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Libby Dam 2011 Sluiceway Release Study: Total Dissolved Gas and Temperature Monitoring

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Introduction

A substantially higher than normal snowpack in the Kootenai River watershed in water year 2011 necessitated drawing down the Koocanusa Reservoir to below 2,350 feet in elevation, more than 100 feet below full pool elevation (2,459 feet), to provide increased storage space for expected higher than normal runoff. In order to provide the increased water storage space, the Seattle District Army Corps of Engineers (Seattle District) increased releases from Libby Dam by discharging an additional 5 thousand cubic feet per second (kcfs) through the dam's sluice gates from April 30 to May 9, 2011. Powerhouse flows ranged from 16.3 kcfs to 20 kcfs for a total discharge ranging from 21.3 kcfs to 25 kcfs.

Total dissolved gas (TDG) supersaturation is generated by spilling water from the spillway and sluiceway 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 from spillway releases was conducted in 2002 and 2010 (Schneider, 2003; USACE 2011). These investigations determined that the TDG exchange in spillway flows ranged from about 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 and 2010. 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.

Little information exists on TDG saturations resulting from sluiceway releases at Libby Dam. TDG studies were conducted from 1972 – 1975 during a period of time when the powerhouse was not yet operating and all project regulation was accomplished with releases through the sluiceways (Battelle 1974; Graham 1979). The TDG saturation resulting from sluiceway releases measured during 1972-1975 ranged from 128-150 percent, with an average value of 138 percent. Since power generation came online at Libby Dam in 1975, the sluiceways have seen infrequent use.

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.

Purpose and Objectives

Montana's state water quality standard for TDG is 110 percent saturation. The purpose of this study was to more clearly understand total dissolved gas exchange processes and thermal properties associated with sluiceway operations at Libby Dam and the resultant transport and mixing in the Kootenai River below the project. In particular, this study focused on measuring the lateral gradient of TDG saturations and temperatures present in the Kootenai River at the David Thompson Bridge about 0.3 miles downstream of the dam, the site of TDG studies during the 1970s and at the USGS tailwater gage about 0.6 miles downstream, the site of the existing water quality compliance point. The major objectives of this study were:

- To monitor TDG saturations at the existing compliance point location
- To study the lateral mixing of sluiceway releases and powerhouse water in the Kootenai River immediately downstream of Libby Dam
- To study TDG exchange and mixing properties in the Kootenai River downstream of Libby Dam.
- To monitor TDG saturations under various sluiceway release patterns to better understand TDG exchange in sluiceway releases.

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 sluiceway operations.

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, with the powerhouse becoming operational in 1975. Libby dam has three sluices that are individually regulated by 10-foot-wide by 17-foot-high hydraulically operated tainter gates. The sluices have an intake invert at elevation 2,201.5 feet and empty into the spillway stilling basin. 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).

Sluiceway Operations

Discharges through sluiceways at Libby Dam have historically created elevated total dissolved gas levels in the Kootenai River below the dam. Before power generation came online, all day-to-day regulation of the project was accomplished with releases through the sluiceways. Sluiceway TDG saturations were measured about 0.3 miles downstream of Libby Dam at the David Thompson Bridge during 1972-1975 (Battelle 1974; Graham 1979). Sluiceway discharge during this period ranged from 3 to 35 kcfs. TDG below the dam during sluiceway operation ranged from 128-145 percent, with an average value of 138 percent. During the period these readings were taken, discharges would have been entirely from the sluiceways since the powerhouse was not yet online, and a lateral TDG gradient as seen presently with combined powerhouse and spillway operation would not have been present. Since power generation came online at Libby Dam in 1975, the sluiceways have seen infrequent use.

The Libby Dam sluiceways operate with an open channel flow regime downstream of the service gates. The high velocity open channel flow regime and the resulting turbulent flow provide the

opportunity for air to be entrained in the sluiceway flow. In addition, aerators, intended to mitigate cavitation issues, also add to air entrainment in sluiceway flows. In the past, cavitation near the sluiceway service gates has caused damage to sluiceway floor surfaces. The dynamic effects of water flowing over a surface discontinuity (a step, surface roughness, etc.) at high velocities can cause the pressure in localized areas of the flow to fall to the vapor pressure of water for the given temperature of the flow. Vapor cavities can occur in these areas, and when transported to higher-pressure areas, these cavities collapse. This collapsing of vapor cavities can in turn damage adjacent surfaces. In the case of the Libby Dam sluiceways, this problem was addressed by adding aeration slots to the sluiceway invert, which are vented to the atmosphere (McGee 1984). This venting to the atmosphere inhibits the formation of vapor cavities in the vicinity of the aeration slot, and thus helps mitigate cavitation damage.

In general, the use of the sluiceways will contribute cold water to powerhouse releases because the sluices have an intake invert elevation of 2201.5 feet, about 257 feet below full pool elevation of 2459 feet. Water temperatures at the elevation of the sluices generally range from about 4 to 6 degrees Celsius. To control powerhouse release temperatures to the river below the project, Libby Dam was designed with a selective withdrawal system to withdraw water from various reservoir elevations during power operations. The selective withdrawal system consists of 14 vertical slots, each with 22 ten-foot-high gates or bulkheads that extends about 250 feet below full pool, from elevation 2459 feet down to elevation 2209 feet. The effectiveness of the selective withdrawal system is largely dependent on the vertical temperature gradient present in the forebay. Typically, during the May-June timeframe, the sluiceways withdraw cold water from deep in the pool, while the powerhouse releases warmer water from higher in the pool via the selective withdrawal structure. Under a combination powerhouse and sluiceway flow scenario, lateral temperature gradients may persist for some distance downstream of the project, as the mixing zone between powerhouse and sluiceway flows develops, similar to the TDG saturation gradient seen presently with spillway and powerhouse flows.

Study Approach

An array of six (6) instruments, consisting of five (5) data loggers and one (1) real-time instrument, were deployed in the Kootenai River to measure lateral and longitudinal TDG saturations and temperatures in the Kootenai River generated by Libby Dam powerhouse and sluiceway operations. The general locations of these water quality monitoring stations are shown in Figures 3 and 4, and a description of each station is presented in Table 1. Data were collected by the water quality instrumentation at either 30 minute intervals (data loggers) or 60 minute intervals (real-time instrument) 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.

One real-time instrument (LBQM) was deployed in the Kootenai River 0.6 miles downstream of Libby Dam at the USGS gage as shown in Figure 4. 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. This real-time station was installed in late March 2011 and was operation during the entire sluiceway releases. Five data loggers (TMSNP-1, TMSNP-2, TMSNP-3, LBCP, and HAUL) were deployed in the Kootenai River for the study on May 3, 2011 about 3 days after sluiceway releases began. Three of these data loggers (TMSNP-1, TMSNP-2, TMSNP-3) were deployed in the Kootenai River about 0.3 miles downstream of Libby Dam at the David Thompson Bridge as outlined in Table 1 and shown in Figure 3. These instruments were deployed along a transect to monitor the lateral mixing between spillway and powerhouse flows at the David Thompson Bridge. The sampling stations were skewed towards the left bank to best capture the maximum TDG saturations in sluiceway flows. These stations were positioned in a transect representing 5, 20, and 40 percent normalized distance from the left bank (Figure 4 and Table 1). Station LBCP was the location of the official compliance monitoring station for Libby Dam during the 2010 spill test. It was located at the USGS gage and was positioned off of the left bank at a location representing about 20% normalized distance from the left bank (Figure 4).

The remaining sampling station (HAUL) was located about 8.6 miles downstream of the project to measure the TDG pressures in the Kootenai River under open-channel flow conditions (Figure 4). The HAUL instrument was located off of the right bank about 8.6 miles downstream in the Kootenai River at the constriction of the river at an old haul bridge site. 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. The cables were then attached to shore to prevent the loss of the housing and instrument. The real-time instrument was deployed using slightly different techniques. 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 Sutron 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 2011* (USACE 2010). 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 TDG saturations of 100 percent, 113 percent,

126 percent, and 140 percent. If any measurement differed by more than 0.5 percent saturation from the primary standard, the sensor was adjusted and rechecked over the full calibration range. All calibrations were within 0 to 0.5 percent saturation.

Laboratory calibrations of the water quality probe's temperature sensor were performed using a NIST traceable thermometer. If the measurements differed by more than 0.2°C, the probe was not used. All calibrations were within 0.2°C for temperature.

Once the 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 all other data were acceptable and were used in this report.

Problems with receiving real-time hourly TDG, temperature and barometric data were encountered at station LBQM on May 5th from 0900 to 1500 hours. The missing data for station LBQM was due to DCP malfunctions and programming problems. No data were missing for TDG logger stations TMSNP 1-3, LBCP, and HAUL. However, the missing barometric pressure data at station LBQM resulted in an inability to calculate TDG saturations at all logger stations on May 5th from 0900 to 1500 hours.

Results and Discussion

Project Operations

Sluiceway releases were conducted from April 30th to May 9th, 2011. A total of seven (7) events were classified during sluiceway operations in 2011 (Table 2). Each event represents a unique set of sluiceway release, powerhouse release, or unit sluice discharge conditions. Events 1 and 7 represent pre and post conditions with no sluiceway release, while events 2 through 6 represent different powerhouse and sluiceway discharge combinations as well as changes in the number of sluices used (Table 2). For the entire operation, total sluice discharge ranged from 4.3 to 5.0 kcfs, number of sluices used ranged from 2 to 3, unit sluice discharge ranged from 1.67 to 2.5 kcfs, and powerhouse discharge ranged from 16.3 kcfs to 20.0 kcfs. Sluiceway releases were passed through two sluices from April 30th to May 6th and through 3 sluices from May 6th to May 9th. In general, sluiceway releases were held constant at 5 kcfs during the entire operation except for the 24 hour period from 1400 May 5 to 1400 May 6, 2011 when releases were reduced to 4.3 kcfs.

The forebay surface elevation ranged from about 2,350 ft on April 30th to 2,338 ft on May 9th, with a relatively constant decrease of about 1 foot per day. The selective withdrawal system was maintained at elevation 2,295 ft resulting in a constant elevation for powerhouse releases. The tailwater elevation varied little during this time period and ranged only about 1 to 2 feet during sluiceway discharges, resulting in relatively constant depths for the water quality probes located at the David Thompson Bridge and the USGS gage. The depths of all probes were maintained at a depth greater than the compensation depth for TDG saturations greater than 135 percent (i.e. about 10.5 feet). 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 water temperatures associated with sluiceway operations were similar at all stations except station HAUL during the study (Figure 5). Lake Koocanusa was well mixed during the sluiceway releases, with only minor differences in temperatures between the lake's surface and bottom. Forebay temperature profiles from April 30th through May 9th at 1600 hours show that near surface waters at elevation 2330 feet experienced a small increase in temperatures during this time period, but waters below about 2300 feet remained isothermal and warmed only slightly from about 3.5 to 4.5° C (Figure 6). Water temperatures in the Kootenai River immediately below Libby Dam ranged from about 3.5 to 5.0º C with a warming trend measured from April 30th through May 12th. Lateral water temperature gradients were minor in the Kootenai River at the David Thompson Bridge due to the combined sluiceway and powerhouse releases (Figure 5), largely because there was little temperature variation between the depth of powerhouse releases (2295 ft.) and sluiceway releases (2201.5 ft.) (Figure 6). Temperatures measured downstream at station HAUL showed greater diurnal variation and ranged from about 4º C to 6º C, reflecting the greater influence of atmospheric heat exchange in warming the Kootenai River downstream

of the dam. During the nighttime the change in water temperature between Libby Dam and the HAUL was small, as seen by similar temperatures at all stations. However, during the day, the Kootenai River temperatures increased by about 1°C at the HAUL station (Figure 5).

TDG Saturations

Total dissolved gas levels presented in the following sections are reported as either TDG pressure in millimeters (mm) Hg or as TDG saturation (percent). Water quality monitoring stations providing information on nearfield and compliance TDG processes were stations TMSPN 1-3, LBQM and LBCP (see Figure 4). The HAUL station provides information on downstream TDG processes (see Figure 4).

Nearfield and Compliance Stations

TDG saturations and pressures measured along a transect at the David Thompson Bridge showed the development of lateral gradients in TDG between sluice flows along the left bank and powerhouse flows along the right bank (Figure 7). For the entire sluiceway operation, the median TDG saturations measured at the David Thompson Bridge ranged from 131.2 to 136.4 percent at the 5 percent normalized distance from the left bank (TMSPN-1) and from 127.1 to 133 percent at the 40% distance (TMSPN-3), with a maximum TDG saturation at stations TMSPN-1 and TMSPN-3 of 138.1 and 134.2 percent, respectively (Table 3). For events 1 and 7 (pre and post sluice flows), median TDG saturations measured from powerhouse flows ranged from 100.7 to 103.1 percent and are likely representative of powerhouse TDG saturations during sluiceway releases (Figure 8 and Table 3). For events 2 through 6, TDG saturations were greatest when powerhouse discharges were lowest and sluiceway releases were highest (i.e. events 2 and 3). For example, on May 4th at 1000 hours when powerhouse discharge increased from 16.3 kcfs to 19.3 kcfs and sluiceway flows were held constant at 5 kcfs, median and maximum TDG saturations measured along a transect at the David Thompson Bridge (TMSPN 1-3) decreased by about 2 percent (Figure 8 and Table 3).

The David Thompson Bridge data clearly showed the development of lateral gradients in TDG saturations during sluiceway releases, with higher TDG saturations extending farther across the river during sluiceway releases with lower powerhouse discharges (Figure 9). The maximum TDG was consistently observed along the left bank with some mixing between spillway and powerhouse flows measured on the left bank at the David Thompson Bridge at station TMSPM-1. Elevated TDG saturations extended across at least 40 percent of the Kootenai River which is similar to results from the 2002 and 2010 spill tests for spillway releases (Schneider 2003, USACE 2011). The 2002 and 2010 TDG saturation data collected along the transect at the USGS tailwater gage (located about 0.3 miles downstream of the David Thompson Bridge) indicated that the unit spillway discharge was the most important causal parameter in determining the TDG exchange in spillway flows at Libby Dam. Because sluiceway operations were held constant from 4.3 to 5.0 kcfs, determining a meaningful relationship between sluiceway discharge and TDG saturation was difficult. However, decreases in TDG saturations were measured during events 5 and 6 (Figure 9). Event 5 represents a decrease in sluiceway releases from 5.0 to 4.3 kcfs, which corresponds to a decrease in unit sluice discharge from 2.5 to 2.15 kcfs, with an increase in powerhouse flow from 19.3 to 20.0 kcfs. Event 6 represents an

increase in sluiceway releases from 4.3 to 5.0 kcfs but a change in operation from 2 sluices to 3 sluices, which corresponds to a decrease in unit sluice discharge from 2.15 to 1.67 kcfs. The lower TDG saturations during events 5 and 6 suggest that both unit sluice discharge and powerhouse discharge are important in determining downstream TDG saturations from sluiceway releases.

The TDG pressure response at the David Thompson Bridge Stations TMPSN 1-3 to a sluiceway discharge of 5 kcfs at Libby Dam were slightly less than the response measured at the same location during sluiceway releases from 1972-1975 (Battelle 1974; Graham 1979). TDG below the dam from 1972-1975 during sluiceway discharges of about 5 kcfs ranged from 128-145 percent, with an average value of 138 percent. During the 2011 operations, the median TDG saturations measured at the David Thompson Bridge ranged from 129.5 to 132.8 percent, with a maximum TDG saturation range of 135.3 to 138.1 percent (Table 3). The lower TDG saturations measured in 2011are likely due to the powerhouse being offline during the 1972-1975 sluiceway operations. The mixing of powerhouse and sluiceway flows, and the formation of a lateral TDG gradient seen in 2011 would not have been present in 1972-1975.

TDG saturations measured at the fixed monitoring station LBQM and the compliance station LBCP are shown in Figure 10 and Table 3. Both stations are located on a transect at the USGS gage about 0.3 miles downstream of the David Thompson Bridge. Median TDG saturations at LBQM and LBCP ranged from 128.3 to 134.3 percent and 125.9 to 131.7 percent, respectively. Maximum TDG saturations at LBQM and LBCP ranged from 131.3 to 137.2 percent and 128.1 to 132.6 percent, respectively. Similar to the David Thompson Bridge stations, TDG saturations were greatest during events 2 and 3 when powerhouse discharges were lowest and sluiceway releases were greatest. The TDG saturation at LBQM (5 percent distance from left bank) was consistently about 2 to 3 percent greater than at LBCP (20 percent distance from left bank) which was similar to the relationship measured during spillway releases in 2010 (USACE 2011). In addition, the TDG saturations at LBQM and LBCP on the left bank at the USGS station were consistently lower than saturations measured upstream at TMPSN-1 (5 percent distance from left bank) and TMPSN-2 (20 percent distance from left bank) by about 2 to 3 percent during the entire study (Figure 10). The lower TDG saturations on the left bank downstream of the David Thompson Bridge are likely due to the continued development of a mixing zone between the lower TDG powerhouse waters and the higher TDG sluiceway waters.

3 Sluice vs. 2 Sluice Operations

A statistical summary of the TDG pressure and saturation during sluiceway operations at all stations is listed in Table 3. Project operations are shown in Table 2. The initial sluiceway discharge of 5 kcfs from 2 sluices with powerhouse flows of 16.3 to 16.6 kcfs during events 2 and 3 resulted in an abrupt increase in TDG saturations that approached an upper limit of about 138.1 percent as observed at station TMPSN-1 (Figure 9). The increase in powerhouse flows to 19.3 kcfs on May 4 at 1000 (event 4) while sluiceway releases remained constant at 5 kcfs reduced median TDG saturations by about 2 percent at TMPSN-1. The reduction in sluiceway releases from 5 kcfs to 4.3 kcfs on May 5 at 1400 (event 5) with a corresponding increase in powerhouse flows from 19.3 kcfs to 20.0 kcfs resulted in a further reduction in median TDG saturations by about 3 percent at TMPSN-1. On May 6 at 1400 (event 6) sluiceway releases

were increased from 4.3 to 5 kcfs and flow was distributed from 3 sluices while powerhouse flows remained constant at 20.0kcfs. TDG saturations remained relatively constant even though sluiceway flows were increased and powerhouse flows remained constant.

The impact of releasing sluiceway flows via 2 sluices versus 3 sluices can be assessed by comparing TDG saturations generated during these two operations for events with similar powerhouse flows which are events 4 and 6. For event 4, from May 4 at 1000 to May 5 at 1300 sluiceway releases were 5 kcfs from 2 sluices with 19.3 kcfs powerhouse discharge. For event 6, from May 6 at 1400 to May 9 at 0900 sluiceway releases were 5 kcfs from 3 sluices with 20.0 kcfs powerhouse discharge. These two operations are similar except for the use of 2 sluices versus 3 sluices. The median TDG saturation at station TMPSN-1for event 6 was about 2 percent lower than for the similar 2 sluice operation during event 4 (Figure 9). Similar TDG reductions were also measured at stations TMPSN-2, TMPSN-3, LBQM, and LBCP (Table 2).

The lower TDG saturations observed at stations TMPSN 1-3, LBQM and LBCP for a sluiceway discharge of 5 kcfs from 3 sluices (1.67 kcfs per sluice) during event 6 versus 2 sluices (2.5 kcfs per sluice) with similar powerhouse flows (19.3 to 20.0 kcfs) during event 4, suggests that at Libby Dam the unit sluice discharge is an important causal parameter in determining TDG pressures in sluiceway flows. Similar results were determined for spillway operations at Chief Joseph Dam (Schneider and Carroll 1999) and Libby Dam (Schneider 2003). These data suggest that modest TDG reductions during sluiceway operations may be possible by using 3 sluices to reduce the unit sluice discharge.

Downstream Kootenai River

In-river processes were monitored in the Kootenai River at a distance of about 8.6 miles (station HAUL) 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. 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).

Downstream mixed river TDG saturations measured at station HAUL were substantially less than nearfield TDG saturations measured at the David Thompson Bridge and USGS stations (Figure 10). TDG saturations measured at the HAUL station remained less than 115 percent during sluiceway operations. The median downstream TDG saturations measured during sluiceway operations ranged from 110.3 percent to 111.4 percent, with maximum TDG saturations ranging from 111.4 to 113.7 percent (Table 3). In general, the highest TDG saturations were measured during project operations with the greatest sluiceway discharge and lowest powerhouse discharge. Diurnal variations in TDG saturations were more pronounced at the HAUL station compared to the nearfield and compliance stations located immediately downstream of Libby Dam (Figure 10).

Conclusions

- The initial sluiceway discharge of 5 kcfs from 2 sluices with powerhouse flows of 16.3 to 16.6 kcfs during events 2 and 3 resulted in an abrupt increase in TDG saturations that approached an upper limit of about 138.1 percent as observed at station TMPSN-1. For the entire sluiceway operation, the median TDG saturations measured at the David Thompson Bridge ranged from 127.1 to 136.4 percent, with a maximum TDG saturation of 138.1 percent.

- The TDG saturations measured along a transect at the David Thompson Bridge showed the development of lateral gradients in TDG between sluiceway flows along the left bank and powerhouse flows along the right bank, with higher TDG saturations extending farther across the river during sluiceway releases with lower powerhouse discharges.

- The lower TDG saturations observed for a sluiceway discharge of 5 kcfs from 3 sluices (1.67 kcfs per sluice) versus 2 sluices (2.5 kcfs per sluice) with similar powerhouse flows suggests that at Libby Dam the unit sluice discharge is an important causal parameter in determining TDG pressures in sluiceway flows. These data suggest that modest TDG reductions during sluiceway operations may be possible by using 3 sluices versus 2 sluices.

- The TDG pressure response at the David Thompson Bridge to a sluiceway discharge of 5 kcfs at Libby Dam were slightly less than the response measured at the same location during sluiceway releases from 1972-1975. The difference in TDG saturations measured in 2011are likely due to the powerhouse being offline during the 1972-1975 sluiceway operations.

- Median TDG saturations measured at the fixed monitoring station LBQM and the compliance station LBCP ranged from 128.3 to 134.3 percent and 125.9 to 131.7 percent, respectively. Maximum TDG saturations at LBQM and LBCP ranged from 131.3 to 137.2 percent and 128.1 to 132.6 percent, respectively. The TDG saturation at LBQM was consistently about 2 to 3 percent greater than at LBCP which was similar to the relationship measured during spillway releases in 2010.

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Tables

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

Station Code	Station Name	Station Location	Lat	Lon	Deployment Period
LBQM	Permenant TDG Station	USGS tailwater gage 5% distance from left bank	48.40061	-115.31861	4/1/2011 - 9/30/2011
LBCP	MDEQ Compliance Station	USGS tailwater gage 20% distance from left bank	48.40064	-115.31888	5/3/2011 - 5/12/2011
TMPSN-1	—	David Thompson Bridge 5% distance from left bank	48.40624	-115.31680	5/3/2011 - 5/12/2011
TMPSN-2	—	David Thompson Bridge 20% distance from left bank	48.40643	-115.31718	5/3/2011 - 5/12/2011
TMPSN-3	—	David Thompson Bridge 40% distance from left bank	48.40629	-115.31697	5/3/2011 - 5/12/2011
HAUL	—	Haul Bridge 10% distance from right bank	48.37166	-115.42951	5/3/2011 - 5/12/2011

Table 2. Summary of project operations from April 29 through May 9, 2011.

Event Number	Starting Date and Time	Ending Date and Time	Duration (Hours)	Powerhouse Discharge (kcfs)	Sluiceway Releaase (kcfs)	Number of Sluices Used	Discharge per Sluice (kcfs)
1	4/29/11 10:00	4/30/11 8:00	23	16.6	0	0	0
2	4/30/11 9:00	5/2/11 10:00	50	16.6	5	2	2.5
3	5/2/11 11:00	5/4/11 9:00	47	16.3	5	2	2.5
4	5/4/11 10:00	5/5/11 13:00	28	19.3	5	2	2.5
5	5/5/11 14:00	5/6/11 13:00	24	20.0	4.3	2	2.15
6	5/6/11 14:00	5/9/11 9:00	68	20.0	5	3	1.67
7	5/9/11 10:00	End of Test	—	20.0	0	0	0

Table 3. Statistical summary of total dissolved gas properties in the Kootenai River from April 29 to May 10, 2011.

Event Number	1	2	3	4	5	6	7
Starting Date and Time	4/29/11 9:00	4/30/11 9:00	5/2/11 11:00	5/4/11 10:00	5/5/11 14:00	5/6/11 14:00	5/9/11 10:00
Ending Date and Time	4/30/11 8:00	5/2/11 10:00	5/4/11 9:00	5/5/11 13:00	5/6/11 13:00	5/9/11 9:00	5/10/11 9:00
Duration (Hours)	24	50	47	28	24	68	24
Powerhouse Discharge (kcfs)	16.6	16.6	16.3	19.3	20.0	20.0	20.0
Sluiceway Releaase (kcfs)	0	5	5	5	4.3	5	0
Number of Sluices Used	0	2	2	2	2	3	0
Discharge per Sluice (kcfs)	0	2.5	2.5	2.5	2.15	1.67	0
TMPSN-1 Median TDG (%)	—	—	136.4	134.4	131.2	132.3	103.1
TMPSN-2 Median TDG (%)	—	—	133.3	131.3	128.7	129.8	103.1
TMPSN-3 Median TDG (%)	—	—	133.0	130.4	127.1	129.2	103.1
LBQM Median TDG (%)	100.7	134.3	134.3	131.3	128.3	129.7	103.1
LBCP Median TDG (%)	—	—	131.7	129.0	125.9	128.0	103.0
HAUL Median TDG (%)	—	—	111.4	111.1	110.3	111.2	103.2
TMPSN-1 Maximum TDG (%)	—	—	138.1	135.9	133.6	134.6	105.2
TMPSN-2 Maximum TDG (%)	—	—	135.3	132.1	130.4	131.7	104.9
TMPSN-3 Maximum TDG (%)	—	—	134.2	131.4	129.0	131.3	104.9
LBQM Maximum TDG (%)	101.7	137.2	137.2	132.4	131.3	131.5	104.9
LBCP Maximum TDG (%)	—	—	132.6	130.6	128.1	130.0	105.0
HAUL Maximum TDG (%)	—	—	113.4	113.3	111.4	113.7	104.9

Figures

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

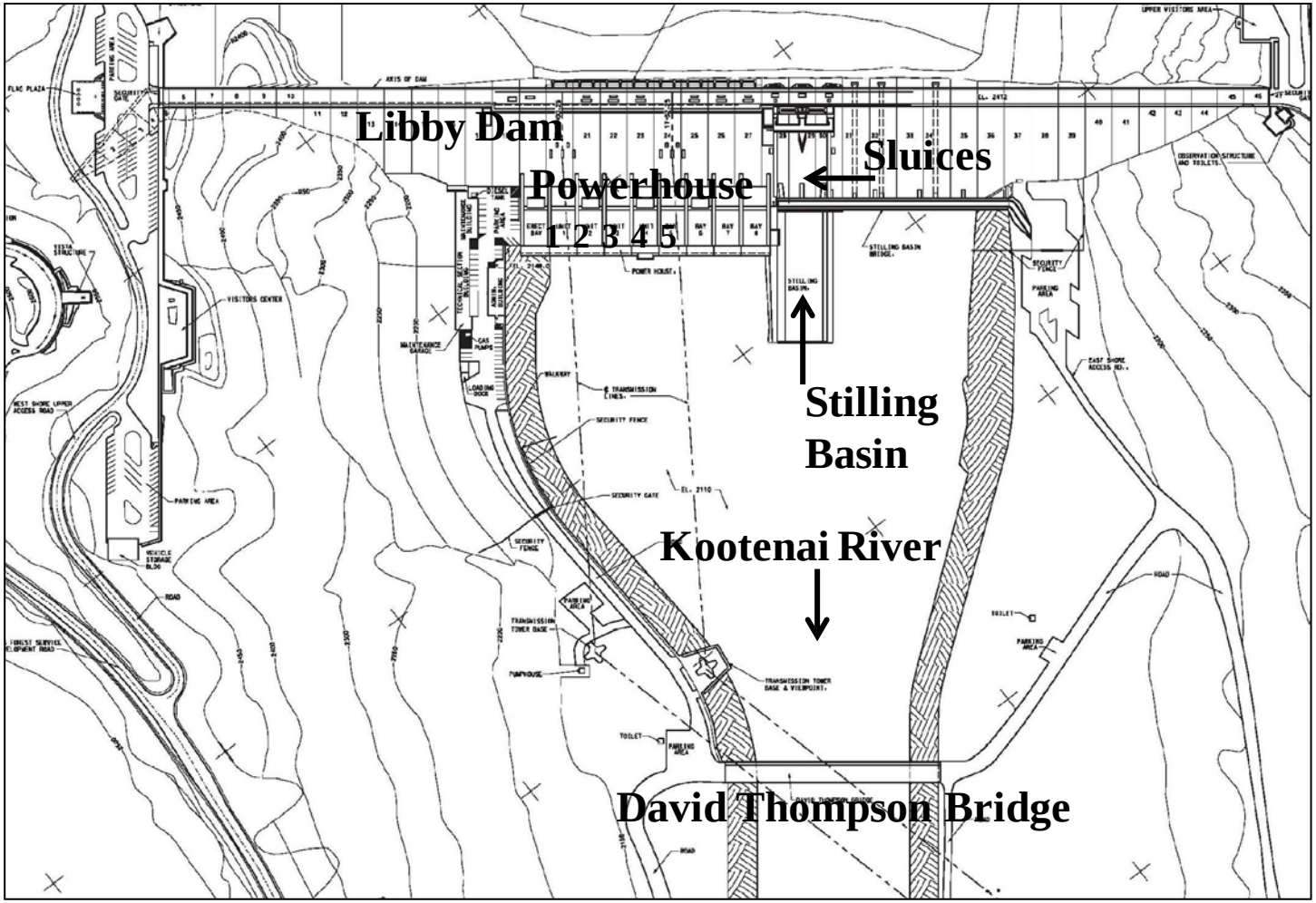

Figure 2. Libby Dam powerhouse, sluiceway, and stilling basin layout.

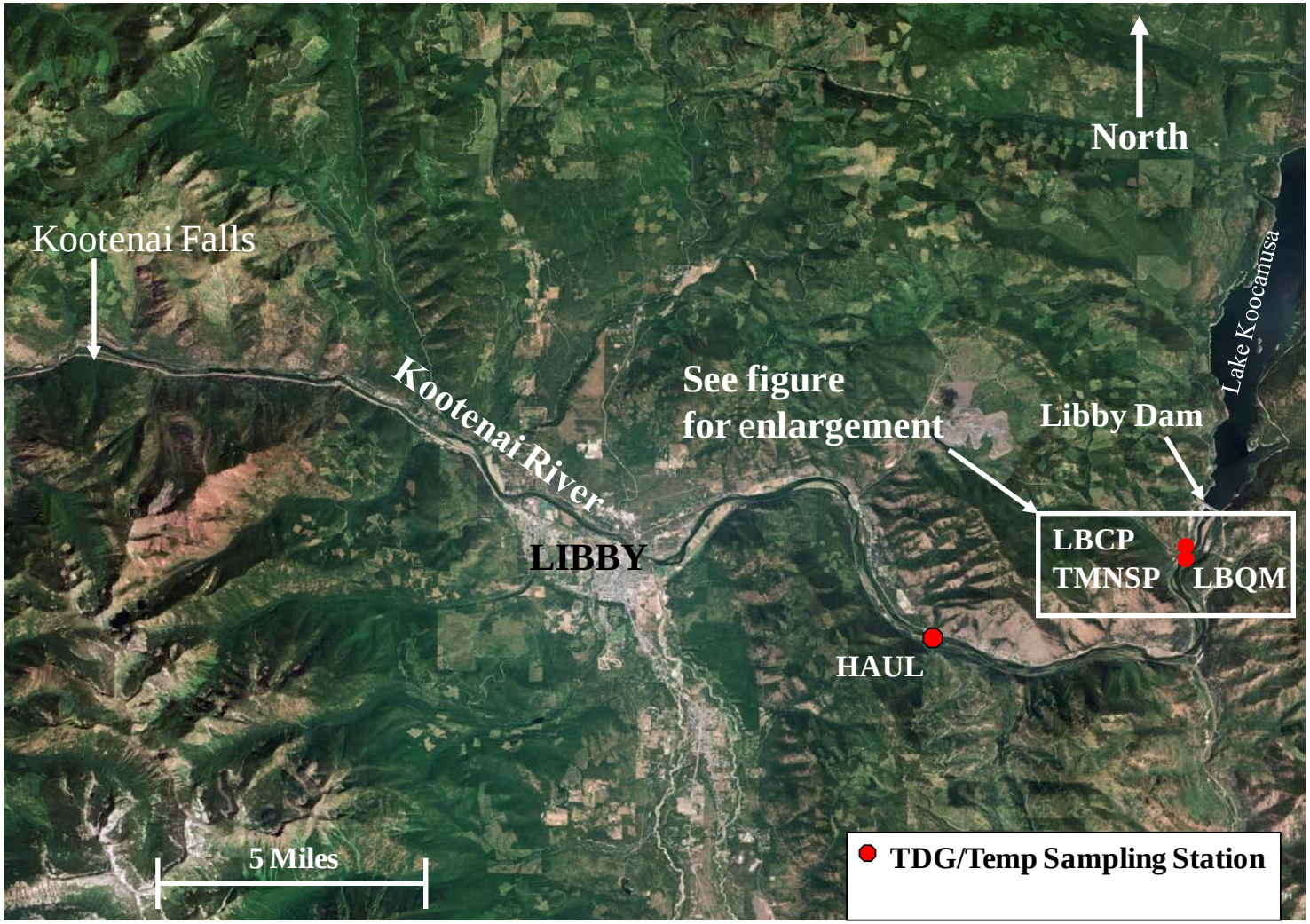

Figure 3. TDG and temperature monitoring stations downstream of Libby Dam.

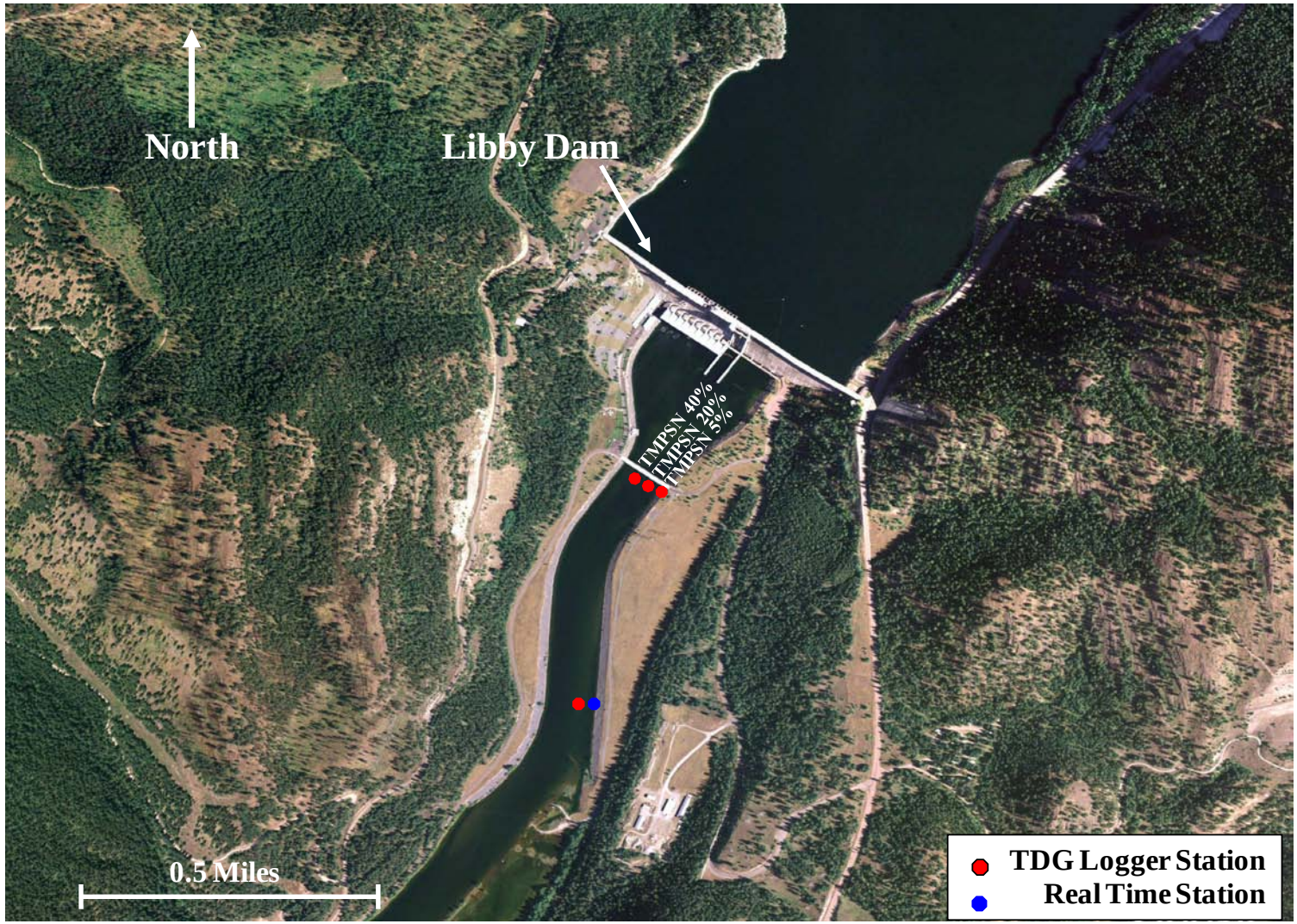

Figure 4. TDG and temperature monitoring stations at the David Thompson Bridge and USGS gauging station.

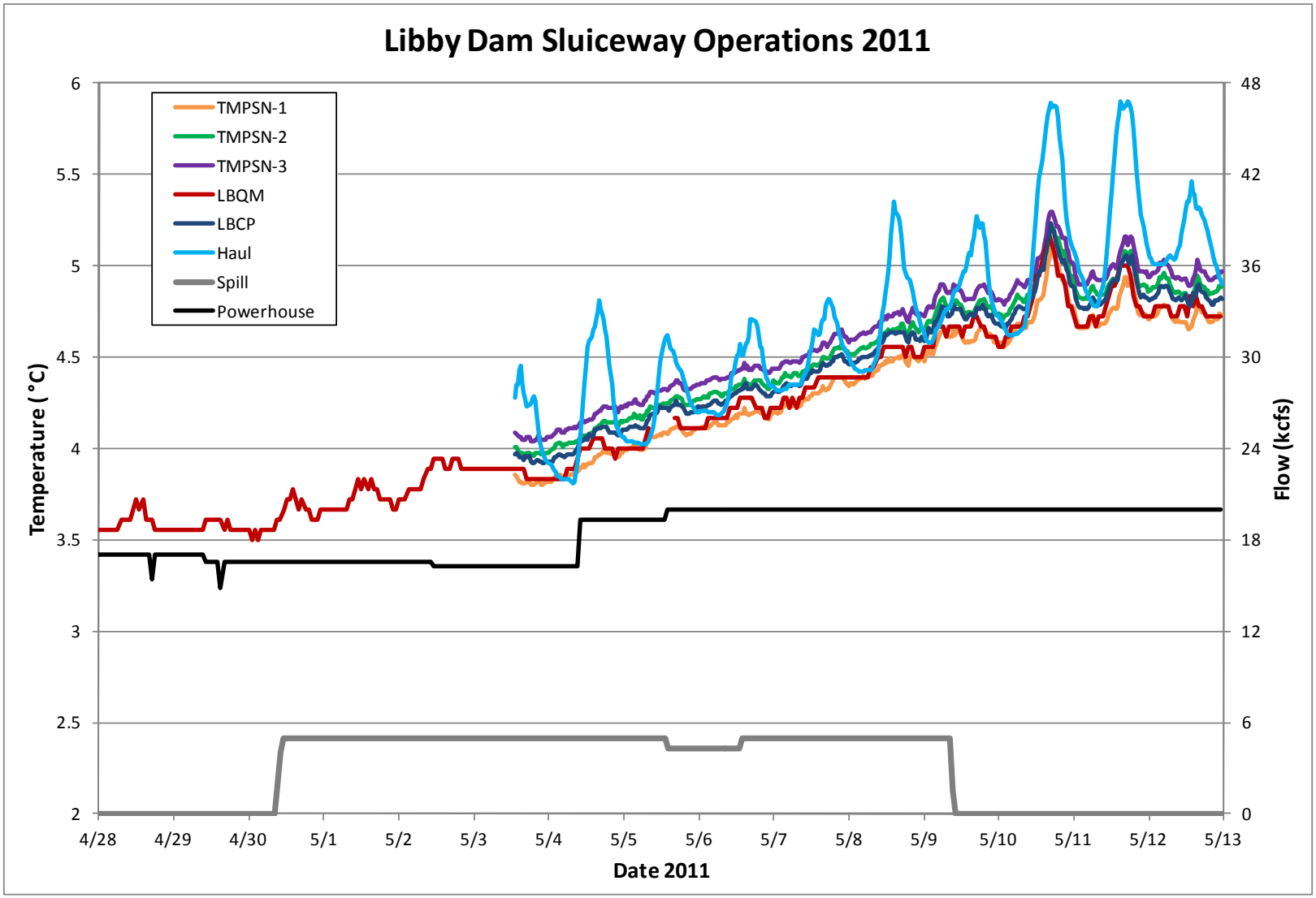

Figure 5. Time history of Kootenai River temperatures during sluiceway operations.

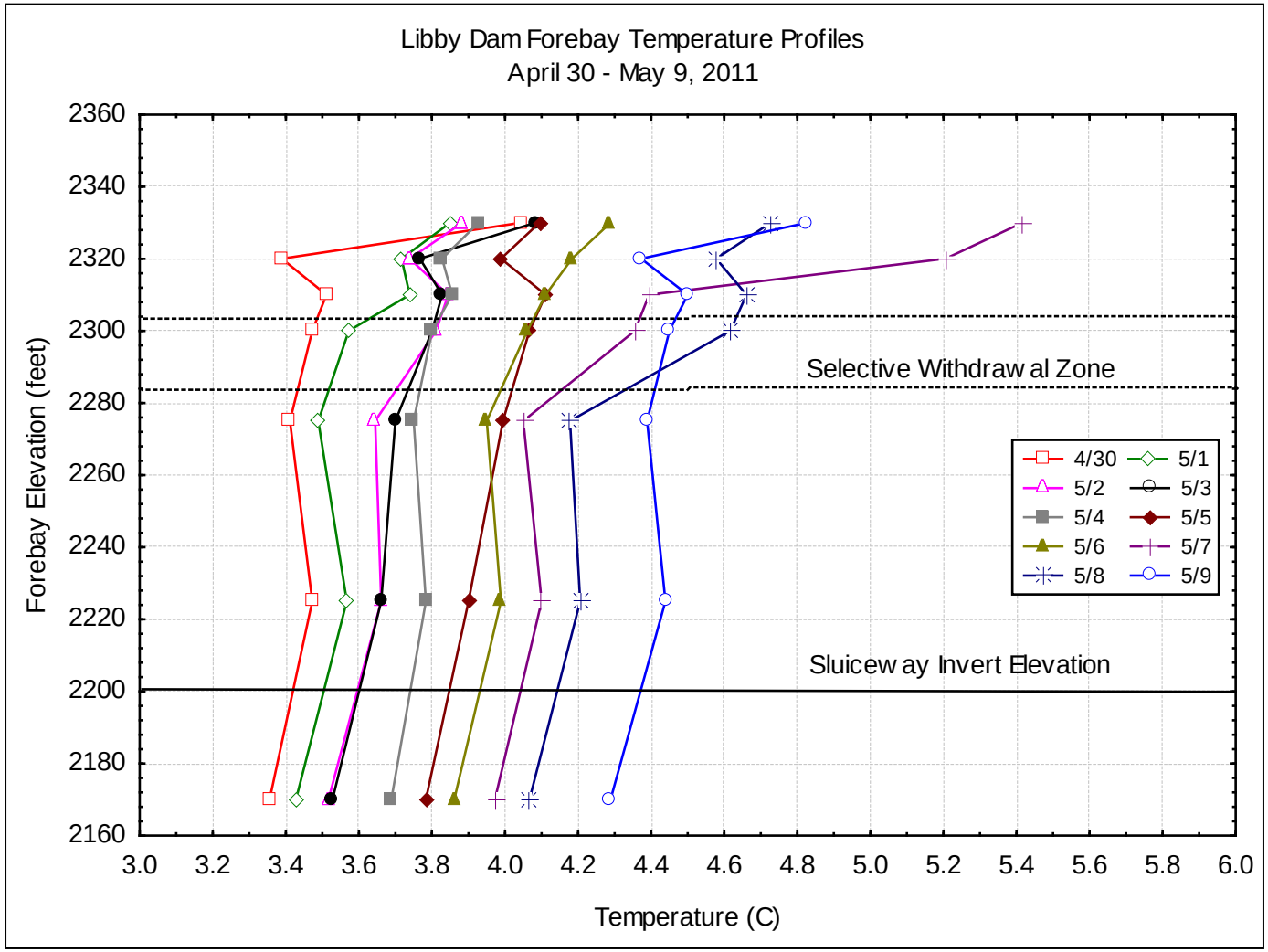

Figure 6. Libby Dam forebay temperature profiles during sluiceway releases, April 30 – May9, 2011.

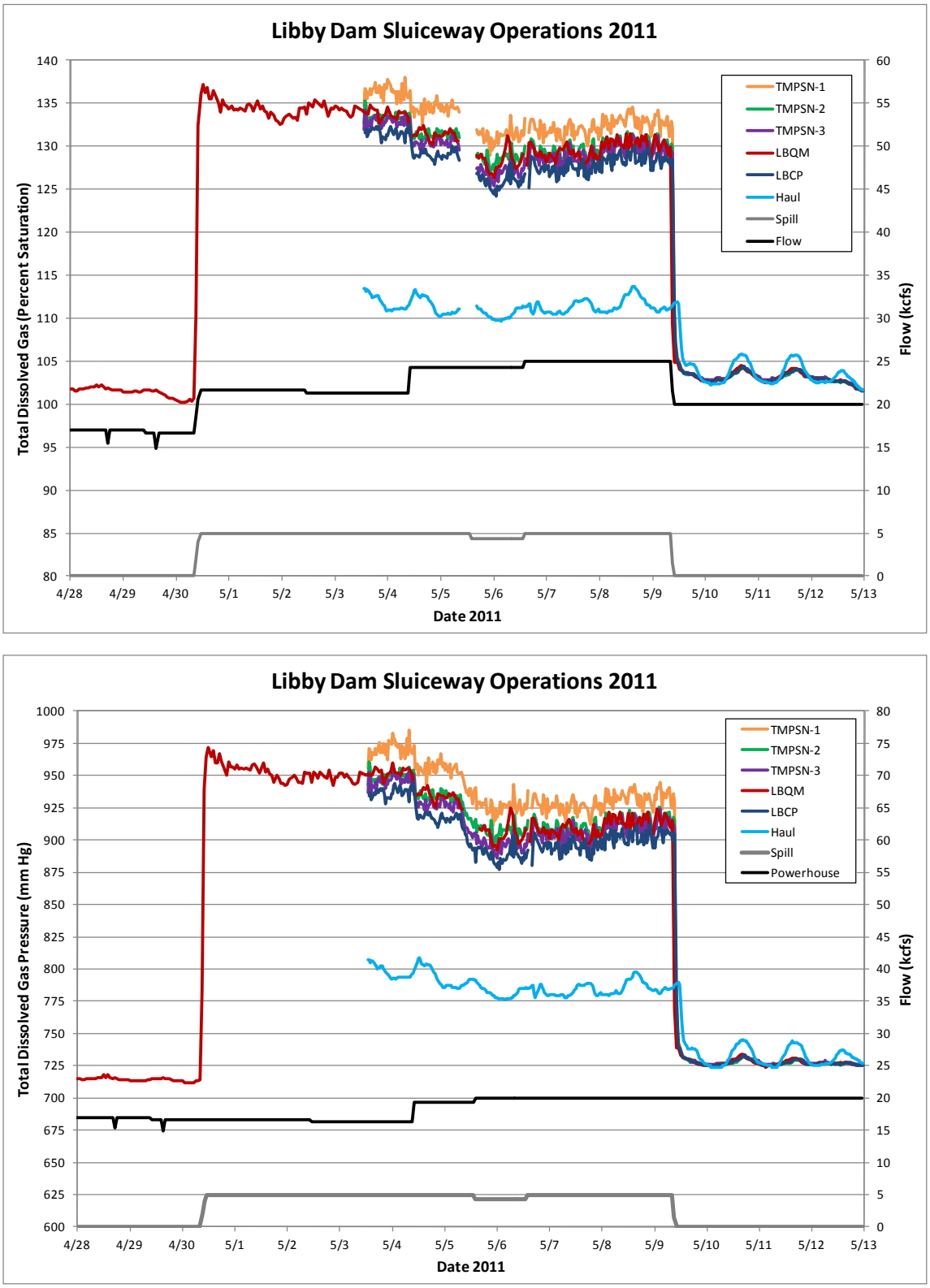

Figure 7. Time history of TDG saturations (top panel) and pressures (bottom panel) in the Kootenai River during sluiceway operations.

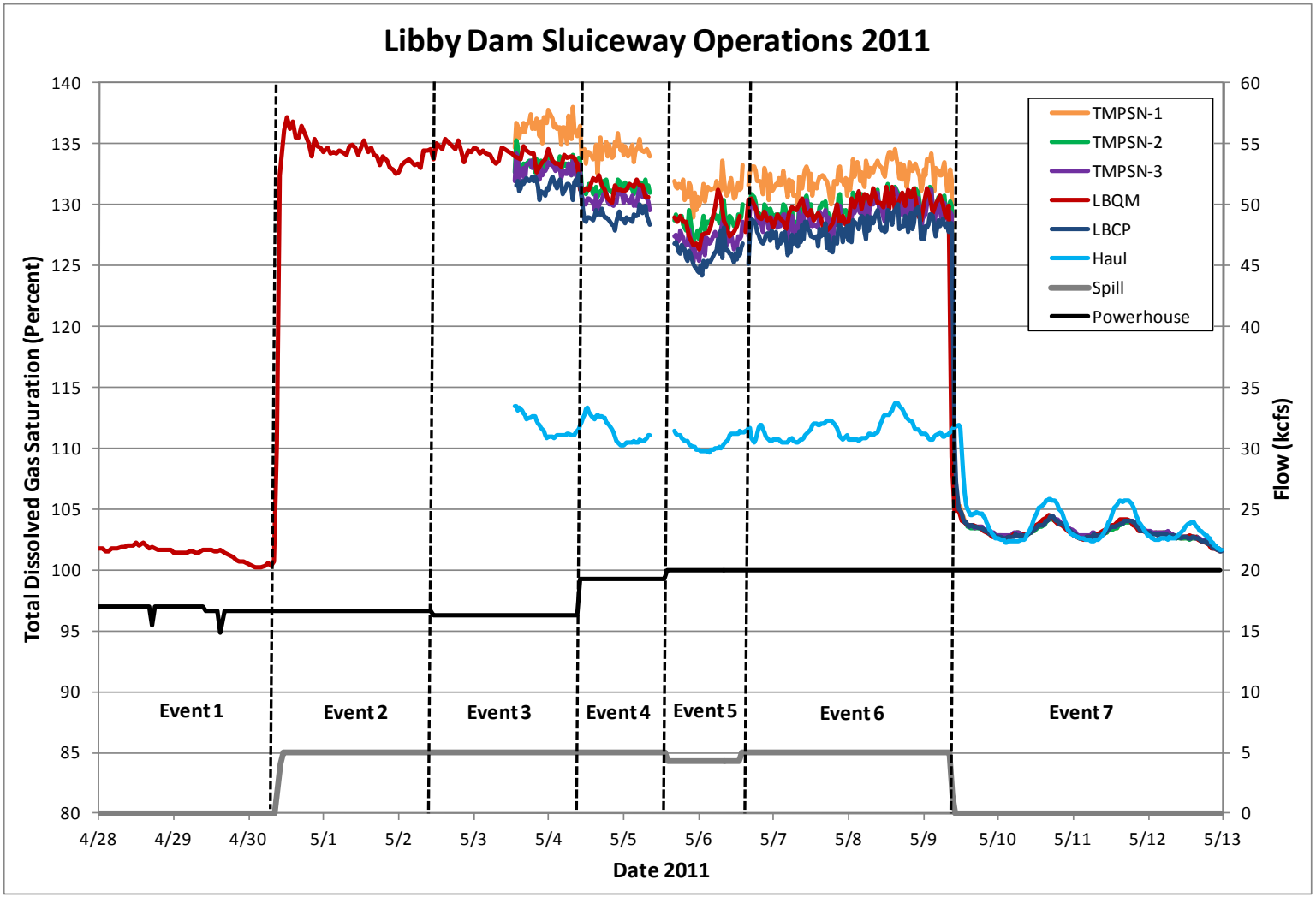

Figure 8. Time history of TDG saturations in the Kootenai River during sluiceway operations for the seven (7) events.

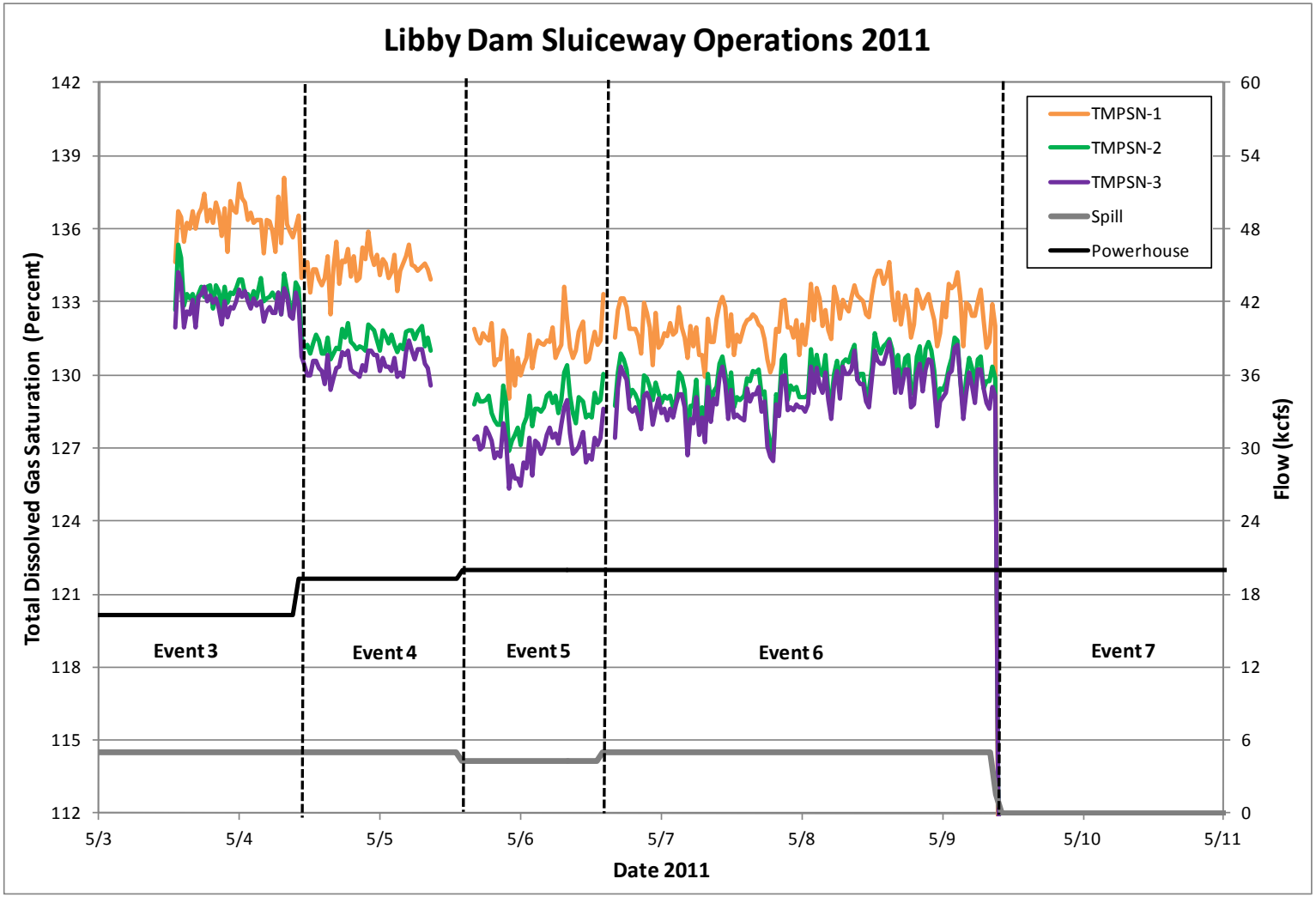

Figure 9. Time history of TDG saturations in the Kootenai River at the David Thompson Bridge during sluiceway operations for events 3 – 7.

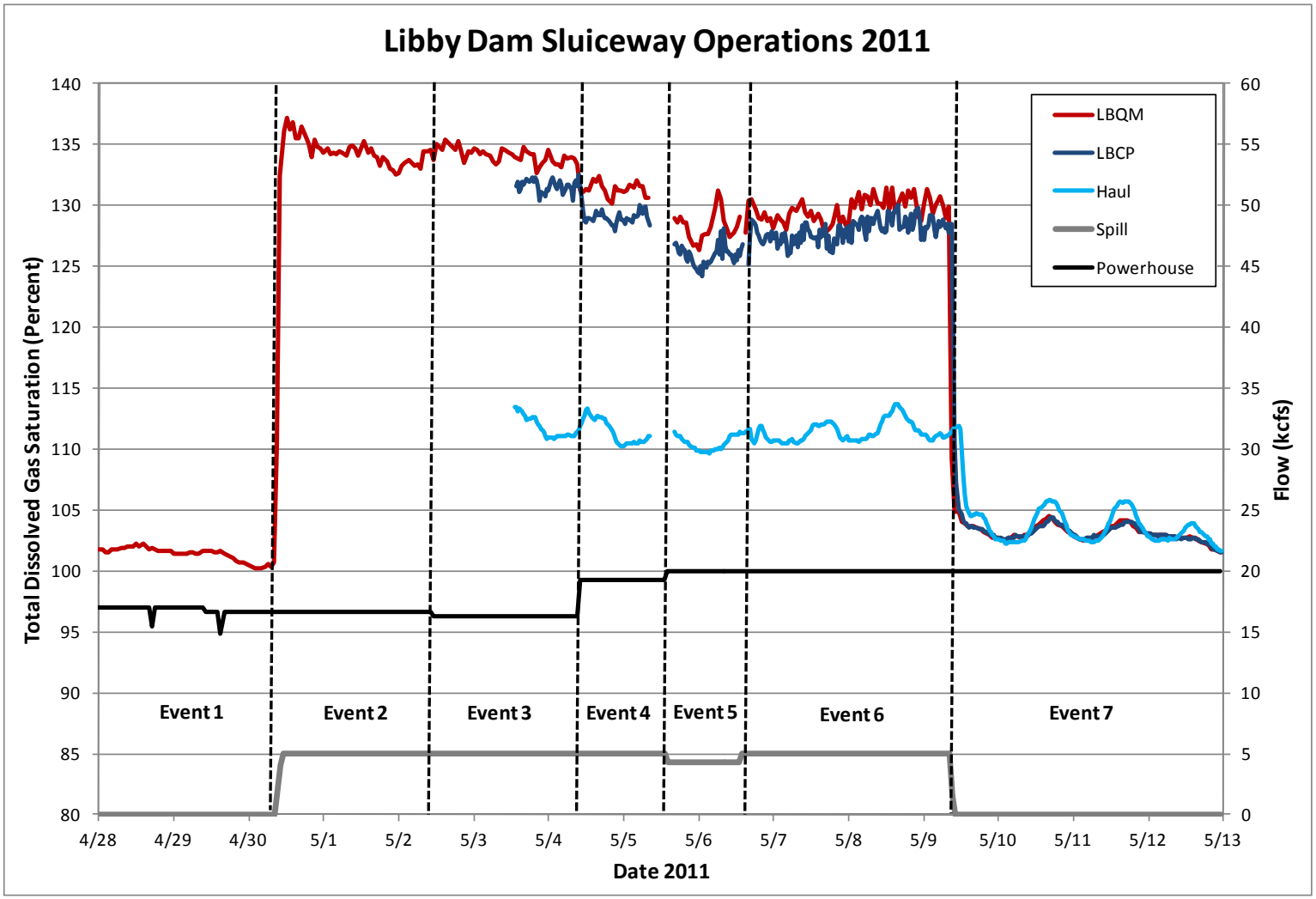

Figure 10. Time history of TDG saturations in the Kootenai River at the USGS gage and downstream station during sluiceway operations for events 1 – 7.