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Libby Dam 2010 Spill Test: Total Dissolved Gas and Temperature Monitoring

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Introduction

The U.S. Fish and Wildlife Service (USFWS) issued their Biological Opinion on the effects of the operation of Libby Dam on the endangered Kootenai River white sturgeon (sturgeon), threatened bull trout, and the sturgeon's designated critical habitat (BiOp) to the U.S. Army Corps of Engineers (Corps) and Bonneville Power Administration (BPA) on February 18, 2006. For the 2006 BiOp, the USFWS developed a Reasonable and Prudent Alternative (RPA) designed to achieve habitat attributes/measures deemed necessary to adequately provide for successful Kootenai sturgeon spawning and natural in-river reproduction in the Kootenai River near Bonners Ferry, Idaho. RPA Action 1.3 originally provided that the action agencies "implement test releases of powerhouse plus 10,000 cfs three or more times during the next ten years (2006 to 2016), three times within the next four years (2006 – 2009), if conditions allow." The USFWS clarified the RPA to the 2006 BiOp on December 29, 2008, in accordance with the provisions to a settlement agreement in *Center for Biological Diversity v. United States* involving the Corps, the U.S. Fish and Wildlife Service (USFWS), the State of Montana, Kootenai Tribe of Idaho (KTOI), and the Center for Biological Diversity (CBD). The clarified RPA Action 1.5 outlines certain conditions required for providing voluntary spill above powerhouse capacity from Libby Dam for 2010 – 2013, should the operation of Libby Dam in water years 2008 and 2009 be determined by the USFWS not successful in terms of aiding sturgeon reproduction and recruitment. The USFWS, in consultation with a team of regional biologists, made this determination in both 2008 and 2009, triggering the provisions for the Corps to operate Libby Dam in 2010 to provide a sturgeon flow augmentation in the form of spill.

Total dissolved gas (TDG) supersaturation is generated by spilling water at Libby Dam as a result of the entrainment of air and transfer of gas into solution at depth in the stilling basin. Libby Dam is located at River Mile (RM) 221.9 on the Kootenai River and is a headwater project with no upstream sources of TDG supersaturation. A detailed investigation of TDG exchange at Libby Dam was conducted in 2002 (Schneider, 2003). This investigation determined that the TDG exchange in spillway flows ranged from 104 to 134 percent saturation and was a direct function of the specific spillway discharge. Moreover, strong lateral gradients in TDG saturation were measured in the Kootenai River 0.6 miles below Libby Dam at RM 221.3 during spillway releases in 2002. The maximum TDG saturations were consistently observed along the left channel bank (the convention for left and right is looking downstream) with decreasing TDG saturations along a transect moving from left bank to right bank. TDG saturations measured along the right bank were similar to powerhouse releases and ranged from about 104 to 106 percent. The spillway is to the left of the powerhouse.

Total dissolved gas (TDG), water temperature, and associated water quality processes are known to impact anadromous and resident fishes in the Columbia River system. Dams may alter a river's water quality characteristics by increasing TDG levels due to releasing water through the spillways and by altering temperature gradients due to the creation of reservoirs. Spilling water at dams can result in increased TDG levels in downstream waters by plunging the aerated spill water to depth where hydrostatic pressure increases the solubility of atmospheric gases. Elevated TDG levels generated by spillway releases from dams can promote the potential for gas bubble trauma in downstream aquatic biota (Weitkamp and Katz 1980; Weitkamp et al. 2002); this condition is analogous to decompression sickness, or "the bends," in human divers. Water temperature has a significant impact on fish survivability, TDG saturations, the biotic community, chemical and biological reaction rates, and other aquatic processes.

To address the provisions of the clarified RPA Action 1.5, the Corps conducted a spill test during June 2010. The water quality compliance point for the spill test was at the site of the existing USGS tailwater gage, located approximately 0.6 miles downstream of Libby Dam at RM 221.3.

Purpose and Objectives

Montana's state water quality standard for TDG is 110 percent saturation. In accordance with the provisions of the settlement agreement, the Corps sought and obtained a temporary waiver from the Montana Department of Environmental Quality (MDEQ) for this spill event. Questions remained concerning dissolved gas dynamics following previous Libby Dam spill events in 2002 and 2006. The purpose of this study was to more clearly understand total dissolved gas exchange processes and thermal properties associated with spillway operations at Libby Dam and the resultant transport and mixing in the Kootenai River below the project for a distance of about 30 miles, to the area downstream of Kootenai Falls. In particular, this study focused on measuring the lateral gradient of TDG saturations and temperatures present in the Kootenai River at the USGS tailwater gage located 0.6 miles downstream of the dam (RM 221.3), the site of the water quality compliance point. The major objectives of this study were:

- To monitor TDG saturations at the compliance point location set forth by MDEQ in their March 24, 2010 TDG waiver
- To study the lateral mixing of spill and powerhouse water in the Kootenai River immediately downstream of Libby Dam
- To study TDG exchange properties in the Kootenai River downstream of Kootenai Falls
- To monitor temperatures in the Kootenai River at the USGS gage to assure that they are maintained at or above 8 degrees centigrade during the spill test.

These objectives were addressed using data collection and analysis methods to evaluate temperature and TDG exchange characteristics in the Kootenai River before, during, and after spillway operations. The study focused on the Kootenai River from Libby Dam to Kootenai Falls, Montana.

Methods and Materials

Background

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 and 11 miles east of the town of Libby, Montana (Figure 1). 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. Approximately 28 miles downstream of Libby Dam the Kootenai River passes over Kootenai Falls, a 200 foot high series of stepped falls.

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).

2002 Spill Test

A detailed TDG study at Libby Dam was conducted in 2002 (Schneider, 2003). Spillway flows ranged from 0.7 to 15.6 kcfs with total river flows ranging from 23.5 to 40 kcfs. This investigation determined the TDG exchange in spillway flows ranged from 104 to 134 percent saturation and were a direct function of the specific spillway discharge. The TDG saturation in spillway releases, as measured immediately below the stilling basin, increased as an exponential function of the spillway discharge, and increased abruptly from 104 to 129 percent saturation as spill discharge increased from 0.7 to 4.0 kcfs. A mild increase in TDG saturations from 129 to 134 percent was observed as spillway discharges increased from about 4 to 15 kcfs. The passage of water through the powerhouse did not change the TDG saturations in the Kootenai River, and TDG pressures in powerhouse releases measured during the test ranged from 102 to 104 percent.

The TDG characteristics in the Kootenai River below Libby Dam are dominated by the development of a mixing zone between spillway and powerhouse releases and in-river processes such as degassing at the air/water interface, lateral mixing and thermal heat exchange. The rapid development of a mixing zone and in-river processes result in decreasing TDG saturations in the Kootenai River downstream of the dam. A detailed investigation of lateral gradients in TDG saturations was conducted 0.6 miles downstream of the dam at RM 221.3, the USGS tailwater gage, by deploying 5 TDG monitoring instruments along a lateral transect a locations representing 10, 30, 50, 80, and 90 percent normalized distance from the left bank (Schneider 2003). These data indicated that the 10 percent normalized distance from the left bank had highest TDG saturations with only a slight decrease in TDG saturations between the 10 percent and 30 percent distance with a more rapid decrease measured between the 50 percent and 80 percent normalized distance from the left bank (Figure 3). TDG saturations measured at the 90 percent normalized distance were dominated by powerhouse releases to the Kootenai River.

Schneider (2003) concluded that in-river processes (lateral mixing, tributary mixing, degassing at the air/water interface) mix spillway and powerhouse flows downstream of Libby Dam. A strong lateral TDG saturation gradient exists in the Kootenai River about 3.5 miles downstream at the Highway 37 Bridge immediately upstream of the Fisher River. However, TDG saturations in the Kootenai River are generally well mixed by about 8.6 miles downstream of the dam at the constriction of the river at an old haul bridge site.

Study Approach

An array of eleven (11) instruments, consisting of seven (7) data loggers and four (4) real-time instruments, were deployed in the Kootenai River to measure lateral and longitudinal TDG and temperature saturations in the Kootenai River generated by Libby Dam powerhouse and spillway operations. The general locations of these water quality monitoring stations are shown in Figures 4, 5, 6 and 7, and a description of each station is presented in Table 1. Data were collected by the water quality instrumentation at 60 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 gauging station to calculate the TDG percent saturation. Equations relating barometric pressure to elevation were used to calculate barometric pressures at downstream stations based on pressures measured at the USGS gauging station.

Four real-time instruments (LBQM, LIBM, LBCP-1, and LBCP-2) were deployed in the Kootenai River 0.6 miles downstream of Libby Dam at the USGS gage as shown in Figures 6 and 7. Station LBQM is the current fixed TDG monitoring station for Libby Dam and is positioned off of the left bank at a location representing about 5 percent normalized distance from the left bank. Station LIBM is the current fixed temperature monitoring station for Libby Dam and is positioned off of the right bank at a location representing about 95 percent normalized distance from the left bank. Station LBCP was the official compliance monitoring station for Libby Dam during the spill test. It was located off of the left bank at a location representing 20 percent normalized distance from the left bank. Station LBCP consisted of two water quality probes (LBCP-1 and LBCP-2) that were anchored together, positioned at the same location and represented redundant TDG probes at the compliance location.

Seven data loggers (USGS-3, USGS-4, USGS-5, HAUL, USFALLS, DSFALLS-LB, and DSFALLS-RB) were deployed in the Kootenai River for the study. Three data loggers (USGS-3, USGS-4, and USGS-5) were deployed in the Kootenai River 0.6 miles downstream of Libby Dam at the USGS gage as outlined in Table 1 and shown in Figure 7. These instruments were deployed along a transect with stations LBQM, LBCP, and LIBM to monitor the lateral mixing between spillway and powerhouse flows at the USGS gage. The sampling stations were skewed towards the left bank to best capture the development of the mixing zone between spillway and powerhouse flows. These stations were positioned in a transect representing 5, 20, 30, 50, 70, and 95 percent normalized distance from the left bank (Figure 7 and Table 1).

The remaining sampling stations (HAUL, USFALLS, DSFALLS-LB, and DSFALLS-RB) were located about 8.6, 28, and 30 miles downstream of the project to measure the TDG pressures in the Kootenai River under open-channel flow conditions and after passing over Kootenai Falls (see Figures 4 and 5). One instrument (HAUL) was located mid-channel about 8.6 miles downstream in the Kootenai River at the constriction of the river at an old haul bridge site. One instrument (USFALLS) was located mid-channel about 28 miles downstream in the Kootenai River immediately upstream of Kootenai Falls. The farthest downstream sampling station consisted of two instruments (DSFALLS-LB and DSFALLS-RB) located about 30 miles downstream in the Kootenai River at left bank and right bank locations downstream of Kootenai Falls.

All data loggers were housed in perforated PVC pipe housings and deployed on the bottom of the river with weights and cables. The cables were then attached to shore to prevent the loss of the housing and instrument. The four real-time instruments were deployed using slightly different techniques. Stations LIBM and LBCP were 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 MiniSonde MS4A/MS5 TDG probes. Additional instrumentation for both real-time stations consisted of a Common Sensing TBO-L electronic barometer, a Sutron 9210 XLite DCP, a radio transmitter, and a power source. For real-time stations, the TDG probe, DCP, and radio transmitter were powered by a 12-volt battery that was charged by a solar panel.

Quality-Assurance Procedures

Data quality assurance and calibration procedures included calibration of instruments in the laboratory following procedures outlined in the *Corps of Engineers Plan of Action for Dissolved Gas Monitoring 2010* (USACE 2009). All primary standards were National Institute of Science and Technology (NIST) traceable and maintained according to manufacturers' recommendations. A new TDG membrane was assigned to each probe at the beginning of the study.

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 and 300 mm mercury (Hg) above barometric pressure, which represented TDG saturations from 100 to 139% (Table 2). If any measurement differed by more than 5 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 2 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 2. If the measurements differed by more than 0.2°C, the probe was not used. As seen in Table 2, 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.

A quality assurance review of all stations showed that only data from station DSFALLS-RB were suspect. Data collected at DSFALLS-RB between June 21 at 1100 and June 28 at 2300 were rejected due to the probe drifting out of calibration. All other data were acceptable and were used in this report.

Temporary Total Dissolved Gas Waiver

As discussed above, Montana Department of Environmental Quality (MDEQ) issued a temporary waiver of the 110 percent TDG standard on the Kootenai River in a letter dated March 24, 2010. This temporary waiver was specific to the June 2010 spill test and set forth a series of conditions for the spill test. Some key provisions regarding TDG saturation and temperature requirements for the Kootenai River during the June 2010 spill test are outlined below (paraphrased from the MDEQ waiver):

- TDG shall not exceed 123 percent as measured by calculating the average of the 12 highest hourly readings in any 24 hour period immediately preceding the calculation
- The specific location of the compliance point will be at the 20% "normalized distance" from left bank (looking downstream) at RM 221.3 (about 0.6 miles downstream of the dam at the site of the existing USACE tailwater TDG fixed monitoring station and USGS tailwater gage)

- The TDG compliance location shall be at a depth equal to or below a compensation depth of 7.6 feet below the water surface
- Water temperature shall be maintained at or above 8 degrees centigrade, as measured at the USGS gage at river mile 221.3, downstream of Libby Dam.

Compliance Station Sampling Procedures

The water quality compliance station (LBCP) consisted of two water quality probes (LBCP-1 and LBCP-2) secured together and located at the 20% normalized distance from the left bank at the USGS tailwater station. Two probes were used to provide redundancy in case a probe failed during the spill test. Measurements were made every hour and the data were transmitted via radio directly to the Seattle District's HEC-DSS water quality database. Water quality data from LBCP-1 and LBCP-2 were averaged together (LBCP-Avg) to represent the official compliance point data for meeting the MDEQ temporary total dissolved gas waiver. Figure 8 shows that TDG data measured by LBCP-1 and LBCP-2 were similar and that averaging the two instruments provided an accurate measurement of TDG at the compliance location. There was little bias with the median difference between the two instruments of 0.14 percent saturation.

Results and Discussion

Project Operations

Water quality instruments were deployed on June 3rd and removed on June 28th, 2010. Total river discharge from Libby Dam ranged from 16 kcfs to 36 kcfs during this time period. Spillway operations were conducted from June 10th through June 17th, 2010, with spillway discharge ranging from 2 kcfs to 9 kcfs (Table 3). The forebay surface elevation ranged from about 2,419 ft on June 3rd to 2,428 ft on June 28th, with a relatively constant forebay elevation of about 2,423 ft during spillway operations between June 10 and 17th. The tailwater elevation varied with total project discharge and ranged only about 3 feet during spillway discharges, resulting in relatively constant depths for the water quality probes located along a transect at the USGS gage (Figure 9). The depths of all probes, including the compliance location station LBCP-Avg, were maintained at a depth greater than the compensation depth of 7.6 feet outlined in the MDEQ temporary waiver during the entire study. The compensation depth is the depth above which degassing will occur due to decreased hydrostatic pressure. To measure TDG accurately, a probe must be placed below the minimum calculated compensation depth.

Water Temperature

The forebay of Libby Dam was thermally stratified during the study period. Forebay temperature profiles from June 10th through June 17th at 1400 hours are shown in Figure 10. Water temperatures in the forebay ranged from about 4°C at a depth of 150 feet to over 14°C near the water surface. The water temperature at the elevation of the spillway crest (elevation 2405 feet) ranged from about 10°C to 12°C, while water temperatures at the elevation of the selective withdrawal gates regulating powerhouse release depths (elevation range 2367 to 2388 feet) ranged from about 9°C to 10°C during the spill test (Figure 10). The surface water temperatures experienced a general increase from June 10 to 15 followed by a sharp decrease from June 16 to 17. These changes in surface water temperatures reflect the changing atmospheric temperatures during the spill test. A substantial cooling trend in air temperatures occurred from June 16 to 18 which is reflected in the decrease in surface water temperatures at the forebay.

The depth of the selective withdrawal gates together with the changes in the thermal structure of forebay resulted in variability in the water temperatures released from Libby Dam during the spill test. Lateral water temperature gradients were measured in the Kootenai River at the USGS gage transect due to the combined spillway and powerhouse releases (Figure 11). No lateral gradient existed from left bank to right bank prior to or after spillway operations. However, during spillway discharges the water temperatures near the left bank, which represents spillway flows, were warmer than water temperatures near the right bank, which represents powerhouse flows. The difference between left bank and right bank temperatures during spillway operations was about 1°C. Little to no diurnal variation in water temperatures was measured at the USGS gage transect. Water temperatures measured at the compliance location (LBCP-Avg) were at or above 8°C during spillway operations as stipulated by the MDEQ temporary waiver (Figure 11).

A slight warming trend in the Kootenai River was measured from Libby Dam downstream to Kootenai Falls (Figure 12). It is likely that tributary inflow temperatures to the Kootenai River from the Fisher River and Libby Creek were warmer than the mainstem during June, resulting in a warming of the Kootenai River downstream of the dam. A diurnal variation in the Kootenai River became more pronounced the greater the distance from Libby Dam. During the nighttime the change in water temperature between Libby Dam and Kootenai Falls was small, as seen by similar temperatures at stations HAUL, USFALLS, and DSFALLS-LB/RB. However, during the day, the Kootenai River temperatures increased by about 1°C (Figures 11 and 12). The substantial cooling trend that occurred at Libby Dam from June 16 to 18 is seen in the near uniformity of Kootenai River temperatures from Libby Dam downstream to Kootenai Falls during this period.

TDG Saturations

Total dissolved gas levels presented in the following sections are reported as either pressure in millimeters (mm) Hg or as TDG saturation (percent). Water quality monitoring stations providing information on nearfield and compliance station TDG processes were stations LBQM, LBCP-Avg, USGS 3-5, and LIBM (see Figure 7). Information on downstream TDG process were stations HAUL, USFALLS, DSFALLS-LB and DSFALLS-RB (see Figures 4 and 5). A statistical summary of the TDG pressures and saturations at all water quality stations for pre-spill, post-spill, and event spillway conditions is presented in Table 4.

Nearfield and Compliance Stations

The TDG saturations measured along a transect at the USGS tailwater gage (see Figure 7) showed the development of lateral gradients in TDG between spillway flows along the left bank and powerhouse flows along the right bank (Figure 13). The median TDG saturations measured at the USGS tailwater gage ranged from 103.5 percent on the right bank (LIBM) to 123.3 percent on the left bank (LBQM), with a maximum TDG saturation at stations LIBM and LBQM of 104.2 and 125.7 percent, respectively (Table 4). As seen in Figure 13, TDG saturation gradients were strongest during the highest spillway discharges with the greatest TDG saturations along the left bank reflecting spillway flows. The TDG saturations measured along the right bank varied little with spillway discharge and closely resembled powerhouse releases.

The median TDG saturation lateral distribution for spillway discharges of 2, 5, 6, 6.5, 7, 8, and 9 kcfs is shown in Figure 14. These data clearly show the development of strong lateral gradients in TDG saturations during spillway releases with TDG extending farther across the river for higher spill events. The maximum TDG was observed along the left bank with little mixing between spillway and powerhouse flows. For spillway flows of 5 kcfs or greater, elevated TDG saturations extended across at least 50 percent of the Kootenai River. These data are similar to results from the 2002 spill test presented in Figure 3 (Schneider 2003). The similarity of the 2002 and 2010 TDG saturation data collected along the transect at the USGS tailwater gage indicates that the unit spillway discharge is the most important causal parameter in determining the TDG exchange in spillway flows at Libby Dam. Although slight changes in water temperature and barometric pressure may result in small differences in TDG saturations measured at the USGS tailwater gage during spill operations, the overriding factor determining TDG saturations at Libby Dam as measured at the USGS tailwater gage remains unit spillway discharge. Thus, it is likely that a relationship could be made between TDG saturations measured at the fixed monitoring station LBQM and saturations at normalized distances from the left bank based on the lateral transect TDG saturation data collected in 2002 and 2010.

TDG saturations measured at the compliance station were similar for stations LBCP-1 and LBCP-2 and for the average of the two stations LBCP-Avg (Figure 15). These data, together with Figure 8 showing a 1:1 relationship between LBCP-1 and LBCP-2, confirm that averaging the two probes at the compliance location provided an accurate measurement of TDG saturations at the 20 percent normalized distance from the left bank. Figure 15 shows that TDG saturations measured at LBCP-Avg as individual hourly readings exceeded 123 percent during spills of 8 kcfs or greater. However, TDG saturations measured at LBCP-Avg by calculating the average of the 12 highest hourly readings in any 24 hour period immediately preceding the calculation as outlined in the MDEQ temporary waiver did not exceed 123 percent during spillway operations (Figure 15).

Downstream Kootenai River

In-river process were monitored in the Kootenai River at distances of about 8.6 miles (station HAUL), 28 miles (station USFALLS), and 30 miles (DSFALLS-LB and DSFALLS-RB) downstream of Libby Dam. Schneider (2003) concluded that during spillway operations, Kootenai River TDG saturations were generally well mixed at about 8.6 miles downstream of the dam at the site of an old haul bridge near river mile 213.3 and continued to be well mixed downstream to Kootenai Falls. In-river processes such as lateral mixing, tributary dilution, degassing at the air-water interface, thermal heat exchange, and biological productivity are likely responsible for TDG saturations in the Kootenai River becoming mixed downstream of the USGS tailwater gage (Schneider 2003).

TDG saturations measured downstream of the USGS tailwater gage (see Figure 4) decreased with distance from Libby Dam as the river approached Kootenai Falls and then increased downstream of Kootenai Falls (Figure 16). The median downstream TDG saturations measured during spillway operations decreased from 110.7 percent at the HAUL station to 107.9 percent at the UPFALLS station located immediately upstream of Kootenai Falls. The median TDG saturations measured downstream of Kootenai Falls ranged from 118.7 percent at DSFALLS-LB to 116.5 percent at DSFALLS-RB (Table 4). During periods with no spill, median TDG saturations were similar from the dam to station USFALLS located immediately above Kootenai Falls and ranged from about 102 to 104 percent (Table 4). During these no-spill periods, median

TDG saturations downstream of Kootenai Falls ranged from about 115 percent along the left bank (DSFALLS-LB) to about 113 percent along the right bank (DSFALLS-RB) (Table 4).

Diurnal variations in TDG saturations were most pronounced at the HAUL and USFALLS stations and were highly attenuated at the two stations (DSFALLS-LB and DSFALLS-RB) downstream of Kootenai Falls (Figure 16). During sampling periods with no spill, TDG saturations ranged from 101 to 105 percent at stations HAUL and USFALLS due to thermally induced TDG pressure response to diurnal heat exchange (see Figure 12). Non-spill median TDG conditions measured at these downstream stations were similar to those measured near Libby Dam at the USGS tailwater gage (Table 4). During spillway operations, diurnal TDG variations ranged from about 110 to 113 percent at station HAUL and from about 107 to 111 percent at station USFALLS due to daily heat exchange. The median increase in TDG saturations at stations HAUL and USFALLS resulting from spillway operations was about 8.2 percent and 6.0 percent, respectively (Table 4).

A lateral gradient in TDG saturations was observed downstream of Kootenai Falls with the left bank station (DSFALLS-LB) consistently having higher TDG saturations during both non-spill and spill periods (Figure 15). The lateral gradient measured downstream of the falls is somewhat surprising given the narrow channel and turbulent mixing conditions below the falls. During the deployment period the left bank station consistently had on average TDG saturations about 2 percent greater than the right bank except during the non-spill period from about June 21 to June 28 when TDG pressures at the right bank station decreased while pressures at the left bank station remained stable. Since flows in the river were relatively stable after June 21 (see Table 3) no reason for a change in the lateral TDG gradient at the right bank and not the left bank can be determined. It is likely that the drifting observed at DSFALLS-RB was due to fouling of the TDG membrane.

Schneider (2003) concluded that Kootenai Falls caused a significant increase in TDG saturations to the Kootenai River and that the TDG loading to the river below the falls were independent from the TDG loading produced by spillway operations at Libby Dam. Data collected before, during, and after spillway operations in 2010 at left bank and right bank station below Kootenai Falls support this conclusion. During sampling periods with no spill, median TDG saturations ranged from 115.2 to 115.4 percent at DSFALLS-LB and from 113.5 to 113.8 percent at DSFALLS-RB (Table 4). During spillway operations, median TDG saturations ranged from 118.7 percent at DSFALLS-LB to 116.5 percent at DSFALLS-RB (Table 4). The median increase in TDG saturations at stations DSFALLS-LB and DSFALLS-RB resulting from spillway operations was about 3.5 percent and 3.0 percent, respectively (Table 4). These median TDG increases are substantially less than 6.0 percent measured immediately upstream of the falls at station USFALLS.

The consistently high TDG saturations measured below Kootenai Falls during non-spill and spill conditions suggest that the falls are the major source of TDG to the Kootenai River downstream of the falls. Moreover, the small increase in TDG saturations measured downstream of the falls during spill conditions relative to immediately upstream, indicate that the TDG saturations downstream of the falls are largely influenced by flow and river depth and not by TDG loadings from Libby Dam. For example, during non-spill conditions TDG saturations measured below the falls at DSFALLS-LB increased from about 115 to 117 percent as flows increased from 18kcfs to 27kcfs. These TDG increases were independent of Libby Dam spill and suggest the importance of flow and river depth in determining TDG loadings below Kootenai Falls.

Conclusions

- TDG saturations measured at the compliance station showed little to no difference between stations LBCP-1 and LBCP-2 or the average of the two stations LBCP-Avg. Review of the data confirm that using an average of the two probes at the compliance location provided an accurate measurement of TDG saturations at the 20 percent normalized distance from the left bank. .

- TDG saturations measured at the compliance location did not exceed 123 percent as measured by calculating the average of the 12 highest hourly readings in any 24 hour period immediately preceding the calculation as outlined in the MDEQ temporary waiver.

- Water temperatures measured at the compliance location were at or above 8°C during spillway operations as stipulated by the MDEQ temporary waiver.

- The TDG saturations measured along a transect at the USGS tailwater gage showed the development of lateral gradients in TDG between spillway flows along the left bank and powerhouse flows along the right bank with TDG extending farther across the river for higher spill events.

- The similarity of the 2002 and 2010 TDG saturation data collected along the transect at the USGS tailwater gage indicates that the unit spillway discharge is the most important causal parameter in determining the TDG exchange in spillway flows at Libby Dam.

- The consistently high TDG saturations measured below Kootenai Falls during non-spill and spill conditions suggest that the falls are the major source of TDG to the Kootenai River downstream of the falls. Moreover, the small increase in TDG saturations measured downstream of the falls during spill conditions relative to immediately upstream, indicate that the TDG saturations downstream of the falls are largely influenced by flow and river depth and not by TDG loadings from spill at Libby Dam.

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Tables

Table 1. Summary of total dissolved gas and temperature sampling stations.

Primary Station Name	Secondary Station Name	Station Location	Lat	Lon	Elev (ft)
LBQM	Permenant TDG Station	USGS 5% Distance From Left Bank	48.40061	-115.31861	2135
LBCP-1	Compliance Station-1	USGS 20% Distance From Left Bank	48.40064	-115.31888	2134
LBCP-2	Compliance Station-2	USGS 20% Distance From Left Bank	48.40064	-115.31888	2134
USGS-3	—	USGS 30% Distance From Left Bank	48.40067	-115.31905	2127
USGS-4	—	USGS 50% Distance From Left Bank	48.40066	-115.31938	2133
USGS-5	—	USGS 70% Distance From Left Bank	48.40042	-115.31988	2132
LIBM	Permenant Temperature Station	USGS 95% Distance From Left Bank	48.40060	-115.32014	2138
HAUL	—	Haul Bridge Mid Channel	48.37166	-115.42951	2086
USFALLS	—	Above Falls Mid Channel	48.44757	-115.68443	2029
DSFALLS-LB	—	Below Falls Left Bank	48.44828	-115.79388	1920
DSFALLS-RB	—	Below Falls Right Bank	48.44894	-115.79492	1920

Table 2. Difference between the primary standard thermometer and the laboratory calibrated instrument.

		Deviation from Temp Standard	Deviation from TDG Standard (mm Hg)	
Station Name	**Date**	**Temp, °C**	**BP + 0**	**BP + 300**
LBQM	06/03/10	0.0	0	0
LBCP-1	06/03/10	-0.1	-1	-1
LBCP-2	06/03/10	-0.1	-2	-2
USGS-3	06/03/10	-0.1	-1	-2
USGS-4	06/03/10	0.0	-1	-1
USGS-5	06/03/10	-0.1	0	1
LIBM	06/03/10	-0.1	-1	-1
HAUL	06/03/10	0.0	-1	-2
USFALLS	06/03/10	-0.1	2	2
DSFALLS-LB	06/03/10	-0.1	0	0
DSFALLS-RB	06/03/10	-0.2	-3	0

Table 3. Summary of project operations from June 3 through June 28, 2010.

Starting Date (mm/dd/yy hr:min)	Ending Date (mm/dd/yy hr:min)	Duration (Hours)	Total River Flow (kcfs)	Spill Flow (kcfs)
6/3/10 14:00	6/8/10 05:00	112	17.7	0
6/8/10 06:00	6/9/10 04:00	23	21.1	0
6/9/10 05:00	6/10/10 06:00	25	27	0
6/10/10 07:00	6/10/10 10:00	4	32	5
6/10/10 11:00	6/10/10 13:00	3	33	6
6/10/10 14:00	6/10/10 16:00	3	34	7
6/10/10 17:00	6/10/10 20:00	4	34.3	7.3
6/10/10 21:00	6/11/10 15:00	19	34	7
6/11/10 16:00	6/11/10 18:00	3	33.5	6.5
6/11/10 19:00	6/13/10 12:00	42	34	7
6/13/10 13:00	6/13/10 20:00	8	33.5	6.5
6/13/10 21:00	6/14/10 06:00	10	34	7
6/14/10 07:00	6/14/10 10:00	4	35	8
6/14/10 11:00	6/14/10 12:00	1	34	7
6/14/10 13:00	6/15/10 05:00	20	33.5	6.5
6/15/10 06:00	6/15/10 07:00	1	34	7
6/15/10 08:00	6/15/10 10:00	2	36	9
6/15/10 11:00	6/15/10 17:00	7	33.5	6.5
6/15/10 18:00	6/15/10 20:00	3	34	7
6/15/10 21:00	6/16/10 19:00	23	33.5	6.5
6/16/10 19:00	6/16/10 20:00	1	33	6
6/16/10 21:00	6/17/10 05:00	9	32	5
6/17/10 06:00	6/17/10 07:00	1	29.5	2.5
6/17/10 08:00	6/18/10 06:00	24	27	0
6/18/10 07:00	6/19/10 05:00	23	24	0
6/19/10 06:00	6/21/10 06:00	48	22	0
6/21/10 07:00	6/25/10 05:00	95	20	0
6/25/10 06:00	6/27/10 05:00	48	18	0
6/27/10 06:00	6/28/10 05:00	24	17	0
6/28/10 06:00	6/28/10 23:00	18	16	0

Table 4. Statistical summary of total dissolved gas properties in the Kootenai River from June 3 to June 28, 2010.

	Pre-Spill Conditions			Post-Spill Conditions			Event Conditions During Spillway Operations								
Station	N	Median Total Pressure (mm Hg)	Median TDG (Percent)	N	Median Total Pressure (mm Hg)	Median TDG (Percent)	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)	Median Delta Pressure (mm Hg)	Median Delta TDG (Percent)
LBQM	161	724	103.0	305	722	102.8	168	869	123.3	883	125.7	779	111.3	145	20.3
LBCP-Avg	143	725	103.1	272	723	102.9	168	862	122.1	877	124.9	762	108.9	137	19.0
USGS-3	161	724	102.9	304	724	102.9	168	854	121.1	871	124.2	761	108.7	130	18.2
USGS-4	161	725	103.2	304	722	102.9	168	836	118.4	855	121.9	750	107.1	111	15.2
USGS-5	161	725	103.2	304	722	102.9	168	743	105.5	748	106.3	727	103.8	18	2.3
LIBM	144	724	103.1	178	723	102.9	168	729	103.5	734	104.2	719	102.4	5	0.5
HAUL	162	721	102.5	298	722.5	102.4	151	783	110.7	798	113.6	760	108.3	62	8.2
USFALLS	165	721	102.0	297	723	102.2	167	766	107.9	789	111.6	745	105.9	45	6.0
DSFALLS-LB	165	818	115.2	296	821	115.4	167	844	118.7	854	119.6	833	117.1	26	3.5
DSFALLS-RB	165	806	113.5	92	809	113.8	150	827	116.5	842	118.1	821	115.3	22	3.0

Figures

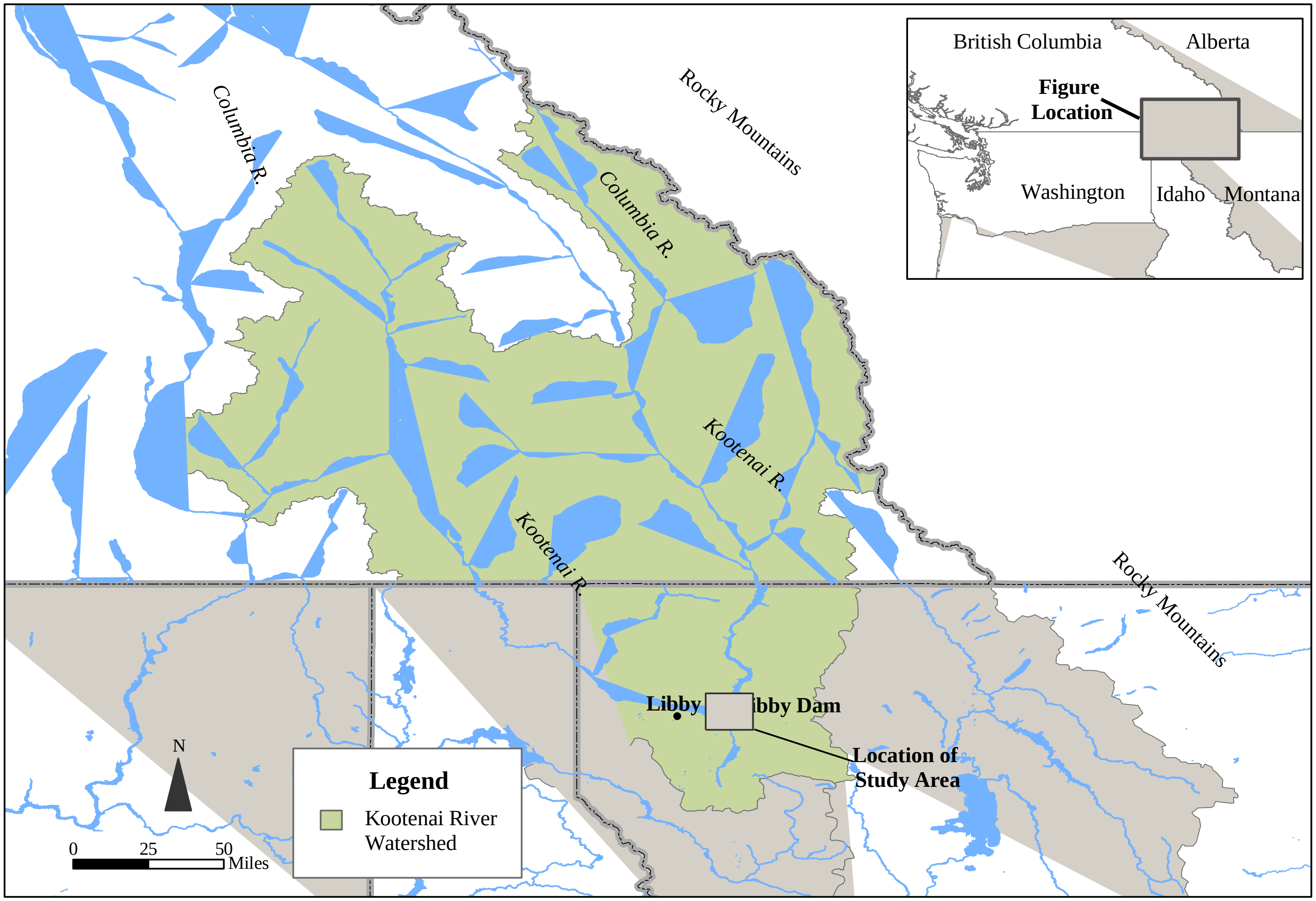

Figure 1. Location of the study area within the Kootenai River watershed.

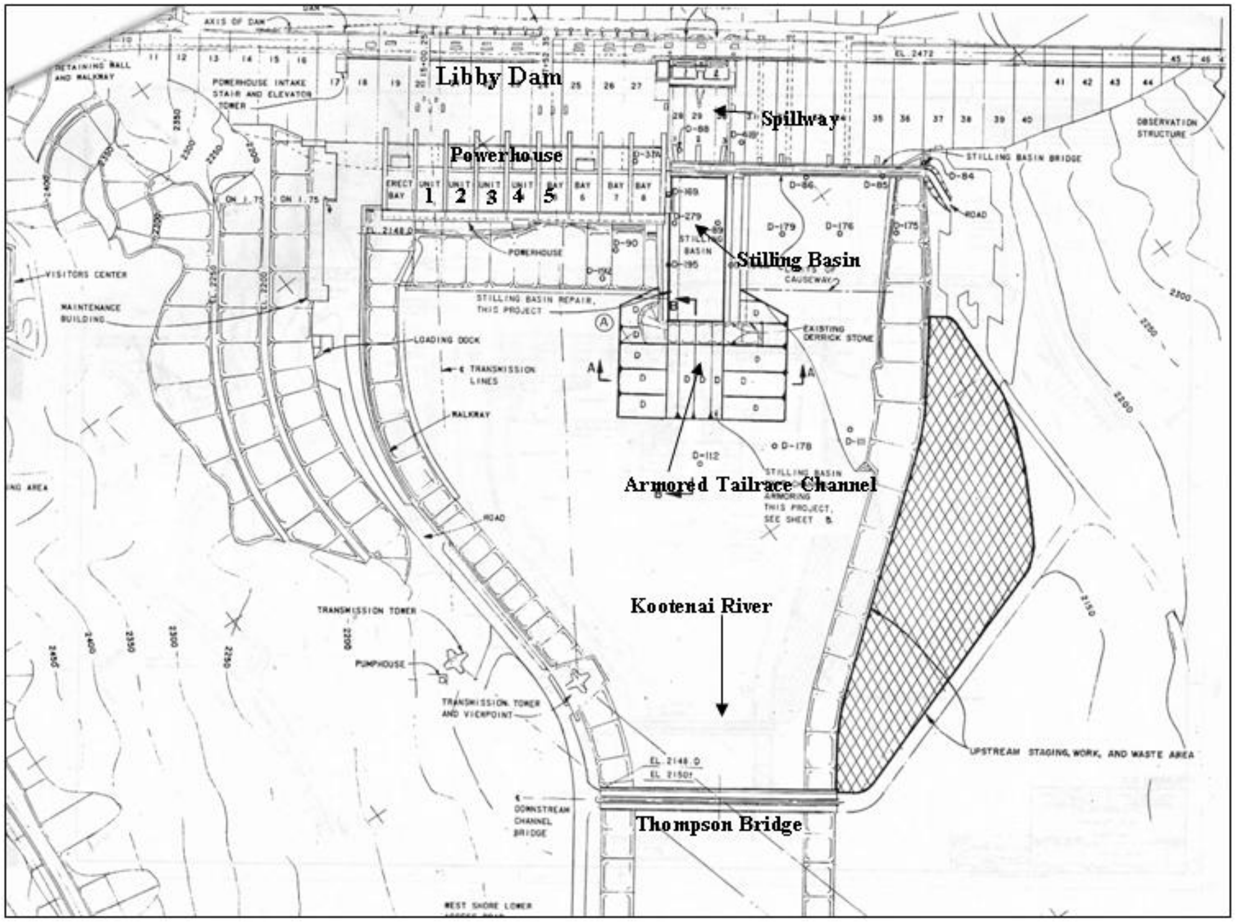

Figure 2. Libby Dam powerhouse, spillway, and stilling basin layout.

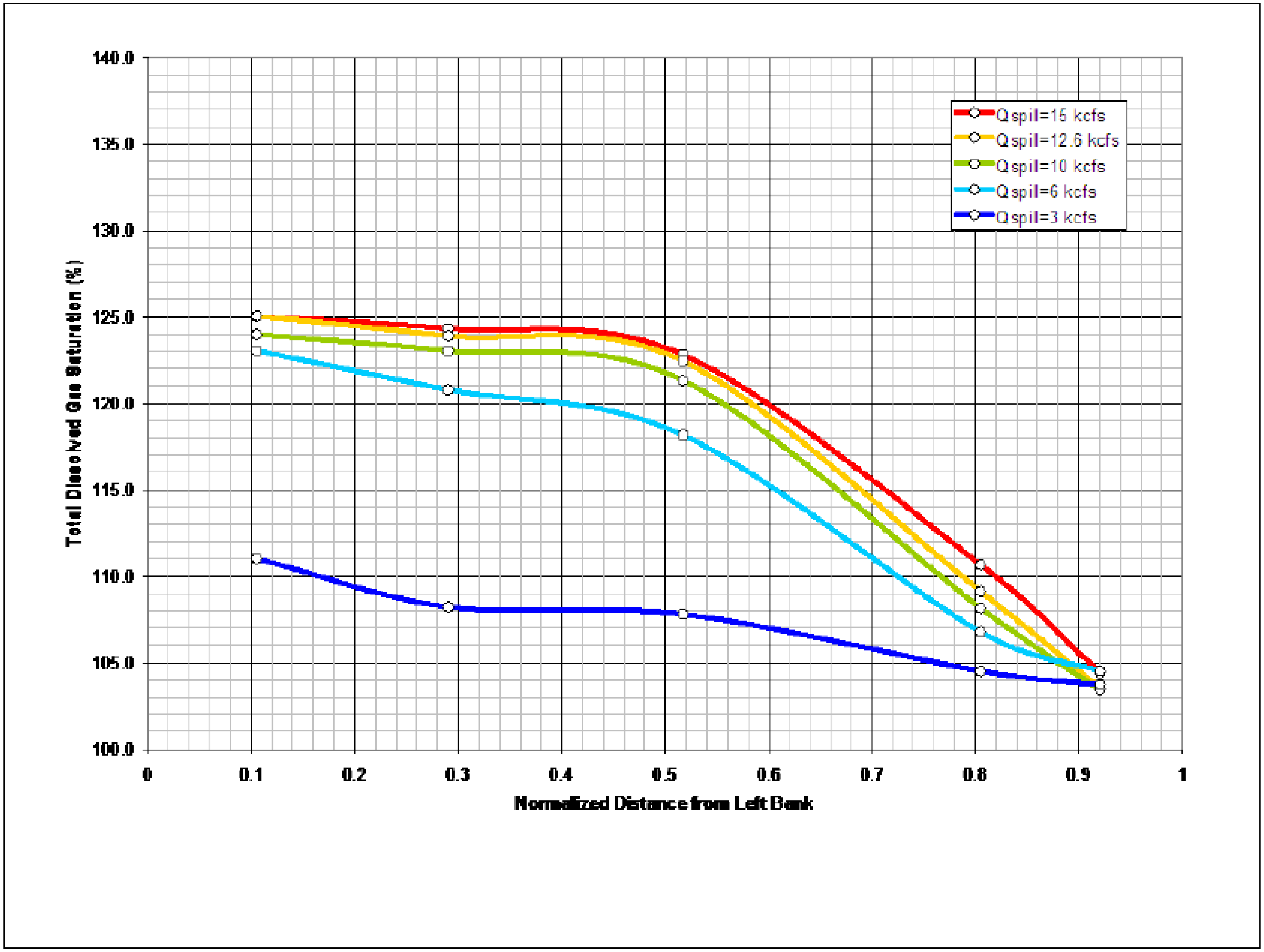

Figure 3. Lateral TDG saturation measured in the Kootenai River during spillway operations in 2002 at the USGS gage for spill discharges of 3, 5, 10, 12.6, and 15 kcfs.

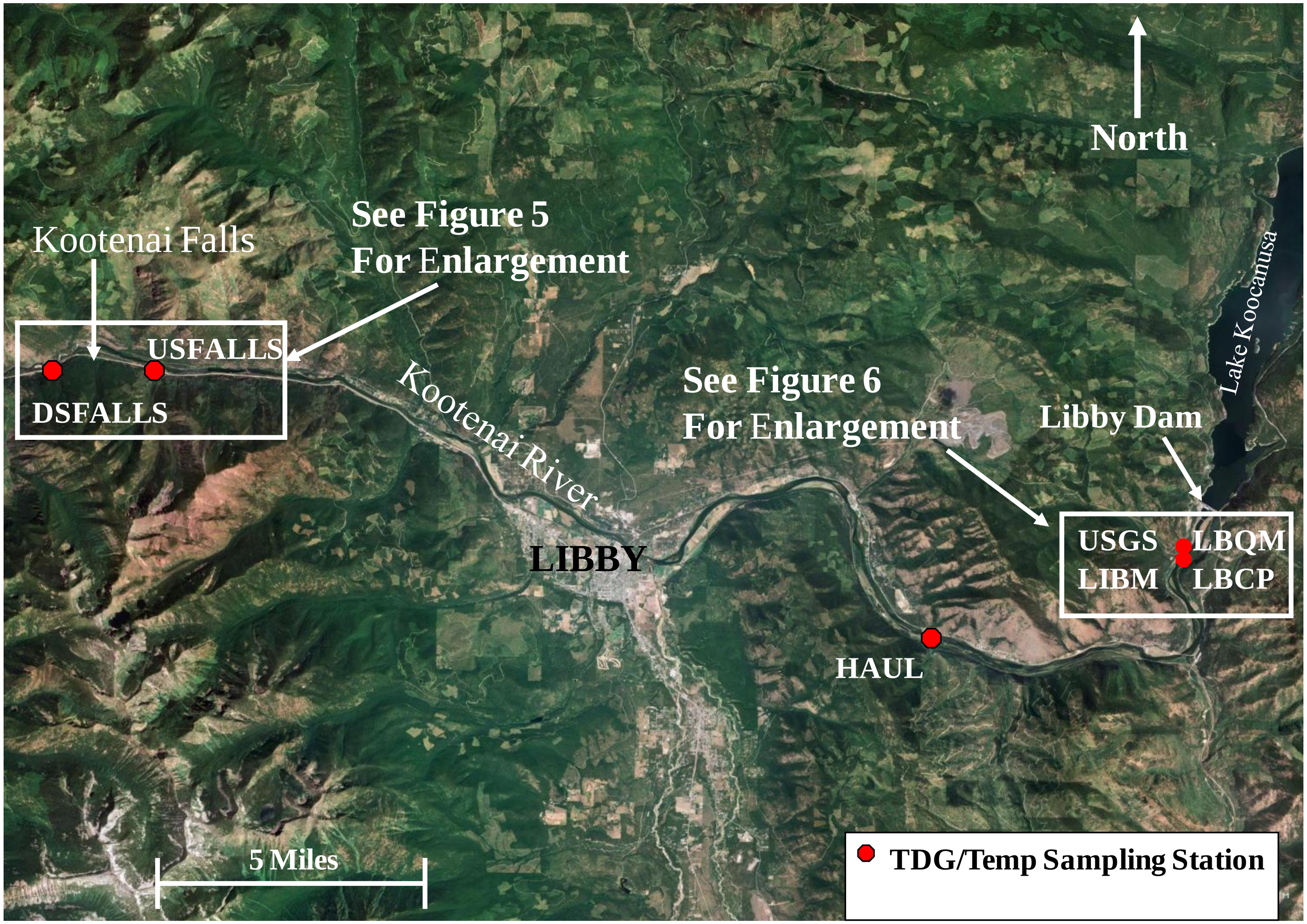

Figure 4. TDG and temperature monitoring stations downstream of Libby Dam to Kootenai Falls.

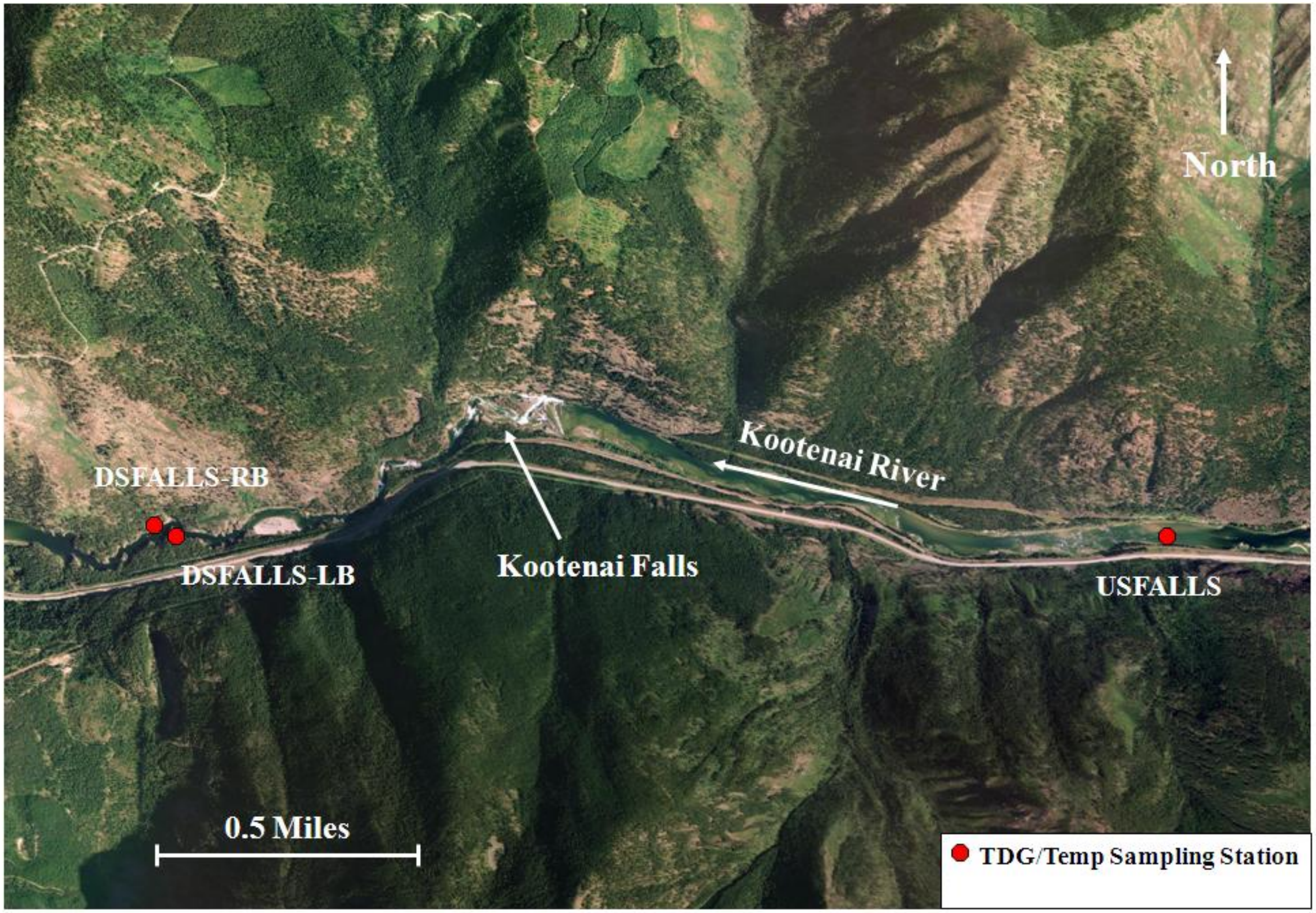

Figure 5. TDG and temperature monitoring stations upstream and downstream of Kootenai Falls.

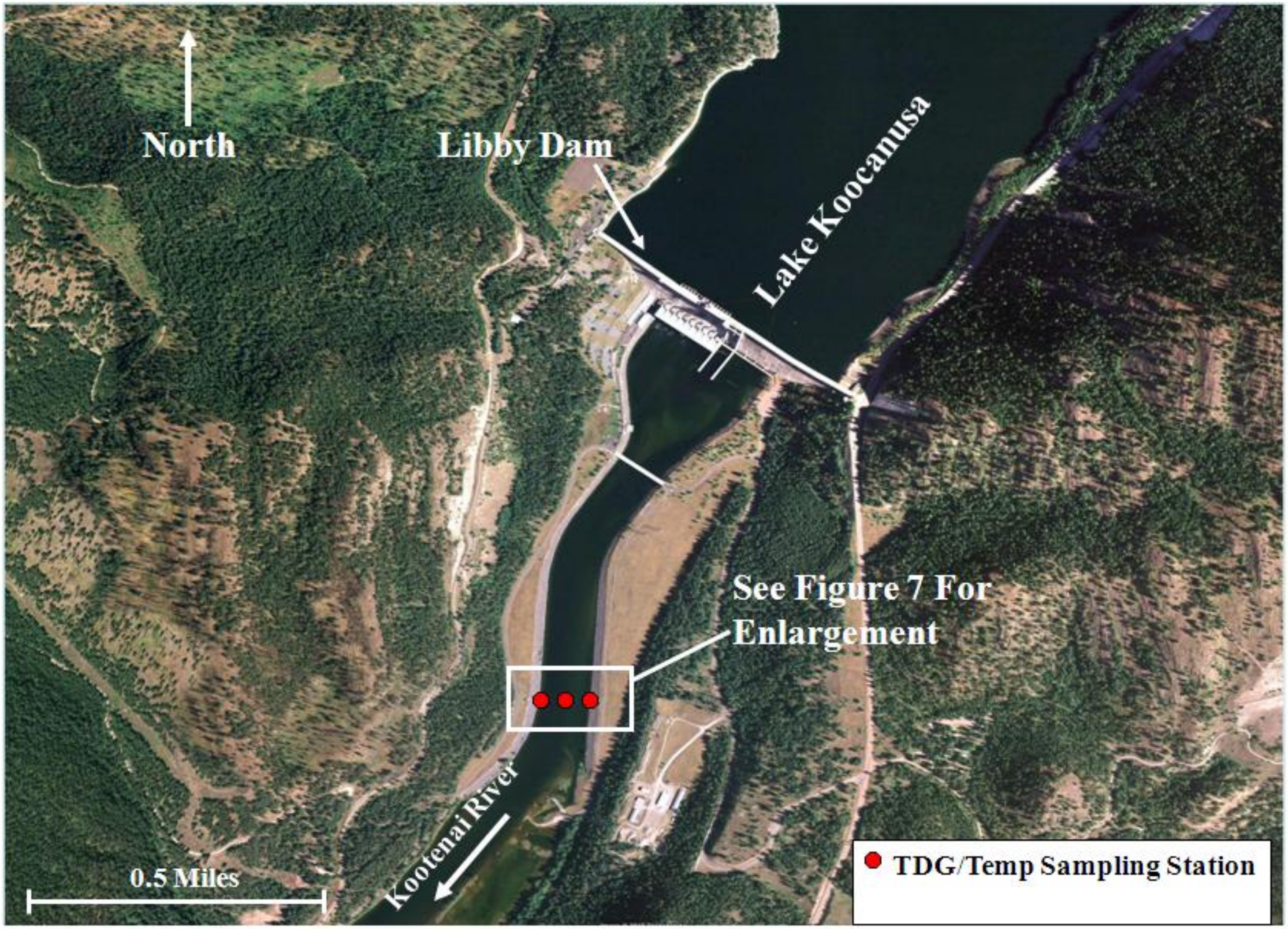

Figure 6. TDG and temperature monitoring stations below Libby Dam.

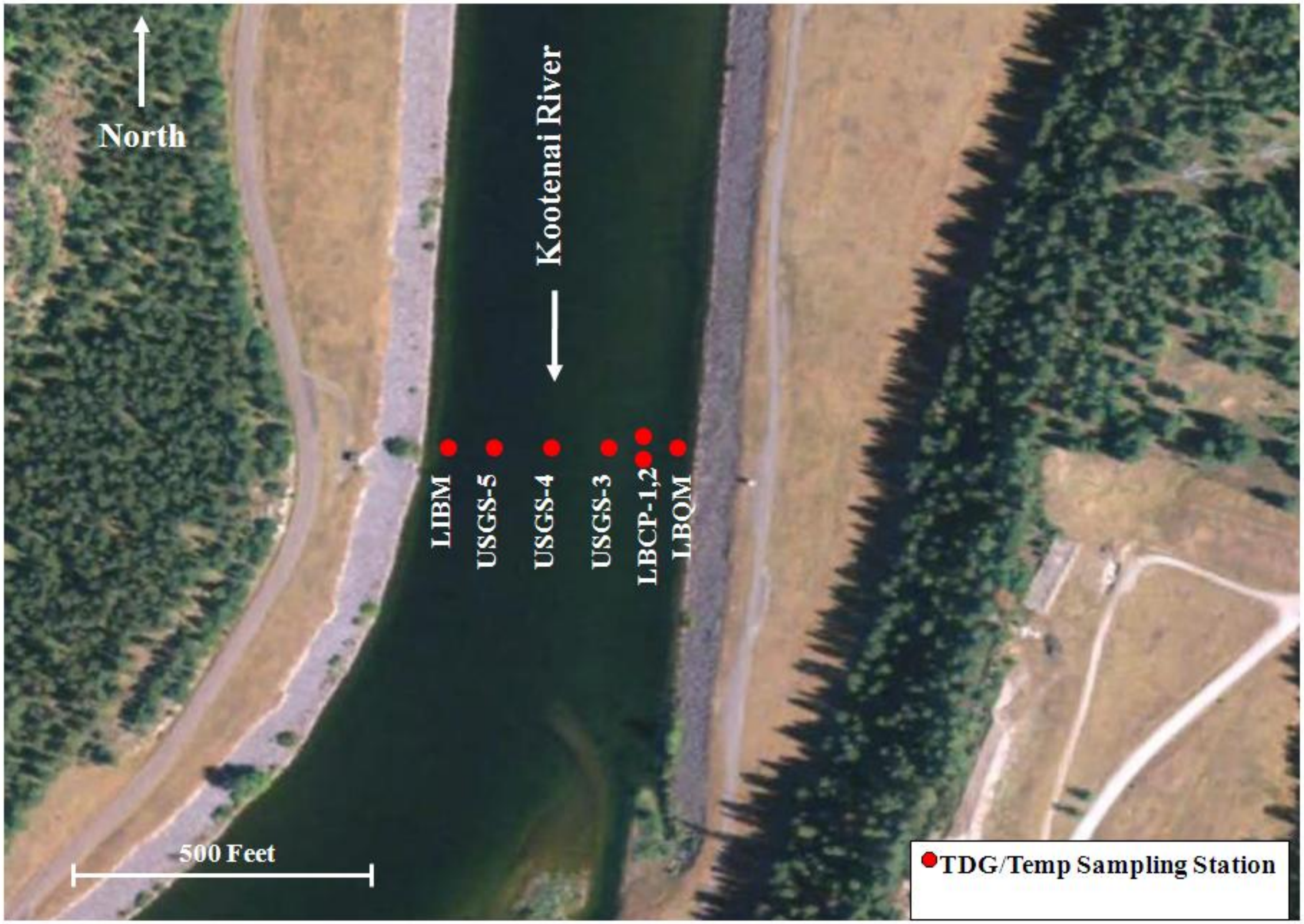

Figure 7. TDG and temperature monitoring stations at the USGS gauging station.

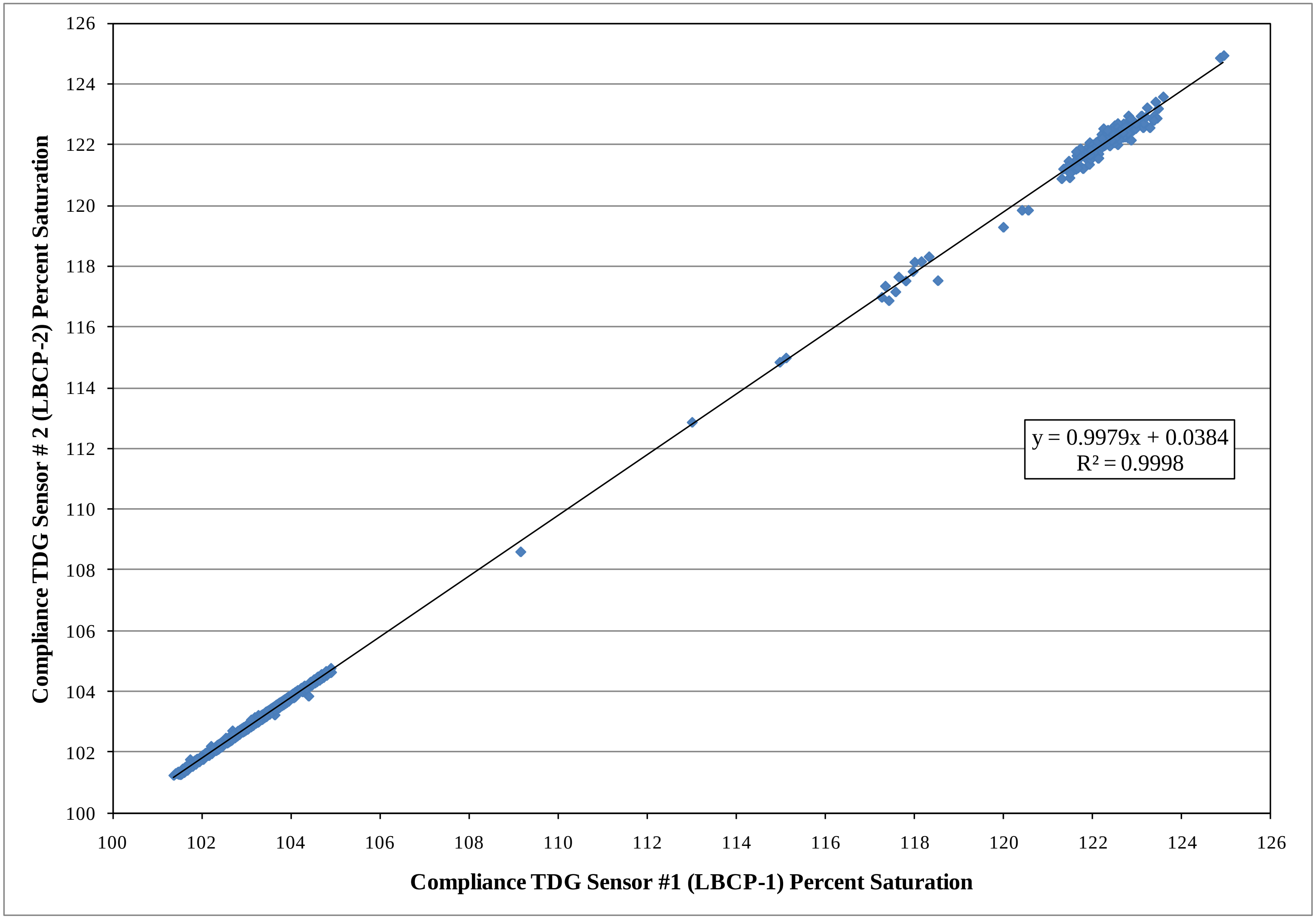

Figure 8. Comparison of TDG measured by LBCP-1 and LBCP-2.

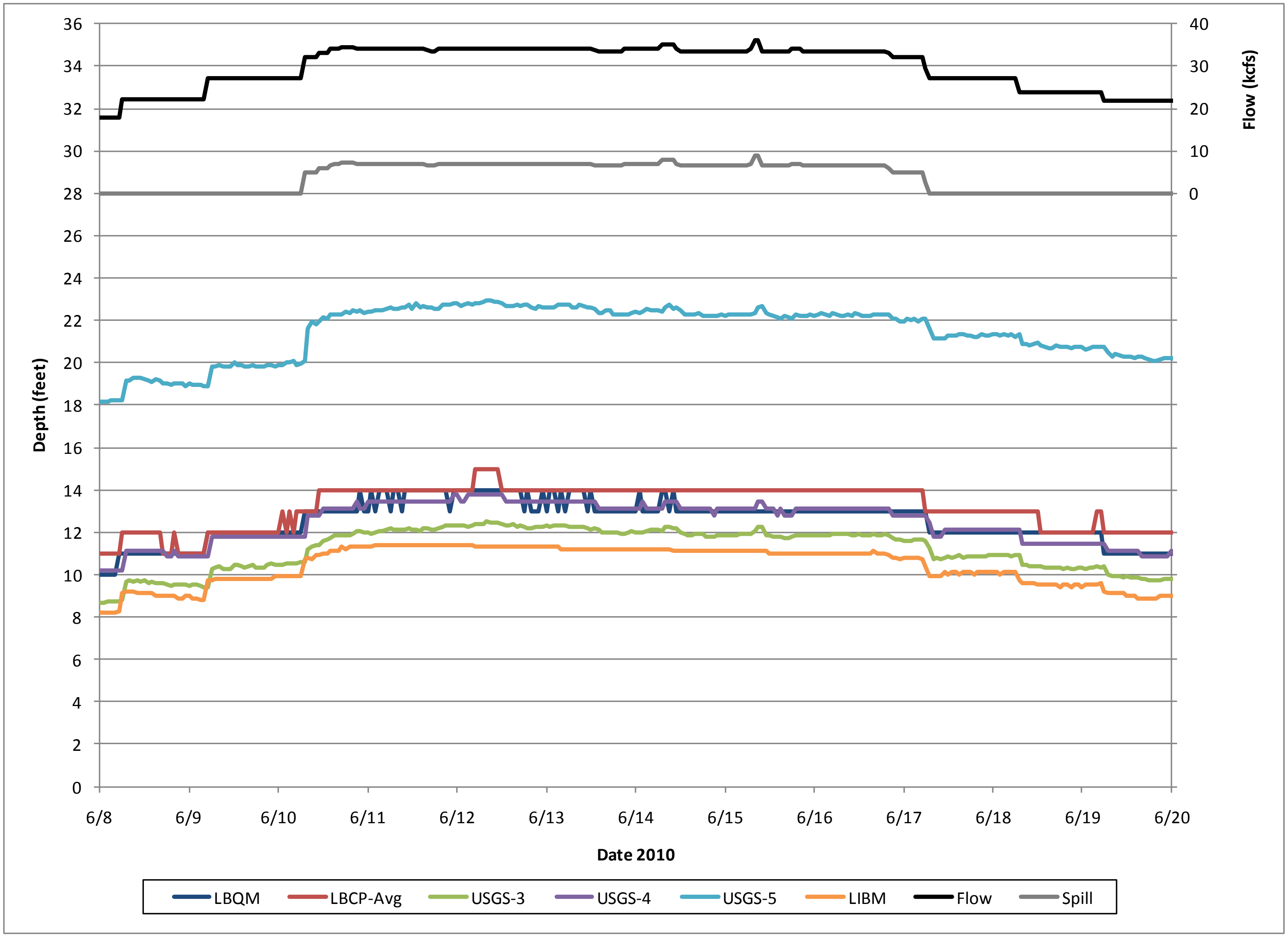

Figure 9. Water quality instrument depths at the USGS tailwater gage during spillway operations.

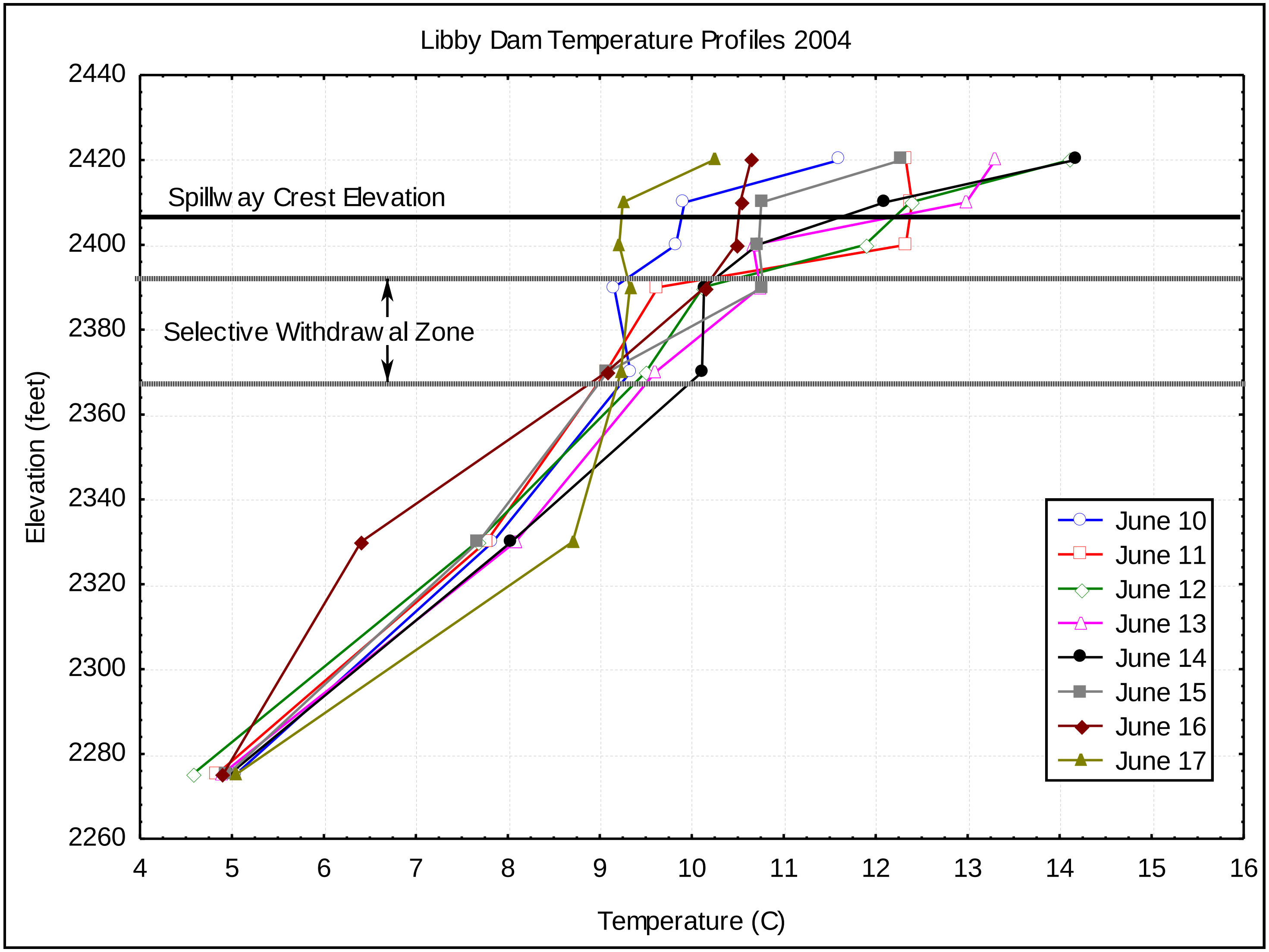

Figure 10. Libby Dam forebay temperature profiles during the spill test, June 10 – 17, 2010.

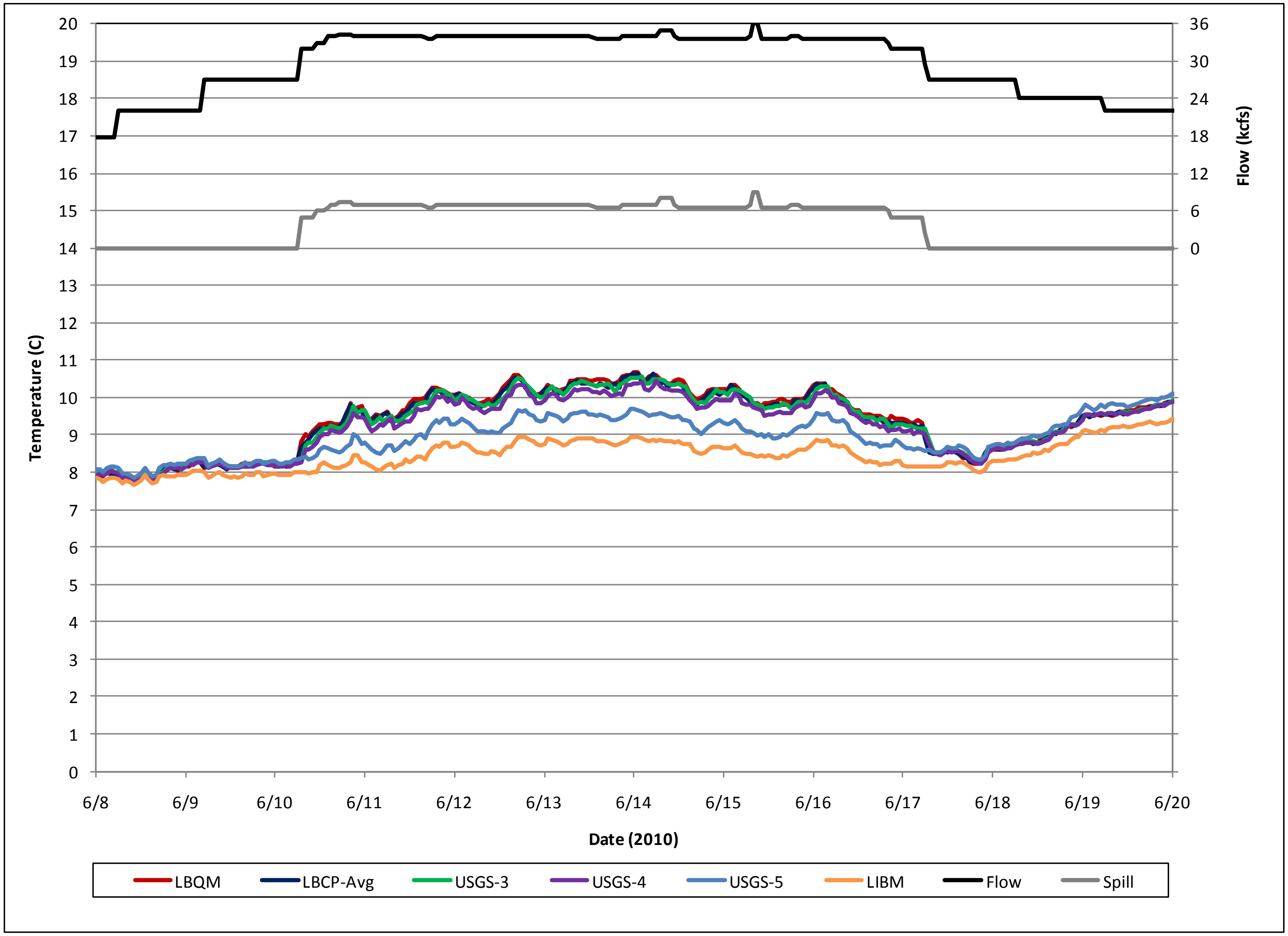

Figure 11. Time history of Kootenai River temperatures at the USGS tailwater gage.

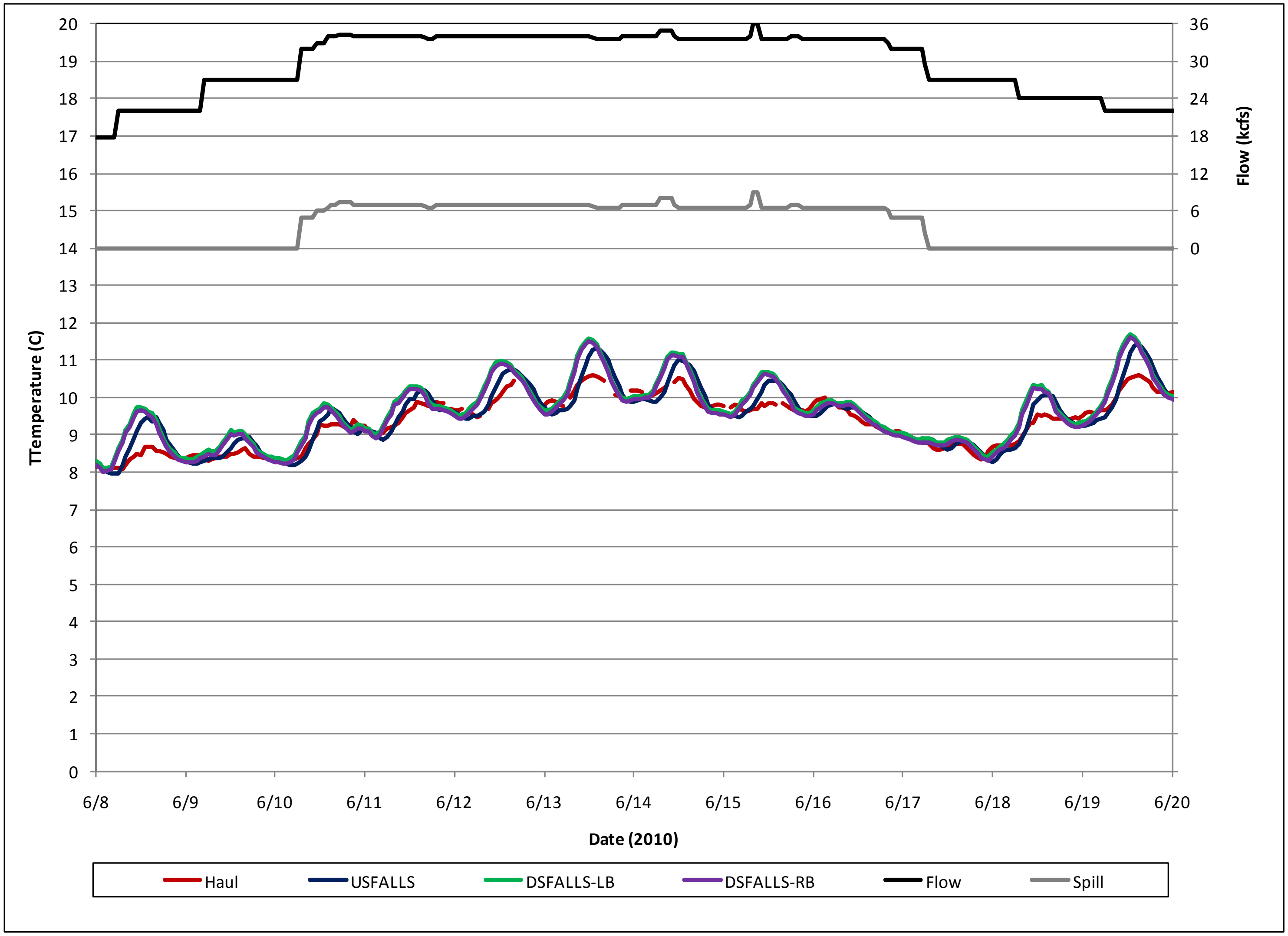

Figure 12. Time history of Kootenai River temperatures downstream of Libby Dam from the Haul Bridge station to downstream of Kootenai Falls.

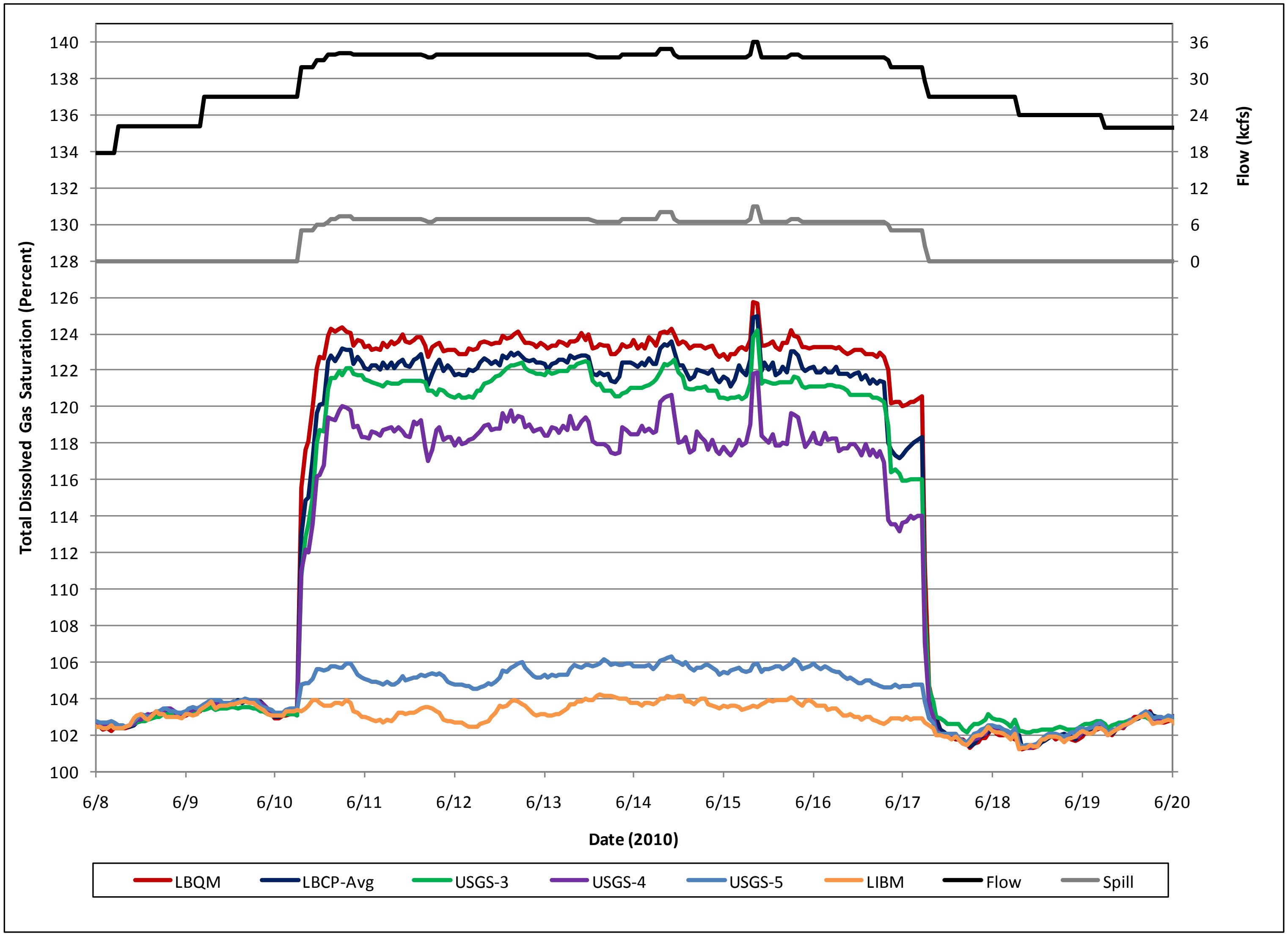

Figure 13. Time history of Kootenai River TDG saturations at the USGS tailwater gage.

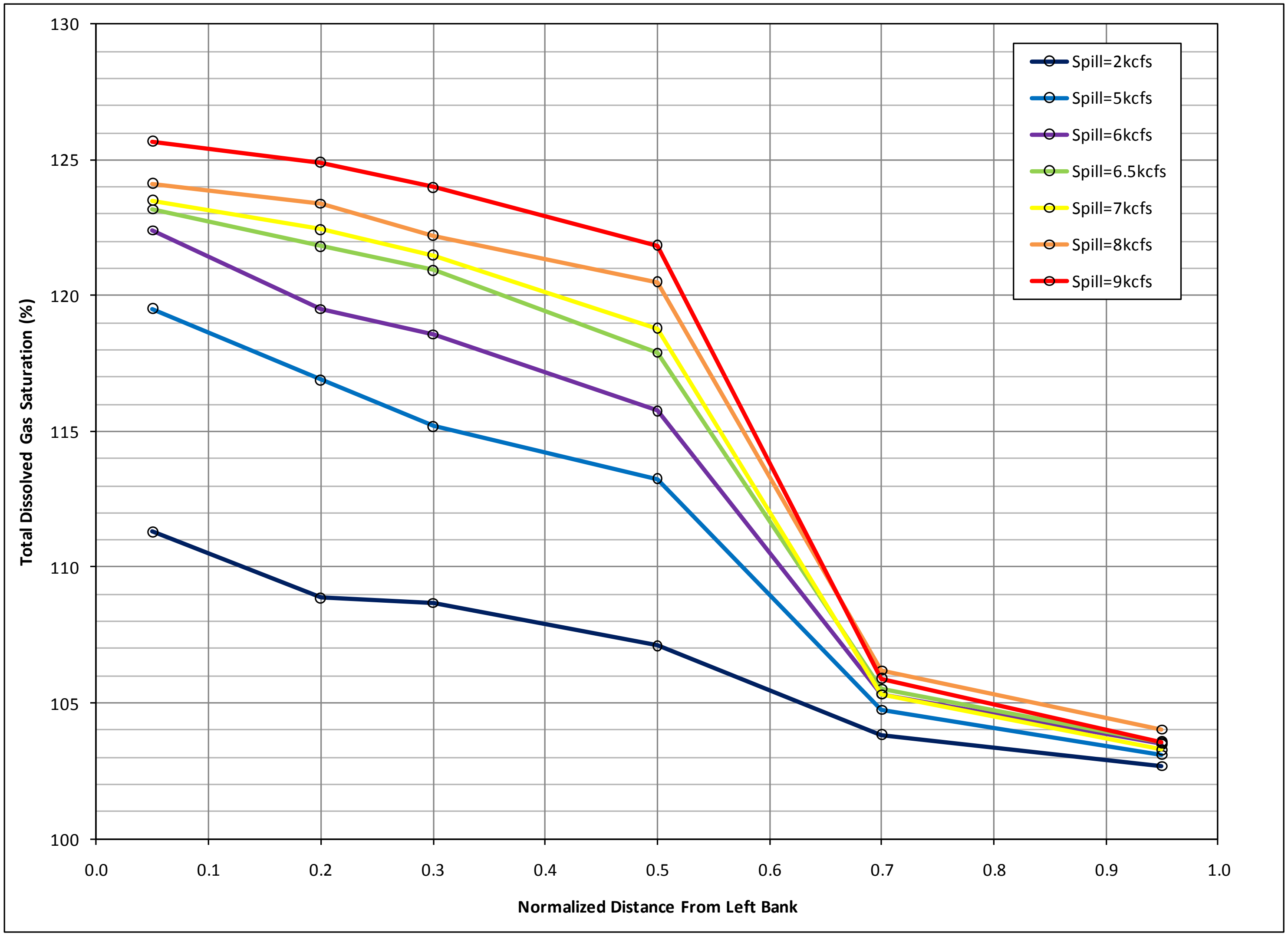

Figure 14. Lateral median TDG saturations along a transect at the USGS tailwater gage for spill discharges of 2, 5, 6, 6.5, 7, 8, and 9 kcfs .

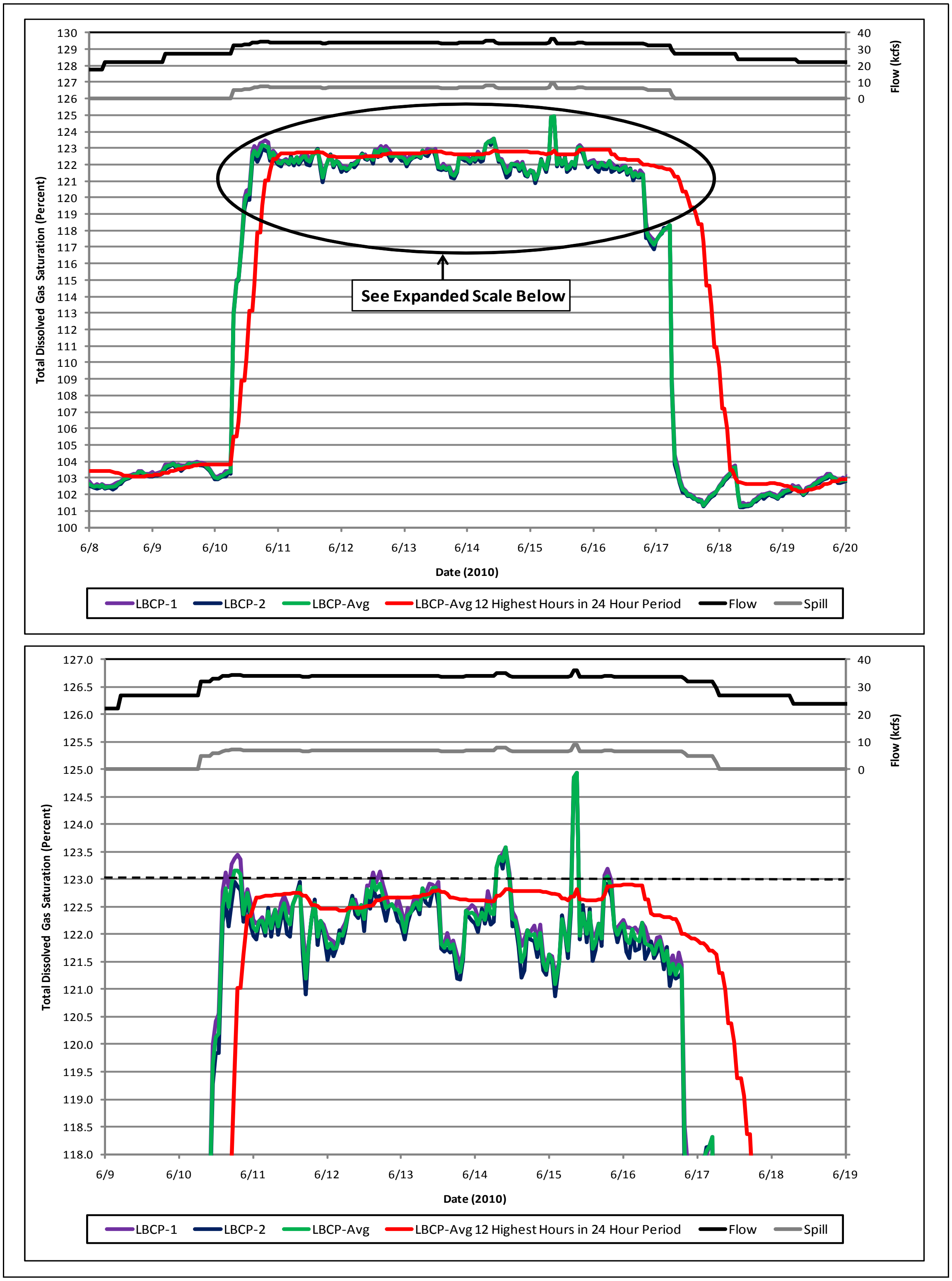

Figure 15. Time history of Kootenai River TDG saturations at the compliance station (top panel) and with an expanded scale (bottom panel) showing that compliance station TDG, as measured by the 12 highest hours in a 24 hour period, did not exceed 123 percent.

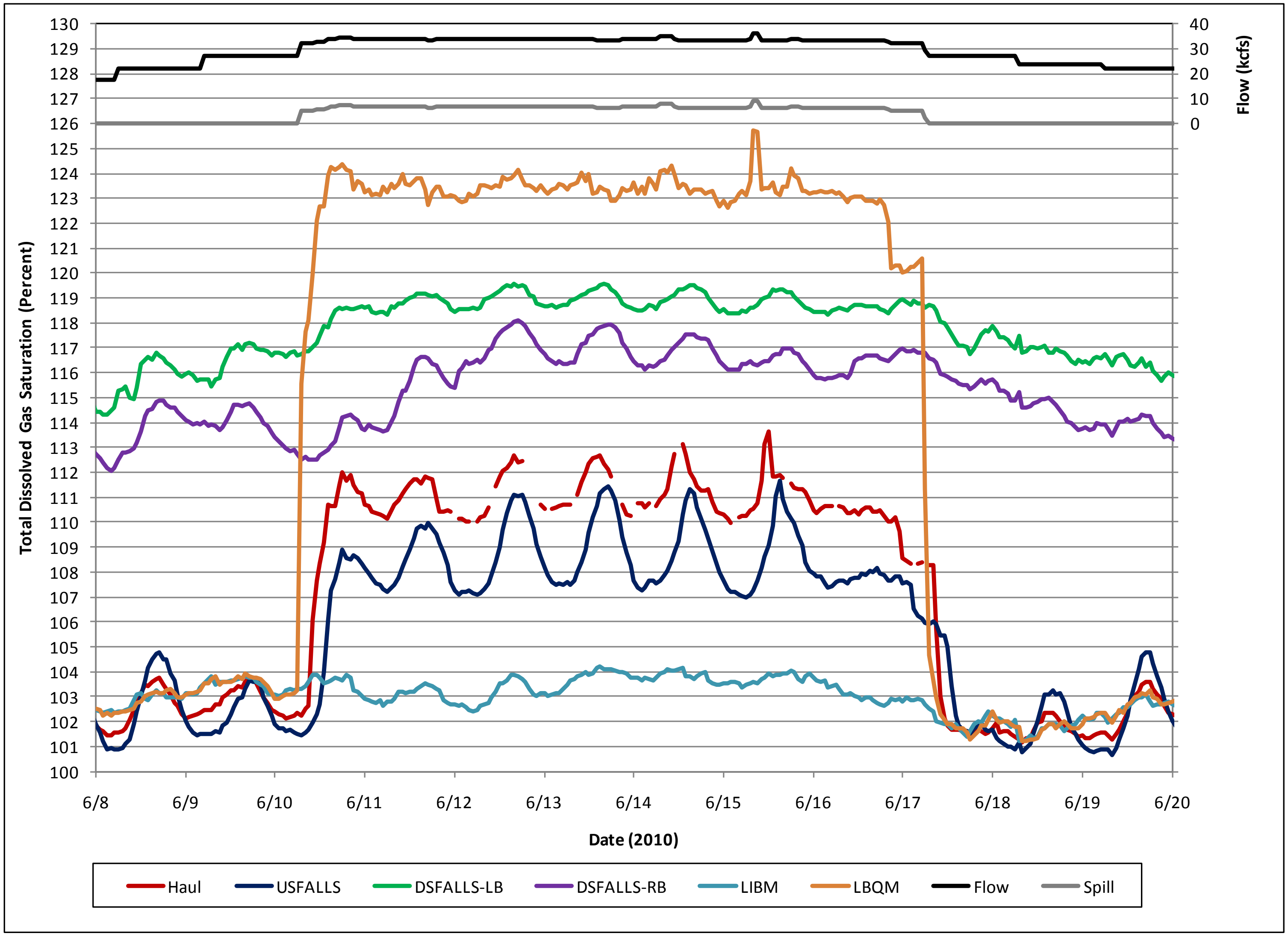

Figure 16. Time history of Kootenai River TDG saturations as measured downstream of Libby Dam from the USGS tailwater (stations LIBM and LBQM) to downstream of Kootenai Falls.