# Wells Dam Spillway Total Dissolved Gas Evaluation

23 May to 6 June 2005

## FINAL REPORT

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Prepared for

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# Contents

# Preface

This document reports the findings of a study conducted at Wells Dam from 23 May to 6 June 2005. The study was conducted by Columbia Basin Environmental and funded by the Public Utility District No. 1 of Douglas County. The use of trade names in this document should not be interpreted as an endorsement by either party.

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# Summary

During the spring of 2005, the Public Utility District No. 1 of Douglas County commissioned a total dissolved gas (TDG) study at the Wells Hydroelectric Project (FERC No. 2149) located at river mile 515.8 on the Columbia River. The study was implemented by Columbia Basin Environmental and was designed to describe total dissolved gas pressures resulting from eight pre-arranged spill scenarios consisting of different combinations of spillway and powerhouse operating conditions. An array of water quality data loggers were installed in the tailrace of Wells Dam for a period of two weeks between 23 May and 6 June, 2005. Each water quality logger was programmed to record water temperature and TDG pressure at ten-minute intervals. To better understand TDG dynamics at Wells Dam, the powerhouse and spillway were operated through a predetermined range of operational scenarios that varied the total flow, total spill, generation output, and location of the spillway discharge.

Total spillway discharges ranged from 26-38% of the total project discharge and were considered inadequate for developing TDG production curves for the spillway. An examination of historical data collected between 1998 and 2005 by the Wells Dam forebay and tailwater permanent monitors indicated that tailwater TDG saturations were dependent on both forebay TDG saturations and the total spillway discharge. The results indicated that an increase of 1 kcfs in spill resulted in a corresponding increase in tailwater saturations of 0.1%.

A simple mass balance approach was used to predict mean downstream TDG saturations. This approach assumed that powerhouse release waters diluted spill flows, rather than being gassed by spill. Comparisons of estimated and empirical tailwater TDG saturations indicated that powerhouse releases water exited the stilling basin with an increase of 3.9-8.0% in TDG saturation over forebay values. The trend was consistent across all eight scheduled tests. Operational patterns consisting of spill over generating turbines resulted in higher increases than other configurations.

Spill from the west side of the spillway resulted in consistently higher TDG saturations than similar spill discharges from the east side. This may have resulted from the greater depth in the west side of the stilling basin. Flat spill patterns consisting of near equal distribution of spill across the entire spillway yielded higher TDG saturations than crowned spill for similar total project discharges. This supported the idea of gassed powerhouse discharge since flat spill patterns involved more spill over generating units than did crowned spills.

The Wells Dam forebay monitor exhibited diel temperature cycles of over 1 C that were not reflected by the tailwater stations. This may have been the result of surface flows trained along the face of the dam and likely did not reflect the overall forebay temperature. Because of the relationships between temperature and TDG pressure, it was recommended that the forebay monitor be repositioned to a location upstream of the dam.

# 1.0. Introduction

The total dissolved gas (TDG) pressure of water describes the total pressure exerted by the constituent gasses as determined by their concentration and solubility. There are numerous natural and anthropogenic influences on dissolved gas concentrations and pressures including, but not limited to, community metabolism, heating, aeration devices, water falling over dams, weirs, or waterfalls, and turbine venting. It is possible for TDG pressures to exceed the equilibrium pressure resulting in TDG *supersaturation*. Supersaturated water will tend to lose gas to the atmosphere; however, this may be slow in the absence of turbulent flow.

The detrimental effects of the exposure of aquatic organisms to water characterized by elevated dissolved gas pressures were identified as early as 1905 (Marsh and Gorham 1905). Exposure to supersaturated water may result in *gas bubble trauma* (GBT), a condition similar to nitrogen narcosis ("the bends") in divers. As fish move vertically in the water column, gasses dissolved in the bloodstream under greater hydrostatic pressure may rapidly leave solution. This may lead to gill and skin blistering and "pop-eye." The presence of GBT has been documented throughout the Columbia River Basin, the most notable occurrence resulting in large fish kills at the John Day Dam (Beiningen and Ebel 1970).

This document summarizes the results of the latest in a series of studies undertaken by the Public Utility District No. 1 of Douglas County to better understand how operations at the Wells Hydroelectric Project affect downstream TDG saturations.

## *1.1. Site Description*

The Wells Hydroelectric Project (FERC No. 2149) is located on the Columbia River near Azwel, Washington at river mile 515.8 (Figure 1) and is owned and operated by the Public Utility District No. 1 of Douglas County (District). The Wells Hydroelectric Facility is a hydrocombine meaning that the powerhouse, spillway, switchyard, fish ladders, and fish bypass system are integrated into a single structure with the spillways situated directly above the turbine intakes and draft tubes. The overall length of the dam is 4,460 feet, of which the hydrocombine comprises 1,165 feet. The project consists of eleven vertical lift spill gates and ten generating units with a maximum nameplate capacity of 840 MW. The hydraulic capacity of the powerhouse is 220 kcfs and the maximum spillway capacity is 1,180 kcfs. The project operates with a head ranging from 65 to 72 feet and is affected by the backwater of the Rocky Reach Hydroelectric Project (FERC No. 2145) located approximately 36.1 miles downstream.

Wells Dam spillway operations consist of *forced* spill (inflows in excess of powerhouse capacity) and *bypass* spill (spill of a portion of the total river volume to assist the out migration of juvenile salmonids). Forced spill occurs any time the total river discharge exceeds the powerhouse's total capacity. Excessive flows may result from low demands for power, high total river flows (>220 kcfs at Wells Dam), or in the event of equipment failure. Bypass spill at Wells Dam typically occurs between April and August comprising a percentage of the total project discharge divided between Spillbays 2, 4, 6, 8, and 10 as a function of the operating turbines. Bypass spill is dependent on project operations and total river flow and generally results in spills of 5-12% of the total project discharge. Spillbays 2 and 10 have top-spill gates, while the remaining bays have underflow gates.

## 1.2. Background

### 1.2.1. Water Quality Regulations

The water quality standard for TDG pressure for Class A waters in the state of Washington is as follows:

> *Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection* (WAC 173-201A-030 (2) (iii)).

The National Oceanographic and Atmospheric Association (NOAA) Fisheries has requested spill at selected hydroprojects within the Columbia River Basin to assist with juvenile salmonid out migrations. The state of Washington developed the following waiver to the aforementioned standard:

> ***Special fish passage exemption for sections of the Snake and Columbia rivers:*** *When spilling water at dams is necessary to aid fish passage, total dissolved gas must not exceed an average of one hundred fifteen percent as measured at Camas/Washougal below Bonneville dam or as measured in the forebays of the next downstream dams. Total dissolved gas must also not exceed an average of one hundred twenty percent as measured in the tailraces of each dam. These averages are based on the twelve highest hourly readings in any one day of total dissolved gas. In addition, there is a maximum total dissolved gas one hour average of one hundred twenty-five percent, relative to atmospheric pressure, during spillage for fish passage.*

In addition to the waiver for fish passage, the state of Washington allows for the following consideration for flood control:

> *The water quality criteria herein established for total dissolved gas shall not apply when the stream flow exceeds the seven-day, ten-year frequency flood* (WAC 173-201A-060 (4) (a)).

### 1.2.2. Historical Data

The District has maintained a permanent TDG fixed monitoring system (TDGFMS) consisting of two Hydrolab® MiniSonde® multiprobes that measure water temperature and TDG pressure throughout the fish bypass spill season at Wells Dam. The TDGFMS is typically in service from 1 April until 15 September, which allows for an additional two weeks of data collection before and after the juvenile salmonid migration. The forebay probe (WEL) has been in operation since 1996 and the tailwater probe (WELW) since 1998. Atmospheric pressure data are collected via an aneroid barometer located on the surface deck of the dam. In addition to the TDGFMS, the District has collected periodic grab data to evaluate lateral and longitudinal distributions in TDG pressure. The results of these studies indicated minor gradients of less than 2% saturation across the width of the tailrace (Klinge 1998).

The District undertook more intensive studies to evaluate spill at Wells Dam during the 2003 and 2004 fish passage seasons. Both studies employed an array of data loggers arranged in a grid throughout the Wells Dam tailwater. The findings of those efforts were summarized in reports for the District (CBE 2003, 2004). The previous studies indicated that the tailwater TDGFMS (WELW) exhibited a delayed response to operational changes by Wells Dam when compared to mid- and upstream locations. Despite this delay, averages of the twelve highest daily TDG saturations (the compliance measure used by the State of Washington) varied little between stations.

The 2003 study also attempted to determine the fate of powerhouse release water by comparing upstream and downstream volume weighted TDG saturations. The results of these studies were limited by the range of flow conditions tested, but implied that the TDG pressures of powerhouse release water may have been influenced by spill. The 2004 study generally supported previous findings, indicating that Wells Powerhouse release water was gassed by spilled water. Temperature spikes apparent at the WEL site were not measured 800 feet upstream of the dam. This implied that the WEL site may have been influenced by surface flows and, therefore, may not have been representative of overall forebay temperatures and TDG pressures.

## *1.3. Objectives*

This study sought to expand the findings of previous work at Wells Dam with the following primary objectives:

1. to determine the degree to which Wells Powerhouse release water is influenced by spillway operation, i.e. dilution or adsorption,

and

2. to explore ameliorative operational scenarios for reducing TDG production.

## *1.4. Approach*

Previous studies required no special operations by the project, instead allowing flows to proceed based on power and fish passage requirements. Occasionally, high flows were measured; however, the distribution of flow was typically varied between turbines and spillways such that downstream probes rarely reached equilibrated values for a given flow condition.

### 1.4.1. Spill Shaping

The 2005 study requested three hours of static operation for each test condition to allow steady state conditions to be reached throughout the study area and to allow all probes to reach equilibration. Two principle test scenarios were devised to address the requirements of this study. Series one tests sought to examine the interaction of Wells Dam powerhouse and release flows by dividing flows between the east and west sides of the dam. Because the Wells Dam powerhouse and spillway were configured as a hydrocombine, it was difficult to sample undiluted powerhouse and spill release during normal operation. Dividing powerhouse and spillway flows provided the best opportunity to measure undiluted spillway TDG saturations. Water was spilled on both generating and non-generating units by shifting powerhouse and spillway discharge between opposite sides of the dam.

Series two tests examined TDG production under different spill configurations for moderate and high flow spill events. Spillway discharges were shaped in a uniform (flat) or non-uniform (crowned) configuration for relatively moderate and high total river flows. Flat spills were characterized by near equal distribution of the total spillway discharge between all of the bays, while crowned spill more closely represented the spillway patterns employed by Wells for the same total flows. High and moderate flows were simulated by increasing total project discharge. Table 1 summarizes the test matrix for this study.

### 1.4.2. Mass Balance

To evaluate the impact of Wells Dam operations on downstream water quality, mean TDG saturations were compared using an upstream/downstream approach first developed by H.T. Odum to determine the influence of community metabolism on dissolved oxygen concentrations in flowing waters and a Florida turtle-grass community (Odum 1956, 1957).

The approach described herein attempted to reflect both the TDG saturation and volume of water affected and provided a simple way of evaluating the performance of the Wells Spillway under different operational scenarios. More importantly, this approach allowed indirect inferences about the influence of Wells Powerhouse flows on tailwater TDG saturations, i.e. dilution or adsorption. If spill and powerhouse TDG saturations were sufficiently represented, the mean tailwater TDG saturation for a given condition could be estimated. Since degassing was not considered and it was assumed there was no gas adsorption by powerhouse release water, estimated TDG saturations should have been less than or equal to empirical values. This may be restated in the form of testable hypotheses as

$$H_0 : TDG_{est} - TDG_{obs} \leq 0$$

$$H_a : TDG_{est} - TDG_{obs} > 0.$$

# 2.0. Methods

As with past studies, sensor deployment was timed to coincide with the spring freshet to maximize the opportunity to sample high spillway discharges without negatively impacting power generation. Test conditions were designed to target spill patterns thought to have the best chance of improving spill to TDG production ratios. Each test condition was held at, or near, steady state conditions for a period of at least three hours.

The original study plan included two transects, each consisting of three sensors distributed laterally across the width of the river. Transect A would be approximately 1100 feet downstream of the dam with Transect B about three miles downstream at the location of the tailwater TDG monitor (WELW). At the request of the Washington Dept. of Ecology, a third transect was to be included at a future potential compliance zone located approximately 2500 feet downstream. A problem with the equipment supplier reduced the probes available for the study, therefore Transect A was installed 2500 feet downstream and the near-dam transect was omitted.

## *2.1. Instrumentation*

Five Hydrolab® multi-parameter data loggers (sondes) were utilized for the period of study plus the two seasonal fixed monitor instruments operated by the District. Each sonde was equipped with sensors for water temperature, TDG pressure, and depth. All probes were calibrated to NIST traceable standards for temperature and TDG pressure both prior and subsequent to field deployment following the methodologies outlined in Appendix A. Data were recorded along a ten-minute interval for the period of study. Atmospheric pressure data were collected at the Wells Dam forebay TDGFMS location and corrected to the tailwater elevation for the downstream sites. Hourly data for water quality and operations were obtained for ancillary hydroprojects from the Columbia River Operational HydroMet System (CROHMS) operated by the U.S. Army Corps of Engineers, Northwest Division. Probes at these sites also consisted of Hydrolab® sondes maintained as described in Appendix A.

## *2.2. Field Deployment*

Sondes were distributed in two downstream transects of three instruments distributed across the lateral width of the river. Station locations based on GPS coordinates collected at the time of deployment and retrieval are depicted in Figure 2. Table 2 summarizes the deployment information for the 2005 study.

### 2.2.1. Forebay

The forebay TDGFMS (WEL) was permanently deployed in a perforated pipe attached to the face of the dam at a depth of approximately 4.5 m (15 feet). This probe served to represent background TDG saturations for the Wells forebay.

### 2.2.2. Transect A

Transect A consisted of three probes and was located approximately 2500 ft. downstream of the dam (A1, A2, and A3 in Figure 2). Each probe was housed in a 200 lb. steel case that served to both anchor the station and protect the sonde. Anchors were attached to a series of surface floats via 5/16” diameter steel cables that allowed installation and retrieval by boat. Figure 3 illustrates the deployment rigging used for Transect A.

### 2.2.3. Transect B

Transect B consisted of two sondes in addition to the tailwater TDGFMS (WELW) located about three miles downstream of the dam. Probes were installed in a manner similar to Transect A (depicted in Figure 3) while the TDGFMS was permanently installed in a perforated pipe on the river's east bank (Figure 4).

## 2.3. Data Analysis

Data collected for the Wells Spillway study were obtained from the following sources:

1. field transect data – water temperature and TDG pressure (mm Hg) reported every ten minutes for seven sites (the forebay and tailwater TDGFMS and five auxiliary sites)

2. CROHMS data – web-based database of hourly project operation and water quality data maintained by the U.S. Army Corps of Engineers, Northwest Division

3. ten minute project operations data – total project discharge, total spillway discharge, turbine output by unit, and pool elevations for the forebay and tailwater reported every ten minutes from the District Power Operations Database

4. control room operator logs – individual spill gate settings recorded at the time of occurrence

The sondes utilized TDG sensors that reported the total pressure at the depth of sample collection. Pressures were converted to TDG pressure as a percentage of surface saturation as

$$TDG_{sat} = \frac{TDG_i}{BP_i} \times 100$$

where

$TDG_{sat} =$ TDG pressure expressed as percentage of surface saturation

$TDG_i =$ TDG pressure at station $i$, mm Hg

$BP_i =$ Atmospheric pressure at station $i$, mm Hg

Equation 1

### 2.3.1. Data Preparation

Data for the various data sets were merged by date and time. Control room operator logs were used to identify study events and determine individual spill gate discharges. Spill levels were reported as discharge (kcfs) for Bays 2 and 10 and as gate opening (feet) for the remaining spillbays. Individual spillbay discharge was necessary for analyses; therefore, gate openings were converted to discharge using the following relationship developed from data provided by the District:

$$Q_G = 0.2TW + 1.7G - 154.6$$

where

$$Q_G = \text{discharge of spillway G, kcfs}$$

$$TW = \text{tailwater elevation, ft above MSL}$$

$$G = \text{spillgate G opening, ft}$$

Equation 2

Total discharge estimates based on Equation 2 disagreed slightly with the electronic data set. These discrepancies were reconciled by determining the percentage each spillbay contributed to the total spill based on Equation 2 estimates and then applying those percentages to the ten-minute data sets.

Wells Powerhouse generator output was reported in megawatts. The percentage each generator contributed to the total power output was applied to total powerhouse flow estimates (computed as total project flow less estimated spill flow) to approximate individual turbine discharges.

Once the data sets were merged, individual test events were identified. Data for each test were visually inspected to select equilibrated values to be used in subsequent analyses. Figure 5 depicts data for Test 1D collected at Transect A to illustrate typical TDG senor response and equilibration times. Equilibrated data were then summarized by test condition for subsequent data analyses.

### 2.3.1. Mass balance analysis

To examine the influence of powerhouse and spillway release water, upstream and downstream TDG saturations were compared using the simplified mass balance approach used in prior studies. The forebay TDGFMS (WEL) represented background TDG saturations, or 100% of the upstream flow, which were assumed to be unaffected by Wells Dam operations. Downstream flows were assumed to consist of both powerhouse (background) and spillway water, each characterized by different TDG saturations. It was assumed that water passed through the powerhouse unchanged, thus WEL data represented powerhouse release TDG saturations. The TDG saturations of spilled water should vary with pattern and volume spilled. The highly turbulent flows characteristic of the stilling basin promoted gas exchange, both with air entrained by spill and lost to the atmosphere. Upon exiting the stilling basin, off gassing occurred much more slowly, thus more closely approximating “equilibrated” spill TDG saturations.

Assuming that spill and powerhouse flows were adequately reflected by data collected at Transects A and B, the estimated mean downstream TDG saturation could then be represented as

$$TDG_{Wells} = \frac{\left(Q_{PH} \times TDG_{PH}\right) + \left(Q_{SP} \times TDG_{SP}\right)}{\left(Q_{PH} + Q_{SP}\right)}$$

where

$TDG_{Wells}$ = the flow - weighted average TDG saturation exiting the Wells tailwater (µTransect B)

$Q_{PH}$ = the total powerhouse discharge

$TDG_{PH}$ = the average TDG saturation of powerhouse release water (WEL)

$Q_{SP}$ = the total spillway discharge

$TDG_{SP}$ = the average TDG saturation of the spillway release water.

Equation 3

Substituting mean Transect B values for $TDG_{Wells}$, Equation 3 could be rearranged to solve for $TDG_{SP}$ as

$$TDG_{SP} = \frac{\left(\left(Q_{PH} + Q_{SP}\right) \times TDG_{Wells}\right) - \left(Q_{PH} \times TDG_{PH}\right)}{Q_{SP}}.$$

Equation 4

Comparisons of actual and calculated values for $TDG_{Wells}$ and $TDG_{SP}$ were used to evaluate the performance of the different spill scenarios and to indirectly determine the effect of powerhouse flows, i.e. dilution or adsorption.

# 3.0. Results and Discussion

All eight of the pre-arranged spill scenarios were achieved during the study. Start and end times for the eight spill tests are presented in Table 3. Mean generator and spillbay discharges are summarized by unit in Table 4. In addition to the eight scheduled tests, an unplanned high spill event occurred between 26 and 27 May 2005. This event was unscheduled and occurred during relatively minor power demand. Flow distributions varied between turbines and gates; therefore, these data were excluded from mass balance analyses but included in the final dataset as they represented the highest spill levels of the study (100 kcfs representing 50% of total project flow). Graphical representations of the turbine and spillway patterns for the eight spill scenarios are included as Appendix B.

Data were available for all sites and pre and post study calibrations indicated that all probes performed within acceptable limits, as presented in Table 5. Equilibrated data for each test were summarized by station. Tables 6 and 7 depict test summaries for temperatures and TDG saturations, respectively. Mean tailwater elevations and sensor depths for each site are plotted by test as Figure 6. Sensor depth was highly correlated with tailwater elevation with the deepest values corresponding to the higher flow events. The mean tailwater elevation for the eight scheduled tests ranged from 710.6 feet above mean sea level (feet MSL) during Test 1B to 716.4 feet MSL during Test 2C. The maximum tailwater elevation for the entire study period of 719.8 feet MSL occurred on 25 May 2005 with a total project discharge of 225.5 kcfs.

Table 7 presents test averages for the 2005 spill study. These data represented equilibrated values and were utilized in subsequent analyses.

## *3.1. Hydrology*

River flows were below average compared to historical values, ranging from a maximum daily average discharge of 177.2 kcfs on 27 May 2005 to a minimum of 41.1 kcfs on 5 June. Figure 7 displays daily average flows at Wells Dam for the 1997, 2001, and 2005 water years. These data were selected from the CROHMS dataset (1995-present) to illustrate flows for relatively high (1997) and low (2001) river conditions.

Spillway discharges occurring outside of the requested test periods consisted of standard fish bypass spill through Gates 2, 4, 6, 8, and 10. The maximum spill discharge of 100 kcfs occurred during the aforementioned unscheduled spill event on 27 May 2005. Daily average spills ranged from a minimum of 5.8 kcfs to a maximum of 26.1 kcfs occurring on 5 June and 27 May 2005, respectively.

One significant spill event averaging 27.8 kcfs occurred at Chief Joseph Dam, approximately 29.5 miles upstream of Wells Dam, on 25 May between 14:00 and 23:00. This was followed by a short term spill event lasting for two hours around 0:00 on 27 May 2005. Chief Joseph operations and downstream TDG saturations are presented in Figure 8. With the notable exception of 25 May, TDG saturations measured at the Chief Joseph tailwater FMS (CHQW) generally reflected upstream values with no clear influence by the dam on downstream TDG saturations measured at CHQW or WEL.

As previously discussed, tailwater elevations ranged from 704.8 to 719.8 feet MSL during the 2005 study. Wells tailwater elevations typically fluctuated by about ten feet during an operational day, mainly as a function of the total project discharge. Figure 9 depicts the bathymetry for the Wells Hydroproject from immediately upstream of the dam to approximately 2,700 feet downstream. The Wells Dam stilling basin is relatively deep to allow for the draft tube outlets and, presumably, as a result of scouring from spill. The thalweg follows the east side of the river until about 0.5 miles downstream, where the channel begins to exhibit a more uniform morphometry.

Because the sensors were anchored to the river bottom, their depth varied with variations in tailwater elevation as seen in Figure 6. This was more apparent at the shallower sites along Transect A than Transect B, which had a relatively wide, deep channel.

## *3.2. Temperature*

Hourly water temperatures for Wells, Chief Joseph, and Rocky Reach dams are displayed in Figure 10 with hourly TDG saturations presented in Figure 11. Both the Wells (WEL) and Rocky Reach (RRH) forebay TDGFMS exhibited large daily fluctuations in water temperature when compared to the other sites. Temperatures measured at the WEL site ranged from a minimum of 10.9 C on the morning of 23 May 2005 to a maximum of 14.2 C on the afternoon of 29 May 2005. Temperature may significantly affect the TDG saturation of surface waters, as mentioned in Section 1.0. Figure 12 depicts water temperatures and TDG saturations for the Wells fixed monitoring stations reported every ten minutes for the same period shown in Figures 9 and 10. Note that temperatures measured by the forebay probe were more erratic than those downstream. The highest temperatures typically coincided with low project discharges during off peak hours – generally characterized by lesser flows throughout the Columbia River system.

The contrast between forebay and tailwater temperatures apparent in Figure 12 highlighted a potential problem with the forebay sensor location. The WEL probe was secured in a pipe attached to the upstream face of the dam. Figure 13 depicts temperature data collected upstream of the dam during the 2004 study. Note that temperatures measured approximately 800 feet upstream (FB1 and FB2) closely matched data collected downstream (WELW), without the relatively dynamic temperature fluctuations reported by the forebay TDGFMS (WEL). Forebay TDG saturations displayed a strong correlation with temperature as demonstrated by the relationships in Figure 14. The data points circled in Figure 14 represented the 25 May Chief Joseph Dam spill event. When these data were excluded, the correlation between temperature and TDG saturation was stronger ($R^2$=0.72).

## *3.3. TDG Production Curves*

Historical TDGFMS data for Wells Dam collected between 1998 and 2005 indicated a relatively weak ($R^2$=0.67) linear relationship between WELW and WEL as depicted in Figure 15. When total spill was considered, a stronger linear relationship was described as

$$WELW = 0.89(WEL) + 0.14(Q_{SP}) + 12.42$$

$$R^2 = 0.91$$

where

$WELW$ = Wells tailwater TDG saturation

$WEL$ = Wells forebay TDG saturation

$Q_{SP}$ = Total discharge of the Wells Spillway (kcfs).

Equation 5

Figure 16 presents WELW TDG saturations predicted from Equation 5 plotted against actual values collected from 1998-2005. Values predicted from Equation 5 closely matched actual values and indicated an increase of approximately 0.7 % saturation for every 5 kcfs increase in Wells total spill, or 0.1 % per 1 kcfs increase in spill. If the percentage of the total project flow consisting of spilled water were substituted for total spill, mean tailwater TDG saturations were best predicted as

$$WELW = 0.90(WEL) + 0.27(P_{SP}) + 9.98$$

$$R^2 = 0.88$$

where

$WELW$ = Wells tailwater TDG saturation

$WEL$ = Wells forebay TDG saturation

$P_{SP}$ = Spillway discharge as a percentage of the total project flow.

Equation 6

Residual analyses revealed a stronger correlation between predicted TDG saturations and the percentage of spill than with total spill. Therefore, Equation 5 was deemed the more appropriate representation.

### 3.4. Spill Shaping

Previous studies had not requested specific spill patterns and normal project operation (spill over load) made it difficult to estimate distinct TDG saturations for spill and powerhouse releases. During the 2005 effort, tests 1B and 1C separated spill flows in an attempt to measure undiluted spillway and powerhouse TDG saturations.

The Wells Dam spillway consists of both top-spill and underflow gates; however, assuming there was no difference in the TDG exchange characteristics for the different spillway designs, a simple method for reducing maximum downstream TDG saturations could be a uniform (or flat) spill pattern. By distributing the total spillway discharge across all bays, the total discharge by any one bay was reduced. This had often resulted in lesser overall downstream TDG saturations during studies at other regional dams, albeit potentially expanding the total volume of water influenced by spill.

The Series 2 tests examined the difference between uniform and non-uniform spill distributions for moderate and high total project discharges. Figures 17 through 24 depict TDG saturations for paired tests measured at Transects A and B.

### 3.4.1. Loaded versus unloaded spill

Series 1 testing explored the potential differences between spill over generating and non-generating turbines for both the east and west sides of the dam. Tests 1A and 1B examined spill from the east side of the spillway over generating (1A) and non-generating (1B) units and the results of these tests for Transects A and B are depicted in Figures 17 and 18, respectively. Test 1A resulted in a gradient of 5% across Transect A with the highest values measured along the west bank. The gradient persisted all the way to Transect B with east bank values equal to those at Transect A, and mid-channel stations that were nearly equal. In contrast, Test 1B resulted in less of a gradient at Transect A with the highest values along the west half of the river. Transect B TDG saturations were nearly uniform for Test 1B.

Tests 1C and 1D represented spill from the west side of the spillway over generating and non-generating units, respectively. As demonstrated by Figures 19 and 20, a gradient of nearly 8% TDG saturation was observed at Transect A with the west bank stations displaying the highest values for test 1C at both transects. As with Test 1A, the gradient persisted to Transect B, although the east station (WELW) yielded higher values than east river (A1) values measured upstream. Test 1D resulted in near uniform values at Transects A (Figure 19) and B (Figure 20). The maximum TDG saturations were less for both transects than those for Test 1C. The volume of water influenced by spill was greater as indicated by the elevated saturations at all stations for Test 1D in contrast to the more localized influence indicated for Test 1C.

Spill from the west side of the spillway resulted in higher average TDG saturations for both transects and appeared to be independent of generation. Average TDG saturations were identical for the paired tests (1A/1B and 1C/1D) as summarized in Table 8.

### 3.4.2. Crowned versus Flat Spill

Series 2 tests explored the influence of shaping spill at moderate and high flows. Figures 21 and 22 display TDG saturations measured for crowned (or non-uniform) and flat (or uniform) spills at moderate flows for Transects A and B. A TDG gradient of 3.5% saturation was observed for Test 2A at Transect A, with the highest values represented by the mid-channel and west bank stations. The gradient was apparent, though less pronounced, at Transect B, with little change from upstream values. Test 2B resulted in near uniform TDG saturations across each transect, although the outer stations demonstrated slightly higher saturations than the mid-channel station for Transect A.

The trends observed at moderate flows were also expressed at higher flows, with a persistent gradient across both transects (Figures 23 and 24). West river TDG saturations were higher for both patterns and characterized by little change from the upstream transect. Uniform spill patterns resulted in higher TDG saturations than non-uniform patterns for both flow conditions. Differences between mean Transect A and B TDG saturations were generally less for the Series 2 tests than for the Series 1 tests. Figure 25 displays TDG saturations for Transect A, Transect B and WEL averaged by spill test. Note that there was little difference in mean TDG saturations for Tests 1A/1B and 1C/1D, while uniform spill tests 2B and 2D resulted in higher TDG saturations than the corresponding non-uniform tests (2A and 2C in Figure 25).

Figure 26 depicts both the average TDG saturations measured for the forebay and tailwater stations (left axis) and the average change in TDG saturations from upstream to downstream as the difference in WEL and Transect B (right axis). Tests 1A, 1C, 1D, 2B, 2C, and 2D all resulted in an increase of around 7% saturation over forebay values. Tests 1B and 2A resulted in increases of 4.2% and 5.6%, respectively.

### 3.5. Mass Balance

Values from Table 8 were substituted into Equation 3 to solve for $TDG_{Wells}$ by allowing the maximum TDG saturation for Transect A to represent $TDG_{spill}$. Allowing TDG saturations for the forebay (WEL) to represent $TDG_{PH}$ assumed that powerhouse release water was not gassed by spill, but instead served to dilute spilled releases. Predicted and actual mean Transect B TDG saturations are plotted by test as Figure 27. In all tests, actual Transect B values exceeded predicted TDG saturations. A t-test analysis indicated that there was sufficient evidence at the 0.05 level of significance to reject the null hypothesis that the estimated Transect B TDG saturations were less than or equal to observed values.

Substituting Table 8 values into Equation 4 to solve for $TDG_{SP}$ again demonstrated marked differences from actual values as seen in Figure 28. Given the significant differences evident in Figures 27 and 28, Equations 3 and 4 did not fully describe TDG processes.

If one assumed that the powerhouse release was gassed by spill, the mass balance approach described by Equation 3 would underestimate downstream values. To explore this concept further, the minimum Transect A saturation was substituted for $TDG_{PH}$ in Equation 3 and used to compute mean Transect B values. When this estimate was compared to observed values, there was insufficient evidence at the 0.05 level of significance to reject the hypothesis that there was no difference between the two. The results of this approach are summarized in Figure 29. Results for all of the mass balance analyses are summarized in Table 9.

### 3.6. Compliance with water quality standards

Table 10 summarizes TDG saturations as the average of the twelve highest daily values, used as one measure of compliance with state water quality standards. The only value to exceed this standard was measured in the Rocky Reach forebay for 28 May 2005, one day after the unscheduled high spill event of 27 May. The twelve hour average for RRH was 120.4%, some 5.4% higher than the allowable limit. Instantaneous TDG saturations at or above 125% were measured throughout the Wells tailwater for a period about three hours with a total spillway discharge of 100.0 kcfs, which represented approximately 50% of the total project flow.

# 4.0. Conclusions

Total river flows at Wells Dam for 2005 were moderate and comparable to flows during the 2003 and 2004 studies. The average daily discharge at Wells Dam peaked at 178.7 kcfs on 27 May 2005. This was similar to the maximum daily average flows for 2003 (167.3 kcfs on 22 May 2003) and 2004 (170.1 kcfs on 29 June 2004), but represented only about 50% of the maximum daily average for 1997 (364.1 kcfs on 12 June 1997), which had the highest flows for the last ten years. Total spillway discharges for the 2005 study ranged from 26.0% to 37.7% of the total project flow. At 7Q10 flows (246 kcfs for Wells Dam) spill would represent approximately 11.6%, assuming the powerhouse were operating at full capacity (220 kcfs). It is more likely that power demand and mechanical constraints would preclude such operation, thus requiring additional spill. The higher background TDG saturations (upstream spill), deeper tailwater, and more turbulent flows experienced during 7Q10 discharges may reduce the ability to extrapolate from the 2005 study results.

Diel temperature cycles were much more pronounced at the Wells forebay monitor site than at the tailwater station (Figure 12). This was consistent with the results of the 2004 study (Figure 13) which had indicated that temperatures measured at the same depth (15 feet) approximately 800 feet upstream of the dam were up to 1 C less than at the forebay station and tracked with tailwater values. One explanation is that surface flows due to spill and/or generation train warmer waters past the forebay probe. Temperatures measured under this scenario would reflect the relatively thin surface layer of water rather than the bulk of the forebay. For the same concentration of a dissolved gas (or gasses) an increase in temperature results in a comparable increase in total gas pressure (Henry's Law). The silastic tubing used for TDG membranes allows diffusion of gasses while excluding the effects of hydrostatic pressure and is the limiting factor in the rapidity of the TDG probe's response to changes. If a TDG sensor is allowed to equilibrate to a given pressure and then heated, TDG pressures will rise quickly as the gasses within the membrane expand. This continues until the probe reaches the new equilibration point for the warmer temperature. Because ancillary probes did not exhibit similar temperature fluctuations, it is likely that the forebay site was not always representative of actual forebay conditions. The simplest solution to this problem would be to relocate the forebay monitor to a location upstream and away from the face of the dam.

Spillway discharges for the eight test events of this study ranged from about 26% to 38% of the total project flow. Spill over a wider range of flows would be needed to develop meaningful TDG production equations for the Wells Spillway. An examination of historical data collected by the Wells TDGFMS indicated that tailwater TDG saturations (WELW) were best explained as a function of background TDG pressures (WEL) and total spill as described by Equation 5. This relationship indicated that every 1 kcfs of additional spill corresponded to an increase of 0.1 % saturation in the tailwater. Previous work indicated that each 5% increase in Wells spill as a percentage of the total project discharge corresponded to a 0.5% in mean downstream TDG saturations (CBE 2003). Past research indicated a 1% increase in TDG saturation for every 4% increase in spill, as determined from the Wells TDGFMS (Klinge 1998). Additional data collected under a wider range of spills will be needed to refine and consolidate these estimates.

Spill from the west spillbays led to higher TDG saturations than similar spill volumes from the east spillbays. This trend was independent of which side of the powerhouse was operating. Lateral gradients observed along Transect A and Transect B indicated that powerhouse flows may have trained spillway releases with gradients of up to 5% saturation persisting to Transect B, approximately 3 miles downstream of the spillway. The west side of the Wells Dam stilling basin is deeper by 10 to 20 feet than the east side and is fairly uniform to the west shore. In contrast, the east side of the stilling basin is adjacent to the earthen portion of Wells Dam and gradually shallows toward the east shore. The deeper channel promotes a greater plunge depth for spilled water and, as a result, may promote gas adsorption.

Crowned spill events resulted in lower TDG saturations than flat spill events for the same total spill and total project discharges. Test 2B (flat spill, moderate flow) yielded TDG saturations approximating Test 2C (crowned spill, high flow) even though the latter test was characterized by higher total river and spill flows, in addition to a deeper tailwater. Flat spill events added spillbays to evenly distribute total spill, thus all operating turbines released water directly into spill. This was in contrast to the crowned spill events, where some bays and generators were idle. This may have effectively increased the volume of water spilled, thus increasing average downstream TDG saturations.

Mass balance analyses indicated that Wells Dam powerhouse release water was gassed by spill at the dam. Data consistently indicated a greater volume of water affected by the Wells Dam spillway than could be explained by the volume of water and TDG saturations measured for the spillway. Relationships between flow-weighted values indicated that the effective TDG saturation of powerhouse release waters was between 3.9-8.0% higher than reported by the forebay monitor. The greatest discrepancies occurred during the spill over load (1A and 1D) and flat spill tests (2B and 2D). These tests included more spill over generating units than the other tests allowing more direct interaction between the different flows.

It is important to note that the mass balance approach was highly dependent on forebay TDG saturations to represent background (i.e. powerhouse) values. It was possible that potential problems with the forebay station location may have magnified (or lessened) the perceived impact of different tests. Upstream spill from Chief Joseph Dam also influenced Wells Forebay TDG saturations. Despite these problems, the consistency and statistical significance of these results indicated that 100% of the Wells Powerhouse release waters were gassed by spill. This supported findings from prior studies that had indicated powerhouse flows were gassed by spill rather than diluting it.

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# Tables

Table 1. Test Matrix for 2005 Wells Dam Spill Evaluation

| Test | Description |
|---|---|
| 1A | Spill over load, east spill/east generation |
| 1B | Divided spill load, east spill/west generation |
| 1C | Divided spill load, west spill/east generation |
| 1D | Spill over load, west spill/west generation |
| 2A | Crowned spill, modest flow |
| 2B | Flat spill, modest flow |
| 2C | Crowned spill, high flow |
| 2D | Flat spill, high flow |

Table 2. Deployment locations for 2005 Wells Dam Spillway Evaluation.

| Serial No. | Station ID | Location (WGS-84) Latitude | Location (WGS-84) Longitude |
|---|---|---|---|
| 42187 | A1 | 47.93971 | -119.85968 |
| 42200 | A2 | 47.94063 | -119.86141 |
| 42195 | A3 | 47.94124 | -119.86393 |
| 42188 | B2 | 47.91400 | -119.89700 |
| 32707 | B3 | 47.91464 | -119.89799 |
| 33254 | WEL | 47.94722 | -119.86508 |
| 32639 | WELW | 47.91304 | -119.89625 |

Table 3. Test Dates and Times for 2005 Wells Dam Spillway Evaluation

| Test | Start Time | End Time | Duration (min.) | n |
|---|---|---|---|---|
| **1A** | 5/24/05 22:00 | 5/25/05 1:00 | 180 | 19 |
| **1B** | 6/1/05 2:00 | 6/1/05 5:00 | 180 | 19 |
| **1C** | 6/1/05 22:00 | 6/2/05 1:00 | 180 | 19 |
| **1D** | 6/3/05 23:00 | 6/4/05 3:00 | 240 | 25 |
| **2A** | 5/23/05 8:00 | 5/23/05 11:00 | 180 | 19 |
| **2B** | 5/25/05 8:00 | 5/25/05 11:00 | 180 | 19 |
| **2C** | 5/23/05 13:00 | 5/23/05 16:00 | 180 | 19 |
| **2D** | 5/26/05 13:00 | 5/26/05 16:00 | 180 | 19 |

Table 4. Mean Unit Discharge for the Wells Dam 2005 Spillway Evaluation

| | | **Discharge (kcfs)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Test** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **Total** |
| 1A | Spillbay | 0.0 | 1.1 | 0.0 | 2.1 | 0.0 | 3.4 | 4.6 | 5.8 | 4.6 | 5.2 | 4.6 | 31.3 |
| | Generator | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.8 | 15.9 | 15.6 | 15.9 | | 63.2 |
| 1B | Spillbay | 0.0 | 1.8 | 0.0 | 3.0 | 0.0 | 4.4 | 5.4 | 4.4 | 5.4 | 3.5 | 5.4 | 33.5 |
| | Generator | 0.0 | 16.1 | 16.2 | 16.0 | 15.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 64.2 |
| 1C | Spillbay | 6.4 | 3.4 | 6.4 | 4.7 | 4.7 | 4.7 | 0.0 | 2.9 | 0.0 | 3.4 | 0.0 | 36.6 |
| | Generator | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.1 | 15.2 | 14.9 | 15.3 | | 60.5 |
| 1D | Spillbay | 5.9 | 1.6 | 5.9 | 4.3 | 5.9 | 4.3 | 0.0 | 4.3 | 0.0 | 1.6 | 0.0 | 33.8 |
| | Generator | 0.0 | 16.0 | 16.1 | 16.2 | 15.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | 64.2 |
| 2A | Spillbay | 0.0 | 1.3 | 0.0 | 3.3 | 8.3 | 6.2 | 8.3 | 3.3 | 0.0 | 1.3 | 0.0 | 32.0 |
| | Generator | 0.0 | 0.0 | 15.2 | 15.1 | 15.0 | 15.2 | 15.2 | 15.3 | 0.0 | 0.0 | | 91.0 |
| 2B | Spillbay | 4.1 | 1.6 | 2.9 | 4.3 | 2.9 | 4.3 | 2.9 | 4.3 | 2.9 | 3.4 | 4.1 | 37.5 |
| | Generator | 0.0 | 0.0 | 14.4 | 14.3 | 14.2 | 14.4 | 14.4 | 14.5 | 0.0 | 0.0 | | 86.3 |
| 2C | Spillbay | 0.0 | 2.3 | 0.0 | 5.4 | 11.3 | 6.9 | 11.3 | 6.9 | 0.0 | 2.3 | 0.0 | 46.3 |
| | Generator | 0.0 | 16.0 | 16.1 | 15.9 | 15.9 | 16.1 | 16.0 | 16.2 | 15.9 | 0.0 | | 128.0 |
| 2D | Spillbay | 5.3 | 1.8 | 5.0 | 4.6 | 5.0 | 4.6 | 5.0 | 4.6 | 5.0 | 3.4 | 0.0 | 44.1 |
| | Generator | 0.0 | 15.4 | 15.5 | 15.3 | 15.2 | 15.4 | 15.6 | 15.5 | 15.2 | 1.7 | | 124.9 |

# Table 5. Water Quality Sensor Calibration Data for 2005 Wells Dam Spillway Evaluation

| S/N | Date | BP (mmHg) | Temperature (ºC) | | | TDG Pressure (mm Hg) | | | | Deviation from TDG Standard (mm Hg) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Std | Probe | Diff | BP + 0 | BP + 100 | BP + 200 | BP + 300 | BP + 0 | BP + 100 | BP + 200 | BP + 300 |
| 32707 | 05/21/05 | 759 | 15.5 | 15.4 | 0.1 | 758 | 858 | 958 | 1058 | 1 | 1 | 1 | 1 |
| 42187 | 05/21/05 | 759 | 15.5 | 15.5 | 0.0 | 758 | 858 | 958 | 1058 | 1 | 1 | 1 | 1 |
| 42188 | 05/21/05 | 759 | 15.6 | 15.6 | 0.0 | 759 | 859 | 959 | 1059 | 0 | 0 | 0 | 0 |
| 42195 | 05/21/05 | 759 | 15.4 | 15.4 | 0.0 | 759 | 859 | 959 | 1059 | -1 | -1 | -1 | -1 |
| 42200 | 05/21/05 | 759 | 15.5 | 15.5 | 0.0 | 759 | 859 | 959 | 1059 | 0 | 0 | 0 | 0 |
| 32639 | 05/22/05 | 744 | 10.9 | 10.8 | 0.1 | 743 | 843 | 943 | 1042 | 1 | 1 | 1 | 2 |
| 33254 | 05/22/05 | 743 | 11.0 | 11.0 | 0.0 | 742 | 842 | 942 | 1043 | 1 | 1 | 1 | 0 |
| 32707 | 06/06/05 | 752 | 16.4 | 16.4 | 0.0 | 751 | 851 | 951 | 1051 | -1 | -1 | 1 | 1 |
| 42187 | 06/06/05 | 752 | 16.4 | 16.4 | 0.0 | 751 | 851 | 951 | 1051 | -1 | -1 | 1 | 1 |
| 42188 | 06/06/05 | 752 | 16.3 | 16.2 | 0.1 | 751 | 851 | 952 | 1052 | -1 | -1 | 0 | 0 |
| 42195 | 06/06/05 | 752 | 16.3 | 16.3 | 0.0 | 752 | 851 | 951 | 1051 | 0 | -1 | 1 | 1 |
| 42200 | 06/06/05 | 752 | 16.4 | 16.4 | 0.0 | 757 | 857 | 958 | 1058 | -5 | -5 | -6 | -6 |
| 32639 | 06/05/05 | 735 | 12.9 | 12.8 | 0.1 | 734 | 834 | 934 | 1034 | -1 | -1 | 1 | 1 |
| 33254 | 06/05/04 | 734 | 13.1 | 13.1 | 0.0 | 734 | 834 | 934 | 1034 | 0 | 0 | 0 | 0 |

Table 6. Summary Data for Water Temperatures for the Wells Dam 2005 Spillway Evaluation

| | Test | Water Temperature (ºC) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **WEL** | **WELW** | **A1** | **A2** | **A3** | **B2** | **B3** |
| **Mean** | 1A | 11.1 | 11.0 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 |
| | 1B | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| | 1C | 12.6 | 12.6 | 12.7 | 12.7 | 12.7 | 12.6 | 12.7 |
| | 1D | 13.0 | 12.9 | 13.0 | 13.0 | 12.9 | 12.9 | 12.9 |
| | 2A | 11.1 | 10.9 | 11.0 | 11.0 | 11.0 | 11.0 | 11.1 |
| | 2B | 11.3 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 |
| | 2C | 11.3 | 11.2 | 11.2 | 11.2 | 11.3 | 11.2 | 11.3 |
| | 2D | 11.3 | 11.2 | 11.2 | 11.2 | 11.2 | 11.1 | 11.2 |
| **Maximum** | 1A | 11.2 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 |
| | 1B | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| | 1C | 12.6 | 12.6 | 12.7 | 12.7 | 12.7 | 12.7 | 12.7 |
| | 1D | 13.0 | 12.9 | 13.0 | 13.0 | 13.0 | 12.9 | 12.9 |
| | 2A | 11.2 | 10.9 | 11.0 | 11.1 | 11.1 | 11.0 | 11.1 |
| | 2B | 11.3 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 |
| | 2C | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.2 | 11.3 |
| | 2D | 11.5 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 |
| **Minimum** | 1A | 11.1 | 11.0 | 11.1 | 11.1 | 11.1 | 11.1 | 11.1 |
| | 1B | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 | 12.5 |
| | 1C | 12.6 | 12.6 | 12.7 | 12.6 | 12.6 | 12.6 | 12.7 |
| | 1D | 13.0 | 12.9 | 13.0 | 13.0 | 12.9 | 12.9 | 12.9 |
| | 2A | 11.1 | 10.9 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| | 2B | 11.3 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 |
| | 2C | 11.3 | 11.2 | 11.2 | 11.2 | 11.3 | 11.2 | 11.3 |
| | 2D | 11.3 | 11.2 | 11.1 | 11.1 | 11.2 | 11.1 | 11.2 |

Table 7. Summary Data for TDG Saturations for the Wells Dam 2005 Spillway Evaluation

|  | Test | BP (mmHg) WEL | TDG %Saturation |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  | WEL | WELW | A1 | A2 | A3 | B2 | B3 |
| Mean | 1A | 752.7 | 105.6 | 111.3 | 111.3 | 113.7 | 116.3 | 113.2 | 114.0 |
|  | 1B | 741.0 | 108.6 | 112.3 | 114.3 | 114.0 | 112.5 | 113.7 | 112.3 |
|  | 1C | 742.3 | 107.6 | 112.4 | 111.9 | 116.7 | 119.3 | 115.5 | 116.8 |
|  | 1D | 741.5 | 107.8 | 114.2 | 115.8 | 115.7 | 116.8 | 115.7 | 115.2 |
|  | 2A | 748.5 | 105.4 | 109.7 | 109.3 | 112.2 | 112.8 | 111.2 | 112.0 |
|  | 2B | 753.4 | 106.4 | 112.7 | 114.4 | 113.1 | 115.4 | 113.5 | 114.2 |
|  | 2C | 746.8 | 106.6 | 113.0 | 112.0 | 114.7 | 116.1 | 114.2 | 115.5 |
|  | 2D | 747.2 | 109.1 | 115.1 | 114.9 | 115.6 | 117.6 | 115.7 | 116.7 |
| Maximum | 1A | 752.9 | 105.7 | 111.5 | 111.3 | 113.7 | 116.4 | 113.2 | 114.1 |
|  | 1B | 741.2 | 108.6 | 113.0 | 114.3 | 114.2 | 112.6 | 113.9 | 112.6 |
|  | 1C | 742.4 | 107.7 | 112.8 | 112.1 | 117.1 | 119.5 | 116.1 | 116.9 |
|  | 1D | 741.7 | 107.8 | 114.4 | 115.8 | 115.8 | 116.9 | 115.7 | 115.3 |
|  | 2A | 748.8 | 105.6 | 110.2 | 109.5 | 112.4 | 112.9 | 111.5 | 112.4 |
|  | 2B | 753.6 | 106.4 | 113.0 | 114.5 | 113.2 | 115.6 | 113.6 | 114.3 |
|  | 2C | 747.0 | 106.7 | 113.1 | 112.2 | 114.8 | 116.1 | 114.2 | 115.6 |
|  | 2D | 747.5 | 109.1 | 115.3 | 115.0 | 115.7 | 117.9 | 115.8 | 116.8 |
| Minimum | 1A | 752.6 | 105.5 | 111.1 | 111.3 | 113.7 | 116.1 | 113.1 | 113.9 |
|  | 1B | 740.9 | 108.5 | 111.3 | 114.2 | 113.9 | 112.3 | 113.6 | 111.6 |
|  | 1C | 742.2 | 107.6 | 111.8 | 111.4 | 116.2 | 119.0 | 115.0 | 116.8 |
|  | 1D | 741.4 | 107.7 | 113.9 | 115.8 | 115.7 | 116.7 | 115.7 | 115.1 |
|  | 2A | 748.3 | 105.1 | 109.2 | 109.2 | 111.9 | 112.6 | 111.0 | 111.8 |
|  | 2B | 753.4 | 106.3 | 112.4 | 114.4 | 113.0 | 115.3 | 113.4 | 114.1 |
|  | 2C | 746.8 | 106.6 | 112.8 | 111.9 | 114.6 | 115.9 | 114.1 | 115.4 |
|  | 2D | 747.0 | 109.0 | 114.7 | 114.8 | 115.5 | 117.3 | 115.6 | 116.6 |

Table 8. Project Operation and TDG Saturation Spill Test Means

| Test | n* | Discharge (kcfs) | | | %Spill | Elevation (ft MSL) | | TDG %Saturation | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Project | Spill | Power | %Spill | Forebay | Tailwater | WEL | WELW | A1 | A2 | A3 | B2 | B3 |
| **1A** | 4 | 94.5 | 31.2 | 63.2 | 33.1% | 778.8 | 710.8 | 105.6 | 111.3 | 111.3 | 113.7 | 116.3 | 113.2 | 114.0 |
| **1B** | 9 | 97.6 | 33.4 | 64.2 | 34.2% | 778.4 | 710.6 | 108.6 | 112.3 | 114.3 | 114.0 | 112.5 | 113.7 | 112.3 |
| **1C** | 5 | 97.1 | 36.6 | 60.5 | 37.7% | 778.9 | 710.6 | 107.6 | 112.4 | 111.9 | 116.7 | 119.3 | 115.5 | 116.8 |
| **1D** | 5 | 98.2 | 34.0 | 64.2 | 34.6% | 778.6 | 710.8 | 107.8 | 114.2 | 115.8 | 115.7 | 116.8 | 115.7 | 115.2 |
| **2A** | 7 | 122.9 | 31.9 | 91.0 | 26.0% | 778.9 | 712.5 | 105.4 | 109.7 | 109.3 | 112.2 | 112.8 | 111.2 | 112.0 |
| **2B** | 4 | 123.8 | 37.6 | 86.3 | 30.3% | 780.3 | 712.5 | 106.4 | 112.7 | 114.4 | 113.1 | 115.4 | 113.5 | 114.2 |
| **2C** | 5 | 174.4 | 46.4 | 128.0 | 26.6% | 778.8 | 716.4 | 106.6 | 113.0 | 112.0 | 114.7 | 116.1 | 114.2 | 115.5 |
| **2D** | 7 | 168.9 | 43.9 | 124.9 | 26.0% | 780.2 | 716.0 | 109.1 | 115.1 | 114.9 | 115.6 | 117.6 | 115.7 | 116.7 |

*Refers to equilibrated values.

Table 9. Summary Data from Mass Balance Analyses

| Test | TDG %Saturation | | | | | | |
|---|---|---|---|---|---|---|---|
| | Empirical | | | | Predicted | | |
| | Avg Transect A TDG | Avg Transect B TDG | Max Transect A TDG | Min Transect A TDG | Avg Transect B TDG (assumes no change to powerhouse release) | Avg TDG of Spilled release | Avg Transect B TDG (assumes PH release gassed to Min Transect A) |
| **1A** | 113.8 | 112.8 | 116.3 | 111.3 | 109.1 | 127.4 | 113.0 |
| **1B** | 113.6 | 112.8 | 114.3 | 112.5 | 110.5 | 120.8 | 113.1 |
| **1C** | 116.0 | 114.9 | 119.3 | 111.9 | 112.0 | 126.9 | 114.7 |
| **1D** | 116.1 | 115.0 | 116.8 | 115.7 | 110.9 | 128.8 | 116.1 |
| **2A** | 111.4 | 111.0 | 112.8 | 109.3 | 107.3 | 127.0 | 110.2 |
| **2B** | 114.3 | 113.5 | 115.4 | 113.1 | 109.1 | 129.8 | 113.8 |
| **2C** | 114.3 | 114.2 | 116.1 | 112.0 | 109.1 | 135.2 | 113.1 |
| **2D** | 116.0 | 115.8 | 117.6 | 114.9 | 111.3 | 135.0 | 115.6 |

Table 10. Average of 12 Highest Daily TDG Saturations

| Date | CHQW | WEL | WELW | A1 | A2 | A3 | B2 | B3 | RRH |
|---|---|---|---|---|---|---|---|---|---|
| 5/23/2005 | 107.0 | 106.2 | 110.1 | 109.3 | 111.5 | 111.3 | 110.7 | 111.4 | 107.0 |
| 5/24/2005 | 107.5 | 105.9 | 108.5 | 109.1 | 109.7 | 108.0 | 108.9 | 108.1 | 107.2 |
| 5/25/2005 | 116.1 | 106.7 | 111.6 | 111.6 | 112.5 | 114.0 | 112.1 | 113.2 | 109.0 |
| 5/26/2005 | 107.4 | 108.4 | 113.4 | 113.2 | 115.0 | 115.7 | 114.1 | 114.7 | 110.9 |
| 5/27/2005 | 108.5 | 108.0 | 116.7 | 114.7 | 117.6 | 117.8 | 117.1 | 118.2 | 113.9 |
| 5/28/2005 | 110.4 | 109.4 | 110.0 | 109.4 | 111.2 | 112.2 | 110.5 | 111.5 | 120.4 |
| 5/29/2005 | 111.2 | 110.7 | 110.6 | 110.1 | 111.4 | 112.5 | 110.9 | 111.8 | 114.1 |
| 5/30/2005 | 111.1 | 109.7 | 110.9 | 110.4 | 112.4 | 112.3 | 111.5 | 111.8 | 112.1 |
| 5/31/2005 | 109.2 | 109.4 | 111.0 | 111.2 | 112.2 | 112.3 | 111.4 | 111.7 | 111.3 |
| 6/1/2005 | 110.1 | 108.8 | 111.8 | 112.4 | 112.7 | 111.7 | 112.1 | 111.4 | 110.6 |
| 6/2/2005 | 109.6 | 108.5 | 112.1 | 111.8 | 112.9 | 113.1 | 112.7 | 113.6 | 110.6 |
| 6/3/2005 | 109.5 | 108.5 | 110.1 | 110.1 | 111.4 | 110.7 | 110.6 | 110.3 | 111.6 |
| 6/4/2005 | 110.0 | 109.0 | 112.8 | 112.4 | 113.1 | 112.9 | 113.3 | 112.8 | 111.9 |

# Figures

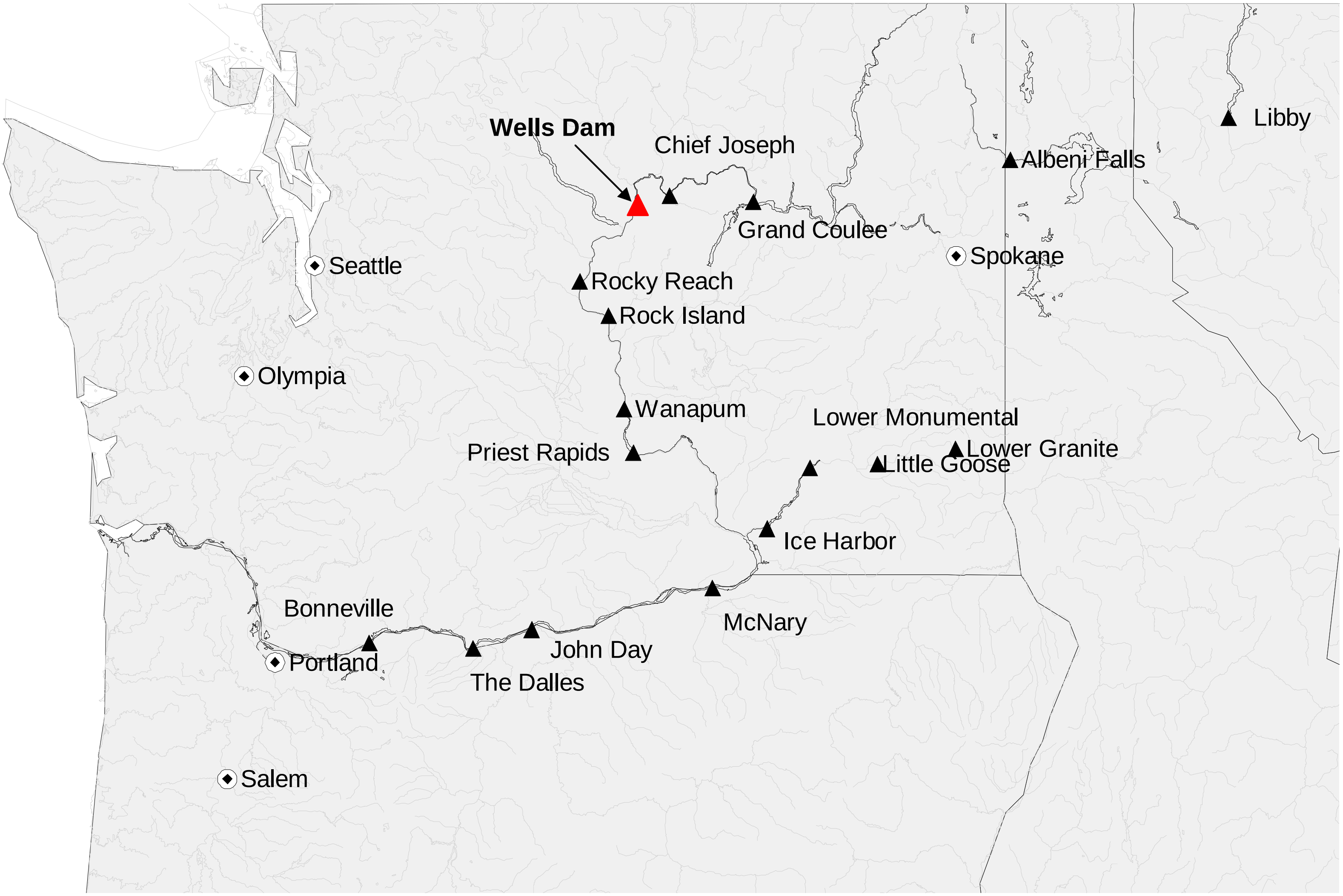

Figure 1. Regional map indicating location of Wells Dam.

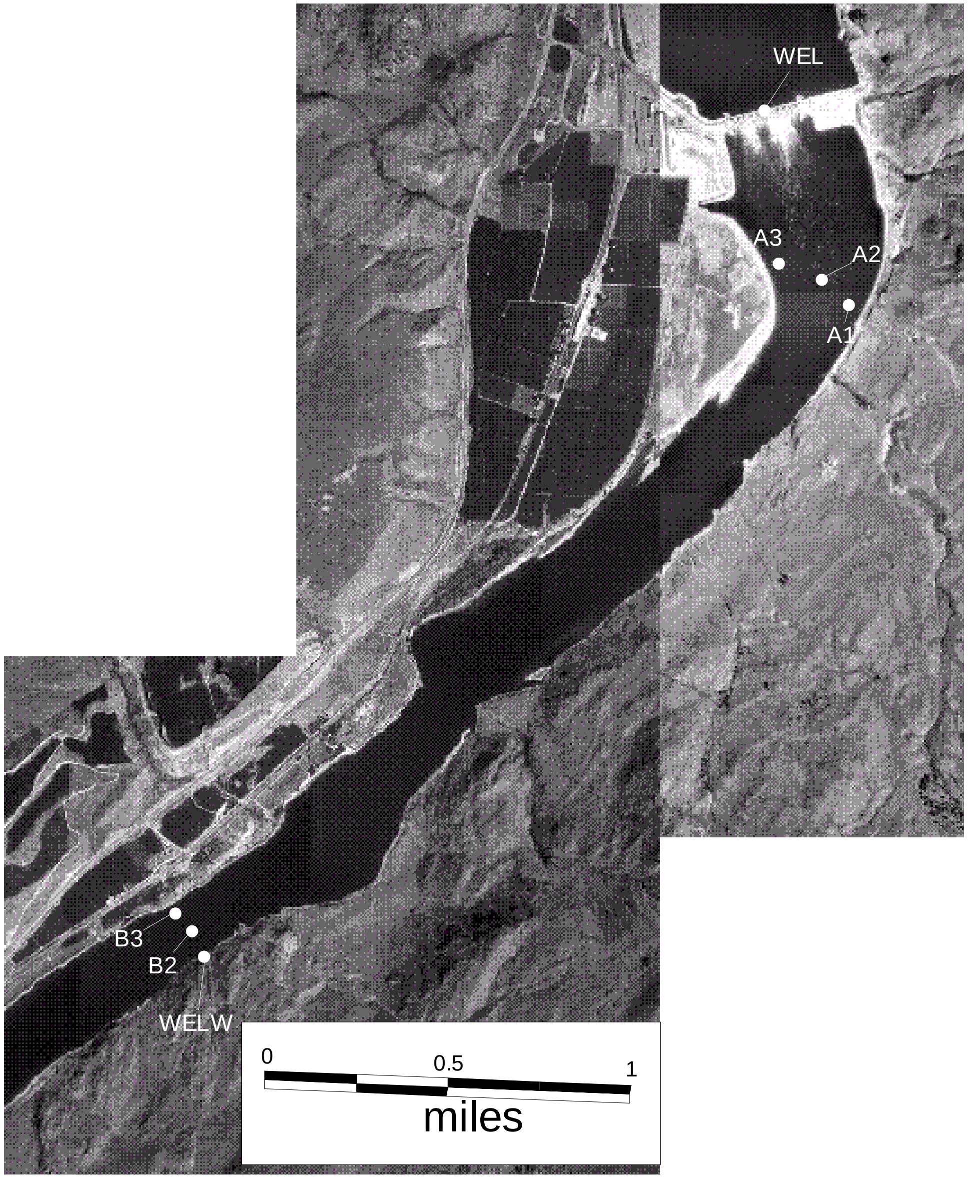

Figure 2. Deployment locations for 2005 Wells Dam Spillway evaluation.

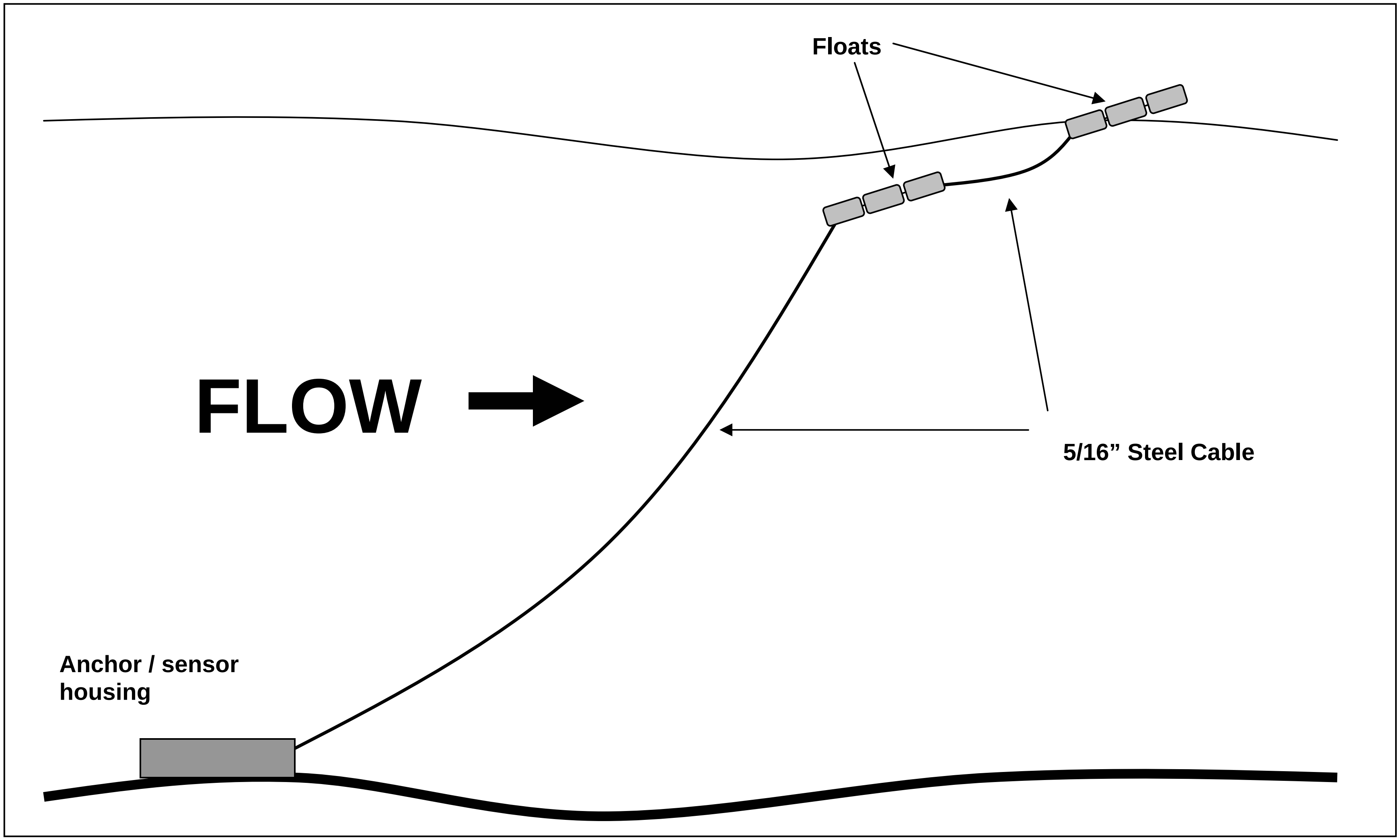

Figure 3. Schematic representation of anchor and buoy deployment rigging.

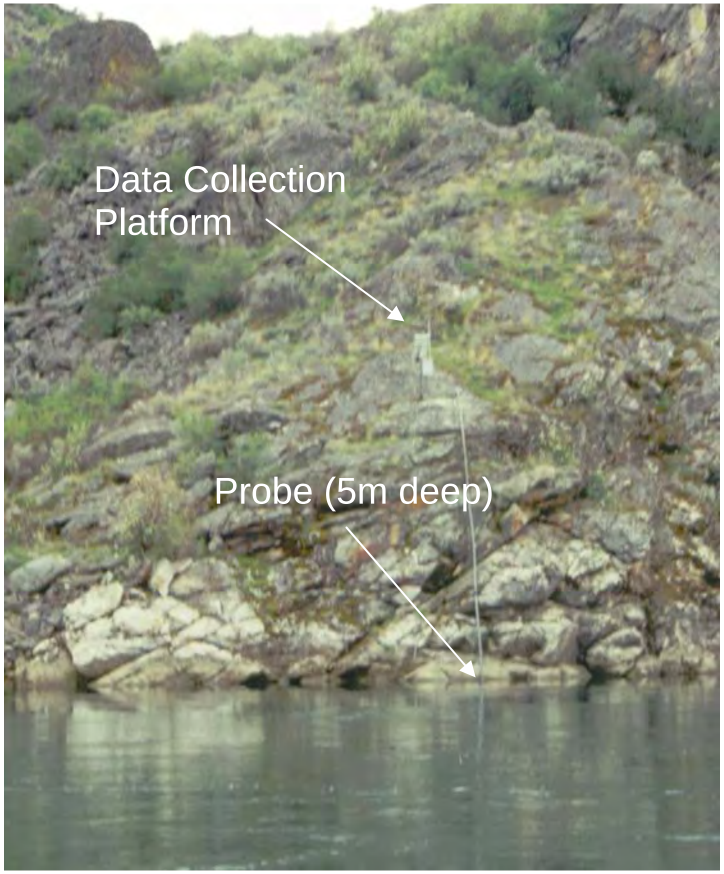

Figure 4. Wells Dam tailwater fixed water quality monitoring station.

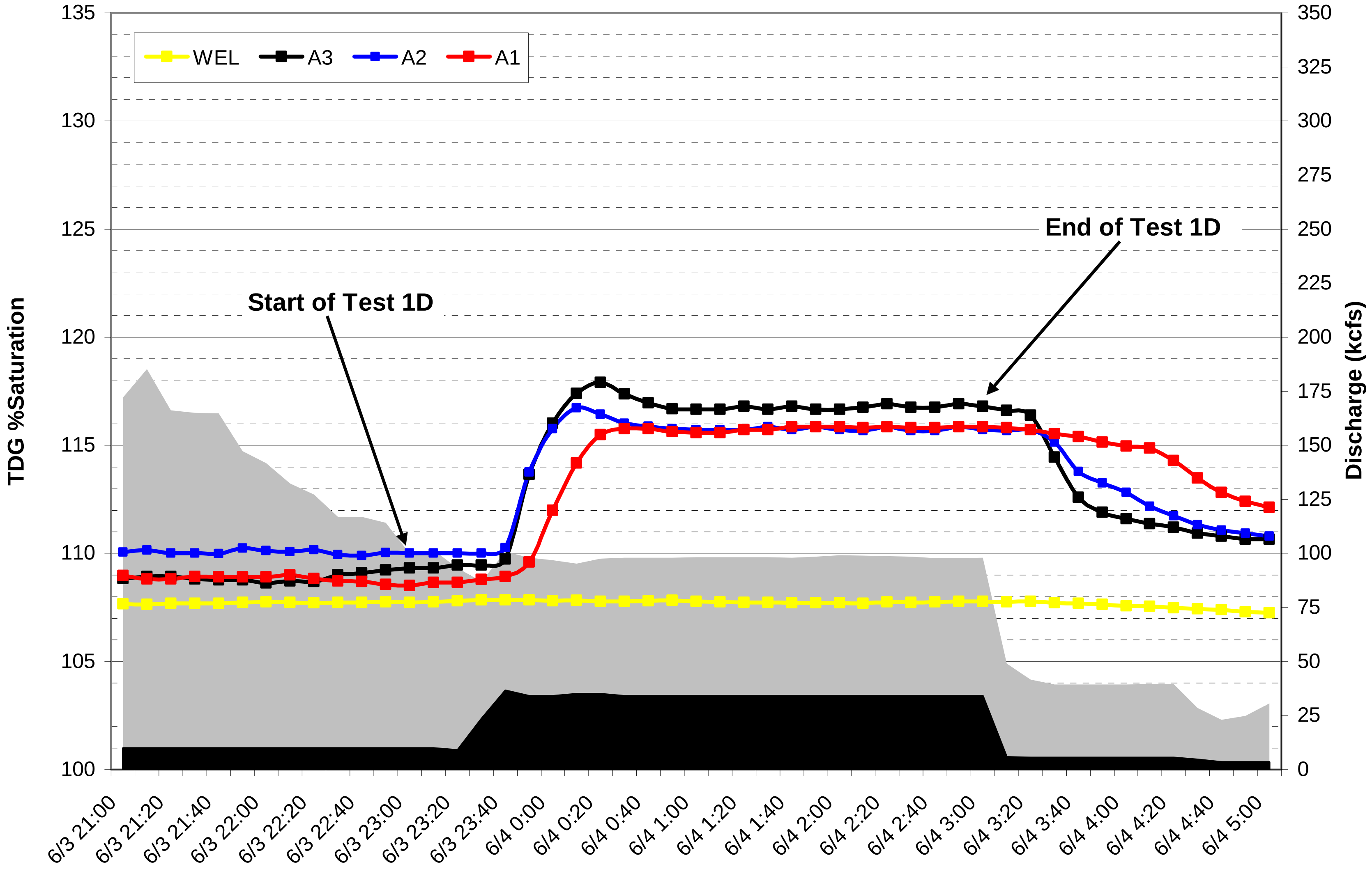

Figure 5. Transect A TDG saturations for Spill Test 1D, 3 June 23:00 to 4 June 03:00 2005.

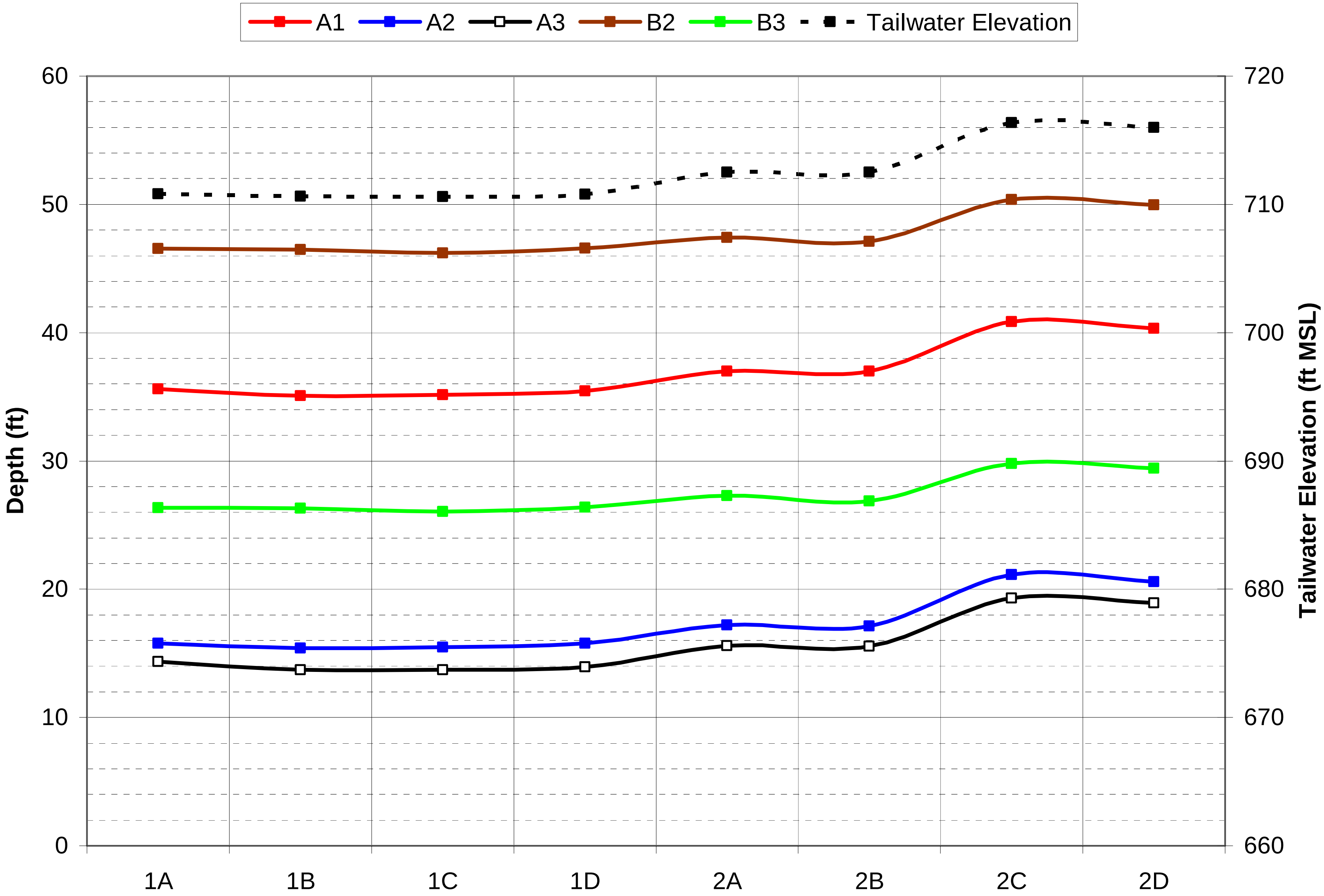

Figure 6. TDG probe depths and tailwater elevations averaged by test.

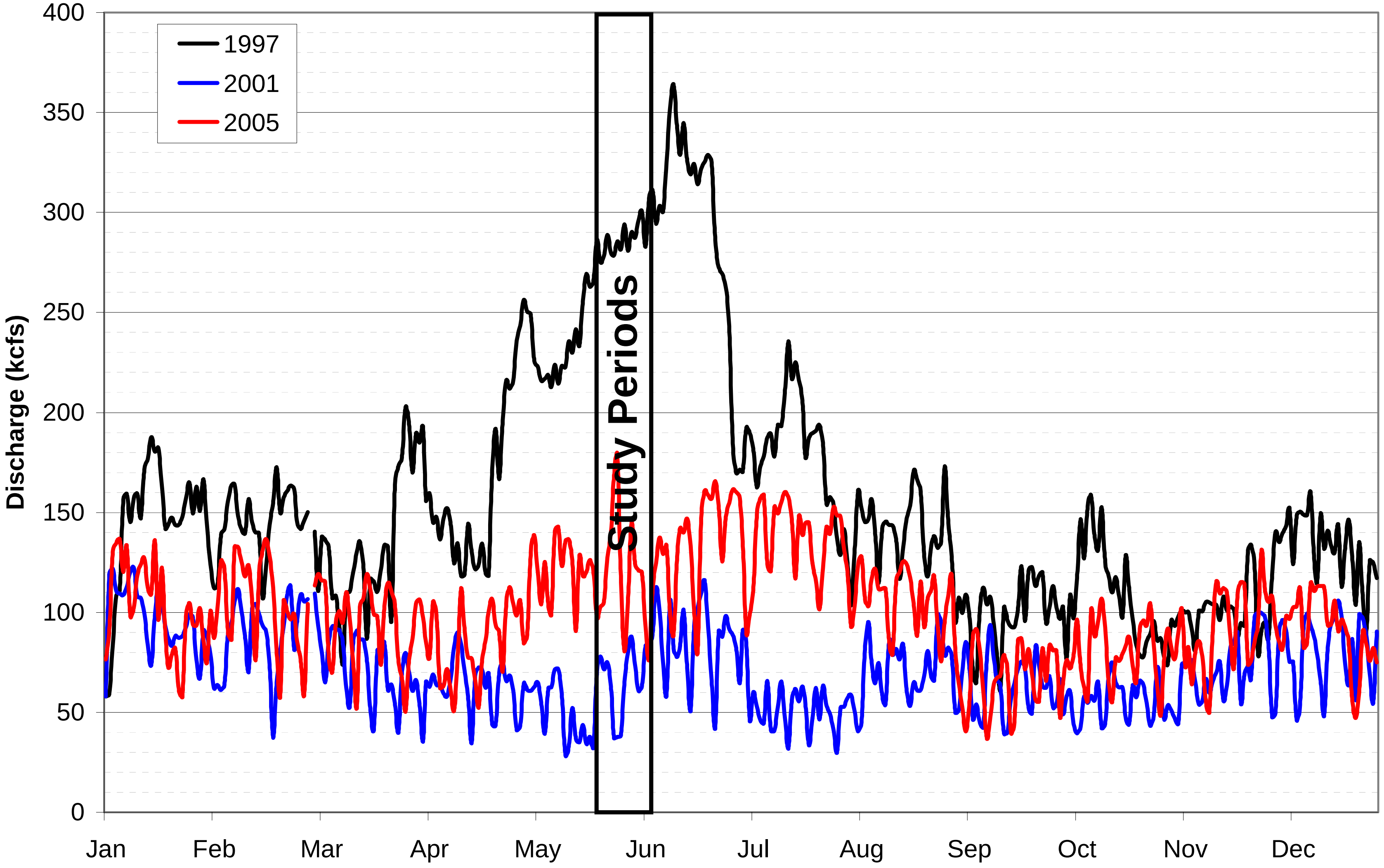

Figure 7. Mean daily discharge for Wells Dam for the years 1997, 2001, and 2005.

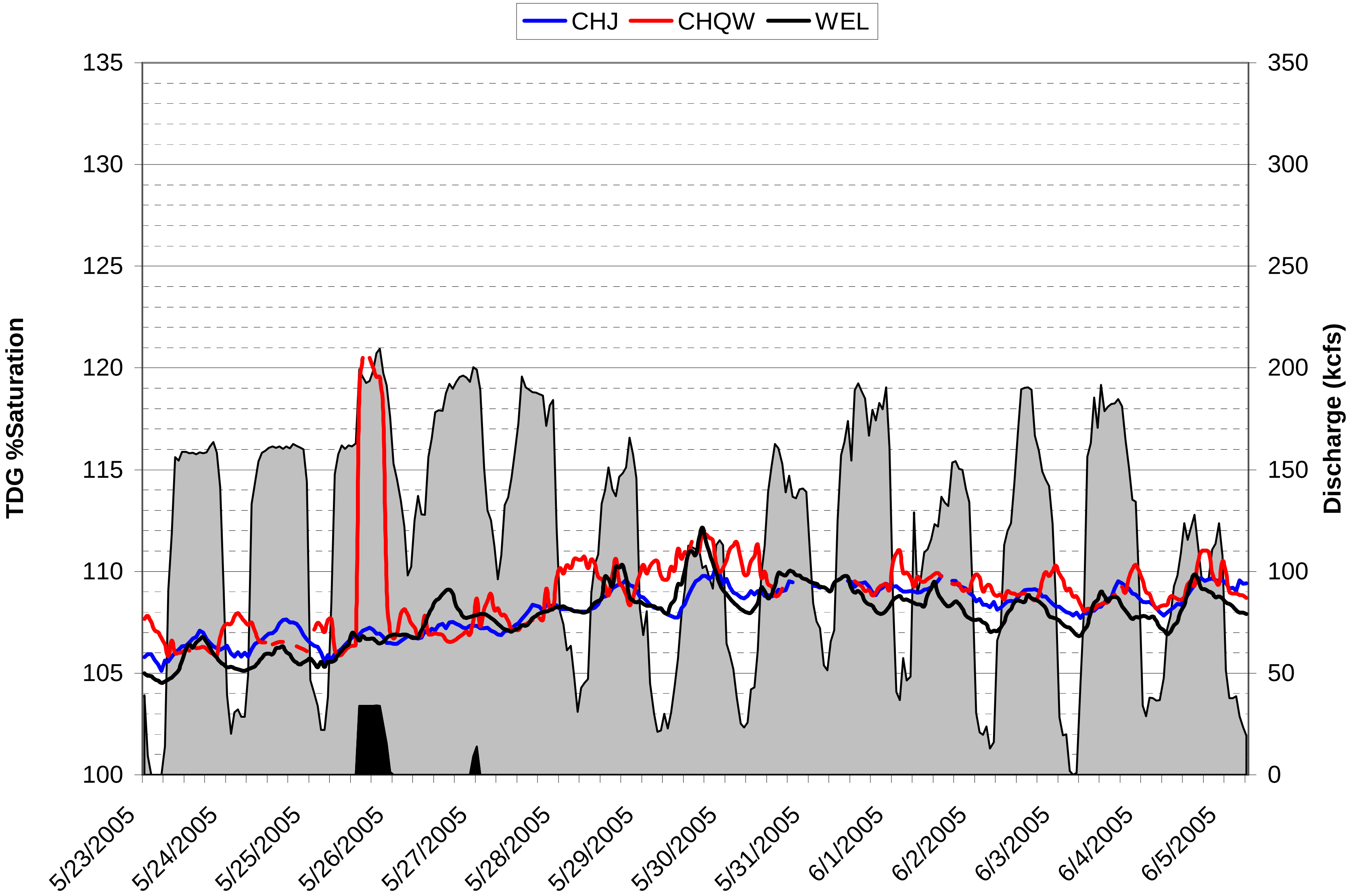

Figure 8. Total project and spill discharges for Chief Joseph Dam plotted with FMS TDG saturation data as reported by CROHMS.

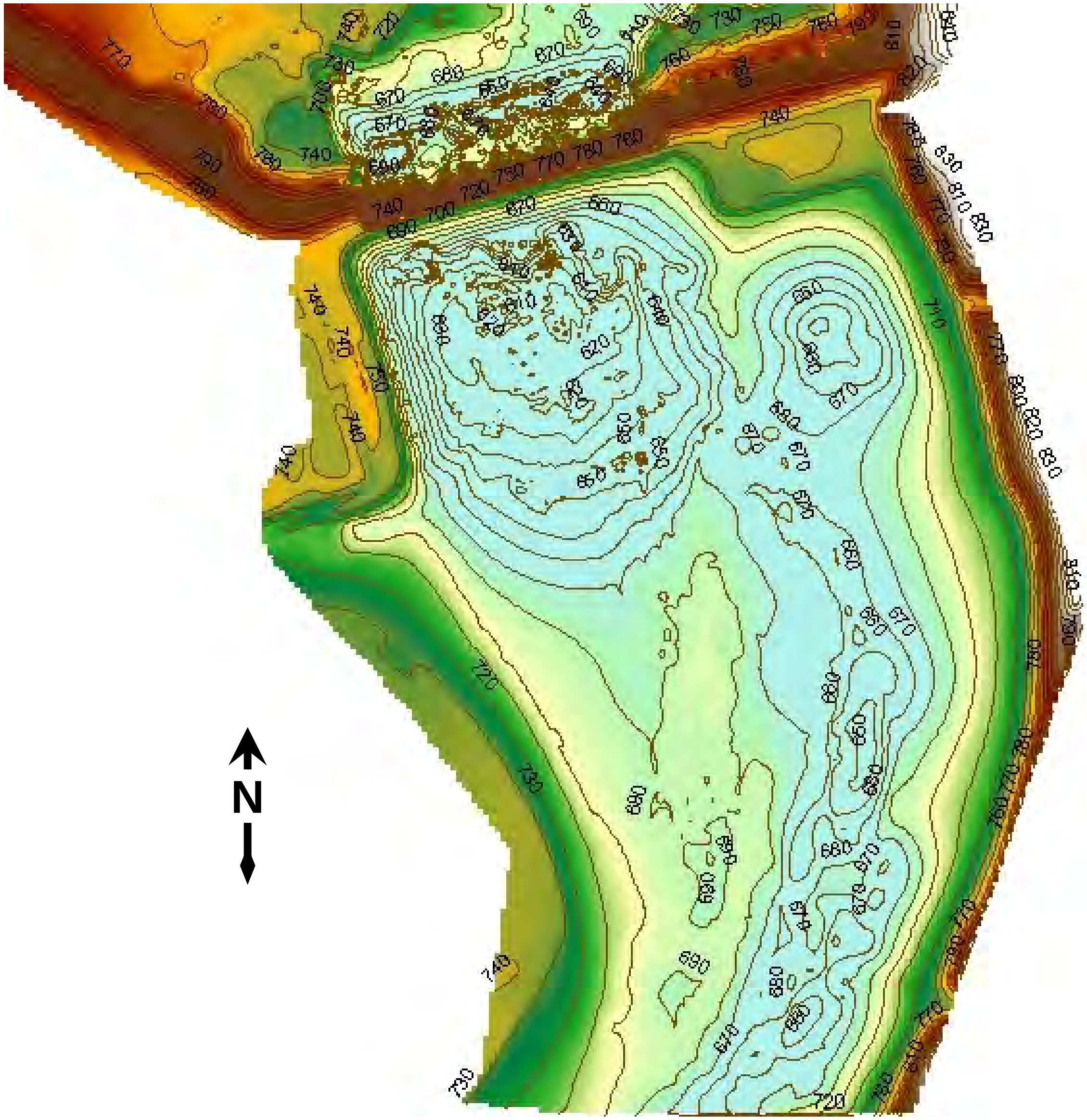

Figure 9. Wells Dam tailrace bathymetry. (Image provided by Jacobs Civil, Inc.)

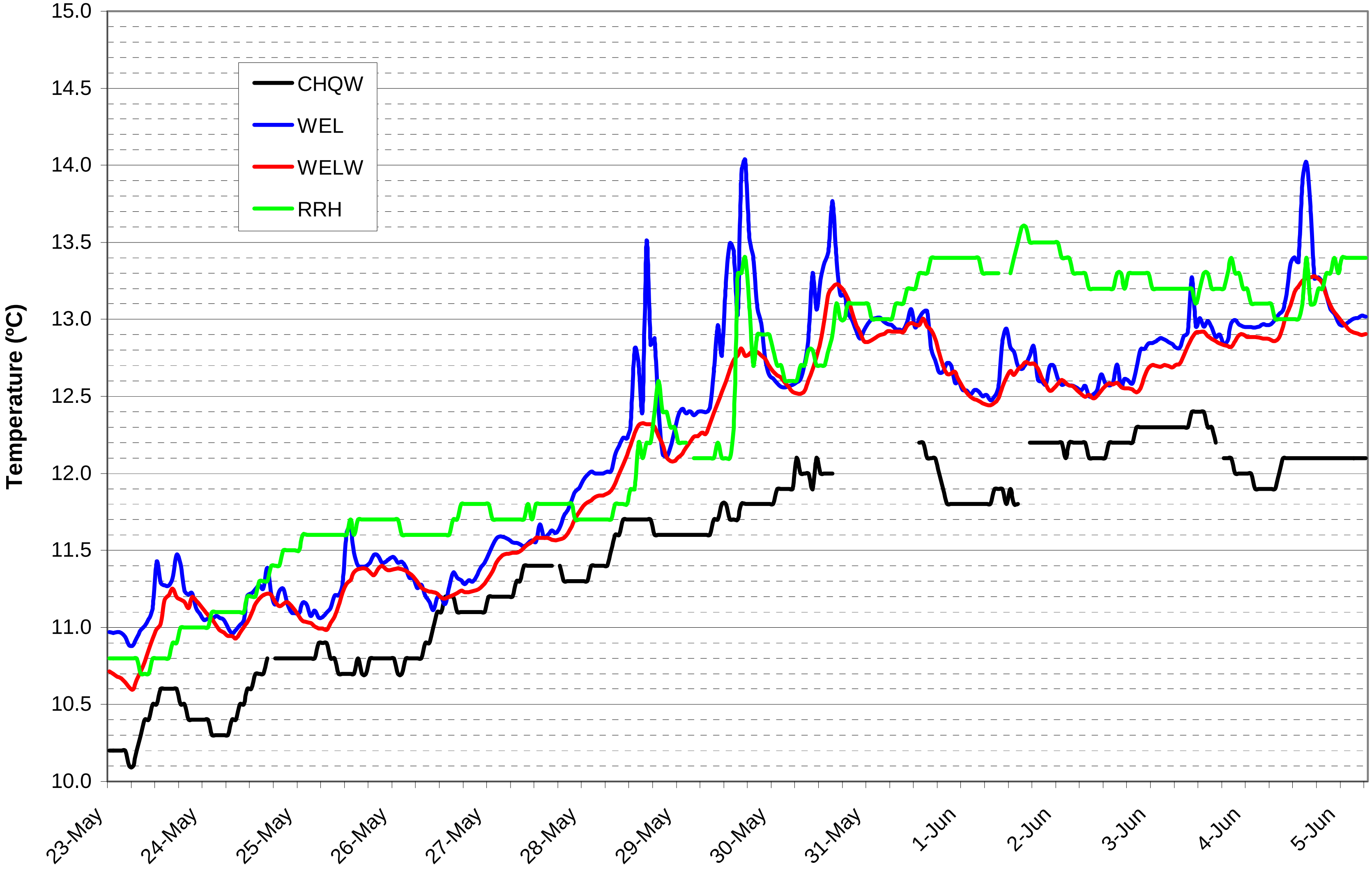

Figure 10. Hourly temperatures for the CHJ tailwater, Wells Dam, and the RRH forebay as reported the CROHMS.

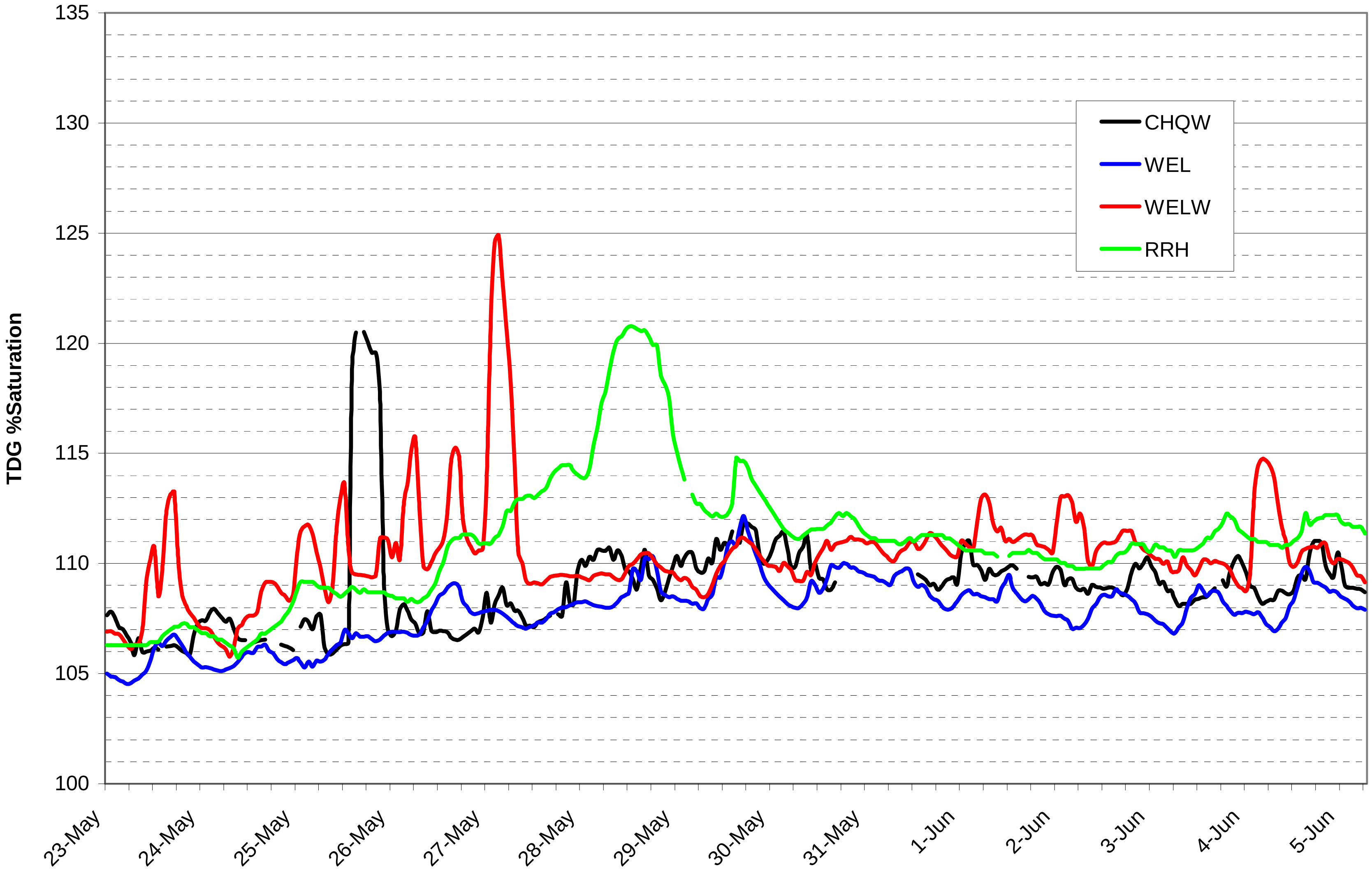

Figure 11. Hourly TDG saturations for the CHJ tailwater, Wells Dam, and the RRH forebay as reported the CROHMS.

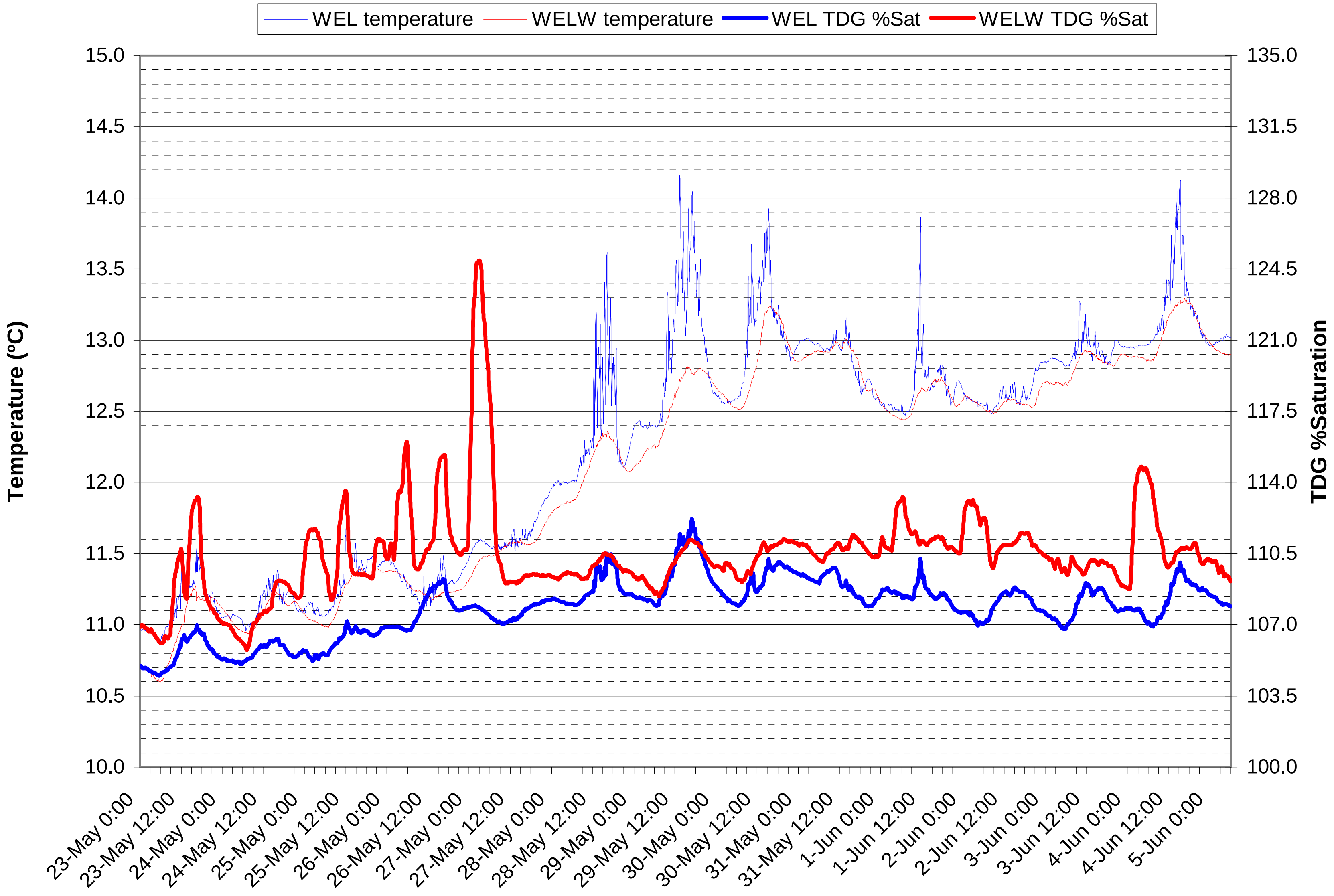

Figure 12. Water temperatures and TDG saturations reported for the Wells Dam permanent TDG monitors.

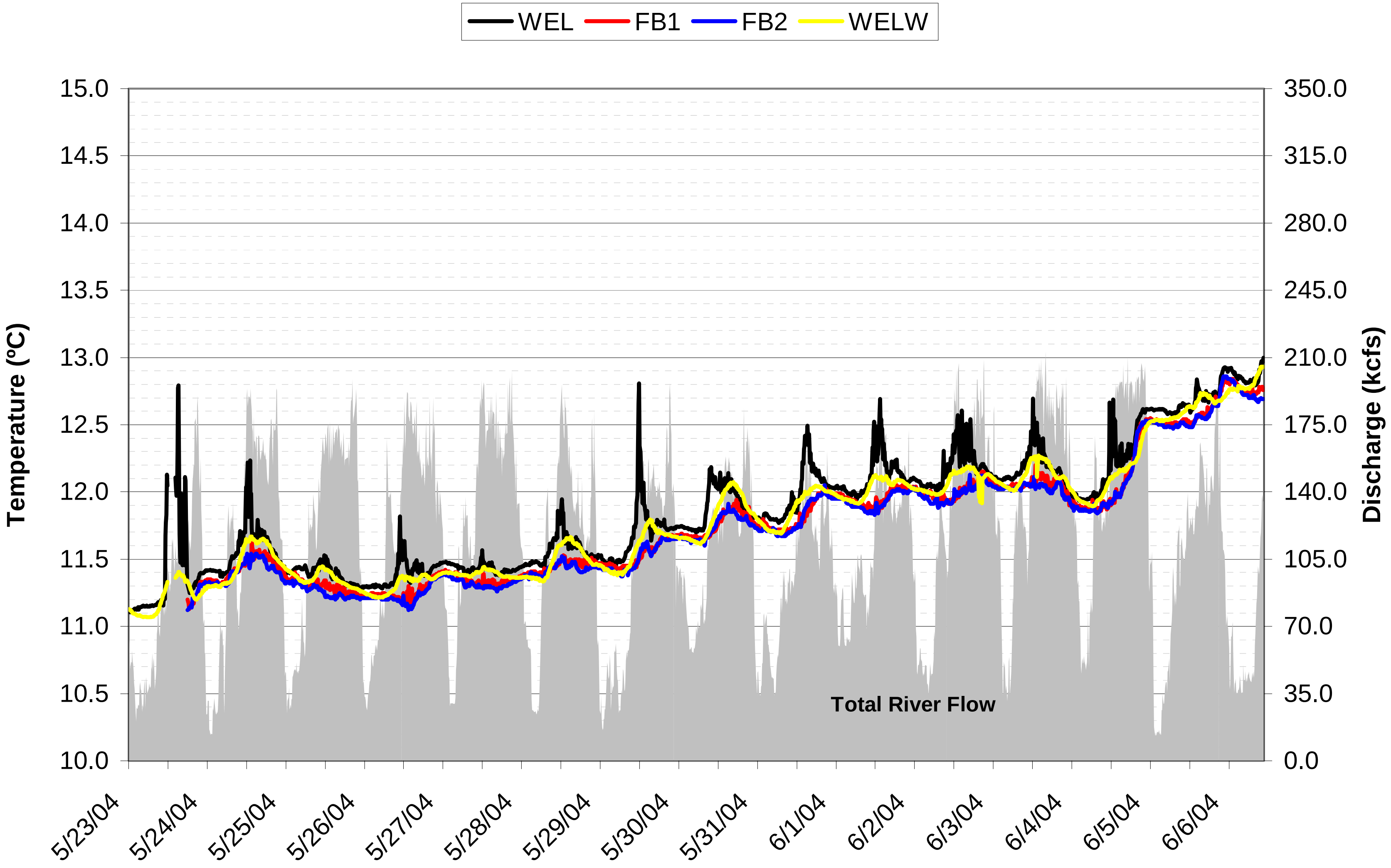

Figure 13. Water temperatures measured in the Wells Dam Forebay between 23 May and 6 June, 2004.

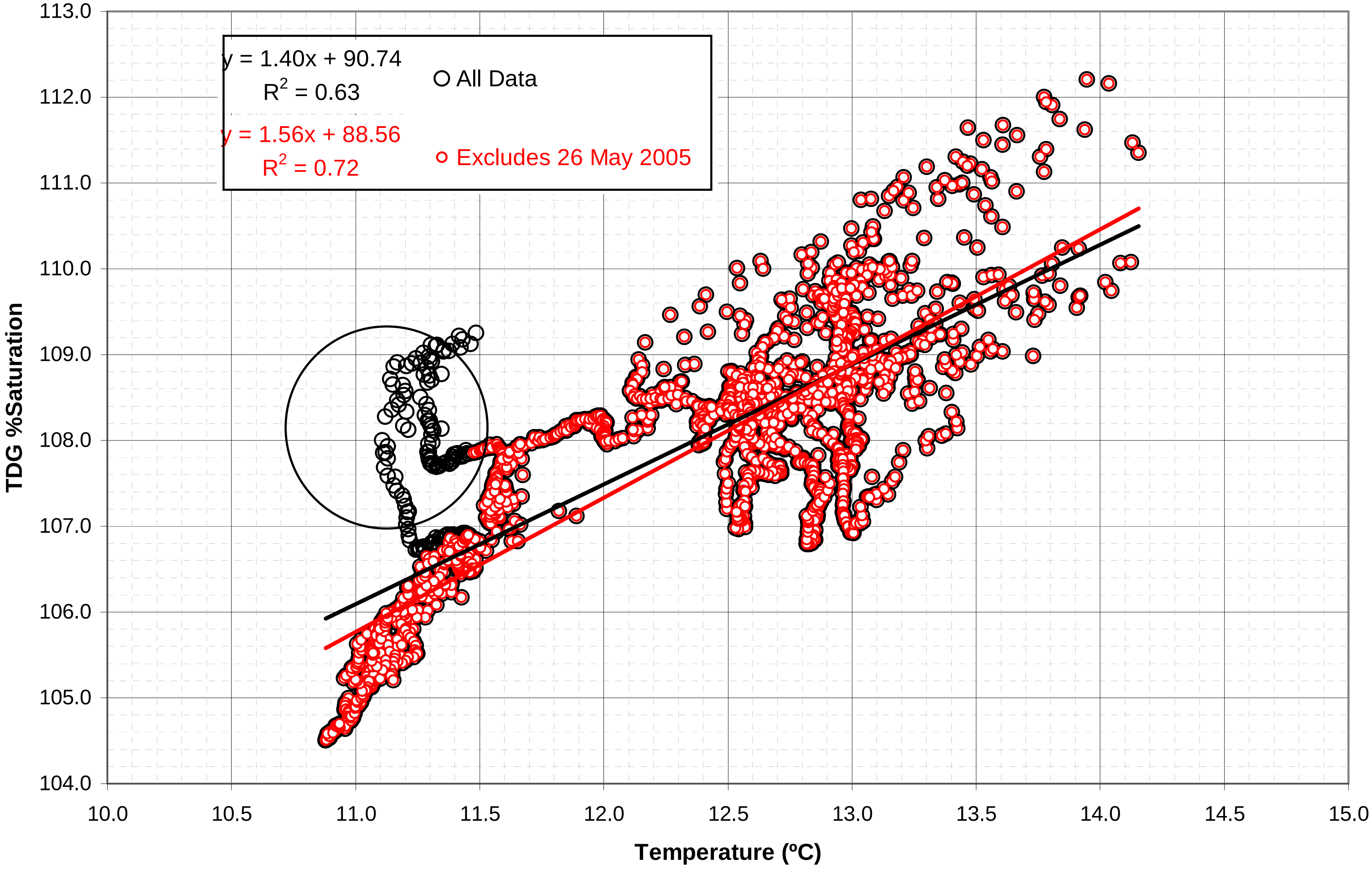

Figure 14. Wells Dam forebay (WEL) water temperatures plotted against TDG saturations.

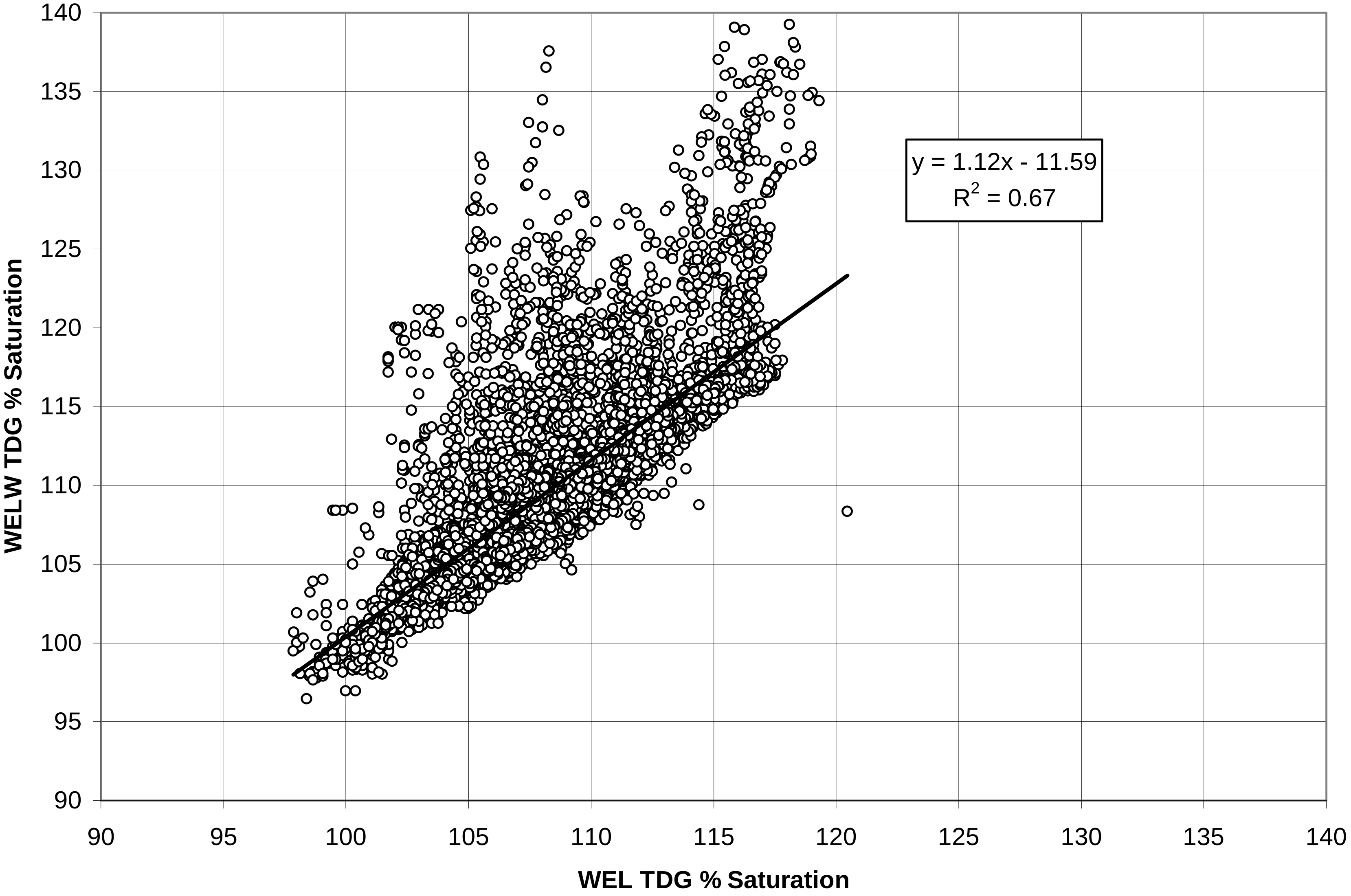

Figure 15. Relationship between WELW and WEL for 1998-2005.

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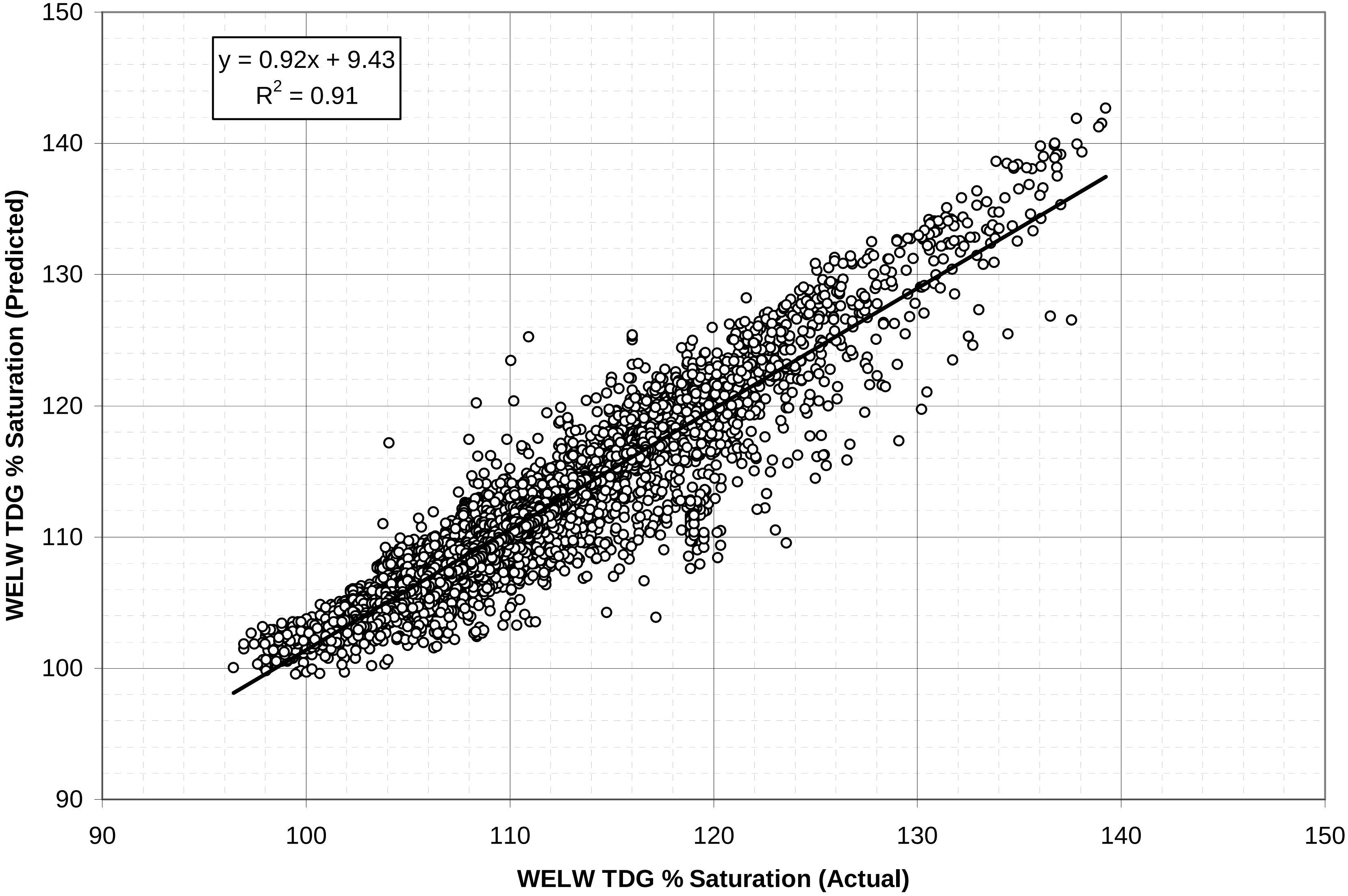

Figure 16. Predicted versus actual WELW TDG saturations.

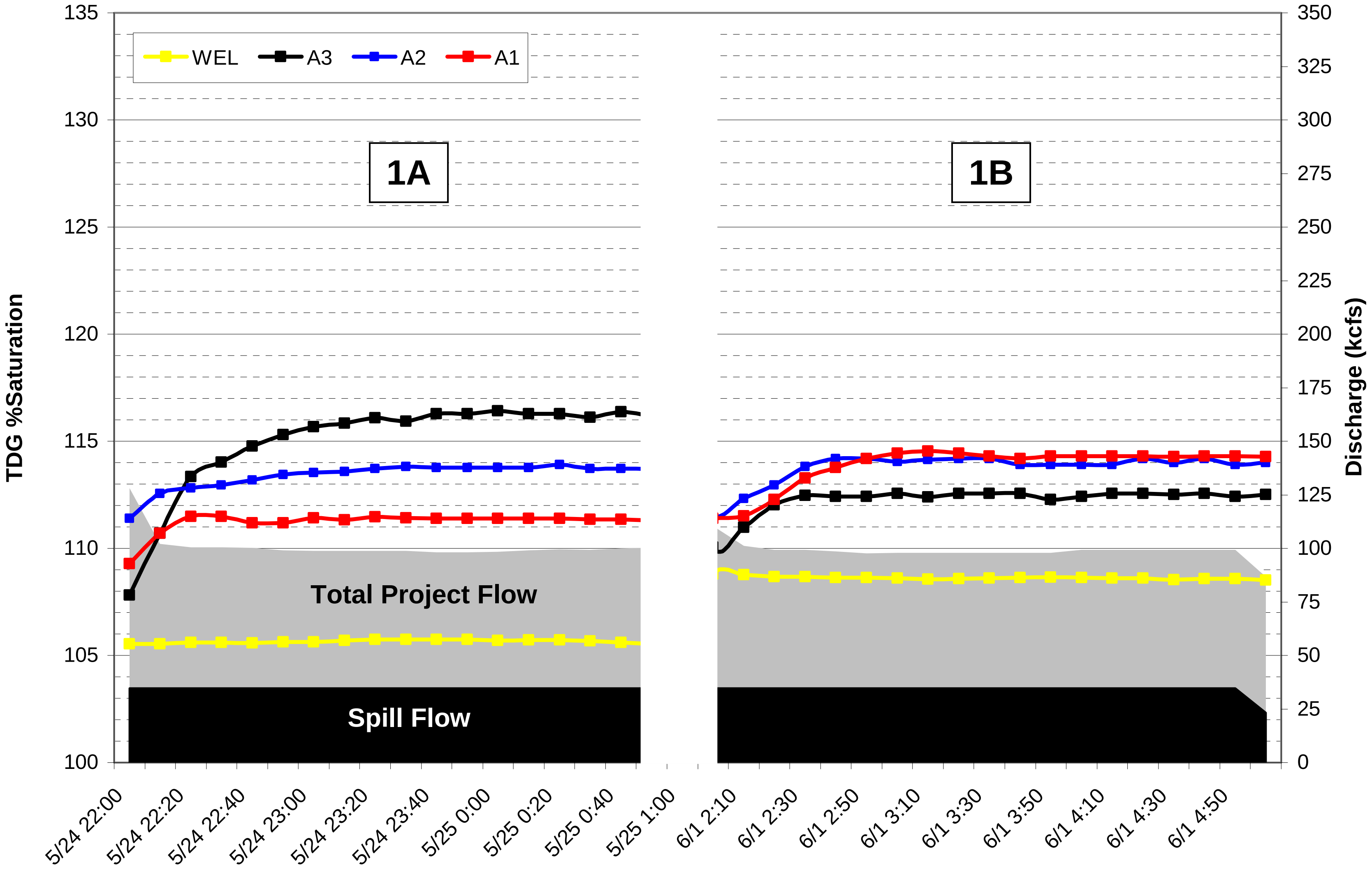

Figure 17. Project operation and Transect A values for tests 1A and 1B.

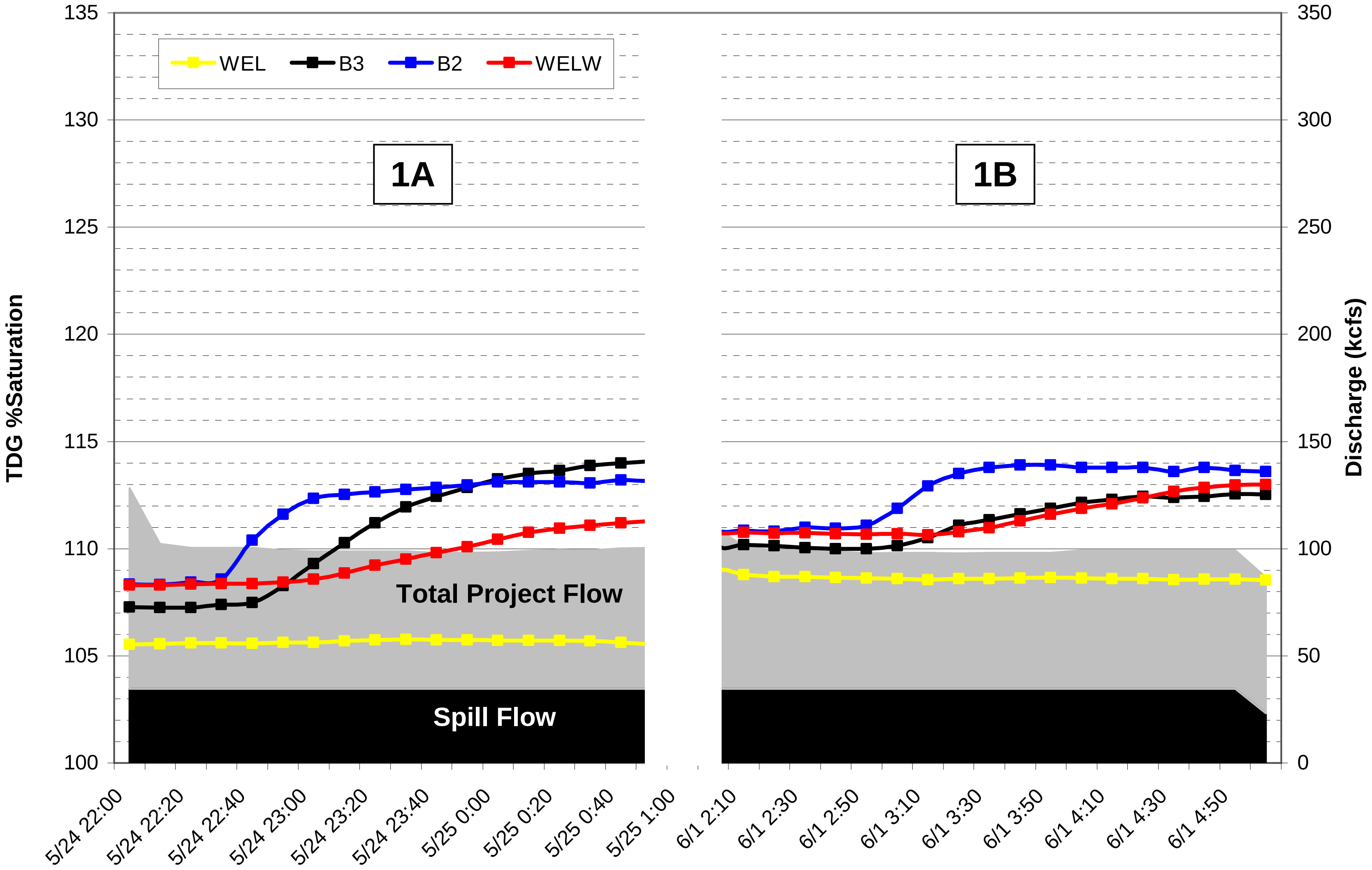

Figure 18. Project operation and Transect B values for tests 1A and 1B.

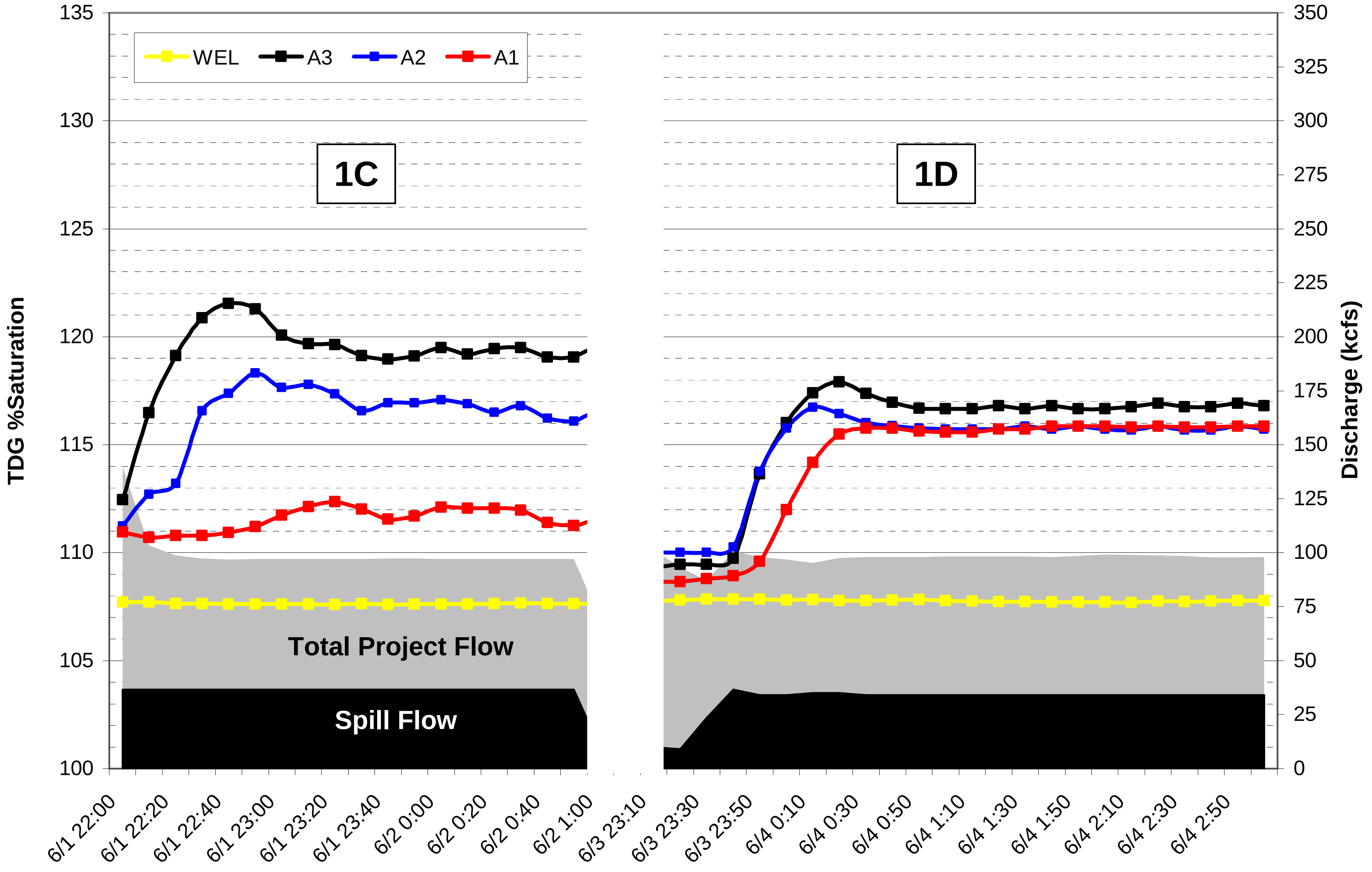

Figure 19. Project operation and Transect A values for tests 1C and 1D.

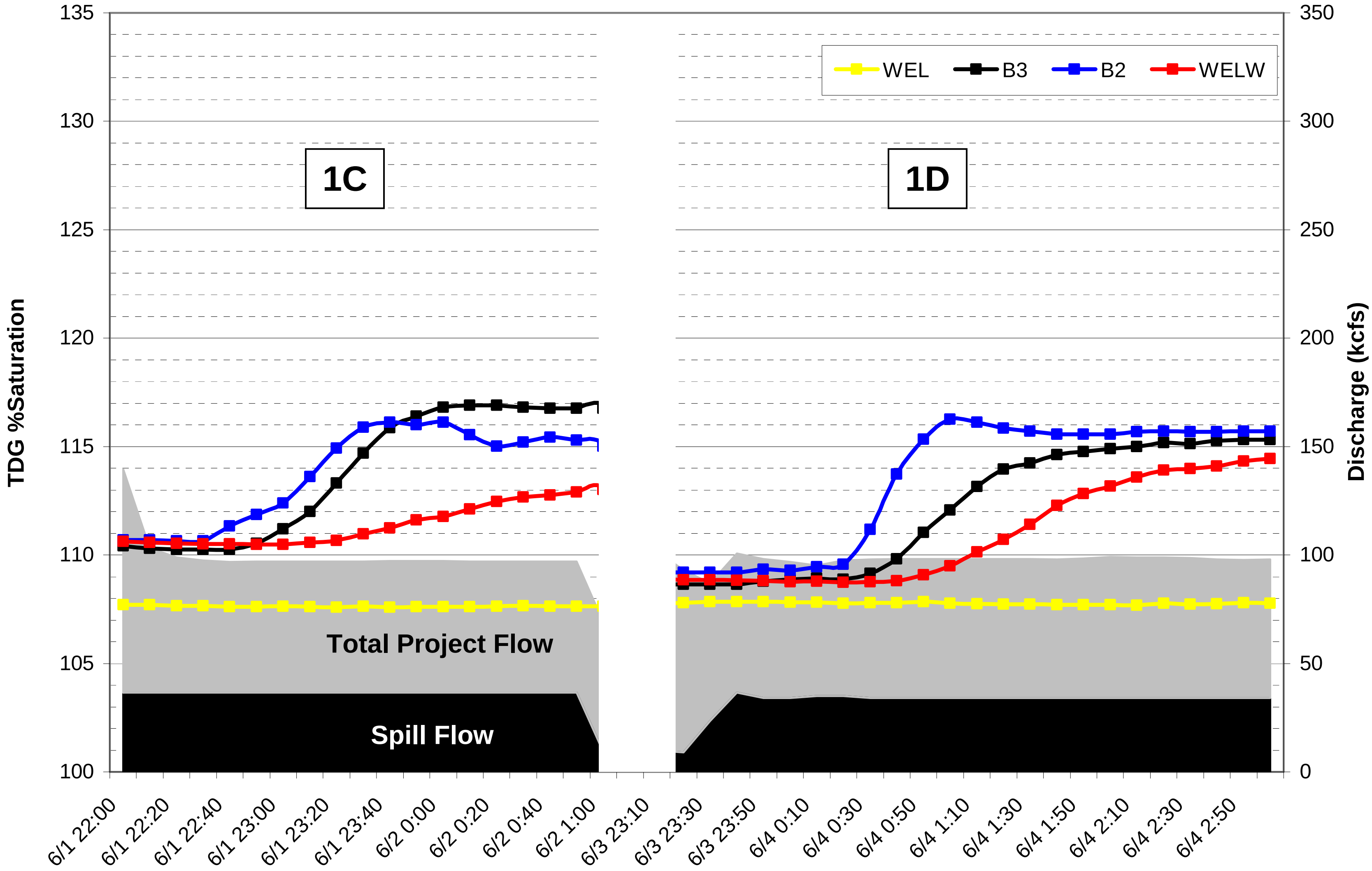

Figure 20. Project operation and Transect B values for tests 1C and 1D.

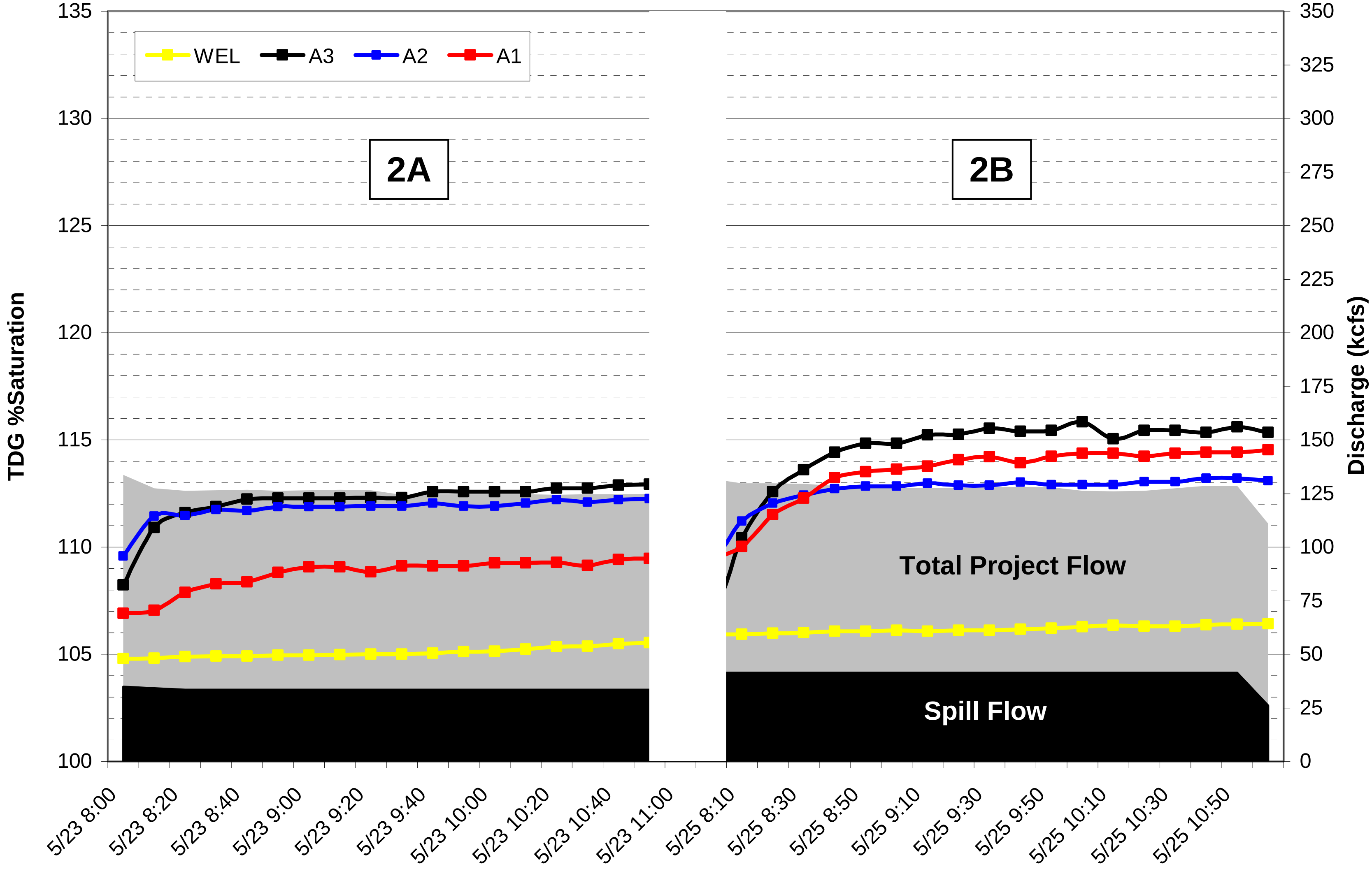

Figure 21. Project operation and Transect A values for tests 2A and 2B.

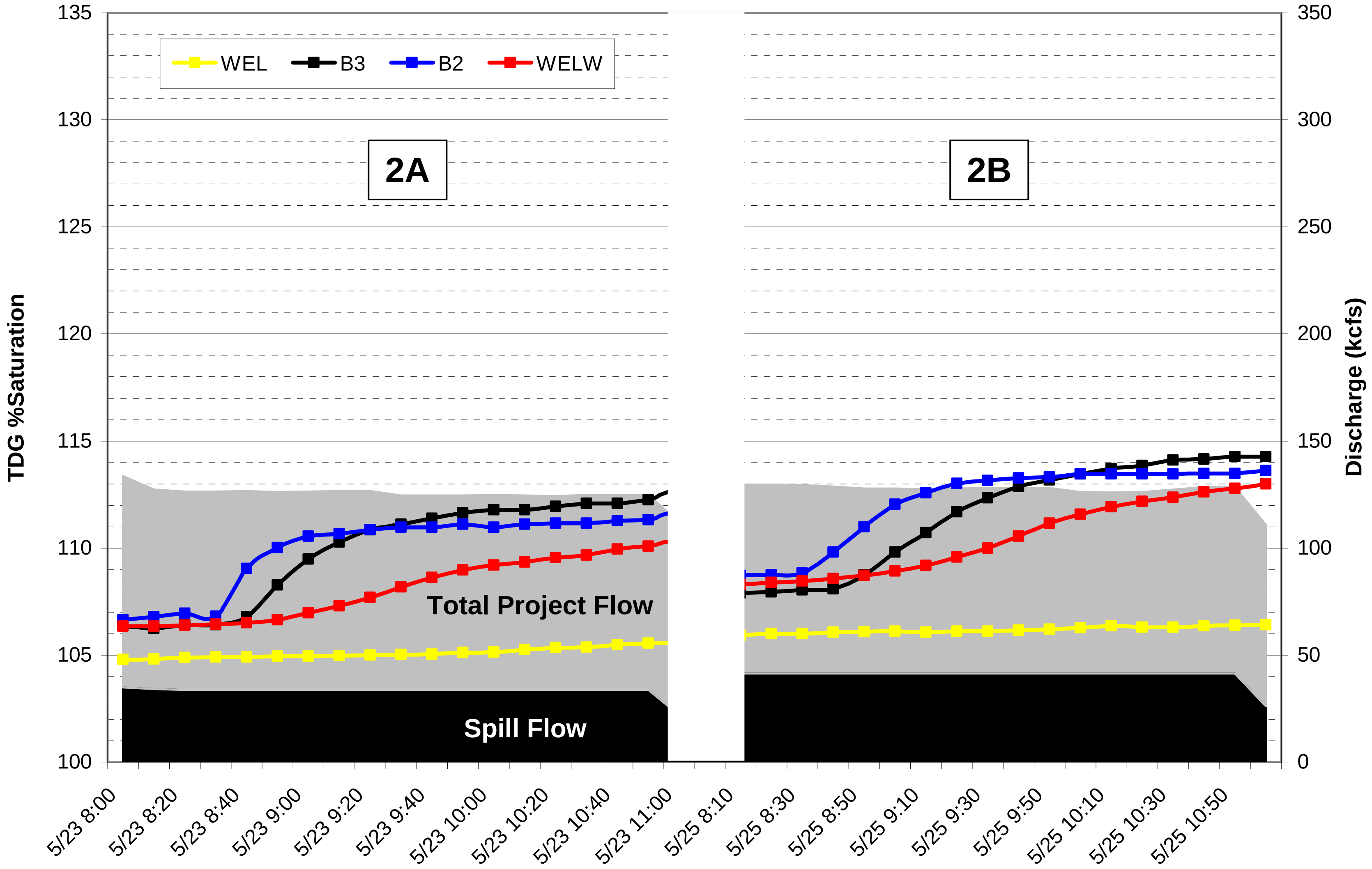

Figure 22. Project operation and Transect B values for tests 2A and 2B.

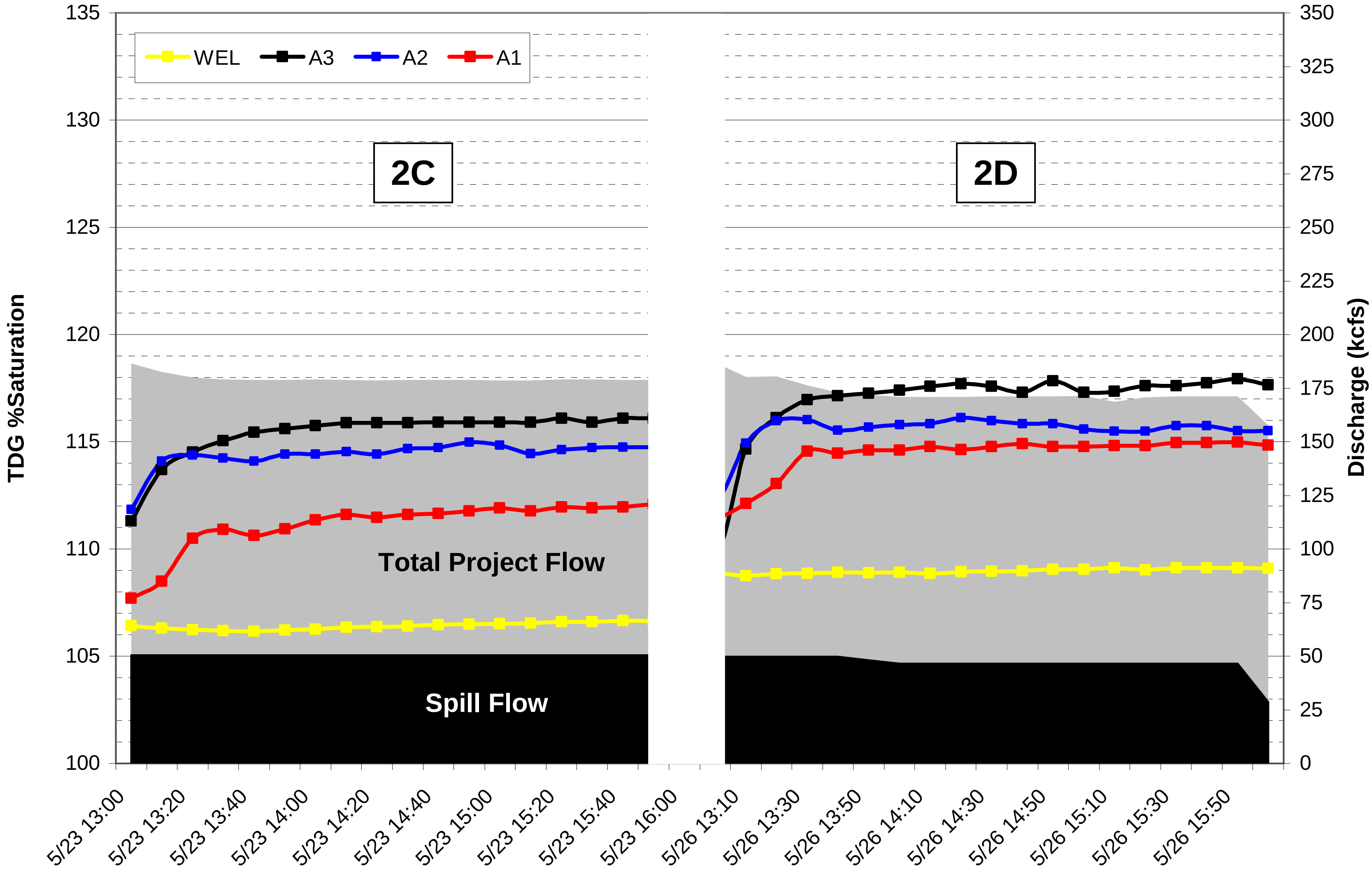

Figure 23. Project operation and Transect A values for tests 2C and 2D.

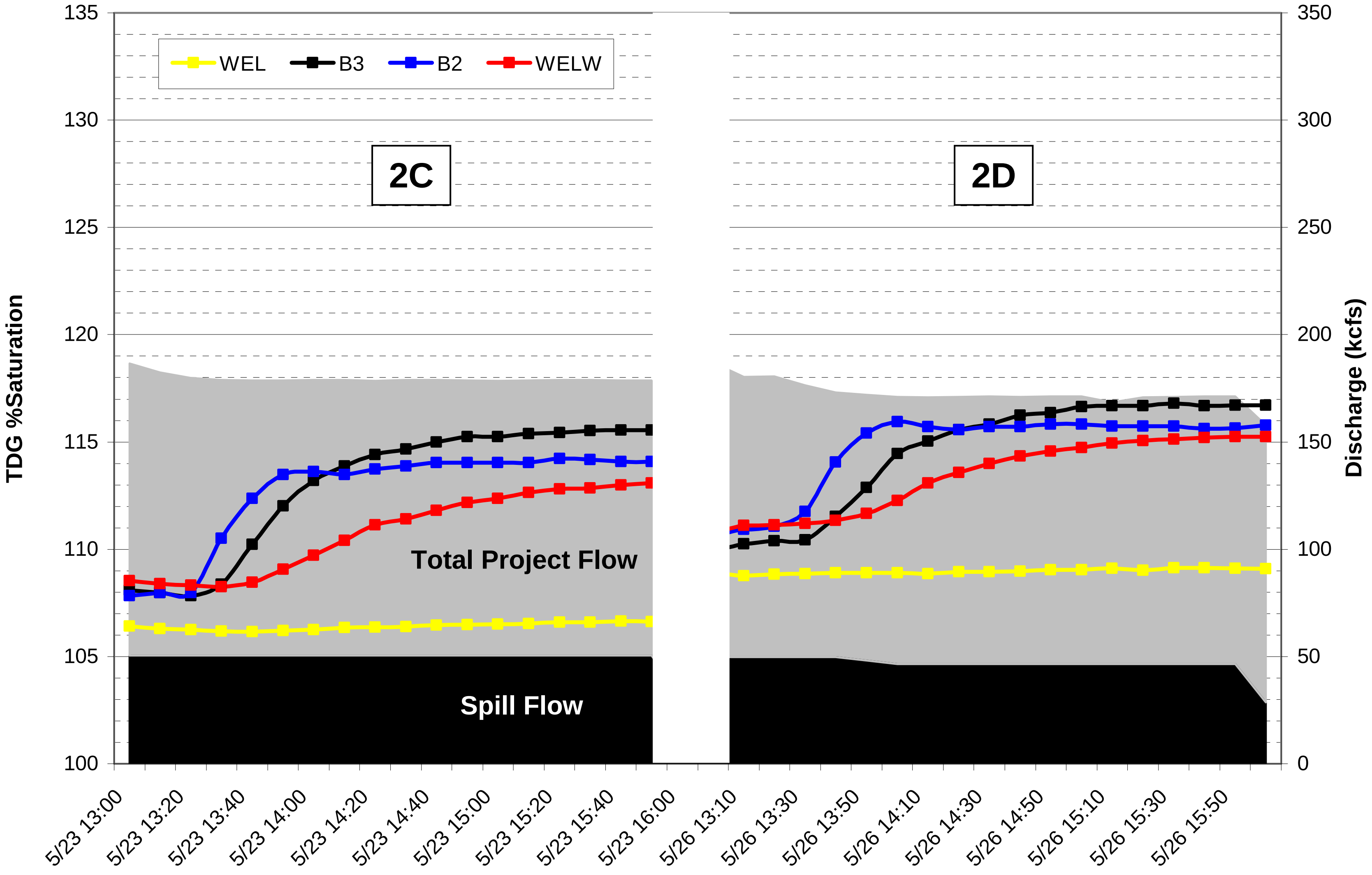

Figure 24. Project operation and Transect B values for tests 2C and 2D.

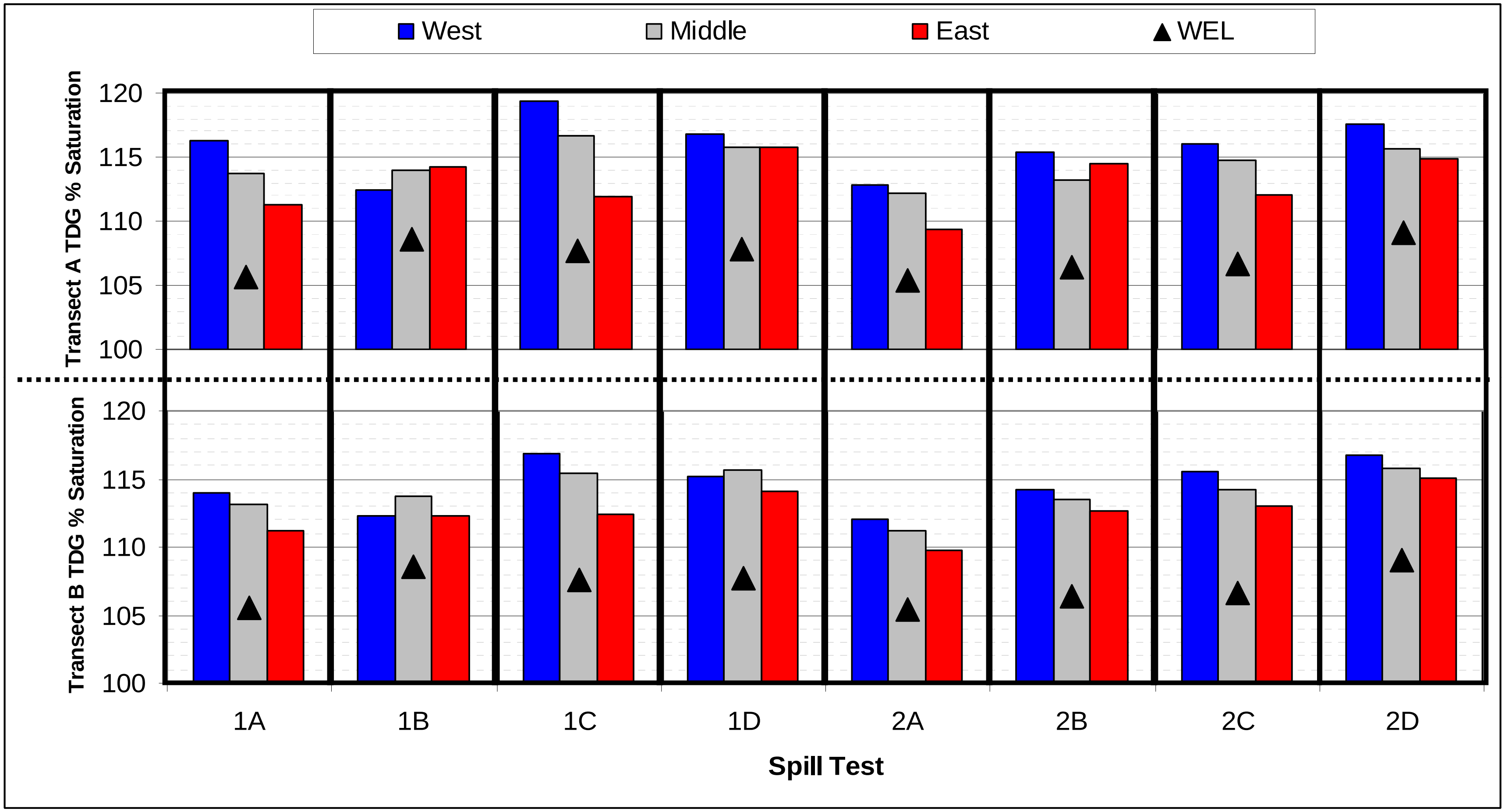

Figure 25. Upstream and downstream TDG saturations averaged by spill test.

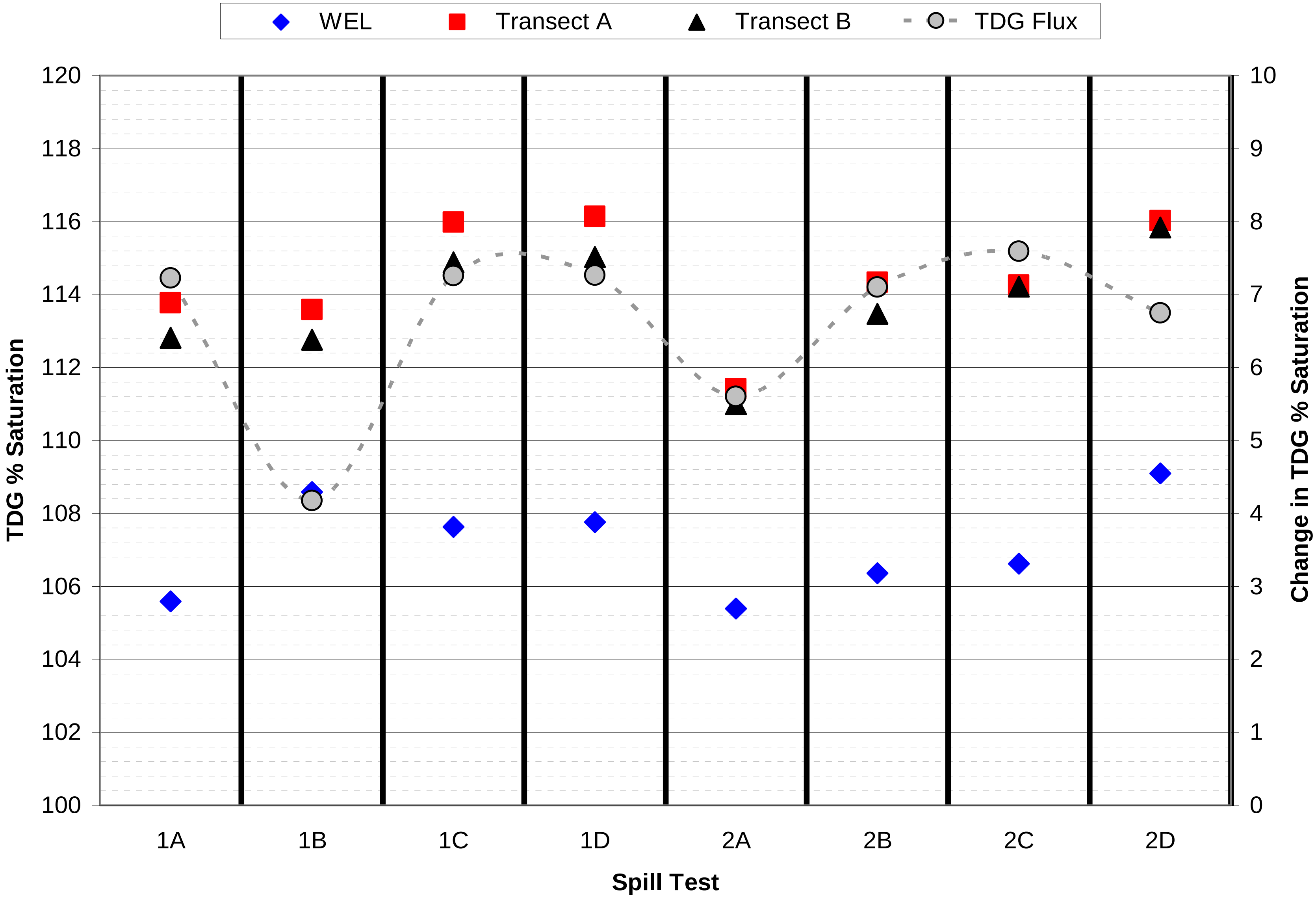

Figure 26. Mean TDG saturations by test for WEL, Transect A, and Transect B. TDG flux measures the difference in TDG saturations from WEL to Transect B.

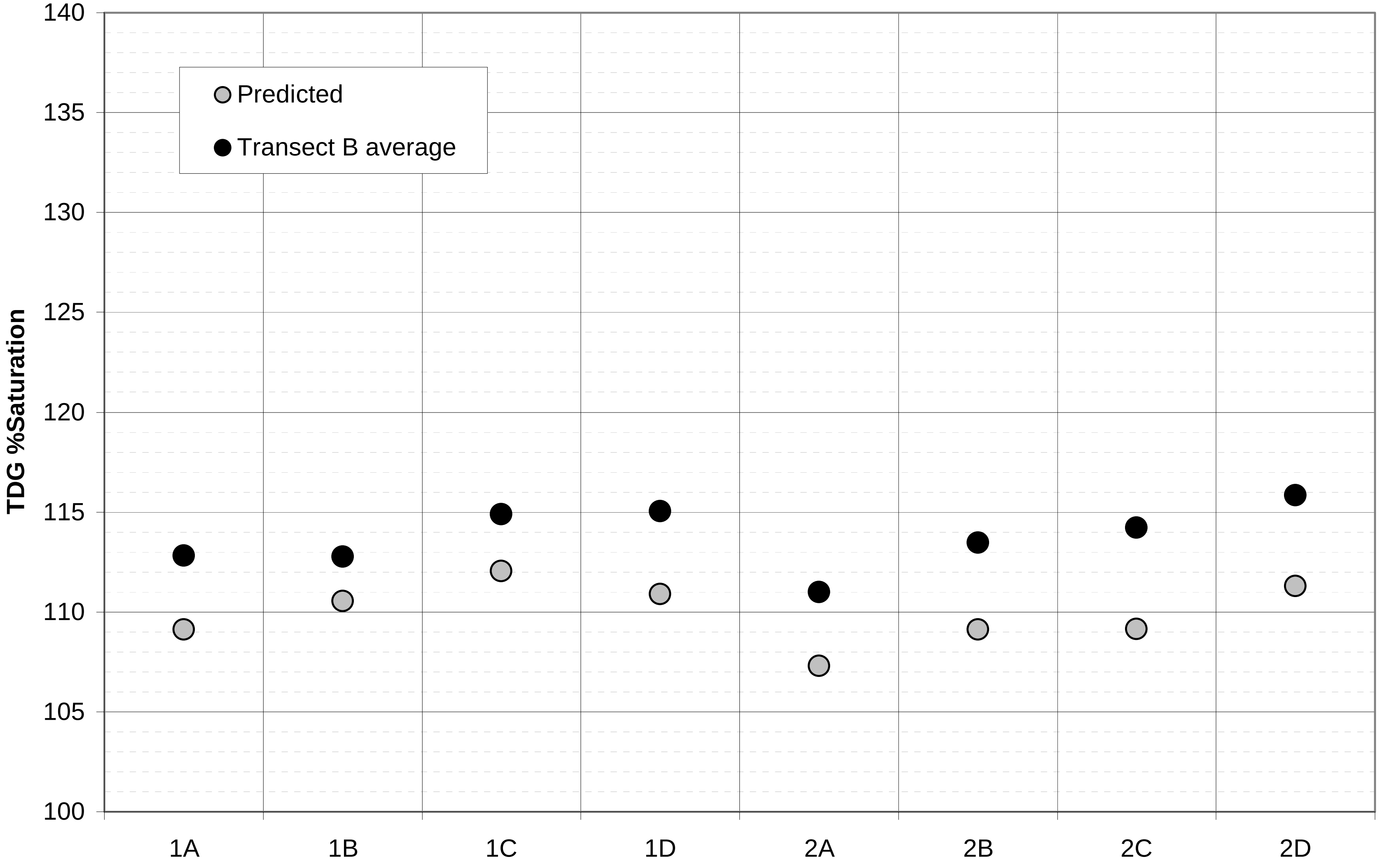

Figure 27. Empirical and predicted mean Transect B TDG saturations assuming no gassing of powerhouse release.

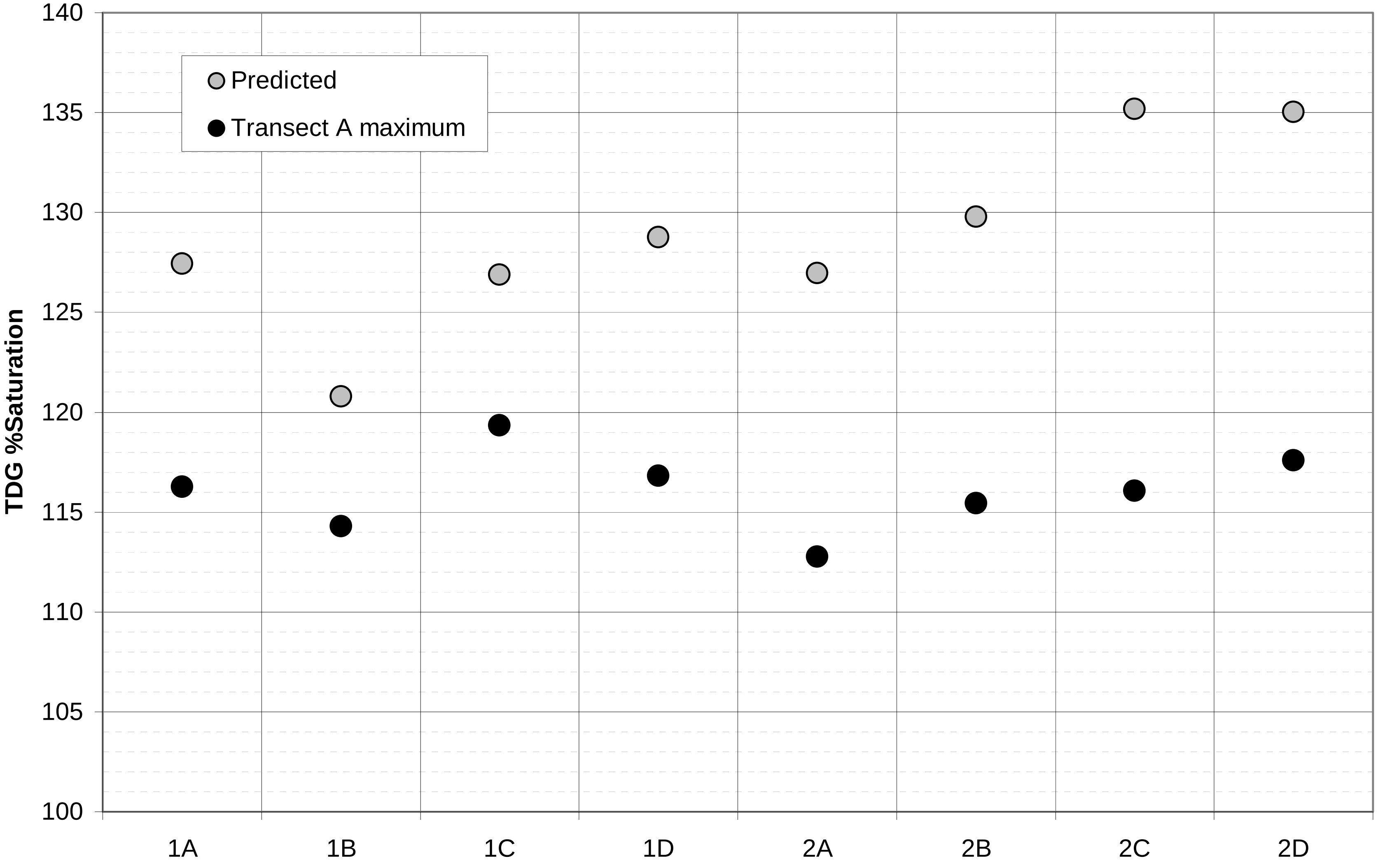

Figure 28. Empirical and predicted spillway TDG saturations assuming no gassing of powerhouse releases.

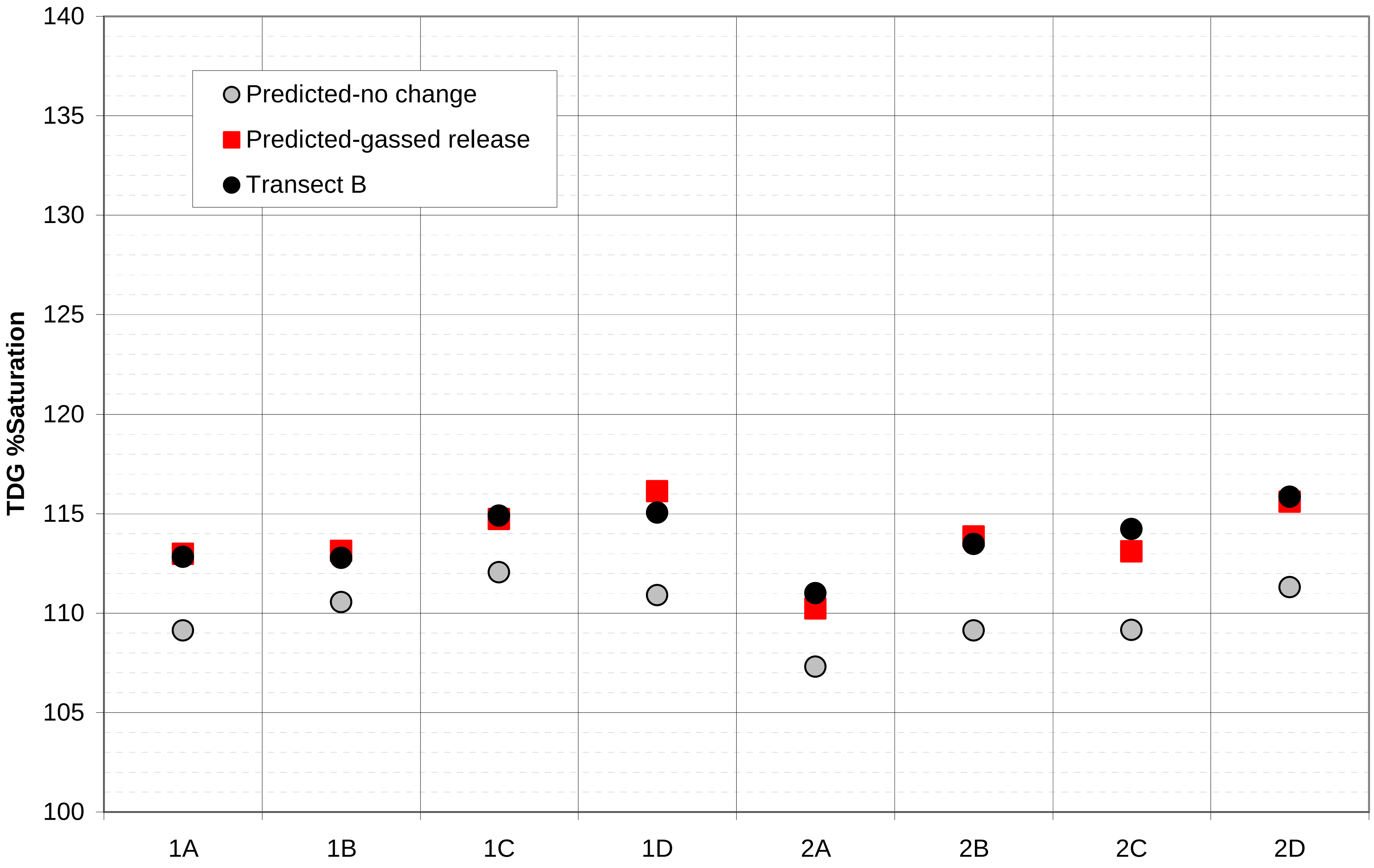

Figure 29. Predicted and actual Transect B weighted TDG saturations assuming some gassing of powerhouse releases.

# Appendix A. Calibration procedures for Hydrolab® multiprobes

Following is an outline of the quality assurance/quality control (QA/QC) procedures utilized by Columbia Basin Environmental (CBE) in the handling of Hydrolab® multiprobes. All probes should be checked prior and subsequent to deployment. Individual sensors require different calibration methods, as described by the equipment manufacturer.

## A. MiniSonde®/DataSonde® Temperature sensor

Temperatures reported by multiprobes are to be compared to an NIST traceable mercury thermometer. Sonde and standard values should agree within ± 0.2 ºC. Temperature sensors are factory calibrated; therefore, probes failing temperature calibrations will be removed from service.

*Manufacturer stated accuracy/precision: ± 0.1 ºC/0.01 ºC*

## B. MiniSonde®/DataSonde® depth sensor

Sensors are to be air-calibrated such that the depth equals 0 m (or feet, depending on depth units) in air (no storage cup) or they will be adjusted.

*Manufacturer stated accuracy/precision: ± 0.1 m/0.01 m*

## C. MiniSonde®/DataSonde® Total Dissolved Gas sensor

1. Slowly loosen TDG membrane (if installed), being careful not to break the seal with the probe. Monitor the TDG pressure as the membrane is removed. Pressures should decrease by ~200 mmHg and slowly increase to ambient BP; otherwise, the membrane may be damaged. Visually inspect membrane and carefully clean tubing prior to storing.
2. Perform four-point TDG calibration:
    a. Attach NIST traceable pressure gage to TDG sensor and release pressure.
    b. Check TDG zero against primary standard (mercury barometer) pressure and document readings.
    c. Using the pressure gage, gradually add sufficient pressure to bracket the expected *in situ* values (typically, 300 mmHg). The TDG sensor should report pressures equivalent to the ambient BP (zero) plus the additional pressure, e.g. at BP=760 mmHg with 300 mmHg added pressure, the sensor should report 1060 mm Hg.
    d. Check the TDG sensor at BP, BP+100 mmHg, BP+200 mmHg, and BP+300 mmHg and document readings.
    *e.* If TDG sensor measurements differ from calibration values by more than ± 1 mmHg, the sensor's calibration should be adjusted. Set the TDG sensor at both ambient BP and BP+300 mmHg and recheck across the entire range.

3. Install a fresh TDG membrane. Monitor the TDG pressure as the membrane is attached. Pressure should increase as the seal is formed and then slowly return to ambient BP.
4. Replace sensor guard, if so equipped.
5. Perform final membrane check by immersing entire sensor in carbonated water, i.e. seltzer water. The TDG pressure should increase rapidly and exceed ~1000 mm Hg. Remove sensor from seltzer water and ensure that the pressure gradually returns to atmospheric levels. If pressures do not rise rapidly or if they spike and immediately return to atmospheric pressures, the membrane may be damaged. Repeat steps 7-9 with a new membrane. (*Note: It is important that the sensor guard be replaced BEFORE performing the membrane integrity check as it is possible to damage the membrane during this action.*)

*Manufacturer stated accuracy/precision: ± 1.2 mmHg/ 0.1 mmHg*

# Appendix B. Spillway and Turbine Patterns for the 2005 Wells Dam Spillway Study

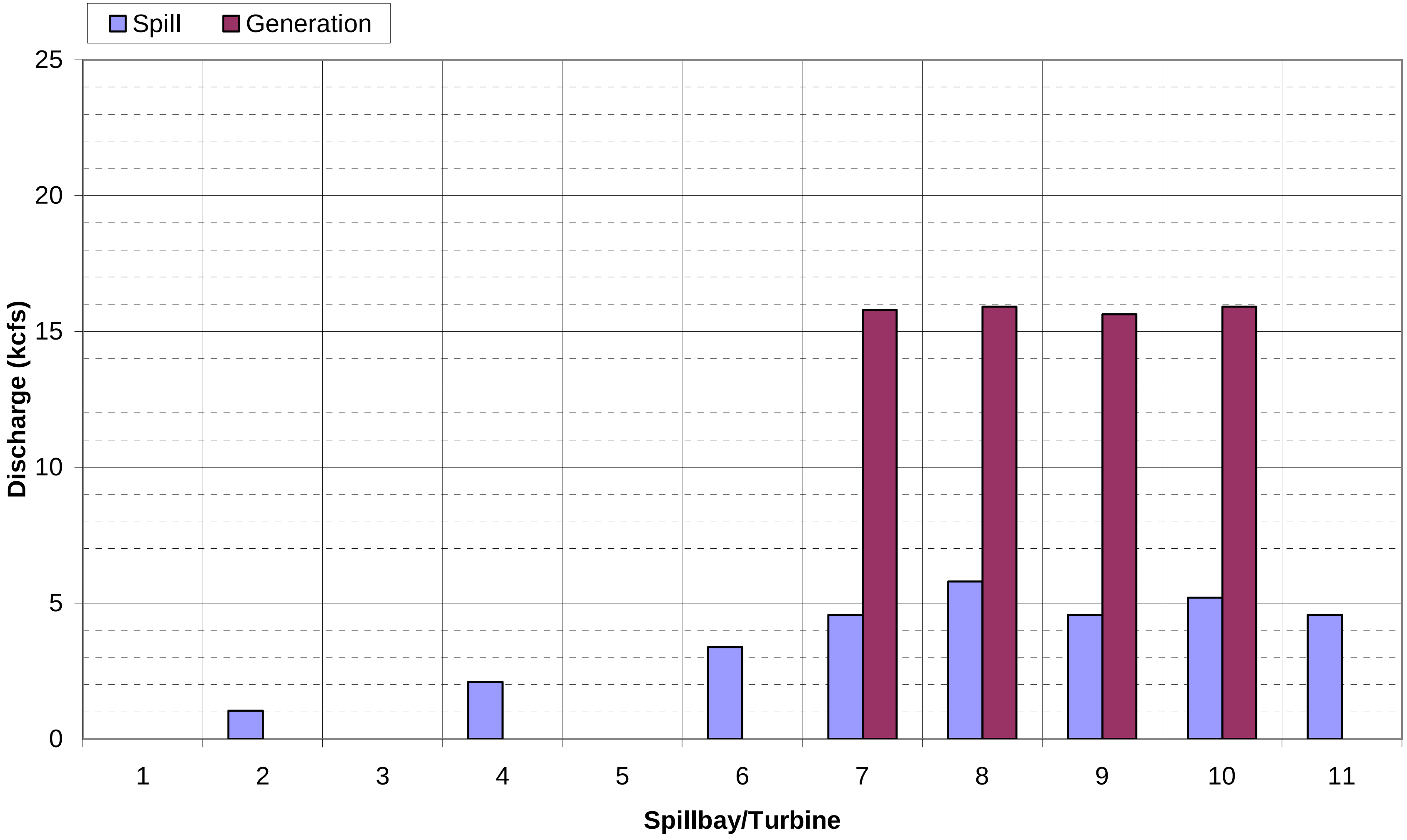

Figure B1. Spill and generator patterns for Spill Test 1A.

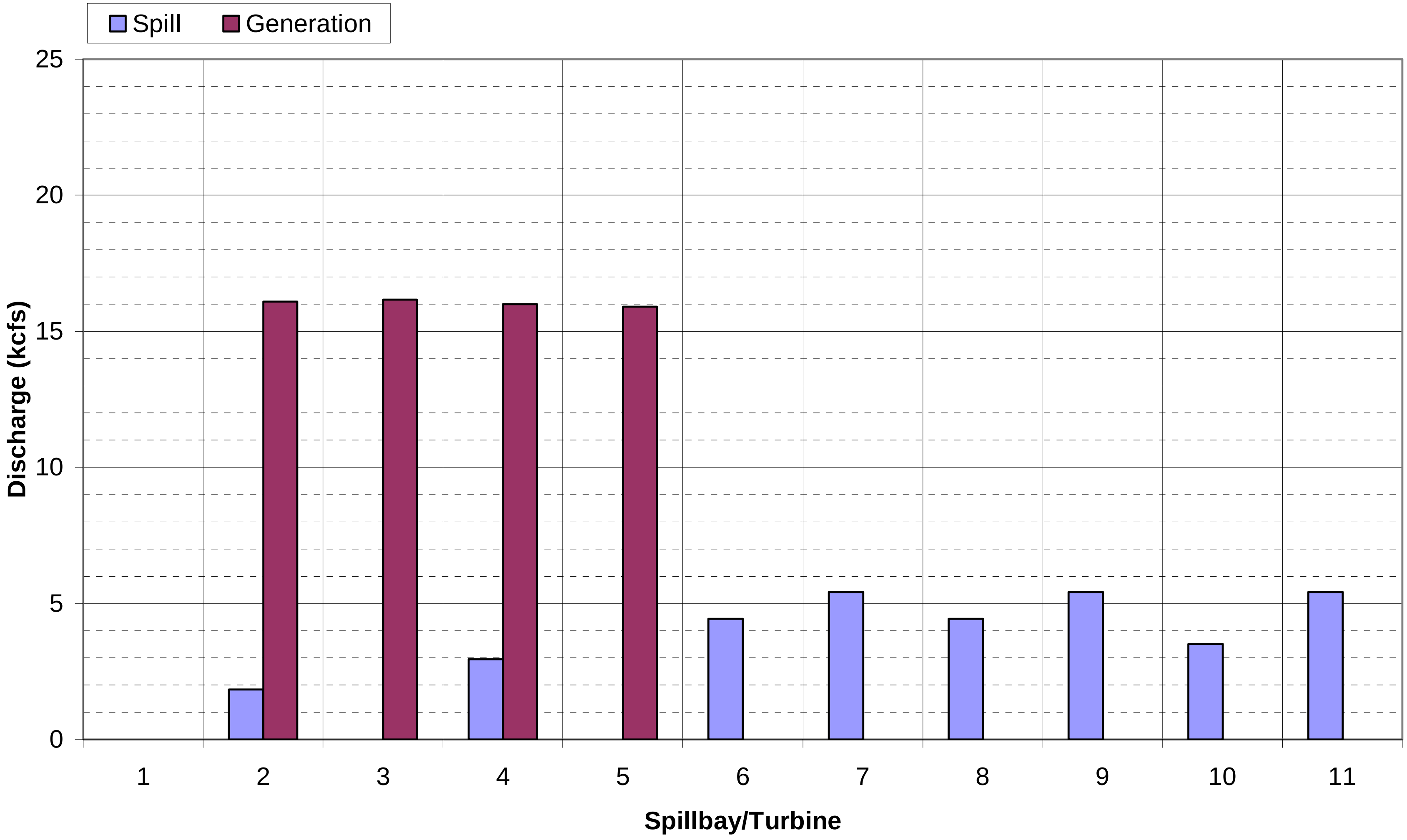

Figure B2. Spill and generator patterns for Spill Test 1B.

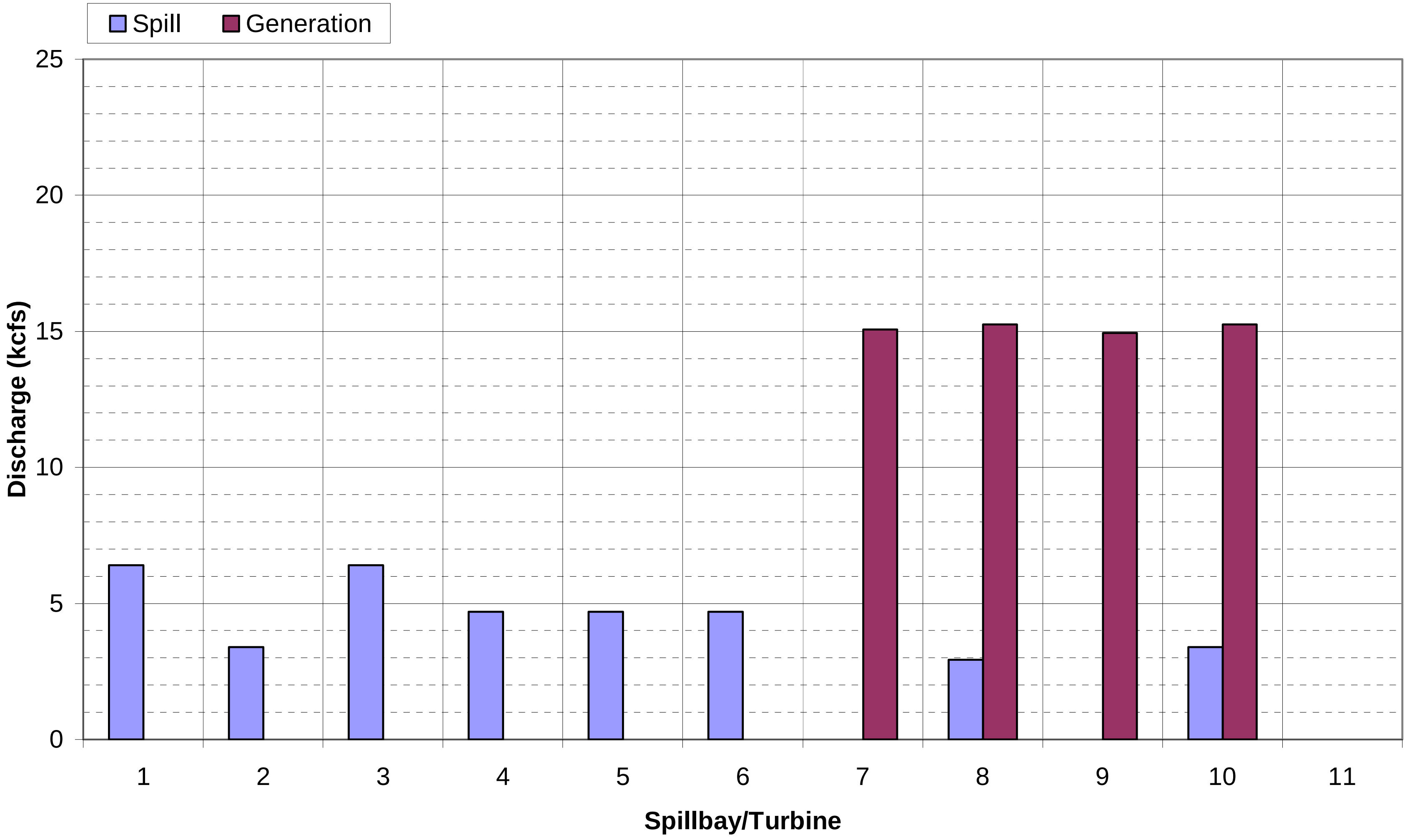

Figure B3. Spill and generator patterns for Spill Test 1C.

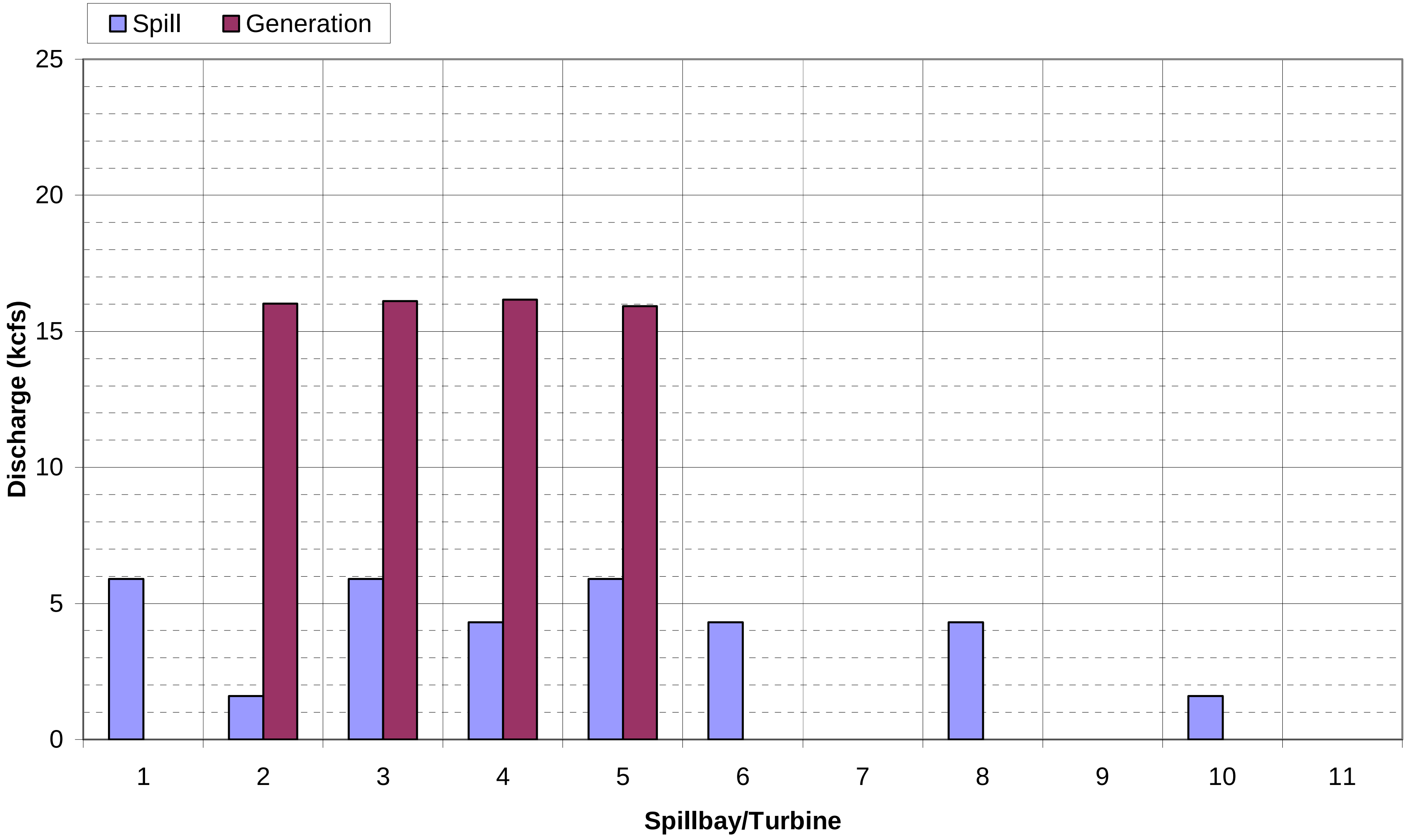

Figure B4. Spill and generator patterns for Spill Test 1D.

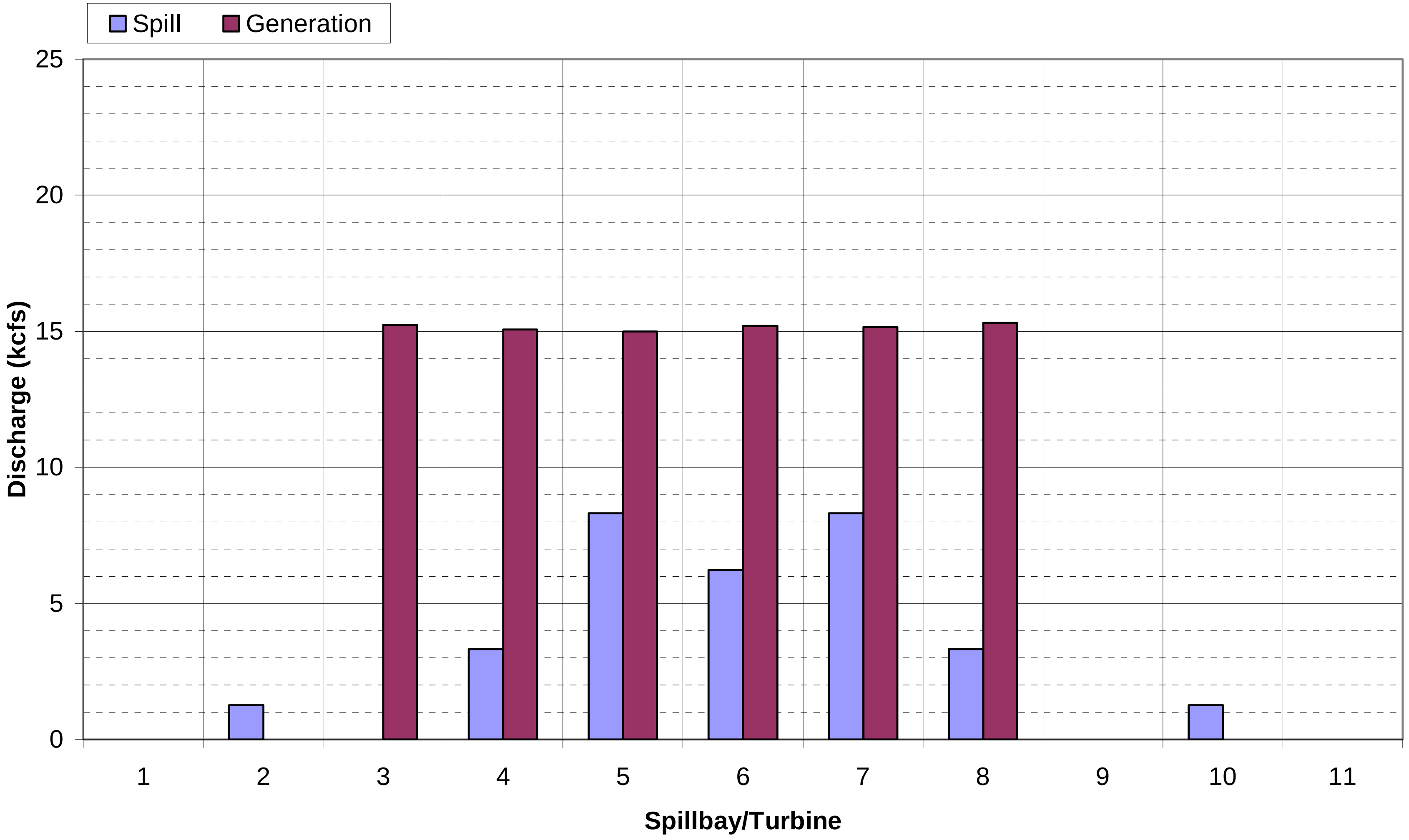

Figure B5. Spill and generator patterns for Spill Test 2A.

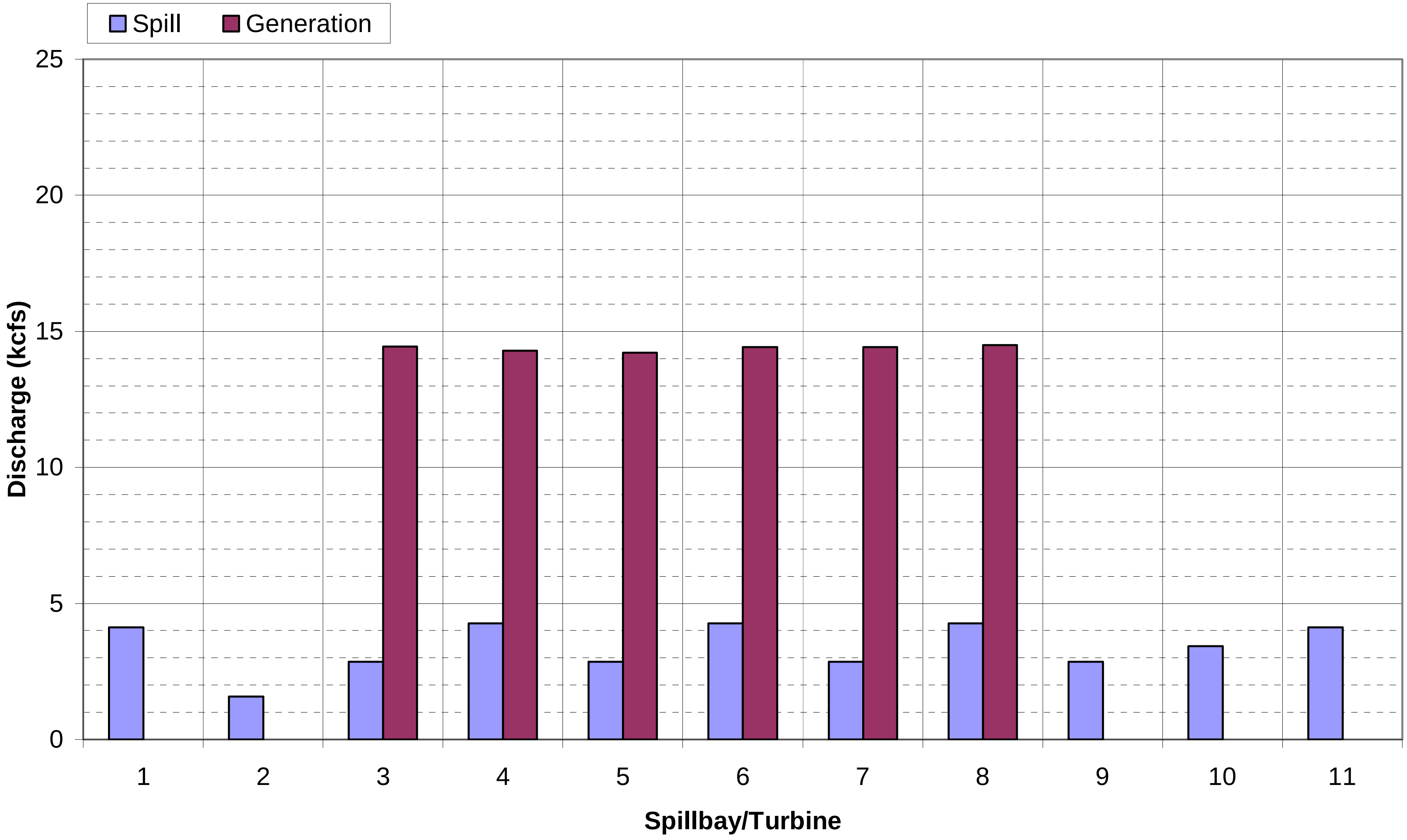

Figure B6. Spill and generator patterns for Spill Test 2B.

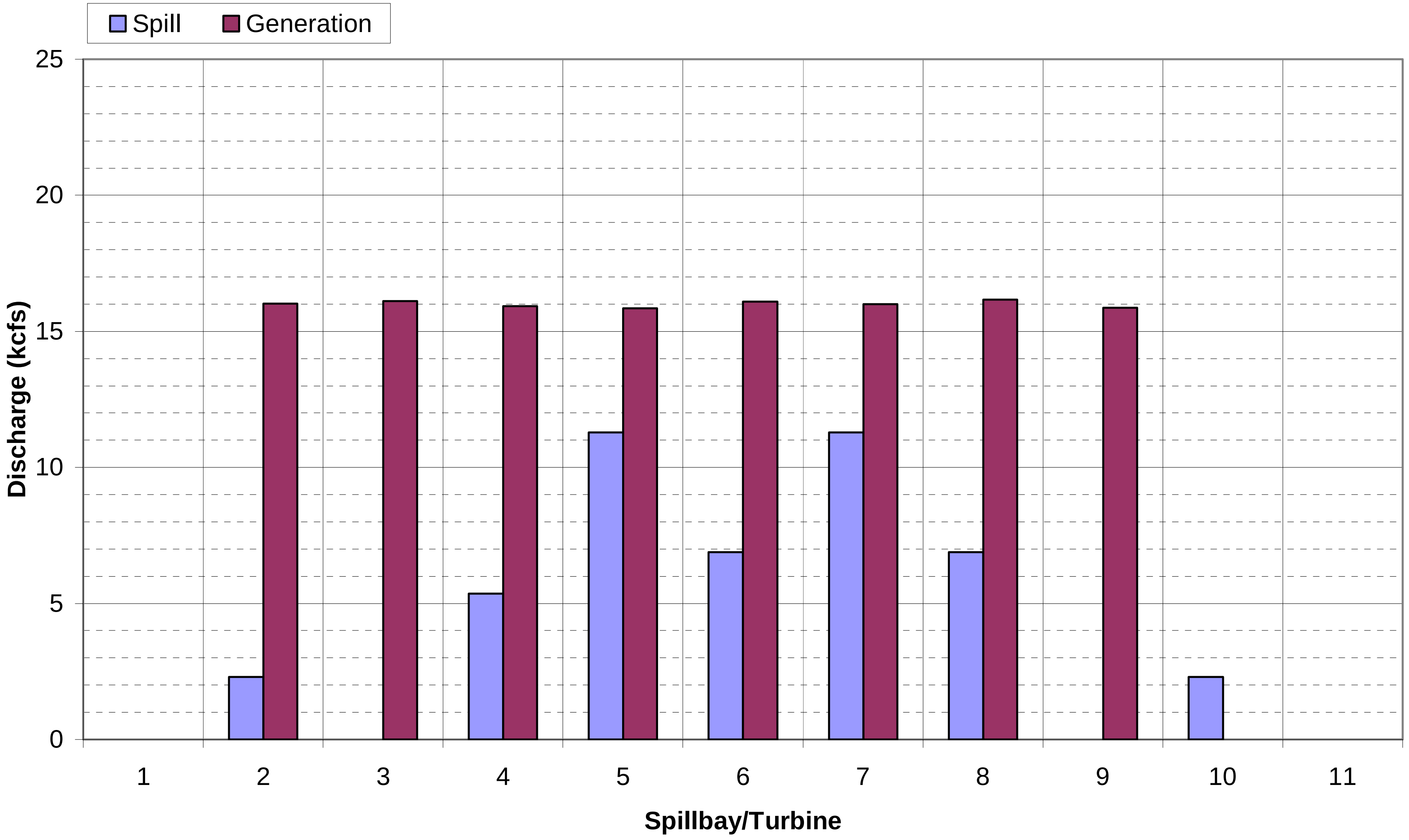

Figure B7. Spill and generator patterns for Spill Test 2C.

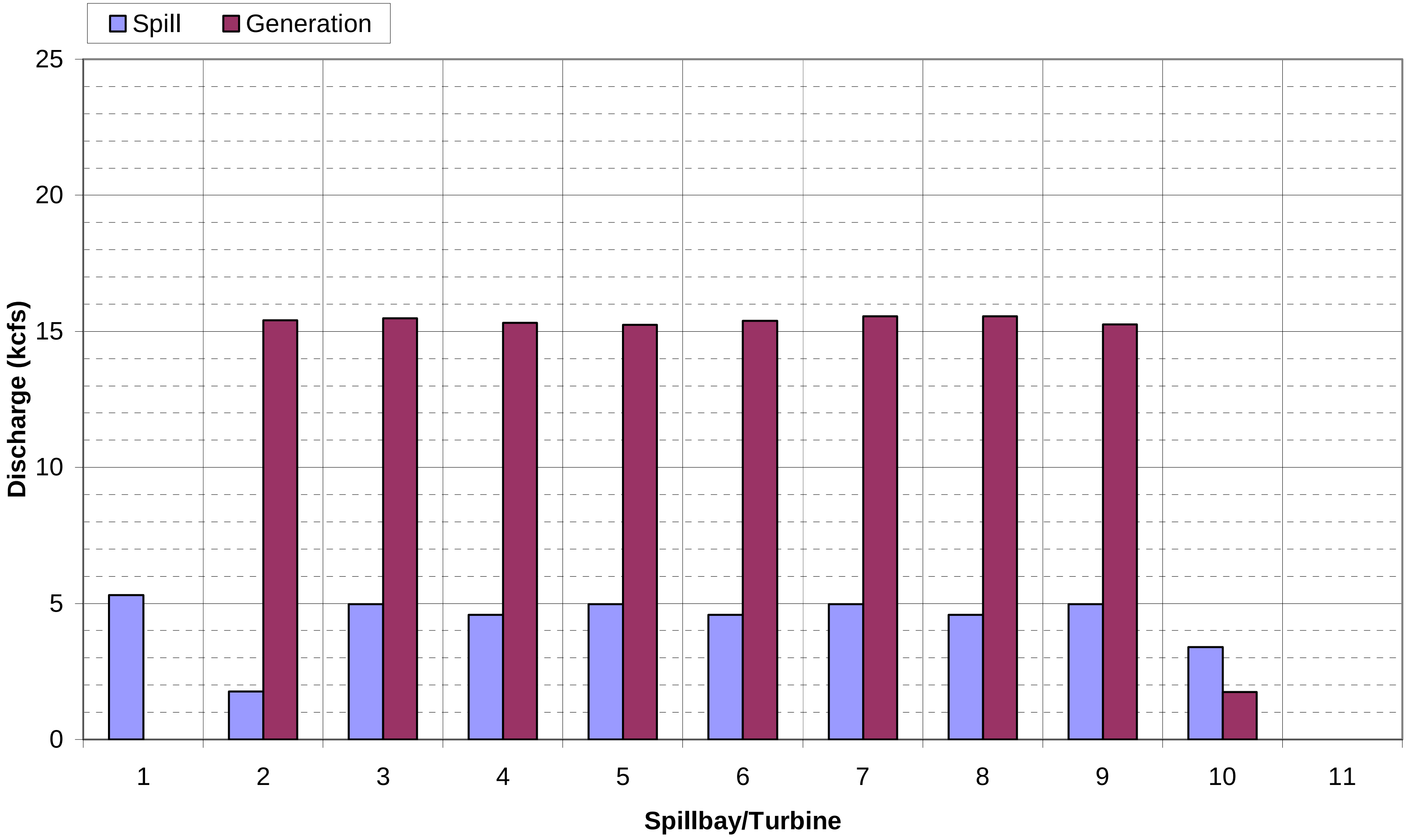

Figure B8. Spill and generator patterns for Spill Test 2D.