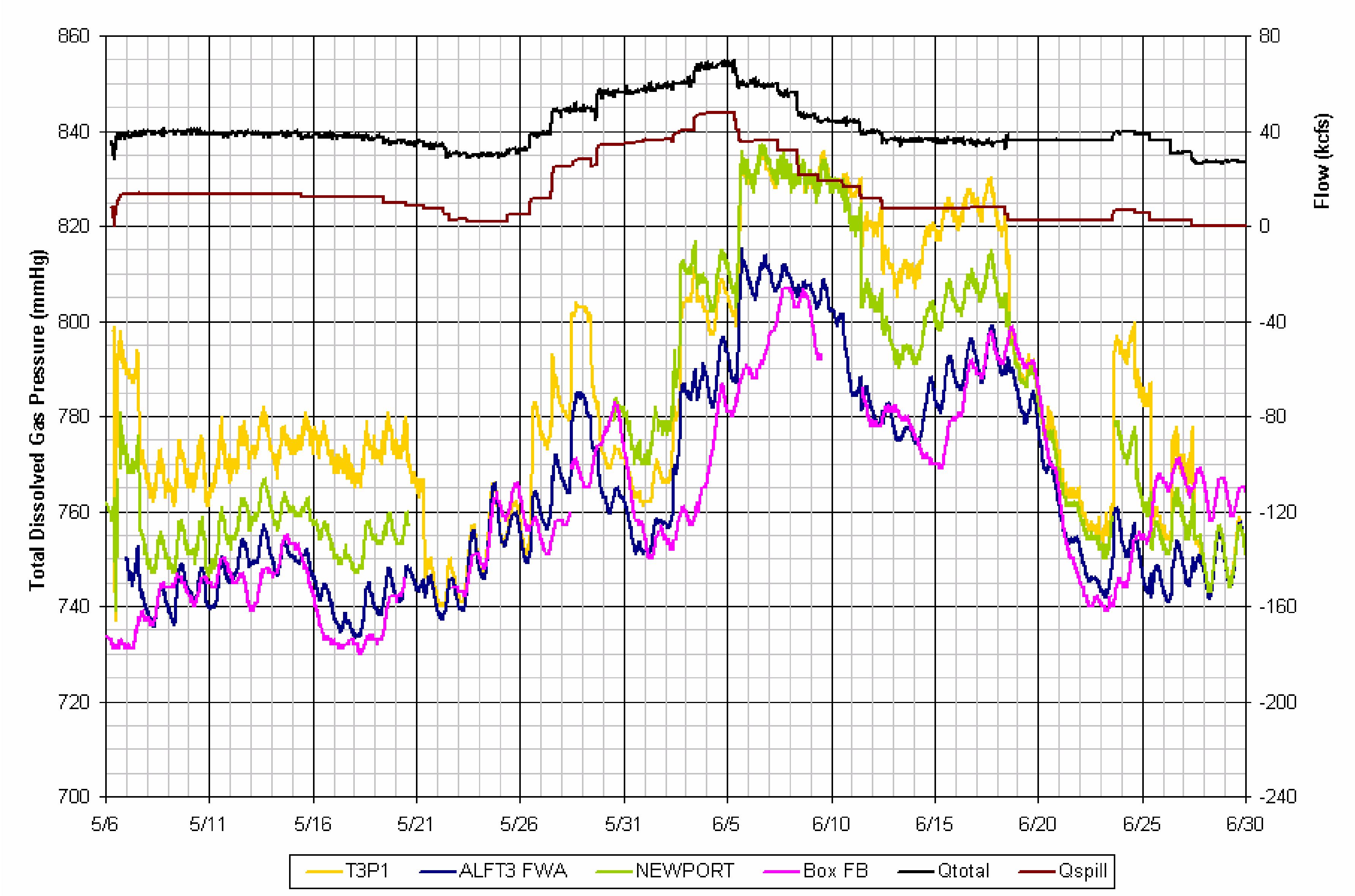

Figure D5. Total Dissolved Gas Pressures Measured at Albeni Falls Dam Transect T3, Newport, and Box Canyon Forebay Sites

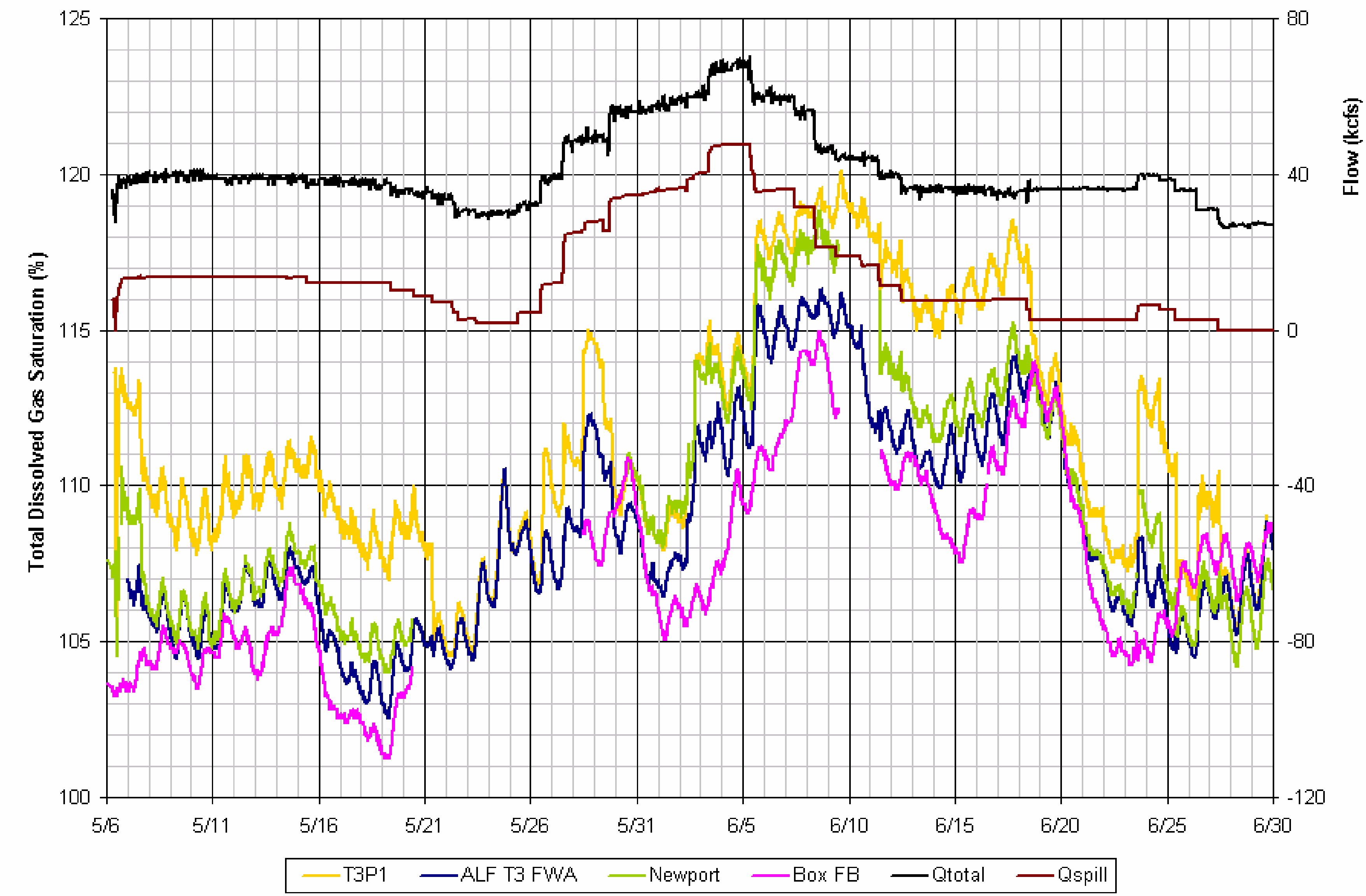

Figure D6. Total Dissolved Gas Saturations Measured at Albeni Falls Dam Transect T3, Newport, and Box Canyon Forebay Sites