Libby Dam January 2005 Relay Maintenance Operations Total Dissolved Gas Monitoring Study

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Contents

Tables

Figures

Introduction

A planned mandatory relay maintenance outage operation occurred at Libby Dam on January 20, 2005, which required the project to operate all five generating units on speed-no-load for station service for about 13 hours. It is estimated that each unit passed 500 cubic feet per second (cfs) while on speed-no-load for a total powerhouse flow of 2,500 cfs. In order to limit the biological impact of streambank exposure due to low flows on the Kootenai River, the spillway was used to keep river flow as close to 4,000 cfs as possible. It is estimated that the project passed about 1,800 cfs over the spillway for a total river flow of about 4,300 cfs.

Total dissolved gas (TDG) pressures in water can be effected by spillway releases and speed-no-load operations at dams (Schneider and Carroll 2003). Spilling water can increase TDG saturations by plunging the aerated spill water to depth where hydrostatic pressure increases the solubility of atmospheric gases. Speed-no-load operations can increase TDG saturations in released waters because air is aspirated into a turbine to prevent cavitation and allow smooth operation of the turbine. When air is introduced into a turbine, the opportunity exists for mass transfer to occur resulting in increased TDG saturations (Schneider and Carroll 2003).

Field studies conducted by the Seattle District Corps of Engineers (Seattle District) indicated the potential for increased TDG pressures in the Kootenai River from spillway releases and speed-no-load operations at Libby Dam. To better understand the TDG exchange processes that may occur during mandatory maintenance operations, the Seattle District designed a water quality study to quantify the effect of speed-no-load and spillway releases on TDG saturations in the Kootenai River.

Purpose and Scope

The Seattle District Corps of Engineers, in cooperation with Columbia Basin Environmental, monitored TDG saturations in the Kootenai River during the January 2005 mandatory maintenance operation. The purpose of the study was to define and quantify the processes that contributed to dissolved gas transfer during spillway releases and speed-no-load operations at Libby Dam. The major objectives of this study were:

- Describe dissolved gas exchange processes (exchange, mixing, transport) in the Libby Dam tailwater during spillway and speed-no-load operations.
- Describe resulting TDG pressures in the Kootenai River associated with spillway releases and speed-no-load operations.

These objectives were addressed using data collection and analysis methods to evaluate total dissolved gas exchange characteristics in the Kootenai River. Total dissolved gas saturation data were collected from two (2) real-time TDG probes and nine (9) automatic TDG loggers. The monitoring was conducted from January 19 to 21, 2005 during the outage maintenance event, and focused on the Kootenai River from Libby Dam downstream for about 8.5 miles.

Methods and Materials

Site Characterization

Libby Dam is located at river mile 221.9 on the Kootenai River in Montana about 40 miles south of the Canadian border, as shown in Figure 1. The dam is approximately 11 miles east of the town of Libby, Montana and 221.9 miles upstream from the confluence of the Kootenai River with the Columbia River in British Columbia. The Kootenai River originates in the Rocky Mountains of British Columbia at an elevation exceeding 11,000 feet, flows southward toward Montana, and enters Lake Koocanusa approximately 40 miles north of the international border. Lake Koocanusa is the 90-mile long reservoir formed by Libby Dam, and has a gross storage capacity of 5.81 million acre feet (MAF), a maximum depth of 350 feet, and a mean water residence time of about 9 months. Downstream of Libby Dam, the Kootenai River flows south for about 3.5 miles to the mouth of the Fisher River and then flows northwest through the town of Libby, Montana before entering Idaho. The Kootenai River downstream of Libby Dam follows a free flowing course with an average slope of about 5 feet per mile and is broken intermittently by rapids and white water at the confluences of tributary streams.

Libby dam is a straight concrete gravity gate-controlled dam, 370 feet high and 2,887 feet long at the dam crest as shown in Figure 2. Construction of the project was initiated in 1966 and the dam became operational for flood control in 1972. Libby dam has two spillway bays and releases water from the reservoir by raising a 48-foot-wide by 59-foot-high tainter gate above the crest of the spillway located at elevation 2,405 feet. The stilling basin has a length of about 250 feet, a width of 116 feet and an average depth ranging from 51.5 to 54.5 feet for typical flow conditions. Training walls bound the stilling basin on both sides (Figure 2).

The powerhouse was designed to hold eight hydroelectric generating units; however, only five units, each with a capacity of 120 MW, have been installed. These units are labeled 1-5 starting from the right bank (Figure 2). Generating units 1 through 4 were installed in the 1970s and are Francis-type turbines similar in design. Generating unit No. 5 was installed in 1984 and represents a slightly more efficient design of the Francis-type turbine. The remaining three turbines have not been installed.

Project Operations

The relay maintenance outage that occurred at Libby Dam on January 20, 2005 required the powerhouse to go offline for about 13 hours to allow for necessary repair work. In order to provide station service and to maintain flows in the Kootenai River near 4,000 cfs, the powerhouse ran all 5 turbines on speed-no-load and the spillway was used during the maintenance operation. The following timetable outlines the project operations on January 20, 2005:

- **Time 0545** Unit 3 stops passing 4,000 cfs generation flow and all units go to speed-no-load.
- **Time 0600** Spillway gate 1 opened to 5-feet.
- **Time 0624** Spillway gate 2 opened to 5-feet.
- **Time 0630** Spillway gates 1 and 2 operating at 5-foot opening.
- **Time 1458** Close spillway gate 2.
- **Time 1911** Close spillway gate 1, all units off speed-no-load, resume 4,000 cfs generating flow through unit 3.

Speed-no-load flows through each turbine were estimated to be 500 cfs for a total powerhouse speed-no-load flow of 2,500 cfs. On January 20, 2005 the forebay elevation ranged from 2,408.5 feet to 2,408.8 feet, which was too low to provide controlled spillway flows over the spillway crest elevation of 2,405 feet. Therefore, the tainter gates were opened up 5 feet and reservoir water was allowed to flow uncontrolled over the spillway crest resulting in an unknown flow of spillway water. Therefore, a spillway discharge of about 1,800 cfs using both spillway gates and about 800 cfs using one spillway gate was estimated by subtracting the 2,500 cfs powerhouse releases from the total river flow measured 0.6 miles downstream at the USGS gaging station. Estimated project operation, Kootenai River, and Fisher River flows are shown in Figure 3.

The closure of spillway gate 2 at 1458 hrs was in response to apparent spillway TDG generation rising above apparent powerhouse TDG generation as measured 0.6 miles downstream at the USGS gaging station (see Results and Discussion section below). Closing spillway gate 2 was an attempt to reduce the amount of TDG being generated by the spillway.

Data Collection

An array of eleven (11) instruments, consisting of nine (9) data loggers and two (2) real-time instruments, were deployed in the Kootenai River to measure lateral and longitudinal TDG saturations in the Kootenai River generated by Libby Dam powerhouse and spillway operations. The general location of these water quality monitoring stations are shown in Figures 4 and 5, and a description of each station is presented in Table 1. Data were collected by the water quality instrumentation at 10 to 15 minute intervals and included the date, time, instrument depth, water temperature, TDG pressure, and internal battery voltage. In addition, barometric pressure and air temperature were monitored near Libby Dam at the USGS gaging station to calculate the TDG percent saturation. Manual sampling was used where and when necessary to supplement the automated approach.

Three sampling stations were located immediately below Libby Dam (Figure 5). An instrument was deployed from the draft tube deck (DTD) directly into releases from powerhouse unit 4 at a depth of about 20 feet to determine the TDG saturations resulting from speed-no-load operations. This instrument was located at the end of a cable and was free to move with the transient current at this location. A second instrument (PWH1) was added during the speed-no-load and spillway operations to capture TDG saturations associated with powerhouse units 1 and 2. This instrument was located off of the right bank about 0.1 miles downstream of the dam. A third instrument (SPW1) was located about 250 ft downstream from the stilling basin end sill to determine TDG saturations associated with spillway operations (Figure 3).

A total of four instruments were deployed at the Thompson Bridge (TMPSN1-4) sampling transect located about 0.4 miles below the dam as shown in Figure 5. Station TMPSN1 was located off of the left bank to capture the higher TDG saturations associated with the spillway releases. Station TMPSN4 was located off of the right bank to capture the TDG saturations associated with the powerhouse speed-no-load releases. Stations TMPSN2 and TMPSN3 were located at quarter points across the river to determine the interaction and mixing characteristics between spillway and powerhouse flows.

Two real-time instruments were deployed in the Kootenai River at the Libby Dam tailwater U.S. Geological Survey (USGS) gaging station, which is the site of the existing fixed monitoring station for TDG and temperature, located about 0.6 mile downstream of the dam (Figure 5). Station LBQM was located off of the left bank or spillway side of the river to capture TDG saturations associated with spillway releases, while station LIBM was located off of the right bank or powerhouse side of the river to capture TDG saturations associated with the powerhouse speed-no-load releases. These real-time stations transmitted data via radio every fifteen minutes to the Seattle District's HEC-DSS water quality database.

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 (see Figure 4). One instrument (HWY37) was located off of the right bank at the Highway 37 Bridge, about 3.5 miles below the dam. This instrument was located just above the confluence of the Fisher River with the Kootenai River and represented downstream TDG saturations in the Kootenai River before mixing with the Fisher River. The constriction of the Kootenai River at an old haul bridge, about 8.5 miles below the dam was also chosen as a sampling location. One instrument was located adjacent to the right channel bank (HAUL). This location was the farthest downstream monitoring stations and represented TDG saturations in the Kootenai River after mixing with the Fisher River.

All data loggers were housed in perforated PVC pipe housings and deployed on the bottom of the river with weights and cables with the exception of the instrument deployed from the draft tube deck (DTD). The cables were then attached to shore to prevent the loss of the housing and instrument. The two real-time instruments were deployed using slightly different techniques. Station LIBM was set up similar to the data loggers using a perforated PVC pipe housing, weights, and cables to deploy the instrument on the bottom of the river. Station LBQM was deployed in an anchored perforated PVC pipe that extended out into the river but not to the bottom of the river. The water quality probes used in the study were Hydrolab DataSonde 4 and MiniSonde 4a TDG probes. Additional instrumentation for both real-time stations consisted of a Common Sensing TBO-L electronic barometer, a Geomation 2380 data collection platform (DCP), a radio transmitter, and a power source.

Quality Assurance Procedures

Data quality assurance and calibration procedures included calibration of instruments in the laboratory following procedures outlined in the *U.S. Corps of Engineers Plan of Action for Dissolved Gas Monitoring 2003* (USCOE 2002). All primary standards were National Institute of Science and Technology (NIST) traceable and maintained according to manufacturers recommendations.

Water quality probes were laboratory calibrated using the following procedures. TDG pressure sensors were checked in air with the membrane removed. Ambient pressures determined from the NIST traceable mercury barometer served as the zero value for total pressure. The slope for total pressure was determined by adding known pressures to the sensor. Using a NIST traceable digital pressure gauge, comparisons were made at pressures of 0, 100, 200, and 300 mm Hg above barometric pressure, which represented TDG saturations from 100 to 139% (Table 2). If any measurement differed by more than 1 mm Hg from the primary standard, the sensor was adjusted and rechecked over the full calibration range. As seen in Table 2, most calibrations were within 0 to 1 mm Hg of total dissolved gas.

Laboratory calibrations of the water quality probe's temperature sensor were performed using a NIST traceable thermometer and are shown in Table 3. If the measurements differed by more than 0.2°C the probe was not used. As seen in Table 3 most calibrations were within 0.1°C for temperature.

Once the real-time data and logger data were received and missing data were flagged, the following quality assurance review procedures occurred. First, tables of raw data were visually inspected for erroneous data resulting from DCP malfunctions or improper transmission of data value codes. Second, data tables were reviewed for sudden increases in temperature, barometric pressure, or TDG pressure that could not be correlated to any hydrologic event and therefore may be a result of mechanical problems. Third, graphs of the data were created and analyzed in order to identify unusual spikes in the data.

The quality assurance review of the data is still ongoing. Missing data occurred at real-time stations LIBM and LBQM from January 19, 2005 at 1900 hours to January 20, 2005 at 0630 to 0700 hours due to DCP malfunctions and programming problems. A preliminary quality assurance review of all stations shows no data to be suspect, and all data were used in this draft report.

Results and Discussion

Water Temperature

The water temperature associated with spillway flows and powerhouse releases were similar at all stations except station HAUL during the study (Figure 6). Lake Koocanusa was completely mixed and isothermal on January 20, 2005 so little difference in temperatures existed between the lake surface and bottom. Water temperatures in the Kootenai River immediately below Libby Dam ranged from about 4.8º C to 5.2º C. Temperatures measured downstream at station HAUL ranged from about 2.5º C to 4.2º C and reflect the influence of colder Fisher River water mixing together with the warmer Kootenai River water and atmospheric heat exchange. Because of the very small ranges in water temperatures observed between the dam and the confluence with the Fisher River during the January 20, 2005 operations, it is unlikely that temperature variation had a significant influence on observed TDG saturations measured during the study.

Nearfield TDG Saturations

Total dissolved gas levels presented in the following sections are reported as either pressure in millimeters (mm) of mercury (Hg) or as TDG saturation (percent). TDG saturation was determined by dividing the TDG pressure by the barometric pressure observed at the USGS gaging station monitoring station (LBQM) located about 0.6 miles downstream of Libby Dam. The barometric pressure decreased from 711 mm Hg to 708 mm Hg during the maintenance operation on January 20. Water quality monitoring stations providing information on nearfield TDG processes were stations SPW1, DTD, PWH1 and TMPSN1-4 (see Figure 5).

Spillway Flows

The TDG saturation measured downstream of the stilling basin at Station SPW1 increased from a minimum of about 94 percent to a maximum of about 128 percent during spillway releases at Libby Dam (Figure 7). A statistical summary of the TDG pressure and saturation at SPW1 is listed in Table 4. The initial spill discharge of about 1,800 cfs resulted in an increase in TDG pressure that approached an upper limit of about 127.5 percent after 3 to 6 hours as observed at station (SPW1). The closing of spillway gate 2 on January 20 at 1458 hours initially reduced TDG saturations by about 1 percent at SPW1, but TDG saturations recovered and increased to 128.1 percent after 3 hours of the reduced spillway discharge.

The lack of any significant decrease in TDG pressures observed at station SPW1 after closing one spillway gate suggests that at Libby Dam the unit spillway discharge is an important causal parameter in determining TDG pressures in spillway flows. Similar results were determined for

Chief Joseph Dam (Schneider and Carroll 1999). With a limited array of TDG stations, it can be difficult to clearly define the rate of the development of the mixing zone between powerhouse and spillway flows. However, manual sampling on January 20 at 1600 hours (1 hour after spillway gate 2 closed) at the end of the stilling basin where limited interaction between powerhouse and spillway flows would be expected, resulted in a TDG saturation of 127 percent or nearly the same level as observed at station SPW1. This manual sample suggests that station SPW1 was representative of spillway discharge from the stilling basin before mixing with powerhouse flow.

The spillway TDG pressures measured below the stilling basin at SPW1 were similar to pressures measured along the left bank at the Thompson Bridge (TMPSN1) (Figure 7). TDG saturations measured at Stations TMPSN1 were lower by only 1 to 2 percent than measured upstream at SPW1 with a median and maximum TDG saturation of 125.6 percent and 127.3 percent, respectively, compared to 126.9 percent and 128.1 percent, respectively, at SPW1. The closing of spillway gate 2 at 1458 hours resulted in an initial decrease in TDG saturations at TMPSN1 from 126.3 percent to 124.7 percent, but saturations recovered and increased to 127.3 percent by 1800 hours (Figure 7).

The TDG pressure response at SPW1 to a spillway discharge of about 1,800 cfs at Libby Dam was slightly greater than the response measured at the same location during the TDG exchange study in 2002 (Schneider and Carroll 2003) as shown in Figure 8. In 2002, the maximum TDG saturation measured for a spillway discharge of 3,000 cfs was 125.1 percent, which is slightly lower than the 127.5 percent maximum value recorded during the 1,800 cfs discharge. It should be noted that the 3,000 cfs discharge in 2002 lasted only 2 hours and equilibrium conditions were likely not attained. Interestingly, after 2 hours of spilling 1,800 cfs on January 20, 2005 TDG saturations at SPW1 were about 125 percent and did not reach equilibrium of 127.5 percent until 3 to 6 hours after spill was initiated. The inclusion of the TDG exchange data from this investigation with the data collected during the 2002 study suggests a steeper increase in TDG saturation as a function of spill discharge (Figure 8) for flows less then 3,000 cfs. The estimated spillway capacity as limited by the 110% TDG saturation water quality standard as directed by the state of Montana, is likely closer to 1,000 cfs assuming a linear increase to TDG saturation as a function of spill discharge for flows less than 1,800 cfs.

Speed-no-load Flows

The TDG saturation generated by the powerhouse during speed-no-load operations, as measured at Station DTD and PWH1, were substantially greater than during generation flows (Figure 7). Station DTD was located directly in the releases from unit 4 while station PWH1 was located off of the right bank and largely measured releases from unit 1. As seen in Figure 7, TDG saturations at station DTD increased rapidly from about 94 percent to 114 percent after speed-no-load operations were initiated at 0545 hours. TDG saturations appeared to stabilize at 114 percent until 1500 hours when TDG saturations increased again to about 120 percent. TDG saturations rapidly decreased after speed-no-load operations ceased at 1911 hours.

The TDG pressures measured immediately below the powerhouse at station PWH1 were similar to pressures measured along the right bank at the Thompson Bridge (TMPSN4) (Figure 7). These data suggest that station TMPSN4 is representative of speed-no-load flow conditions along the right bank of the river, which is significant because of the limited data available for station PWH1. TDG saturations were consistently higher by about 5 percent at station TMPSN4 than at station DTD during the entire operation suggesting that each turbine generates slightly different TDG pressures during speed-no-load operations. The measurement of TDG pressures in bubbly flow at station DTD may also reflect provisional observations prior to the completion of mass transfer processes. Visual observations during the operation concluded that unit 5 was not putting out much air compared to units 1 – 4, and powerhouse operators noted that unit 5 was running rough. These data suggest that less air was being aspirated into unit 5 resulting in lower TDG pressures being generated by this unit. Because station DTD was adjacent to unit 5, the lower TDG pressures measured at this station may be partly due to dilution from unit 5.

TDG saturations at TMPSN4 rapidly increased from about 94 percent to 122 percent at 0700 hours before stabilizing at about 119 percent at 0900 hours. TDG saturations remained stable until 1500 hours when saturations increased to 126.4 percent by 1800 hours. Similar increases in powerhouse TDG saturations after 1500 hours were noted at station DTD where TDG saturations increased from about 114 percent to 120 percent, and at station PWH1 where TDG saturations increased from about 119 percent to 122.9 percent before data collection stopped at 1545 hours. A statistical summary of the TDG pressures and saturations at stations DTD, PWH1, and TMPSN4 is listed in Table 4.

The abrupt increase in TDG saturations measured at stations downstream of the powerhouse during the speed-no-load operations at 1500 hours is of interest and the cause is unknown. No change in water temperature occurred that could account for the increase in TDG pressures (Figure 7) and no operational changes were made at the powerhouse during this time period, although an operational change at the spillway was made at 1458 hours. However, the closing of spillway gate 2 appears unrelated to the rise in saturations measured below the powerhouse at station TMPSN4 because an identical response was detected at station DTD located directly in the discharge from unit 4. It is possible that an increase in the amount of air automatically injected into the units occurred after a prolonged period of running at speed-no-load to prevent cavitation and to allow the units to run smoother. The aspiration of air into the turbines may also be sensitive to backpressure levels related to tailwater stage, which were reduced about 0.6 ft when the spillway gate 2 was closed.

A similar increase in TDG saturations was measured on May 23, 2004 after a prolonged period of operating unit 3 at speed-no-load and passing about 500 cfs. However, on that date unit 1 continued to pass about 3,500 cfs generation flow resulting in some data interpretation difficulties because the mixing of speed-no-flow with generating flow below the powerhouse was unknown. Regardless, during the May 23, 2004 operation, TDG saturations measured at station LBQM, located 0.6 miles downstream at the USGS gage, increased after initiating speed-no-load from about 106 percent to 109 percent, remained stable for 18 hours, and then increased to about 111.5 percent until speed-no-load was ended after 24 hours. No operational changes occurred to account for the second rise in TDG pressure after 18 hours on speed-no-load.

Therefore, it is possible that running the units at Libby Dam for an extended period of time on speed-no-load results in a secondary increase in TDG saturations over initial conditions.

Extensive spillway discharge monitoring at dams in the Columbia River Basin has shown that for spillway discharges, the background TDG pressures do not impact the resulting TDG pressures in spillway flows exiting the stilling basin (Schneider and Carroll 1999, Schneider and Carroll 2003). Instead, resulting TDG pressures from spill are largely a function of unit spillway discharge and depth of the stilling basin and tailwater channel. For speed-no-load operations little data has been collected to determine if background TDG pressures play a role in the resulting TDG pressures generated by a turbine. From our limited data collected during speed-no-load operations at Libby Dam on May 23, 2004 and on January 20, 2005 it may be possible that the initial TDG pressure in the water passing through the turbine is important in determining the resulting TDG pressures exiting the unit on speed-no-load.

During the May 23, 2004 operation, the maximum TDG pressures produced by speed-no-load were estimated to range from 920 mm Hg to 1036 mm Hg (130 to 145 percent). These saturations assume mass conservation of TDG and that data measured at station LBQM represented completely mixed conditions. This estimated range is substantially greater than the maximum TDG pressure of 896 mm Hg (126.4 percent) measured at TMPSN4. However, background TDG pressures on May 23, 2004 were 746 mm Hg (about 106 percent) resulting in an estimated maximum delta pressure of 174 to 290 mm Hg (delta saturation of 24 to 39 percent). For the January 20, 2005 operation, background TDG pressures at station TMPSN4 were 665 mm Hg (94.1 percent) resulting in a maximum delta pressure of 231 mm Hg (delta saturation of 32.3 percent). The delta pressure data between the May 23, 2004 and January 20, 2005 speed-no-load operations are similar suggesting that initial TDG pressures passing through the turbines may play an important role in determining the resulting downstream TDG pressures.

Kootenai River Downstream TDG Saturations

Water quality stations providing information on downstream mixing and in-river TDG processes were located at the Thompson Bridge (TMPSN1-4), USGS gage (LIBM and LBQM), Highway 37 Bridge (HWY37), and the Haul Bridge (HAUL) (see Figures 4 and 5).

Thompson Bridge to USGS Gaging Station

A strong lateral gradient in TDG saturations was evident across the Kootenai River at the Thompson Bridge (Stations TMPSN1-4) located 0.4 miles downstream (Figure 9). The median TDG saturations measured at the Thompson Bridge ranged from 119.5 percent on the right bank (TMPSN4) to 125.6 percent on the left bank (TMPSN1) (Table 4). As seen in Figure 10, TDG saturation gradients were strongest between 0600 hours and 1500 hours with TDG saturations about 6 percent higher on the left bank (TMPSN1) than on the right bank (TMPSN4). These data reflect the higher TDG saturations being generated by the spillway during this period of time. After 1500 hours TDG saturations generated by the powerhouse speed no load operations increased resulting in little to no lateral gradient in TDG saturations at the Thompson Bridge.

The TDG saturations measured at the USGS gaging station showed a smaller lateral gradient than observed at the Thompson Bridge indicating more uniform TDG conditions (Figure 10). The TDG saturations at LIBM on the right bank at the USGS station were consistently higher than saturations measured upstream at TMPSN4 by about 2 percent between 0700 hours and 1500 hours (Figure 10). The greater TDG saturations on the right bank downstream of the Thompson Bridge are likely due to the continued development of a mixing zone between the lower TDG powerhouse waters and the higher TDG spillway waters. After 1500 hours the TDG saturations at LIBM increased to levels measured at TMPSN4 due to the increase in TDG saturations generated by the powerhouse.

TDG saturations measured on the left bank at station LBQM responded very slowly to the spillway discharge compared to upstream station TMPSN1. Indeed, TDG saturations measured at LBQM did not reach equilibrium until about 1500 hours, which is 9 hours after spill began. Conversely, TDG saturations at TMPSN1 appeared to reach equilibrium by about 0900 hours, after only 3 hours of spill. The significantly slower response time at LBQM suggests that the station location may have had poor flow circulation around the instrument or that the TDG membrane experienced response problems possibly due to the style of the membrane or presence of entrapped air bubbles against the membrane. The slow response time at station LBQM makes comparisons to TMPSN1 difficult. However, after 1500 hours TDG saturations decreased at station LBQM even though TDG saturations increased below the stilling basin (SPW1) and along the left bank at the Thompson Bridge (TMPSN1) (Figure 10). The cause for the slight decrease in LBQM saturations is unknown, but may be related to the depth of the probe at LBQM.

It is recommended to deploy TDG instrumentation below the compensation depth to minimize the possibility of a bubble induced measurement bias. If the probe is above the compensation depth, the measured TDG saturations may be less than if they were measured at a greater depth. The compensation depth is the depth where the saturation concentration for total dissolved gasses is equal to the local concentration of total dissolved gasses. No exchange would occur between an air bubble located at the compensation depth and the water column. For our study with a background barometric pressure of about 708 mm Hg, the compensation depth for TDG saturations of 120 percent and 125 percent are about 6.2 feet and 7.6 feet, respectively. Station LBQM was deployed at a depth of 6 feet, which is above the compensation depth for these TDG saturations. Moreover, after spill was reduced at 1458 hours, the depth of the river fell resulting in a TDG probe depth at LBQM of only 5 feet. Because the probe at LBQM was above the minimum compensation depth, the measured TDG saturations may be less than if they were measured at a greater depth.

Highway 37 Bridge to Haul Bridge

Downstream TDG saturations in the Kootenai River were monitored on the right bank at the Highway 37 bridge (HWY37) located about 3.5 miles downstream and the Haul Bridge (HAUL) located about 8.6 miles downstream (Figures 9 and 10). The median TDG saturation measured at station HWY37 was 119.7 percent with a maximum saturation of 120.2 percent (Table 4). These values are slightly less than the median and maximum values detected upstream at stations

LIBM (121.7 and 126.6 percent, respectively) and LBQM (124.2 and 125.5 percent, respectively). TDG saturations were considerable lower at the Haul Bridge station (HAUL) with a median and maximum TDG saturation of 111.9 percent and 113.7 percent, respectively (Figure 10 and Table 4).

The largest tributary to the Kootenai River in the study area is the Fisher River, located at the Highway 37 Bridge. The flow in the Fisher River ranged from about 500 cfs to 1800 cfs from January 19 to 21, 2005 with a fairly constant flow of about 1000 cfs during the study period on January 20, 2005 (Figure 3). Station HWY37 was positioned upstream of the confluence of the Fisher and thus represents downstream TDG saturations in the Kootenai River before mixing and dilution with the Fisher River. The small TDG saturation decrease between station LIBM and HWY37 was likely due to riverine TDG exchange processes such as surface exchange at the air-water interface. The larger TDG saturation decrease between station HWY37 and station HAUL was likely a combination of surface exchange at the air-water interface, dilution from the Fisher River and temperature induced TDG pressure changes.

Conclusions

- The TDG saturation measured downstream of the stilling basin increased from a minimum of about 94 percent to a maximum of about 128 percent during spillway releases of about 1,800 cfs at Libby Dam

- TDG saturations below the stilling basin did not decrease after spillway gate 2 was closed suggesting that at Libby Dam the unit spillway discharge is an important causal parameter in determining TDG pressures in spillway flows.

- An estimated spillway discharge at Libby Dam of about 1,000 cfs will yield a local TDG saturation of 110% below the spillway assuming a linear relationship between observed TDG saturation and spill discharge for flows less than 1,800 cfs.

- During speed-no-load operations, the TDG saturation measured downstream of the powerhouse increased from about 94 percent at 0600 hours to about 119 percent at 0900 hours. Powerhouse TDG saturations remained stable until 1500 hours when saturations increased to about 126 percent by 1800 hours.

- The TDG levels associated with speed-no-load releases were generally less than the TDG levels observed below the spillway during the dual gate spillway operation. However, following the reduction in spill discharge, an increase in average TDG pressures as measured at the four Thompson Bridge sampling stations and at the two sampling stations at the USGS gauge was observed. The TDG data associated with the single spill gate operation implies little difference between the TDG levels associated with powerhouse speed-no-load and spillway releases. An increase in TDG generated during speed-no-load releases after the reduction in spill may account for these contradicting TDG loading observations.

- The visual observations of flow conditions below the powerhouse taken together with observations of TDG pressures, support the hypothesis that individual turbines at Libby Dam generated different TDG pressures during speed-no-load operations on January 20, 2005. From the limited data collected, units 4 and 5 produced the lowest TDG pressures during speed-no-load operations.

- A strong lateral gradient in TDG saturations was evident across the Kootenai River during powerhouse speed-no-load and spillway releases. From 0600 to 1500, the maximum downstream TDG saturation was observed along the left channel bank (spillway side). After 1500, TDG saturations along the right bank (powerhouse side) increased to similar levels measured along the left bank suggesting that an increase in TDG from powerhouse releases occurred.

- The mixing of the Fisher River with the Kootenai River substantially reduced TDG saturations from the project.

- TDG exchange is minimized when both spillway gates are operated simultaneously. Limited data showed little to no change in TDG saturations below the stilling basin when spill was reduced to only one spillway bay.

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Tables

Table 1. Summary of total dissolved gas sampling stations.

Site Identifier	Station Name	Latitude	Longitude	Distance from Libby Dam (mi)	Approximate Depth (ft)	Sampling Period
DTD	Libby Dam Powerhouse Unit 4	48.40996	115.31604	0	21.4	01/19/05 18:00 to 01/21/05 09:30
SPW1	Below Stilling Basin	48.40814	115.31475	0.1	18.5	01/19/05 16:00 to 01/21/05 10:00
PWH1	Libby Dam Powerhouse Right Bank	48.40951	115.31704	0.1	7.2	01/20/05 09:15 to 01/20/05 15:30
TMPSN1	Thompson Bridge Left Bank	48.40637	115.31683	0.4	14.5	01/19/05 14:00 to 01/21/05 09:00
TMPSN2	Thompson Bridge Left Center	48.40652	115.31710	0.4	11.2	01/19/05 14:00 to 01/21/05 09:00
TMPSN3	Thompson Bridge Right Center	48.40665	115.31739	0.4	10.0	01/19/05 14:00 to 01/21/05 09:00
TMPSN4	Thompson Bridge Right Bank	48.40679	115.31776	0.4	6.5	01/19/05 14:00 to 01/21/05 09:00
LIBM	USGS Gage Right Bank	48.40083	115.31972	0.6	14.9	01/19/05 16:00 to 01/21/05 09:00
LBQM	USGS Gage Left Bank	48.40061	115.31861	0.6	6.0	01/19/05 13:00 to 01/21/05 09:00
HWY37	Highway 37 Bridge Right Bank	48.36452	115.32640	3.5	6.0	01/20/05 14:15 to 01/21/05 11:15
HAUL	Old Haul Bridge Right Bank	48.37185	115.42890	8.6	4.0	01/19/05 19:00 to 01/21/05 08:00

Table 2. Difference between the primary total dissolved gas standard and the laboratory calibrated instrument.

				TDG Pressure (mm Hg)				Deviation from TDG Standard (mm Hg)			
Calibration Type	**Probe**	**Date**	**BP (mmHg)**	**BP + 0**	**BP + 100**	**BP + 200**	**BP + 300**	**BP + 0**	**BP + 100**	**BP + 200**	**BP + 300**
Pre-deployment	TMPSN2	01/19/05	710	710	810	910	1010	0	0	0	0
Pre-deployment	SPW1	01/19/05	710	710	810	910	1010	0	0	0	0
Pre-deployment	TMPSN3	01/19/05	710	710	810	910	1010	0	0	0	0
Pre-deployment	TMPSN1	01/19/05	710	710	809	909	1010	0	1	1	0
Pre-deployment	TMPSN4	01/19/05	710	710	810	910	1010	0	0	0	0
Pre-deployment	DTD	01/19/05	709	710	810	910	1010	-1	-1	-1	-1
Pre-deployment	HAUL	01/19/05	709	709	809	909	1010	0	0	0	-1
Pre-deployment	LIBM	01/19/05	710	710	810	910	1010	0	0	0	0
Pre-deployment	LBQM	01/19/05	709	709	808	908	1009	0	1	1	0
Pre-deployment	PWH1	01/19/05	709	709	809	909	1009	0	0	0	0
Pre-deployment	HWY37	01/19/05	709	709	809	909	1009	0	0	0	0
Post-deployment	TMPSN2	01/21/05	710	710	810	910	1010	0	0	0	0
Post-deployment	SPW1	01/21/05	710	710	810	910	1011	0	0	0	-1
Post-deployment	TMPSN3	01/21/05	710	710	810	910	1010	0	0	0	0
Post-deployment	TMPSN1	01/21/05	710	710	810	910	1010	0	0	0	0
Post-deployment	TMPSN4	01/21/05	710	710	809	909	1010	0	-1	1	0
Post-deployment	DTD	01/21/05	710	710	810	910	1011	0	0	0	-1
Post-deployment	HAUL	01/21/05	710	709	809	910	1010	-1	-1	0	0
Post-deployment	LIBM	01/21/05	710	710	809	909	1010	0	-1	1	0
Post-deployment	LBQM	01/21/05	710	709	809	909	1009	-1	-1	1	1
Post-deployment	PWH1	01/21/05	710	709	809	909	1009	-1	-1	1	1
Post-deployment	HWY37	01/21/05	710	710	810	910	1010	0	0	0	0

Table 3. Difference between the primary standard thermometer and the laboratory calibrated instrument.

			Temperature (ºC)		
Calibration Type	**S/N**	**Date**	**Standard**	**Probe**	**Difference**
Pre-deployment	TMPSN2	01/19/05	4.9	4.8	0.1
Pre-deployment	SPW1	01/19/05	5.0	4.9	0.1
Pre-deployment	TMPSN3	01/19/05	5.1	5.0	0.1
Pre-deployment	TMPSN1	01/19/05	4.9	4.9	0.0
Pre-deployment	TMPSN4	01/19/05	4.7	4.7	0.0
Pre-deployment	DTD	01/19/05	5.3	5.2	0.1
Pre-deployment	HAUL	01/19/05	5.2	5.3	-0.1
Pre-deployment	LIBM	01/19/05	14.6	14.5	0.1
Pre-deployment	LBQM	01/19/05	5.4	5.4	0.0
Pre-deployment	PWH1	01/19/05	5.5	5.4	0.1
Pre-deployment	HWY37	01/19/05	5.4	5.4	0.0

Table 4. Statistical summary of total dissolved gas properties in the Kootenai River from January 19 to January 21, 2005.

	Background Conditions				Event Conditions During Speed-No-Load and Spillway Operations									
Station	Start Time End Time	N	Median Total Pressure (mm Hg)	Median TDG (Percent)	Start Time End Time	N	Median Total Pressure (mm Hg)	Median TDG (Percent)	Maximum Total Pressure (mm Hg)	Maximum TDG (Percent)	Minimum Total Pressure (mm Hg)	Minimum TDG (Percent)	Maximum Delta Pressure (mm Hg)	Maximum Delta TDG (Percent)
DTD	1/19/05 18:00 1/20/05 05:50	73	666	94.2	1/20/05 06:00 1/20/05 19:30	84	810	114.1	854	120.5	665	94.2	189	26.3
SPW1	1/19/05 18:00 1/20/05 05:50	73	665	94.1	1/20/05 06:00 1/20/05 19:30	84	901	126.9	907	128.1	665	94.1	242	34.0
PWH1	—	—	—	—	1/20/05 09:15 1/20/05 15:30	38	843	118.7	871	122.9	665	94.1	206	28.8
TMPSN1	1/19/05 18:00 1/20/05 05:50	73	665	94.1	1/20/05 06:00 1/20/05 19:30	84	892	125.6	901	127.3	665	94.1	236	33.2
TMPSN2	1/19/05 18:00 1/20/05 05:50	73	665	94.1	1/20/05 06:00 1/20/05 19:30	84	893	125.8	901	127.3	665	93.6	236	33.7
TMPSN3	1/19/05 18:00 1/20/05 05:50	73	665	94.1	1/20/05 06:00 1/20/05 19:30	84	883	124.5	899	127.0	664	93.5	235	33.5
TMPSN4	1/19/05 18:00 1/20/05 05:50	73	665	94.1	1/20/05 06:00 1/20/05 19:30	84	849	119.5	896	126.4	665	94.1	231	32.3
LIBM	1/19/05 18:00 1/19/05 20:45	22	666	94.4	1/20/05 06:00 1/20/05 19:30	84	863	121.7	896	126.6	664	93.4	232	33.2
LBQM	1/20/05 06:00 1/20/05 07:00	5	664	93.4	1/20/05 06:00 1/20/05 19:30	84	880	124.2	889	125.5	664	93.4	225	32.1
HWY37	—	—	—	—	1/20/05 14:30 1/21/05 03:00	75	847	119.7	853	120.2	686	96.7	167	23.5
HAUL	1/19/05 18:00 1/20/05 05:50	73	697	96.0	1/20/05 09:00 1/21/05 03:00	109	792	111.9	805	113.7	685	96.4	120	17.3

Figures

Figure 1. Location of the study area within the Kootenai River watershed.

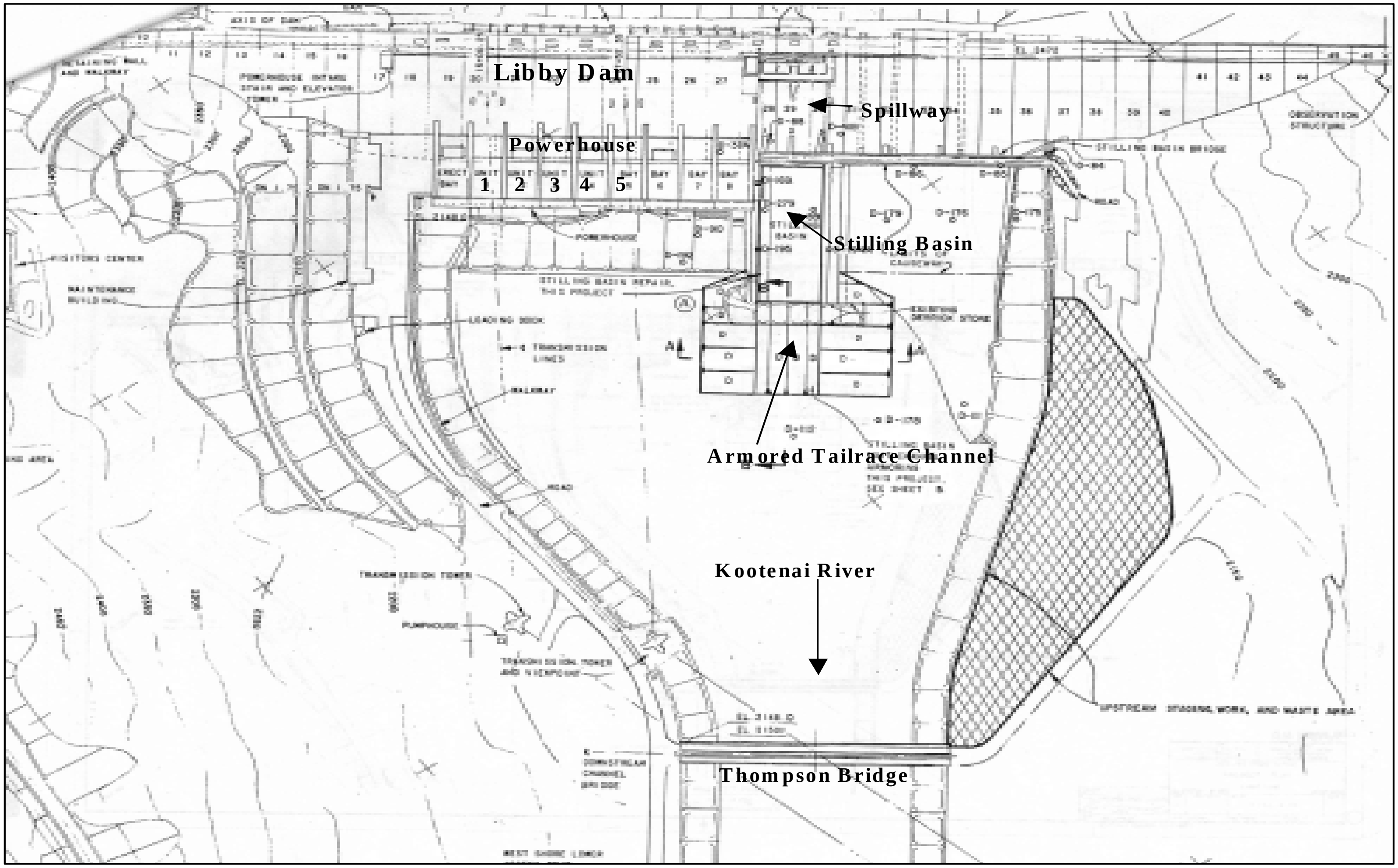

Figure 2. Libby Dam powerhouse, spillway, and stilling basin layout.

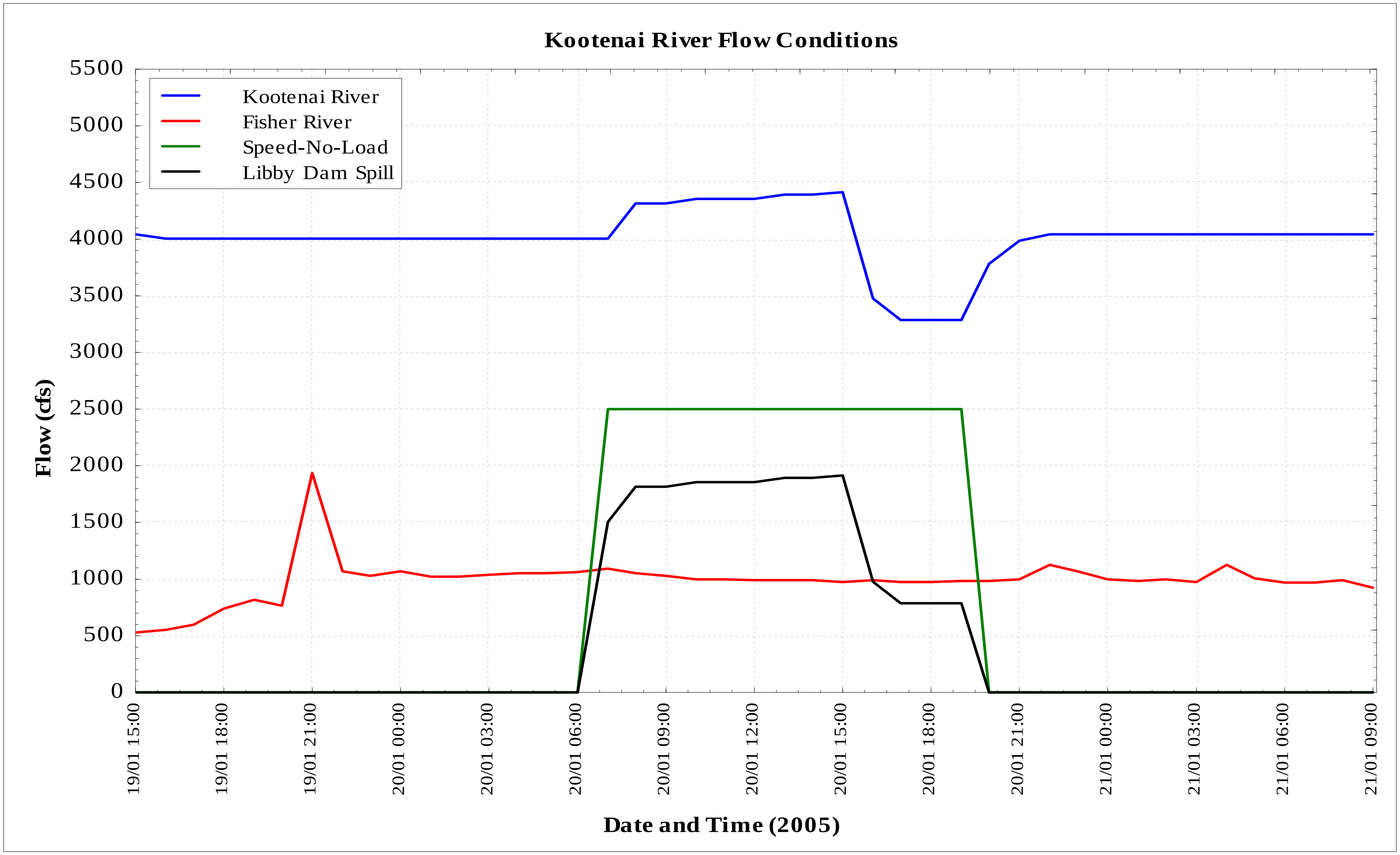

Figure 3. Estimated project operation, Kootenai River and Fisher River flows.

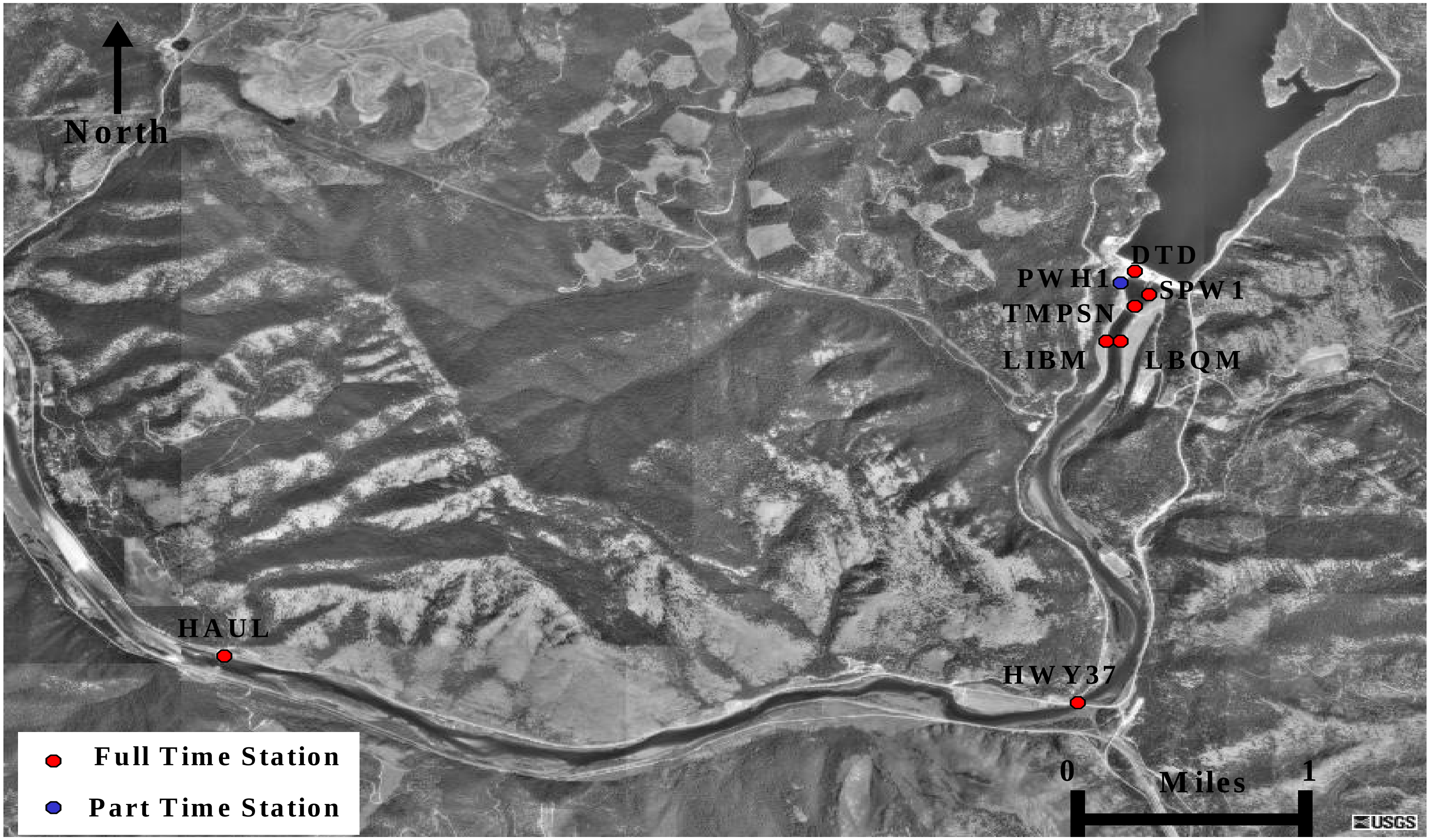

Figure 4. TDG sampling stations in the Kootenai River near Libby Dam.

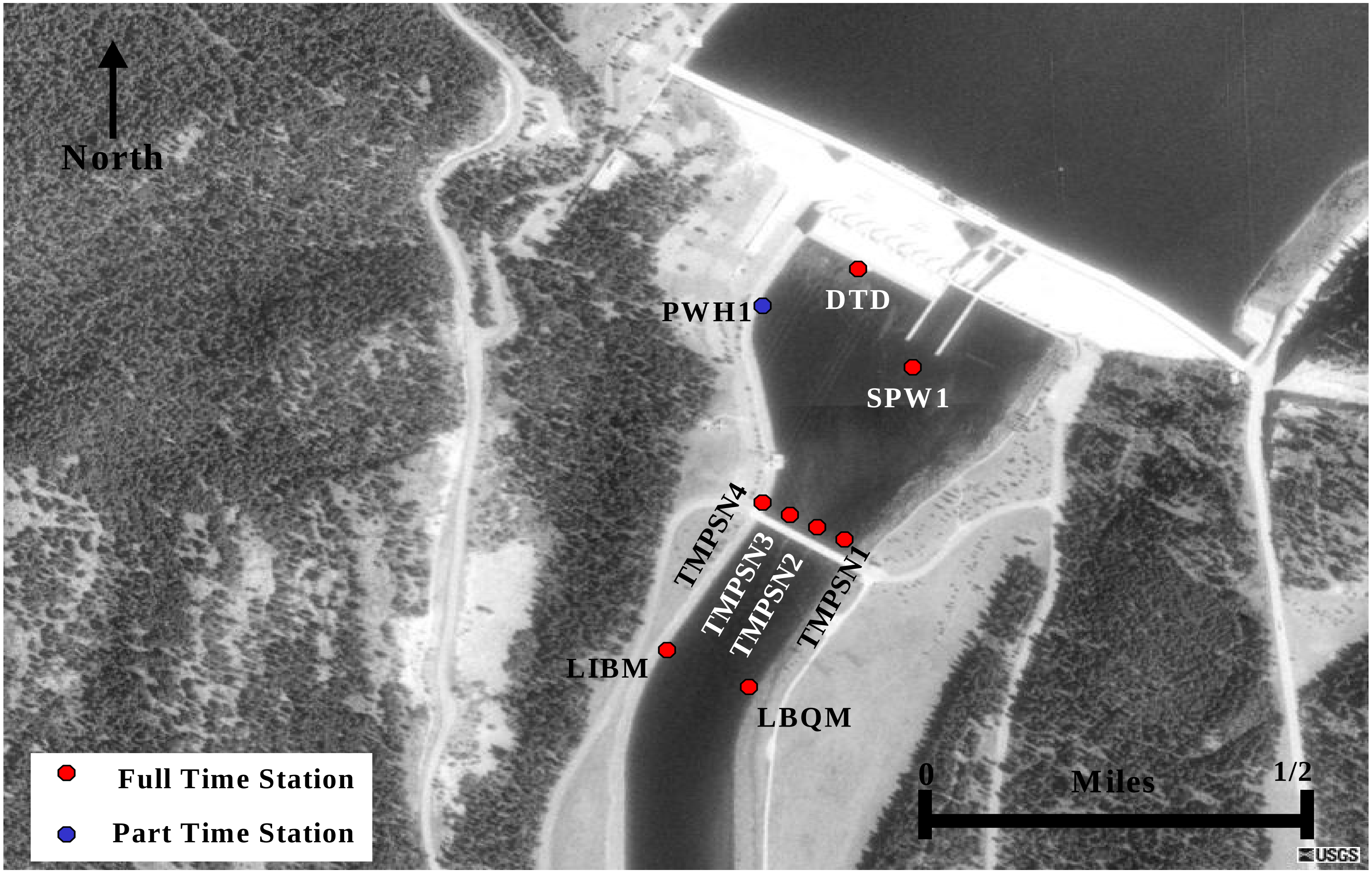

Figure5. TDG sampling stations in the Kootenai River immediately below Libby Dam.

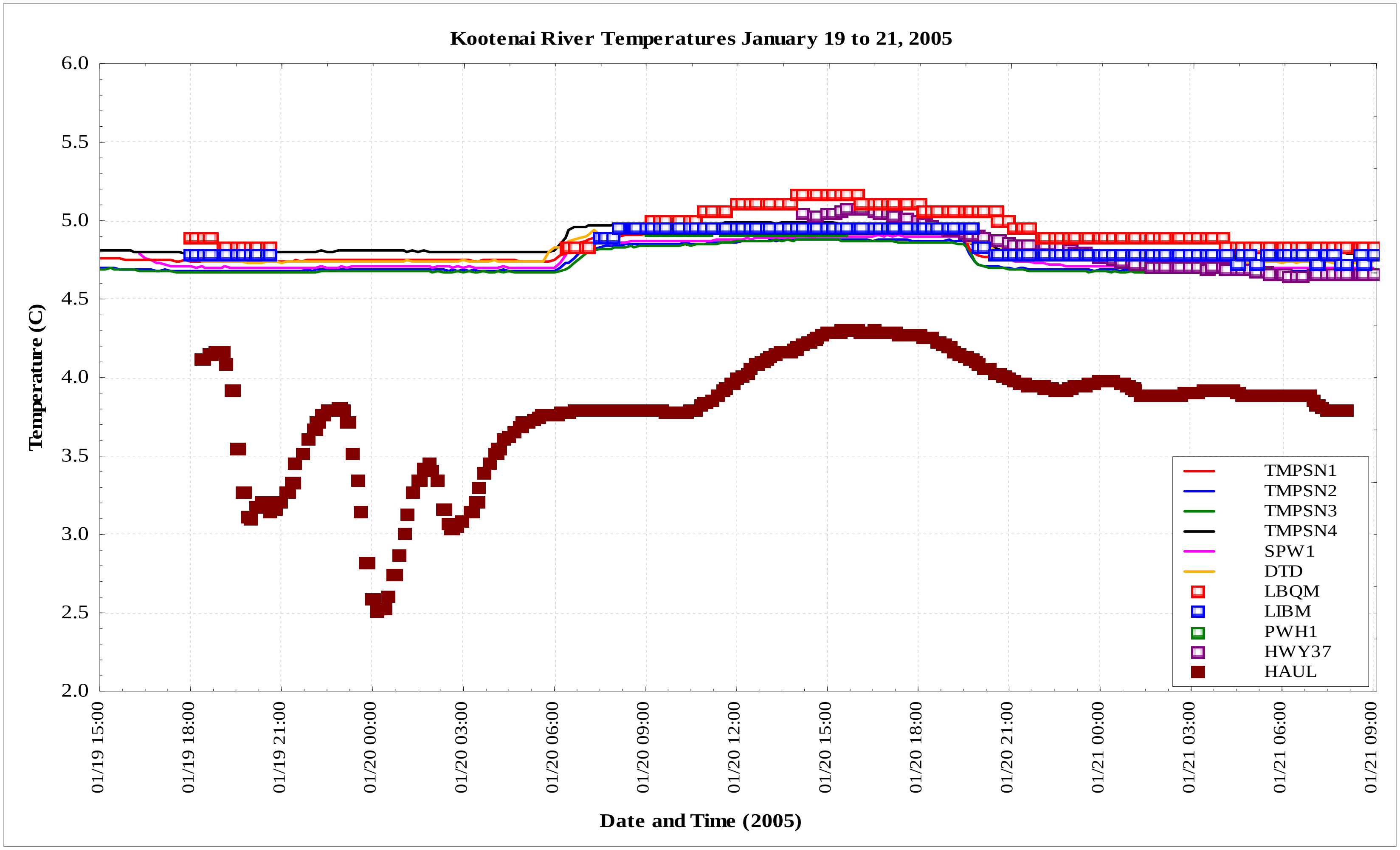

Figure 6. Kootenai River temperature conditions below Libby Dam January 19 to 21, 2005.

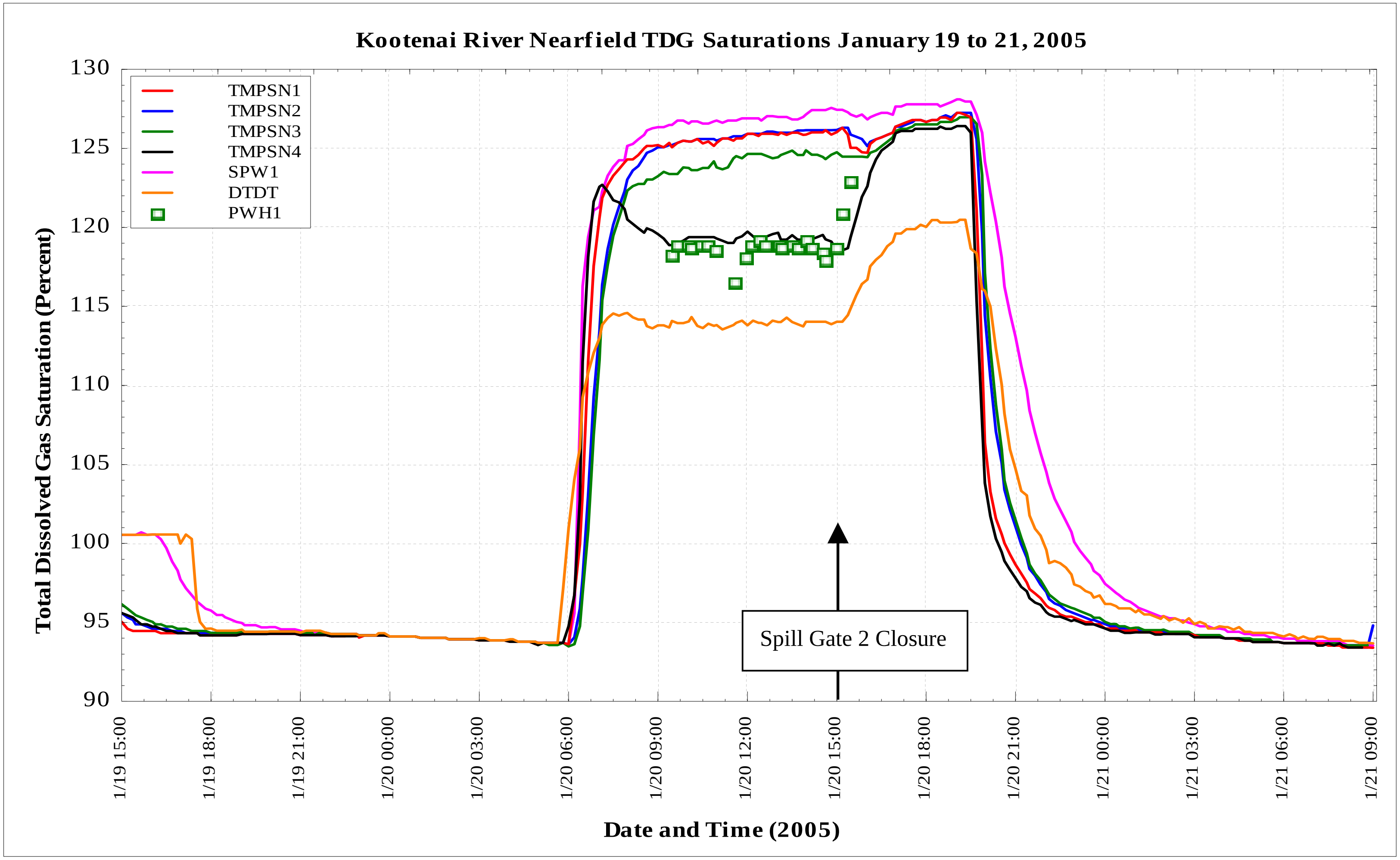

Figure 7. **Total dissolved gas saturations in the Kootenai River immediately below Libby Dam January 19 to 21, 2005.**

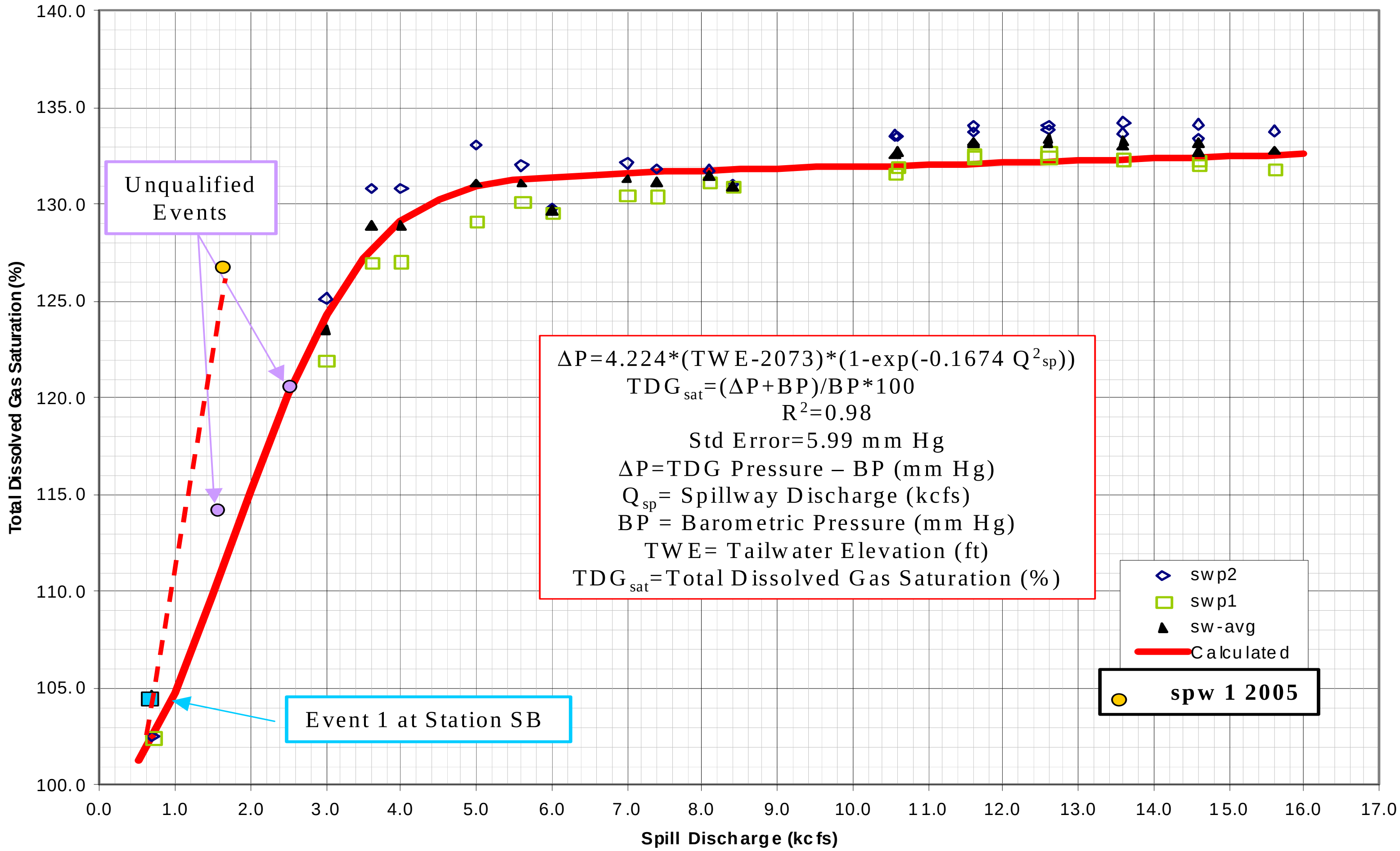

Figure 8. **Libby Dam Total Dissolved Gas Saturation as a function of total spillway discharge at Sampling Stations SWP1 & SWP2, 2002 and SPW1 2005, (Note: spill distributed uniformly over both bays).**

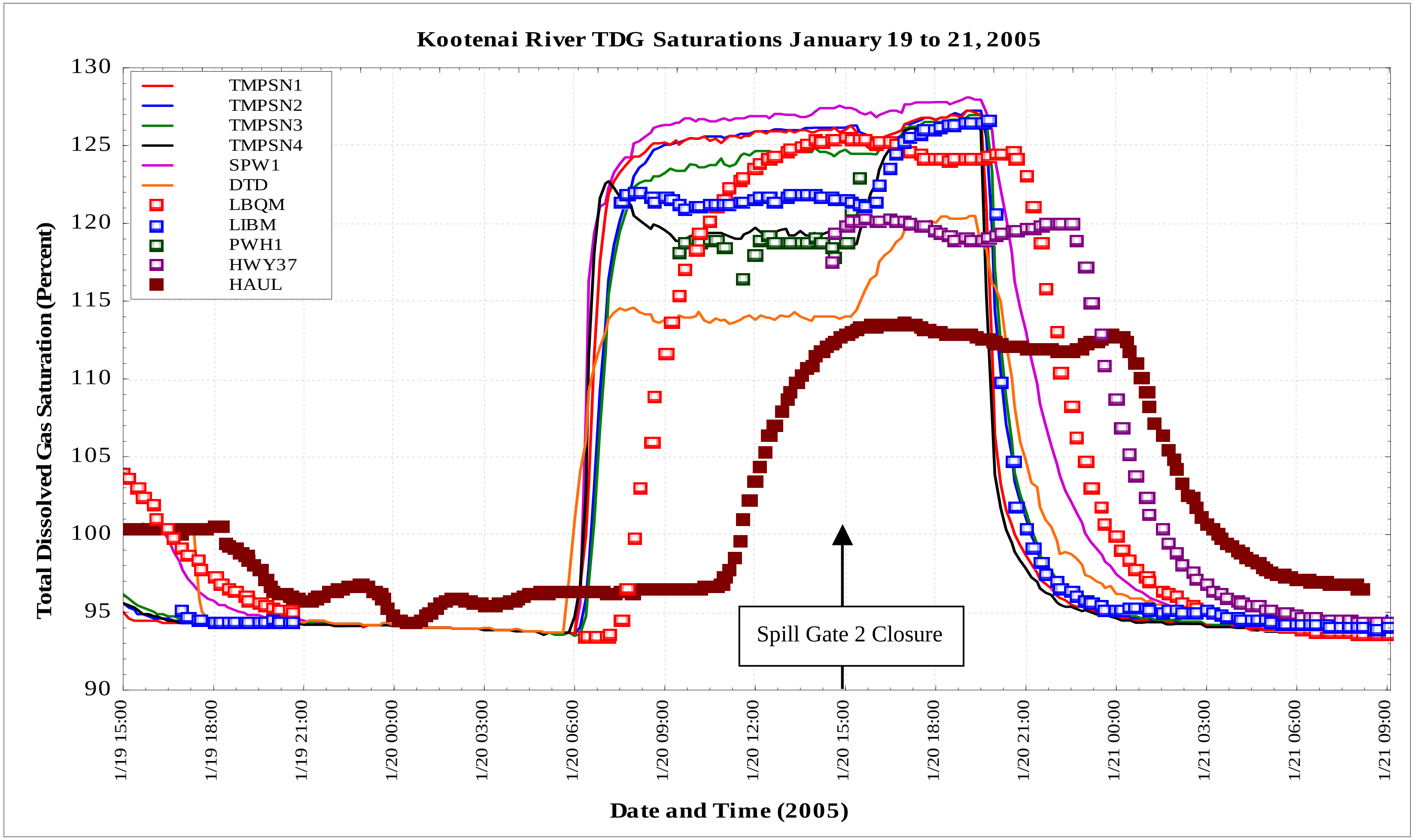

Figure 9. Total dissolved gas saturations in the Kootenai River below Libby Dam January 19 to 21, 2005.

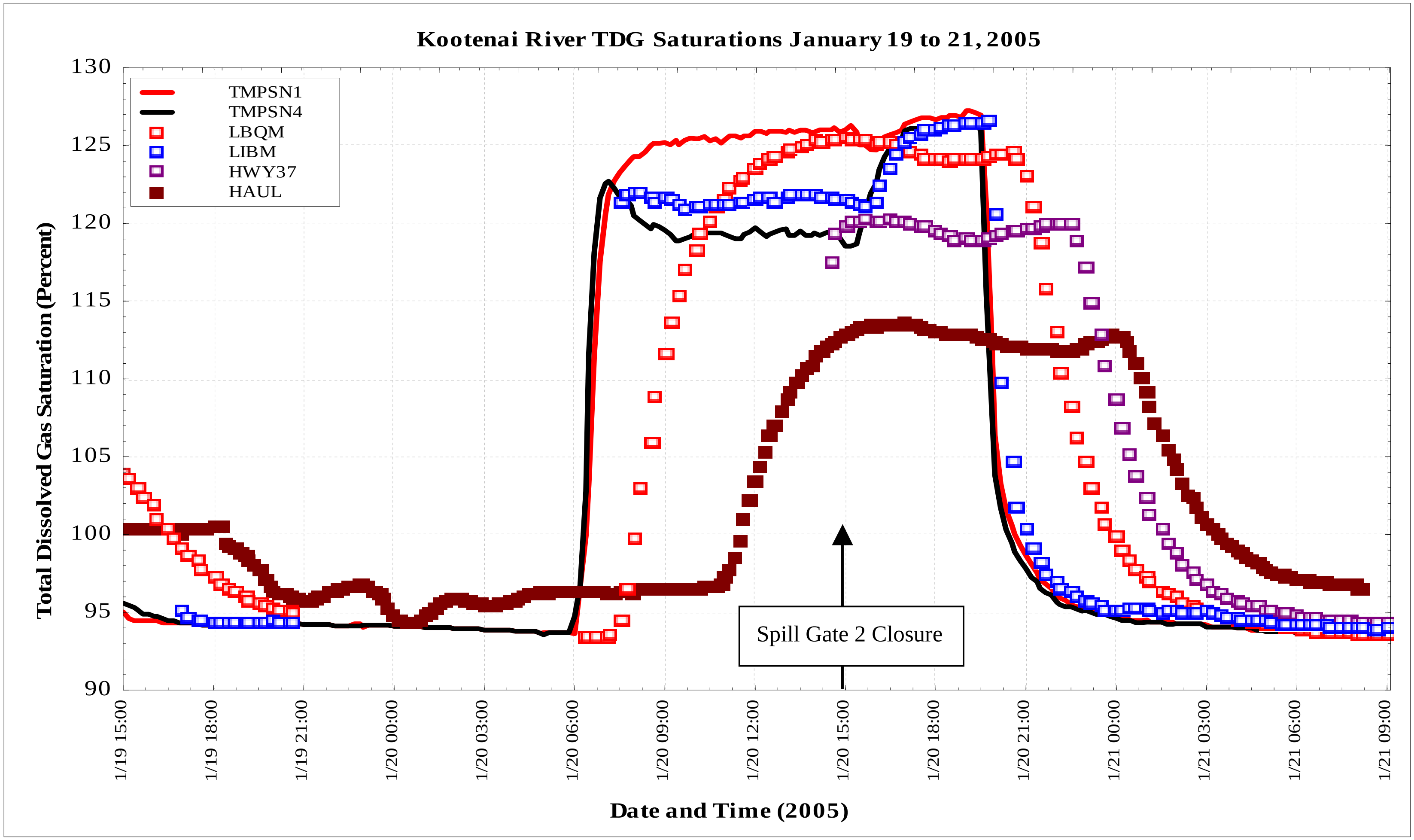

Figure 10. Total dissolved gas saturations in the Kootenai River downstream of Libby Dam January 19 to 21, 2005.