# Total Dissolved Gas Exchange at Libby Dam, Montana June-July 2002



Prepared For

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# Executive Summary

A spill test was conducted at Libby Dam, Montana as part of a larger investigation of project impacts relating to the Endangered Species Act of 1973 and the Clean Water Act. The purpose of the proposed test was to determine the impacts of spill on the total dissolved gas (TDG) pressures in the Kootenai River downstream from Libby Dam. The major water quality findings from this study are listed as follows:

a. Spillway releases resulted in the elevation of TDG pressures in the Kootenai River. The TDG saturation in spillway releases increased as an exponential function of the spillway discharge. The TDG saturation in spillway releases ranged from 104 percent during a 0.7 thousand-cubic-feet-per-second (kcfs) spill to 134 percent during a 15.6 kcfs spill.

b. Strong lateral gradients in TDG saturation were present in the Kootenai River below Libby Dam during spillway releases. The maximum TDG saturation was consistently observed directly below the spillway and along the left channel bank while the lowest TDG saturations were associated with powerhouse releases along the right channel bank.

c. The existing Libby Dam tailwater water quality monitoring station for TDG pressure is located on the right bank and samples waters biased by powerhouse releases. The TDG saturation at the tailwater fixed monitoring station below Libby Dam ranged from 103-106 percent.

d. The cross-sectional average TDG saturation in the Kootenai River increased incrementally as a function of the percent of total river flow spilled. The average TDG saturation in the Kootenai River generally declined with distance below the project during prolonged periods of constant operation. The cross-sectional average TDG saturation in the Kootenai River reached a peak level of 116.9 percent during the 15.6 kcfs spill event. The average TDG saturation in the Kootenai River remained below 110 percent for spillway flows up to 4 kcfs.

e. Kootenai Falls caused a significant increase in TDG saturation of the Kootenai River throughout the study period. The TDG loading below the falls were always greater than and independent from the TDG loading produced by spillway operations at Libby Dam during the study period. The TDG saturation below the falls ranged from 116 to 121 percent throughout the study period.

f. The passage of water through the powerhouse generally does not change the TDG pressures in the Kootenai River. The TDG saturation of powerhouse releases from Libby Dam generally ranged from 102-104 percent.

g. Riverine processes influence the TDG pressures in the Kootenai River. These processes includes mixing of project releases, tributary inflow dilution, temperature induced pressure changes, biological productivity, and air-water mass exchange.

h. The TDG saturation in the Kootenai River at the US/Canadian border was not influenced by the TDG supersaturation caused by spillway operations at Libby Dam.

i. The thermal stratification in the forebay of Libby Dam influences the vertical distribution of TDG pressure. The TDG saturation in the warmer surface water of Lake Koocanusa can frequently exceed the state water quality standard for TDG of 110 percent.

j. The release water temperatures from the spillway were warmer than water temperatures released through the powerhouse throughout the study period. A lateral temperature gradient is generated in the Kootenai River below the dam, which may bias temperature observations at tailwater sampling stations and temperature management decisions.

# Preface

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The following document summarizes the impacts of spillway releases at Libby Dam during June 24-July 9 of 2002 on the total dissolved gas saturation in the Kootenai River. The document refers to several digital video clips of flow conditions and to an animation of data collected during this study. These materials can be reviewed only in the digital version of this report.

# 1 Introduction

Total dissolved gas (TDG) generated by aerated releases from dams promotes the potential for gas bubble trauma in downstream aquatic biota. Field studies conducted by the U.S. Army Engineer District, Seattle, indicated the potential for high TDG resulting from spill at Libby Dam, located on the Kootenai River at river mile (RM) 221.9 in Montana (U.S. Army Engineer District Seattle 1980). To quantify TDG exchange during spillway operations at Libby Dam, the Seattle District tasked the U.S. Army Engineer Research and Development Center (ERDC), Environmental and Coastal and Hydraulics Laboratories to conduct a comprehensive test of TDG exchange resulting from a range of spillway releases at Libby Dam.

The study described spatial and temporal dynamics in TDG near the dam and in the Kootenai River to better understand the gas exchange processes during spill releases from the project. The mixing between powerhouse and spillway releases was also investigated since this was important to the spatial distribution and total flux of TDG introduced into the downstream river. In addition, the study characterized mass transport, time of travel, mixing, and degassing of dissolved gas that occur in the Kootenai River from Libby Dam to below Kootenai Falls at RM 194, and at the U.S. – Canadian border at RM 105.9. Results from this study provided information to be used in spill management at Libby Dam and to avoid water quality problems associated with TDG and potential harmful impacts on downstream aquatic life.

# 2 Objectives

The purpose of this field study was to define and quantify processes that contributed to dissolved gas transfer during spill releases at Libby Dam. In general, the transfer of dissolved gas is a function of the unit spillway discharge, spill pattern, spillway geometry, stilling basin and tailwater depth and flow conditions, forebay TDG concentration, project head differential, and water temperature. This study focused on resolving questions regarding accurate source and sink descriptions of mass conservation of dissolved gases in the Kootenai River below the dam. TDG time-history information across the fixed-station sampling array, as related to specific project operations, was of particular interest. The data were analyzed to provide estimates of the gas transfer throughout the tailwater area and to provide an understanding of the nature of gas exchange processes within the stilling basin and in the downstream tailrace channel. The specific objectives of the field investigations were as follows:

*a.* Describe dissolved gas exchange processes (exchange, mixing, transport) in the Libby Dam tailwater for various spillway/powerhouse operational scenarios.

*b.* Describe resulting TDG pressures downstream to the Kootenai Falls reach associated with the test spillway/powerhouse operational scenarios.

*c.* Provide recommendations for future water quality (WQ) monitoring as needed.

*d.* Provide recommendations for minimizing TDG resulting from Libby Dam spillway operations.

The conclusions should help identify operational measures that may reduce TDG supersaturation in the Kootenai River in the event of a spill.

# 3 Approach

A comprehensive study of the TDG exchange resulting from spill releases at Libby Dam was conducted to describe the spatial and temporal dynamics in TDG levels in the Kootenai River.  This study required the deployment of an array of automated remote logging water quality instruments capable of sampling the complete time-histories of TDG pressures in the river/reservoir system. Water quality was monitored throughout the study. Parameters of interest included depth, water temperature, TDG pressure, dissolved oxygen concentration, and internal battery voltage of the gas sensors. These data were collected automatically at 15-min intervals during the study. Manual sampling was used where and when necessary to supplement the automated measurements.

The sampling stations were generally at a fixed position in an array intended to establish the prominent processes contributing to the TDG exchange and mixing in the Kootenai River.  TDG sampling was conducted in the forebay of Libby Dam to establish the ambient conditions prior to passage through the dam. Sampling stations were also sited just downstream of powerhouse and spillway releases in locations where the instrumentation could be safely deployed and retrieved.  These near-field sampling stations were positioned to measure the characteristics of spillway and powerhouse releases prior to mixing. Downstream water quality stations were grouped at specified river cross-sections to characterize the temporal and spatial TDG patterns in the Kootenai River.  The influence of Kootenai Falls on TDG properties in the Kootenai River was of particular interest in this study because of the highly aerated flow conditions present at this natural river feature.

Libby Dam operations were originally scheduled to be systematically varied through a series of spillway releases, once the water quality instrumentation was in place.  Spill discharge was scheduled to range from 2 to 10 kcfs[1] on a 1 kcfs interval with each spill event having a 3-hr duration.  This original spill schedule was followed during the first morning of the test on June 25 but discontinued thereafter because of flood control operations.  The flood-control operations dictated the attributes of spillway releases from Libby Dam throughout the sampling period from June 25 through July 7, 2002.  Appendix A contains the original plan of study for the Libby Dam TDG exchange investigation.

A number of safeguards were built into the original study to protect the aquatic environment in the Kootenai River.  To maintain TDG within limits designed to provide a margin of safety for aquatic organisms, real-time measurements of TDG were taken at a downstream checkpoint within 1 mile of the dam (Appendix A).  Biological monitoring of captured and captive fish was conducted throughout the study period.  Fish monitoring protocols were established to provide documentation of gas bubble disease (GBD) symptoms in these sampled fish populations. The spill study was to be terminated if any of the biological or water quality protocols were achieved.

[1] Thousand cubic feet per second

# 4 TDG 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. The atmospheric compositions of these gases are 20.95, 78.09, 0.93, and 0.03 percent, respectively. Henry's Law is an equation of state that relates the solubility of a given gas to the partial pressure. The constant of proportionality is called Henry's constant or the Bunsen coefficient. This equation relates the mass concentration of a constituent gas to the partial pressure at equilibrium. The constant of proportionality is a function of barometric pressure, temperature, and salinity. The mass concentration of dissolved gases in water can be determined from estimates of the TDG pressure, water temperature, and barometric pressure assuming atmospheric composition of gases in solution. Thus, for constant temperature and pressure conditions, the TDG can be represented as either a concentration or pressure in conservation statements.

The solubility of a gas in water is dependent on the ambient pressure of the gas, water temperature, and salinity. The total pressure experienced by entrained air bubbles in the water column is composed of barometric pressure and hydrostatic pressure. Thus, the solubility of gas in water doubles at a depth of about 33 ft in response to a doubling of the total pressure. The compensation depth is where the total pressure is equal to partial pressure of the TDG. At this depth, the saturation concentration is equal to the ambient concentration in the water. The solubility of gas in water is inversely proportional to the temperature. If the total dissolved gas concentration of 30 mg/l (907 mm Hg, 110.0 percent) is held constant in a water sample at one-atmosphere of pressure, and the temperature is raised from $20^{o}$ to $21^{o}$ C, the TDG pressure will increase by 17 mm Hg (924 mm Hg, 112.0 percent). Under these conditions, an increase in temperature of one degree will result in an increase in the TDG saturation of 2 percent.

## 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 TDG 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 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 dissolved gas pressure responses that result in changes to supersaturated conditions (Colt 1984). Biological activity involving the production or consumption of oxygen will influence the TDG 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 vortices that provide a vehicle for air entrainment. In general, the TDG concentrations are not significantly altered by near-field flow conditions in the forebay.

### 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.

### Turbine passage

There is little opportunity for entrained air to be introduced into the confined flow path through a turbine, except during turbine start-up 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 for 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.

### 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 in the spillway flow causing 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 nearly all of the powerhouse flow was entrained into spillway releases and gassed to comparable pressures.

### 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 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 maximum TDG pressures experienced below the 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. While above the compensation depth, the air bubbles strip dissolved gas from the water column. The entrained air content decreases as the flow moves downstream 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 ft of the stilling basin. The reduction of TDG pressures downstream from the aerated flow regime is 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 (USACE, 2002). 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 very different TDG pressures. The interaction of project powerhouse and spillway flows establishes a mixing zone. As discussed previously, 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 are mixed with spillway releases and effectively add to the spillway discharge from a project. As a consequence, the amount of hydropower releases available for dilution of spillway releases in the mixing zone downstream is reduced.

The development of the mixing zone below a project will influence the spatial distribution of TDG properties in the downstream pool. The understanding of mixing zone development is critical to the interpretation of observed downstream TDG pressures. In regions where the mixing between powerhouse and spillway releases is incomplete, lateral gradients in TDG pressure will be 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 operations, 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, evaporation, 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 significantly higher than tailwater water temperatures and TDG pressures influenced by these thermal differences.

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 TDG pressure at the air-water interface is driven towards equilibrium with atmospheric conditions. Where the in-pool degassing rates exceed to addition of TDG pressures at a dam, the total dissolved gas pressures will undergo a net reduction over the length of a pool.

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 dissolved oxygen (DO) concentrations. A 1 mg/l variation in DO will result in a variation of TDG pressure ranging from 12 to 17 mm Hg[2] (millimeters of Mercury) depending upon water temperature.

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[2] One millimeter of mercury (mm Hg) is equal to 0.03937 inches of mercury

# 5 Site Characterization

Libby Dam is located at river mile 221.9 on the Kootenai River in Lincoln County, Montana, about 40 miles south of the U.S. – Canadian boundary, as shown in Figure 1. The dam is approximately 11 miles east of the town of Libby, MT (RM 204) and approximately 222 river miles upstream from the confluence of the Kootenai River (Canadian spelling is Kootenay) with the Columbia River in British Columbia. Behind Libby Dam, Lake Koocanusa is 90 miles long at full pool (48 miles within the U.S.), extends north into the Canadian province of British Columbia, and has a storage capacity of almost 5 million acre-ft. Full pool elevation of Lake Koocanusa is 2,459 ft[3].

The dam is a straight concrete gravity gate-controlled dam, 370 ft high (from the streambed) and 2,887 ft long at the dam crest as shown in Figure 2. Construction of the project was initiated in 1966. The dam became operational for flood control in 1972. The powerhouse was designed to hold eight hydroelectric generating units. However, only five Francis-type turbines, each with a capacity of 120 MW, have been installed. The first unit came on line in 1975. Generating unit No. 5 went on line in 1984. The remaining three turbines have not been installed. Libby Dam is authorized for flood control, hydroelectric power, and other purposes, including recreation.

The system flood-control objective of Libby Dam is to provide up to 4.98 million acre-ft of water storage to help control floods on the lower Columbia River below Bonneville Dam. The local flood-control objective of Libby Dam is to protect the Bonners Ferry area from river stages in excess of el 1,764. During flood season, the Water Management Division operates Libby Dam to minimize downstream flood impacts.

A water temperature management structure or selective withdrawal system allows dam operations to select water from various lake levels, thus providing accurate control over release water temperatures. This water management system is used to benefit the downstream fishery during the summer months when thermal stratification is evident in Lake Koocanusa. During the summer, the river temperature is usually maintained between 52 and 56 deg Fahrenheit, according to criteria developed for local trout. The selective withdrawal system consists of 14 slots, each with 21 gates or bulkheads. Adding or removing the bulkheads that control the movement of water to each of the five active penstocks maintains temperature control. The profile view of structural details of the penstock and controlling gates are shown in Figure 3.

The two spillway bays and three sluiceways allow the dam to release water from the reservoir without passing it through the generators. The spillway releases water from the upper levels of the reservoir by raising a 48-ft-wide by 59-ft-high tainter gate above the crest of the spillway located at el 2,405 as shown in Figure 3. The face of the spillway attains an angle of 54 deg from the vertical and is initially separated by a center pier as shown in Figure 4. The

[3] All elevations cited herein are in feet and reference to the NGVD Datum. To convert to meters, multiply number of feet by 0.3048 meters.

invert elevation of the sluiceway inlet is at el 2,201. Each sluiceway conduit is 10 ft wide and 22 ft high and exits near the base of the spillway at el 2,142.

The conventionally designed stilling basin has a length of about 250 ft from the toe of the spillway to the end sill and a width of 116 ft and is shown in Figure 5. The stilling basin invert elevation is 2,073 resulting in an average depth of flow ranging from 51.5 to 54.5 ft for typical flow conditions. Training walls bound the stilling basin on both sides. A 12-ft-high sloped end sill defines the end of the stilling basin. The adjoining tailwater channel is armored by rock, defining a trapezoidal section near the exit from the stilling basin, as shown in Figure 6. This protected channel bed extends 150 ft below the stilling basin and ties into the natural channel bed at an elevation of 2,100 ft.

The use of the spillway or sluiceways has been limited since the mid-1980s due to concerns about creating damaging levels of TDG supersaturation downstream of Libby Dam in the Kootenai River.

The Kootenai River follows a free-flowing course downstream of Libby Dam, dropping an average of 5 ft per mile. The Kootenai River becomes shallow below the dam, approaching a thalweg depth of about 23 ft near the David Thompson Bridge (powerhouse access road). The river reach between Libby Dam and Kootenai Falls is characterized by a series of riffles and pools, as shown in Figures 7 and 8. West of Libby, MT (RM 204), the river passes over Kootenai Falls (RM 193) shown in Figure 9. The 200-ft-high series of stepped falls act as a natural fish migration barrier and influences river water quality characteristics.

The Kootenai River Canyon continues downstream from Kootenai Falls (RM 193) to about RM 161, at the river's confluence with the Moyie River, upstream of the town of Bonners Ferry, ID (RM 153). From the lower end of the canyon to the town of Bonners Ferry, the floodplain widens and consists of a braided meandering channel with typical depths less than 30 ft. At Bonners Ferry, the river gradient flattens and meanders north in a sinuous pattern through a narrow, flat floodplain bounded by mountains, crossing the Canadian border (Figure 10), and forming a delta as it enters Kootenay Lake at Creston, British Columbia. The Kootenai River floodplain downstream of Bonners Ferry, commonly known as Kootenai Flats, is farmed and the river is confined by nearly continuous levees, which extend beyond the Canadian border. The river is deep and slow moving in this reach, with very little gradient, and its water-surface elevation is directly affected by the elevation of Kootenay Lake, which can back up as far as Bonners Ferry.

# 6 Study Design

An array of 31 TDG instruments was deployed in the Kootenai River to measure the TDG pressures from Libby Dam to the Canadian border. The data collected by the water quality instrumentation during the study included the date, time, instrument depth, water temperature, TDG pressure, dissolved oxygen concentration (selected stations), and internal battery voltage. The quality control and assurance measures for water quality data are described in Appendix B. The general location of sampling transects are shown in Figure 11 and a description of these station locations is listed in Table 1. The general philosophy behind the sampling array was to determine the magnitude and variation of TDG saturation in the Kootenai River caused by Libby Dam operations.

Water quality data were collected above and below Libby Dam from June 23 through July 9 at 15-min intervals. Manual sampling was used where and when necessary to supplement the automated approach. In addition, barometric pressure and air temperature were monitored near the Libby project at a similar interval to allow the calculation of TDG percent saturation. A record of Libby Dam operating conditions critical to the evaluation of study results including forebay water-surface elevation, tailwater elevation, powerhouse discharge, and spillway discharge was maintained throughout the study period.

A TDG instrument was deployed from the floating log boom in the forebay (FB) of Libby Dam at a depth of about 10 ft. The depth of this instrument was fixed but the elevation changed as the forebay elevation fluctuated during the study. A manual profile of TDG pressure was also taken during June 25. The sampling location of this forebay station is shown in Figure 12.

Four sampling stations were located immediately below Libby Dam. A station was deployed from the draft tube deck (DTD) directly into releases from Turbine 4. This instrument was located at the end of a cable and was free to move with the transient current at this location. Two instruments were located about 250 ft downstream from the stilling basin end sill as shown in Figure 12. The station labeled SPWP2 was aligned with the left training wall bounding the stilling basin (downstream reference) while the station SPWP1 was positioned between station SPWP2 and the left bank. The fourth temporary sampling station (SB) was located in the stilling basin along the right training wall about 150 ft downstream from the face of the spillway. The instrument in the stilling basin was removed after the first spill event because of the high velocities and frequent exposure of the instrument to atmospheric conditions.

A total of four instruments were deployed at the Thompson Bridge sampling transect located at RM 221.4, about 0.4 mile below the dam as shown in Figure 12. The sampling station (TMPSNP1) was added during the first day of spill near the left bank to capture the higher TDG pressures associated with spillway releases. The remaining three stations were located at quarter points across the river. The instrument at station TMPSNP3 malfunctioned and no data were obtained from this mid-river station.

Five instruments were deployed in the Kootenai River at the Libby Dam tailwater U.S. Geological Survey gaging station (USGSP1-P5) located at RM 221.3, about 0.6 miles below the dam as shown in Figure 13. The sampling stations were skewed toward the left bank to capture the development of the mixing zone between the spillway and powerhouse flows. The tailwater fixed monitoring station (LIBM) was located near the right bank on this transect.

The real-time TDG instrument (RTM2), used for the TDG compliance determination for the study, was originally sited about 40 ft from the right channel bank at Alexander Creek campground about 1.4 miles downstream of the dam. This station was repositioned (RTM1) to the left channel bank on June 26 as shown in Figure 14 to capture the higher TDG pressures associated with spillway releases. Station RTM1 was found to replicate information upstream on station USGSP1 and was removed from service on June 27.

Several auxiliary TDG instruments were located near the fish pens used for biological assessment of study impacts. These stations were labeled as MFW1, MFW2, and MFW3 and were located near the left channel bank at RM 221.1, 220.7, and 220.2, respectively, as shown in Figure 14. These instruments were generally positioned at depths ranging from 0.5 to 2 m, but were not deployed throughout the entire study period. The sampling station at MFW1 was active only during the daylight hours on June 25 and was removed because it was redundant with nearby sampling stations. The records from station MFW2 were available throughout the study period with the exception of an 18-hr window during June 25-26. Station MFW3 was deployed on June 28 and retrieved on July 9.

The remaining sampling stations were located more than 1 mile downstream of the project to measure the TDG pressures in the Kootenai River under open-channel flow conditions. Three instruments were located at the Highway 37 Bridge (FISHERP1-3) at RM 218.4, about 3.5 miles below the dam. This sampling transect was located just above the confluence of Fisher River with the Kootenai River. The instrument located at the center station (FISHERP2) malfunctioned and no data were collected. The constriction of the Kootenai River at an old haul bridge at RM 213.3 was also chosen as a sampling location. The two sampling stations were located adjacent to the left and right channel bank (HAULP1 and HAULP5).

Three sampling transects UPLIBBY, DSLIBBY, and USFALLS were located at RM 206.8, 200.1, and 195.5, respectively, as shown in Figure 11. Each of these transects consisted of a left and right bank sampling station. Station names along the left channel bank of the Kootenai River were identified with the two-letter identifier P1 and right bank stations were labeled P5. A single sampling station (DSFALLS) was located downstream of Kootenai Falls near the left bank downstream of the cascading aerated flow in the falls reach. The Kootenai Falls consists of several narrow chutes and plunge pools generating highly aerated flow conditions as shown in Figure 9. Additional manual sampling was conducted in the region around the sampling station below the falls (DSFALLS). The instrument located at the right bank station DSLIBBYP5 malfunctioned and no data were collected.

Two additional sampling stations (TROY and Porthill) were located near Troy, MT at RM 186.2 or about 35.7 miles below the dam, and at Porthill, ID at

RM 105.9 or about 116 miles below the dam. These stations were sited on the right bank to compliment the sampling of TDG conditions below the Kootenai Falls.

Additional measurements of water temperature were collected in the forebay of Libby Dam, in the Fisher River, and in Libby Creek. A string of eight thermistors were deployed from the log boom upstream of Libby Dam at depths of 1.6, 4.9, 9.8, 16.4, 32.8, 65.6, 98.4, and 196.9 ft. These sensors were maintained at a constant depth and moved relative to the forebay pool elevation. A single thermistor was deployed near the right bank of the Fisher River and in Libby Creek several hundred feet upstream of the confluence with the Kootenai River.

Dissolved oxygen concentrations were collected at selected stations throughout the sampling array. The stations with dissolved oxygen data are as follows: FB, DTD, SPWP1, SPWP2, USGSP1-P5, USFALLSP1, DSFALLSP1, RTM2, and Porthill.

# 7 Project Operation

In the original study design, spillway flows at Libby Dam were to be increased from 2 kcfs up to a maximum of 10 kcfs in 1 kcfs increments. Each flow would be maintained for a 3-hr duration over a 3-day testing period (June 25-27). The water quality instruments were deployed on June 23 and the spill test began on June 25, as scheduled. However, high project inflows coupled with limited lake storage resulted in forced spill conditions superceding the scheduled test spill conditions. The forced spill conditions began on June 25 and lasted 13 days until July 7. With the exception of the first day, the powerhouse releases remained nearly constant at full capacity ranging from 24.4 to 25 kcfs.

The forebay surface elevation ranged from 2,450 to 2,457.3 as shown in Figure 15. The total project head ranged from 325 to 331 ft during the study period. The tailwater elevation varied with total project discharge and ranged only about 3 ft from el 2,124.5 to el 2,127.4 ft. resulting in a stilling basin depth of from 51.5 to 54.4 ft (stilling basin invert el 2,073. ft) as shown in Figure 16.

The spillway discharge ranged from 0.7 kcfs to 15.6 kcfs during the rise and fall of the flood hydrograph as shown in Figure 17. The percent of river spilled ranged from 3 percent to 39 percent. The spillway was shut down for about an hour on June 28 to accommodate the removal of structural monitoring equipment on the spillway tainter gates. Both spillway gates were opened to equal settings throughout the study period. Spill discharges were determined by calculating the difference between powerhouse flows and the total discharge determined at the USGS tailwater gage since there was some uncertainty associated with the spillway rating curve.

The forced spill conditions resulted in a wider range of spill events with a longer duration than scheduled in the original study plan. Spillway flows less than 4 kcfs were limited because of the volume of forced spill required for pool storage management. The study period was therefore, subdivided into a series of events where a constant spill flow having a 1 hr or longer duration was achieved. Steady spillway operation for at least 1 hr was required for steady conditions to develop at sampling stations within 1-mile of the dam. A total of 23 spill events were identified using this criterion, as listed in Table 2 and shown in Figure 17. The shortest events lasted only 1.75 hrs. The longest event of 43.75 hrs, occurred during July 1-3. The TDG exchange immediately below Libby Dam was determined for each event and the TDG response evaluated as a function of project operations.

# 8 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 June 25-27. The following observations pertain to several notable characteristics of those flow conditions.

Turbulent aerated flow developed on the spillway face at Libby Dam due to the roughness of the gate lip and the turbulent boundary layer of the flow on the spillway face. The flow conditions on the spillway face, stilling basin, and adjoining tailrace channel on June 26 are shown in Figure 18. The flow remained highly aerated during passage down the spillway face.

The aerated flow plunged into 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 highly turbulent aerated flow condition extended throughout the stilling basin for most of the flow conditions observed. The stilling basin flow conditions for a 3-kcfs spill are shown in Figure 19. The most of the air entrained in this flow was gone as water exited the stilling basin. Surface foam provided a means to visualize the movement of spillway flow into the downstream channel. A small portion of spill water was drawn toward the powerhouse past the end of the right training wall (Figure 20).

The aerated spill water exiting the stilling basin quickly encountered water exiting the powerhouse. The dynamic interaction showing the transport of powerhouse and spillway releases in the tailwater channel are shown in the video clip accessed in Figure 20 for a spillway flow of 3 kcfs. The powerhouse flow quickly forced the spillway flows against the left bank as the flow moved downstream past Thompson Bridge. Several areas of recirculation were apparent as shown in the video clip. The eddy below the dam on the left bank was bounded by spillway releases and likely contained TDG pressures undiluted from powerhouse flows.

The flow conditions below the powerhouse were characterized by a series of boils associated with flow exiting the draft tubes of the five active turbines. The surface flow conditions below the powerhouse are shown in Figure 21. The entrainment of air into powerhouse flows was minimal in this region of the exit channel.

The channel properties downstream of the Thompson Bridge are responsible for establishing the lateral flow and velocity distribution in the Kootenai River below Libby Dam. The video of developing flow conditions, observed from the hillside below the dam, provides an alternative view of these flow conditions, as accessed through Figure 22.

## Libby Dam Forebay and Powerhouse Flows

### Water temperature

The forebay of Libby Dam remained thermally stratified throughout the study period. Forebay temperature profiles from June 24 through July 8 at 1400 hours on 2-day intervals are shown in Figure 23. The surface temperature in Lake Koocanusa varied widely, ranging from 19.4$^{o}$ C[4] on June 26 to only 11.2$^{o}$ C on June 30. The surface layers experienced a general cooling trend from June 24-July 1 followed by increasing temperatures after July 1. The water temperatures at the elevation of the spillway crest (el 2,405) ranged from 10-12$^{o}$ C, which corresponded closely with the release water temperatures. A nearly linear change in water temperatures was observed below a depth of 65 ft exhibiting a slope of 1.0 to 1.4$^{o}$ C per 32.8 ft of change in elevation. Water temperatures in the reservoir varied from a minimum of 5$^{o}$ C at a depth of 197 ft, to over 22$^{o}$ C near the water surface.

The adjustment of the selective withdrawal gates regulating powerhouse releases, together with changes in the vertical thermal structure and rising forebay elevation, caused significant variability over the study period in the water temperatures released from Libby Dam. The rising forebay elevation changed the submergence of the spillway crest and selective withdrawal inlet elevation relative to the in-pool vertical thermal structure. The near surface water temperatures in the forebay (FB), and corresponding temperatures below the powerhouse draft tube deck (DTD) and spillway (SPWP1) are shown in Figure 24. The water temperatures below the dam remained similar at both sampling stations during non-spill periods. The initiation of spillway flows resulted in an abrupt 2$^{o}$ C increase in water temperature below the spillway, reflecting the higher release point associated with flow over the spillway crest. The temperature differences between powerhouse and spillway releases decreased during the study as the selective withdrawal gates were adjusted to pull powerhouse water from shallower depths in the forebay for the purpose of releasing target water temperatures.

As discussed in this section, the geographic region experienced a general cooling trend during the first half of the study followed by a warming trend during the second half of the study. The effects of these meteorologic conditions were reflected in the time-history of water temperatures in the forebay of Libby Dam (Figure 25). The surface waters undergo a wide range of temperatures during the study period in contrast to the water temperature below a depth of 98 ft (30 m). The water temperatures between 65.6 ft (20 m) and 98 ft (30 m) most closely track the observed temperatures below the powerhouse at Libby Dam. The water temperatures at 1.6 ft (0.5 m) depth were as much as 8$^{o}$ C warmer than observed in the forebay at a 9.0 ft depth (TDG station labeled FB in Figure 25). These thermal properties are important in characterizing the TDG pressures observed in the forebay.

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[4] Convert degrees Celsius ($^{o}$C) to degrees Fahrenheit ($^{o}$F) using the following equation: $^{o}$F = 9/5 $^{o}$C+32

### Total dissolved gas

The TDG levels reported herein are express as pressure in mm of mercury or as TDG saturation. TDG saturation was determined by dividing the TDG pressure by the barometric 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 and near the US - Canadian border or at larger distances from the dam. However, during this study, the variation in barometric pressure was small, ranging from about 700 to 710 mm of mercury, with no indication of a strong weather front passage through the study area.

The TDG pressure in Lake Koocanusa just upstream of Libby Dam was recorded at a station labeled (FB) at a depth of 9.0 ft on a 15-min interval at the log boom throughout the study period. In addition to these data, a manual vertical profile was collected from the face of the dam between the powerhouse and spillway on June 25 at 1000 hours. A water quality instrument was lowered to a depth of 117 ft and allowed to equilibrate to the TDG pressure. The instrument was then raised from 7 to 10 feet and held in place for one to three minutes before being raised to the next elevation. The TDG pressure and depth were logged on a 1-min interval during this vertical manual sample. The TDG pressure was also monitored in the turbine discharge below the powerhouse from an instrument deployed from the turbine deck at station DTD.

The TDG saturation at the forebay station (FB) was consistently higher than observed below the powerhouse at station DTD. A statistical summary of TDG saturation at all sampling stations during active spill from Libby Dam from June 25 to July 7 is listed in Table 3. The average TDG saturation at station FB was 106.2 percent, as compared to 102.7 percent below the powerhouse at station DTD. The time-history of TDG pressures in the forebay and below the powerhouse are shown in Figure 26 along with the barometric pressure recorded in the office complex near the powerhouse. The TDG pressure in the forebay responded to general thermal patterns with warmer temperatures resulting in higher TDG pressures. The TDG saturation at station FB exceeded 110 percent for an extended period from July 6-9, as shown in Figure 27.

The frequency analysis for the TDG saturation listed in Table 3 summarizes observations at levels starting at 105 percent through 135 percent on a 5 percent interval. The state of Montana and federal water quality standard for TDG saturation is 110 percent. The TDG saturation numeric criteria of 115, 120, and 125 percent is used by the states of Washington and Oregon to define acceptable conditions for spill used for fish passage purposes on the Columbia and Snake Rivers (12 hr average of 115 percent at dam forebay, 12 hr average of 120 percent in tailwater of dam, 1-2 hr average of 125 percent). The TDG saturation at the forebay station (FB) exceeded 110 percent about 9.1 percent of the time when Libby was spilling during the study period. It is likely that the TDG saturation in the waters above 10 ft attained TDG saturations even higher than observed at station FB. The rising water temperatures cause a reduction in the saturation concentration of atmospheric gases in water. The thermal stratification inhibits vertical mixing because of the density differences caused by the temperature variation. Without contact with the atmosphere for gas exchange, the heated subsurface waters are driven to higher pressures and higher levels of supersaturation.

The manual TDG forebay profile conducted on June 25 at 1000 hours, found the TDG pressure at a depth of 117 ft was 724 mm of mercury. The corresponding TDG pressure measured below the powerhouse during this time period was 729 mm of mercury, only 5 mm higher than observed at depth in the forebay. These data support the hypothesis that water passing through the powerhouse generally retains TDG pressures established in the forebay. The TDG pressures measured above a depth of 117 ft were sampled for a limited time, generally from 1 to 2.5 mins. This sample time period proved to be too short in most cases for equilibrium conditions to be reached at these depths. A qualitative interpretation of the manual vertical TDG distribution consists of nearly uniform TDG conditions below el 2,405, with rising TDG pressures associated with waters having warmer temperatures. This qualitative assessment of the vertical TDG profile was based upon the rate of change of the TDG saturation at each elevation and the equilibrated TDG saturation observations at nearby monitoring stations (DTD and FB).

The TDG pressure below the powerhouse remained nearly constant during the study with a mean pressure of 728 mm of mercury. The corresponding TDG saturation at the forebay (FB) and below the powerhouse (DTD) is shown in Figure 27. The TDG saturation in powerhouse releases generally ranged from 102 to 105 percent saturation during the study period. The general trend towards higher TDG saturation in powerhouse releases as the study progressed, is likely attributed to the warming of the forebay.

In two instances on June 28, and July 7-8, the TDG saturation below the powerhouse (DTD) experienced an abrupt increase of 20-40 mm of mercury. A change in project operations involving the cessation of spill or change in powerhouse operation accompanied these events. Different explanations could account for these TDG patterns. The periodic abrupt increase in TDG saturation below the powerhouse could be related to the aspiration of air into operating turbines. A change in the selective withdrawal system could pull warmer surface waters containing higher TDG pressures. The transport of spilled water containing higher TDG pressures could be drawn into the area below the powerhouse.

### Dissolved oxygen

Direct measurements of dissolved oxygen concentrations were maintained throughout the study period at selected sampling stations. Oxygen represents a prominent component of atmospheric gasses making up the TDG pressures in the Kootenai River. This independent measure of oxygen concentration provides another means of quantifying the impacts of spillway releases on water quality conditions in the Kootenai River and subsequent fate of DO as these waters are transported downstream.

The dissolved oxygen concentration in powerhouse releases (DTD) remained relatively constant throughout the study period ranging from 9.6 to 10.2 mg/l, as shown in Figure 28. The dissolved oxygen saturation concentration at station DTD was determined from water temperature using the formulation presented in Colt (1984) is labeled DTD-DOsat in Figure 28. The observed DO concentrations in project releases (DTD) were consistently less than the saturation concentration (DTD-DOsat) throughout the study period indicating project releases were subsaturated for oxygen and supersaturated in terms of TDG pressure. The DO percent saturation at station DTD ranged from 90 to 102 percent while the TDG percent saturation ranged from 102 to 110 percent, as shown in Figure 29.

The DO conditions in the forebay surface water (FB) were much more dynamic than observed in project releases. The reservoir surface waters DO dynamics involve both air/water exchange and chemical/biological exchange processes. The DO concentrations at the forebay station (FB) were similar to conditions in powerhouse releases (DTD) but exhibited a larger variance ranging from 9.3 to 10.5 mg/l, as shown in Figure 28. The DO percent saturation ranged from 90 percent to 117 percent, while the TDG percent saturation ranged from 102.5 to 115 percent, as shown in Figure 30.

## Spillway Flow

### Water temperature

The water temperatures associated with spillway flows changed gradually throughout the study period and were distinctive from the water temperature of powerhouse flows, as shown in Figure 24. The water temperature of spillway flows ranged from 9.6$^{o}$ C to 12$^{o}$ C on July 7, the final day of the spill. This small variation in water temperature influenced the rate and total mass of dissolved gasses exchanged during spillway releases. However, the small variation in water temperatures did not have an identifiable influence on the TDG pressures observed in spillway flows.

### Total dissolved gas

The TDG saturation in spillway flows, as measured downstream of the stilling basin at station SPWP1 and SPWP2, were significantly greater than conditions observed in the forebay and below the powerhouse. Station SPWP2 was located near the center of the spillway flow downstream from the left training wall, while station SPWP1 was located closer to the left bank near the peripheral of the spill discharge. These stations were located in an area of the tailwater channel with minimal impact by dilution from powerhouse releases.

The first day of spill on June 25, with discharges ranging from 0.7 to 6 kcfs, resulted in an increase in TDG pressure from 102 percent to 130 percent below the spillway as shown in Figure 31 and with an expanded time scale in Figures 32-34. The TDG saturation at station SPWP2 was generally about 1-2 percent higher than levels measured at station SPWP1 for spill discharge greater than 5 kcfs. A larger difference in TDG saturation at station SPWP1 and SPWP2 were observed for spill less than 5 kcfs. A statistical summary of the TDG saturation for each spill event for stations SPWP1 and SPWP2 is listed in Tables 4 and 5, respectively. The highest TDG saturation of 134.2 percent occurred for event 16 during a spill discharge of 13.6 kcfs at station SPWP2. The variation in the TDG saturation was less than 1 percent saturation at stations SPWP1-2 for spill discharges greater than 10 kcfs.

The TDG saturation remained high throughout the study period directly below the spillway. The TDG saturation exceeded 130 percent at stations SPWP1 and SPWP2 about 78.4 percent and 87.9 percent of the time as listed in Table 3. The TDG saturation exceeded 120 percent at both stations more than 98 percent of the time during spill from Libby Dam.

The TDG exchange response to increasing spillway discharge at Libby Dam was 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 high head at both projects caused the rapid change in TDG saturation associated with spillway discharges up to 4.0 kcfs/bay. 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 TDG extreme below the spillway at Libby Dam was unexpected, given the stilling basin depth at Chief Joseph Dam was 39 ft compared to 53 ft at Libby Dam.

At Chief Joseph Dam, the unit spillway discharge was an important causal parameter in determining the TDG exchange in spillway flows. For this study, both spill bays were operated identically resulting in total spillway discharge and unit or specific spillway discharge being identical measures of spillway operation. Thus, to determine the relationship between spillway discharge and TDG pressure, the delta pressure (ΔP) defined as the difference between TDG pressure and barometric pressure was regressed against total spillway discharge in kcfs.

The ΔP pressure was averaged over stations SPWP1 and SPWP2 and an exponential curve was fit through these data as a function of the total spillway discharge, as shown in Figure 35. The form of the regression equation used in this relationship is shown in Equation 1.

$$\Delta P = c_1(1 - e^{-c_2 Q_{sp}}) \quad (1)$$

where $c_1$ and $c_2$ are regression coefficients and $Q_{sp}$ is the total spillway flow in kcfs. The average TDG pressure at the sampling station in the stilling basin (SB) was used only for conditions associated with the first event when the total spill discharge was 700 cfs. The data from event 23 was not included in this evaluation because of conflicting operations records.

For spillway flows up to 4.0 kcfs, ΔP increases rapidly with discharge. For discharges greater than 4.0 kcfs, the ΔP increased gradually approaching a maximum ΔP equal to the coefficient $c_1$. A nonlinear least-squared regression was used to estimate the coefficients in Equation 1,giving $c_1$ = 231.75 mm mercury and $c_2$ = 0.4436 per kcfs. The r-squared coefficient for Equation 1 was 0.96, with an average residual of –0.8 mm of mercury and a standard error of 8.97 mm of mercury.

Two additional data points labeled as unqualified events (purple symbols) were added to Figure 35. These data were from events of low spillway discharge with a duration of less than 1 hr. It is not known whether steady-state conditions were achieved at the tailwater channel sampling stations because these events were of such short duration. The data from the unqualified events were not used in any of the regression analyses presented in this report. However, the available data from these unqualified events were consistent with the exponential response equation generated from the longer duration events. TDG saturation as a function of total spillway discharge is shown in Figure 36.

An alternative relationship between the ΔP and spill discharge squared was also evaluated using Equation 2. The square of the discharge represents the momentum of the release. Equation 2 only slightly improved the match between the curve and the ΔP response data compared to Equation 1. The upper limit for TDG exchange is still a constant equal to the value of coefficient $c_1$.

$$\Delta P = c_1(1 - e^{-c_2 Q_{sp}^2}) \quad (2)$$

A nonlinear least-squared regression gave $c_1$ = 226.08 mm of mercury and $c_2$ = 0.1517 per (kcfs)$^2$. The observed data are shown with the estimated TDG pressure and saturation using Equation 2 in Figures 37 and 38, respectively. The r-squared coefficient for the nonlinear least-squared equation was 0.97, with an average residual of - 0.8 mm of mercury and a standard error of 7.82 mm of mercury.

A third formulation builds on the previous two equations by adding the depth of the stilling basin as a multiplier of the exponential function of spill discharge squared as shown in Equation 3. The stilling basin depth is represented as the difference between the tailwater elevation (TWE) and invert elevation of the stilling basin (2,073 ft). The magnitude of the upper TDG pressure limit will be a function of the depth of flow in the stilling basin with deeper flow conditions resulting in a greater TDG exchange. The tailwater elevation is highly correlated to total river flow with the greatest TDG exchange for a given spill discharge associated with capacity powerhouse generation.

$$\Delta P = c_1(TWE - 2073)(1 - e^{-c_2 Q_{sp}^2}) \quad (3)$$

A nonlinear least-squared regression was used to estimate the coefficients $c_1$ and $c_2$ in Equation 3 as 4.224 mm mercury per ft and 0.1674 per (kcfs)$^2$, respectively. The observed data are shown with the estimated TDG pressure and saturation using Equation 3 in Figures 39 and 40, assuming capacity powerhouse generation. The r-squared coefficient for the nonlinear least-squared equation was 0.98, the average residual was – 0.6 mm of mercury, and the standard error was 5.99 mm of mercury. Again, Equation 3 represents a modest improvement over the previous two equations. This formulation results in an increase in total pressure of 4.2 mm of mercury for every 1-ft rise in tailwater elevation during large spill flows.

### Dissolved oxygen

The dissolved oxygen concentrations in spillway releases (SPWP1) were highly correlated to the TDG pressures observed directly below the spillway. The DO concentration ranged from 11.2 to 13.0 mg/l, which was consistently greater than the DO saturation concentration that ranged between 10.1 and 10.6 mg/l (Figure 41). The DO percent saturation at station SPWP1 ranged from 115 to 123 percent while the TDG percent saturation ranged from 122 to 132.7 percent as shown in Figure 41. These data suggest DO was under-represented in waters released from the spillway at Libby Dam in terms of atmospheric ratios of gasses.

## Kootenai River (RM 221.3 to Falls)

### Water temperature

Lateral water temperature gradients were observed in the tailwater channel below Libby Dam caused by combined spillway and powerhouse releases and non-uniform selective withdrawal gate configurations. The water temperatures near the left bank, which is below the spillway, were generally warmer than water temperatures below the powerhouse (right bank) during concurrent project releases as shown in Figure 24. The difference between the left and right bank temperature at the USGS transect was generally about 0.6 $^{o}$C (Figure 42).

Tributary inflow temperatures to the Kootenai River were considerably warmer than main stem temperatures during the study period. The hourly water temperatures in the Fisher River and in Libby Creek (Figure 11) were compared to water temperatures in Kootenai River at the Highway 37 Bridge as shown in Figure 43. The water temperatures in Fisher River and Libby Creek were generally from 1 to 6 $^{o}$C warmer than in the Kootenai River and exhibited a considerable diurnal variation in temperature that was not apparent in the main stem Kootenai River upstream of the confluence with Fisher River.

A general warming trend in Kootenai River was observed below Libby Dam to the U.S. - Canadian border. A diurnal variation in Kootenai River water temperatures developed with increasing amplitude in the reach between the Highway 37 bridge and below Kootenai Falls as shown in Figure 44. During warm days, the Kootenai River temperature varied by as much as 2.5 $^{o}$C below Kootenai Falls. During the nighttime, the change in water temperatures from Libby Dam to the falls was very small and in some cases, a net decrease in average water temperatures occurred. The opposite condition takes place during the heat of the day when water temperatures increased during passage between Libby Dam and the downstream sampling stations. The warmest conditions were generally observed at the Porthill station near the U.S. - Canadian border.

The longitudinal change in Kootenai River water temperatures below Libby Dam were estimated by calculating the daily average water temperatures at sampling stations. The daily average water temperature from Libby Dam to the Porthill station at the U.S. - Canadian border for June 25, July 1, and July 8 are shown in Figure 45 as a function of river mile. The change in the daily average Kootenai River water temperature was found to vary linearly as a function of river mile over the study reach for each of these dates as indicated by the linear regression between river mile and daily average water temperature (Figure 45). The rate of warming varied between the selected days and will depend upon the hydrometeorological conditions across the river basin. The daily water temperatures in Kootenai River increased at a rate of 0.09 $^{o}$C over a 10-mile reach on July 8, to 0.26 $^{o}$C over a 10-mile reach on June 25.

### Total dissolved gas

The TDG characteristics below Libby Dam in the Kootenai River are dominated by the development of the mixing zone between spillway and powerhouse releases and in-river processes. The mixing zone extended from the dam to the old Haul Bridge sampling transect (HAUL). The prominent in-river processes include lateral mixing, tributary dilution, degassing at the air/water interface, thermal heat exchange, and biological productivity.

**Mixing zone.**

In the Kootenai River, powerhouse and spillway flows interact immediately below the stilling basin. The stilling basin training walls effectively limit the immediate interaction between spillway and powerhouse releases below the dam. The flow exiting the stilling basin contains high velocities and turbulence levels that promote the entrainment of powerhouse flows. The zone of highly aerated flow extended beyond the end of the stilling basin for spillway flows greater than 6 kcfs as shown in Figure 46. It is likely that some portion of powerhouse flows encountered the highly aerated flow conditions below the stilling basin during these higher spill rates and were subjected to the accelerated exchange of atmospheric gasses. The downstream movement of Libby Dam releases quickly extended across the entire river by the Thompson Bridge, forcing spillway flows against the left channel bank.

A strong lateral gradient in TDG saturation was evident across the river at both Thompson Bridge and the USGS transects. The lateral TDG saturation distribution is shown in Figure 47 for all the sampling stations within 0.6 mile of the dam during event 14. The peak TDG pressures below the spillway dropped continuously from 133 percent at station SWP2, to 126 percent at Thompson Bridge (TMPNP1), to 125 percent at station USGSP1. The largest reduction in peak TDG saturation consistently occurred between the tailrace channel sampling station (SWP2) and Thompson Bridge. The lateral TDG saturation distribution on the USGS transect for spill discharges of 3, 6, 10, 12.6, and 15 kcfs is shown in Figure 48. These data clearly show that elevated TDG extended across the channel for higher spill events.

The peak TDG saturation observed at the Thompson Bridge was considerably smaller than observed below the spillway. The TDG saturation at station TMPSNP1 was consistently less than TDG measured upstream at station SPWP2 by about 6.8 percent saturation on average. The TDG saturation never exceeded 130 percent at Thompson Bridge. The time-history of project operations and TDG saturation between the dam and Thompson Bridge is shown in Figures 31-34. The average TDG saturation by spill event for sampling stations at Thompson Bridge is listed in Table 6. The TDG saturation near the left channel bank remained above 120 percent during most of the study (98.2

percent of the study) and exceeded 125 percent over 58.3 percent of the time. The TDG saturation on the right side of the channel closely resembled powerhouse releases as shown in Figure 31-34 except for the high spill events on July 1-3. The TDG saturation at station TMPNP4 exceeded 105 percent saturation less than 1 percent of the time (Table 3).

The extent and duration of peak TDG levels continued to decline as the mixing zone developed between Thompson Bridge and the USGS sampling transect, a distance of about one-quarter mile. The maximum TDG saturation along the right bank at station USGSP1 was consistently less than observed at Thompson Bridge (Figure 49). The reduction in TDG saturation between these stations was generally smaller during the high percent river spill events. The TDG saturation at station USGSP5 was consistently higher (1-2 percent) than the TDG saturation at station DTD suggesting the influence of spillway flows has been extended to a small degree to the right channel bank within 0.6 mile of the dam. The peak instantaneous TDG pressures at the USGS station USGSP1 were generally about 5-6 percent saturation less than observed above Thompson Bridge. The TDG saturation near the left bank of the USGS transect exceeded 115 percent, 120 percent, and 125 percent saturation about 95.6, 82.8, and 14.9 percent of the time during spill at Libby Dam.

The average TDG saturation in the Kootenai River was a function of both the percent river spilled and the TDG content of spillway flows. The average TDG saturation by spill event for the USGS sampling stations is listed in Table 7. The highest average TDG saturation in the Kootenai River observed on the USGS transect was 119.7 percent during spillway flows of 14.6 to 15.6 kcfs. Spill discharge of 3 kcfs and less resulted in an average TDG saturation in the Kootenai River of less than 110 percent for capacity powerhouse flow.

#### TDG Compliance.

The existing TDG compliance fixed monitoring station (LIBM) below Libby Dam is located on the right bank at the USGS gaging station, as shown in Figure 13. The TDG saturation at the fixed monitoring station did not exceed the state criteria of 110 percent for TDG saturation during the study period (Figure 49). The fixed monitoring station sampled waters mostly discharged from the powerhouse, while the peak and average river TDG pressures associated with spill at Libby Dam were not reflected in data from station LIBM as shown in Figure 49. A monitoring station located near the left bank at the USGS gaging station provided a much more detailed description of the impact of spill on the TDG conditions in the Kootenai River. The TDG saturation near the left bank at station USGSP1 exceeded 110 percent saturation over 97 percent of the time during the study.

Three conditions were identified to protect the fisheries below Libby Dam during the spill test. The failure of any one of these conditions was sufficient to terminate the spill test. A compliance location within 1-mile of the dam was used to measure the 3-hr and 1-hr average TDG saturation in the Kootenai River. The spill test was suspended if the 3-hr average TDG saturation exceeded 120 percent or the one-hour average TDG saturation exceeded 125 percent. The third criterion involved the identification of signs of gas bubble disease in either the captive fish or fish captured via electro fishing.

The spill test TDG compliance station was originally located at station RTM2 about 1.4 miles downstream of the dam, as shown in Figures 13 and 14. The TDG saturation at station RTM2 did rise above background conditions as a result of spill but was biased by releases from the powerhouse. The compliance station was relocated to the left channel bank at station RTM1 on June 25. The TDG saturation at station RTM1 was heavily influenced by the TDG saturation associated with spillway flows. The TDG saturation at station RTM1 exceeded 120 percent saturation during June 26-27 before forced spillway releases at Libby Dam replaced the spill test. The data observed at station RTM1 closely approximated data from station USGSP1 (Figure 50). Hence, station RTM1 was not deployed after June 27 because of the redundancy with USGSP1 station.

### Fish cage locations.

A series of sampling stations were positioned downstream of the USGS site to support the captive fish monitoring study conducted by the Montana Department of Fish and Wildlife (Dunnigan 2002). Captive fish were held in hoop traps at three locations labeled MFW1, MFW2, and MFW3 along the left bank as shown in Figures 13 and 14. TDG instruments were deployed at each of these sites during a portion of the testing period. The TDG saturation at the fish cage locations is displayed in Figures 50 and 51. The TDG saturation at the most upstream fish pen (MFW1) responded similarly to data collected at the USGSP1 station, reaching a maximum value of 122 percent during Event 3, a spill of 6 kcfs. This instrument was moved closer to the channel bank during the second day of the spill to a station labeled RTM1 with the TDG saturation again closely reproducing the observations at station USGSP1. A TDG station at the first fish cage location was not redeployed after June 27 because of the redundancy of TDG conditions observed at station USGSP1. The TDG exposure history at the first fish cage location based on data from the USGSP1 station exceeded 115, 120, and 125 percent saturation 95.6, 82.6, and 14.9 percent of the time, respectively, from June 25 at 700 hours to July 7 at 1300 hours (Table 3).

The second fish cage sampling station (MFW2) was located about 0.4 miles downstream from the first fish cage location in a braided section of the river. This sampling site was located farther away from the left bank of the Kootenai River than the other two fish cage locations resulting in more moderate levels of exposure to TDG saturation during spillway releases. The average TDG saturation at station MFW2 was 115.6 percent compared to 122.6 percent at station USGSP1. The TDG exposure history at the second fish cage location exceeded 115, 120, and 125 percent saturation 67.1, 0.3, and 0.0 percent of the time (Table 3).

The third fish cage sampling station (MFW3) was located near the left channel bank about 1.3 miles downstream from the first fish cage location. The average TDG saturation at station MFW3 was 119.8 percent, ranging from 124.2 to 106.1 percent. The TDG exposure history at the third fish cage location exceeded 115, 120, and 125 percent saturation 91.6, 57.0, and 0.0 percent of the time.

A summary of the average TDG saturation at station MFW1, MFW2, and MFW3 by spill event is listed in Table 8.

### In-river processes.

A strong lateral TDG saturation gradient was evident at the Highway 37 Bridge at station FISHERP1 and P2 about 3.5 miles from the dam as shown in Figure 52. The average TDG saturation at station FISHERP1 was 118.4 compared to 107.4 on the right channel bank at station FISHERP3. However, TDG saturation was generally well mixed laterally at the Haul Bridge transect, about 8.6 miles from the dam, and at sampling stations downstream from this location. The average TDG saturation at the Haul Bridge transect near the left (HAULP1) and right (HAULP2) channel banks were 112.4 and 111.2 percent, respectively. A daily rise and fall in the TDG saturation was apparent at these sampling stations indicating an influence from solar heating and cooling cycles.

The largest tributary above Kootenai Falls is the Fisher River located at the Highway 37 Bridge about 1.7 miles downstream of the dam. The flow in the Fisher River ranged from 1,250 kcfs on June 24 to 473 on July 9. The TDG pressure of 720 mm of mercury or about 102 percent TDG saturation was measured in the Fisher River on June 26. The water temperature was also measured in the Fisher River near the confluence with the Kootenai River. The Fisher River was considerably warmer than the Kootenai River as shown in Figure 43. The degree of influence of the Fisher River flows on TDG saturation in the Kootenai River can be illustrated by examining conditions on June 27. The average TDG saturation in the Kootenai River at the Highway 37 Bridge was 112.7 percent for a flow of 32 kcfs. The discharge in the Fisher River was 1.2 kcfs with a TDG saturation of 102 percent. The flow-weighted average TDG saturation for the Kootenai River downstream of the Fisher River confluence was 112.2 percent or about a 0.5 percent reduction in the average TDG saturation in the river. The degree of dilution caused by Fisher River diminished during the study period. Several other small inflows such as Libby Creek, contributed to additional dilution of the TDG pressures in the Kootenai River.

The change in heat content of the Kootenai River can result in a significant increase or decrease in TDG pressures under constant mass conditions. A 1°C increase in water temperature can result in a 2-3 percent point increase in TDG supersaturation if the mass of atmospheric gases remains nearly constant. As the Kootenai River experiences daily changes in water temperature, a corresponding response to the TDG pressure will also be present. The strong diurnal variations in TDG pressures at the sampling stations upstream and downstream of Libby, MT, as shown in Figure 53, are clearly a response to the daily solar heating and cooling cycles present in the Kootenai River during the study period. The change in TDG pressure between transects USLIBBY and DSLIBBY was small. The maximum TDG pressures at station DSLIBBYP1 did not exceed 116 percent.

### Time of travel.

The initiation of spill or cessation of spill created a distinctive volume of water for which the TDG content could be used to estimate the time of travel and average velocity in a specific river reach. The frequency of sampling for TDG pressures of 15 min limited this evaluation to stations located well downstream of the project. The 2-hr shutdown of spill on June 28 created a slug of water detected at downstream sampling stations later in the day. The minimum TDG pressures observed at Fisher Bridge stations associated with this spill outage occurred about 1.5-hr after the event resulting in an average reach velocity of 2.3 mph. The travel times for this unique event from Libby Dam to the HAUL, USLIBBY, DSLIBBY, and USFALLS transects were 3.12 hr, 5.25 hr, 6.25 hr, and 7.5 hr, respectively. The average reach velocity for the HAUL, USLIBBY, DSLIBBY, and USFALLS transects was 2.5 mph, 2.87 mph, 3.5 mph, and 3.65 mph, respectively. The continuously increasing reach velocity reflected the steepening channel gradient as the Kootenai River approached the Kootenai Falls area.

**TDG Loading.**

The average instantaneous Kootenai River TDG pressure was calculated for the downstream transects throughout the study period. The averaging of multiple TDG pressure observations on a transect was important in the mixing zone region. The discharges from the powerhouse and spillway were paired up with TDG pressures observed at stations DTD and SPWP1-2 to estimate the average flow-weighted cross-sectional properties at the dam.

The observed flow distribution at the USGS gage was used to flow-weight the TDG pressures observed at each of the five sampling stations at this transect. A water quality transect consisting of five sampling stations was located at the USGS gaging station below the dam for the purpose of estimating the TDG loading produced during spillway operations. This transect was chosen because of the available velocity and flow distribution data across the channel. Velocity data obtained from January 6, 1994 USGS records during a total river flow of 19,553 cfs were used to estimate the cumulative distribution of flow across the channel at this location. The cumulative flow distribution versus normalized distance from left bank and lateral position of the TDG sampling stations is shown in Figure 54. This figure indicates most of the flow in the Kootenai River is located in the right half of the channel at the USGS gage. The flow weighting coefficients used to estimate the average cross-sectional TDG pressure and saturation were determined to be 11.22, 13.73, 27.29, 40.52, and 7.24 for stations USGSP1, USGSP2, USGSP3, USGSP4, and USGSP5, respectively.

An arithmetic mean of multiple sampling stations was applied, at the remaining sampling transects downstream of the USGS gage to calculate average river TDG pressures. In several cases, a single station was used to estimate the average TDG pressure in the Kootenai River. These transects were downstream of the mixing zone associated with Libby Dam releases.

Spillway releases at Libby Dam resulted in a net increase in the TDG content of the Kootenai River. The net increase in the TDG saturation in the Kootenai River was estimated by comparing the TDG characteristics in powerhouse flow (DTD) with the flow-weighted average TDG saturation on downstream transects. The daily average TDG saturation was used to estimate the gross change in TDG pressure in the Kootenai River below Libby Dam as listed in Table 9. The net change in the daily average TDG saturation of the Kootenai river was estimated as the difference between the TDG content of powerhouse releases (DTD) and the flow-weighted average conditions on the USGS transect. The change in TDG saturation at Libby Dam (ΔTDG Dam column in Table 9) ranged from less than 1 percent during days without spill to a maximum change of 15.1 percent saturation on July 2, 2002.

Estimates of the daily average flow-weighted TDG saturation in the Kootenai River were determined at the dam and at the USGS transect. The average flow-weighted TDG saturation exiting Libby Dam was estimated using Equation 4 where the TDG saturation of powerhouse flow was estimated by observations from station DTD and the average TDG saturation on stations SPWP1-SPWP2 was applied to spillway flows. The entrainment discharge was assumed to be zero for this calculation. The flow-weighted average TDG saturation exiting Libby Dam consistently underestimated the average conditions measured at the USGS transect by 3 to 4 percent saturation (Table 9). The difference in daily average TDG saturation between Libby Dam and the USGS transect could be attributed to a non-zero entrainment discharge (i.e. powerhouse flows exposed to aerated flow conditions), uncertainty in the flow distribution at the USGS transect, and underestimation of bulk TDG saturation of spillway releases as measured at stations SPWP1-2.

$$TDG_{avg} = \frac{(Q_{sp} + Q_{ent})TDG_{sp} + (Q_{gen} - Q_{ent})TDG_{gen}}{Q_{tot}} \qquad (4)$$

where:

| | | |
|---|---|---|
| $Q_{tot}$ | = | Total River Flow (kcfs) |
| $Q_s$ | = | spillway discharge (kcfs) |
| $Q_{gen}$ | = | generation discharge (kcfs) |
| $Q_{ent}$ | = | entrainment discharge (kcfs) |
| $TDG_{gen}$ | = | TDG saturation of generation discharges (percent) |
| $TDG_{avg}$ | = | average TDG saturation on transect USGS (percent) |
| $TDG_{sp}$ | = | TDG saturation of spillway discharges (percent) |

The characteristics of a non-zero entrainment discharge were investigated using the daily average flow and TDG saturation observations below Libby Dam. The entrainment discharge ($Q_{ent}$) was calculated for each day by rearranging Equation 4 assuming the TDG saturation at station DTD represented powerhouse flows, the average TDG saturation on station SPWP1-2 represented spillway flows, and the daily flow-weighted TDG saturation on the USGS transect reflected average river conditions. The estimated entrainment discharge remained nearly constant for conditions on June 26-July 6 ranging from about 4 to 5 kcfs (Table 9). The entrainment discharge remained constant while the daily spillway discharge ranged from 2.2 to 15.6 kcfs. The errors in the estimation of the entrainment discharge will increase for decreasing percent river spill conditions.

The average daily change in TDG saturation per river mile was estimated between the USGS transect and USFALLS station. The reduction in average daily TDG saturation between these two stations ranged from 3.7 to 5.9 percent which results in a rate of change of 0.16 to 0.22 percent per mile. This change in TDG pressure encompassed dilution for tributaries, thermal changes, and the loss of TDG mass through exchange at the water surface. The average rate of change in the Kootenai River from below the falls (DSFALLS) to the station at TROY was also estimated as shown in Table 9.

The travel time of project releases to the Kootenai River at Troy was estimated to be less than 10 hr for the total river flows experienced during the study period. The duration of many of the spill events was greater than 10 hr enabling the establishment of quasi-steady conditions in the Kootenai River from Libby Dam to Troy, MT. The instantaneous longitudinal profile of TDG pressure is displayed in Figure 55 exactly 10 hr into specific test events. The TDG saturation curve corresponding with generation-only flows on June 25 at 0000 hours showed a small rise in average TDG pressure to the sampling stations above the falls. When Libby Dam was spilling water, a decline in average TDG pressure was typically observed between the dam and Kootenai falls. The reduction in average TDG pressure is due to dilution from tributary inflows and off gassing at the air/water interface. The degassing process was likely accelerated in rapids where standing and breaking waves increases the surface area for TDG exchange between the water and air. The reduction in average TDG pressure generally ranged from 4 to 7 percent saturation between the dam and the sampling stations above the falls during spillway activity in June and July of 2002 as observed during the early morning hours.

The longitudinal average TDG pressures during a constant spill of 7 kcfs on June 27 is illustrated in Figure 56 for 0200, 0600, 1000, 1400, and 1800 hours, respectively. The greater daily heating that occurred at greater distances downstream of the dam resulted in rising TDG pressures as the day progressed. The reduction in average TDG pressure from Libby Dam to the station just above the falls ranged from 3.5 percentage points at 1800 hours to 6.5 percentage points during cooler temperatures at 0600 hours.

## Kootenai Falls

### Water temperature

A prominent daily variation in water temperature was present during the study period as the Kootenai River passes through Kootenai Falls as shown in Figure 44. This variation in temperature resulted in a similar variation in the saturation concentration of dissolved atmospheric gasses and led to an inverse relationship between water temperature and the mass of TDG observed below the falls.

## Total dissolved gas

The deployment period for the two stations located immediately upstream of Kootenai Falls (USFALLS) started shortly before test spills at Libby Dam began, on June 24 and continued through July 11. The TDG saturation in the Kootenai River without spill was nearly uniform from the dam to station USFALLS with the TDG saturations ranging form 102-106 percent. The TDG saturations below the falls (DSFALLS) remained above 114 percent for the entire sampling period indicating a significant increase in TDG pressure was associated with Kootenai River water passing through the falls reach. The series of rapids and plunge pools throughout the Kootenai Falls reach generated highly aerated flow conditions that increased the TDG saturation in the Kootenai River independent from spillway operations at Libby Dam. This condition was demonstrated clearly in the longitudinal TDG saturation variation prior to spill as shown in Figure 55 during June 25 at 0000 hours. The variation of TDG saturation below the falls was likely caused by the variation in the depth of flow at different river discharge conditions.

The TDG pressures observed just upstream of the falls at station USFALLSP1 and USFALLSP5 responded to the rise and fall of elevated TDG pressures associated with spill at Libby Dam. The TDG pressures observed at the two stations upstream of the falls were similar except during the period of July 3-4 (Figure 57). Since no reason for a lateral TDG gradient at this time or place can be identified, the variance observed during this period was likely due to a fouled pressure sensor or shallow depth at the USFALLSP5 instrument. During sampling periods without spill, the TDG saturation ranged from 102-107 percent in response to thermally induced pressure responses to diurnal heat exchange. These non-spill TDG conditions were similar to the TDG levels released from the Libby Dam powerhouse on a daily average basis. The TDG saturation above the falls increased in response to the high spill rates from Libby Dam with the TDG saturation ranging from 110-114 percent during peak river flows of 40 kcfs and 15.6 kcfs spill. The average TDG saturation at this river mile was 4 to 6 percentage points less than observed at the USGS transect. The maximum increase in TDG saturation just above Kootenai Falls resulting from Libby spill was about 7 percentage points on average. Both of these stations demonstrated daily fluctuations in TDG of 2 to 4 percent saturation throughout the study period caused by the daily heat exchange in the river.

The stations downstream of the falls, DSFALLSP1 and TROY, indicated similar temporal patterns of TDG saturation, with the lowest TDG saturations of 114-116 percent occurring during the lowest flow periods on the leading and trailing edge of the release hydrograph (Figure 57). Cross-sectional representativeness of these stations was not verified during this study but was thought to be small because of the narrow channel and turbulent mixing action of the falls. The TDG saturation at station DSFALLSP1 peaked at 120.5 percent on July 2, coinciding with the highest river discharge of 40 kcfs. These flow conditions also generated the deepest flow conditions through the Kootenai Falls river reach. The TDG saturation at the station near TROY peaked at 119.5 percent on July 2. The diurnal variation in TDG saturation was not apparent or highly attenuated at these two stations below the falls because of the short travel time between the aerated flow conditions at the falls and downstream sampling stations.

The persistently high TDG saturation below Kootenai Falls with and without spill from Libby Dam supported the hypothesis that the falls is the major source for the elevated TDG conditions in the Kootenai River downstream of the falls. The aerated flow at Kootenai Falls directly influenced the entire river, unlike spill conditions at Libby Dam. The high flow conditions in the Kootenai River generated deeper flow conditions through the falls reach resulting in the average cross-sectional TDG saturation ranging from 116-120 percent. In contrast, spill operations at Libby Dam resulted in the average cross-sectional TDG saturation in the Kootenai River as measured at the USGS transect ranging from 103 to 119 percent saturation during the same period. The gross average river TDG below the falls for the entire test period was 118 percent, or about 4 percent saturation higher than the 114 percent gross average TDG saturation calculated for the USGS transect. These data and analysis clearly show that Kootenai Falls generated higher average TDG pressures in the Kootenai River than was generated by the forced spillway operations of Libby Dam during June and July of 2002.

The relationship between TDG saturation generated at Kootenai Falls and total river flow was investigated by reviewing data from the 2002 study with data collected during 1972-1975 as documented in Graham (1979). The TDG saturation below the falls was plotted against the total river flow (Figure 58). A linear relationship between TDG saturation below the falls and total river flow was indicated in these data. A 10-kcfs increase in total river flow resulted in a 2.5 percent saturation increase in the TDG saturation below the falls.

The data collected during this study generally supported the claim that the TDG saturation generated from spillway releases did not influence the TDG levels downstream of Kootenai Falls. The higher TDG pressures generated below Libby Dam were correlated with higher TDG pressures below the falls. However, the higher TDG pressures below the falls were also highly correlated with river discharge and depth of flow. A low TDG plume created during a 2-hr spill outage on June 28 passed through the falls reach later that day. The distinct low TDG plume took about 7.25 hours to travel from the dam to the USFALLS transect as indicated by the sag in TDG saturation shown in Figure 59. The TDG saturation at both the USFALLSP1 and USFALLSP2 stations declined about 3.5 percent and then recovered over a 3-hour period. However, the TDG saturation below the falls at station DSFALLSP1 demonstrated a similar response 2 hrs before the arrival of the plume at the upstream transect USFALLS. A closer inspection of the TDG saturation and depth of the instrument at DSFALLSP1 showed the declining TDG pressures were a consequence of the instrument depth approaching zero as shown in Figure 60. The TDG saturation at the DSFALLSP1 station at depths less 1.5 ft were biased by the local conditions in the near-shore area and not representative of the bulk of the water passing through the falls. The change in the depth of flow below Kootenai Falls was probably associated with the passage of the flood wave generated by the reduction in discharge at Libby Dam during the spill outage. This flood wave would propagate at a higher speed than the movement of water in the river and arrive at the falls before the low TDG plume. The signature of the low TDG plume was not observed at either the DSFALLSP1 or TROY stations. A slight decline in TDG saturation of about 1 percent saturation at TROY corresponded with the flood wave passage through the Kootenai Falls reach. These observations supported the proposition that the TDG saturation below Kootenai Falls is independent of TDG generation in spillway releases from Libby Dam. The independence of the resultant TDG saturation below highly aerated flow conditions, from the initial TDG pressure upstream, has been observed at other dams in the Columbia River Basin (USACE 2002).

### Dissolved oxygen

The dissolved oxygen concentrations in Kootenai River below the falls at station DSFALLS averaged about 11 mg/l during the study period. The DO concentration was consistently greater than the DO saturation concentration (DOsat) shown in Figure 61 resulting in a percent saturation for oxygen of 104-109 percent during most of the study period. These data suggest DO was underrepresented in Kootenai River waters below the falls in terms of atmospheric ratios of gasses. The daily oxygen cycle was slightly out of phase with the thermal cycles because of the physical exchange processes. Biological processes negligibly affected dissolved oxygen levels at this location.

## Summary: Kootenai River - Libby Dam to Troy, MT

### Total dissolved gas

An overview of the TDG saturation in Kootenai river from Libby Dam to the sampling station at Troy, MT, is presented in an animation of study data from June 24 through July 10 in Figure 62. This figure contains a time and space plot summarizing the TDG saturation observed in the Kootenai River during the study period. Figure 62 contains the time-history of Libby Dam operations and TDG saturation at key sampling stations: DTD, SWP2, USGSP1, USFALLSP1, DSFALLS, and TROY. A timeline appearing in the upper plot indicates the current date and time of information displayed in the TDG versus river mile plot (bottom plot) and data in the legend. The bottom plot displays the 15-min TDG saturation at the left and right bank stations (left bank square, right bank triangle) and the average cross-sectional TDG saturation (solid line). A second dashed line in the bottom plot indicates the average cross-sectional TDG in the Kootenai River 6 hrs before the current time. This ghost image of recent TDG conditions provides a visual reference for any changes in river conditions. The current date and time, total river flow ($Q_{total}$), and spillway discharge ($Q_{spill}$) are shown in the legend of the bottom plot.

The longitudinal variation in TDG saturation in the Kootenai River are displayed in lower half the fixed frame display in Figure 62 for July 2 at 12:45 hr during a total river flow of 40 kcfs and a spill discharge of 15.6 kcfs. The peak TDG saturation below the spillway of 132.7 percent (SWP2) is contrasted with the minimum TDG saturation passed through the powerhouse at 102.0 percent (DTD) as displayed by the square (left bank) and triangular (right bank) symbols. The peak TDG pressures along the left bank decrease and minimum TDG pressure along the right bank increase until nearly well mixed conditions are obtained at the HAUL transect about 8.6 miles below the dam. The average TDG saturation in the Kootenai River is greatest downstream of Kootenai Falls with a level of about 120 percent at station DSFALLS and 119 percent at TROY. The average TDG saturation (solid blue line) below the dam during this peak spill event was 117 percent and declined steadily below the dam to 112 percent just above the falls. The difference between the current (solid blue line) and previous (6 hours earlier-dashed blue line) average TDG conditions at all the stations except near the sourcing locations (Libby Dam spillway, Kootenai Falls) is an indication of the thermal influence on TDG saturation.

The TDG conditions shown in Figure 62 can be viewed at any time between June 24 (prior to spill) and midnight on July 9 by initiating the animation linked to this figure (go to Figure 62 in this document and click anywhere on the image). The data animation is contained in a separate file called "LibbyTimesSeries V5.avi" which can also be viewed separately outside of this document. Viewing the data in motion illustrates the dependency between project spillway operations and the TDG saturation above Kootenai Falls. The increase or decrease in percent river spilled causes a corresponding increase or decrease in the average TDG characteristics in the Kootenai River. The generation of the peak TDG saturation directly below the dam reaches an upper limit for increasing spillway flows. The propagation of low TDG pressures associated with the 2-hr shutdown of spill on June 28 can be seen in this depiction of the data. The daily rhythm of TDG saturation generated by thermal exchange processes is apparent in the rise and fall of average TDG conditions downstream from the dam. The ever-present influence of Kootenai Falls on the TDG properties in the lower river is shown throughout this presentation of the data.

## Kootenai River at Porthill, ID (International Boundary)

A water quality sampling site was located on Kootenai River near Porthill, Idaho, about 1,200 ft south of the international border and 116 miles downstream from Libby Dam. The elevation of the sampling site was about 1,775 feet above sea level. This sampling station was operational from June 24-July 22. TDG pressure, DO concentration, instrument depth, and water temperature were recorded at 15-min intervals. The TDG saturation was estimated at the Porthill station by estimating the local barometric pressure as a function of the barometric pressure observed below Libby Dam and the elevation difference between the two stations. Time of travel from Libby Dam to the Porthill station was estimated based upon average Kootenai River velocities ranging from 3-4 fps yielding a travel time ranging from 42 to 56 hr.

### Water temperature

The variation in water temperature is often a prominent driver of the cycling of daily TDG patterns. However, at the Porthill station, the daily peak total pressure was often out of phase with the daily peak water temperature as shown in Figure 63. The Kootenai River water temperatures at Porthill ranged from 11.1-15.4$^{o}$C. These water temperatures were several degrees warmer than the release water temperatures from Libby Dam. The average Kootenai water temperatures during the study period at Libby Dam, Troy, and Porthill were 10.13°C, 11.19°C, and 13.31°C, respectively. The diurnal variation in Kootenai river temperatures were much more prominent at Troy than at Porthill.

### Total dissolved gas

During the sampling period at Porthill, the TDG saturation in Kootenai River ranged from 106.4-111.9 percent with a mean value of 109.1 percent as shown in Figure 64. The frequency distribution of hourly TDG saturation at Porthill is summarized in Table 10. The hourly TDG saturation observed in the Kootenai River at Porthill exceeded 110 percent about 19.3 percent of the time. The highest TDG pressures were measured on July 3-4 several days after the peak project releases and spill from Libby Dam. The TDG saturation in the Kootenai River at Porthill was higher than the TDG saturation of powerhouse releases from Libby Dam as measured at station DTD by about 5-7 percent saturation (Figure 64) but well below the TDG saturation observed at Troy. Based on the observations of TDG saturation below Kootenai Falls, it is unlikely that the elevated TDG pressures at Porthill were at all related to the TDG pressures generated from spillway releases at Libby Dam. The elevated TDG saturation at Porthill may be attributed to the TDG exchange at Kootenai Falls.

### Dissolved oxygen

The biological productivity in Kootenai River contributed to daily patterns in TDG pressure at Porthill. The hourly dissolved oxygen concentration were in phase with the TDG saturation as shown in Figure 65. The daily range in DO concentration was from 0.2 to 0.5 mg/l. This variation in DO concentration resulted in a 3 to 7-mm of mercury variation in TDG pressure assuming atmospheric ratios of dissolved gases. The DO saturation never exceeded 100 percent during the study at the Porthill station indicating a significant amount of community respiration occurring in the aquatic system. The DO contribution to the TDG pressure was under represented at Porthill, as was the case at other sampling stations located throughout the study area.

# 9 Conclusions and Recommendations

A field study was conducted at Libby Dam from June 24-July 9 to determine the impacts of spillway releases on the TDG pressure in Kootenai River. An array of TDG instruments were positioned in Kootenai River to measure the peak TDG pressures generated in spillway releases and the resultant transport and mixing of Libby Dam discharges downstream of the project to the US - Canadian border. The major water quality findings from this study are summarized in the following paragraphs.

Thermal stratification in the forebay of Libby Dam influenced the vertical distribution of TDG pressure. During the study period from June 24-July 9, 2002, the TDG saturation in the warmer surface waters (epilimnion) of Lake Koocanusa frequently exceeded the Montana state water quality standard for TDG of 110 percent with peak TDG saturations of 115 percent. The TDG pressure in the cooler deeper waters (hypolimnion) of Lake Koocanusa was significantly less and was similar to powerhouse releases.

The passage of water through the powerhouse generally did not change the TDG pressures. The TDG saturation in powerhouse releases generally ranged from 102 to 104 percent of saturation. However, releasing warmer surface waters through the selective withdrawal system could result in powerhouse release waters containing higher TDG saturations than experienced during this study.

The release water from the spillway was warmer than water released through the powerhouse throughout the study period. As a consequence, lateral temperature gradients were generated in the Kootenai River below the dam, which may have biased temperature observations at tailwater sampling stations and temperature management decisions.

Spillway releases resulted in the elevation of TDG pressures in the Kootenai River. The TDG saturation in spillway releases increased as an exponential function of the spillway discharge. The TDG saturation of spillway releases increased abruptly from 104 to 129 percent saturation as the spill discharge increased from 0.7 to 4.0 kcfs. A mild increase in the TDG saturation of spillway releases of 129 to 134 percent saturation was observed as spillway discharges increased from 4 to 15 kcfs.

A strong lateral gradient in TDG saturation was present in the Kootenai River below Libby Dam during spillway and powerhouse releases. 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 mixing of project releases caused diminishing lateral gradients with increasing distance downstream from the project. The maximum TDG saturation observed at the USGS gage (RM 221.3) was 125 percent, which dropped to 122.5 percent at the Highway 37 Bridge (RM 220.3) and 117 percent at the Haul Bridge (RM 215.6). The TDG pressures in Kootenai River were nearly well mixed at the Haul Bridge transect throughout the study period.

Measurements of TDG from existing tailwater monitoring station at Libby Dam are heavily influenced by powerhouse releases. Consequently, these data underestimate the actual TDG levels in the Kootenai River.

The average TDG saturation in the Kootenai River increased incrementally as a function of the percent of total river flow spilled. The maximum average TDG saturation in the Kootenai River of 116.9 percent was observed at the USGS tailwater gage during the 15.6-kcfs spill. The average TDG saturation in the Kootenai River remained below 110 percent for spillway flows up to 4 kcfs. The average TDG saturation in the Kootenai River generally declined with distance below the project. The peak TDG saturation of 111.2 percent was observed above Kootenai Falls (RM 198) during the highest spill event was considerably less than average conditions estimated directly below the dam. The average reduction in TDG saturation per mile of river during these conditions was estimated to be 0.24 percent saturation/mile. This loss rate estimate included the influences of tributary dilution, heat exchange, biological productivity, and air-water mass exchange.

Riverine processes influenced the TDG pressures in the Kootenai River. They include mixing of project releases, tributary inflow dilution, temperature induced pressure changes, biological productivity, and air-water mass exchange. The diurnal variation in river temperatures could generate a corresponding variation in TDG pressure of 20-mm of mercury (3.0 percent saturation).

Kootenai Falls caused a significant increase in TDG saturation of the Kootenai River throughout the study period. Kootenai Falls recast the TDG pressures of the Kootenai River to levels independent from TDG pressures present upstream of the falls. Prior to the initiation of spill, TDG saturation of water passing through Kootenai Falls increased from 103 percent to 116.1 percent. TDG saturation below the falls attained a maximum level of 120.5 percent during the peak river flow of 40 kcfs and a minimum level of 116 percent prior to spillway activity. The increase in TDG saturation below the falls for higher river flows was likely caused by the greater depth of flow of the river at the falls and not the elevated TDG pressure in the Kootenai River caused by spillway operations at Libby Dam. The TDG loading below the falls was always greater than and independent from the TDG loading produced by spillway operations at Libby Dam during the study period.

The TDG saturation in the Kootenai River at the U.S. - Canadian border was not influenced by the TDG supersaturation caused by spillway operations at Libby Dam. During the study period, the TDG saturation in the Kootenai River at Porthill ranged from 106.4-111.9 percent with a mean value of 109.1 percent. The TDG at Porthill was likely the result of TDG loading occurring 92 river miles upstream at the falls and the increasing water temperatures.

The tailwater fixed monitoring station for TDG saturation should be moved across the river from its current location on the right channel bank. The TDG saturation measured on the left bank across from the USGS gage will reflect elevated TDG conditions when the spillway or sluiceways are operating. These observations can also be used to estimate the TDG conditions downstream in the Kootenai River. Monitoring station locations near the left channel bank of the Kootenai River and upstream from the USGS gage would also be suitable monitoring sites.

Both spillway gates should be operated similarly when the spillway is used at Libby Dam to minimize the exchange of TDG. The ability to broadly distribute spillway releases over the widest possible extent has proven to lessen the level of TDG saturation in spillway releases at other projects. This is also the likely cause for the higher TDG levels associated with sluiceway discharges when compared with spillway flows observed during the 1970s at Libby Dam.

The TDG exchange associated with Kootenai Falls should be revisited in light of these studies' findings. The TDG levels generated at the falls appear to be closely related to the flow rate in the Kootenai River. Since, Libby Dam is the primary regulator of flow in this area, decisions regarding water management will impact the TDG conditions below Kootenai Falls.

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# Appendix A
# Plan of Study for TDG Field Investigations (Spill Test), Libby Dam, FY2002

## Introduction

Total dissolved gas (TDG) generated by aerated releases from dams promotes the potential for gas bubble trauma in downstream aquatic biota. Past TDG tests conducted by the U.S. Army Engineer District, Seattle have indicated the potential of high TDG to result from spill at Libby Dam located on the Kootenai River at river mile (RM) 221.9. The U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory proposed to conduct a comprehensive test of TDG resulting from a range of releases at Libby Dam.

The proposed testing will be directed at describing spatial and temporal dynamics in TDG both near the structure and downstream in the Kootenai River for about 29 miles to just downstream of Kootenai Falls at RM 193. The information gained can be used in better understanding the gas exchange processes, particularly dissolved gas production from overflow spill releases and dissolved gas dissipation downstream from the project. Results from these studies will provide information to be used in spill management at Libby and to avoid water quality problems associated with TDG and potential harmful impacts on downstream aquatic life. The degree of mixing between powerhouse and spillway releases will be investigated since this is important to the total flux of TDG introduced into the downstream habitat. In addition, the study will characterize transport, time of travel, mixing, and degassing of dissolved gas that may occur in the Kootenai River downstream to below Kootenai Falls at RM 193.

## Objectives

The purpose of the field study is to more clearly define and quantify processes that contribute to dissolved gas transfer during spill releases at Libby Dam (see attachment for more details). In general, the transfer of dissolved gas is thought to be a function of the unit spillway discharge, spill pattern, spillway geometry, stilling basin and tailwater depth and flow conditions, forebay TDG concentration, project head differential, and water temperature. This study will focus on resolving questions regarding accurate source and sink descriptions of mass conservation of dissolved gases in Kootenai River below the dam. TDG time-history information as related to specific project operation is of particular interest. The data will be analyzed to provide estimates of the gas transfer throughout the tailwater area that should provide guidance on the relative importance of gas exchange processes within the stilling basin and in the downstream tailrace. The specific objectives of the field investigations are as follows:

a. Describe dissolved gas exchange processes (exchange, mixing, transport) in the Libby Dam tailwater for various spillway/powerhouse operational scenarios

b. Describe resulting TDG pressures downstream to the Kootenai Falls reach associated with the test spillway/powerhouse operational scenarios

c. Provide recommendations for future water quality (WQ) monitoring as needed

d. Provide recommendations for minimizing TDG resulting from Libby Dam project operations

The conclusions drawn from this effort will aid in the identification of operational measures that may reduce TDG supersaturation in the Kootenai River in the event of spill.

## Approach

A single TDG monitoring study will be conducted to address the objectives. This field study will employ an array of automated remote logging water quality instruments capable of describing the complete time-histories while maintaining the spatial density required to quantify the water quality characteristics of the river/reservoir system. Once the water quality instrumentation is in place, the project will be cycled through a series of spill operations of interest combined with constant maximum available powerhouse operation.

Data collected during the study will include water quality, geographic locations of instruments, plant operations, water elevation, and water discharge. Parameters recorded by the WQ instruments will include date, time, instrument depth, water temperature, TDG pressure, dissolved oxygen concentration, and internal battery voltage. The water quality parameter of primary interest is TDG pressure. These data will be collected at 15-min intervals during the deployment period. Manual sampling will be used where and when necessary to supplement the automated approaches. In addition, barometric pressure and air temperature will be monitored near the Libby project at a similar interval to allow the calculation of TDG percent saturation.

TDG instruments will be deployed on two transects, the first being located immediately downstream of the tailrace at Thompson Bridge, RM 221.6, and the second downstream at the Highway 37 bridge upstream of the confluence with Fisher River, RM 218.5 (Figure A1). Each transect will consist of three to five instruments deployed on the bottom of the river. This deployment array will provide direct assessment of the lateral and longitudinal gradients and dynamics in TDG concentrations throughout the study area and subsequently descriptions of the gas exchange characteristics of the existing spillway, sluices, stilling basin, and tailrace.

To maintain TDG within thresholds designed to provide a margin of safety for aquatic organisms, real-time measurements of TDG will be taken at a downstream checkpoint within 1 mile of the dam. The checkpoint instrument will be positioned on the spillway side of the river and monitored to ensure that the TDG levels do not exceed:

a. An average of 125 percent saturation for any 1-hr period, or

b. An average of 120 percent saturation during any 3.5-hr spill interval.

If these thresholds for TDG supersaturation are exceeded at any point, we will immediately stop spilling water and would not exceed the critical spill volume in subsequent spill test intervals. In the event that we exceed the gas thresholds prior to a total spill rate of 10,000 cfs, we may alter our test plan to vary the volume of spill in the two spillways at Libby Dam to further refine the relationship between spill volume per bay and gas levels. However, we would structure test plan modifications to ensure that the spill volume is low enough that the specified TDG thresholds are not exceeded. These and other TDG data will be reviewed at morning meetings on days 2 and 3 of the spill test.

Additional TDG instruments will be deployed in a longitudinal series downstream of the instrument transect at the Highway 37 Bridge and at Fisher River. The deployments will be at approximately 5-mile intervals down to RM 194 and will employ paired instruments (one on each side of the river when possible). A minimum of one instrument will be deployed in the river downstream of Kootenai Falls at RM 193. Auxiliary instrument placement and/or manual water quality profile sampling will be conducted in the forebay of Lake Koocanusa. A logging temperature string will be deployed in the forebay as well to document vertical gradients in the water column.

## Operating Conditions

Spillway discharge will be systematically varied while maintaining constant hydropower discharge during the first part of the field study. The test schedule will allow project TDG rating for a range of spills considered for individual and simultaneous operation of the two spillway gates (Table A1). The spillway gates will be cycled through 1,000 cfs increments of flow for treatment periods of 3.5 hr subject to the previously specified TDG constraints. Visual inspection of the spillway will be conducted between each test event.

The TDG testing is scheduled to last for 3 days from June 25 to June 27 to complete all treatments. Downstream testing will extend long enough to allow for travel time of spilled water to the furthest downstream instrument. The spill test may be extended to include the morning of June 28 to complete any remaining treatments not yet accomplished due to unavoidable delays.

## Fish monitoring

It is intended that no fish will be harmed by the test and that dissolved gas levels will not exceed levels harmful to aquatic biota. The Montana Department of Fish, Wildlife and Parks (MFWP) will assist the study by making personnel and two boats available for fish sampling by electro shocking at various locations between the dam and Kootenai Falls. Sampling will occur during and after the spill tests and will be timed to account for water travel time between Libby Dam and the sampling location, as well as for anticipated time for symptoms to occur. Previous efforts in the Kootenai River have shown that electro shocking during daylight hours does not catch many fish, likely because the fish are deeper than the effective range of the electro fishing equipment. Accordingly, in an effort to observe fish when they are in shallow water and most vulnerable to gas supersaturation, electro shocking will continue into the evening and night after the spill ends each day. The object of the fish sampling will be to obtain live specimens in the affected part of the river and to examine them for signs of gas bubble disease (GBD). This will be done by personnel with training or orientation in recognizing external symptoms in fish. All fish captured will be released unharmed by sampling, but some may be held for observation if GBD symptoms are seen. The Seattle District fish biologist on site will be present in one of the sampling boats, or at another location nearby if it is the consensus of all involved that that would be more advantageous.

Captive fish will also be observed for symptoms of GBD. At least two cages or nets containing mountain whitefish and rainbow trout will be placed in the river in representative locations. The captive fish will be periodically observed during daylight hours for signs of GBD. MFWP and Seattle District personnel will determine the numbers of cages and locations.

Monitoring personnel will record results of sampling. The spill test will cease if GBD symptoms are observed in any fish according to GBD observation protocols agreed upon by MFWP and Seattle District. Sampling personnel will inform the Corps fish biologist on site (by radio if necessary), who will then contact the study manager via radio. The study manager will immediately tell Libby Dam operations personnel to cease the spill. Further fish sampling will be conducted to ensure subsidence of symptoms in fish as well as to document any further symptoms or mortalities if necessary.

Additional monitoring will consist of tracking movements of tagged fish using radio telemetry equipment. Tracking of radio-tagged fish will be done primarily for informational purposes and is not expected to provide a trigger to end the test in the event of unexpected or unusual movement patterns.

## Deliverables

An interim data and final memo report will be submitted by ERDC to Seattle District in accordance with the work schedule given in this proposal. The memo reports should be submitted as a hard copy and in electronic format (pdf files). The report should provide the following information.

a. Study review and description complete with study design and methods

b. Summary of assumptions made in taking the data

c. Statement of data accuracy

d. Discussion of the limitations of the data and/or analysis

e. Extrapolation to higher spill flow or powerhouse flow

f. Documentation of the field study results including text, tabular data, graphical presentation of the data, and any other pertinent information

g. Review and documentation of historical data relevant to the field study and data analysis

## Scheduling of Study

ERDC is being contracted to assist with planning, coordination, and conduct of TDG studies as required at Libby Dam by Seattle District. The work to be performed during FY02 includes field sampling, data analysis, and reporting. The majority of the fieldwork and data analysis will be conducted during June and July 2002. The work should be completed in accordance with the following schedule, subject to unforeseen delays or restrictions.

<u>Schedule</u>

- Data collection 24 June – 28 June 2002
- Data analysis 1 July 2002 through 31 August 2002
- Interim data report and test results 15 August 2002
- Final Report to S 15 September 2002

## Points of Contact

The ERDC primary points of contact (POC) for this work are Joe H. Carroll 541.298.6656 and Mike Schneider 601.634.3424. Seattle District is Layna Goodman 206.764.5523.

| Table A1. Test Schedule for TDG Testing at Libby Dam | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Event | Date | Time | Number Hours | Generation Flow (Kcfs) | Spill per Gate (Kcfs) | Number Gates | Total Spill (Kcfs) | Total Release (Kcfs) |
| Install Equipment | 6/24 | All day | | 25 | 0 | 0 | 0 | 25 |
| Meeting | 6/24 | 1600-1730 | Meeting Room: Dam Visitor Center Basement Auditorium Phone number: (206) 553-4592 | | | | | |
| 1 | 6/25 | 0700-1030 | 3.5 | 23 | 1 | 2 | 2 | 25 |
| 2 | 6/25 | 1100-1430 | 3.5 | 22 | 1.5 | 2 | 3 | 25 |
| 3 | 6/25 | 1500-1830 | 3.5 | 21 | 2 | 2 | 4 | 25 |
| | 6/25-26 | 1830-0700 | | 25 | 0 | 0 | 0 | 25 |
| Meeting | 6/26 | 0700-0900 | Meeting Room: Dam Visitor Center Basement Auditorium Phone number: (206) 553-4592 | | | | | |
| 4 | 6/26 | 0900-1230 | 3.5 | 20 | 2.5 | 2 | 5 | 25 |
| 5 | 6/26 | 1300-1630 | 3.5 | 19 | 3 | 2 | 6 | 25 |
| 6 | 6/26 | 1700-2030 | 3.5 | 18 | 3.5 | 2 | 7 | 25 |
| | 6/26-27 | 2030-0900 | | 25 | 0 | 0 | 0 | 25 |
| Meeting | 6/27 | 0700-0900 | Meeting Room: Dam Visitor Center Basement Auditorium Phone number: (206) 553-4592 | | | | | |
| 7 | 6/27 | 0900-1230 | 3.5 | 17 | 4 | 2 | 8 | 25 |
| 8 | 6/27 | 1300-1630 | 3.5 | 16 | 4.5 | 2 | 9 | 25 |
| 9 | 6/27 | 1700-2030 | 3.5 | 15 | 5 | 2 | 10 | 25 |
| Remove Equipment | 6/28 | All day | | 25 | 0 | 0 | 0 | 25 |

# Appendix B
# TDG Field Studies: Methodology Water Quality Instrument Calibration, Maintenance, and Precision

The Hydrolab Corp. model DS4A® and minisonde 4A® were used exclusively for water quality monitoring in the Libby Dam TDG field studies of 2002. These instruments are wireless and capable of remotely logging temperature, depth, specific conductance, dissolved oxygen (DO), and TDG for a 1-2 week deployment period depending on logging interval and water temperature. Colder waters have a major impact on battery life and can cut the periods to 4 days or less on a 15-min 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 2 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 limits for collected data.

## Calibration of TDG

The Hydrolab tensionometers used for measuring TDG pressures employ semipermeable membranes connected to pressure transducers with associated electronics to directly measure in situ TDG 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 of mercury) 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 of mercury, directly to the transducer, and then adjusting the instrument reading accordingly to properly span the range of interest. The membrane was 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 was performed on the membrane itself before completing the calibration routine. One of the checks employed involved immersing the membrane in seltzer water (supersaturated with carbon dioxide). The expected result of a properly functioning membrane was an immediate jump in the TDG reading of at least 300mm of mercury. Membranes were also visually inspected for leaks and condensation moisture trapped inside the membrane. The leaks would usually appear as large darker spots in the membrane indicating that water had entered the silastic tubing. This could occur from either leaks through a tear in the membrane or water vapor diffusion and then condensation inside the membrane. Defective membranes were 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 served as a calibration chamber. After equilibration in this water bath, multiple instruments could then be calibrated to a standardized instrument. By adding a motor-driven propeller sleeved in a ported cylinder to the 50-gal batch tank, it was possible to achieve a steady state, homogeneous mixture of water approximately 97 percent saturated with air at a constant temperature. One instrument was designated as the standard for comparison and calibrated for specific conductance, depth, and DO (in air). Once the standard instrument and tank were prepared, several Winkler titration analyses were run to further verify the DO concentration in mg/l of the calibration tank. Adjustments were made to agree with the Winkler titration of DO at this point. The remaining instruments were then adjusted to read the same as the standard instrument for DO, specific conductance, and depth. Additional Winkler DO titrations were performed throughout the calibration procedure to ensure consistency for the rest of the instruments.

## Water quality calibration data from COE TDG 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, Kootenai, and Lower Snake Rivers. The status of each of the parameters before and after each calibration check and adjustment was 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 reflected only the calibrations performed on instruments before and after deployments that resulted in readings included in the study database. Logs for instruments requiring large-scale adjustments exceeding factory recommendations were 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 were 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 constituting 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.

Table B1. DGAS post deployment calibration check for drift in DO (mg/l) and TDG (mm of mercury).

| 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 |
| LIBBY Dam | DO | 0 | - | - | - | - |
| | TDG | 34 | -2.0 | 3.0 | 0.17 | 1.17 |
| | | | | | | |
| Combined Years | DO | 1248 | -2.4 | 2.12 | 0.05 | 0.52 |
| | TDG | 1499 | -21.00 | 19.0 | 0.44 | 3.27 |

The mean ±2 standard deviation (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 of mercury ± 6.5 mm of mercury. 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 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 of mercury in the 1996 sampling year to a low of 0.71 mm of mercury SD average for the TDG field studies conducted during the 2001 sampling year. The 34 instruments used in the Libby Dam TDG study during 2002 had a mean drift in the TDG calibration of 0.17 mm of mercury ± 1.17 m of mercury. This indicated that 95 percent of the individual measures for TDG pressure were within 2.34 mm of mercury of the measured value.

Of the approximately 1,500 TDG and DO post-deployment calibrations performed over the seven TDG sampling seasons, a small percentage have resulted in “out of tolerance” readings or other errors during calibration. Though these numbers did not necessarily reflect the number of times the instruments were serviced by field personnel or by factory technicians, they did suggest that there was 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 of mercury 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 of mercury TDG) demonstrated during the Rocky Reach study was within manufacturers specifications of ± 1 mm of mercury TDG pressure.

## Water quality instrument precision for COE TDG field studies

In addition to the calibration accuracy previously described, 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 spillways). 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 1-2 hr 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 inherited in the individual instruments and not due to changing water conditions. The measures were taken and logged on a 15-min time interval for all instruments producing four to eight readings per instrument per selected time period. This design resulted in a grand total of 279 samples of four to eight readings each. The analysis resulted in a mean standard deviation of 0.59 mm of mercury ± 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 CL of ± 1.18 mm of mercury. If this variance was applied to all instruments then paired sample means for separate treatments using the same instrument with differences of more than 2.36 mm of mercury would be significantly different

The same data set has been analyzed by grouping all water quality instruments on a sampling transect. This varied from two to eight instruments on each of six 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 mm of mercury ±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 CL for sample means of ±3.8 mm of mercury.

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 conditions previously cited, the resulting differences were due to uncertainty or bias introduced in the calibration of the individual instruments. The pressure readings were logged on 15-min time intervals in each case. Since the rate of gas diffusion through the membranes used by the TDG instruments was 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 of mercury 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 of mercury (95 percent CI = -3.86 to 4.22 mm of mercury) and saturation, 0.03 percent (95 percent CI = –0.59 to 0.65) were not significantly different from 0.

In light of the previously described quality assurance methods and uncertainty evaluation of the TDG procedures it appeared that with a minimal replication of measures it was possible to significantly discriminate between sample means differing by only a few mm of mercury 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 fell into the same range of about ± one-half percent TDG saturation. ±

Table B2
Paired TDG Sample Log Analysis, Calculations Made on Paired Reading Differences

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

Table 1. Summary of Total Dissolved Gas Sampling Stations

| Station Description | Distance from Libby Dam (miles) | River Mile (miles) | Station Label | Number of Sampling Stations | Location Comments |
|---|---|---|---|---|---|
| Forebay | -0.1 | 222 | FB | 1 | Deployed from Log Boom at Fixed Depth |
| Libby Dam | 0 | 221.9 | DTD | 1 | Draft Tube Deck at Turbine 4 |
| Stilling Basin | 0 | 221.9 | SB | 1 | Temporary Station during 1st Event |
| Below Stilling Basin | 0.1 | 221.8 | SPW | 2 | 250 ft Downstream of Stilling Basin |
| Thompson Bridge | 0.4 | 221.5 | TMPBR | 4 | Left Bank, Quarter Points |
| USGS Gage | 0.6 | 221.3 | USGS | 5 | Left, Right Bank and Three Intermediate Stations |
| Tailwater Fixed Monitoring Station | 0.6 | 221..3 | LIBM | 1 | Deployed in pipe from right bank at USGS gage |
| Real time Monitor 1 | 0.7 | 221.2 | RTM1 | 1 | Left Bank in braided channel |
| MFW Fish Cage 1 | 0.8 | 221.1 | MFW1 | 1 | Left Side of Channel |
| MFW Fish Cage 2 | 1.2 | 220.7 | MFW2 | 1 | Left Side of Channel |
| Real time Monitor 2 | 1.4 | 220.5 | RTM2 | 1 | 40 ft Right Channel Bank |
| MFW Fish Cage 3 | 1.7 | 220.2 | MFW3 | 1 | Left Side of Channel |
| Highway 37 Bridge | 3.5 | 218.4 | FISHER | 3 | Bridge Deployed Left, Center, Right Channel |
| Old Haul Bridge | 8.6 | 213.3 | HAUL | 2 | Left (P1) and Right (P5) Bank |
| Upstream Libby, MT | 15.1 | 206.8 | USLIBBY | 2 | Left (P1) and Right (P5) Bank |
| Downstream Libby, MT | 21.8 | 200.1 | DSLIBBY | 2 | Left (P1) and Right (P5) Bank |
| Upstream of Kootenai Falls | 27.4 | 194.5 | USFALLS | 2 | Left (P1) and Right (P5) Bank |
| Downstream of Kootenai Falls | 30.2 | 191.7 | DSFALLS | 1 | Left Bank |
| Kootenai River near Troy, MT | 35.7 | 186.2 | TROY | 1 | Right Bank |
| Kootenai River at Porthill, ID | 116 | 105.9 | PORTHILL | 1 | Right Bank |

Table 2. Project Operations by Spill Event at Libby Dam, June 25 – July 7, 2002

| Event Number | Starting Date Time (m/dd/yr hr:min) | Ending Date Time (m/dd/yr hr:min) | Duration (hr:min) | Total River Flow (kcfs) | Spill Flow (kcfs) | Generation Flow (kcfs) | Tailwater Elevation (ft) | Forebay Elevation (ft) |
|---|---|---|---|---|---|---|---|---|
| 1 | 6/25/02 7:00 | 6/25/02 9:45 | 2:45 | 23.5 | 0.7 | 22.8 | 2124.5 | 2449.9 |
| 2 | 6/25/02 11:45 | 6/25/02 13:45 | 2:00 | 23.8 | 3.0 | 20.8 | 2124.5 | 2450.3 |
| 3 | 6/25/02 15:00 | 6/25/02 17:45 | 2:45 | 29.0 | 6.0 | 23.0 | 2124.6 | 2450.5 |
| 4 | 6/25/02 18:00 | 6/26/02 8:45 | 14:45 | 29.0 | 4.0 | 25.0 | 2125.4 | 2451.0 |
| 5 | 6/26/02 9:00 | 6/26/02 15:45 | 6:45 | 30.0 | 5.0 | 25.0 | 2125.6 | 2451.7 |
| 6 | 6/26/02 16:00 | 6/28/02 7:45 | 39:45 | 32.0 | 7.0 | 25.0 | 2126.0 | 2452.9 |
| 7 | 6/28/02 10:00 | 6/28/02 13:45 | 3:45 | 32.0 | 7.4 | 24.6 | 2126.0 | 2454.2 |
| 8 | 6/28/02 14:00 | 6/28/02 15:45 | 1:45 | 33.0 | 8.4 | 24.6 | 2126.2 | 2454.3 |
| 9 | 6/28/02 16:00 | 6/30/02 10:45 | 42:45 | 35.0 | 10.6 | 24.4 | 2126.5 | 2455.4 |
| 10 | 6/30/02 11:00 | 6/30/02 12:45 | 1:45 | 36.0 | 11.6 | 24.4 | 2126.7 | 2456.3 |
| 11 | 6/30/02 13:00 | 6/30/02 14:45 | 1:45 | 37.0 | 12.6 | 24.4 | 2126.9 | 2456.4 |
| 12 | 6/30/02 15:00 | 7/1/02 11:45 | 20:45 | 38.0 | 13.6 | 24.4 | 2127.1 | 2456.8 |
| 13 | 7/1/02 12:00 | 7/1/02 13:45 | 1:45 | 39.0 | 14.6 | 24.4 | 2127.2 | 2457.1 |
| 14 | 7/1/02 14:00 | 7/3/02 9:45 | 43:45 | 40.0 | 15.6 | 24.4 | 2127.4 | 2457.3 |
| 15 | 7/3/02 10:00 | 7/3/02 12:45 | 2:45 | 39.0 | 14.6 | 24.4 | 2127.2 | 2457.3 |
| 16 | 7/3/02 13:00 | 7/4/02 9:45 | 20:45 | 38.0 | 13.6 | 24.4 | 2127.1 | 2457.1 |
| 17 | 7/4/02 10:00 | 7/4/02 12:45 | 2:45 | 37.0 | 12.6 | 24.4 | 2126.9 | 2456.9 |
| 18 | 7/4/02 13:00 | 7/4/02 15:45 | 2:45 | 36.0 | 11.6 | 24.4 | 2126.7 | 2456.9 |
| 19 | 7/4/02 16:00 | 7/5/02 10:45 | 18:45 | 35.0 | 10.6 | 24.4 | 2126.5 | 2456.8 |
| 20 | 7/5/02 11:00 | 7/5/02 13:45 | 2:45 | 32.5 | 8.1 | 24.4 | 2126.1 | 2456.8 |
| 21 | 7/5/02 14:00 | 7/6/02 11:45 | 21:45 | 30.0 | 5.6 | 24.4 | 2125.7 | 2456.7 |
| 22 | 7/6/02 12:00 | 7/7/02 9:45 | 21:45 | 28.0 | 3.6 | 24.4 | 2125.3 | 2456.6 |
| 23 | 7/7/02 10:00 | 7/7/02 12:45 | 2:45 | 26.0 | 2.0 | 24.4 | 2125.1 | 2456.6 |

Table 3. Statistical Summary of Total Dissolved Gas Saturation in the Kootenai River During Spill from Libby Dam, 0700 June 25 to 1300 July 7, 2002

| Station | N | TDG | | | | Total Dissolved Gas Saturation Percent Exceedance (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | avg | max | min | stdev | 100 | 105 | 110 | 115 | 120 | 125 | 130 | 135 |
| FB | 1176 | 106.2 | 113.2 | 102.5 | 2.8 | 100 | 55.7 | 9.1 | 0 | 0 | 0 | 0 | 0 |
| DTD | 1176 | 102.7 | 108.6 | 101.6 | 0.7 | 100 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| SPWP1 | 1176 | 130.1 | 132.9 | 102.3 | 4.3 | 100 | 98.6 | 98.3 | 98 | 97.5 | 95.8 | 78.4 | 0 |
| SPWP2 | 1176 | 131.4 | 134.3 | 102.3 | 4.1 | 100 | 98.6 | 98.5 | 98.4 | 98 | 96.9 | 87.9 | 0 |
| TMPSNP1 | 1143 | 124.6 | 127.0 | 104.0 | 2.4 | 100 | 99.7 | 99.4 | 99.3 | 98.2 | 58.3 | 0 | 0 |
| TMPSNP2 | 1176 | 122.4 | 126.4 | 102.5 | 4.6 | 100 | 98 | 96.5 | 93.2 | 80.9 | 22.9 | 0 | 0 |
| TMPSNP3 | 0 | | | | | | | | | | | | |
| TMPSNP4 | 1176 | 103.3 | 107.3 | 102.0 | 0.7 | 100 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| USGSP1 | 1174 | 122.6 | 125.6 | 102.5 | 4.1 | 100 | 98.2 | 97.4 | 95.6 | 82.8 | 14.9 | 0 | 0 |
| USGSP2 | 1175 | 120.9 | 125.4 | 102.5 | 4.8 | 100 | 97.9 | 95.9 | 83.1 | 80.4 | 0.4 | 0 | 0 |
| USGSP3 | 1175 | 118.9 | 123.6 | 103.0 | 4.7 | 100 | 98 | 94.8 | 80.6 | 56.4 | 0 | 0 | 0 |
| USGSP4 | 1175 | 108.2 | 113.4 | 102.7 | 1.9 | 100 | 96.6 | 23.6 | 0 | 0 | 0 | 0 | 0 |
| USGSP5 | 1175 | 104.3 | 106.9 | 103.0 | 0.7 | 100 | 17.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| RTP1 | 85 | 122.1 | 123.4 | 119.5 | 1.3 | 100 | 100 | 100 | 100 | 84.3 | 0 | 0 | 0 |
| RTP2 | 201 | 104.7 | 106.1 | 103.0 | 0.9 | 100 | 33.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| MFW1 | 45 | 109.4 | 122.2 | 102.4 | 7.6 | 100 | 55.3 | 37 | 23.8 | 21.1 | 0 | 0 | 0 |
| MFW2 | 1114 | 115.6 | 120.3 | 102.1 | 3.4 | 100 | 97.5 | 95.4 | 67.1 | 0.3 | 0 | 0 | 0 |
| MFW3 | 906 | 119.8 | 124.2 | 106.1 | 2.7 | 100 | 100 | 99.3 | 91.6 | 57 | 0 | 0 | 0 |
| FISHERP1 | 1176 | 118.4 | 122.5 | 100.4 | 4.1 | 100 | 98.2 | 95.9 | 82.3 | 47.3 | 0 | 0 | 0 |
| FISHERP2 | 0 | | | | | | | | | | | | |
| FISHERP3 | 1176 | 107.4 | 111.7 | 99.9 | 1.8 | 100 | 91 | 6.6 | 0 | 0 | 0 | 0 | 0 |
| HAULP1 | 1176 | 112.4 | 116.8 | 102.0 | 2.9 | 100 | 98.1 | 84.5 | 19 | 0 | 0 | 0 | 0 |
| HAULP5 | 1176 | 111.2 | 115.4 | 102.4 | 2.6 | 100 | 97.4 | 72.6 | 1.1 | 0 | 0 | 0 | 0 |
| USLIBBYP1 | 1176 | 110.9 | 115.7 | 101.4 | 2.8 | 100 | 97.9 | 68.8 | 3.7 | 0 | 0 | 0 | 0 |
| USLIBBYP5 | 1176 | 110.3 | 114.8 | 101.6 | 2.5 | 100 | 98.1 | 62.6 | 0 | 0 | 0 | 0 | 0 |
| DSLIBBYP1 | 1176 | 111.1 | 115.9 | 102.7 | 2.6 | 100 | 98.3 | 69.8 | 4 | 0 | 0 | 0 | 0 |
| DSLIBBYP5 | 0 | | | | | | | | | | | | |
| USFALLSP1 | 1176 | 109.3 | 113.7 | 101.7 | 2.3 | 100 | 95.4 | 43.2 | 0 | 0 | 0 | 0 | 0 |
| USFALLSP5 | 910 | 108.7 | 113.7 | 101.8 | 2.3 | 100 | 91.6 | 35.4 | 0 | 0 | 0 | 0 | 0 |
| DSFALLS | 1089 | 118.2 | 120.7 | 111.6 | 1.6 | 100 | 100 | 100 | 96.9 | 12.5 | 0 | 0 | 0 |
| TROY | 964 | 117.3 | 119.5 | 115.3 | 1.0 | 100 | 100 | 100 | 100 | 0 | 0 | 0 | 0 |
| Porthill | 1173 | 109.8 | 112.7 | 107.7 | 1.1 | 100 | 100 | 39 | 0 | 0 | 0 | 0 | 0 |

| Table 4. Event Statistical Summary of Total Dissolved Gas Properties below the Stilling Basin at Libby Dam, Sampling Station (SPWP1) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Event Number | Spill Flow (kcfs) | Barometric Pressure (mm Hg) | Number of Observations | Mean Total Pressure (mm Hg) | Max. Total Pressure (mm Hg) | Min. Total Pressure (mm Hg) | Std Dev. Total Pressure (mm Hg) | Delta Pressure (mm Hg) | Total Dissolved Gas Saturation (%) |
| 1 | 0.7 | 708.0 | 9 | 725.4 | 728 | 724 | 1.4 | 17.4 | 102.5 |
| 2 | 3.0 | 708.0 | 5 | 863.6 | 867 | 858 | 3.4 | 155.6 | 122.0 |
| 3 | 6.0 | 708.0 | 8 | 917.6 | 919 | 913 | 2.2 | 209.6 | 129.6 |
| 4 | 4.0 | 707.0 | 56 | 898.5 | 901 | 895 | 1.6 | 191.4 | 127.1 |
| 5 | 5.0 | 706.3 | 24 | 912.0 | 915 | 909 | 1.8 | 205.7 | 129.1 |
| 6 | 7.0 | 706.0 | 156 | 921.4 | 924 | 918 | 1.3 | 215.4 | 130.5 |
| 7 | 7.4 | 706.0 | 12 | 921.0 | 924 | 909 | 4.3 | 215.0 | 130.5 |
| 8 | 8.4 | 706.0 | 4 | 924.3 | 925 | 924 | 0.5 | 218.3 | 130.9 |
| 9 | 10.6 | 706.0 | 168 | 929.0 | 933 | 924 | 2.0 | 223.0 | 131.6 |
| 10 | 11.6 | 705.0 | 4 | 934.8 | 935 | 934 | 0.5 | 229.8 | 132.6 |
| 11 | 12.6 | 705.0 | 4 | 934.0 | 935 | 933 | 0.8 | 229.0 | 132.5 |
| 12 | 13.6 | 706.1 | 80 | 934.5 | 937 | 931 | 1.1 | 228.4 | 132.3 |
| 13 | 14.6 | 707.0 | 4 | 934.0 | 935 | 933 | 0.8 | 227.0 | 132.1 |
| 14 | 15.6 | 707.0 | 172 | 932.0 | 939 | 926 | 2.4 | 225.0 | 131.8 |
| 15 | 14.6 | 703.0 | 8 | 930.1 | 933 | 927 | 2.2 | 227.1 | 132.3 |
| 16 | 13.6 | 702.4 | 80 | 929.8 | 933 | 924 | 2.0 | 227.4 | 132.4 |
| 17 | 12.6 | 704.0 | 8 | 934.3 | 935 | 932 | 1.2 | 230.3 | 132.7 |
| 18 | 11.6 | 704.1 | 8 | 932.6 | 935 | 931 | 1.3 | 228.5 | 132.5 |
| 19 | 10.6 | 706.2 | 72 | 931.9 | 934 | 930 | 1.1 | 225.7 | 132.0 |
| 20 | 8.1 | 708.0 | 8 | 928.8 | 929 | 928 | 0.5 | 220.8 | 131.2 |
| 21 | 5.6 | 707.4 | 84 | 921.0 | 924 | 919 | 1.1 | 213.6 | 130.2 |
| 22 | 3.6 | 706.3 | 84 | 897.2 | 901 | 894 | 1.6 | 190.9 | 127.0 |
| 23 | 2.0 | 706.4 | 8 | 870.0 | 876 | 867 | 2.8 | 163.6 | 123.2 |

Table 5. Event Statistical Summary of Total Dissolved Gas Properties below the Stilling Basin at Libby Dam, Sampling Station (SPWP2)

| Event Number | Spill Flow (kcfs) | Barometric Pressure (mm Hg) | Number of Observations | Mean Total Pressure (mm Hg) | Max. Total Pressure (mm Hg) | Min. Total Pressure (mm Hg) | Std Dev. Total Pressure (mm Hg) | Delta Pressure (mm Hg) | Total Dissolved Gas Saturation (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.7 | 708.0 | 9 | 725.1 | 726.0 | 725.0 | 0.3 | 17.1 | 102.5 |
| 2 | 3.0 | 708.0 | 5 | 882.0 | 886.0 | 876.0 | 3.8 | 174.0 | 125.1 |
| 3 | 6.0 | 708.0 | 8 | 917.4 | 919.0 | 915.0 | 1.4 | 209.4 | 129.8 |
| 4 | 4.0 | 707.0 | 56 | 921.1 | 925.0 | 918.0 | 1.8 | 214.1 | 130.8 |
| 5 | 5.0 | 706.3 | 24 | 935.1 | 940.0 | 931.0 | 2.6 | 228.8 | 133.1 |
| 6 | 7.0 | 706.0 | 156 | 926.8 | 933.0 | 918.0 | 3.0 | 220.8 | 132.2 |
| 7 | 7.4 | 706.0 | 12 | 924.6 | 931.0 | 919.0 | 3.7 | 218.6 | 131.9 |
| 8 | 8.4 | 706.0 | 4 | 923.5 | 925.0 | 921.0 | 1.9 | 217.5 | 131.0 |
| 9 | 10.6 | 706.0 | 168 | 935.5 | 943.0 | 927.0 | 2.7 | 229.5 | 133.6 |
| 10 | 11.6 | 705.0 | 4 | 942.5 | 943.0 | 942.0 | 0.6 | 237.5 | 133.8 |
| 11 | 12.6 | 705.0 | 4 | 942.3 | 944.0 | 940.0 | 1.7 | 237.3 | 133.9 |
| 12 | 13.6 | 706.1 | 80 | 941.8 | 944.0 | 938.0 | 1.5 | 235.7 | 133.7 |
| 13 | 14.6 | 707.0 | 4 | 941.8 | 943.0 | 941.0 | 1.0 | 234.8 | 133.4 |
| 14 | 15.6 | 707.0 | 172 | 938.6 | 946.0 | 932.0 | 2.9 | 231.6 | 133.8 |
| 15 | 14.6 | 703.0 | 8 | 937.3 | 943.0 | 933.0 | 3.3 | 234.3 | 134.1 |
| 16 | 13.6 | 702.4 | 80 | 937.8 | 943.0 | 933.0 | 2.2 | 235.4 | 134.2 |
| 17 | 12.6 | 704.0 | 8 | 942.0 | 944.0 | 939.0 | 1.4 | 238.0 | 134.1 |
| 18 | 11.6 | 704.1 | 8 | 940.0 | 944.0 | 938.0 | 1.9 | 235.9 | 134.1 |
| 19 | 10.6 | 706.2 | 72 | 939.1 | 943.0 | 934.0 | 1.5 | 232.9 | 133.5 |
| 20 | 8.1 | 708.0 | 8 | 928.5 | 933.0 | 923.0 | 3.0 | 220.5 | 131.8 |
| 21 | 5.6 | 707.4 | 84 | 929.7 | 934.0 | 921.0 | 2.2 | 222.3 | 132.0 |
| 22 | 3.6 | 706.3 | 84 | 917.4 | 924.0 | 914.0 | 1.9 | 211.1 | 130.8 |
| 23 | 2.0 | 706.4 | 8 | 887.6 | 892.0 | 886.0 | 2.1 | 181.3 | 126.3 |

Table 6. Average Total Dissolved Gas Saturation by Spill Event at and upstream of the Thompson Bridge

| Event | Starting Date Time (m/dd/yr hr:min) | Ending Date Time (m/dd/yr hr:min) | $Q_{river}$ (kcfs) | $Q_{spill}$ (kcfs) | N | TDG Saturation FB (%) | DTD (%) | SPWP1 (%) | SPWP2 (%) | TMPSNP1 (%) | TMPSNP2 (%) | TMPSNP4 (%) | LIBavg* (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6/25/02 7:45 | 6/25/02 9:45 | 23.5 | 0.7 | 9 | 108.5 | 102.5 | 102.5 | 102.4 | | 102.6 | 102.8 | 102.5 |
| 2 | 6/25/02 12:45 | 6/25/02 13:45 | 23.8 | 3.0 | 5 | 108.5 | 102.8 | 122.0 | 124.6 | | 109.4 | 102.6 | 105.4 |
| 3 | 6/25/02 16:00 | 6/25/02 17:45 | 29.0 | 6.0 | 8 | 109.4 | 102.3 | 129.6 | 129.6 | 124.5 | 122.7 | 102.8 | 107.9 |
| 4 | 6/25/02 19:00 | 6/26/02 8:45 | 29.0 | 4.0 | 56 | 109.0 | 102.5 | 127.1 | 130.3 | 121.2 | 115.1 | 102.9 | 106.1 |
| 5 | 6/26/02 10:00 | 6/26/02 15:45 | 30.0 | 5.0 | 24 | 109.2 | 102.3 | 129.1 | 132.4 | 123.3 | 119.8 | 102.9 | 107.0 |
| 6 | 6/26/02 17:00 | 6/28/02 7:45 | 32.0 | 7.0 | 156 | 107.7 | 102.6 | 130.5 | 131.3 | 124.9 | 123.4 | 103.8 | 108.8 |
| 7 | 6/28/02 11:00 | 6/28/02 13:45 | 32.0 | 7.4 | 12 | 105.1 | 102.6 | 130.5 | 131.0 | 125.3 | 123.4 | 102.8 | 109.1 |
| 8 | 6/28/02 15:00 | 6/28/02 15:45 | 33.0 | 8.4 | 4 | 104.3 | 102.5 | 130.9 | 130.8 | 125.1 | 123.9 | 102.8 | 109.7 |
| 9 | 6/28/02 17:00 | 6/30/02 10:45 | 35.0 | 10.6 | 168 | 104.0 | 102.3 | 131.6 | 132.5 | 125.3 | 124.1 | 102.4 | 111.3 |
| 10 | 6/30/02 12:00 | 6/30/02 12:45 | 36.0 | 11.6 | 4 | 103.5 | 102.4 | 132.6 | 133.7 | 126.1 | 124.7 | 102.4 | 112.3 |
| 11 | 6/30/02 14:00 | 6/30/02 14:45 | 37.0 | 12.6 | 4 | 103.3 | 102.3 | 132.5 | 133.7 | 126.3 | 124.7 | 102.4 | 112.8 |
| 12 | 6/30/02 16:00 | 7/1/02 11:45 | 38.0 | 13.6 | 80 | 103.2 | 102.0 | 132.3 | 133.4 | 125.8 | 124.7 | 102.4 | 113.0 |
| 13 | 7/1/02 13:00 | 7/1/02 13:45 | 39.0 | 14.6 | 4 | 102.7 | 101.8 | 132.1 | 133.2 | 126.0 | 124.8 | 102.5 | 113.3 |
| 14 | 7/1/02 15:00 | 7/3/02 9:45 | 40.0 | 15.6 | 172 | 103.2 | 102.0 | 131.8 | 132.8 | 126.1 | 125.3 | 103.4 | 113.8 |
| 15 | 7/3/02 11:00 | 7/3/02 12:45 | 39.0 | 14.6 | 8 | 104.2 | 102.8 | 132.3 | 133.3 | 126.2 | 125.4 | 103.9 | 114.0 |
| 16 | 7/3/02 14:00 | 7/4/02 9:45 | 38.0 | 13.6 | 80 | 106.9 | 103.4 | 132.4 | 133.5 | 126.1 | 125.2 | 104.1 | 114.0 |
| 17 | 7/4/02 11:00 | 7/4/02 12:45 | 37.0 | 12.6 | 8 | 104.5 | 103.1 | 132.7 | 133.8 | 126.4 | 124.9 | 103.4 | 113.4 |
| 18 | 7/4/02 14:00 | 7/4/02 15:45 | 36.0 | 11.6 | 8 | 103.9 | 102.9 | 132.5 | 133.5 | 126.2 | 124.9 | 103.0 | 112.6 |
| 19 | 7/4/02 17:00 | 7/5/02 10:45 | 35.0 | 10.6 | 72 | 105.5 | 103.0 | 132.0 | 133.0 | 125.1 | 124.6 | 103.0 | 111.9 |
| 20 | 7/5/02 12:00 | 7/5/02 13:45 | 32.5 | 8.1 | 8 | 106.3 | 103.5 | 131.2 | 131.1 | 124.6 | 124.1 | 103.3 | 110.4 |
| 21 | 7/5/02 15:00 | 7/6/02 11:45 | 30.0 | 5.6 | 84 | 107.9 | 103.6 | 130.2 | 131.4 | 124.4 | 122.9 | 103.6 | 108.7 |
| 22 | 7/6/02 13:00 | 7/7/02 9:45 | 28.0 | 3.6 | 84 | 112.0 | 104.0 | 127.0 | 129.9 | 121.2 | 117.0 | 104.3 | 107.1 |
| 23 | 7/7/02 11:00 | 7/7/02 12:45 | 26.0 | 2.0 | 8 | 112.7 | 104.1 | 123.2 | 125.7 | 116.3 | 110.9 | 104.4 | 105.7 |

* $LIB_{avg}$ = Flow-weighted average TDG saturation by event at the Libby Dam

| Table 7. Average Total Dissolved Gas Saturation by Spill Event at the USGS Transect | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | Starting Date Time (m/dd/yr hr:min) | Ending Date Time (m/dd/yr hr:min) | $Q_{river}$ (kcfs) | $Q_{spill}$ (kcfs) | N | TDG Saturation | | | | | |
| | | | | | | USGSP1 (%) | USGSP2 (%) | USGSP3 (%) | USGSP4 (%) | USGSP5 (%) | $USGS_{avg}$* (%) |
| 1 | 6/25/02 7:45 | 6/25/02 9:45 | 23.5 | 0.7 | 9 | 102.7 | 102.6 | 103.1 | 102.7 | 103.2 | 102.7 |
| 2 | 6/25/02 12:45 | 6/25/02 13:45 | 23.8 | 3.0 | 5 | 111.0 | 108.2 | 107.8 | 104.5 | 103.7 | 107.2 |
| 3 | 6/25/02 16:00 | 6/25/02 17:45 | 29.0 | 6.0 | 8 | 123.0 | 120.8 | 118.2 | 106.8 | 104.5 | 116.4 |
| 4 | 6/25/02 19:00 | 6/26/02 8:45 | 29.0 | 4.0 | 56 | 116.6 | 112.0 | 110.6 | 105.4 | 104.2 | 110.1 |
| 5 | 6/26/02 10:00 | 6/26/02 15:45 | 30.0 | 5.0 | 24 | 120.8 | 116.4 | 113.8 | 105.9 | 104.4 | 113.1 |
| 6 | 6/26/02 17:00 | 6/28/02 7:45 | 32.0 | 7.0 | 156 | 123.5 | 121.9 | 119.0 | 107.6 | 104.9 | 117.3 |
| 7 | 6/28/02 11:00 | 6/28/02 13:45 | 32.0 | 7.4 | 12 | 123.4 | 121.9 | 119.0 | 107.0 | 103.9 | 117.0 |
| 8 | 6/28/02 15:00 | 6/28/02 15:45 | 33.0 | 8.4 | 4 | 123.8 | 122.6 | 120.3 | 107.4 | 103.7 | 117.8 |
| 9 | 6/28/02 17:00 | 6/30/02 10:45 | 35.0 | 10.6 | 168 | 124.0 | 123.0 | 121.3 | 108.2 | 103.4 | 118.3 |
| 10 | 6/30/02 12:00 | 6/30/02 12:45 | 36.0 | 11.6 | 4 | 124.9 | 123.7 | 122.1 | 108.8 | 103.6 | 118.9 |
| 11 | 6/30/02 14:00 | 6/30/02 14:45 | 37.0 | 12.6 | 4 | 125.1 | 123.9 | 122.4 | 109.1 | 103.5 | 119.2 |
| 12 | 6/30/02 16:00 | 7/1/02 11:45 | 38.0 | 13.6 | 80 | 124.5 | 123.7 | 122.4 | 109.6 | 103.5 | 119.1 |
| 13 | 7/1/02 13:00 | 7/1/02 13:45 | 39.0 | 14.6 | 4 | 124.9 | 124.0 | 122.6 | 110.0 | 104.2 | 119.4 |
| 14 | 7/1/02 15:00 | 7/3/02 9:45 | 40.0 | 15.6 | 172 | 125.0 | 124.3 | 122.8 | 110.7 | 104.4 | 119.7 |
| 15 | 7/3/02 11:00 | 7/3/02 12:45 | 39.0 | 14.6 | 8 | 125.0 | 124.3 | 122.3 | 110.8 | 105.3 | 119.7 |
| 16 | 7/3/02 14:00 | 7/4/02 9:45 | 38.0 | 13.6 | 80 | 124.9 | 124.2 | 122.2 | 110.9 | 105.3 | 119.7 |
| 17 | 7/4/02 11:00 | 7/4/02 12:45 | 37.0 | 12.6 | 8 | 125.1 | 124.0 | 121.8 | 110.1 | 104.6 | 119.3 |
| 18 | 7/4/02 14:00 | 7/4/02 15:45 | 36.0 | 11.6 | 8 | 125.0 | 123.8 | 121.4 | 109.2 | 104.4 | 118.9 |
| 19 | 7/4/02 17:00 | 7/5/02 10:45 | 35.0 | 10.6 | 72 | 124.4 | 123.5 | 121.0 | 108.6 | 104.0 | 118.5 |
| 20 | 7/5/02 12:00 | 7/5/02 13:45 | 32.5 | 8.1 | 8 | 124.1 | 122.8 | 120.1 | 107.9 | 104.4 | 117.9 |
| 21 | 7/5/02 15:00 | 7/6/02 11:45 | 30.0 | 5.6 | 84 | 123.1 | 121.1 | 117.6 | 106.9 | 104.4 | 116.4 |
| 22 | 7/6/02 13:00 | 7/7/02 9:45 | 28.0 | 3.6 | 84 | 118.3 | 114.6 | 111.4 | 106.6 | 104.9 | 111.7 |
| 23 | 7/7/02 11:00 | 7/7/02 12:45 | 26.0 | 2.0 | 8 | 112.5 | 109.7 | 108.8 | 106.0 | 105.2 | 108.5 |

* $USGS_{avg}$ = Flow-weighted average TDG saturation by event at the USGS transect

| Table 8. Average Total Dissolved Gas Saturation by Spill Event at the Fish Cage Locations | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Event | Starting Date Time (m/dd/yr hr:min) | Ending Date Time (m/dd/yr hr:min) | $Q_{river}$ (kcfs) | $Q_{spill}$ (kcfs) | USGSP1 | MFW1 | MFW2 | MFW3 |
| 1 | 6/25/02 7:45 | 6/25/02 9:45 | 23.5 | 0.7 | 102.7 | 102.7 | 102.7 | |
| 2 | 6/25/02 12:45 | 6/25/02 13:45 | 23.8 | 3.0 | 111.0 | 110.3 | 109.2 | |
| 3 | 6/25/02 16:00 | 6/25/02 17:45 | 29.0 | 6.0 | 123.0 | 122.0 | 119.9 | |
| 4 | 6/25/02 19:00 | 6/26/02 8:45 | 29.0 | 4.0 | 116.6 | | 112.1 | |
| 5 | 6/26/02 10:00 | 6/26/02 15:45 | 30.0 | 5.0 | 120.8 | | 112.5 | |
| 6 | 6/26/02 17:00 | 6/28/02 7:45 | 32.0 | 7.0 | 123.5 | | 113.8 | 116.1 |
| 7 | 6/28/02 11:00 | 6/28/02 13:45 | 32.0 | 7.4 | 123.4 | | 113.2 | 117.4 |
| 8 | 6/28/02 15:00 | 6/28/02 15:45 | 33.0 | 8.4 | 123.8 | | 113.8 | 117.8 |
| 9 | 6/28/02 17:00 | 6/30/02 10:45 | 35.0 | 10.6 | 124.0 | | 115.6 | 119.1 |
| 10 | 6/30/02 12:00 | 6/30/02 12:45 | 36.0 | 11.6 | 124.9 | | 117.0 | 120.9 |
| 11 | 6/30/02 14:00 | 6/30/02 14:45 | 37.0 | 12.6 | 125.1 | | 117.4 | 121.1 |
| 12 | 6/30/02 16:00 | 7/1/02 11:45 | 38.0 | 13.6 | 124.5 | | 117.5 | 121.1 |
| 13 | 7/1/02 13:00 | 7/1/02 13:45 | 39.0 | 14.6 | 124.9 | | 118.0 | 123.5 |
| 14 | 7/1/02 15:00 | 7/3/02 9:45 | 40.0 | 15.6 | 125.0 | | 118.6 | 121.9 |
| 15 | 7/3/02 11:00 | 7/3/02 12:45 | 39.0 | 14.6 | 125.0 | | 118.7 | 121.7 |
| 16 | 7/3/02 14:00 | 7/4/02 9:45 | 38.0 | 13.6 | 124.9 | | 118.5 | 121.8 |
| 17 | 7/4/02 11:00 | 7/4/02 12:45 | 37.0 | 12.6 | 125.1 | | 118.5 | 121.9 |
| 18 | 7/4/02 14:00 | 7/4/02 15:45 | 36.0 | 11.6 | 125.0 | | 118.2 | 122.2 |
| 19 | 7/4/02 17:00 | 7/5/02 10:45 | 35.0 | 10.6 | 124.4 | | 117.8 | 121.2 |
| 20 | 7/5/02 12:00 | 7/5/02 13:45 | 32.5 | 8.1 | 124.1 | | 117.7 | 121.1 |
| 21 | 7/5/02 15:00 | 7/6/02 11:45 | 30.0 | 5.6 | 123.1 | | 115.5 | 118.9 |
| 22 | 7/6/02 13:00 | 7/7/02 9:45 | 28.0 | 3.6 | 118.3 | | 111.0 | 114.8 |
| 23 | 7/7/02 11:00 | 7/7/02 12:45 | 26.0 | 2.0 | 112.5 | | 107.6 | 113.1 |

Table 9. Daily Average Total Dissolved Gas Saturation in the Kootenai River below Libby Dam, June 24-July 9, 2002

| date | $Q_{river}$ (kcfs) | $Q_{spill}$l (kcfs) | Total Dissolved Gas Saturation by transect (%) | | | | | | | | | | | ΔTDG[2] Dam | ΔTDG[3] Falls | $Q_{spill}$ eff[4] (kcfs) | $Q_{ent}$[5] (kcfs) | ΔTDG/mile[6] (%/mile) | ΔTDG/mile[7] (%/mile) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DTD | SPW | FWA[1] | USGS | FISHER | HAUL | USLIB | DSLIB | USFALLS | DSFALLS | TROY | | | | | | |
| 6/24/02 | 25.0 | 0.0 | 102.6 | 102.8 | 102.6 | 103.4 | 103.5 | 103.7 | 103.6 | 104.6 | 103.9 | 116.4 | | 0.8 | 12.5 | | | | |
| 6/25/02 | 26.2 | 2.2 | 102.5 | 114.8 | 104.4 | 106.0 | 105.4 | 105.0 | 104.5 | 105.3 | 104.1 | 116.6 | | 3.5 | 12.5 | | | | |
| 6/26/02 | 30.3 | 5.3 | 102.4 | 130.0 | 107.2 | 111.3 | 109.8 | 108.6 | 107.7 | 108.2 | 106.9 | 112.3 | | 8.9 | 5.4 | 9.7 | 4.5 | 0.162 | |
| 6/27/02 | 32.0 | 7.0 | 102.6 | 130.9 | 108.8 | 113.0 | 112.7 | 111.2 | 110.1 | 110.3 | 108.7 | 116.3 | 116.1 | 10.4 | 7.6 | 11.7 | 4.7 | 0.163 | 0.041 |
| 6/28/02 | 32.4 | 7.7 | 103.0 | 129.9 | 109.4 | 113.5 | 112.1 | 110.7 | 109.4 | 109.8 | 108.2 | 116.3 | 116.2 | 10.5 | 8.1 | 12.7 | 5.0 | 0.200 | 0.027 |
| 6/29/02 | 35.0 | 10.6 | 102.3 | 132.0 | 111.3 | 115.2 | 113.5 | 112.3 | 111.1 | 111.2 | 109.4 | 117.8 | 116.8 | 12.9 | 8.4 | 15.2 | 4.6 | 0.216 | 0.193 |
| 6/30/02 | 36.4 | 12.0 | 102.2 | 132.7 | 112.2 | 115.8 | 114.2 | 112.9 | 111.6 | 111.7 | 109.9 | 118.9 | 117.5 | 13.6 | 9 | 16.2 | 4.2 | 0.219 | 0.251 |
| 7/1/02 | 38.9 | 14.5 | 101.9 | 132.6 | 113.3 | 116.5 | 115.1 | 114.0 | 112.4 | 113.0 | 110.9 | 119.9 | 118.1 | 14.6 | 9 | 18.6 | 4.1 | 0.210 | 0.324 |
| 7/2/02 | 40.0 | 15.6 | 101.9 | 132.3 | 113.8 | 117.0 | 115.7 | 114.7 | 113.3 | 113.9 | 111.7 | 120.1 | 118.6 | 15.1 | 8.4 | 19.8 | 4.2 | 0.198 | 0.272 |
| 7/3/02 | 39.0 | 14.6 | 103.0 | 132.7 | 114.1 | 117.1 | 115.8 | 114.9 | 113.4 | 113.9 | 111.8 | 120.0 | 118.6 | 14.1 | 8.2 | 18.6 | 4.0 | 0.201 | 0.264 |
| 7/4/02 | 36.6 | 12.2 | 103.1 | 132.8 | 113.0 | 116.3 | 115.1 | 114.0 | 112.8 | 113.1 | 111.1 | 119.4 | 118.0 | 13.2 | 8.3 | 16.2 | 4.0 | 0.195 | 0.261 |
| 7/5/02 | 32.6 | 8.2 | 103.4 | 131.7 | 110.4 | 114.6 | 113.4 | 112.5 | 111.5 | 112.0 | 110.1 | 118.5 | 117.4 | 11.2 | 8.4 | 12.9 | 4.7 | 0.168 | 0.198 |
| 7/6/02 | 29.0 | 4.6 | 103.8 | 129.6 | 107.9 | 111.8 | 110.9 | 110.1 | 109.3 | 110.0 | 108.1 | | 116.6 | 8 | | 9.0 | 4.4 | 0.137 | |
| 7/7/02 | 26.1 | 1.8 | 104.7 | 119.1 | 106.2 | 107.8 | 107.4 | 107.2 | 106.6 | 107.6 | 106.2 | | 115.7 | 3.1 | | 5.7 | 3.9 | | |
| 7/8/02 | 23.6 | 0.0 | 106.1 | 105.8 | 106.1 | 106.2 | 105.8 | 105.2 | 103.9 | 105.2 | 103.8 | | 115.0 | 0.1 | | | | | |
| 7/9/02 | 24.3 | 0.0 | 104.5 | 104.5 | 104.5 | 104.3 | 104.6 | 104.9 | 104.4 | 105.9 | 104.0 | | 115.8 | -0.2 | | | | | |

[1] FWA Flow weighted average TDG saturation using powerhouse and spillway flows and TDG at stations DTD and SPW
[2] ΔTDG Dam = Change in TDG saturation from forebay to tailwater (Stations DTD to USGS)
[3] ΔTDG Falls = Change in TDG saturation from upstream to downstream of Kootenai Falls (Stations USFALLS to DSFALLS)
[4] Effective spillway discharge determined from total river flow and TDG saturation at DTD, SPW, and USGS
[5] Estimated entrainment discharge = Effective spillway discharge minus observed spillway discharge
[6] Change in daily TDG saturation per mile from the USGS transect to UPFALLS
[7] Change in daily TDG saturation per mile from DSFALLS to Troy

| Table 10. Total Dissolved Gas Saturation Frequency of Occurrence in the Kootenai River at Porthill, ID (June 24-July 22) | | |
|---|---|---|
| TDG (%) | Count | Frequency of Occurrence (%) |
| 106-107 | 75 | 2.8 |
| 107-108 | 253 | 9.6 |
| 108-109 | 937 | 35.5 |
| 109-110 | 863 | 32.7 |
| 110-111 | 428 | 16.2 |
| 111-112 | 82 | 3.1 |
| 112-113 | 0 | 0 |

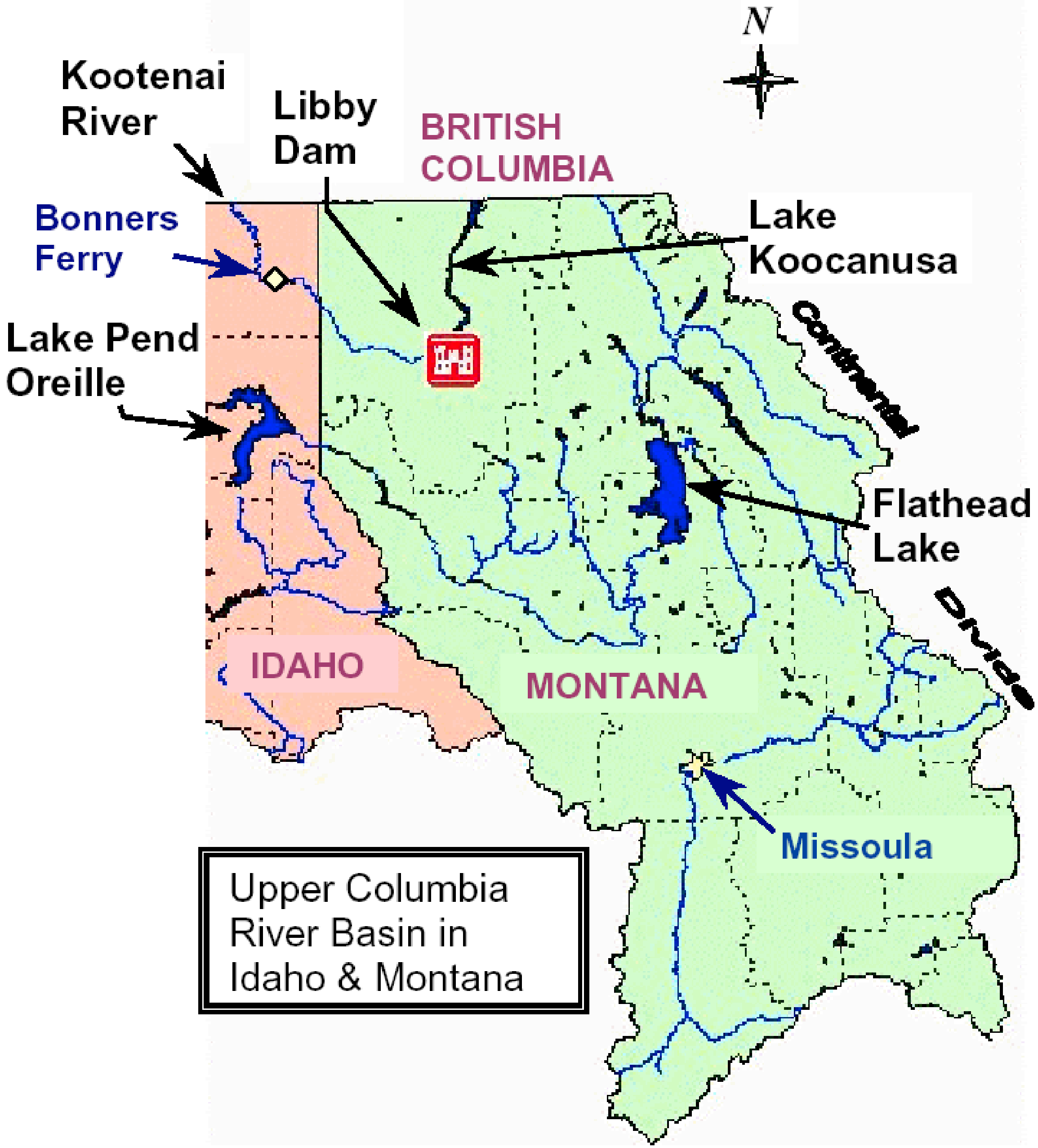
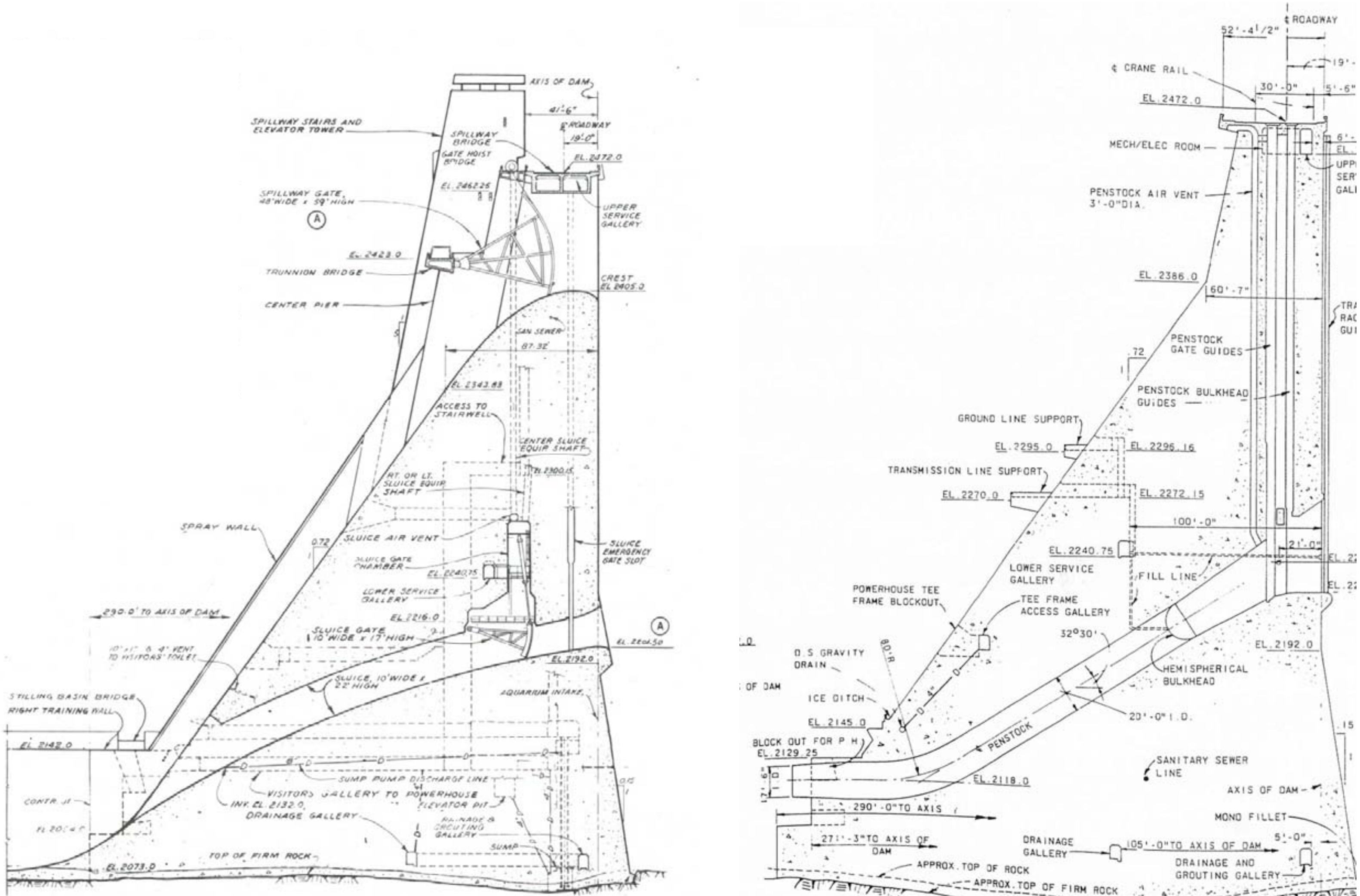



Figure 1. Location of Libby Dam and the Kootenai River within the upper Columbia River Basin

Figure 2.  Libby Dam and powerhouse, Lake Koocanusa, and the Kootenai River




a. Spillway Section

b. Penstock Section

Figure 3. Libby Dam sectioned structural features through the penstock and spillway

Figure 4.  Photo of Libby Dam spillway and stilling basin

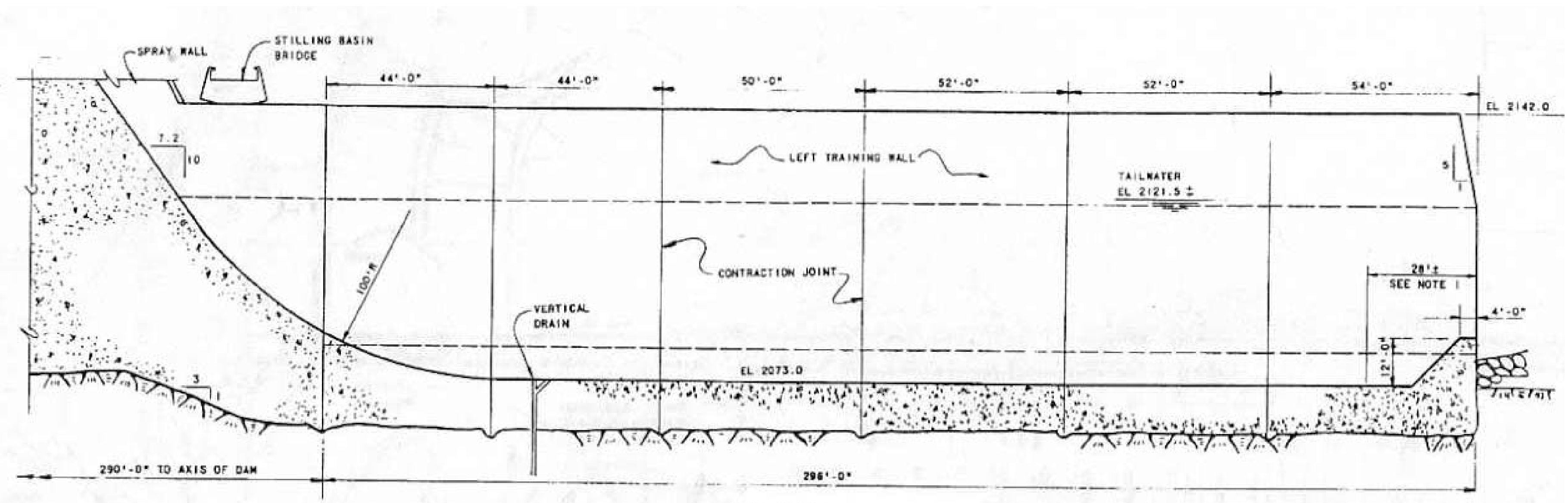



Figure 5. Libby Dam stilling basin features

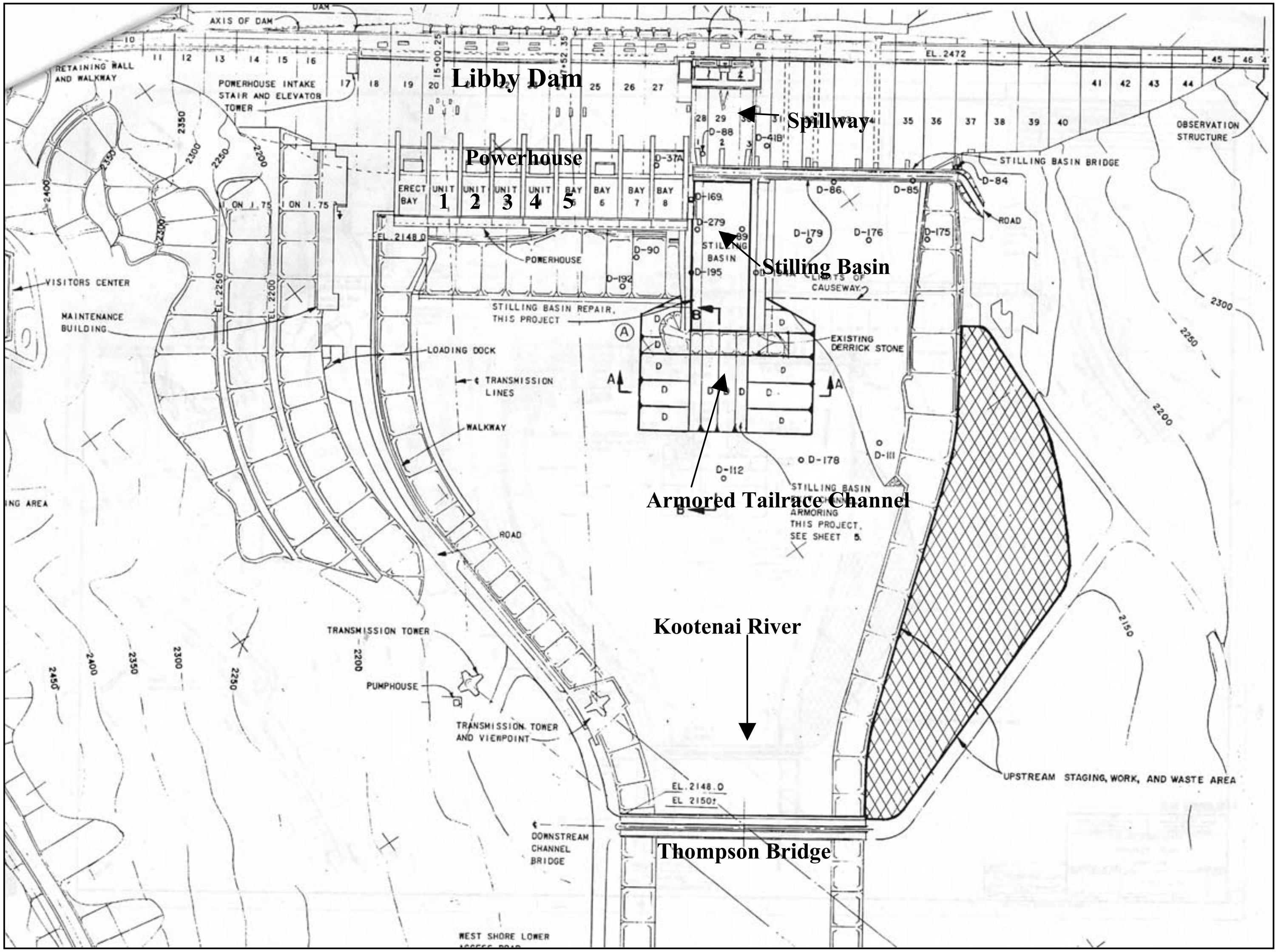



Figure 6. Libby Dam plan view layout

Figure 7. Kootenai River below Libby Dam

Figure 8. China Rapids on the Kootenai River above Kootenai Falls

Figure 9. Kootenai Falls, June 27, 2002 10:44 a.m., total river flow 32,000 cfs

Figure 10.  Kootenai River near the U.S./Canadian border at Porthill

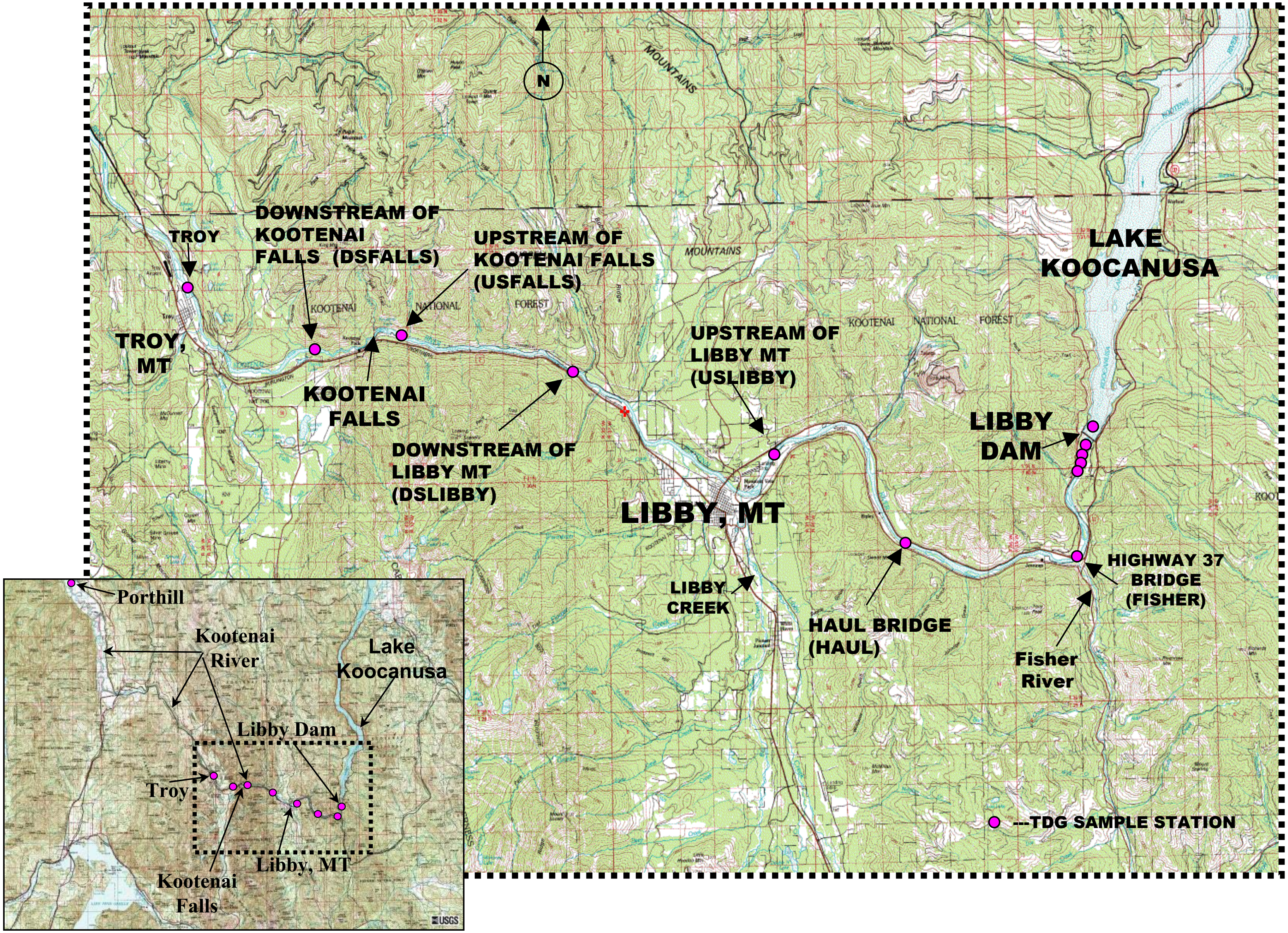



Figure 11. Total dissolved gas sampling transects in the Kootenai River near Libby Dam

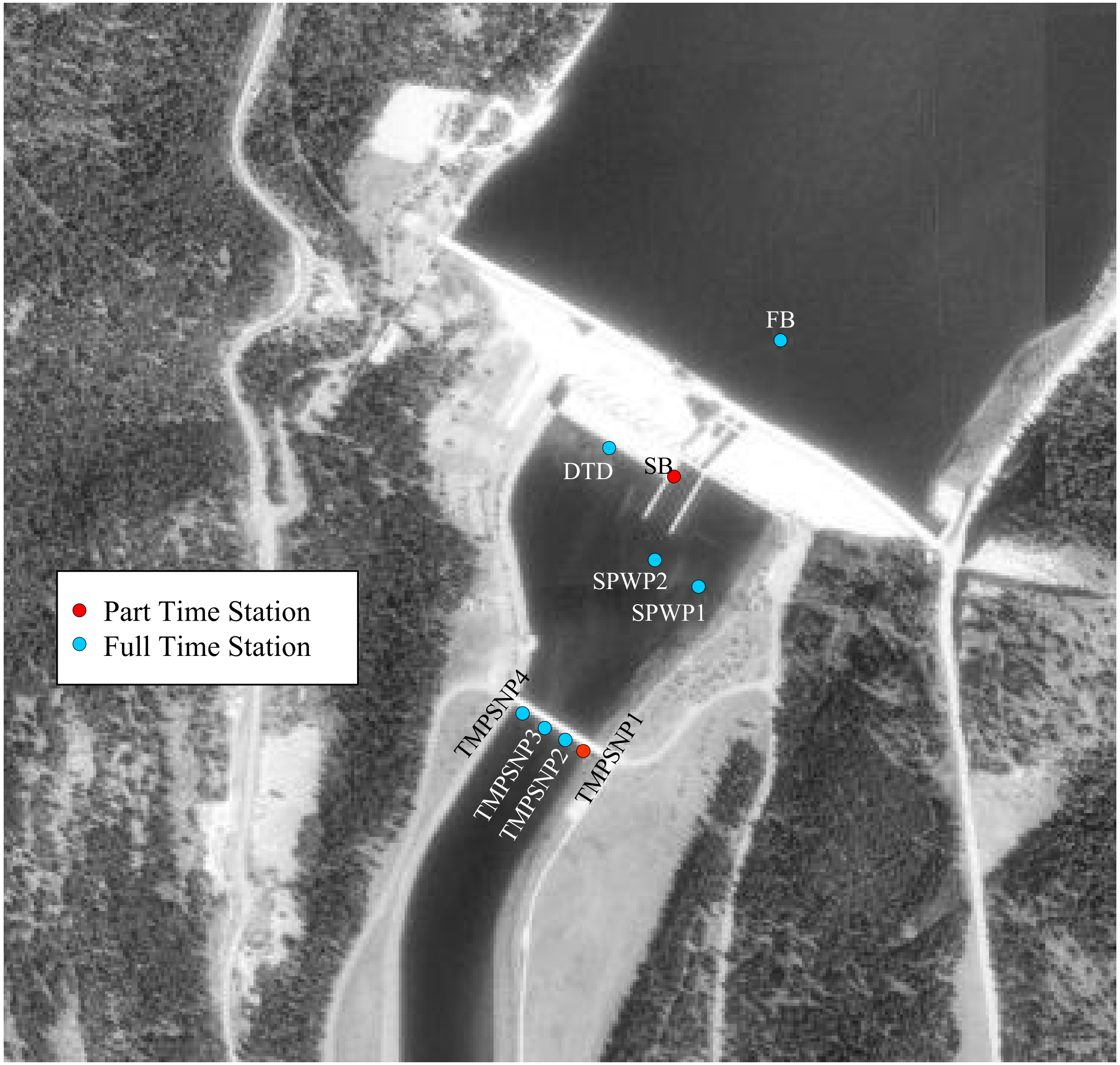



Figure 12. Total dissolved gas monitoring stations above and below Libby Dam

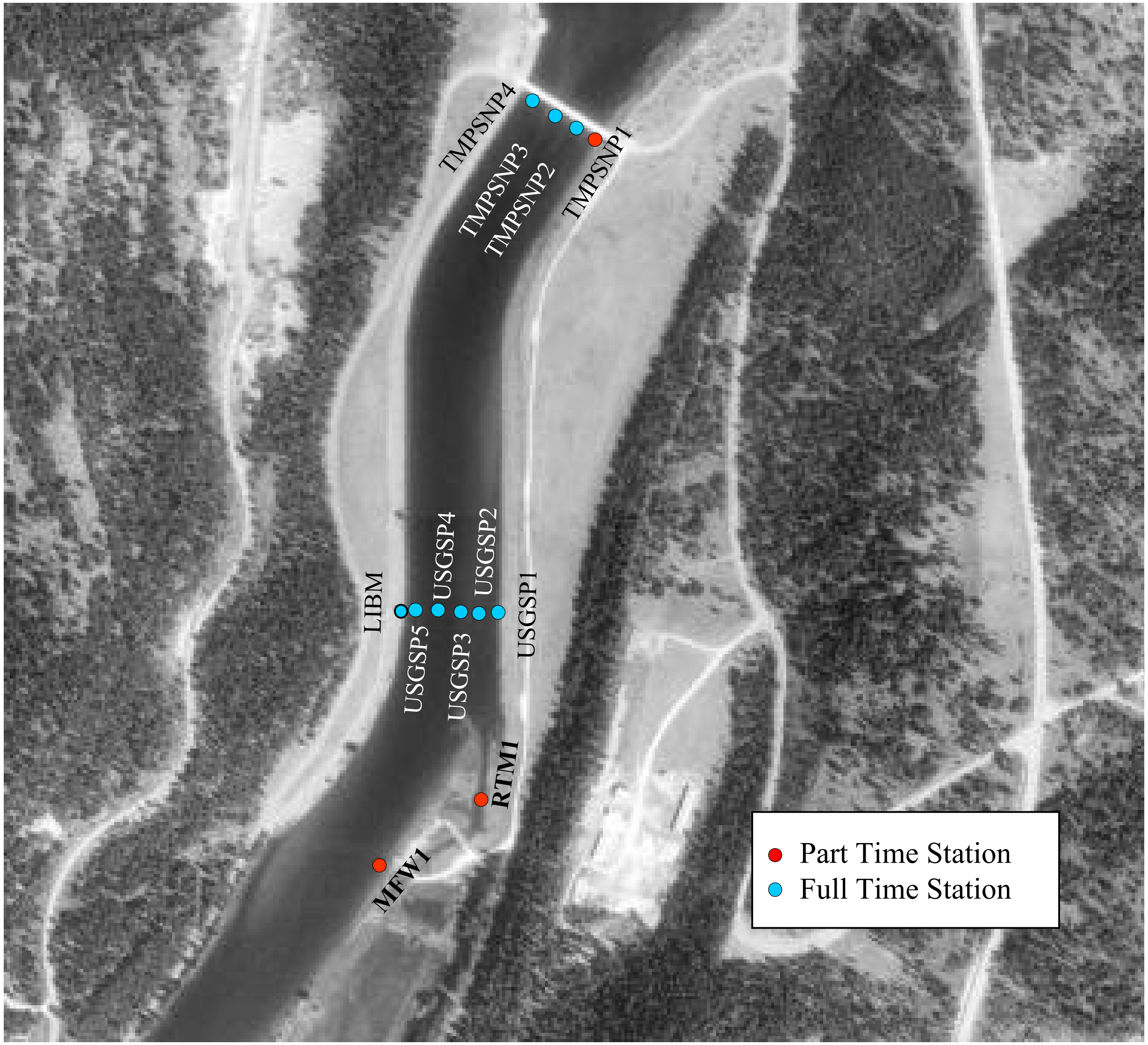



Figure 13. Total dissolved gas monitoring stations at the Thompson Bridge and USGS gaging station

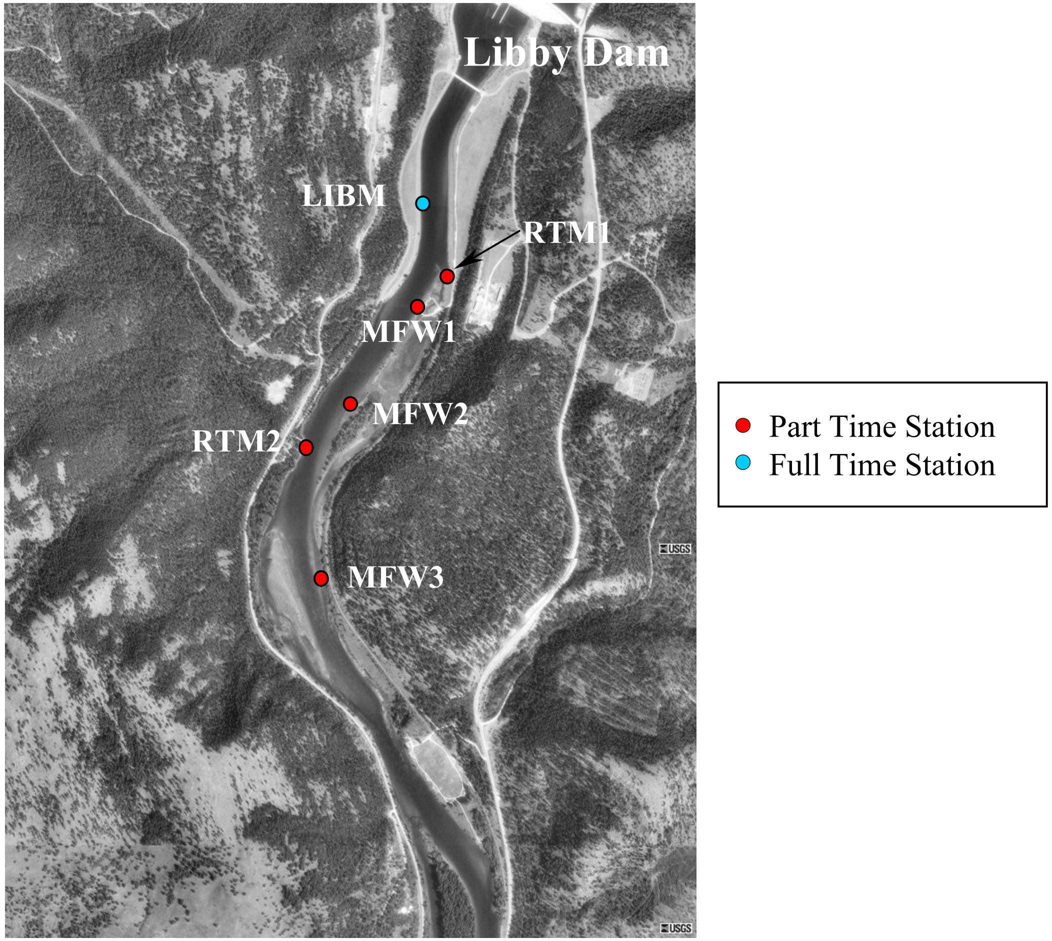



Figure 14. Total dissolved gas monitoring stations in conjunction with Montana Fish and Wildlife (MFW) fish pens

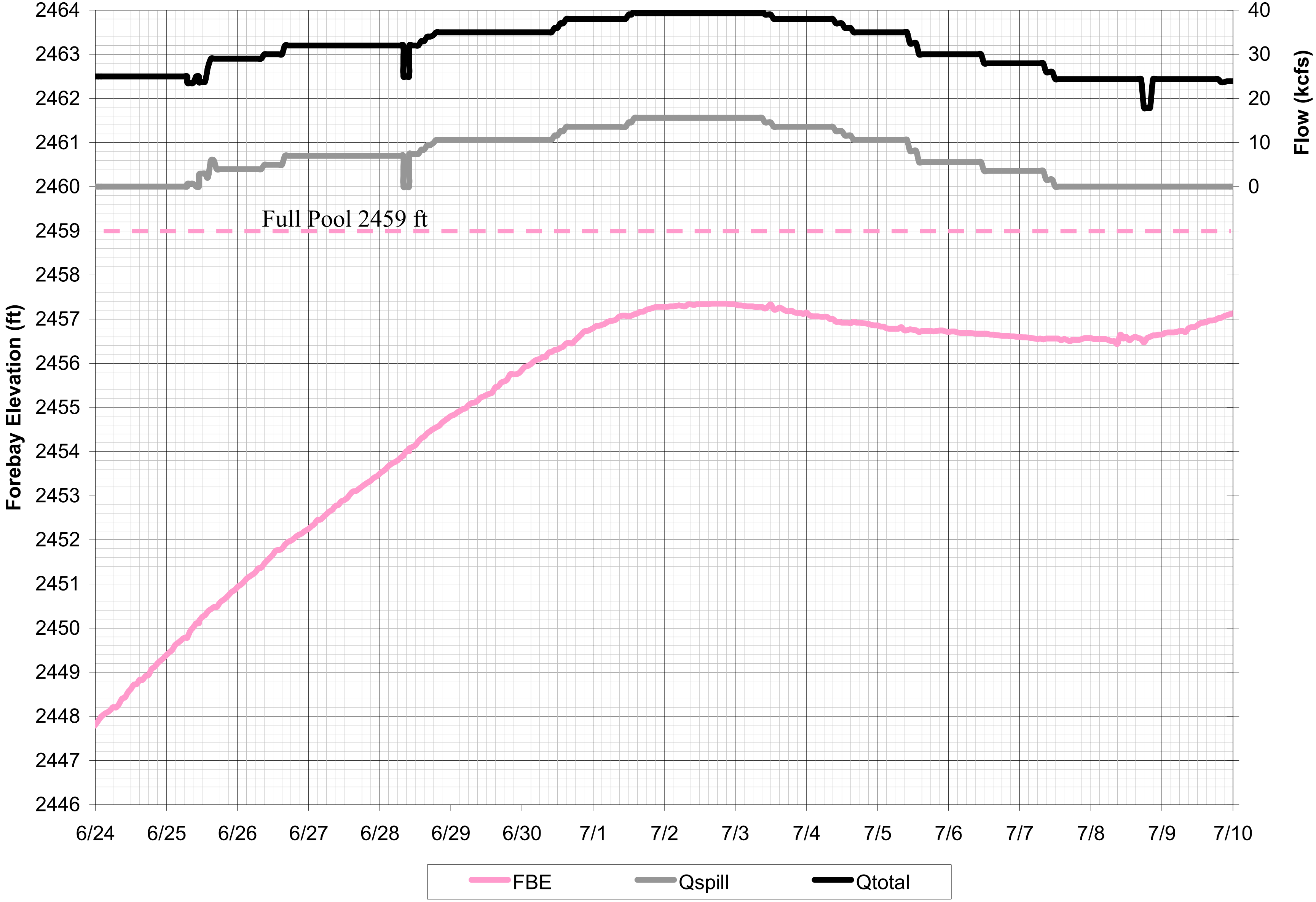



Figure 15. Libby Dam operations and forebay water-surface elevation, June 24 – July 9, 2002

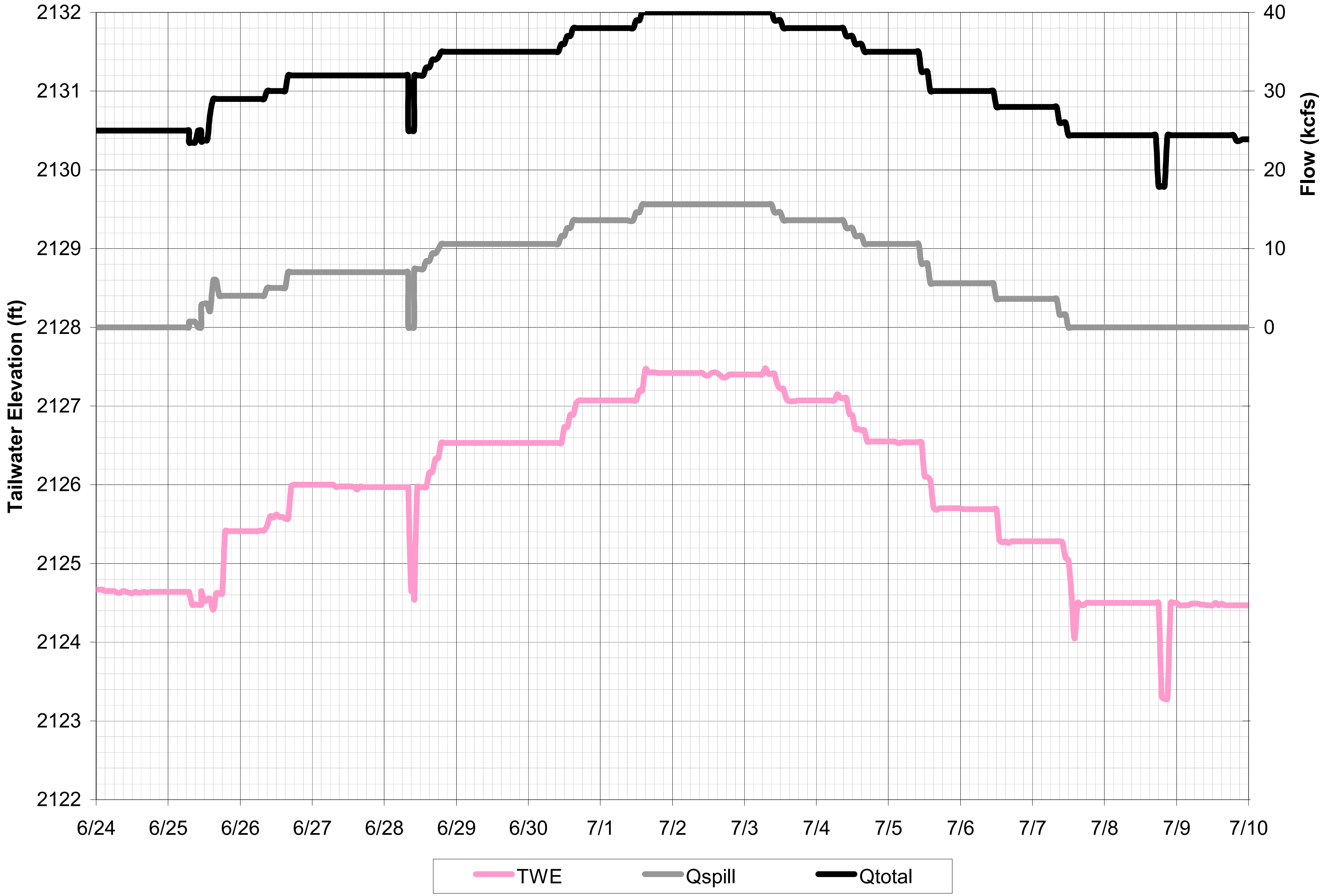



Figure 16. Libby Dam operations and tailwater elevation, June 24 – July 9, 2002

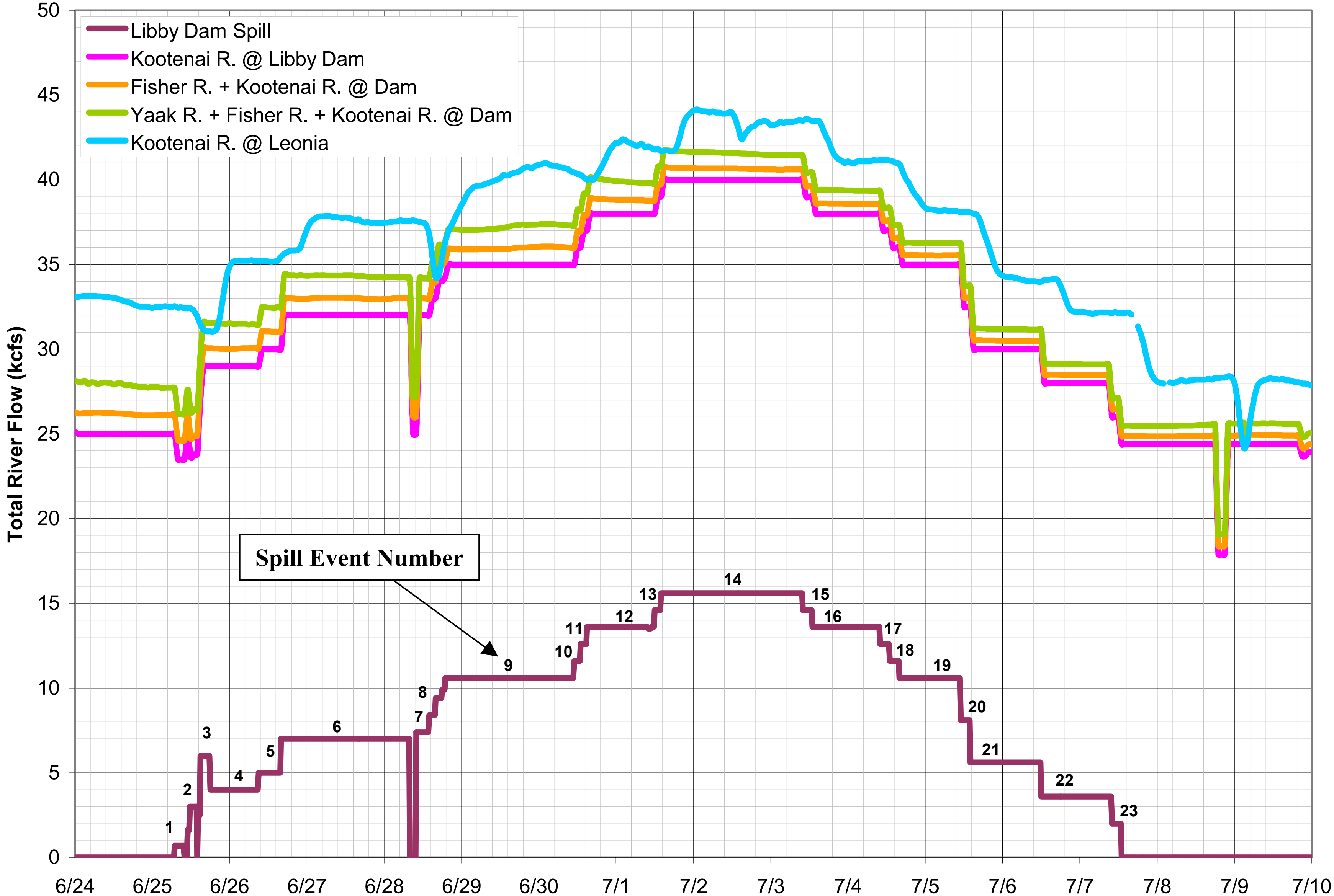



Figure 17. Kootenai River flow conditions below Libby Dam, June 24-July 10, 2002

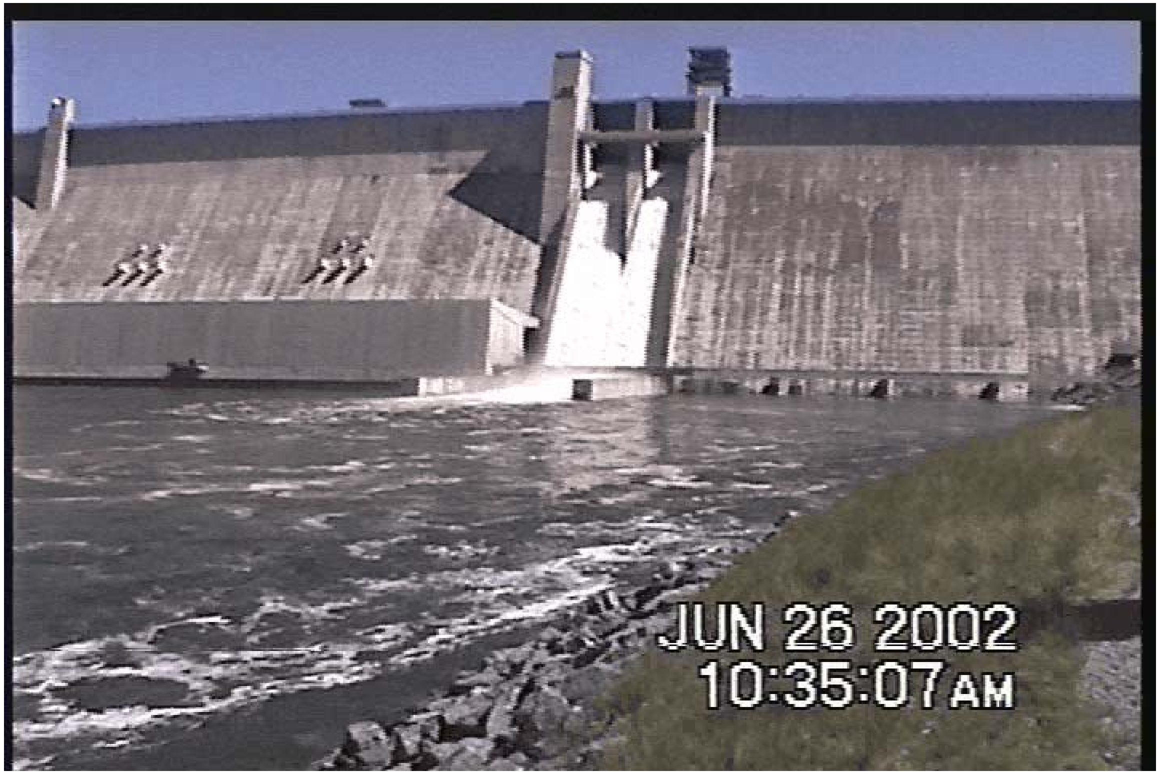



Figure 18. Video of Libby Dam spillway release of 5,000 cfs and powerhouse release of 25,000 cfs on June 26, 2002 at 10:35 a.m. (Click on image to activate the video, requires filename libbyu1proc.avi)


Figure 19. Video of Libby Dam spillway release of 3,000 cfs and powerhouse release of 25,000 cfs on June 25, 2002 at 11:30 a.m.
(Click on image to activate the video, requires filename libbyt1proc.avi)


Figure 20. Video of mixing zone development below Libby Dam for a spillway release of 3,000 cfs and powerhouse release of 25,000 cfs on June 25, 2002 at 11:05 a.m.
(Click on image to activate the video, requires filename libbyx2proc.avi)

Figure 21.  Photograph of flow conditions below the powerhouse at Libby Dam during capacity power generation

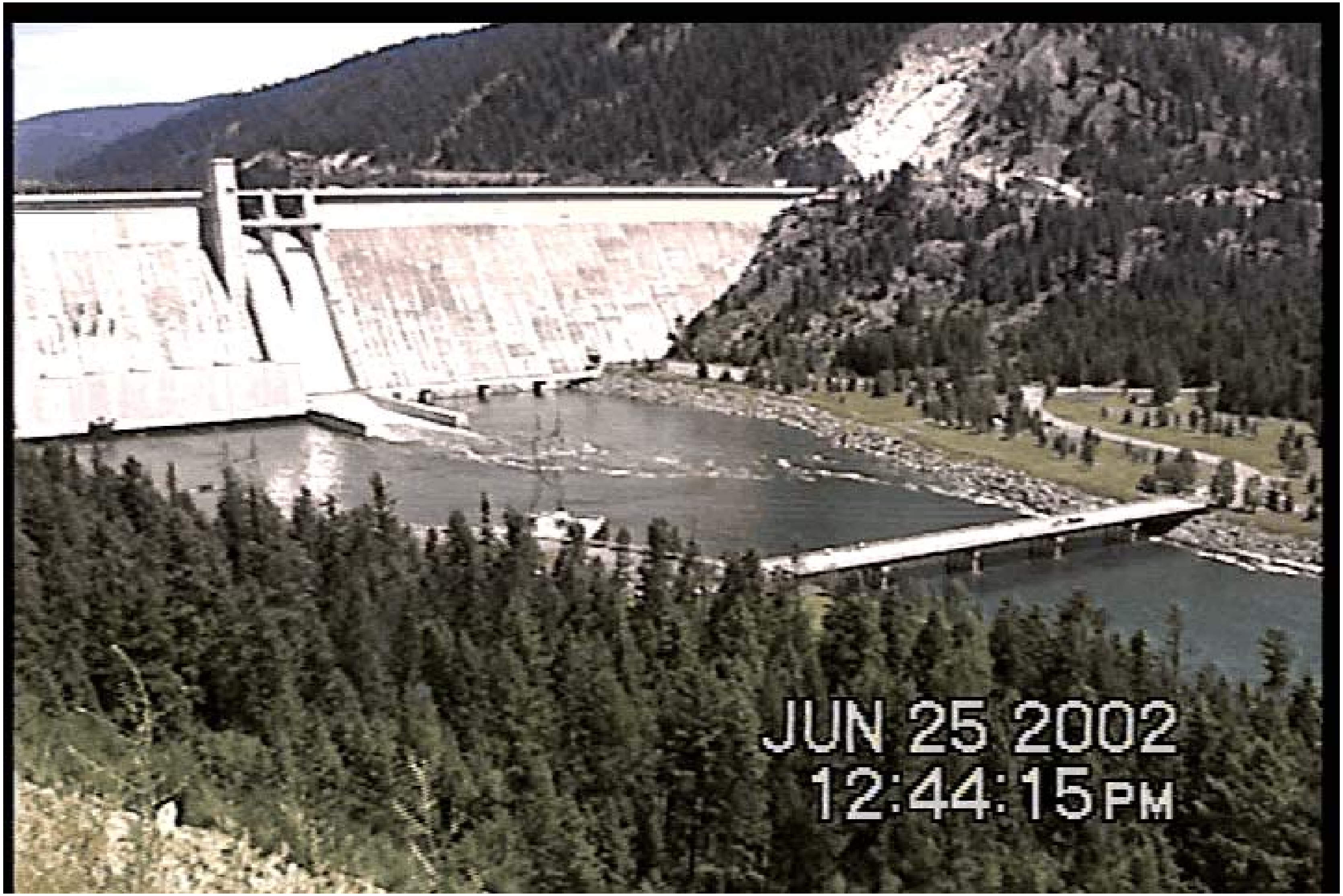



Figure 22. Video of Libby Dam releases on June 25, 2002 at 12:44 p.m.
($Q_{sp}$=3.0 kcfs, $Q_{ph}$=25 kcfs)
(Click on image to activate the video, requires filename libbyz1proc.avi)

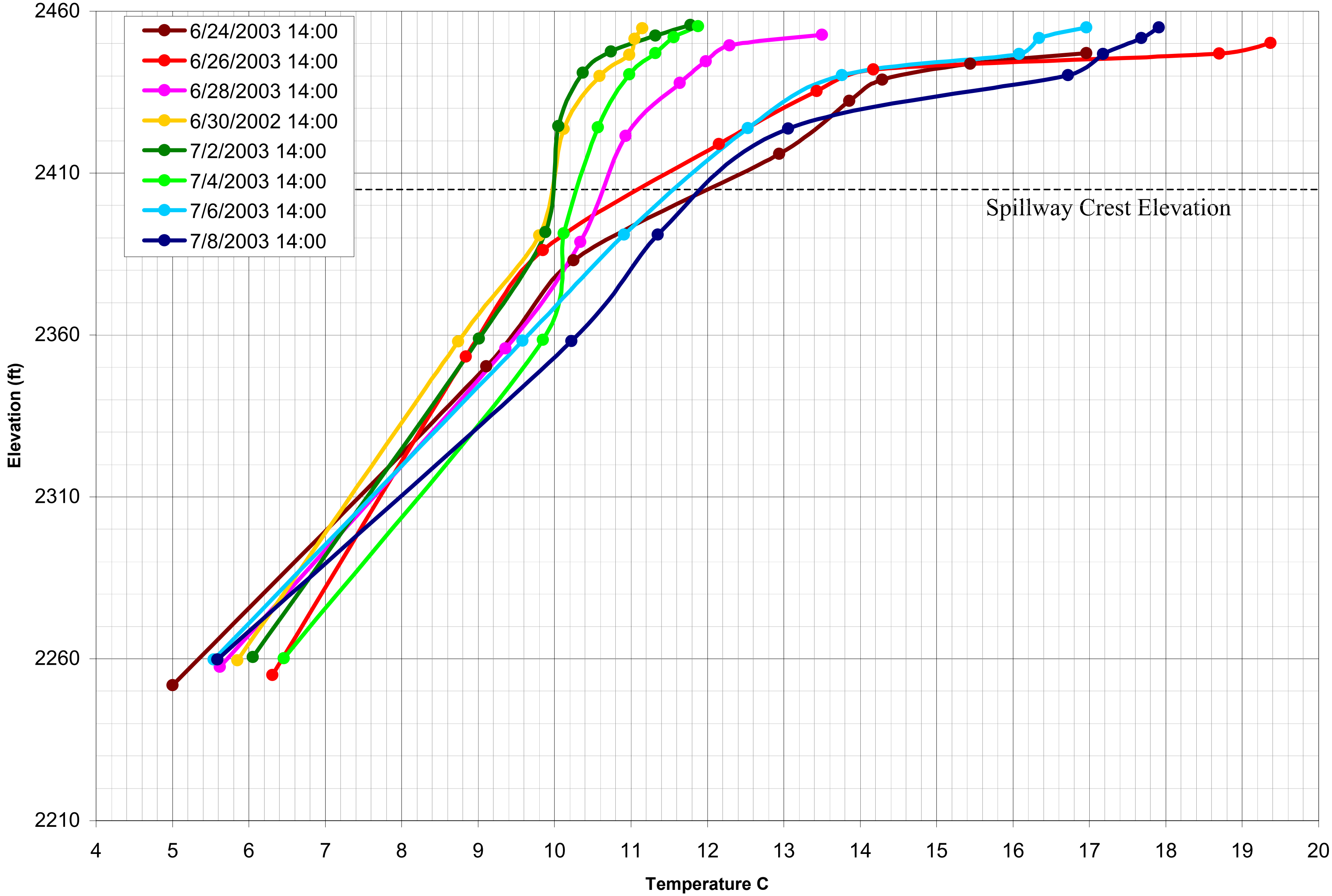



Figure 23. Libby Dam forebay temperature profile at station FB , June 24-July 8, 2002

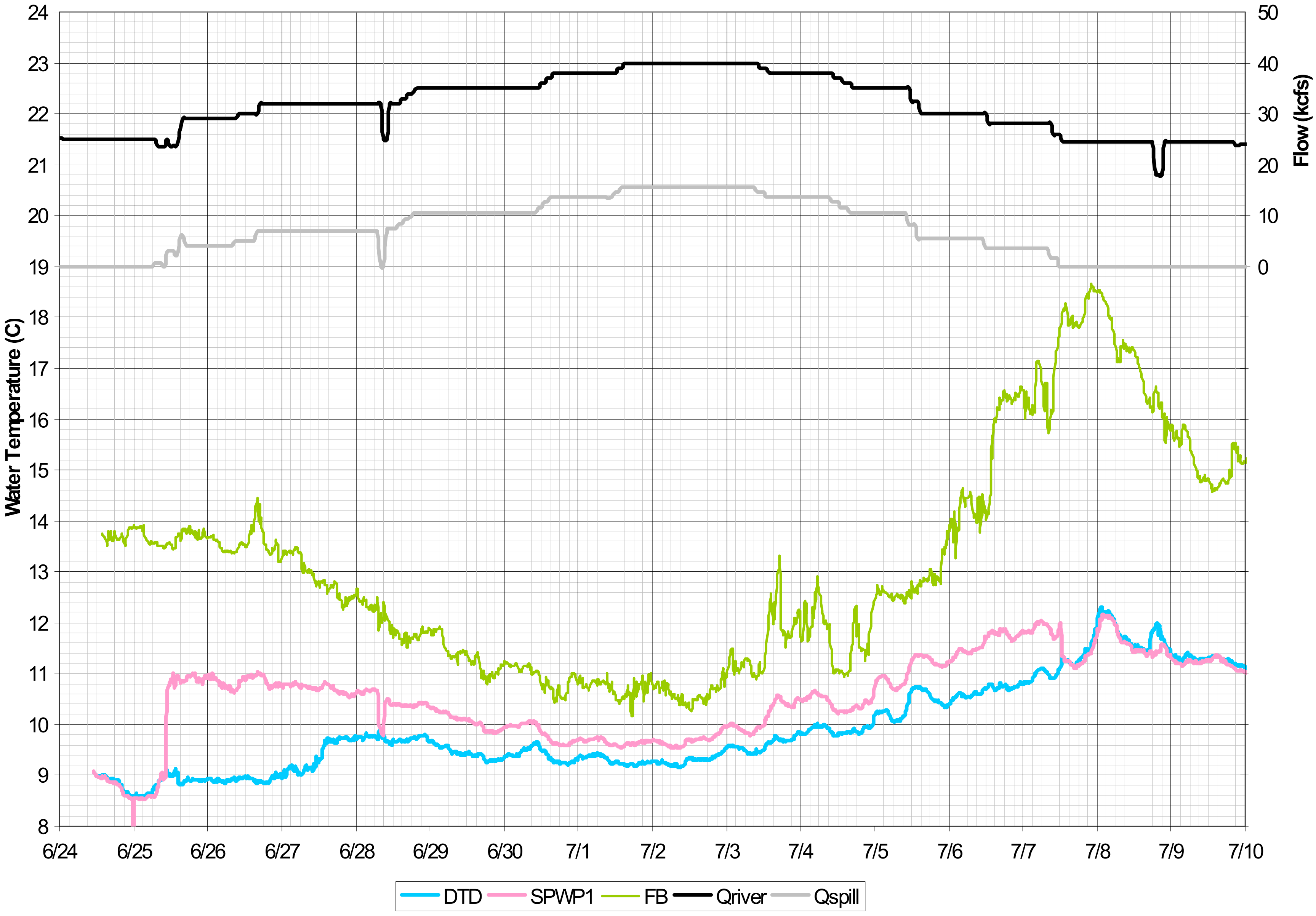



Figure 24. Lake Koocanusa and Kootenai River water temperatures near Libby Dam, June 24-July 9, 2002
(FB-forebay, DTD-powerhouse release, SPWP1-spillway release)

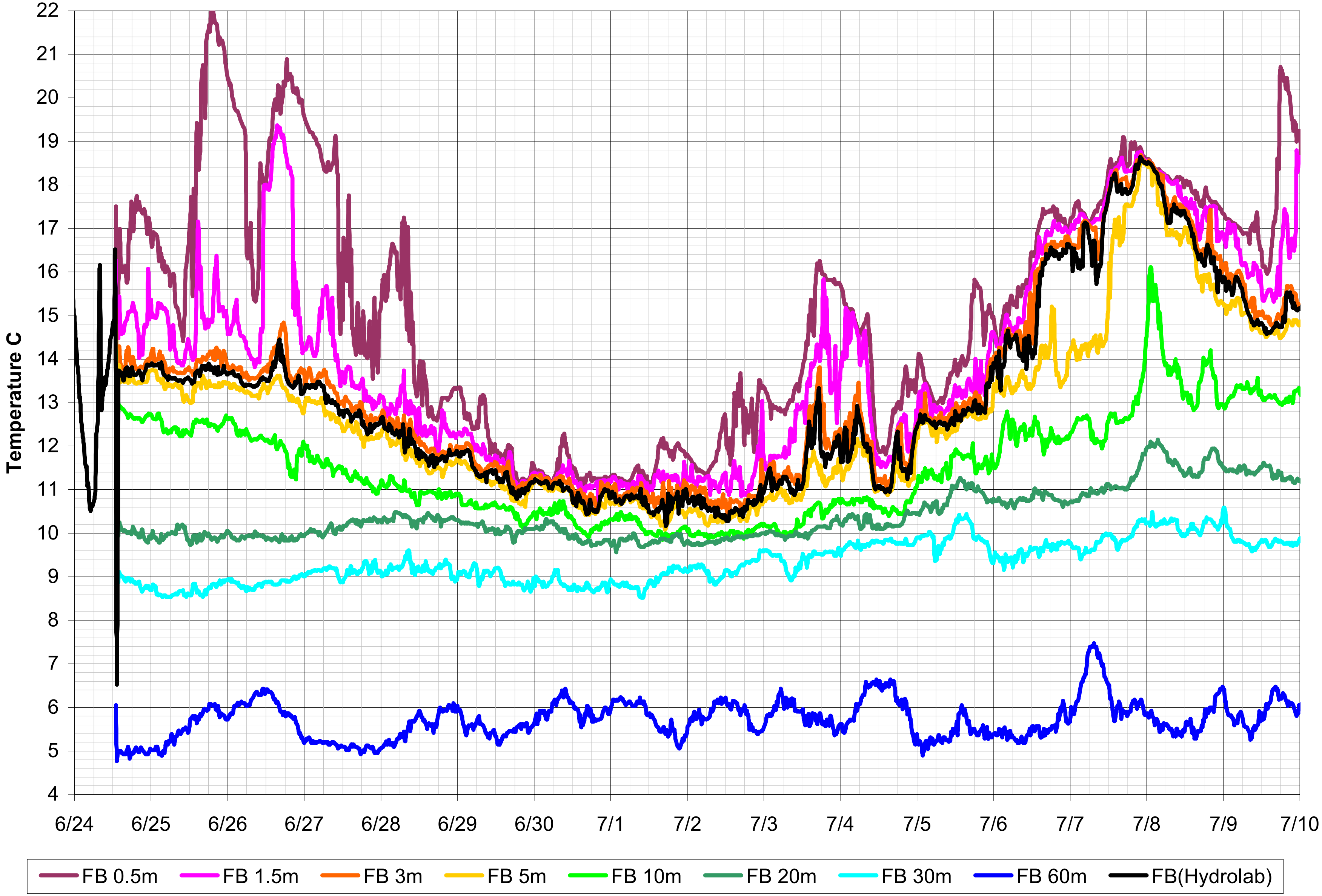



Figure 25. Libby Dam forebay temperatures at station FB , June 24-July 9, 2002

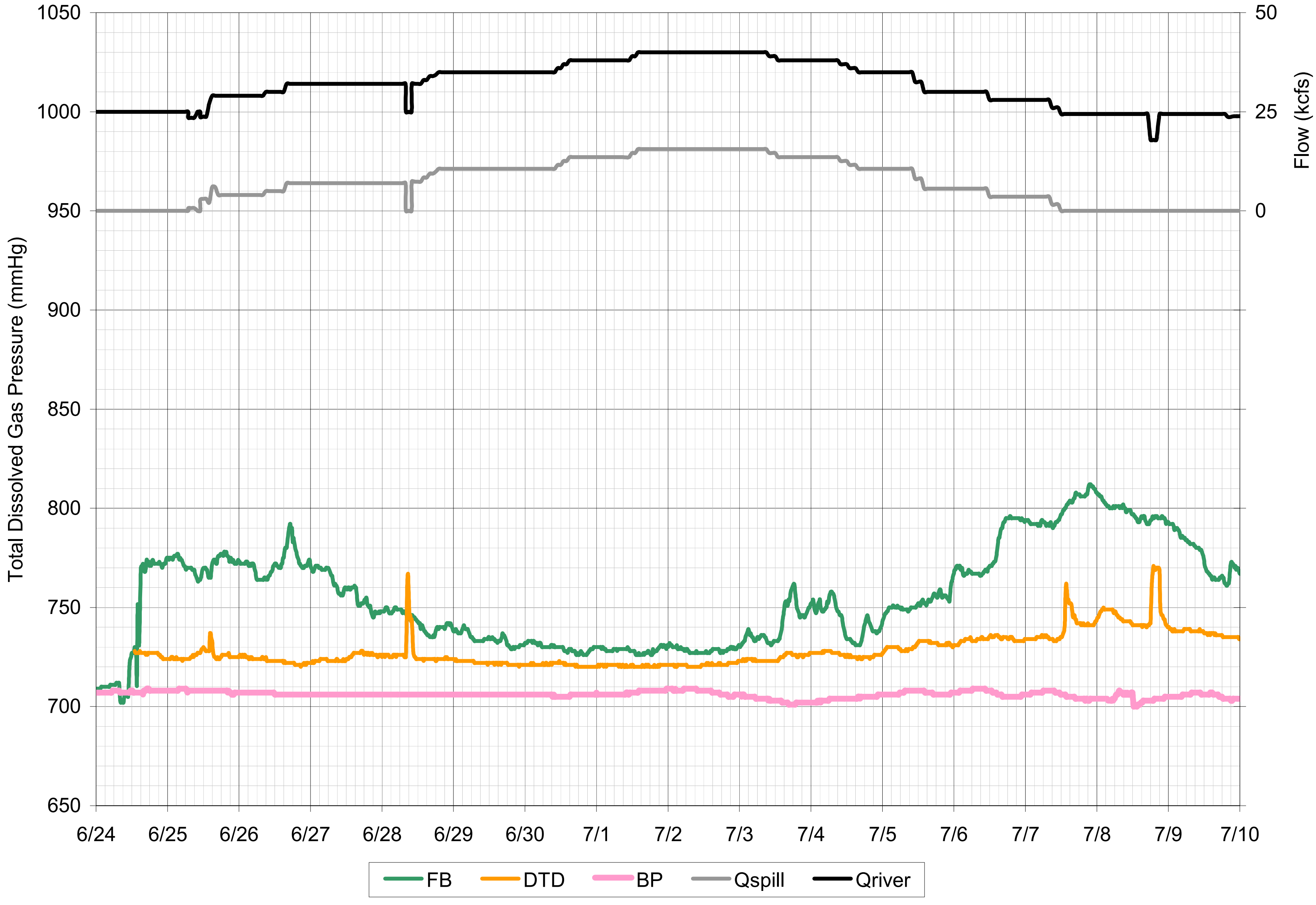



Figure 26. Barometric pressure (BP) and total dissolved gas pressure in the forebay (FB) and below the powerhouse (DTD) of Libby Dam, June 24-July 9, 2002

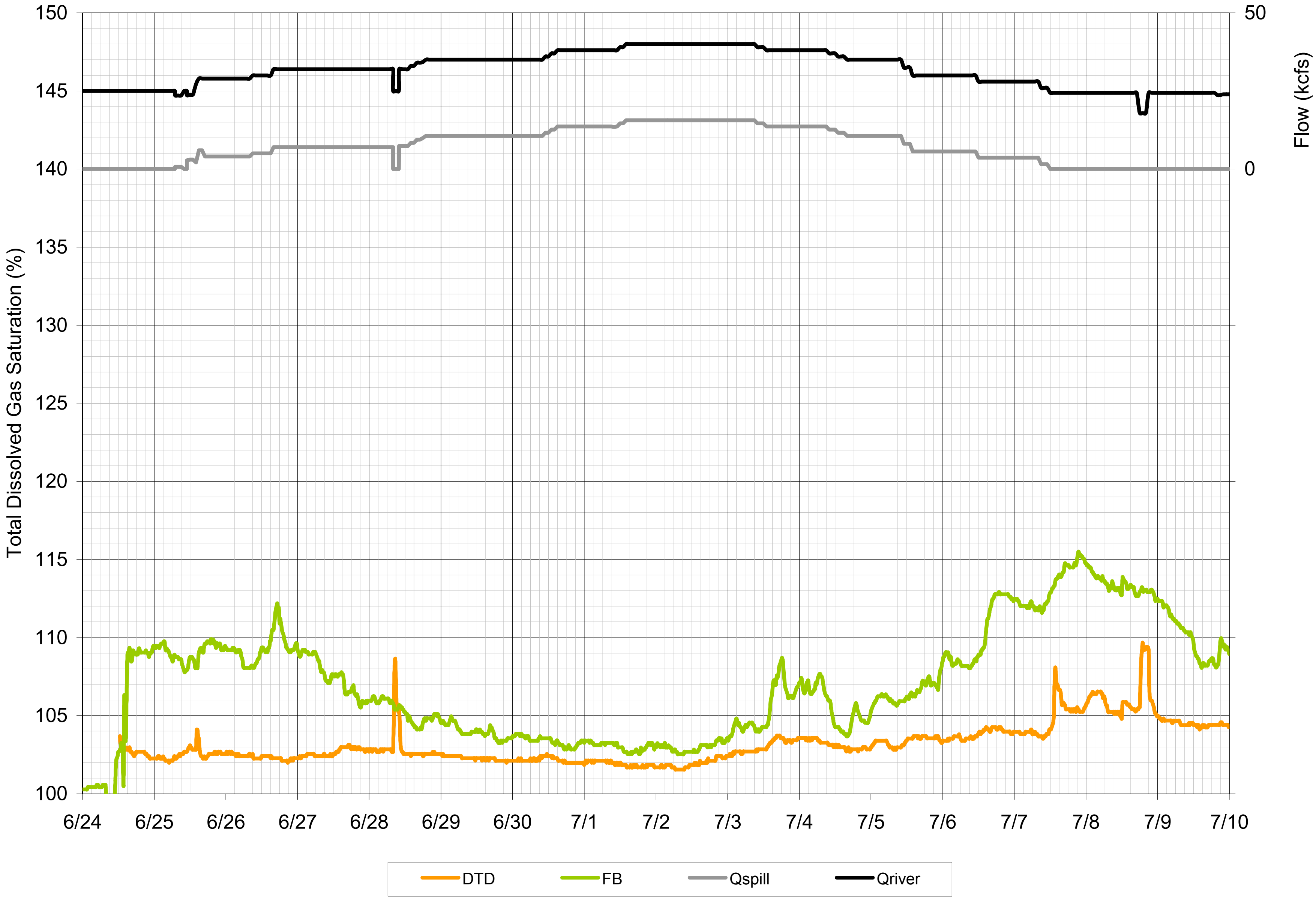



Figure 27. Total dissolved gas saturation in the forebay (FB) and below the powerhouse (DTD) of Libby Dam, June 24-July 9, 2002

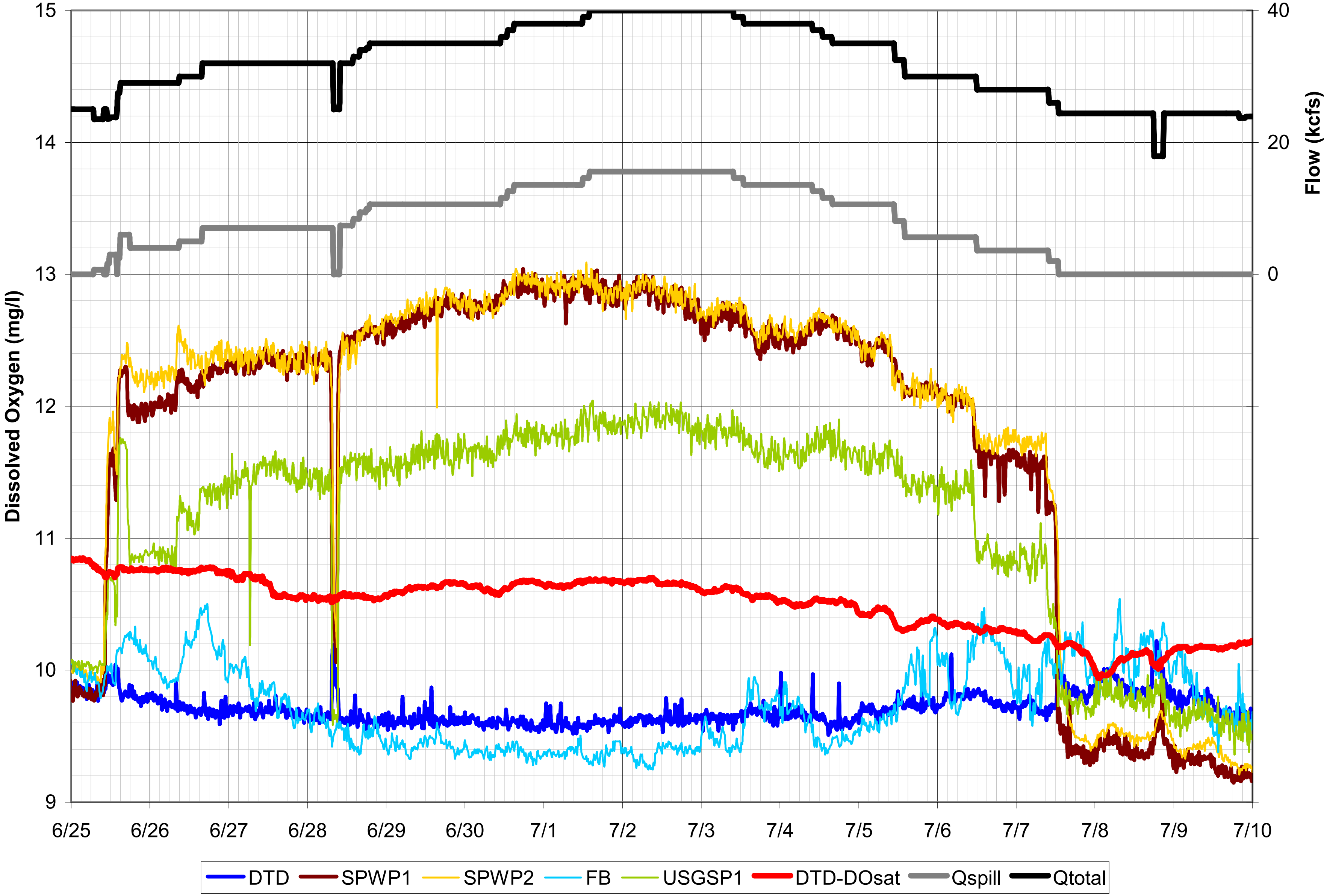



Figure 28. Dissolved oxygen concentration above and below Libby Dam, June 25-July 9, 2002

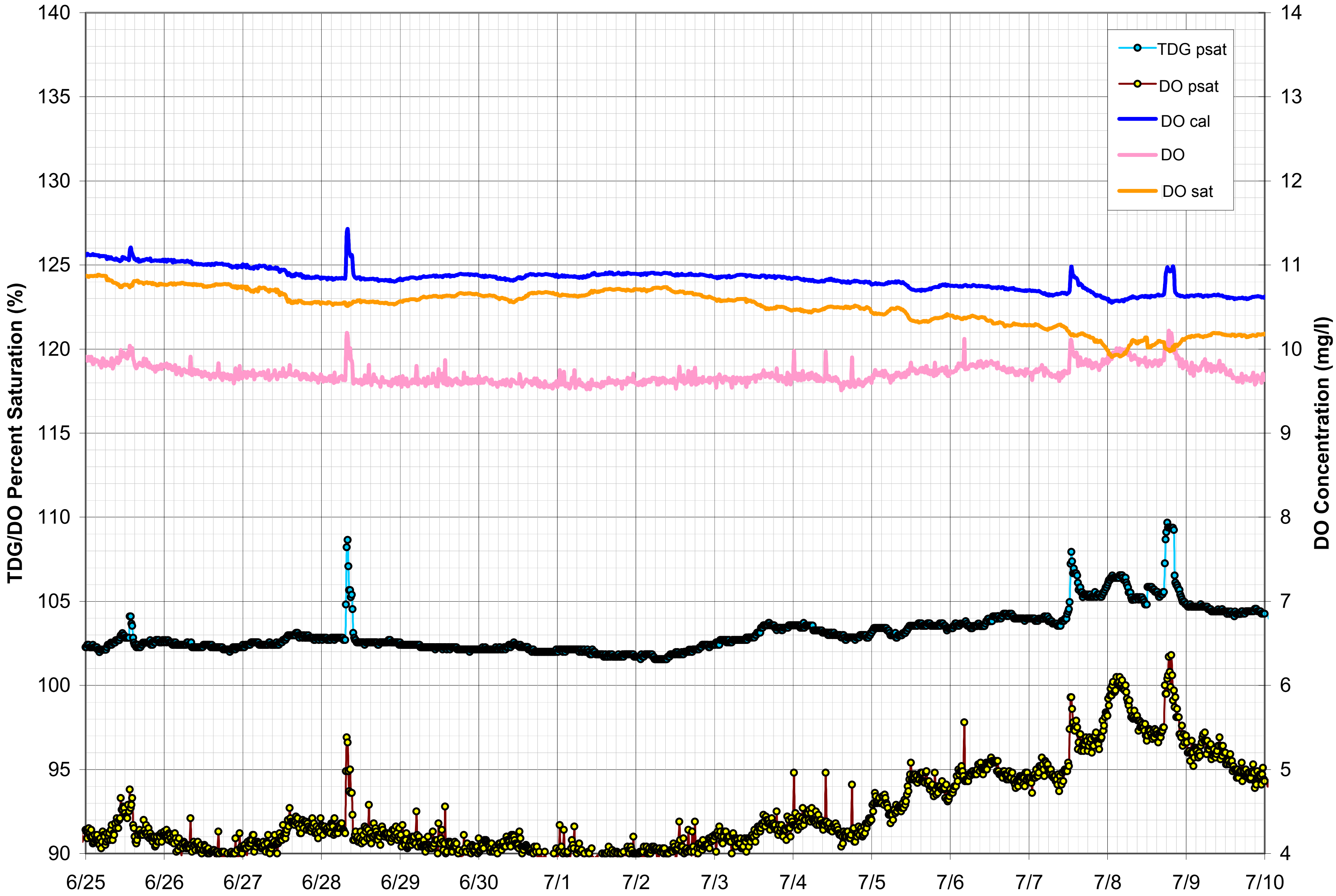



Figure 29. Dissolved oxygen concentration and saturation in Libby Dam powerhouse flows at station DTD, June 25-July 9, 2002 (DO – observed DO concentration, DO sat - calculated DO saturation concentration from temperature, DO cal – Calculated DO concentration from TDG pressure assuming atmospheric ratios of dissolved gasses, DO psat – observed DO percent saturation, TDG psat - observed TDG percent saturation)

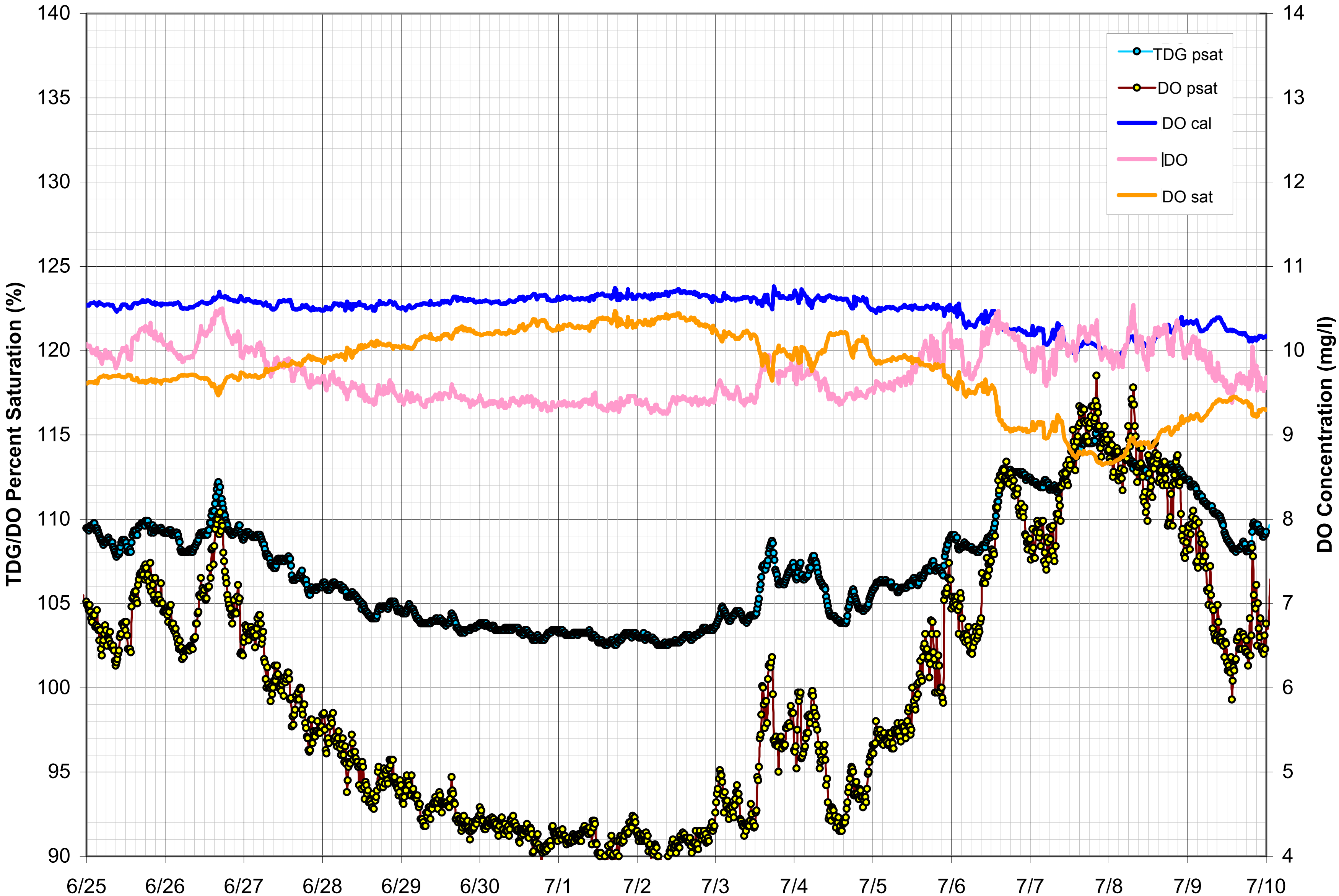



Figure 30. Dissolved oxygen concentration and saturation in the forebay of Libby Dam at station FB, June 25-July 9, 2002 (DO – observed DO concentration, DO sat - calculated DO saturation concentration, DO cal – Calculated DO concentration from TDG pressure assuming atmospheric ratios of dissolved gasses, DO psat – observed DO percent saturation, TDG psat - observed TDG percent saturation)

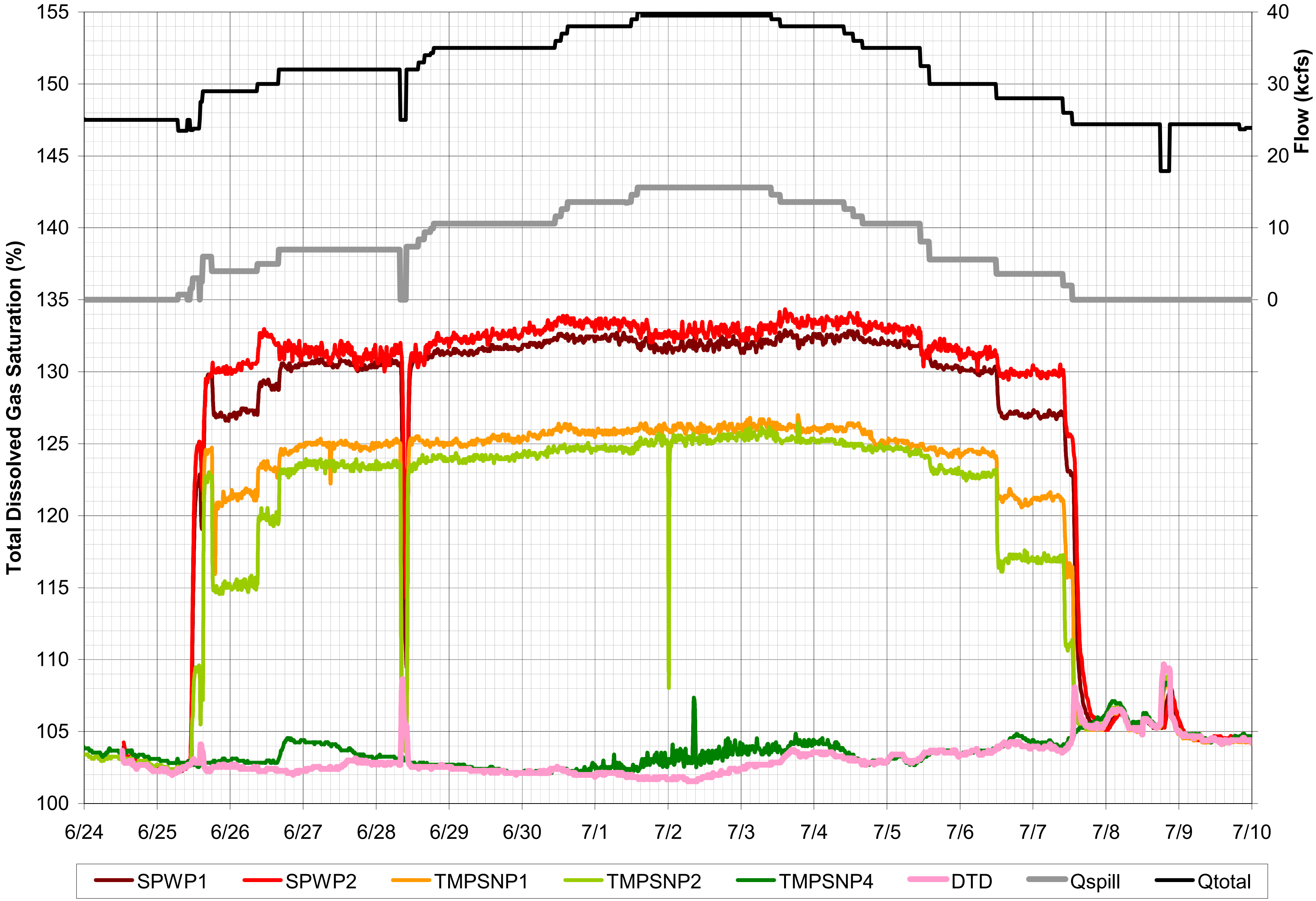



Figure 31. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam spillway and at the Thompson Bridge, June 24-July 9, 2002

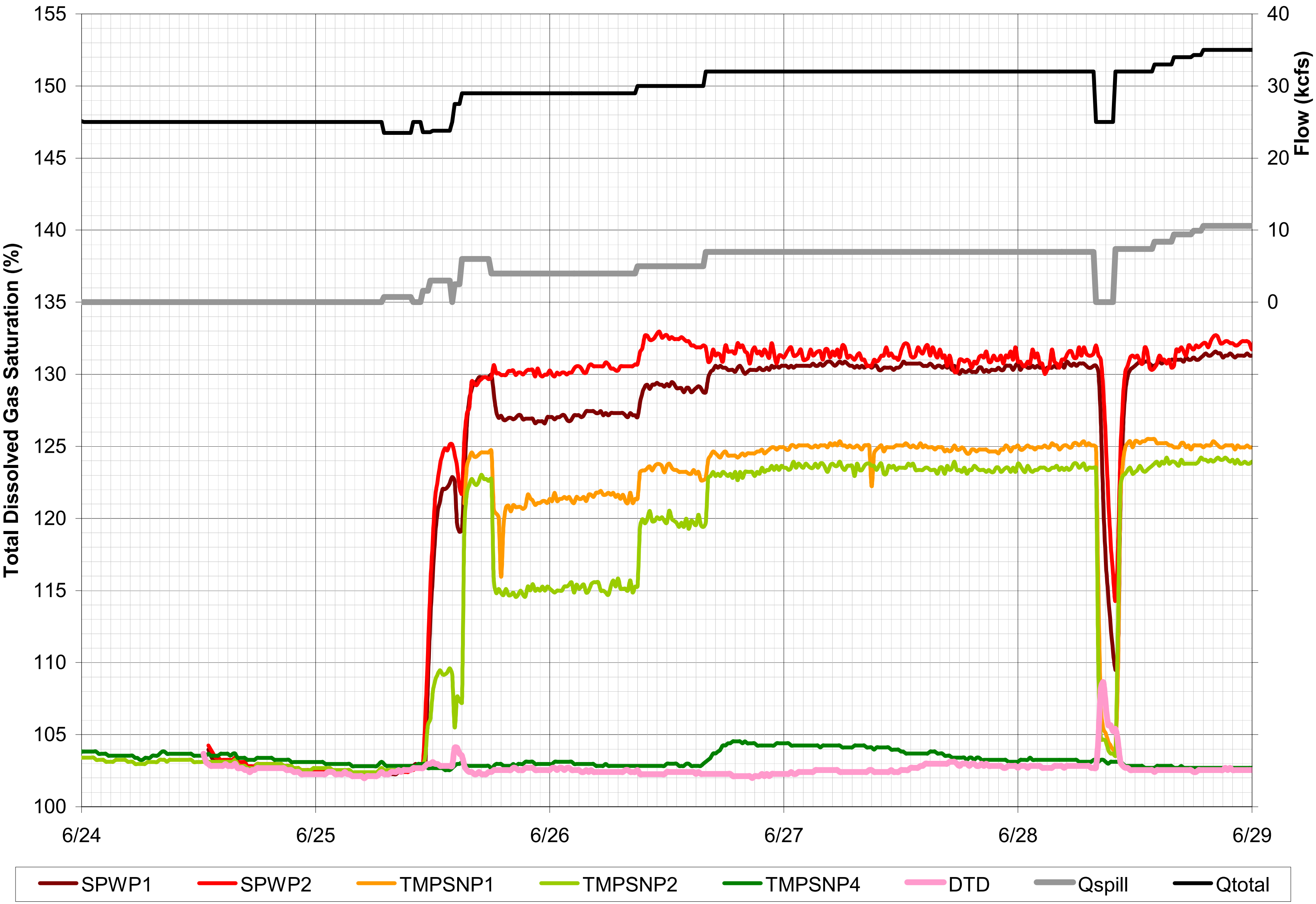



Figure 32. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam spillway and at the Thompson Bridge, June 24 - June 28, 2002

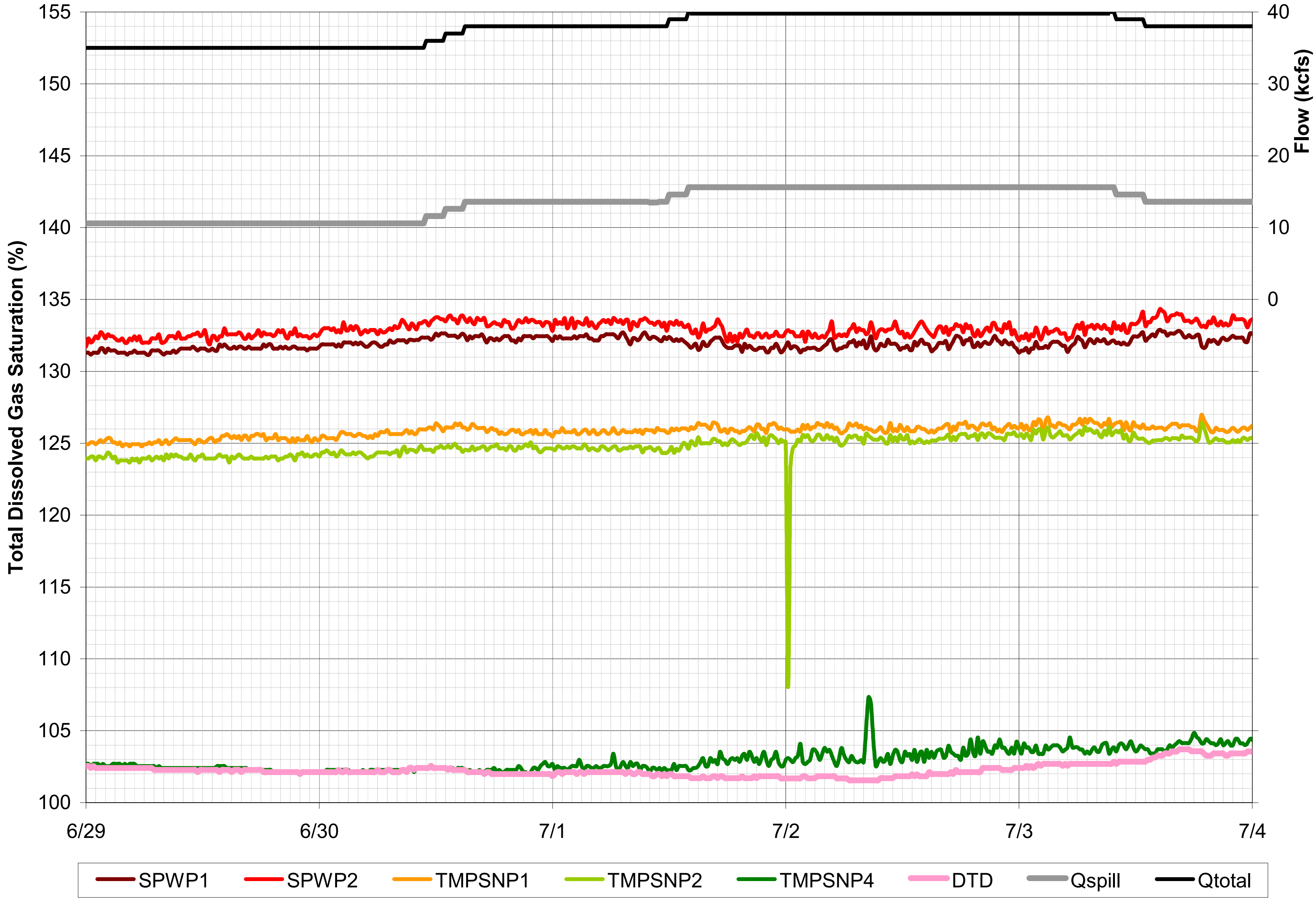



Figure 33. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam spillway and at the Thompson Bridge, June 29-July 3, 2002

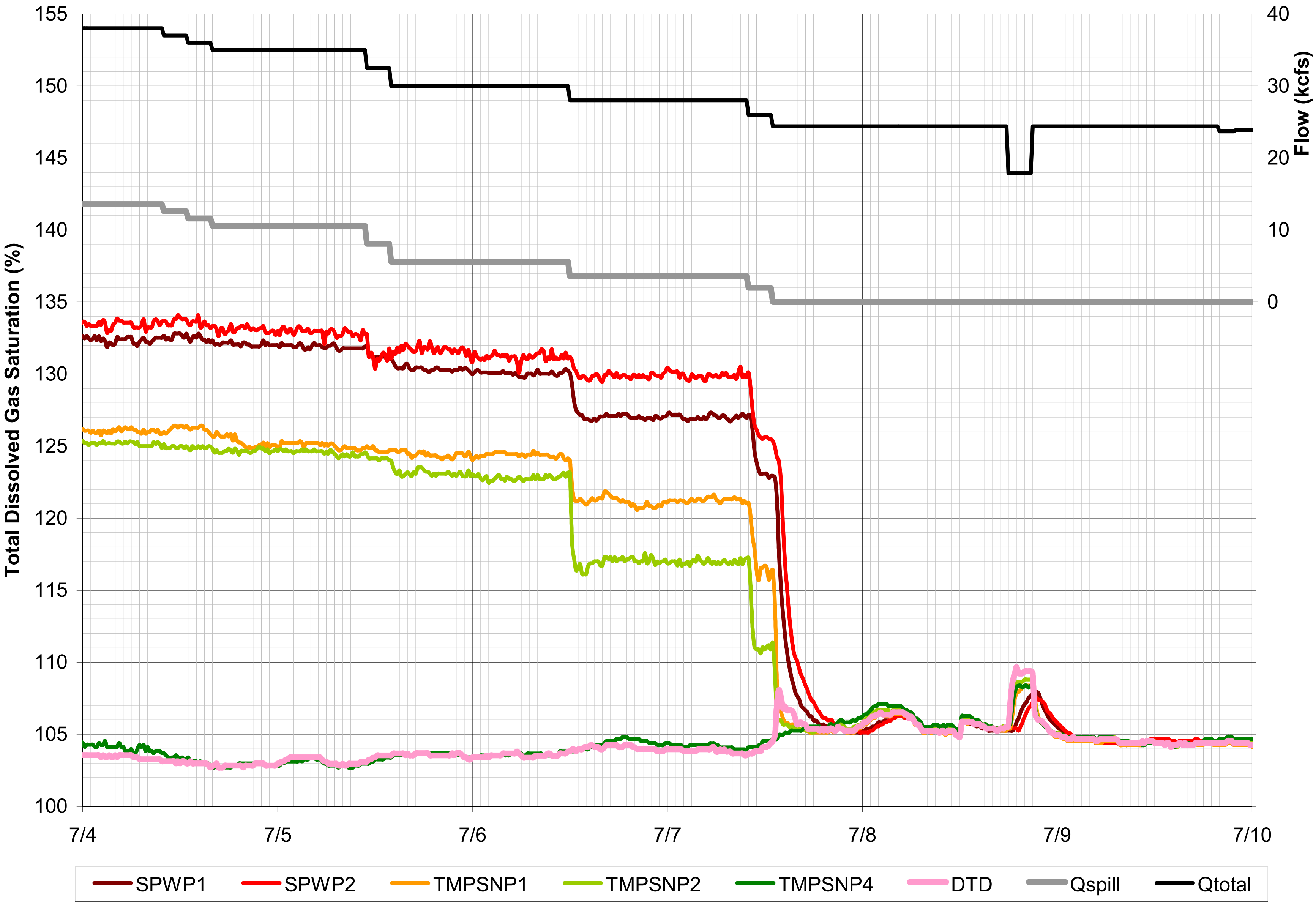



Figure 34. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam spillway and at the Thompson Bridge, June 29-July 3, 2002

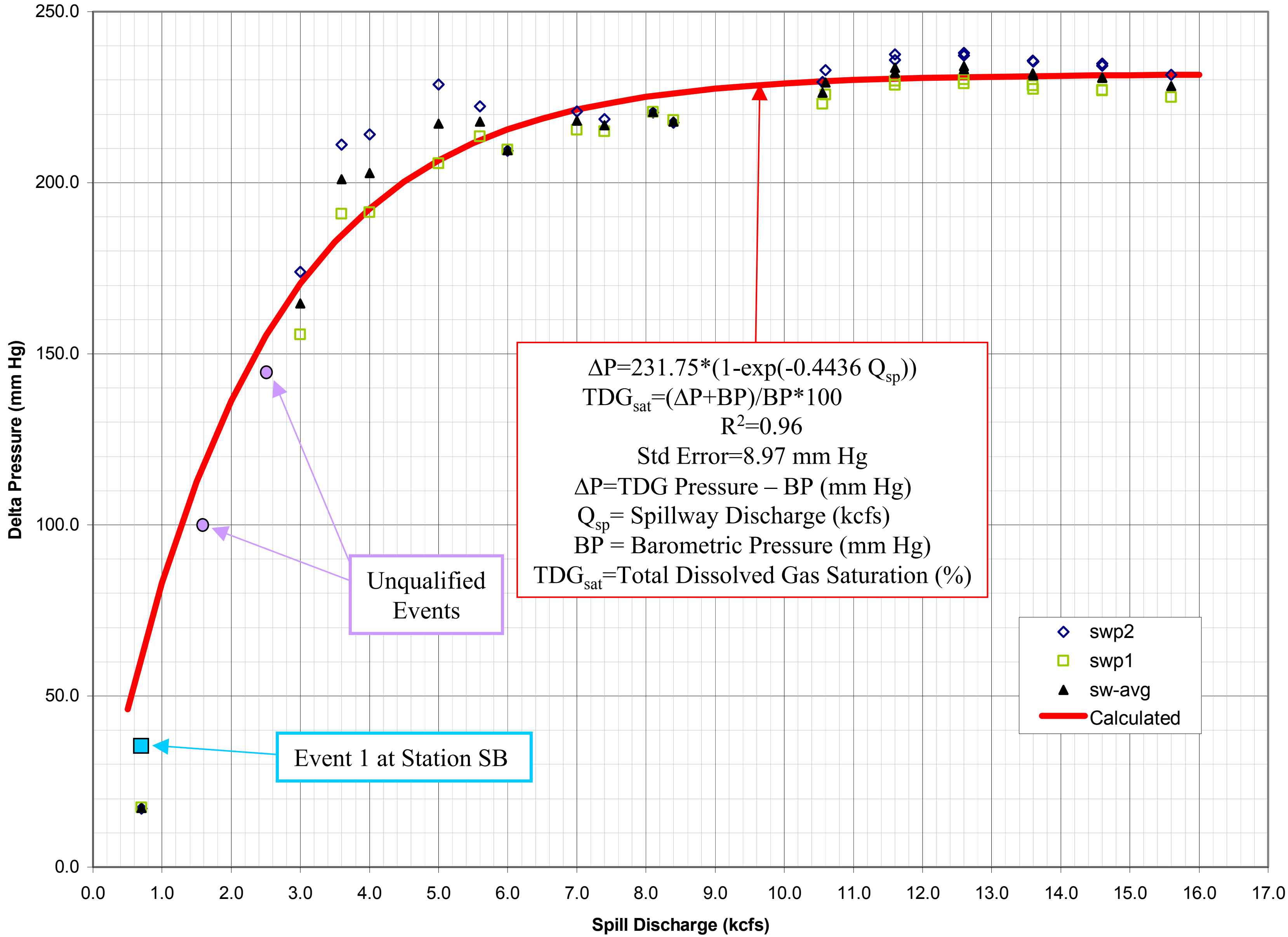



Figure 35. Observed and calculated delta total dissolved gas pressure versus total spillway discharge at Libby Dam, June 24-July 7, 2002 (ΔP=total dissolved gas pressure minus barometric pressure).

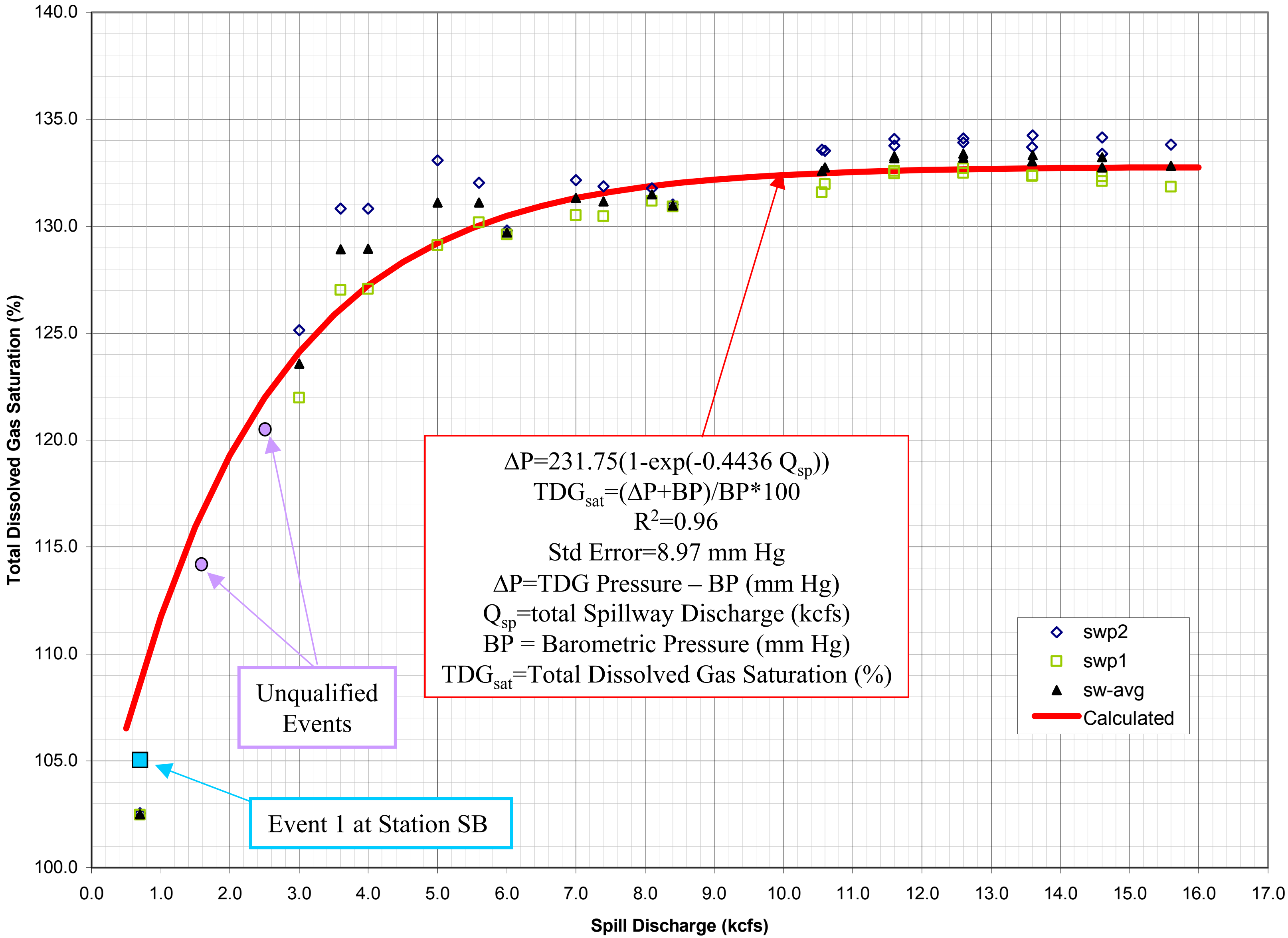



Figure 36. Observed and calculated total dissolved gas saturation versus total spillway discharge at Libby Dam, June 25-July 7, 2002

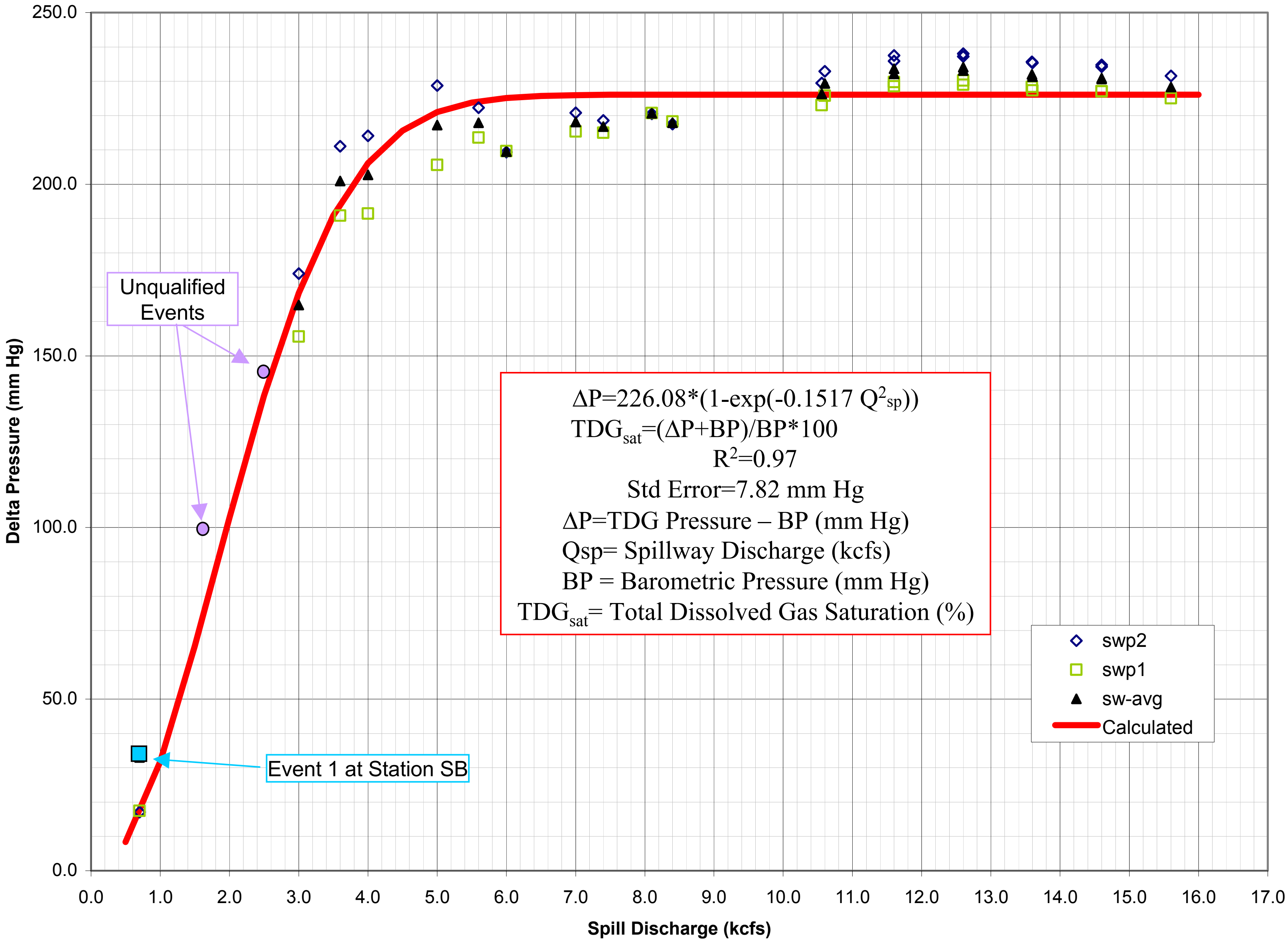



Figure 37. Observed and calculated delta total dissolved gas pressure versus total spillway discharge squared at Libby Dam, June 24-July 7, 2002 (ΔP=total dissolved gas pressure minus barometric pressure)

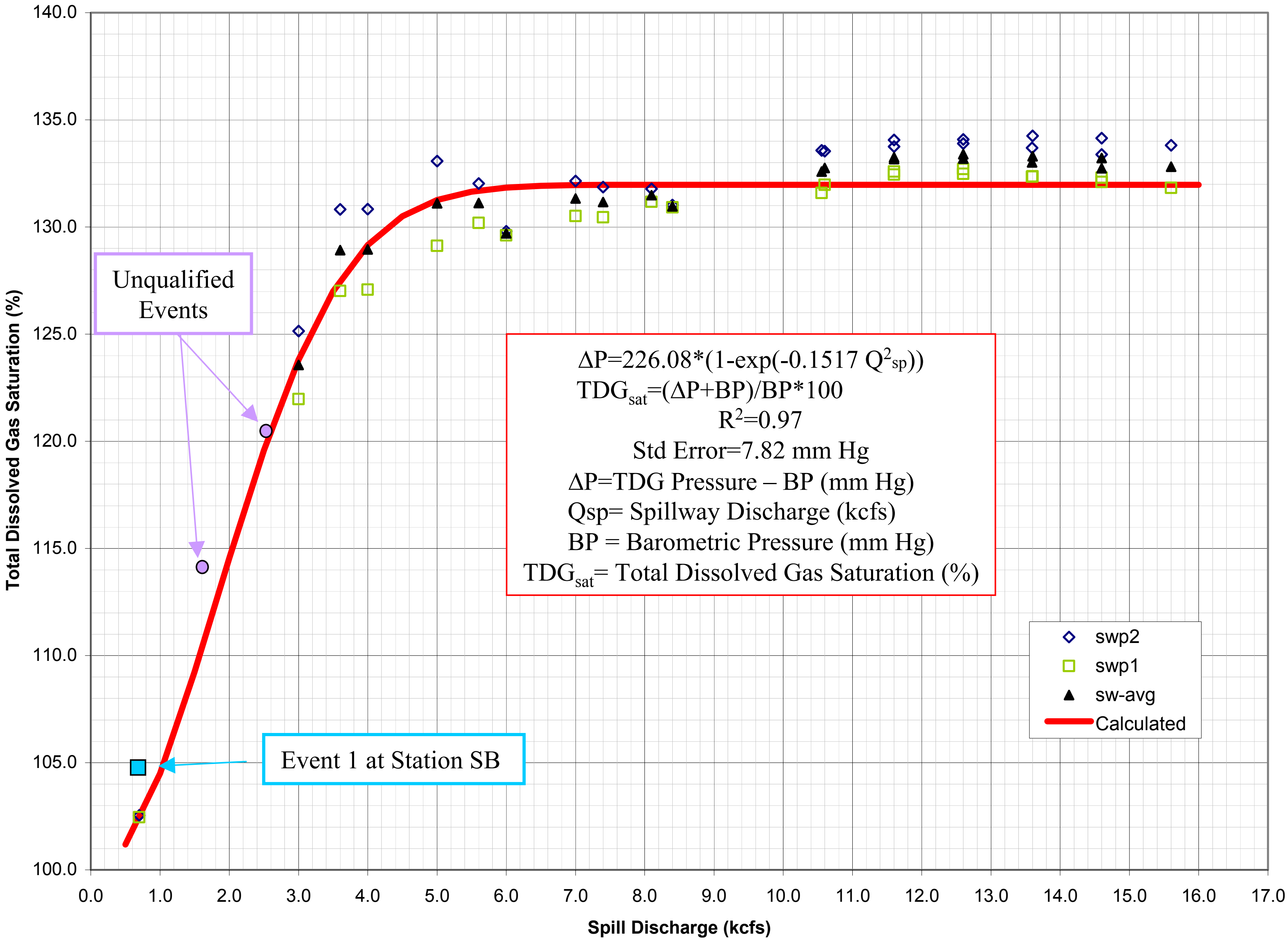



Figure 38. Observed and calculated total dissolved gas saturation versus total spillway discharge at Libby Dam, June 25-July 7, 2002

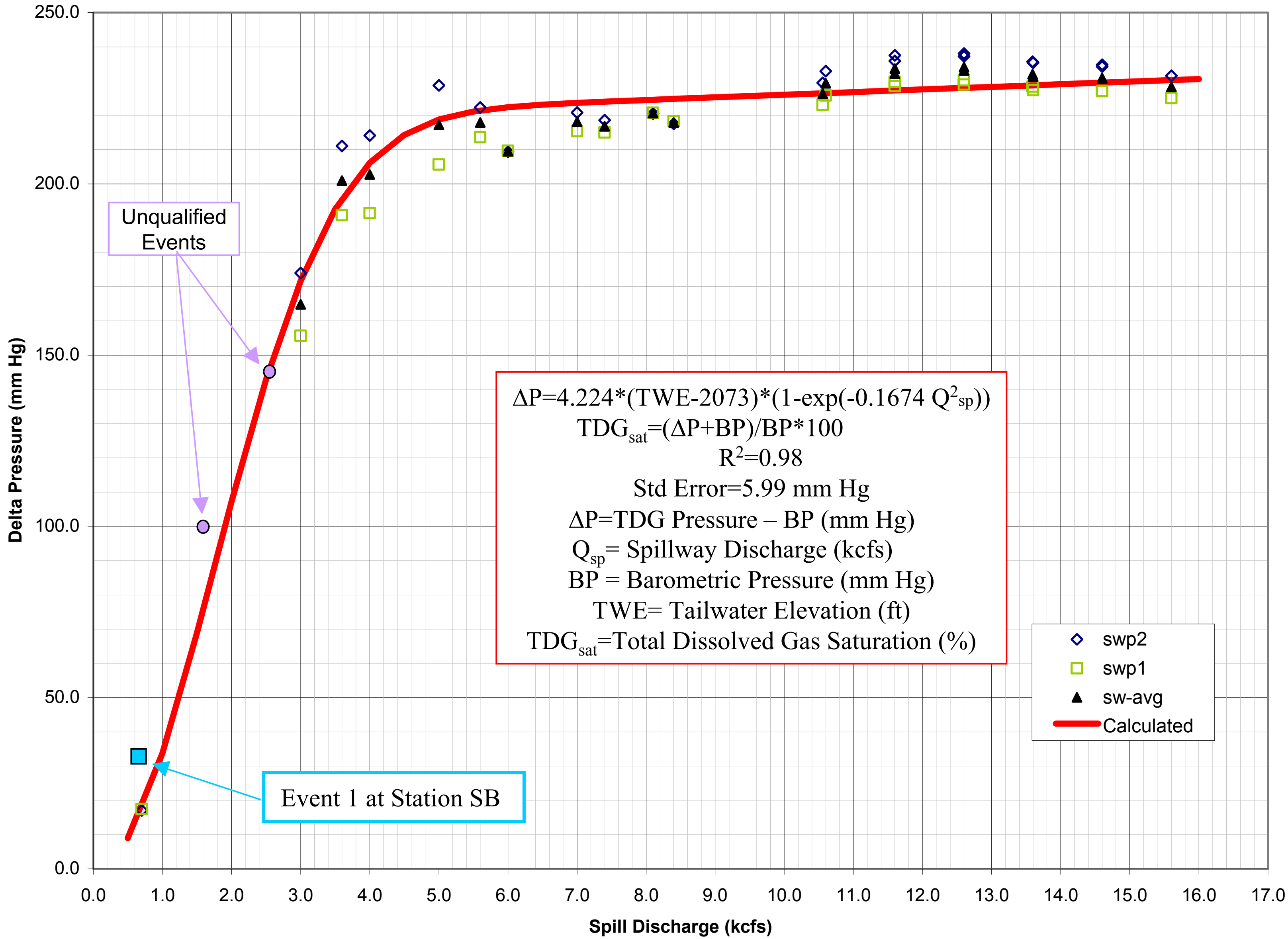



Figure 39. Observed and calculated delta total dissolved gas pressure versus total spillway discharge at Libby Dam, June 24-July 7, 2002 (ΔP=total dissolved gas pressure minus barometric pressure)

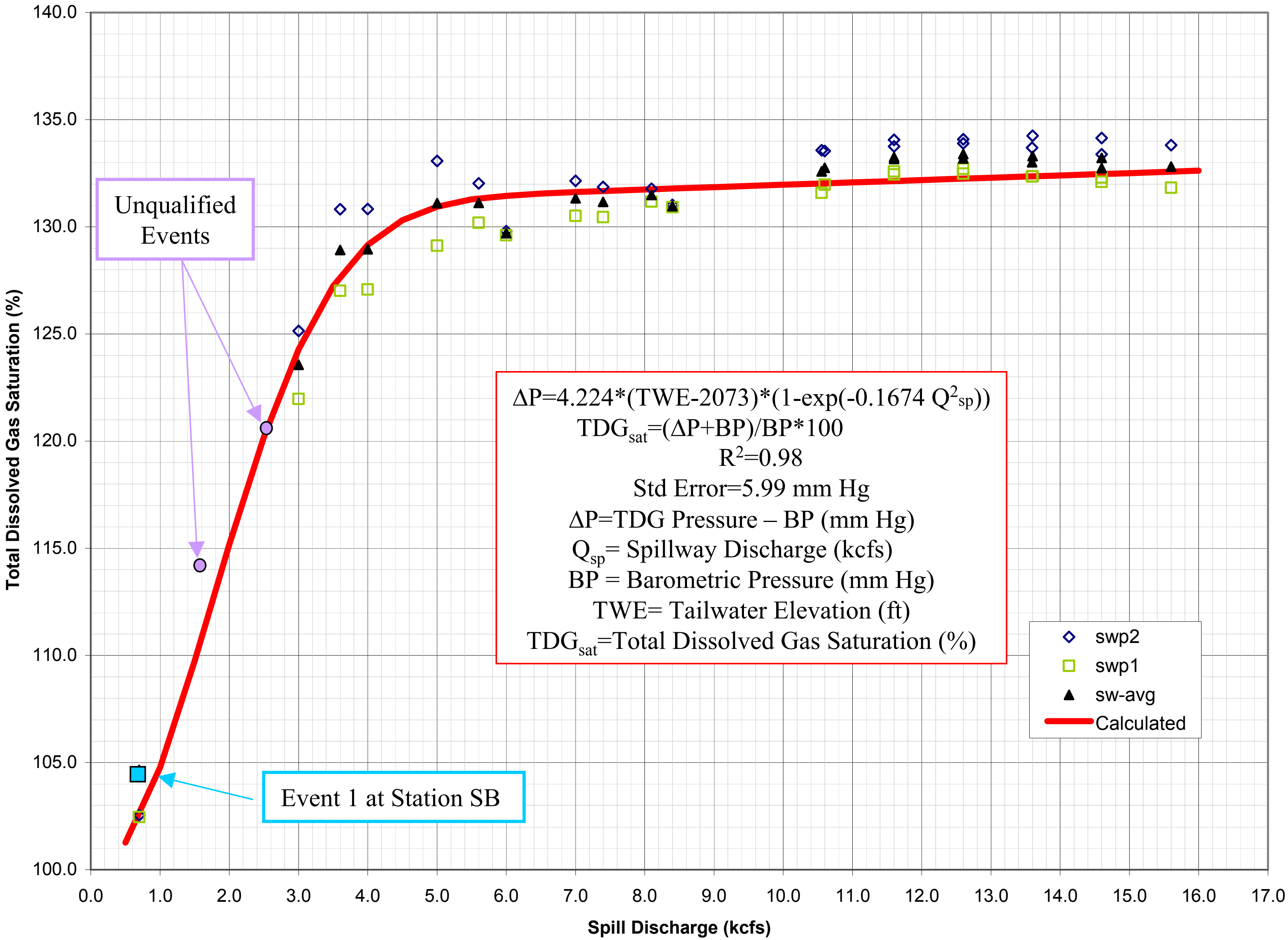



Figure 40. Observed and calculated total dissolved gas saturation versus total spillway discharge at Libby Dam, June 25-July 7, 2002

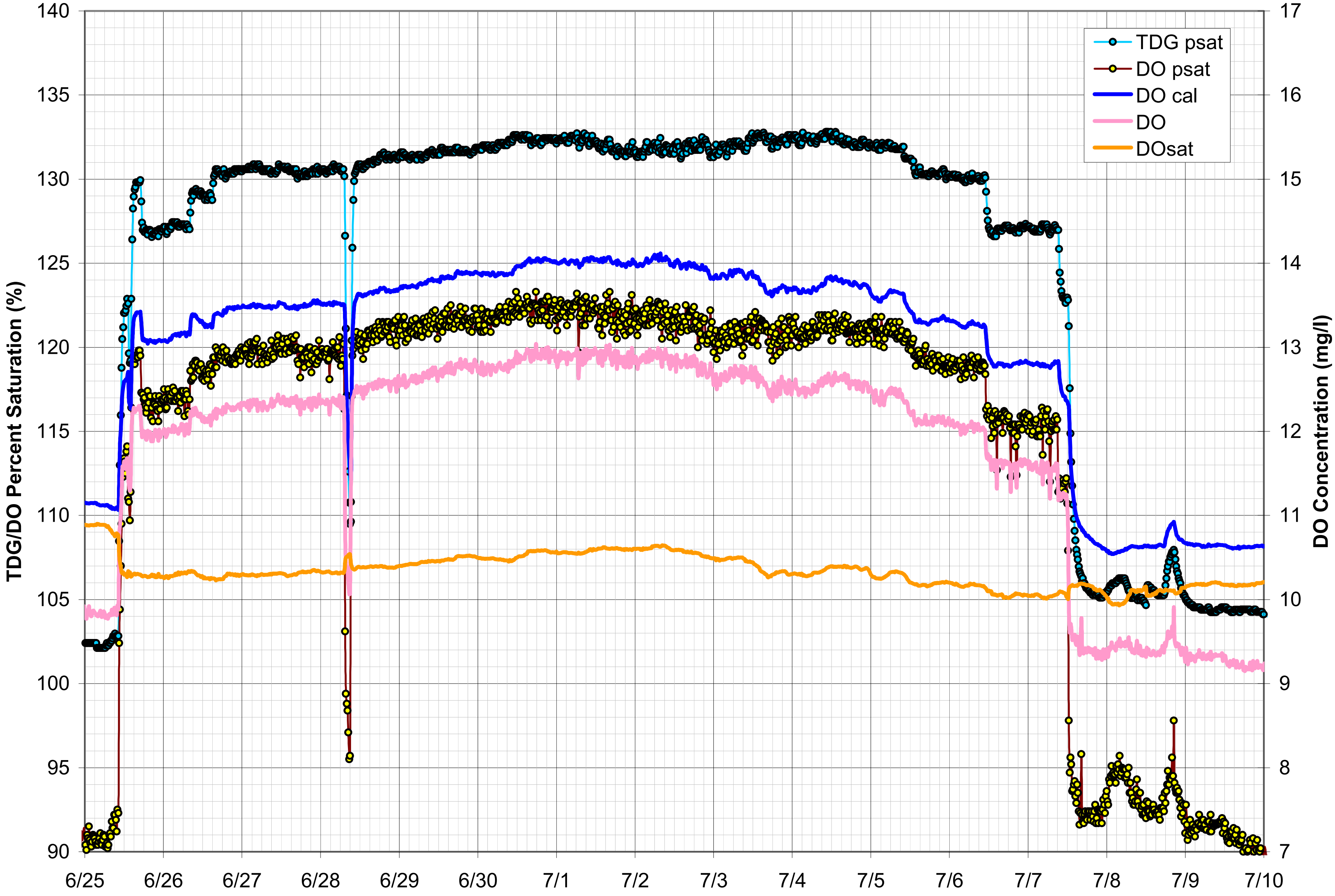



Figure 41. Dissolved oxygen concentration and saturation in spillway flows below Libby Dam at station SPWP1, June 25-July 9, 2002 (DO – observed DO concentration, DO sat - calculated DO saturation concentration, DO cal – Calculated DO concentration from TDG pressure assuming atmospheric ratios of dissolved gasses, DO psat – observed DO percent saturation, TDG psat - observed TDG percent saturation)

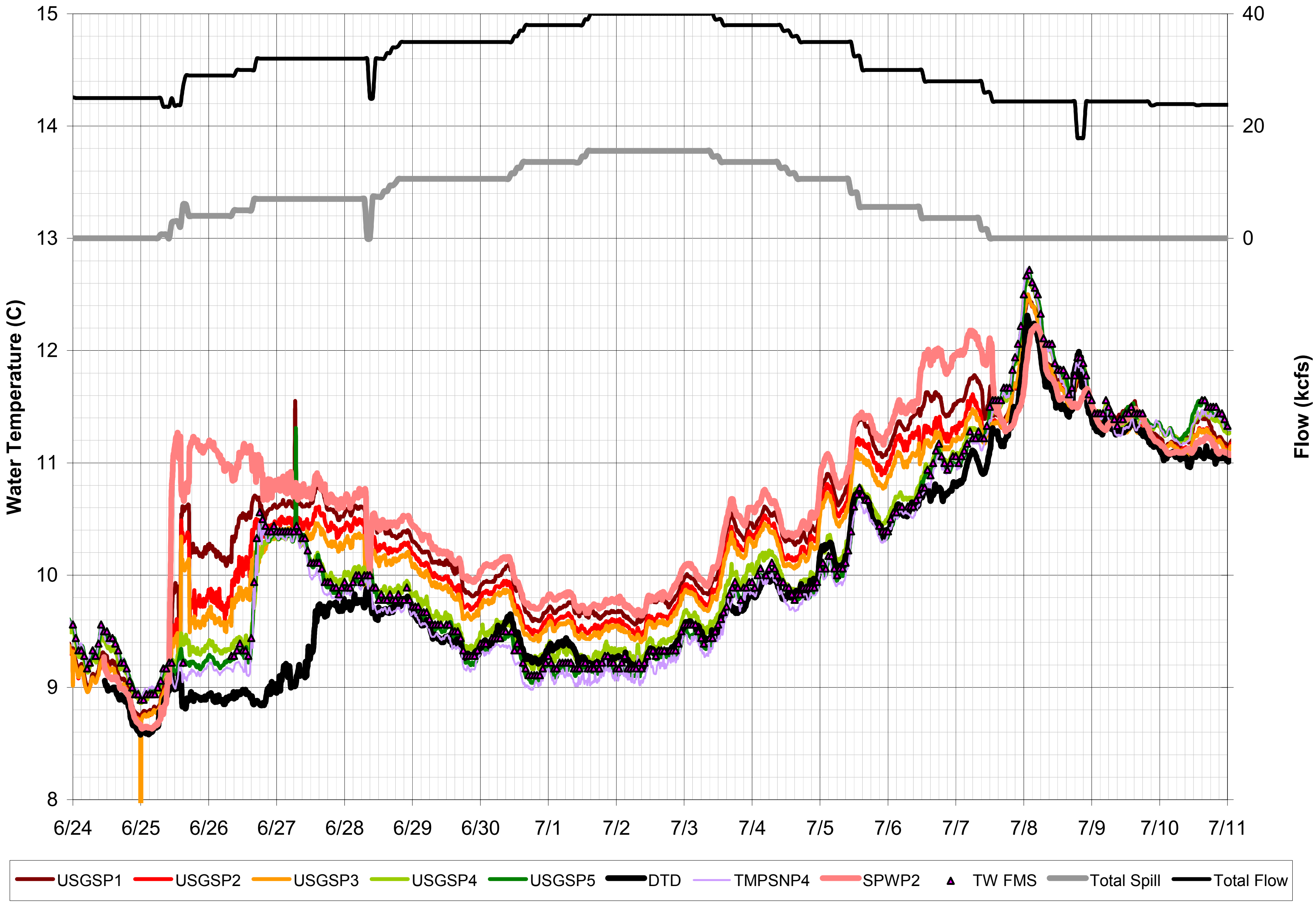



Figure 42. Kootenai River water temperatures in the tailwater channel of Libby Dam at the USGS transect, June 24-July 10, 2002

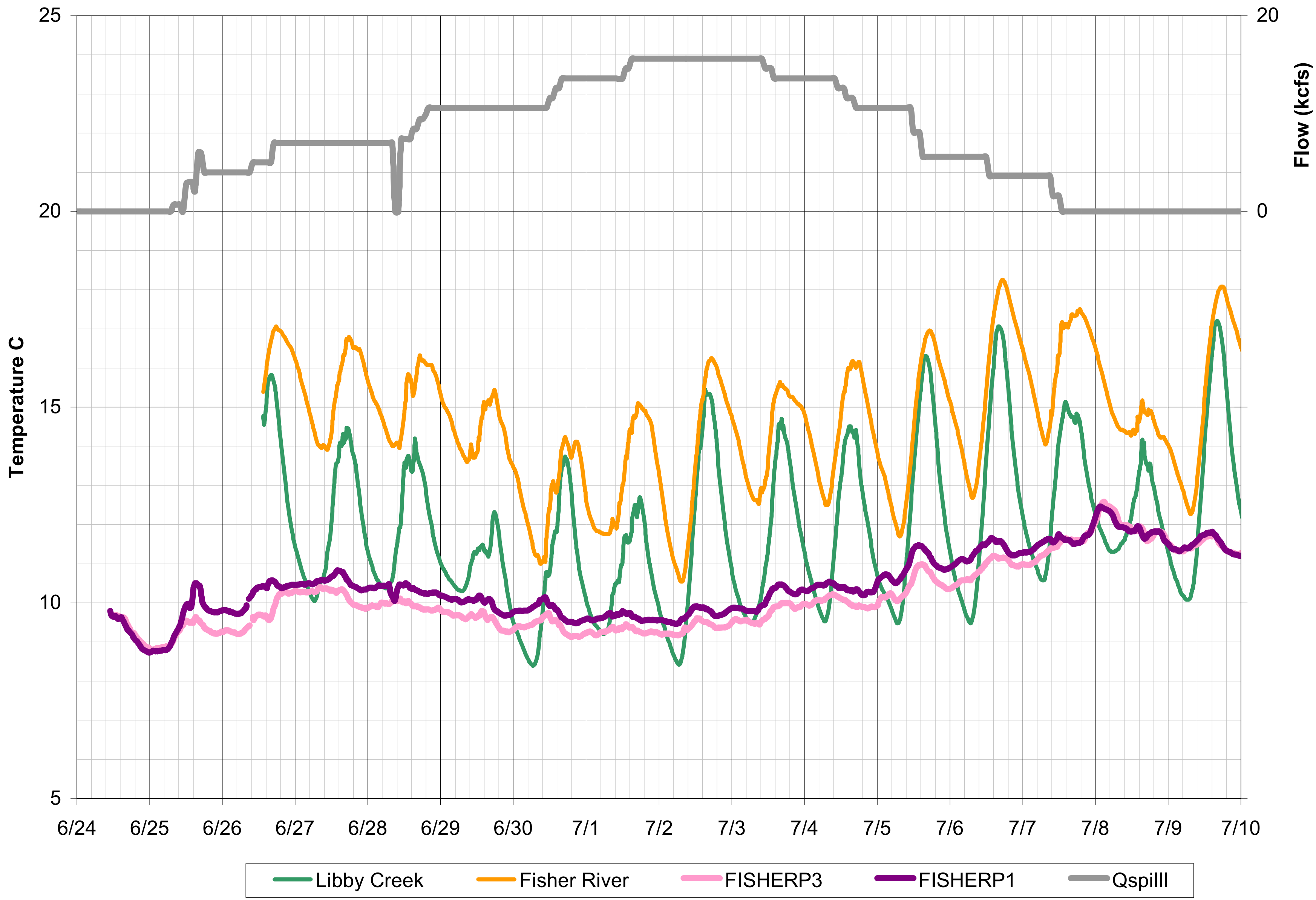



Figure 43. Kootenai River, Fisher River, and Libby Creek water temperatures, June 24-July 9, 2002

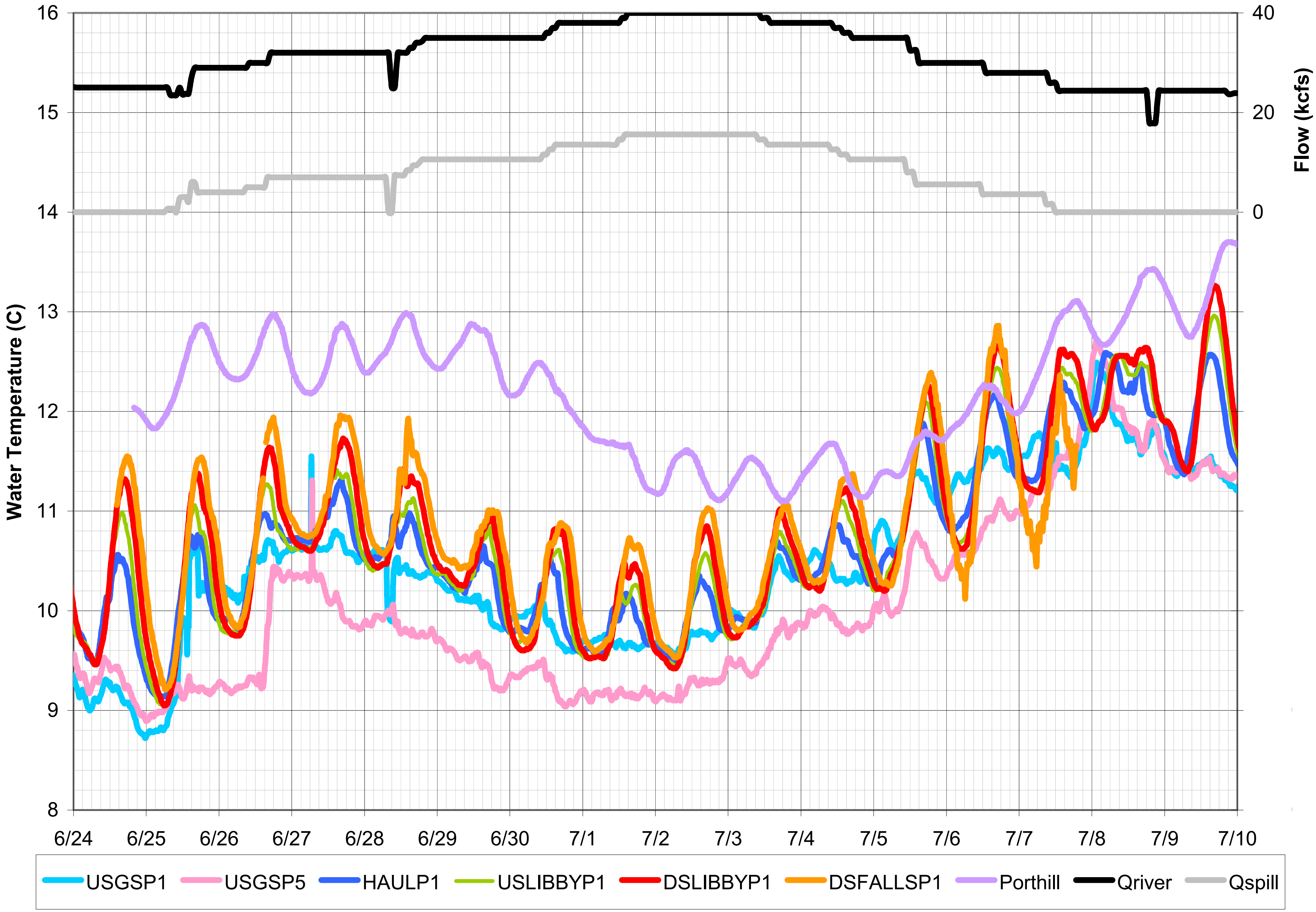



Figure 44. Kootenai River water temperatures from Libby Dam to the U.S./Canadian border, June 24-July 9, 2002

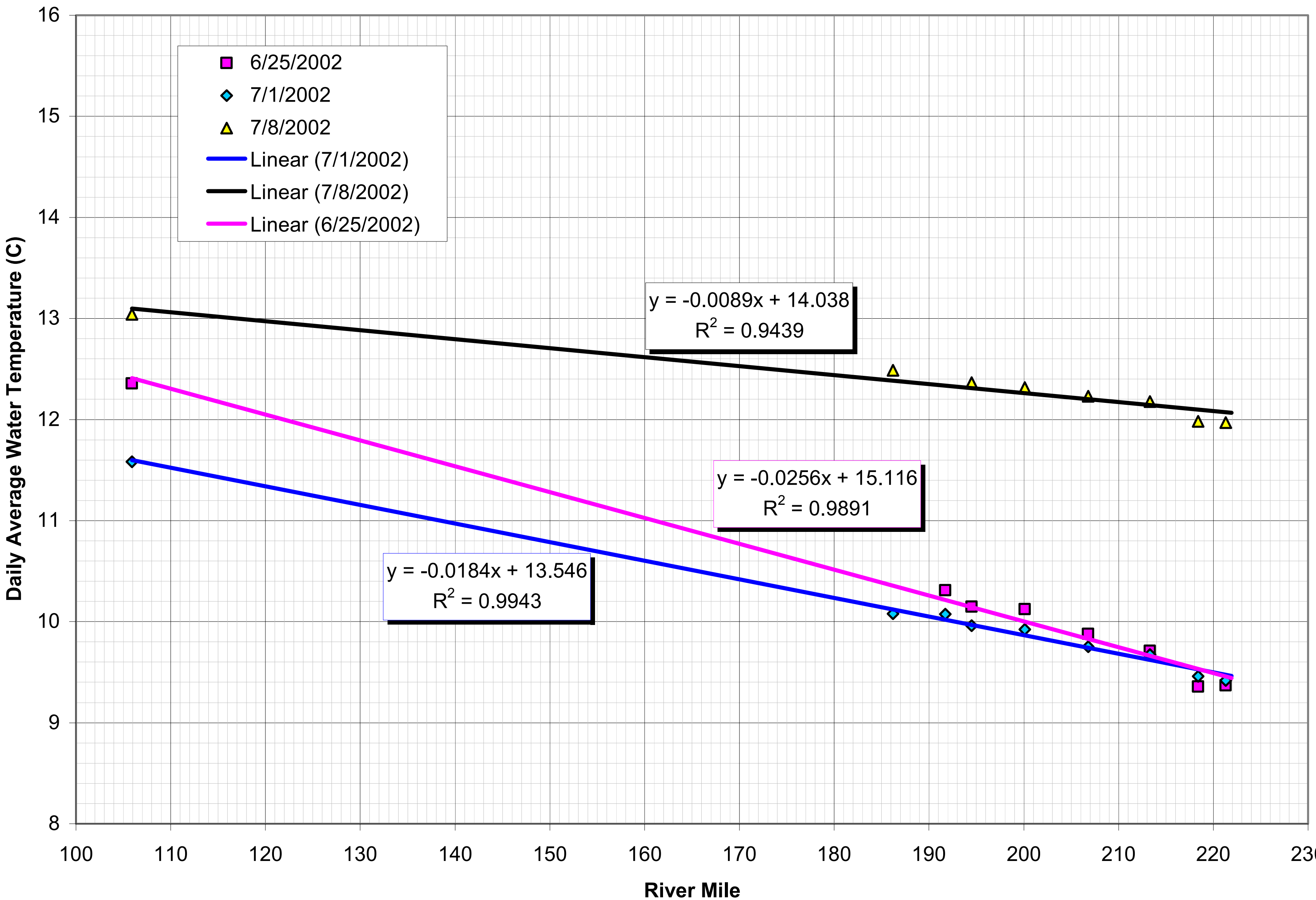



Figure 45. Daily average Kootenai River water temperature from Libby Dam to the U.S./Canadian border

Figure 46.  Libby Dam spill test, June 25, 2002, at 4:56 p.m., spillway discharge 6,000 cfs

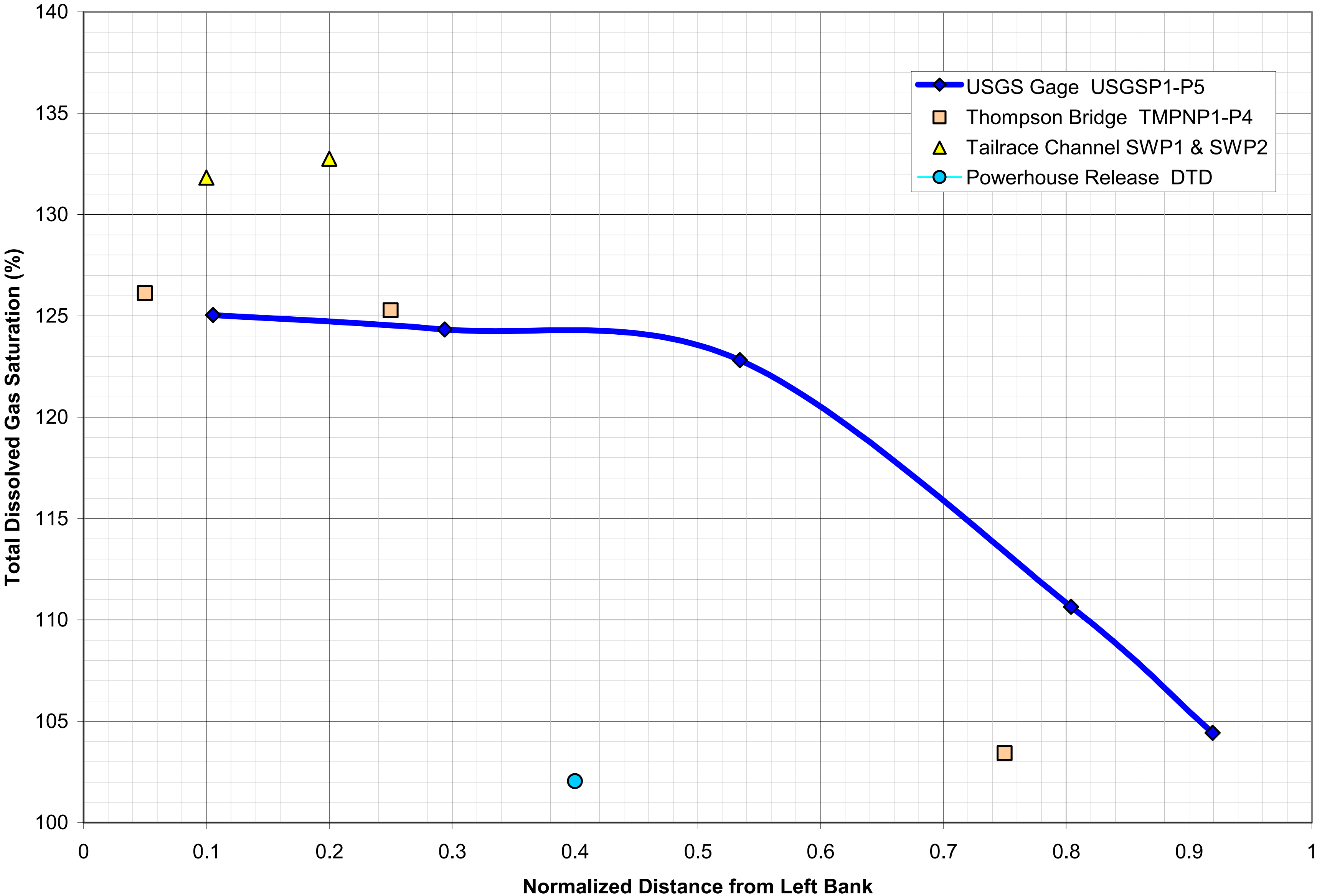



Figure 47. Lateral distribution of TDG saturation below Libby Dam, event 14 $Q_{total}$=40 kcfs, $Q_{spill}$=15.6 kcfs (Normalized distance, left bank=0, right bank=1)

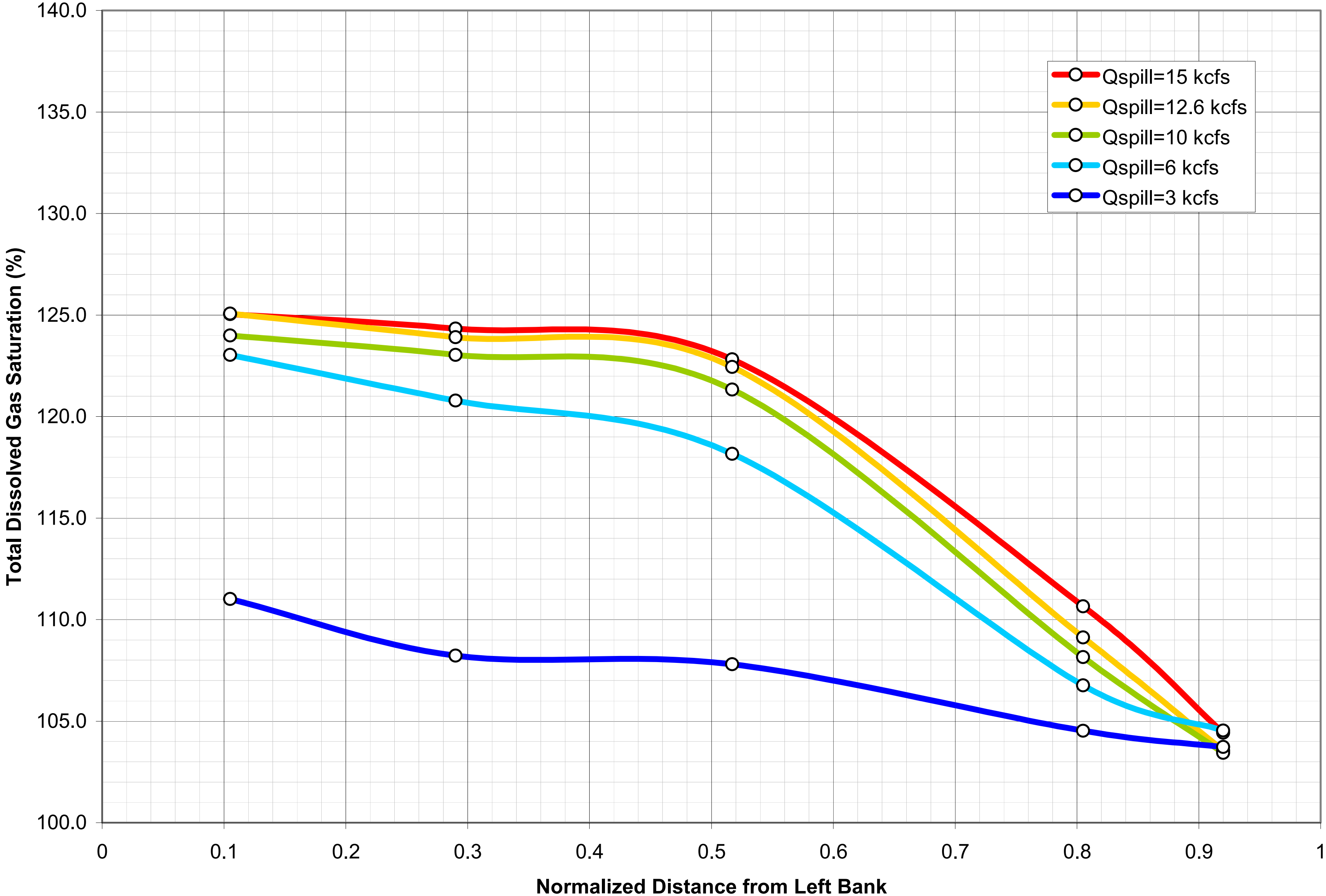



Figure 48. Lateral total dissolved gas saturation at the USGS transect below Libby Dam for spill discharges of 3, 5, 10, 12.6, and 15 kcfs. (Normalized distance, left bank=0, right bank=1)

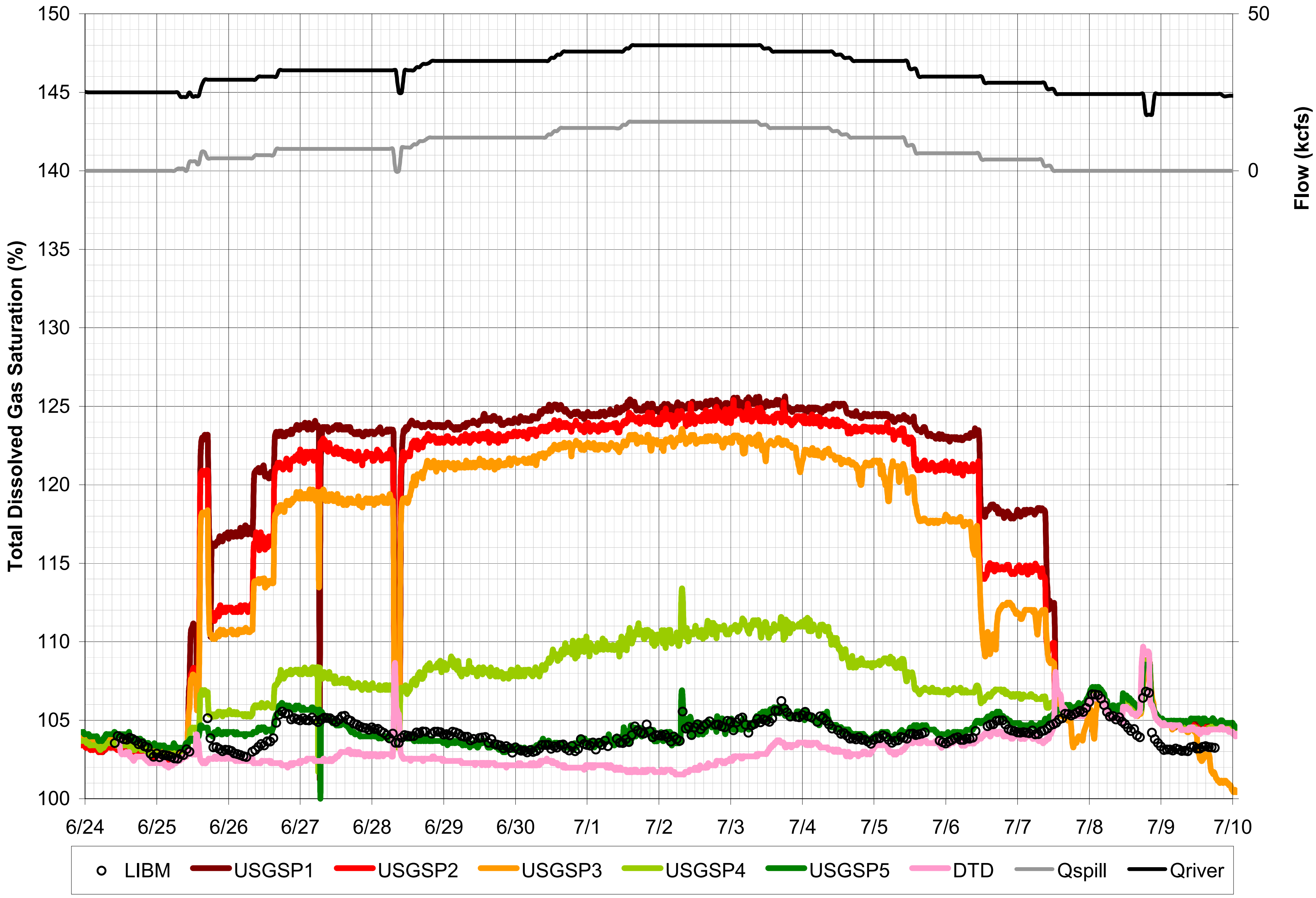



Figure 49. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam at the USGS gaging station, June 24 – July 9, 2002

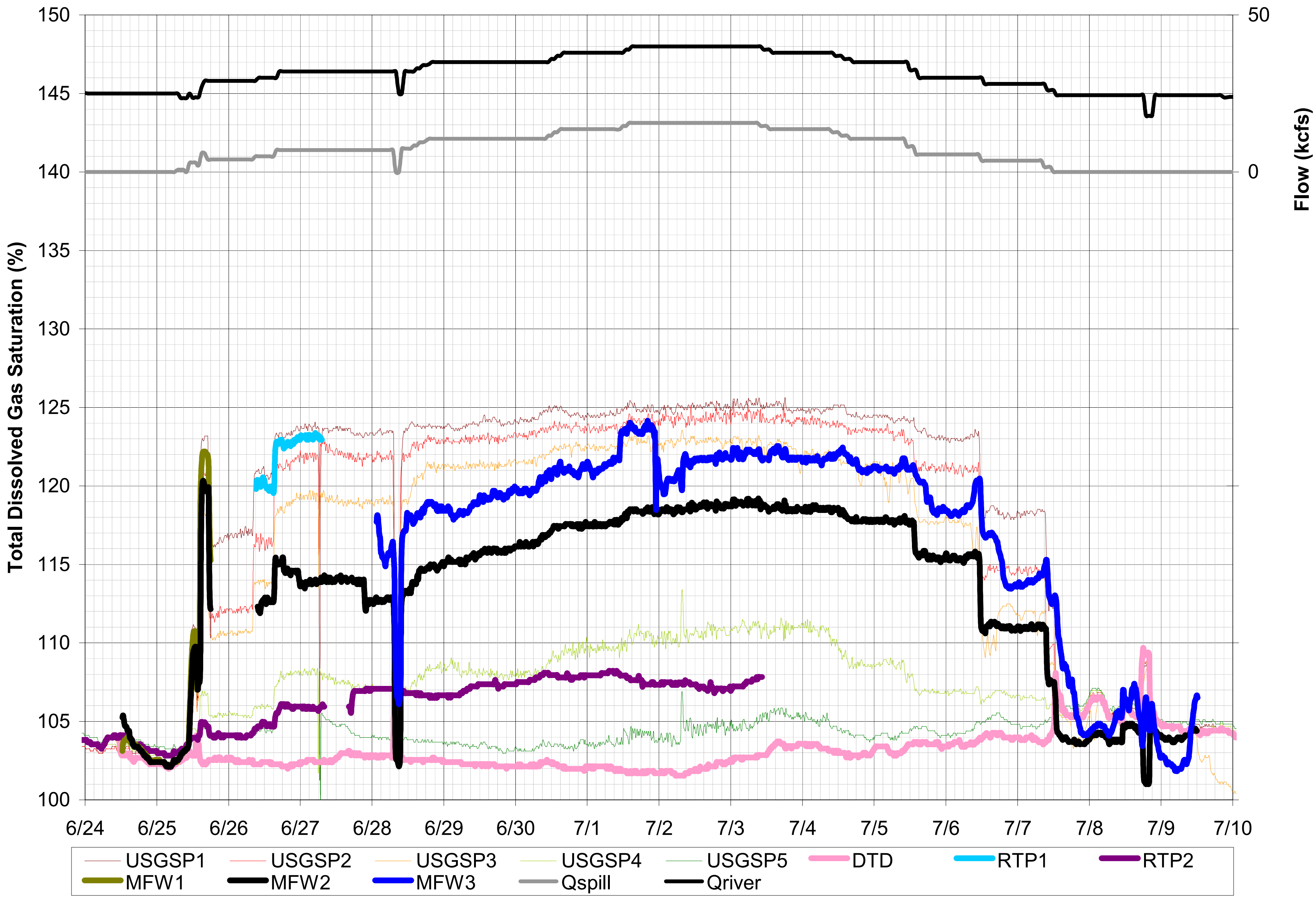



Figure 50. Libby Dam operations and TDG saturation at the USGS transect (USGSP1-P5), real-time monitoring stations (RTP1-2), and fish cage sites (MFW1-3) below Libby Dam, June 24-July 9, 2002

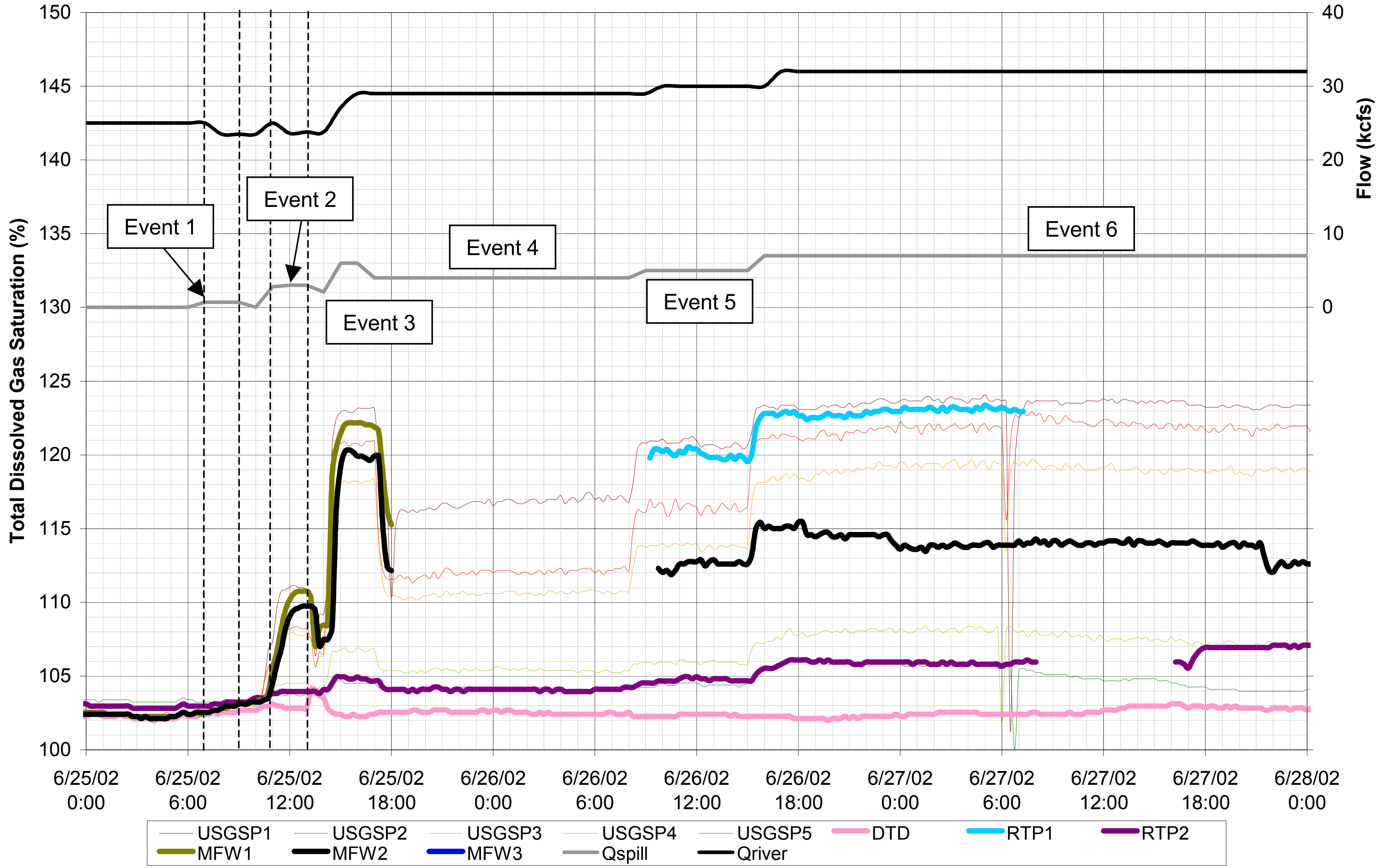



Figure 51. Libby Dam operations and TDG saturation at the USGS transect (USGSP1-P5), real-time monitoring stations (RTP1-2), and fish cage sites (MFW1-3) below Libby Dam, June 25-27, 2002

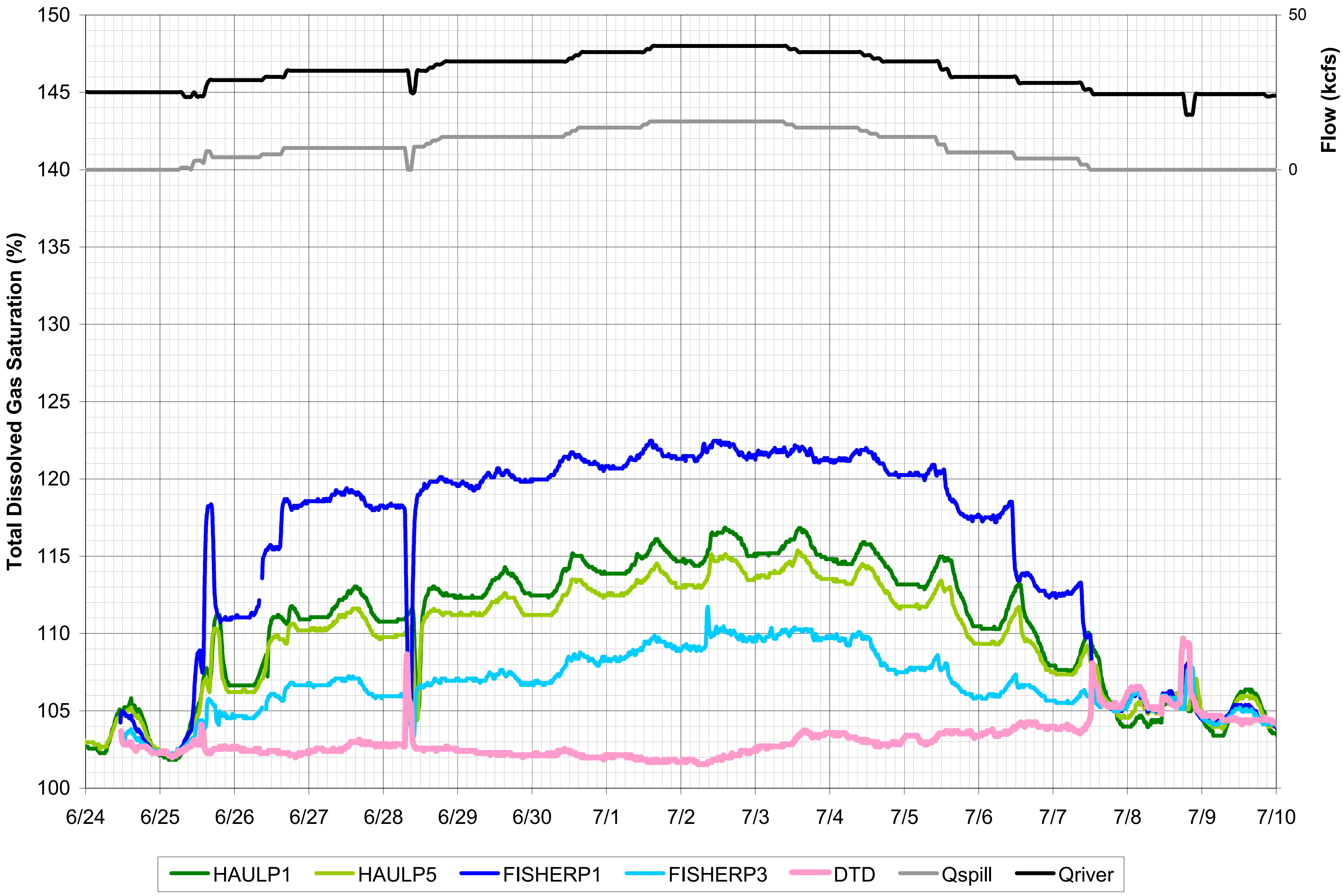



Figure 52. Time-history of Kootenai River total dissolved gas saturation below the Libby Dam at the Fisher and Haul Bridge, June 24 – July 9, 2002

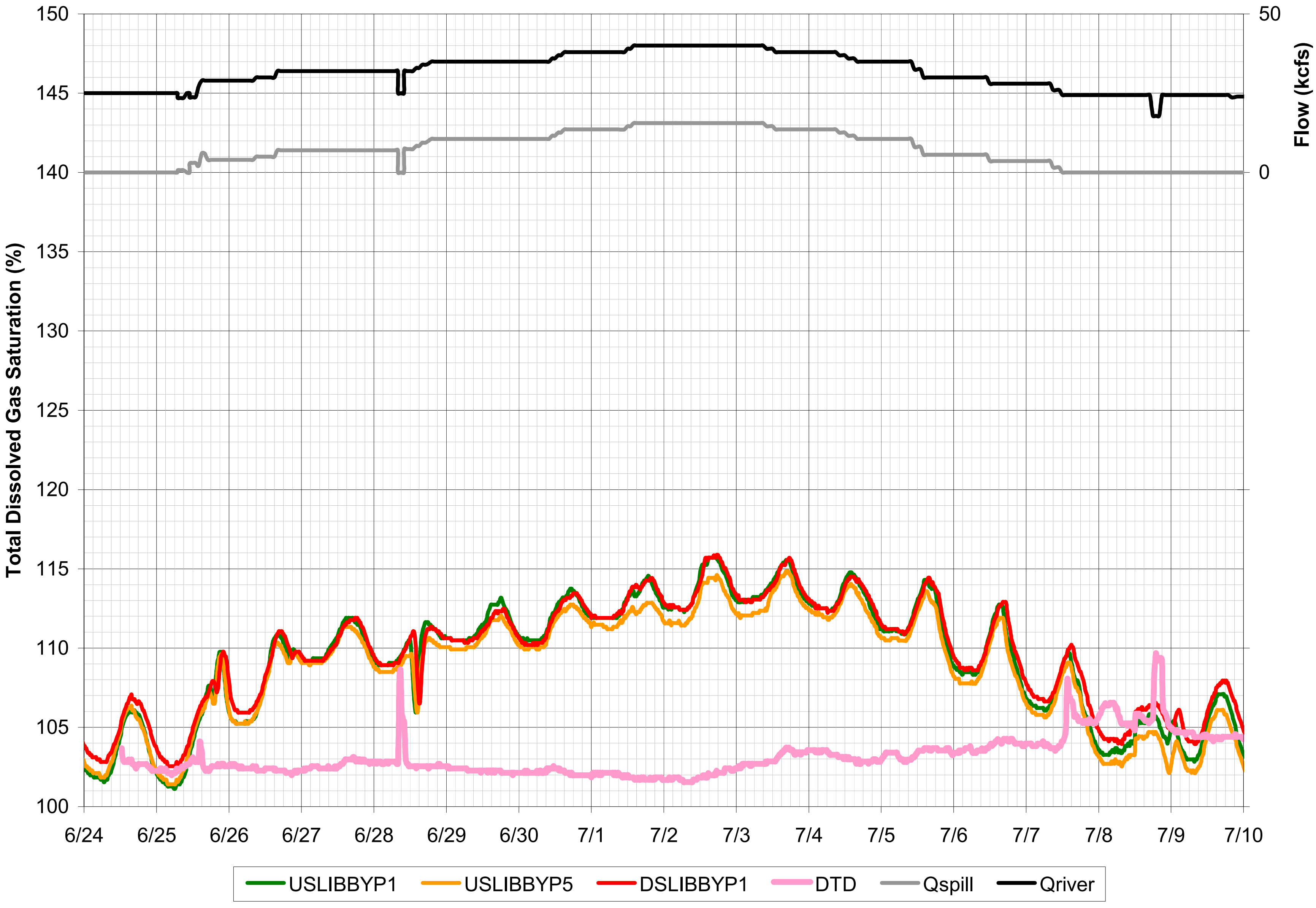



Figure 53. Time-history of Kootenai River total dissolved gas saturation upstream and downstream of Libby Montana, June 24 – July 9, 2002

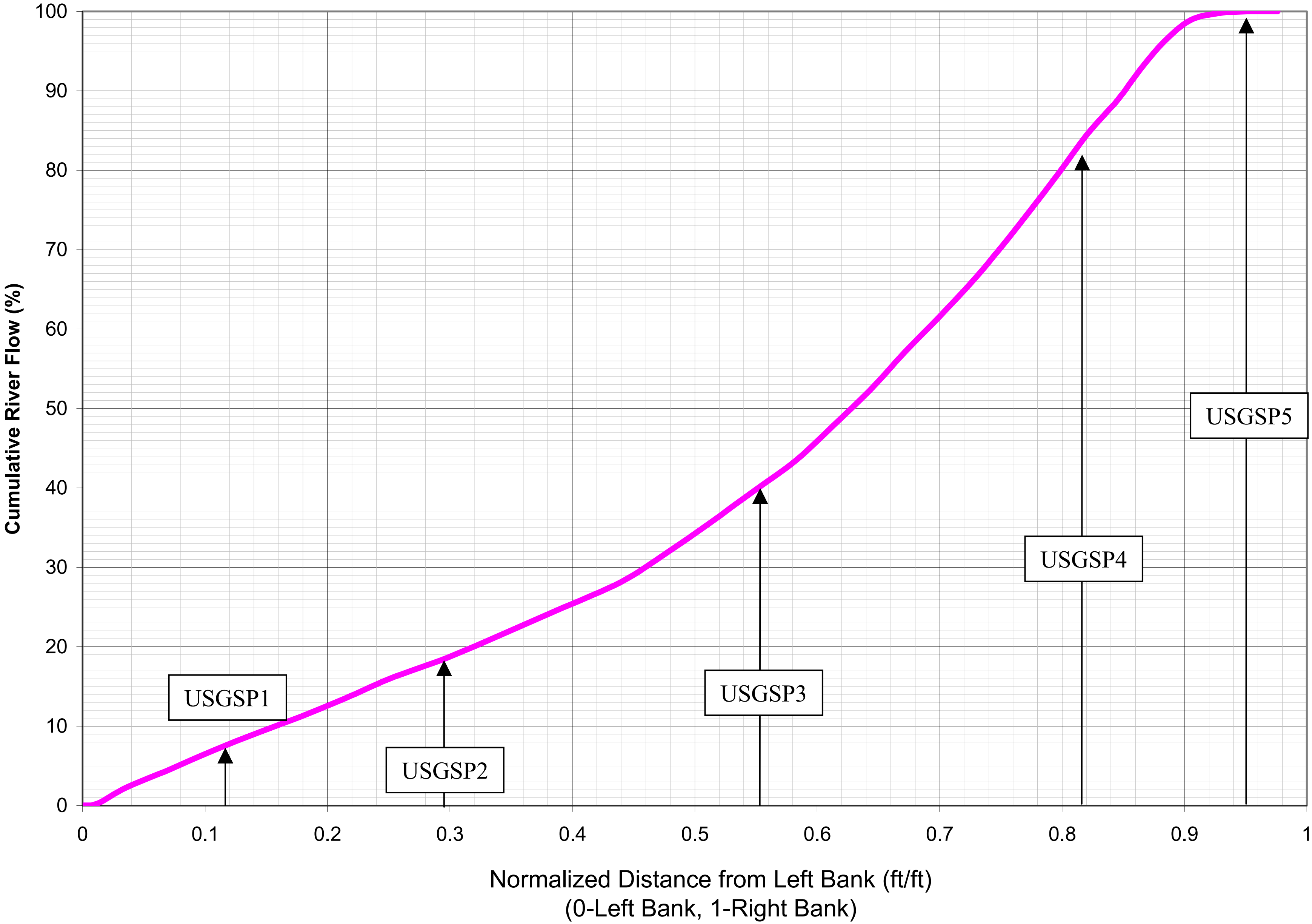



Figure 54. Cumulative riverflow versus normalized distance from left bank at the USGS transect below Libby Dam

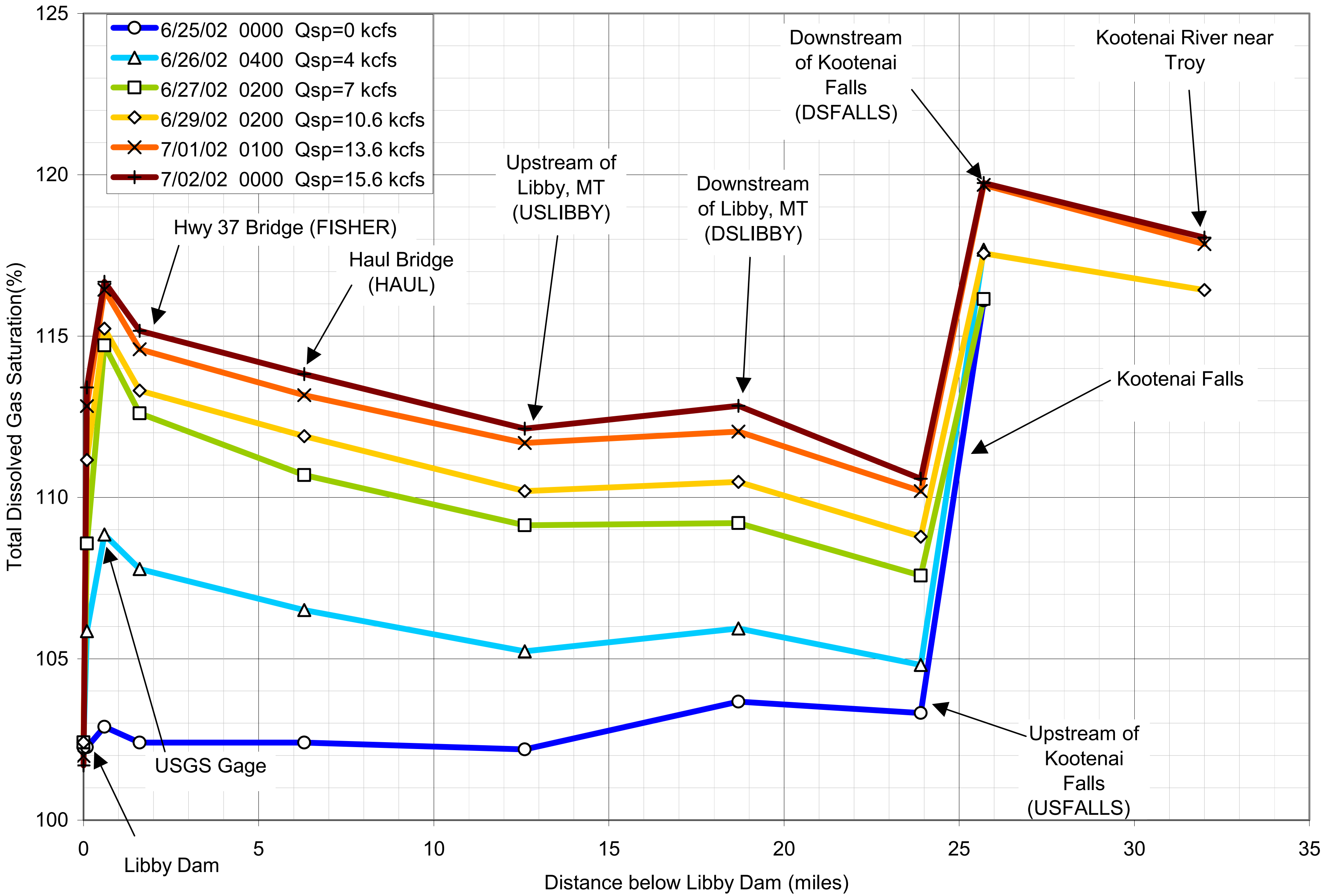



Figure 55. Average total dissolved gas saturation below Libby Dam after 10 hours of constant operation

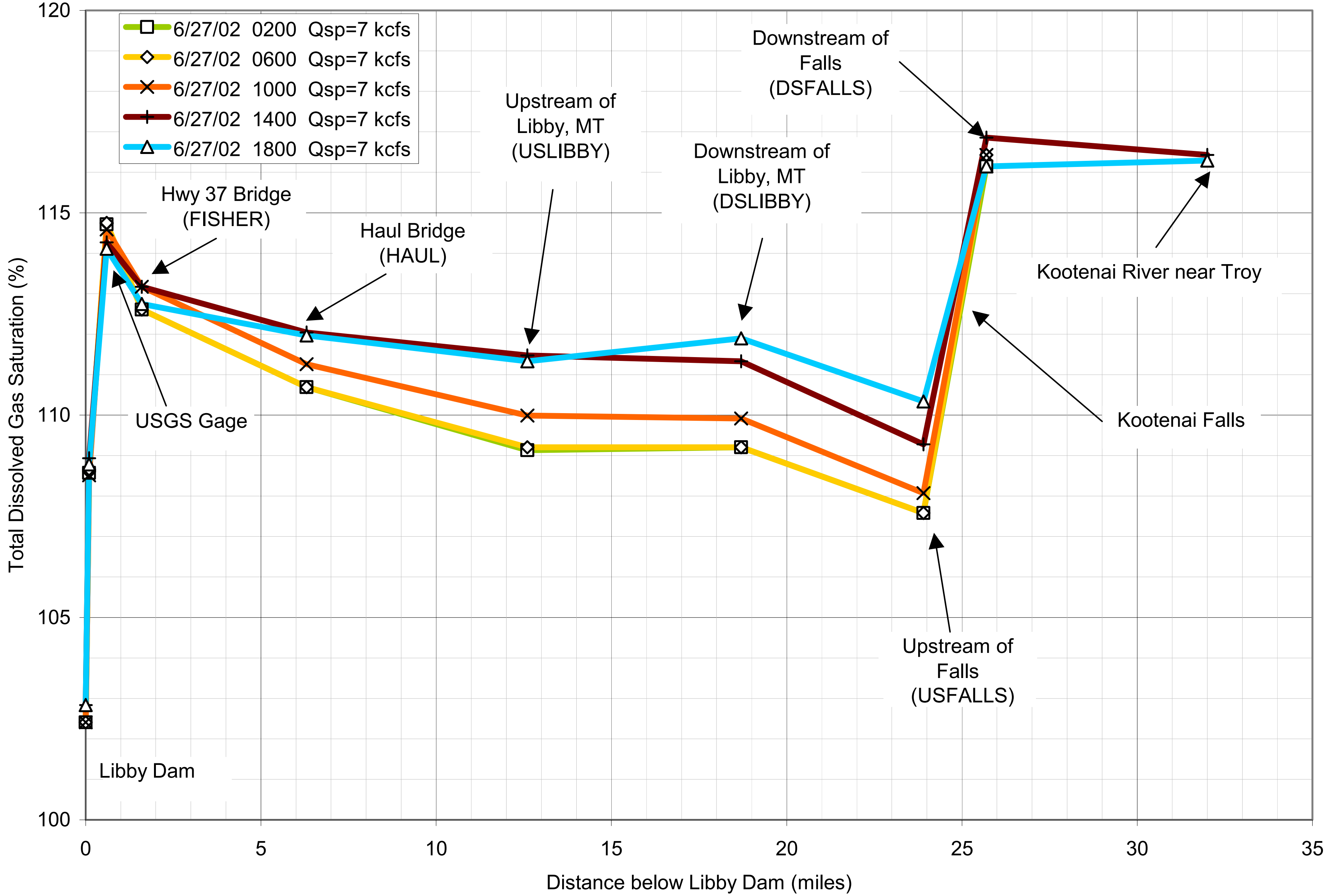



Figure 56. Average total dissolved gas pressure versus distance below Libby Dam during June 27, 2002, $Q_{spill}$=7 kcfs

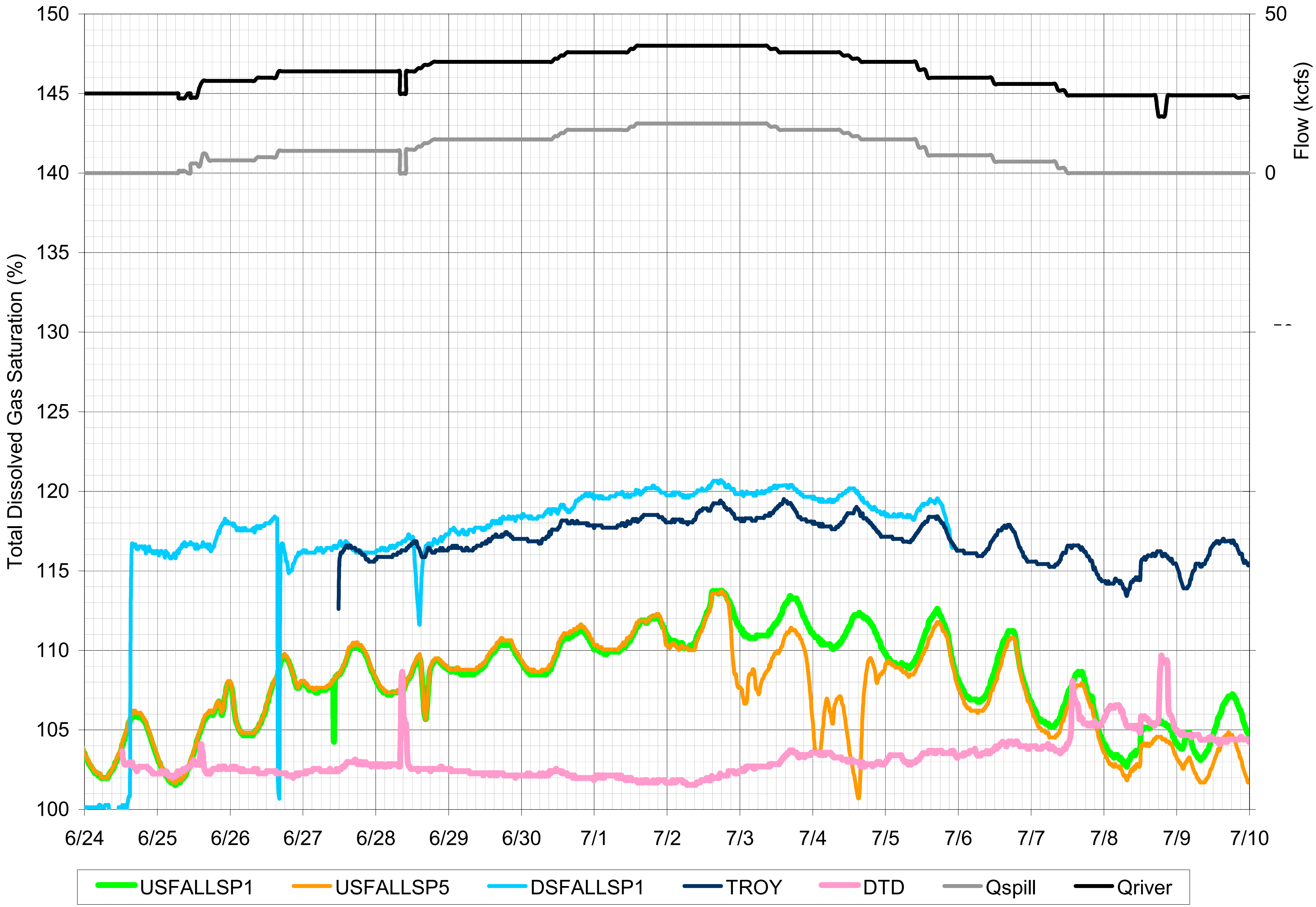



Figure 57. Time-history of Kootenai River total dissolved gas saturation upstream and downstream of Kootenai Falls, June 24 – July 9, 2002

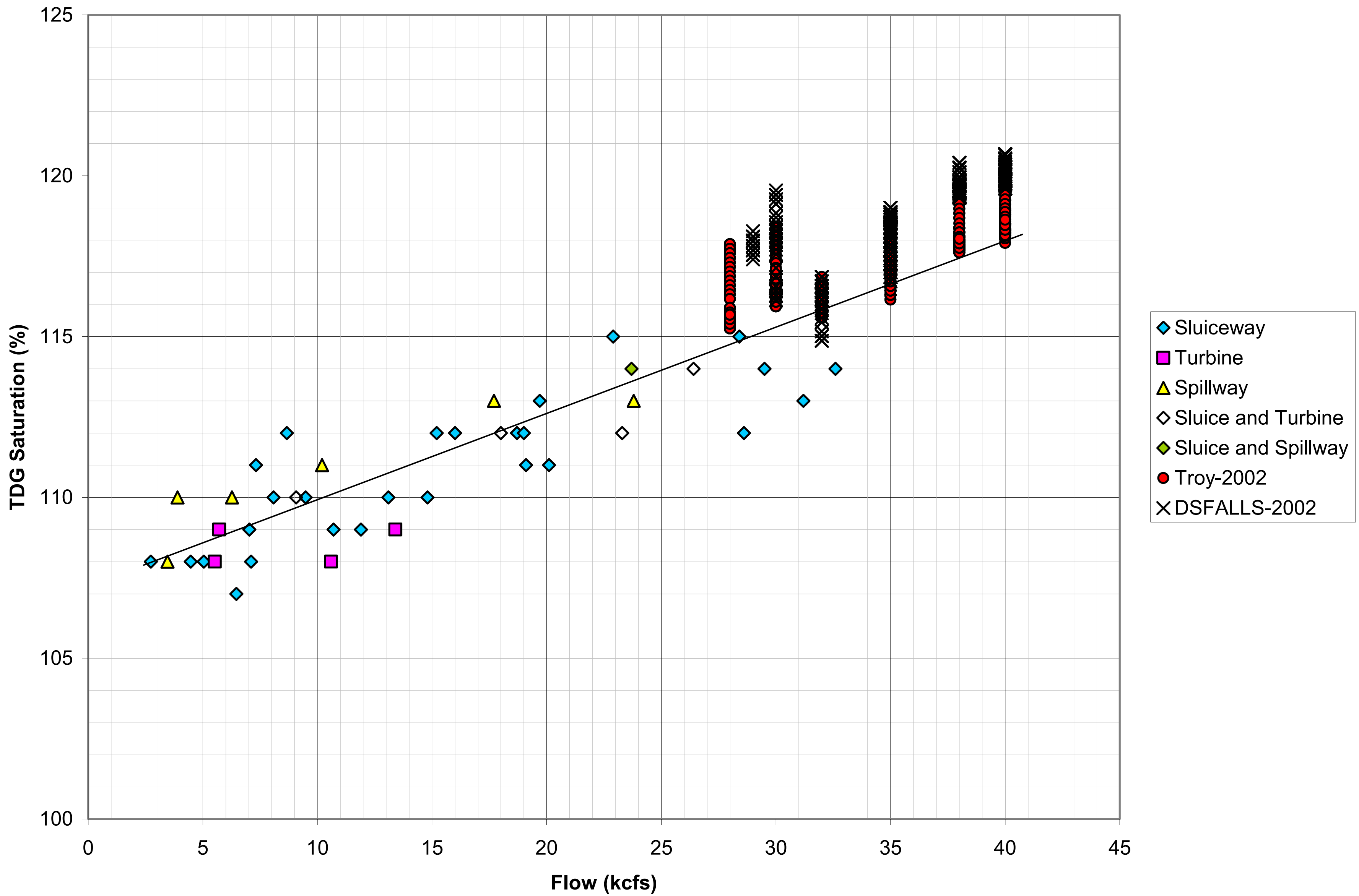



Figure 58. Total dissolved gas saturation downstream of Kootenai Falls as a function river flow, 1972-1975, 2002
(Data is from 1972-1975 unless labeled 2002)

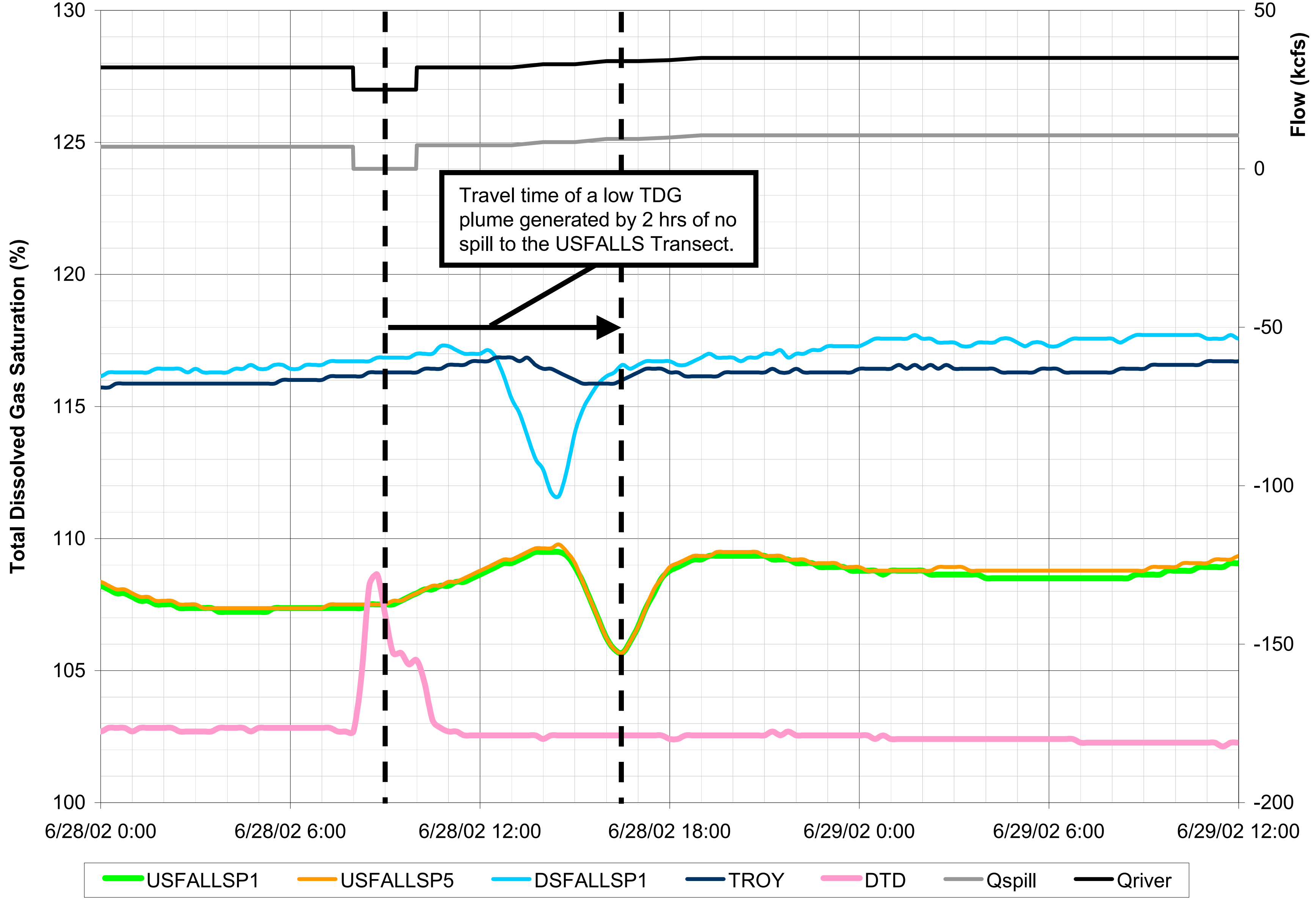



Figure 59. Time-history of Kootenai River total dissolved gas saturation upstream and downstream of Kootenai Falls, June 28 – June 29, 2002

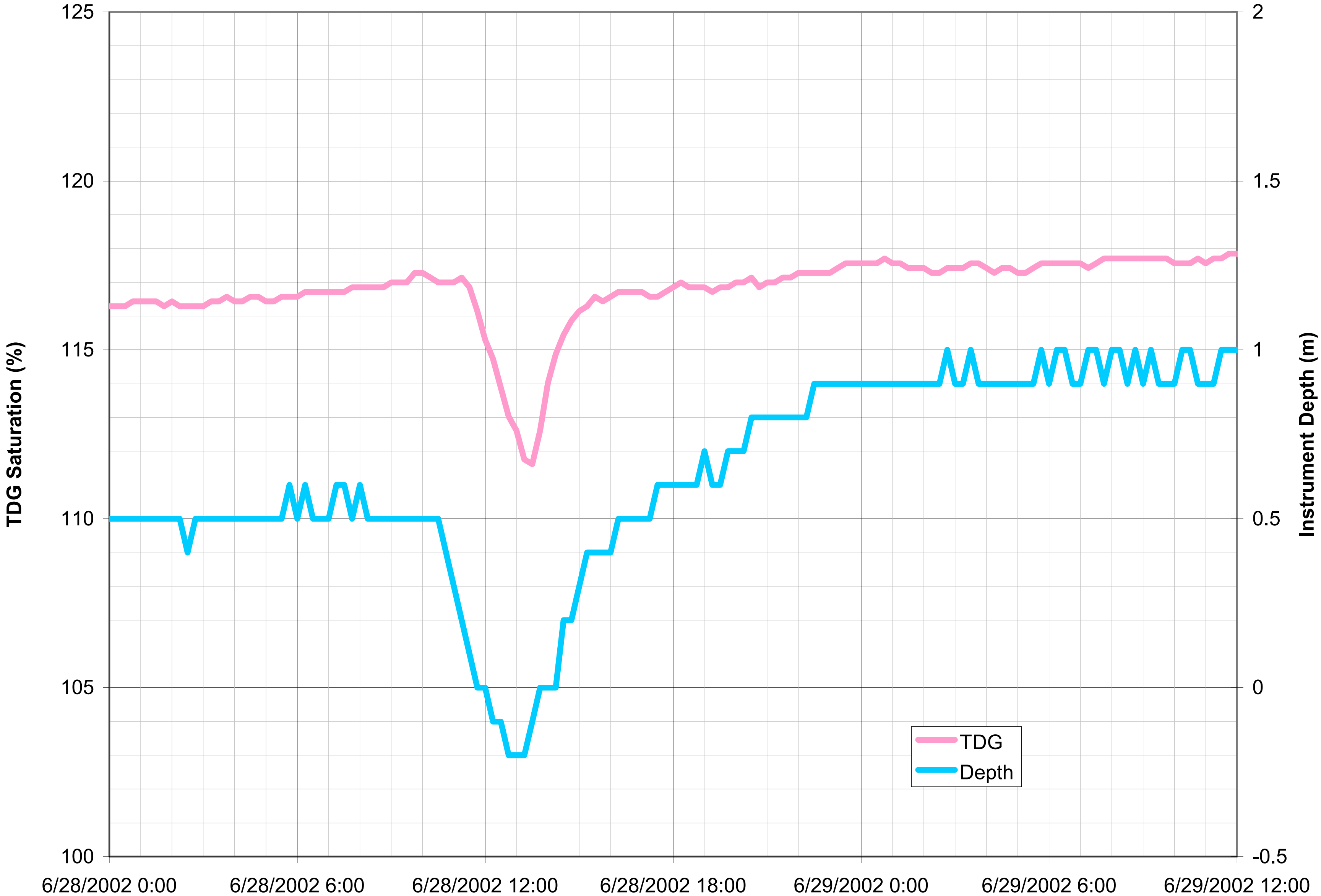



Figure 60. Total Dissolved Gas saturation and instrument depth below Kootenai Falls at station DSFALLSP1, June 28-29, 2002.

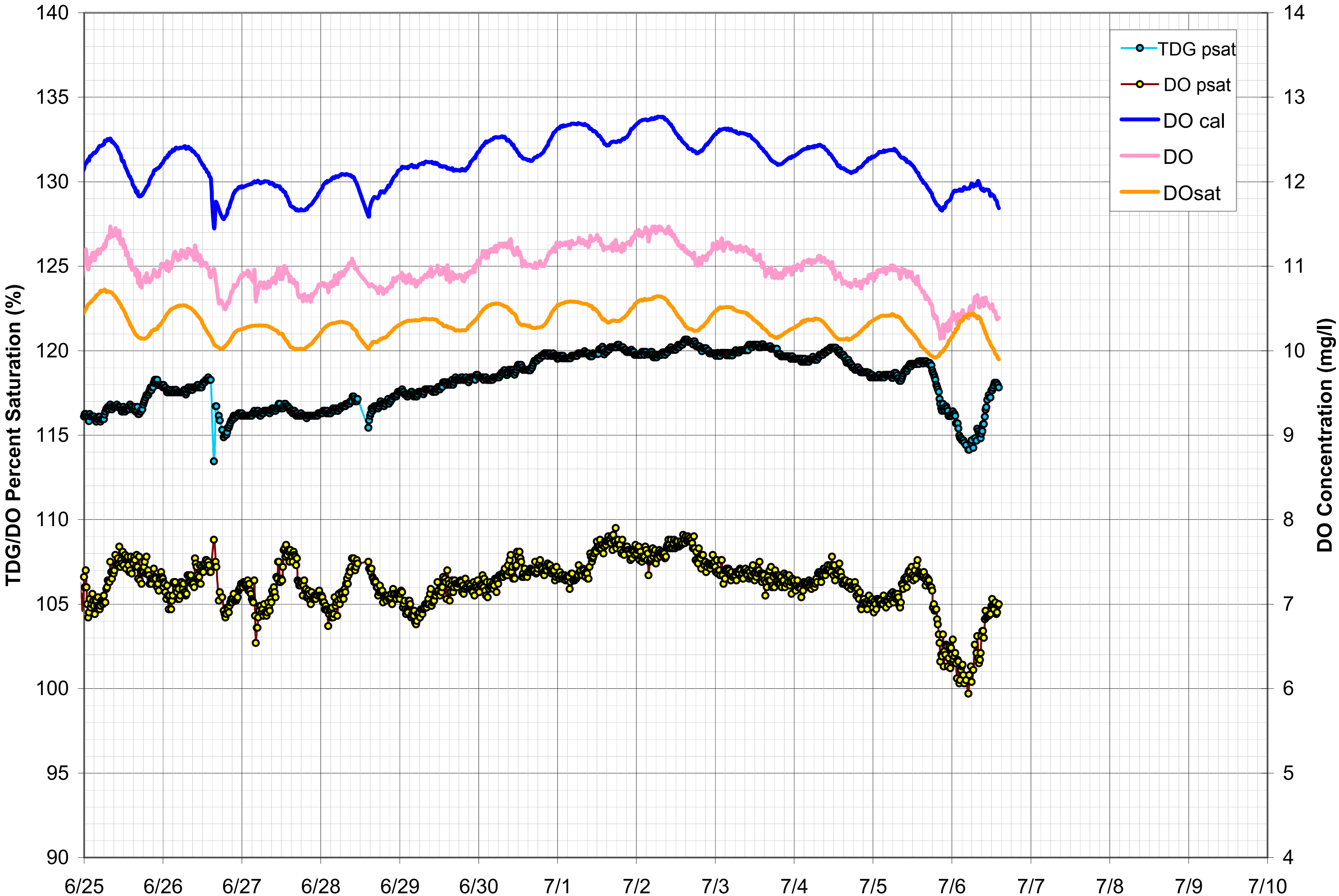



Figure 61. Dissolved oxygen concentration and saturation below Kootenai Falls at station DSFALLS, June 25-July 9, 2002 (DO – observed DO concentration, DO sat - calculated DO saturation concentration, DO cal – Calculated DO concentration from TDG pressure assuming atmospheric ratios of dissolved gasses, DO psat – observed DO percent saturation, TDG psat - observed TDG percent saturation)

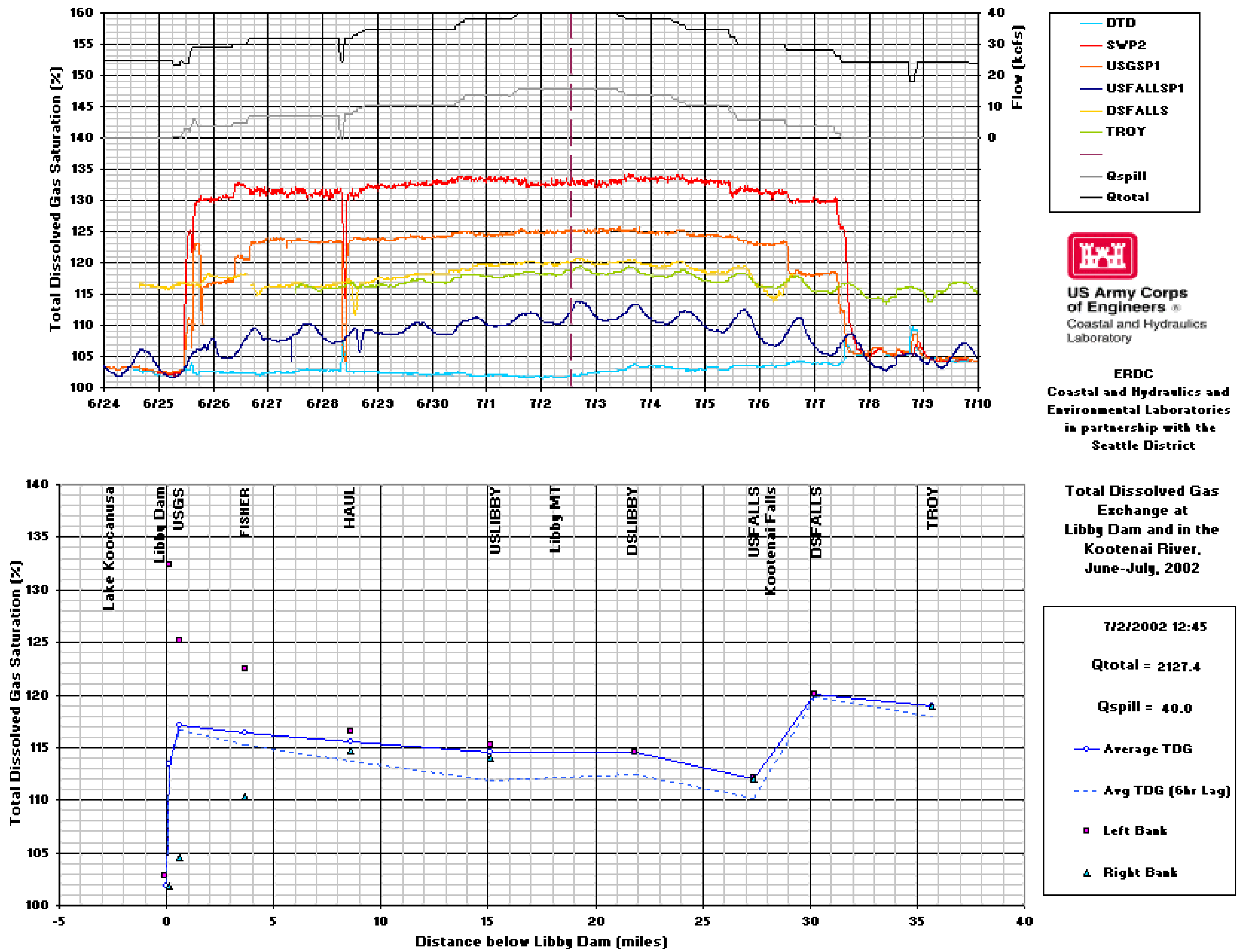



Figure 62. Animation of average cross-sectional and point TDG saturation in the Kootenai River, June 24-July 10, 2002. (Click on figure to initiate data animation, requires file “LibbyTimesSeries v5.avi”)

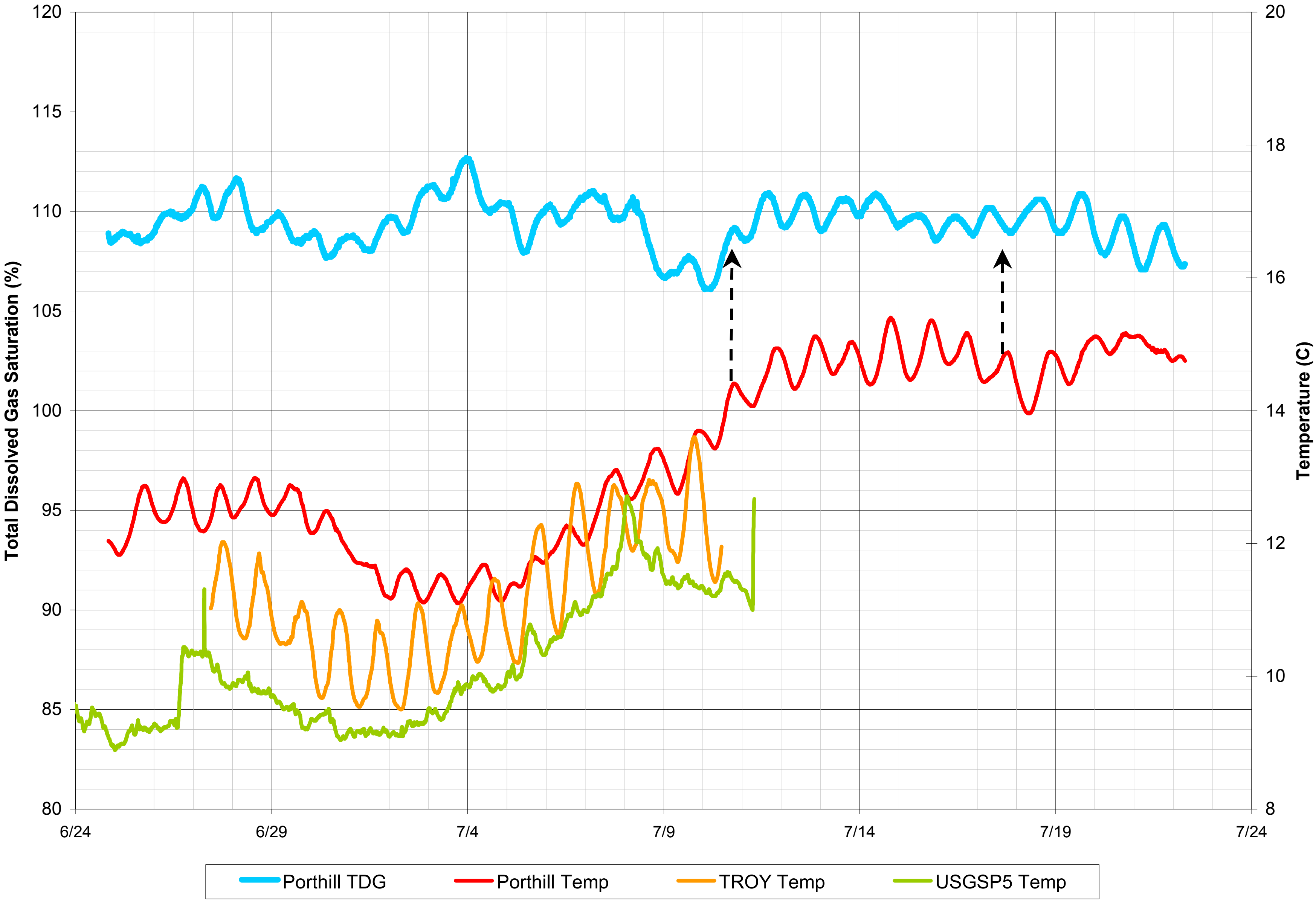



Figure 63. Total dissolved gas saturation at Porthill and water temperatures in the Kootenai River, June 24-July 23, 2002

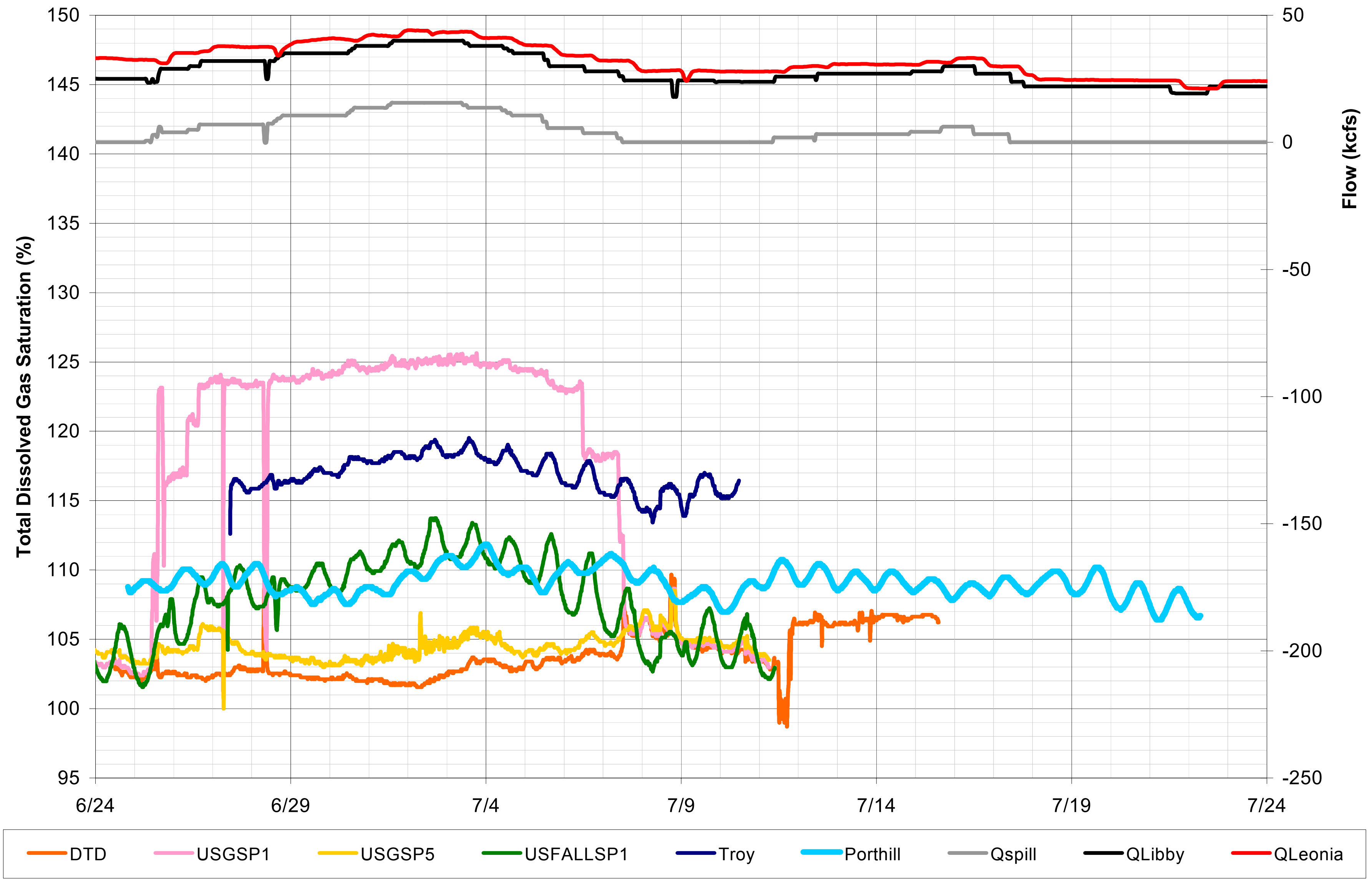



Figure 64. Kootenia River flow and TDG saturation below Libby Dam, June 24-July 23, 2002

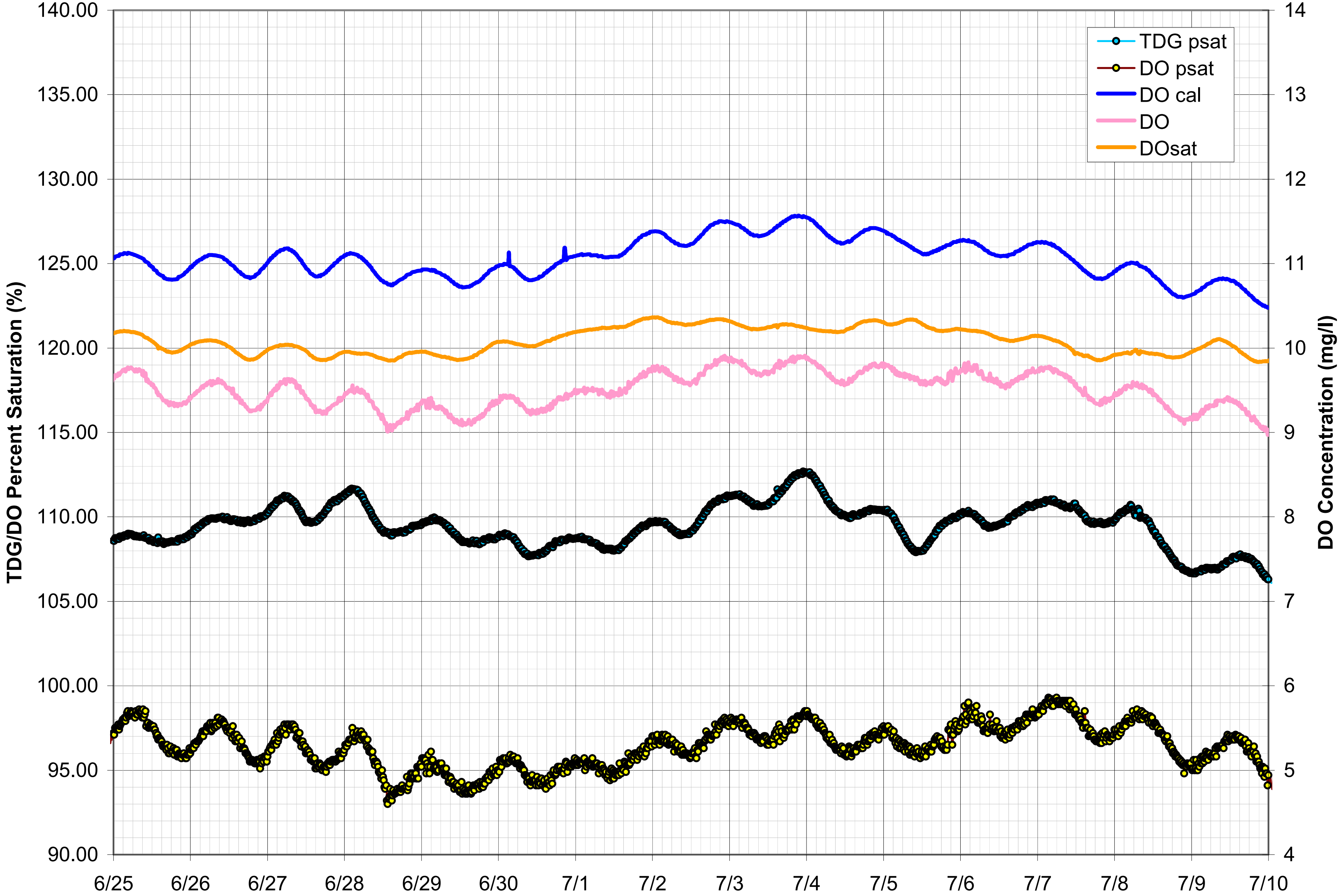



Figure 65. Total dissolved gas saturation and dissolved oxygen concentration in the Kootenai River at Porthill, ID, June 25-July 10, 2002 (DO – observed DO concentration, DO sat - calculated DO saturation concentration, DO cal – Calculated DO concentration from TDG pressure assuming atmospheric ratios of dissolved gasses, DO psat – observed DO percent saturation, TDG psat - observed TDG percent saturation)

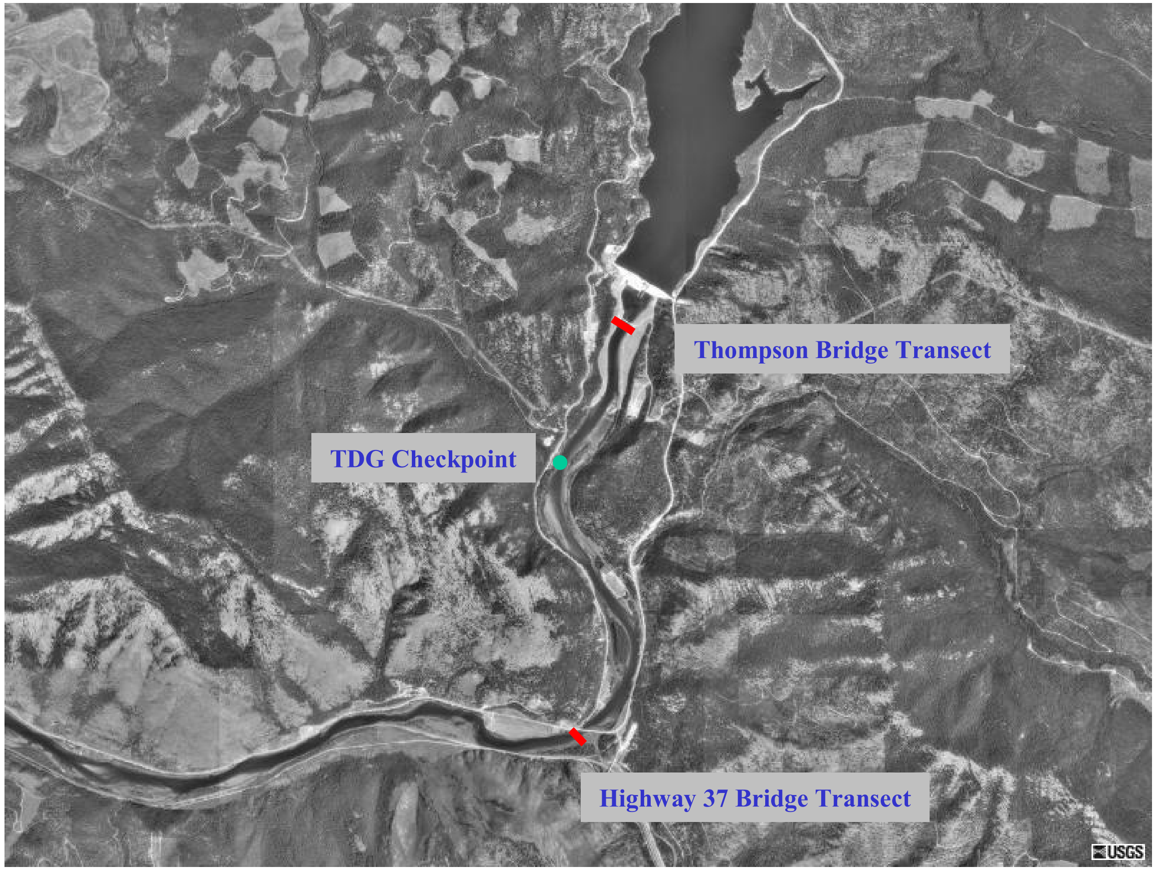



Figure A1. TDG transect sampling station locations with checkpoint station.