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Dissolved Gas Abatement Studies

Ice Harbor Spillway Dissolved Gas Field Studies: Before and After Spillway Deflectors

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Abstract

Based on the results of the Dissolved Gas Abatement Studies, spillway deflectors were adopted for Ice Harbor as a measure to reduce the total dissolved gas (TDG) production during spill operations. Three field studies were conducted at the Ice Harbor Spillway on the lower Snake River to characterize the effects of spill operations on TDG in the Snake River. The first two studies examined TDG production for the original spillway design. The third study characterized TDG production with flow deflectors installed on the spillway face. TDG was significantly reduced for nearly all spill operations with deflectors in place. TDG near the stilling basin was reduced from approximately 150% to approximately 124%. TDG at end of the navigation guide wall was reduced from 135% to 114% for similar operating conditions.

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Preface

These studies were conducted for the U.S. Army Engineer District, Walla Walla (CENWW), under the Dissolved Gas Abatement Studies (DGAS) Program, Program Number U425243. The technical monitor was Martin Ahmann (CENWW-EC-H). Mark Lindgren was the Chief, Hydraulic Design Section (CENWW-EC-H) while Rick Emmert was the NWW DGAS study coordinator.

The work was performed by the Reservoir Water Quality Branch (CEERD-HS-R), Hydraulic Structures Division (CEERD-HS), U.S. Army Engineer Research and Development Center, Hydraulics Laboratory (ERDC-HL). When these studies were conducted, John F. George was Chief, CEERD-HS-R; Glenn A. Pickering was Chief, CEERD-HS. The Deputy Director of ERDC-HL was Richard A. Sager, and the Director was Frank A. Herrmann.

Michael L. Schneider and Steven C. Wilhelms, CEERD-HS-R, were the principal investigators for these studies. They designed the study parameters, deployed and recovered the measurement instruments, and analyzed the data. Calvin Buie (CHL) assisted in study mobilization and instrument deployment and recovery. Lauren Yates (CHL), assisted in data reduction, analysis, and presentation. Schneider, Wilhelms, and Yates prepared the memoranda documenting these studies. Wilhelms and Yates consolidated the memoranda and prepared this special report.

At the time of publication of this report, José E. Sánchez was the Director of CHL. COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director of ERDC.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet per sec, ft^3/s	0.0283	cubic meters per sec, m^3/s
degrees Fahrenheit, ^oF	$(^oF-32)/1.8$	degrees Celsius, ^oC
feet, ft	0.3048	meters, m

Executive Summary

The operation of spillways on the Columbia and Snake Rivers causes the absorption of atmospheric gases (chiefly nitrogen and oxygen) to supersaturated levels that often exceed the acceptable total dissolved gas (TDG) levels set by state and National standards. As a consequence of the supersaturated TDG, migrating salmonids may suffer gas bubble trauma, where bubbles form in their blood stream, sometimes causing death. To address this issue and develop alternatives to reduce TDG at the spillways, the Dissolved Gas Abatement Studies (DGAS) program was initiated. The overall purpose of the DGAS program was to develop structural and operational alternatives to decrease the dissolved gas levels generated during spillway operations. Several potential alternatives were identified and assessed through lengthy analyses and evaluation of historic TDG data from the river, site-specific field studies, and physical models concerning their gas exchange characteristics.

TDG measurements from the shore-based monitoring station downstream of Ice Harbor Dam indicated that the Ice Harbor spillway was a significant contributor to dissolved gas concentrations. Two studies were conducted in the Ice Harbor tailrace on 1–2 May 1996 and 27–28 June 1996 to define the TDG absorption for the existing Ice Harbor spillway and stilling basin design. Spillway deflectors had reduced TDG absorption during spill operations at other Snake and Columbia River dams and were adopted for installation at Ice Harbor. A third field study was conducted at Ice Harbor on 5–9 March 1998 after deflectors had been installed on 8 of the 10 spillway gates. This report summarizes the results of these field studies, which are documented in considerable detail in the appendices.

As many as 40 logging multiparameter instruments were deployed in the tailrace of Ice Harbor spillway and at other locations to measure TDG pressure, water temperature, depth, and dissolved oxygen. Instruments were positioned in or near the stilling basin and in the immediate tailrace area, as well as in the forebay, near the powerhouse releases, and downstream. With this array of instrument and significant variation of project operations, a clear picture can be developed of TDG production caused by spill operations. For the three field studies, spillway discharge and spill patterns were systematically varied with spill bay discharges

ranging from approximately 1,800 ft^3/s per spill bay to 9,400 ft^3/s per spill bay with total spill up to 75,000 ft^3/s. Generation discharges were also sometimes controlled as part of the field study and ranged from zero to a maximum of approximately 60,000 ft^3/s.

Although unjust in its brevity, the TDG production characteristics of the Ice Harbor spillway can be summarized in Figure 14, which shows TDG production with and without spillway deflectors. Without deflectors, for spill discharges of approximately 6,000 ft^3/s per spill bay, TDG saturation of nearly 150% was measured near the stilling basin and 135% was measured at the end of the navigation lock guide wall. With deflectors, however, the TDG levels were significantly reduced to approximately 124% at the stilling basin and 114% at the lock guide wall. This significantly increased the acceptable operational range of the spillway before subjecting the river to unacceptable TDG levels.

1 Introduction

1.1 Background

The operation of spillways on the Columbia and Snake Rivers causes the absorption of atmospheric gases (chiefly nitrogen and oxygen) to supersaturated levels. For many operations, the total dissolved gas (TDG) levels exceed state and National standards in the tailrace and river downstream of the projects. The highly aerated plunging flow in the spillway stilling basin transports enormous volumes of entrained air bubbles to the depth of the stilling basin. The added hydrostatic pressure of the depth causes accelerated absorption of TDG to supersaturated levels. As a consequence of the supersaturated TDG, aquatic life, particularly migrating salmonids, may suffer gas bubble trauma, where bubbles form in their blood stream, sometimes causing death. To address this issue, the Dissolved Gas Abatement Studies (DGAS) program was initiated.

The overall purpose of the DGAS program was to develop structural and operational alternatives to decrease the dissolved gas levels generated during spillway operations on the Snake and Columbia Rivers. The assessment of DGAS alternatives was conducted through analysis of historic data from fixed shore-based monitoring stations, site-specific prototype field studies, physical models, and analytical investigations concerning gas exchange at hydraulic structures.

The analysis of TDG measurements from the shore-based monitoring station downstream of Ice Harbor Dam indicated that the Ice Harbor spillway was a significant contributor to TDG concentrations. Two studies were conducted in the Ice Harbor tailrace on 1–2 May 1996 and 27–28 June 1996 to define the TDG absorption for the existing Ice Harbor spillway and stilling basin design. Spillway deflectors had reduced TDG absorption during spill operations at other Snake and Columbia River dams and were adopted for installation at Ice Harbor. A third field study was conducted at Ice Harbor on 5–9 March 1998 after deflectors had been installed on 8 of the 10 spillway gates. The results of these field studies were documented in memoranda that were provided to the Walla Walla District but were not published as a U.S. Army Engineer Research and Development Center (ERDC) technical report. The understanding about TDG exchange was greatly enhanced as a consequence of this and subsequent studies. Thus, even at this late date, the results find application at other Corps of Engineers projects and other spillways. This report summarizes the results of these field studies, which are documented in more substantial detail in the memoranda that are included as appendices.

1.2 Objectives

The overall objective of these field investigations was to more clearly define and quantify processes that contribute to dissolved-gas transfer during spillway releases and document the resulting dissolved gas downstream of the project. The specific objective of these field studies was to quantify the vertical, lateral, and longitudinal gradients in TDG levels downstream of the spillway and to examine the dissolved gas exchange (both absorption and desorption) downstream of the spillway.

Many aspects of these field investigations at Ice Harbor Dam were experimental in nature. Prior investigations of spillway performance were limited to regions that were accessible by survey boat and outside of the highly turbulent bubbly flow regime. In these studies, instruments were deployed in the high-velocity, extremely turbulent, highly aerated bubbly flow of the stilling basin, end sill area, and near-field tailrace. The response of the TDG instruments to these conditions was unknown. The durability of the instrument in these extreme conditions was a second concern. The deployment and recovery of a large matrix of instruments presented a third challenge.

The objective of the May and June 1996 field studies was to determine the gas exchange characteristics of the Ice Harbor Dam spillway, stilling basin, and tailrace with its original spillway and stilling basin design. The objective of the March 1998 field study was to determine the gas exchange characteristics of the Ice Harbor Dam spillway after installation of eight deflectors on the spillway (deflectors were not installed on the two outside bays).

1.3 Scope of work

As many as 40 logging multiparameter instruments were deployed in the tailrace of Ice Harbor spillway and at other locations and river transects. The instruments measured and logged, on a regular interval during the field studies the following parameters: TDG, water temperature, depth, and dissolved oxygen. In the immediate vicinity of the spillway, the instruments were tethered to multiple longitudinal cables and formed a rectangular array of measurement locations that extended well downstream of the stilling basin. Auxiliary instruments were placed in other locations, such as the forebay to measure upstream TDG, in the tailwater off the powerhouse deck to measure powerhouse TDG, in the McNary forebay in the far-field downstream, and in the Columbia River upstream of the confluence with the Snake River. The mixing between powerhouse and spillway releases was investigated since this interaction is important to the total flux of TDG introduced into the Snake River. The influence of the tailwater depth on the exchange of TDG during spillway operation was also investigated during the 1998 study by controlling hydropower releases. At selected cross sections downstream, TDG was laterally monitored, and the lateral velocity distribution was measured with an acoustic Doppler current profiler to allow TDG flux computations. The comparison of TDG mass flux estimates for different operations could be used to determine the relative importance of various gas exchange processes within the stilling basin and downstream tailrace.

Spillway discharge and spill patterns were systematically varied with spill bay discharges ranging from approximately 1,800 ft^3/s per spill bay to 9,400 ft^3/s per spill bay with total spill up to 75,000 ft^3/s. Generation discharges were sometimes controlled as part of the field study and ranged from zero to a maximum of approximately 60,000 ft^3/s.

1.4 Project description

The powerhouse at Ice Harbor Dam consists of six hydroturbines with a combined discharge capacity of 105 kcfs. The spillway at Ice Harbor Dam has a total length of 590 ft and consists of 10 tainter gate-controlled bays. The elevation of the spillway crest is 391[1]. For the May and June 1996 field studies, there were no spillway deflectors at Ice Harbor Dam. The horizontal apron of the stilling basin is approximately 210 ft long with an invert elevation of 304. With normal tailwater at el 344, the depth in the stilling basin was approximately 40 ft; however, stilling basin depth was over 40 ft during these field studies. There is one row of 8 ft high baffle blocks and a 12 ft high end sill for energy dissipation in the stilling basin. A training wall extending over two-thirds the length of the stilling basin separates spill bays 10 and 1 from the interior bays. The tailwater channel downstream of the stilling basin is generally above el 320. Tailwater elevations ranged from approximately el 338.4 up to approximately el 347.7. Beyond the immediate

[1] Elevations are referenced to the National Geodetic Vertical Datum (NGVD).

vicinity of the tailrace, the river is generally shallow except for the navigation channel, which was excavated on the northern side of the thalway providing depths of 25–30 ft.

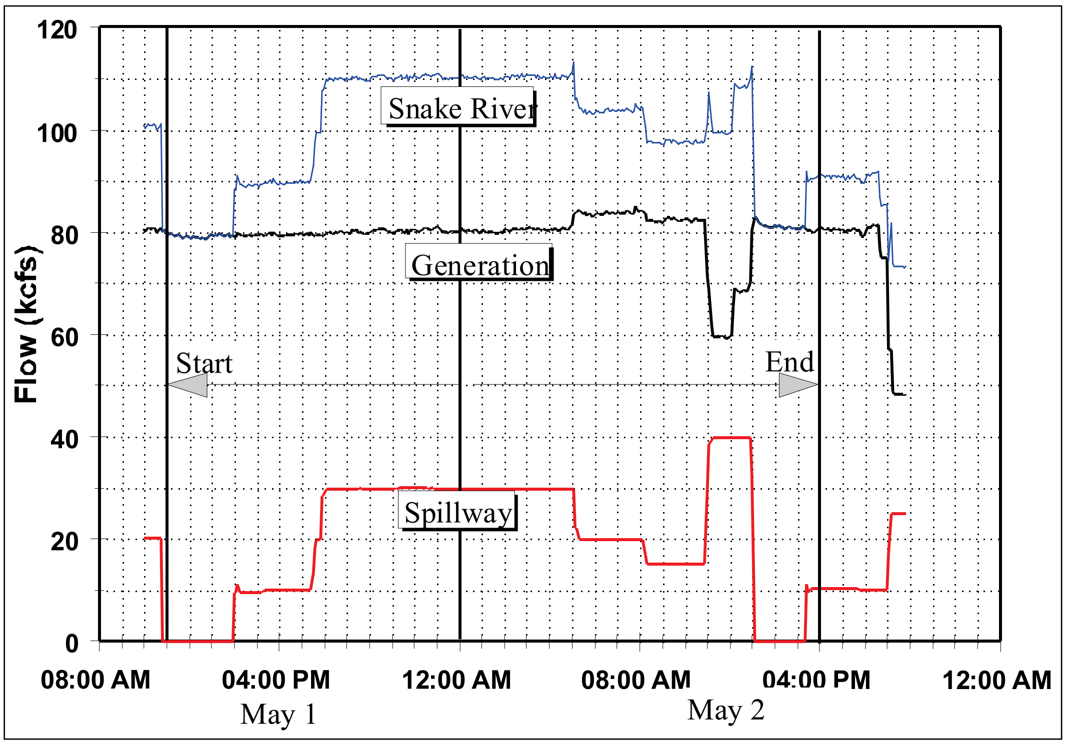
For the 1998 study, the eight central bays had spillway deflectors that were 12.5 ft long, horizontally positioned at el 338.0 with a 15 ft radius toe curve. The interior piers were extended to the downstream end of the deflector to reduce surface turbulence and air entrainment.

2 Field Study Descriptions and Measurements

2.1 1–2 May 1996 field study

Operational conditions and observed data. The first study began on 1 May 1996 at 1100 hours and ended 30 hours later at 1500 on May 2. During this period, seven major operational changes were implemented, as shown in Figure 1.

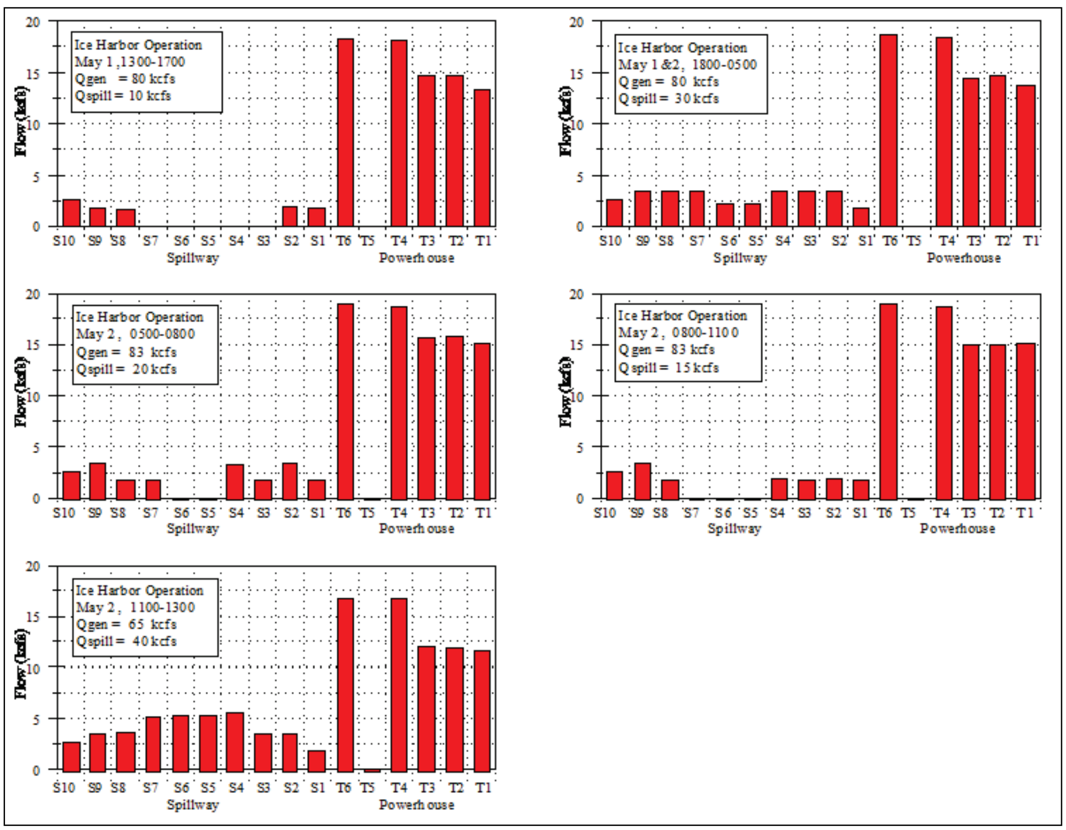
Figure 1. Overall project operations during 1–2 May 1996 study.



The operation of Ice Harbor's 6 turbine units and 10 spillway bays were recorded on 5-minute intervals throughout the study. Spillway discharge was stopped for 3 hours starting on May 1 at 1100 hours to enable the deployment of the instruments in the stilling basin and tailrace. During this period, a generation release of 80 kcfs was maintained through five turbines. Turbine Unit 5 was unavailable for use during the study. The tailwater elevation at the beginning of the testing period was 345.5 ft, and the forebay elevation was 438.5 ft. Water temperature was near 11 °C throughout the study.

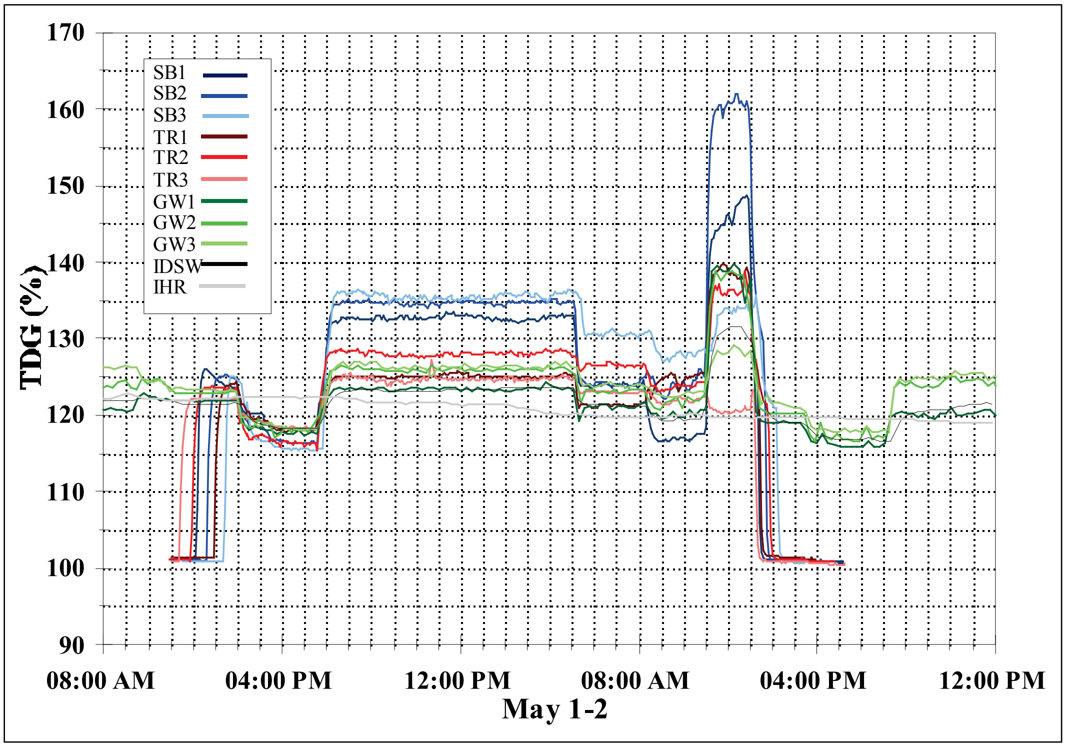
The spillway discharge was initially set to 10 kcfs (May 1, 1400–1700) for a 3-hour duration, raising the total river discharge to approximately 90 kcfs. The nighttime spillway pattern was implemented on May 1 at 1800 hours and continued until May 2 at 0500. During this 11-hour period, the spillway discharge was held constant at 30 kcfs, raising the total river discharge to 110 kcfs. Beginning on May 2 at 0500, the spill discharge was decreased by 10 kcfs resulting in a total spillway discharge of 20 kcfs. Three hours later (0800), the spill discharge was reduced to 15 kcfs. The largest spill event during the study period (40 kcfs) began at 1100 on May 2 and lasted 2 hours. Generation discharge was reduced by 15–20 kcfs during this period to maintain a total river flow of 100–107 kcfs. The spillway discharge was terminated at 1300 hours on May 2 to retrieve the instruments. The distribution of discharge across the spillway and powerhouse for each operating scenario is given in Figure 2.

Figure 2. Operational details during May 1–2 study.



The measured TDG levels for this study are shown in Figure 3, where SB designates measurements near the stilling basin, TR designates measurements in the near tailrace, and GW designates near the end of the lock guide wall. The IHR monitor was in the upstream pool on the face of the powerhouse while the IDSW was a fixed monitor approximately 3.6 miles downstream of the project. The TDG pressures recorded by the instrument array were converted to percent saturation by dividing by the local barometric pressure. The observed data are presented and discussed in detail in Appendix A.

Figure 3. Overall results of TDG measurements, May 1–2.



<u>1–2 May 1996 study conclusions and recommendations</u>. This study of dissolved gas levels in the tailwater at Ice Harbor Dam successfully documented temporal and spatial variations in TDG levels in the immediate vicinity of the stilling basin. This study clearly demonstrated the capability to remotely monitor TDG in high velocity flow near the end of the stilling basin and tailwater channel. The general conclusions from this study are as follows:

- For spillway flows over 20 kcfs, TDG pressures measured at the channel bottom near the stilling basin were significantly greater than levels measured downstream in the tailwater channel. The maximum pressure corresponded to a TDG level of 162% during a 40 kcfs spillway release.
- It was speculated that the extremely high TDG pressures measured in bubbly flow may reflect contributions from entrained air and dissolved

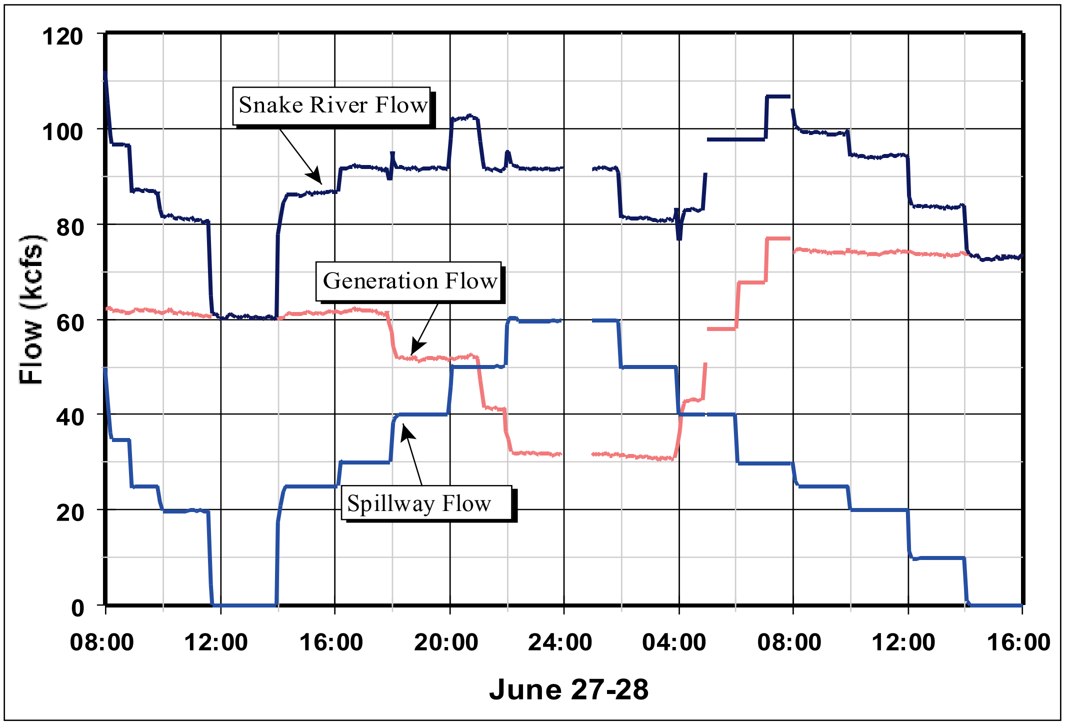
gases. However, from these tests, the influence of entrained air remains unknown and should be investigated.

- Changes in TDG corresponded closely with operational changes. Higher unit spillway discharges resulted in higher levels of TDG on all transects. Gate settings were no greater than 3 stops during this study.
- The observed levels of TDG at the end of the lock guide wall (Transect GW) and 240 ft downstream of the stilling basin (Transect TR) were generally consistent with observations from the Spillway Performance Tests and historic data from the tailwater fixed monitoring station.
- For flows up to 40 kcfs, the similarity of TDG saturation on transects TR and GW suggests that there is very little gas transfer beyond Transect TR, which is approximately 240 ft downstream of the stilling basin end sill. Prior to these observations, the gas transfer in the region outside of the stilling basin had been considered very important in gas transfer processes.
- Spillway discharges with gate settings of 1 stop caused degassing of the flow by up to 6% from approximately 122% to 116%. Similar downstream levels of TDG resulted for 1-stop setting even with forebay TDG levels of only 103% (net uptake). This implies that, for these low spillway flows, TDG production is independent of forebay TDG levels.

2.2 27–28 June 1996 field study

Operational conditions and observed data. After halting spillway flow for more than 2 hours on June 27 to deploy instruments in the stilling basin and tailrace areas, spillway releases were restarted at 1400 and were changed every 2 hours throughout the 24-hour testing. Five uniform spill patterns and seven standard spill patterns were studied. The uniform spill patterns of 2-hour duration were scheduled on June 27 in the following order: 25, 30, 40, 50, and 60 kcfs. A standard spill pattern was used during spillway releases on June 28 with spillway flow decreasing in the following order: 60, 50, 40, 30, 25, 20, and 10 kcfs as shown in Figure 4.

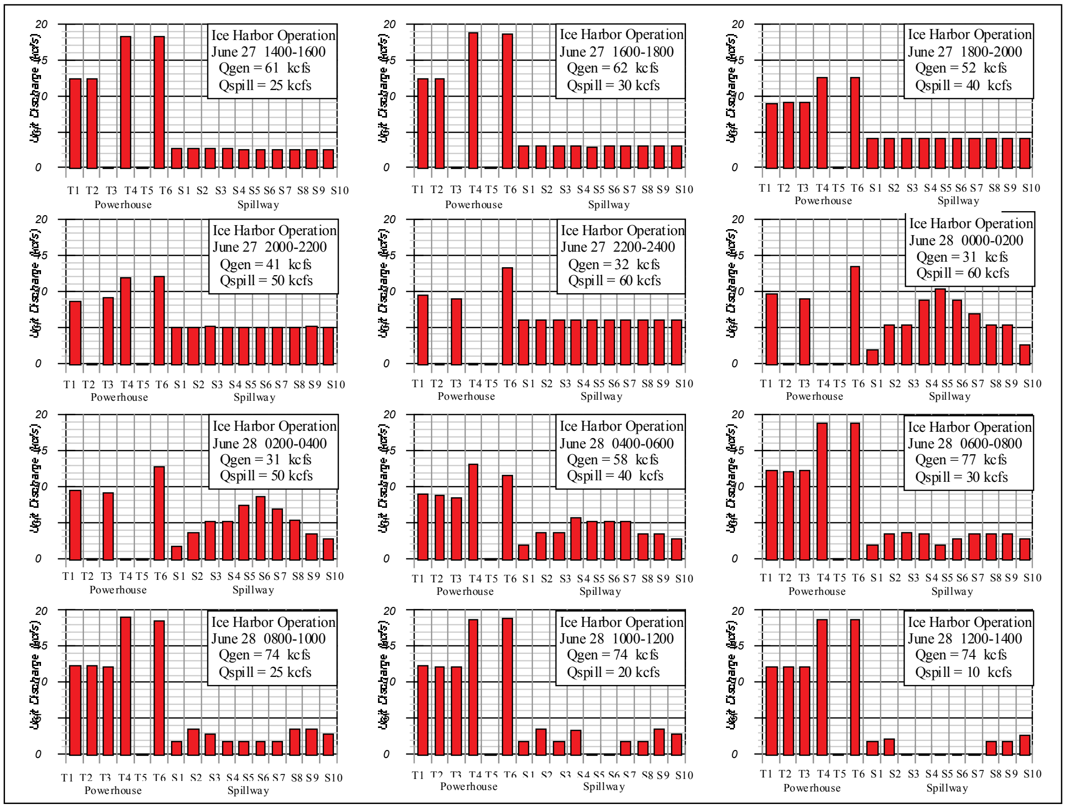
Figure 4. Overall project operations during June 27–28 study.



The generation discharge decreased during high spill periods and increased during low spill periods to maintain relatively constant total river flow rates. Total river flow ranged from 60 kcfs during instrument deployment to 104 kcfs during the morning hours of June 28. The tailwater stage ranged from 343.6 ft during the lowest river flow to a high water level of 346.9 ft during the higher flow events. The discharge for the 10 spillway bays and six turbines is shown graphically in Figure 5 for the entire study period.

The spillway gate settings for all bays were equal during the uniform spill pattern test on June 27. The gate settings ranged from 2.5 kcfs/bay during the 25 kcfs release to 6.0 kcfs/bay during the 60 kcfs spill. The standard spill pattern calls for a nonuniform distribution of discharge across the spillway. The standard 60 kcfs spill pattern calls for unit spillway releases ranging from 10.4 kcfs down to 1.7 kcfs. The spill pattern forms a convex distribution at higher flow rates and transitions to a concave distribution for spills less than 30 kcfs.

Figure 5. Operational details during June 27–28 study.



The TDG pressures, recorded by the instrument array during this June 27–28 field investigation, were converted to percent saturation by dividing by the local barometric pressure as measured by a reference barometer at the fixed monitoring station. The observed data are presented in several time-history plots (Figures 6–8) and discussed in detail in Appendix B. The relationships shown in Figure 9 represent the best estimates for downstream TDG based on total spill and spill pattern.

Figure 6. Overall measurements of stilling basin TDG, June 27–28.

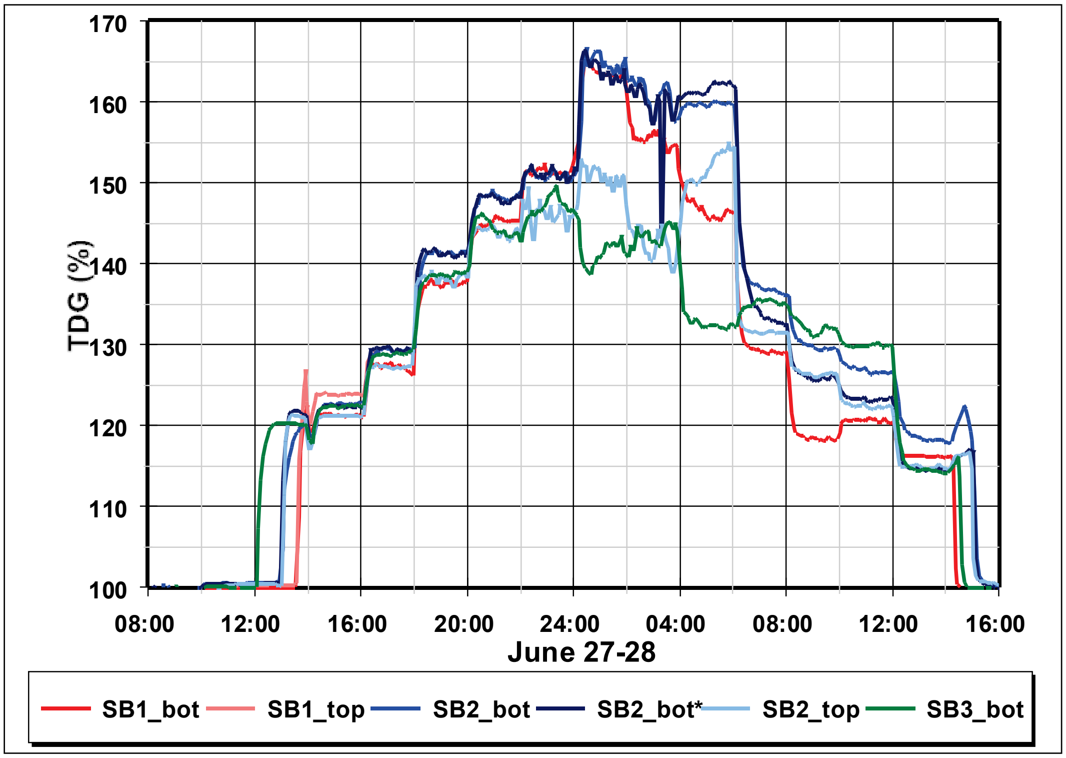


Figure 7. Overall results of tailrace TDG measurements, June 27–28.

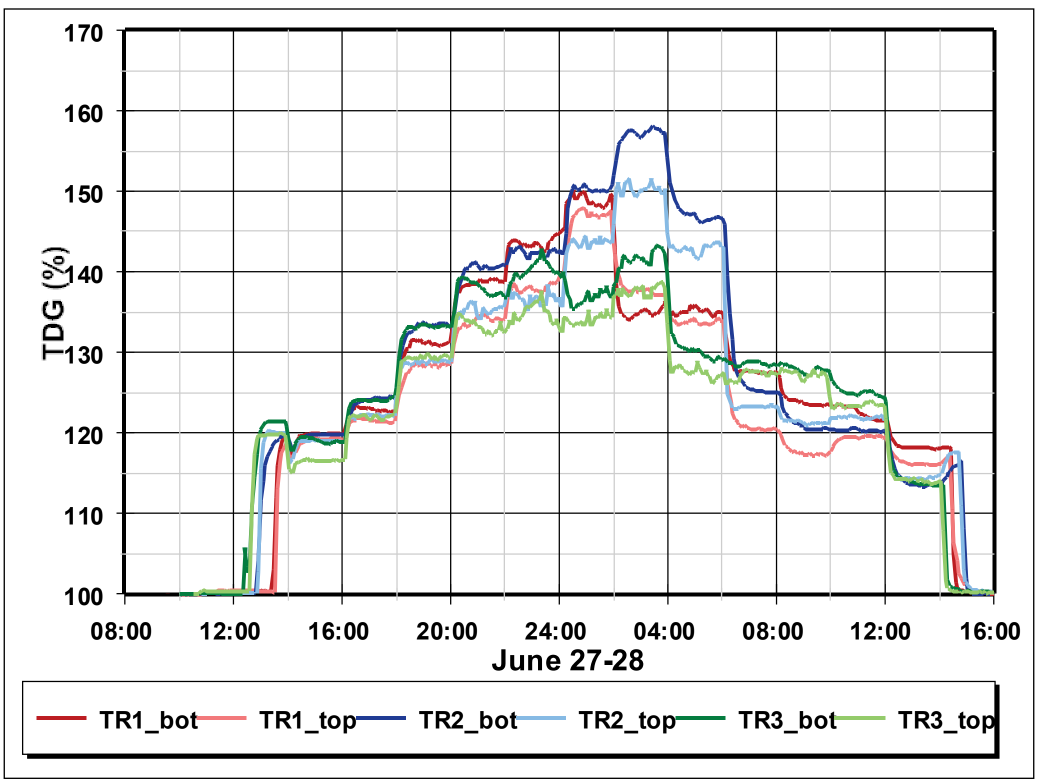


Figure 8. Overall results of upstream (IHR) and downstream TDG measurements, June 27–78.

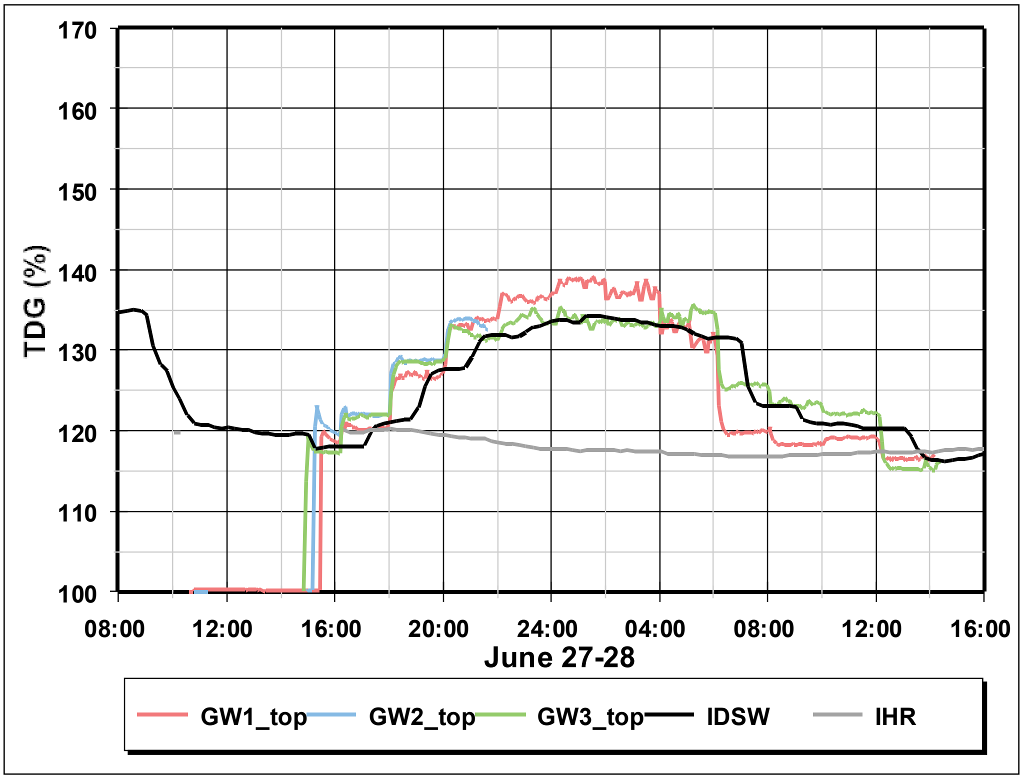
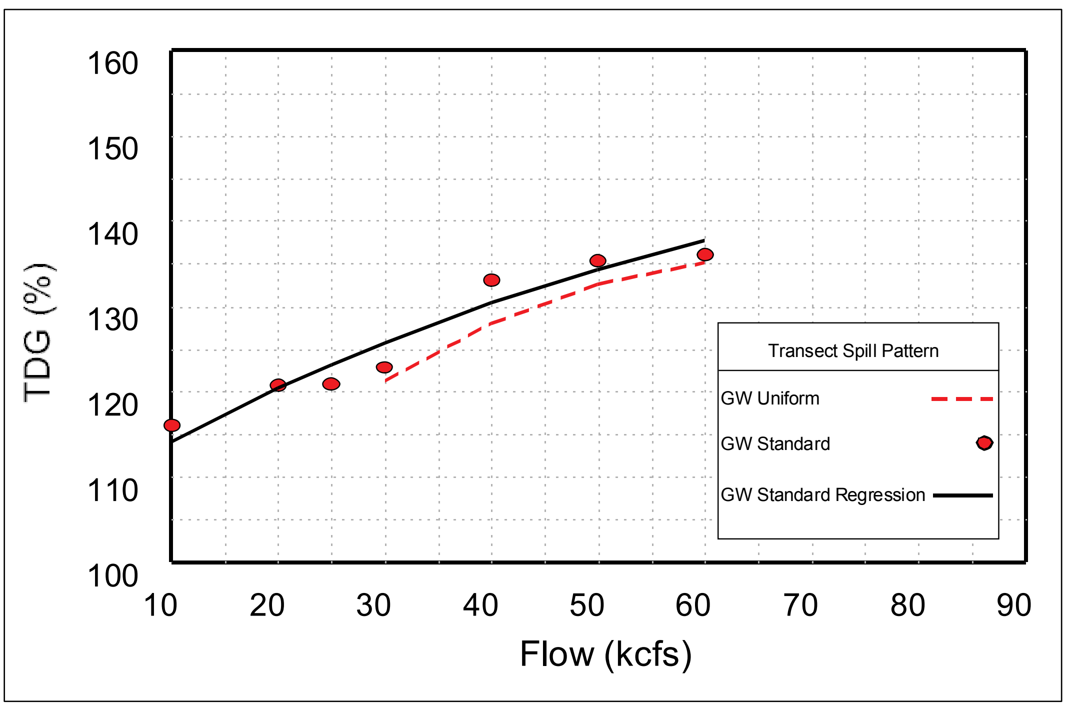


Figure 9. TDG estimates for standard and uniform spill patterns based on June 27–28 field investigation.



27–28 June 1996 study conclusions and recommendations. Several general observations regarding this study are as follows:

- Changes in TDG corresponded closely with operational changes.
- The TDG saturation levels resulting from the uniform spill pattern were generally less than the corresponding TDG pressures generated for the same total spill discharge using the standard spill pattern.
- TDG levels were generally highest at Transect SB, just downstream of the stilling basin, and decreased with distance downstream.
- Vertical gradients in TDG were greatest at Transect SB, just downstream of the stilling basin, for the higher discharges during the standard spill pattern.

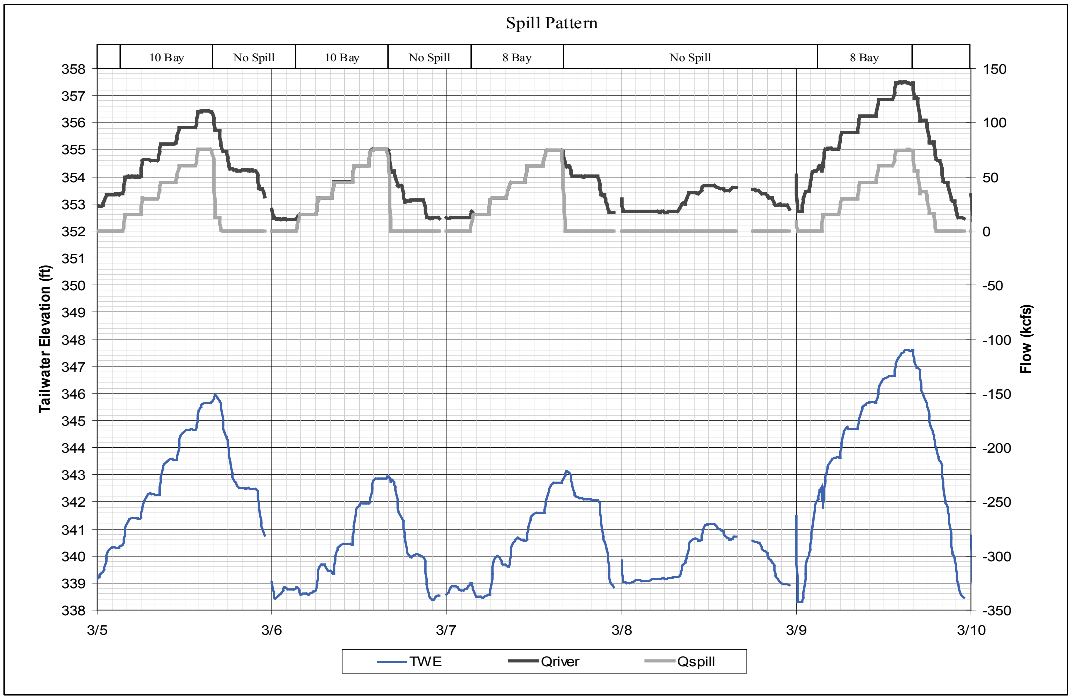
2.3 5–10 March 1998 field study

Operational conditions and observed data. The main objective of this field study was to investigate and document the TDG production characteristics of Ice Harbor Spillway with deflectors installed on 8 of the 10 spill bays for comparison to the previous field studies. Spillway discharge was halted at 0830 on March 4 to allow deployment of instruments. Normal spillway operation was resumed at 1500. Beginning at 0330 on March 5, the first set of conditions was assigned and was changed every 2.5 hours until the conclusion of the daily test schedule at 1600. Each test day was scheduled in the same fashion.

The spillway discharge was increased from 15,000 ft^3/s to 75,000 ft^3/s in 15,000 ft^3/s increments with a uniform spill distribution and a standard spill pattern with and without powerhouse discharges. The overall operating conditions are summarized in Figure 10. More detailed operating conditions for the 20 different tests are shown in Figure 11.

The TDG results are divided into four sets of daily operations. In Appendix C, each set of observed data is presented in several time-history plots with detailed analysis and discussion. The discussion below is based on only the observed TDG levels without regard to the flux of dissolved gas being delivered to the river. An example of the observed time histories of TDG levels across lateral Transects T1–T4 in the immediate vicinity of the structure is shown in Figure 12. These data show that TDG absorption in the stilling basin was directly related to the spill bay discharge. The highest TDG saturation occurred consistently near the longitudinal centerline of the spillway with the peak decreasing with distance downstream.

Figure 10. Overall project operations during 5–10 March 1998 study.



Of particular interest from the observed data were the longitudinal gradients in TDG, which show degassing in the tailrace. Figure 13, which is a profile of TDG along Longitudinal Profile L3, shows a dramatic drop in TDG from the 132% peak to 125% at Transect T2 and even lower at T3. Thus, the production characteristics of the spillway alone should range from approximately 132% down to 119 %.

A summary of the TDG production characteristics of the Ice Harbor Spillway is shown in Figure 14. The addition of spillway deflectors significantly reduced the TDG production at the stilling basin from approximately 150% to 125% at 6,000 ft^3/s/bay. With tailrace degassing, the TDG at the end of the navigation lock guide was reduced from approximately 135% down to approximately 114% at the 6,000 ft^3/s/bay.

5–10 March 1998 field study conclusions and recommendations. The general conclusions from the March 1998 study are as follows:

- Spillway deflectors significantly reduced the TDG supersaturation delivered to the Snake River by more than 50%. The maximum pre-deflector TDG levels of nearly 140% were reduced to 120% with deflectors, as measured at the fixed monitoring station (FMS) downstream.

Figure 11. Detailed project operations during 5–10 March 1998 study.

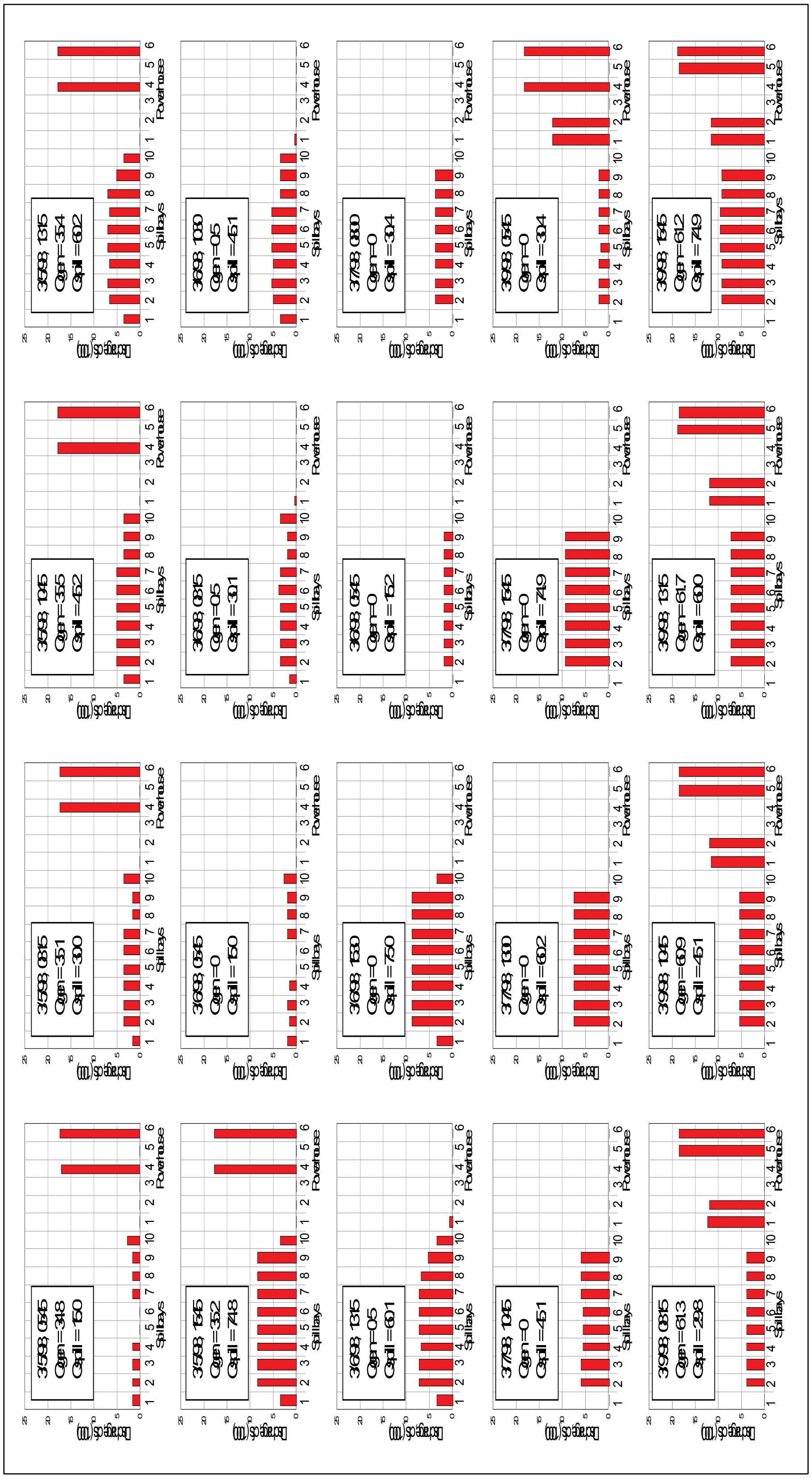


Figure 12. TDG measurements along Transect T1 nearest the structure, March 1998.

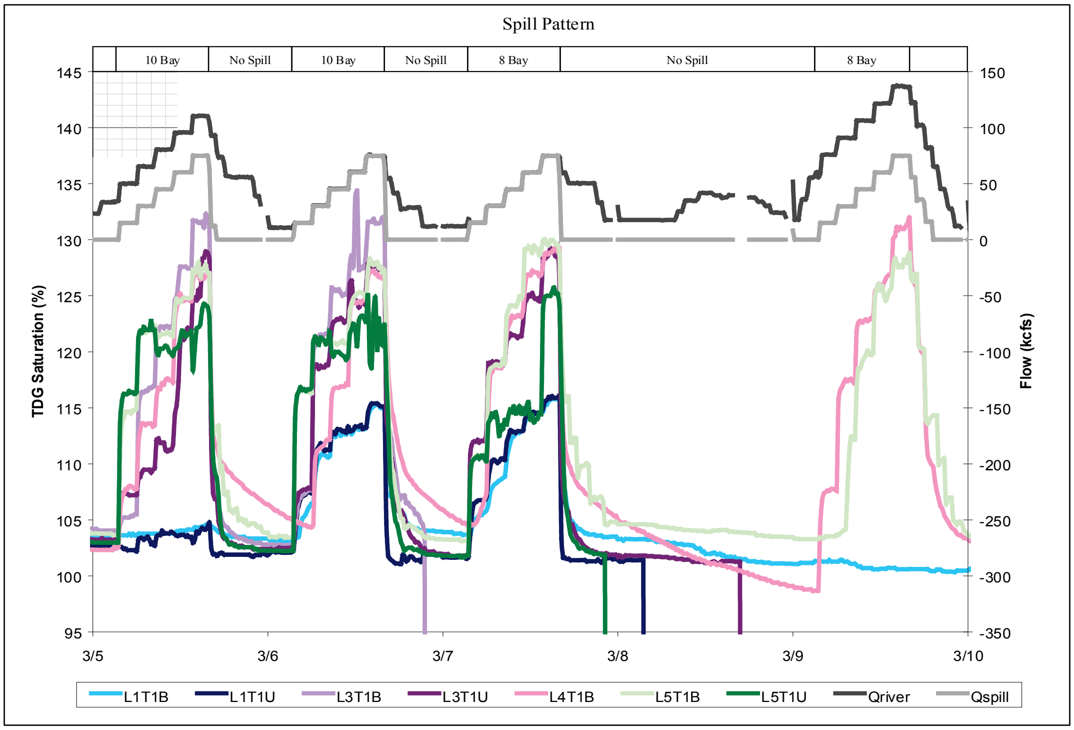


Figure 13. TDG Saturation along Longitudinal Profile L3, March 1998.

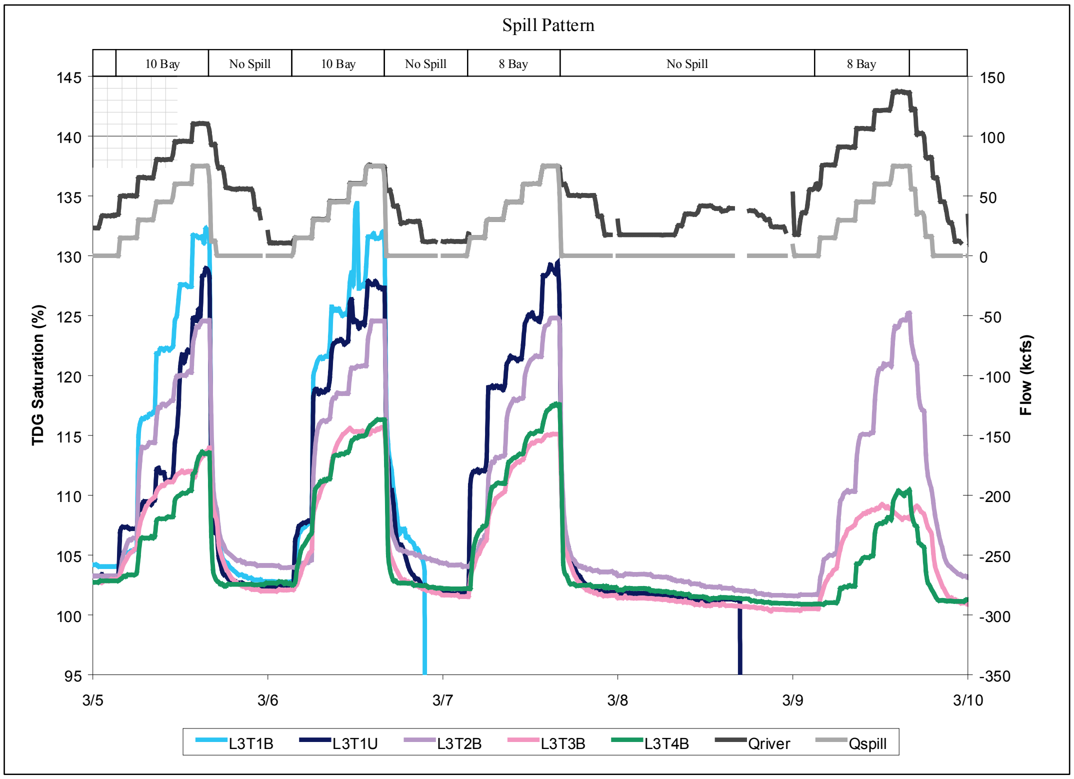
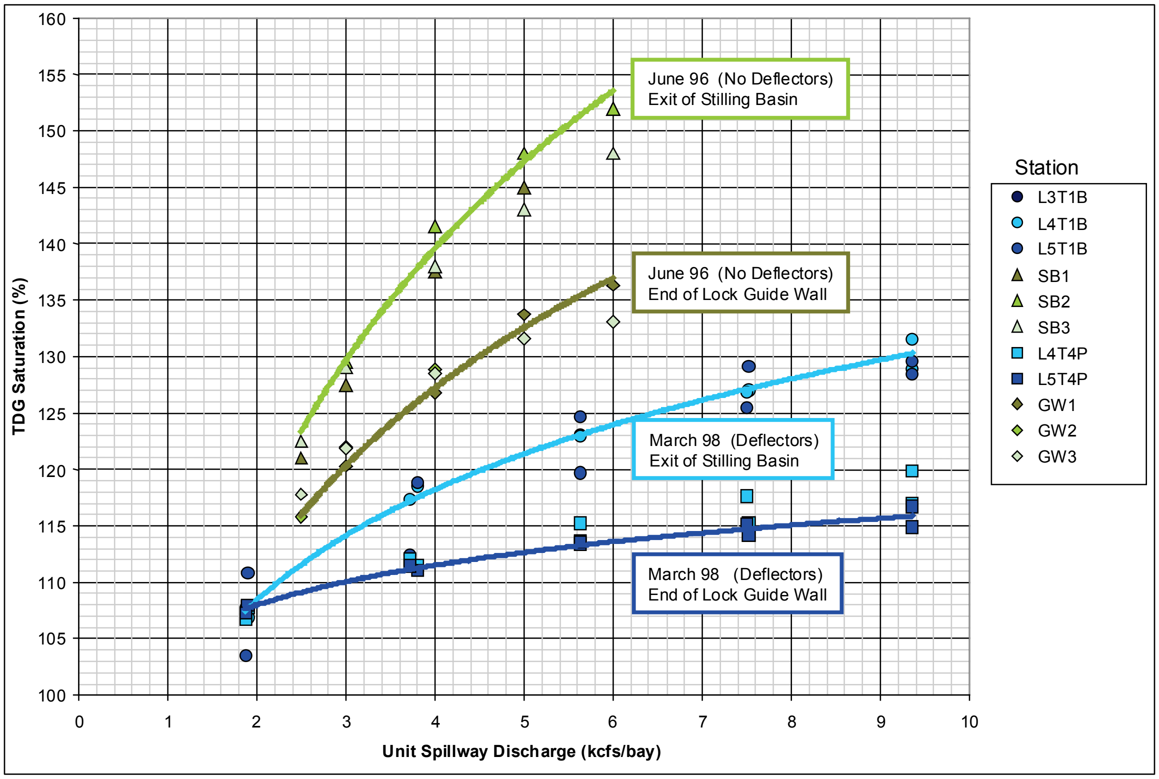


Figure 14. Pre-deflector and post-deflector TDG saturation below Ice Harbor Dam.



- The high levels of TDG absorption in the stilling basin were reduced from as high as 170% to 132% as a result of the flow deflectors.
- TDG saturation was highest at Transect T1, just downstream of the stilling basin, and decreased with distance downstream. The data support the conclusion that gas absorption occurs in the stilling basin while degassing occurs in the tailrace area. Most of the degassing appears to occur within 240 ft downstream of the stilling basin. Only minor reductions in TDG occurred in the next 300 ft.
- The TDG production was found to be primarily a function of the unit specific discharge and secondarily to the tailwater channel depth of flow. The regression model generated from this study is applicable only over the limited range of flow conditions tested. The dependence of TDG exchange on both unit discharge and tailwater elevation provides a direct linkage between powerhouse operation, pool elevation in McNary reservoir, and the TDG content of spillway releases. The concept of a single spillway capacity may not be appropriate in light of the dual dependency of spillway TDG pressures on tailwater depth and unit spillway discharge.
- The lateral entrainment of hydropower releases is evident in visual observations and in the measurements in the immediate tailrace. The

similar TDG production relationships suggest that some of the entrained hydropower water is subjected to gas absorption. Flux calculations based on data from Transect T5 clearly show that between 26 to 40 kcfs is being entrained and *gassed* to near spillway levels. Under some test conditions, all the powerhouse discharge was entrained and recirculating flow was apparent downstream of the powerhouse. The entrainment of powerhouse flow resulted in a significant increase in the TDG loading delivered to the Snake River during this study.

- The TDG pressure in areas of recirculating flow can achieve TDG levels significantly greater than observed in the main spillway release. These regions occur below the north fishway entrance and below the powerhouse during operations where most of the river is spilled.
- Changes in TDG corresponded closely with operational changes. Higher unit spillway discharges resulted in higher levels of TDG on all transects. Larger total river flows associated with hydropower operation also resulted in slightly higher TDG pressures.

3 Conclusions and Recommendations

Several structural alternatives were considered for reducing TDG at Ice Harbor during spillway operation, but based on cost and estimated effectiveness, spillway deflectors were selected. These three field studies clearly show that the deflectors significantly reduced absorbed gas by creating a jet skimming across the tailwater surface reducing the effects of the aerated jet plunging into the deep stilling basin.

The TDG exiting the Ice Harbor tailrace area was reduced from approximately 135% to approximately 114% with a unit spillway discharge of 6 kcfs per bay. Even with a unit discharge of over 9 kcfs per spill bay, the deflected flow produced less TDG (~117%) than the undeflected flow conditions at 3 kcfs per spill bay. At the FMS downstream, the maximum pre-deflector TDG level of nearly 140% was reduced to approximately120% with deflectors.

Changes in TDG corresponded closely with operational changes with higher unit spillway discharges resulting in higher levels of TDG.

In general, total dissolved gas in or very near the stilling basin was much higher than the TDG measured at the navigation lock guide wall downstream. This indicates that significant degassing occurs during passage from the stilling basin to this downstream monitoring location. It seems likely that gas absorption occurs in the deep water of the stilling basin while degassing occurs in the highly aerated, shallower tailrace region. However, there appears to be very little additional gas loss between the lock wall and the fixed monitoring station much farther downstream.

Very small discharge rates, less than 1 kcfs per spill bay, resulted in degassing of the flow by up to 6% from approximately 122% in the forebay to 116% in the tailrace. Similar downstream levels of TDG resulted for small discharges, even with forebay TDG levels of only 103% giving a net uptake. It appears that, for these low spillway flows, TDG production is independent of forebay TDG levels.

Appendix A: Memorandum for Record Subject: Total Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater, 1–2 May 1996

CEWES-HS-L June 13, 1996

MEMORANDUM FOR RECORD

SUBJECT: Total Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater

1. Introduction: The purpose of the Dissolved Gas Abatement Study (DGAS) is to develop structural and operational alternatives to decrease the dissolved gas pressures generated during spillway operations on the Snake and Columbia Rivers. The ultimate effectiveness of gas abatement alternatives will be measured in terms of impacts on the biological community. The assessment of DGAS alternatives will be conducted through analysis of historic data from fixed shore-based monitoring stations, site specific prototype field studies, physical models, and analytical investigations concerning gas exchange at hydraulic structures. This document summarizes the results of a field study conducted in the tailwater channel at Ice Harbor Dam. The purpose of this field investigation was to more clearly define and quantify processes that contribute to dissolved gas transfer during spillway releases. These conclusions will aid in the identification of operational and structural measures that reduce dissolved gas supersaturation.

2. Many aspects of the field investigation at Ice Harbor Dam were experimental in nature. Prior investigations of spillway performance were limited to regions outside of the bubbly flow regime that were accessible by survey boat. In this study instruments were deployed in the high-velocity, extremely turbulent, highly aerated bubbly flow of the stilling basin, endsill area, and near-field tailrace area. The response of the total dissolved gas monitor to these conditions was unknown. The durability of the instrument in these extreme conditions was a second concern. The deployment and recovery of a large matrix of instruments presented a third challenge.

3. Objectives: The objective of this field study was to quantify dissolved gas exchange downstream of the spillway at Ice Harbor Dam. This field experiment was designed to sample TDG pressures on a regular interval throughout the study period. These data could then be integrated to provide estimates of the mass flux of dissolved gas past a given transect. The comparison of mass flux estimates could be used to determine the relative importance of gas exchange processes within the stilling basin and the downstream tailrace.

4. Approach: Lateral and longitudinal gradients in total dissolved gas pressures were investigated in the region downstream of the north section of the spillway, bounded by the end of the stilling basin and tip of the lock guide wall. The transfer of dissolved gas is generally thought to be related to the unit spillway discharge, spill pattern, spillway geometry, stilling basin and tailwater depth and flow conditions, forebay total dissolved gas concentration, project head differential, and water temperature. Because of the limited duration of this study (23 hours), only unit spillway discharge and spill pattern were varied to rigorously investigate spill events up to 40 kcfs. Total dissolved gas pressures were measured with an array of monitors located in the tailwater channel downstream of the spillway during the period of May 1 and 2, 1996. These instruments were deployed along three transects as shown in Figure 1. Three instruments were located on the

bottom on a transect just downstream of the stilling basin (SB). Three instruments were located on the bottom in the tailrace (TR) approximately 200 ft downstream of the SB transect. Three instruments were deployed at mid-depth on a transect off the lock guide wall (GW).

5. Project Description The powerhouse at Ice Harbor Dam consists of 6 hydroturbines with a combined discharge capacity of 105 kcfs. The spillway at Ice Harbor Dam has a total length of 590 feet and consists of 10 gate-controlled bays. There are no spillway deflectors at Ice Harbor Dam. The elevation of the spillway crest is 391 ft mls as shown in Figure 2. The horizontal apron-type stilling basin at Ice Harbor Dam is about 210 ft long with an invert elevation of 304 ft The depth of flow in the stilling basin was over 40 ft during the entire testing period on May 1 and 2. One row of baffle blocks 8 ft high and an end sill 12 ft high provide for energy dissipation in the stilling basin. A training wall extending over two-thirds the length of the stilling basin separates bays 10 and 1 from interior bays. The tailwater channel downstream of the stilling basin is generally above elevation 320 ft with the exception of a large depression located upstream of the end of the lock guide wall.

6. Hydrodynamics. The following description of stilling basin flow was derived through observations of the general physical model of the structure and prototype surface flow conditions. The main spillway flow at Ice Harbor, plunges and moves through the stilling basin as a highly turbulent aerated shear flow. A bottom current directs flow out of the stilling basin and a surface roller returns current back to the dam. This general pattern of circulation is broken up at the baffle
blocks and end sill which direct flow vertically as shown in Figure 2. The spillway discharge from bays 1 and 10 are partially separated from the flow from interior bays by a training wall that extends over three-fourths the length if the stilling basin. The tailwater channel downstream of the powerhouse is shallow causing both generation and spillway discharges to converge to the navigation channel located on the north side of the river. This strong cross flow influenced the locations of the TDG instruments in the tailwater channel. A detailed description of circulation patterns downstream of Ice Harbor Dam as observed in the general physical model can be found in Appendix A.

7. Detailed Descriptions of Instrument Location The SB transect was located about 40 feet downstream of the stilling basin end sill in about 20-25 ft of water. The Common Sensing instruments were sandwiched between two 30-inch-long steel rails to protect the instrument and to ensure a fixed position at the bottom of the channel. The instruments on transect SB were anchored to a steel cable that was secured to the trunion deck on the spillway piers. This also restricted instrument movement and aided instrument recovery. The three instruments on transect SB were downstream of spillway bays 5, 7, and 9. The instruments were located downstream of the northern section of the spillway to reduce the influence of dilution from generation releases. The parameters measured by the Common Sensing instruments were water temperature, total dissolved gas pressure, and dissolved oxygen concentration. These data were recorded in 5 minute intervals.

8. The TR transect was located in the tailrace about 240 ft downstream of the end of the stilling basin. This positioning scheme was selected to sample the same water at each transect. The lateral position of the instruments was offset by about 50 ft to the lock side of the instrument

positions on transect SB because of the orientation of spillway flow. Two of the three Common Sensing instruments deployed on transect TR were encased between steel rails. The third instrument was fastened to a 60-lb steel ring. All three instruments were deployed on the channel bottom in about 20-25 feet of water. The lateral position of the instruments corresponded to the north piers adjacent to spillbays 6, 8, and 10. Additional 150-lb concrete anchors were used to restrict movement of the instrument on the channel bottom.

9. The GW transect was located about 1100 ft downstream of the end of the stilling basin at the end of the lock guide wall. The transect was selected because it represents the downstream extent of bubbly flow during high spillway release events. The lateral spacing of the instruments was about 40 ft as shown in Figure 1. The depth of water along this transect ranged from 15 to 25 ft All three Hydrolab instruments were tethered on 50-ft-long cables between surface floats and bottom anchors. The depths of the instruments varied depending upon the hydrodynamic forces on the surface float. The instrument depths ranged from 8 meters at station GW1 to 2 meters at station GW3. The parameters measures by the hydrolab instruments were water temperature, instrument depth, total dissolved gas pressure, dissolved oxygen concentration, pH, and conductivity. This information was logged in 15 minute intervals.

10. Supplemental TDG pressures were measured at the forebay and tailwater fixed monitoring stations. A fixed TDG monitor (IHR) was located on the upstream face of the powerhouse at Ice Harbor Dam. This instrument provided an estimate of TDG pressures passing through the powerhouse during the study period. Previous studies have indicated small rates (1-2%) of degassing can occur in the turbulent mixing zone directly downstream of the powerhouse. A second fixed monitoring station (ISDW) was located about 3.6 miles downstream of Ice Harbor Dam along the north channel bank. This instrument was located on the north bank of the Snake River to capture TDG associated with spillway releases. The parameters measured at the fixed monitoring stations include water temperature, barometric pressure, total dissolved gas pressure, and dissolved oxygen concentration. This information was logged in 15 minute intervals.

11. <u>Operating Conditions</u> The study began on May 1, 1996 at 1100 hours and ended 30 hours later at 1500 on May 2. During this period, seven major operational changes were implemented. The operation of Ice Harbor's 6 turbine units and 10 spillway bays were recorded in 5 minute intervals throughout the study period. This information was averaged for each hour of the study and is shown in Appendix B, Table B1.

12. Spillway discharge was stopped for three hours starting on May 1 at 1100 hour to enable the deployment of the instruments on transects SB and TR. During this period, a generation release of 80 kcfs was maintained through 5 turbines as shown in Figure 3. Turbine Unit 5 was not available for use throughout the study period. The tailwater elevation at the beginning of the testing period was 345.5 ft and the forebay elevation was 438.5 ft The water temperature was near 11 ^{o}C throughout the duration of this test.

13. The spillway discharge was initially set to 10 kcfs (May 1, 1400-1700) for a three hour duration, raising the total river discharge to about 90 kcfs. The nighttime spillway pattern was implemented on May 1 at 1800 hours and continued until May 2 at 0500. During this 11 hour period, the spillway discharge was held constant at 30 kcfs, raising the total river discharge to

110 kcfs. Beginning on May 2 at 0500, the spill discharge was decreased by 10 kcfs resulting in a total spillway discharge of 20 kcfs. Three hours later (0800), the spill discharge was reduced to 15 kcfs. The largest spill event during the study period of 40 kcfs began at 1100 on May 2 and lasted two hours. Generation discharge was reduced by 15-20 kcfs during this period to maintain a total river flow of 100-107 kcfs. The spillway discharge was terminated at 1300 hours on May 2 to retrieve the instruments.

14. The five different spill patterns and turbine discharge tested are shown in Figure 4 for the duration of the testing period. The discharge from bay 1 and bay 10 was held constant throughout the study period at 1 and 1.5 stops, respectively. Only five active bays were operated with no flow through the middle of the spillway for the 10 kcfs spill. The nighttime spill pattern consisted of discharge from 6 bays at 2 stops, and single stop settings for the remaining bays. For the intermediate spillway flows on the morning of May 2, gate settings ranged from 0 to 2 stops. For the highest spillway discharge, a symmetric distribution of spillway gate settings was established with the center three bays at 3 stops, the outside bays at 1 stop, and intermediate bays at 2 stops.

15. <u>Results</u>   The TDG pressures recorded by the instrument array downstream of Ice Harbor Dam, were converted to percent saturation by dividing by the local barometric pressure (751 mm) as determined by a local reference barometer. The time history of all TDG data are shown in Figure 5. An hourly summary of TDG data at each station has been tabulated in Appendix B in Table B2. Several general observations regarding this data record are as follows:

a. Changes in TDG corresponded closely with operational changes.

b. Higher spillway discharges resulted in higher pressures of TDG on all transects.

c. Low spillway discharges (gate settings of 1 stop) caused degassing of spillway releases compared to forebay concentrations.

d. The TDG on transect SB were generally greater than those observed downstream on transcects TR or GW for higher spillway discharges (>20 kcfs).

e. TDG on transects TR and GW were similar throughout the testing period.

f. TDG pressures on transects SB, TR, and GW were similar during low spillway discharges (<20 kcfs).

g. The variability of TDG pressures for a specific instrument was generally small for constant operating conditions.

h. The range of TDG pressures measured at the tailwater fixed monitoring stations were generally smaller than values observed at any of the near-field stations.

16. The spill discharge was halted by 1100 hours on May 1 to allow the deployment of TDG instruments on transects SB and TR. The instruments on transect GW had been deployed several

days earlier. During the three hours required for instrument deployment, the powerhouse at Ice Harbor Dam was generating power and releasing water at a rate 79.6 kcfs. The forebay TDG saturation was measured at 122.2 percent and falling slowly at a rate of about 0.1 percent per hour. The TDG saturation on transect GW ranged from 122 to 124 percent during this period, slightly greater than observed forebay saturation. These instrument appeared to be located in a region of strong current fed by generation releases. The time of instrument deployment on transects TR and SB are shown in Figure 6 by the abrupt increase in TDG from 101 percent to over 120 percent. The TDG saturation on transects TR and SB ranged from 122-125 percent supersaturation prior to the initiation of spill discharges. The instruments on transects TR and SB were located in a large circulation cell during the non-spill hours. As a result of this flow condition, the TDG pressures may be influenced by TDG pressures associated with spillway releases prior to deployment of the instruments. TDG in this eddy should approach levels in generation releases as mixing and entrainment dilutes water in this region. The TDG pressures on transects TR and SB approach pressures observed near the end of the lock guide wall by 1400.

17. A spillway discharge of 10 kcfs was initiated at 1400 and maintained for three and one-half hours. For this spill event, outside spill bays 1, 2, 8, 9, and 10 were set at stop settings ranging from 1 to 1.5. All the remaining bays were closed. At the initiation of spillway discharge, the TDG saturation at all three near-field transects decreased by about 5 percent from 123 to 118 percent as shown in Figure 6. The forebay TDG saturation (IHR) was slightly greater than 122 percent throughout this period. TDG saturation gradually dropped during the first hour of spillway discharge and leveled off within a range of 115.5 to 118.5 percent. The lowest TDG pressures were observed at stations TR2, SB2, and SB3. The inactivity of releases from interior spill bays caused counter-rotating eddies in the stilling basin. This circulation pattern may have contributed to the slight variation in TDG pressures across the tailwater channel. Measurements at the fixed monitoring station during this period also support the conclusion of spillway degassing. The TDG saturation also dropped from 122 percent to 118 percent during the 10 kcfs spillway release at station IDSW.

18. The nighttime spill pattern was implemented on May 1 at 1800 and continued until May 2 at 0500. During this 11 hour period, the spillway discharge was held constant at 30 kcfs, raising the total river discharge to 110 kcfs. The tailwater elevation ranged from 347.0-347.4 during this operation. The spill pattern consisted of bays 2, 3, 4, 7, 8, and 9 set at 2 stops with the remaining bays set at 1-1.5 stops. The TDG saturation increased significantly above forebay levels on all three near-field transects and at the tailwater fixed monitor as shown in Figures 6 and 7. TDG pressures on transect SB were considerably greater than those observed at the two downstream transects. The TDG ranged from 123 to 128 percent on transects TR and GW as compared to a range of 132.5 to 136 percent on transect SB. The TDG saturation at station SB3 increased from 115.5 to 135 percent supersaturation. The TDG saturation at the tailwater fixed monitor stabilized at 123 percent supersaturation or slightly less than the mean levels observed on transects TR and GW.

19. Beginning on May 2 at 0500, the spill discharge was decreased from 30 kcfs to 20 kcfs. The gate settings were 2 stops or less. The TDG saturation at all stations decreased in response to the reduction in the level of spill as shown in Figure 7. The TDG saturation dropped

consistently by about 2 percent on transects TR and GW and at the downstream fixed monitor. The reduction in gas saturation at transect SB was more varied with about a 5 percent reduction at station SB3 and nearly 10 percent reduction at station SB2. The higher TDG pressures at stations SB3 and TR2 may have resulted from a greater contribution of flow from bay 9 which was operating at a higher unit discharge than the other spillbays. The TDG pressures at stations TR1 and GW1 were slightly less than forebay pressures.

20. Three hours later, at 0800 hours on May 2, the spill discharge was reduced to 15 kcfs. This discharge was achieved by closing Bay No. 7 and reducing the gate setting on Bays Nos. 2 and 4 by one stop. Figure 8 shows the response of TDG saturation to this reduction in spillway discharge. The average TDG saturation on transects GW and TR showed little change and all three stations on transect GW decreased slightly. However, the TDG pressure at station TR1 increased in response to the new spill pattern. The TDG saturation at the downstream fixed monitor dropped about 2 percent to a level slightly lower than the forebay level. The TDG saturation varied considerably on transect SB ranging from 117 percent on station SB1 to 128 percent on station SB3. The TDG pressures at Station SB1 were less than forebay levels.

21. The largest spillway release of 40 kcfs was initiated at 1100 hours on May 2 with a duration of two hours. Generation discharge was reduced 15-20 kcfs during this period to maintain a total river flow of approximately 100-107 kcfs. All of the gates were set with an opening of 3 stops. TDG increased significantly at all stations with the exception of station TR3 as shown in Figure 8. It appears that station TR3 was primarily influenced by releases from bays 9 and 10 which were not changed to achieve the 40 kcfs release. Both lateral and longitudinal gradients in TDG were observed during this spillway release (Figure 9). The TDG saturation was as high as 162 percent on transect SB2. The TDG saturation at station SB1 climbed abruptly to 142 percent with the increased flow, and continued to climb for the duration of the spill event reaching a maximum level of 148 percent. The contribution of flow from bays 8, 9, and 10 probably resulted in lower TDG (134 %) at station SB3. TDG reached a maximum value of 139 percent on transects TR and GW at stations TR1, TR2, GW1 and GW2. The TDG saturation on station GW3 reached a maximum level of only 129 percent. The lower gas readings on the lock side of all three transcects (GW3, TR3, SB3) suggests lateral gradients in TDG of spillway releases persist in the near-field region of the Ice Harbor tailwater channel. Resolving these lateral gradients were important in quantifying the total dissolved gas flux this project releases. Dissolved gas readings at the tailwater fixed monitoring station reached a maximum saturation of 131.5 percent. The lower TDG pressures at the fixed monitoring station can be attributed to lateral mixing of spillway releases, dilution with generation water, and degassing in transit.

22. Discussion. The objective of this investigation was to quantify dissolved gas exchange downstream of the spillway at Ice Harbor Dam. The location of three transects in the immediate tailwater channel of Ice Harbor showed lateral and longitudinal gradients in total dissolved gas pressures. The intent of the sampling design was to monitor dissolved gas pressures of the same spillway discharge at three different locations in its flow path between the end of the stilling basin and tip of the lock guide wall. Changes in the flux of dissolved gas from one transect to

another can be used to estimate the degree of dissolved gas exchange in the stilling basin and in the immediate tailwater channel.

23. Total dissolved gas pressures measured on transect SB were significantly higher than the pressures recorded at the fixed monitor or on transect GW for spillway flows greater than 20 kcfs. The maximum TDG pressure observed on transect SB occurred with the 40 kcfs spillway discharge and corresponded to a saturation of 162 percent. It is likely that dissolved gas pressures higher than those observed at the endsill transect (SB) were present in the stilling basin and adjoining tailwater channel.

24. The interpretation of the Ice Harbor tailwater observations should include processes that produce the high TDG pressures exiting the stilling basin and the abrupt reduction in pressures in a 200-ft-long reach immediately downstream. Two possible explanations were offered for these observations:

a. ***Alternative I.*** The observed data reflect actual total dissolved gas pressures exiting the stilling basin. The reduction in pressure downstream of the stilling basin is attributable to some combination of dilution and degassing.

b. ***Alternative II.*** The observed data were not representative of total dissolved gas pressures, but were biased by exposure to entrained air under hydrostatic pressure. The abrupt reduction in observed pressures can be attributed to the reduced levels of entrained air in the flow at the downstream TR stations.

25. ***Alternative I.*** If the pressure measurements directly downstream of the stilling basin at Ice Harbor Dam accurately reflect dissolved gas pressures, then extremely high rates of gas exchange take place in the stilling basin. From the basic physics of gas transfer, it is known that the exchange of gas from entrained air bubbles to the flow is greatly accelerated at the high local pressures experienced at depth (> 40 ft) in the stilling basin. With the large amounts of air entrained and transported by the flow along the stilling basin floor, it is reasonable to expect higher TDG pressures at the bottom of the stilling basin than at lesser depths. As a consequence, water exiting the stilling basin may exhibit vertical gradients in dissolved gas pressures. It is likely that these vertical gradients will quickly dissipate because of turbulent mixing as the flow moves downstream. The pressure history and exposure time of a parcel of water exiting the stilling basin may vary considerably, due to the high turbulence and complex flow patterns in the stilling basin. These flow patterns together with variations in the amount of entrained air, could account for much of the temporal and lateral variation in TDG pressures observed on transect SB.

26. Additionally, if the SB measurements are accurate, then the reduction in pressures observed at the TR transect can be attributed to some combination of degassing or dilution. Lateral and vertical heterogeneities in TDG pressures could be present just outside of the stilling basin. As a result, the observed TDG pressures at the bottom of the channel would not be representative of water passing through the region. The mixing of these properties outside of the stilling basin could account for the decrease in observed TDG pressures. The entrainment of generation

releases could also account for TDG pressures to decrease along the flow path during high spillway releases.

27. The presence of entrained air and high TDG pressures exiting a deep stilling basin into a shallow tailwater channel could promote processes degassing the water. The hydrostatic pressures in the shallow tailwater channel would result in a net mass transfer from the water to the air bubbles over most of the depth. The hydrostatic pressures at mid-depth of the tailwater channel was consistant with the TDG pressures observed at the downstream tailwater fixed monitoring station. The buoyancy of the air bubbles will cause the distribution of bubbles to rise in the water column as turbulence levels decrease and flow moves downstream. As bubble rise in water with high TDG pressures, both the pressure differential and surface area will increase resulting in a greater potential for mass transfer. The rate of degassing would significantly decrease outside of the region of bubbly flow.

28. ***Alternative II.*** It was conjectured that the TDG pressure observations in the Ice Harbor tailwater might be biased by the presence of entrained air bubbles. If bubbles are in direct and constant contact with the membrane of the TDG monitor, the pressure readings may reflect both the hydrostatic pressure in the entrained air bubbles and the dissolved gas pressure in the water. This scenario is founded upon the assumption that entrained air was present at sufficient levels to influence TDG pressure measurements. If this is the case, the divergence of observed pressures on transects SB and TR during higher discharge conditions may be caused by the higher density of bubbles near the channel bottom at the end of the stilling basin. A higher density of entrained air would result in a greater exposure of the membrane to air bubble pressures (25 ft depth or 1.74 atmospheres). The degree of bias will be a function of the instrument depth, bubble size and distribution, and local turbulence. The steel rails, which acted as ballast and a protective enclosure, shelters the instrument from conditions that exist in free stream flow. The net buoyancy of the bubbles in the vicinity of the pressure sensor will also influence exposure rates to entrained air.

29. A scenario of pressures influenced by entrained air is consistent with the reduction in TDG pressures downstream of the stilling basin. If bubbly flow exists at the measurement locations along transect SB, but does not extend to transect TR, then the TDG pressure difference might be attributable to the pressure bias caused by entrained air. For spillway flows less than 20 kcfs, all of the transects were downstream of the bubbly flow, resulting in similar TDG pressures. Additional experiments are needed to further determine the response of TDG monitors to entrained air bubbles.

30. ***Analysis and Discussion.*** Prior to the findings of this field study, it was assumed that TDG pressures increased as flow pass from the spillway through the stilling basin and through the tailrace area. This conceptual model is not consistent with data from this study assuming TDG observations were not biased by entrained air. The data indicate a rapid and extensive absorption of gas in the stilling basin followed by rapid and extensive desorption or mixing of dissolved gas in the tailrace channel. This alternative model of gas exchange has significant ramifications regarding the effectiveness of structural and operational alternatives for dissolved gas abatement.

31. The following analyses of TDG exchange below Ice Harbor Dam presumes that TDG pressure measurements were unbiased by entrained air. The relative change in mass flux was estimated by computing a simple average of TDG saturation on each transect. This analysis of average transect TDG properties also assumes that a consistent volume of water was being sampled, i.e., same water is being sampled at each transect; TDG observations at the channel bottom were representative of bulk flow conditions; and uniform flow conditions existed across each transect. The heterogeneities in both the flow and TDG fields preclude a rigorous accounting of mass conservation over the study area.

32. The average TDG saturation on all three transects were computed for the five different spillway operations as listed in Table 1. The corresponding average TDG saturation at the tailwater and forebay fixed monitoring stations were also determined. The results indicate TDG saturation were similar on transects TR and GW for all spillway releases up to 40 kcfs. The TDG saturation downstream of the stilling basin were similar at all three transects for total spillway flows less than 20 kcfs. During the period of 1530-1715 on May 1, the TDG saturation ranged from 116.8 percent on transect SB to 117.9 on transect GW. For flows greater than 20 kcfs, the TDG saturation on transect SB were significantly greater than those on transects TR or GW. During the 40 kcfs release from 1130-1245 on May 2, the average TDG saturation ranged from 146.9 percent on transect SB to 131.6 percent on transect TR.

Table 1. Statistics of TDG Saturation at Ice Harbor Dam During Constant Operating Conditions; May 1-2, 1996.

	Day	May 1	May 1-2	May 1	May 2	May 2
	Time	1530-1715	2000-0500	0600-0800	0900-1100	1130-1245
Transect SB TDG (%)	Average	116.8	134.2	126.2	123.0	146.9
	STD	1.1	1.3	3.1	4.5	11.2
	Max	118.4	136.5	131.3	128.8	162.1
	Min	115.4	128.6	123.7	116.5	133.0
	N	63	390	69	72	44
Transect TR TDG (%)	Average	117.7	126.0	123.6	123.6	131.6
	STD	1.0	1.5	2.2	1.3	8.2
	Max	118.8	128.6	126.9	125.6	139.8
	Min	116.0	123.2	121.0	121.3	120.1
	N	63	390	70	71	44
Tran-sect GW TDG (%)	Average	117.9	125.3	122.7	121.6	135.3
	STD	0.4	1.3	1.2	1.2	4.9
	Max	118.5	127.0	124.4	123.0	139.7
	Min	117.2	122.5	120.8	119.6	127.7
	N	21	132	24	24	15
Station IDSW TDG (%)	Average	118.3	123.3	121.3	119.4	131.2
	STD	0.1	0.4	0.1	0.1	0.4
	Max	118.5	123.7	121.4	119.6	131.5
	Min	118.2	121.3	121.2	119.2	130.4

	N	7	44	8	8	5
Station IHR TDG (%)	Average	122.3	121.4	119.8	120.0	119.7
	STD	0.1	0.6	0.1	0.2	0.0
	Max	122.4	122.3	119.9	120.3	119.7
	Min	122.2	120.0	119.7	119.8	119.6
	N	7	44	8	8	5
Opera-tion (kcfs)	Gen	79.6	80.5	84.0	82.6	67.1
	Total Spill	10.0	30.0	20.1	15.3	39.9
	Unit Spill	1.70	3.00	2.51	2.19	3.99

33. The average TDG saturation observed during each operational conditions on May 1-2, 1996 were compared to levels measured during the spillway performance test (SPT) conducted on March 23, 1995 (Wilhelms, 1995). In the spillway performance tests, the TDG pressures were sampled downstream from bay 10 for stop settings ranging from 1 to 12. The observed TDG saturation during the SPT for 1, 2, and 3 stops were 115.0, 126.3, and 135.8 percent respectively. The TDG saturation from transects TR and GW were generally consistent with data from the SPT. The TDG saturation observed during the 40 kcfs discharge on stations TR1, TR2, GW1, and GW2 ranged from 136 to 140 percent and probably reflected water from bays operating at 3 stops. The TDG saturation (115-118 percent) recorded during the 10 kcfs spill test (reflecting a one-stop gate opening) were slightly higher than the comparable SPT observations.

34. The spill patterns sampled during the May 96 study, included combinations of gate settings with a maximum gate setting of 3 stops. An average unit spillway discharge was computed for each of the five spill patterns studied. A comparison of TDG saturation as a function of unit spillway discharge is shown in Figure 10**.** The average TDG data on the near-field transects (SB) during
the May-96 study were generally greater than observations from the SPT for similar unit discharges. However, the data from the downstream fixed monitoring station compared closely to results from the SPT. The slope of the relationship between TDG and unit discharge was similar for the SPT, transect GW, transect TR, and the tailwater fixed monitor IDSW.

35. ***Conclusions and Recommendations.*** This study of dissolved gas pressures in the tailwater at Ice Harbor Dam, successfully documented temporal and spacial variations in TDG pressures in the immediate vicinity of the stilling basin. This study clearly demonstrated the capability to remotely monitor TDG pressures in high velocity flow near the end of the stilling basin and tailwater channel. The general conclusions from this study are as follows:

a. For spillway flows over 20 kcfs, TDG pressures measured at the channel bottom near the stilling basin were significantly greater than levels measured downstream in the tailwater channel. The maximum pressure corresponded to a TDG saturation of 162 percent and occurred at Station SB2 during a 40 kcfs spillway release.

b. It was speculated that the extremely high TDG pressures measured in bubbly flow may reflect contributions from entrained air and dissolved gases. However, from these tests, the influence of entrained air remains unknown and should be investigated.

c. Changes in TDG pressures corresponded closely with operational changes. Higher unit spillway discharges resulted in higher levels of TDG on all transects. Gate settings were no greater than 3 stops during this study.

d. The observed TDG pressures at the end of the lock guide wall (transect GW) and 240 ft downstream of the stilling basin (transect TR) were generally consistent with observations from the Spillway Performance Tests and historic data from the tailwater fixed monitoring station.

e. For flows up to 40 kcfs, the similarity of TDG pressures on transects TR and GW suggested that there was little gas transfer beyond Transect TR, which is approximately 240 feet downstream of the stilling basin end sill. Prior to these observations, the gas transfer in the region outside of the stilling basin had been considered very important in gas transfer processes.

f. Spillway discharges with gate settings of 1 stop caused degassing of the flow by an average of 4.4 percent from 122.3 percent to 117.9 percent.   In the SPT, similar downstream TDG saturation resulted for one stop setting even with a forebay TDG saturation of only 103 percent (net uptake). Thus, this implies that, for these low spillway flows, the TDG pressures of spillway releases are independent of forebay TDG levels. The overall reduction of TDG pressures in the Snake River was small due to the small proportion of river flow that was spilled (<15 %) compared to total river flow.

g. Revisiting the near-field TDG study in the Ice Harbor tailwater would result in a better understanding of the spacial variation in dissolved gas exchange processes. The results from the May 1-2 study are subject to various interpretations. However, the addition of a protective housing or screen around the TDG membrane may reduce the likelihood of exposure to entrained air bubbles. The siting of instruments near the end of the stilling basin at multiple depths would provide information about heterogeneity in TDG and the influence of entrained air on instrument response. The instruments should be deployed during a period when higher spillway releases can be achieved (50-70 kcfs). This data record would provide base line data for subsequent prototype tests at Ice Harbor focusing on the influence of channel depth on TDG pressures.

h. Estimates of the reduction in TDG pressures associated with the structural alternatives of raising the stilling basin and/or tailrace were largely based upon reproducing conditions at The Dalles. The collection of additional TDG data in The Dalles tailwater would enhance understanding of dissolved gas exchange processes in shallow channels. This information would help design raised stilling basins/tailrace channels at other projects. The field study should be designed to determine the TDG pressures at various distances downstream of the spillway over a range of spillway discharges.

i. A detailed near-field TDG study of a project with deflectors would be beneficial to decisions facing the DGAS program. The SPT provided TDG pressures under atypical spill conditions that promoted considerable dilution from generation releases. The use of remote logging TDG instruments would result in a wealth of data detailing both the spacial extent and temporal variation of TDG pressures associated with deflectored spillway flow. This information could be used to develop additional structural measures (raised tailwater channel) to augment the deflectors in reducing TDG pressures.

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Locks, Reservoirs, and Fisheries
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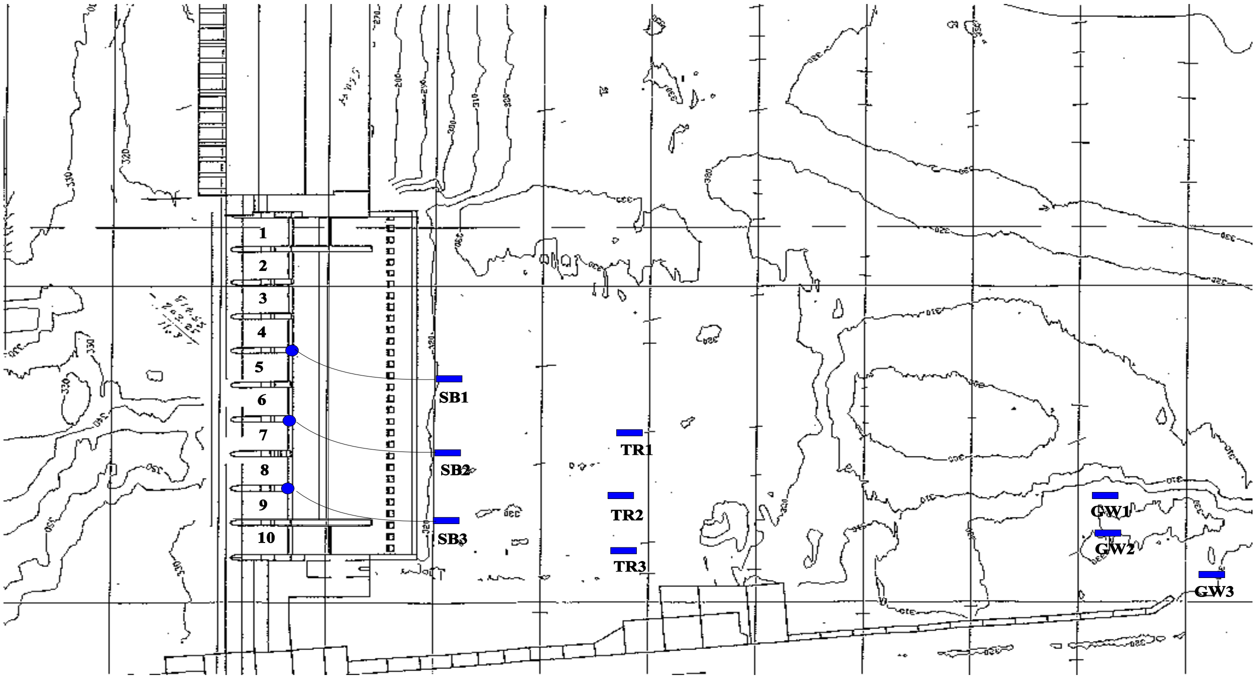

Figure 1. TDG Instrument Location at Ice Harbor Dam, May 1-2, 1996

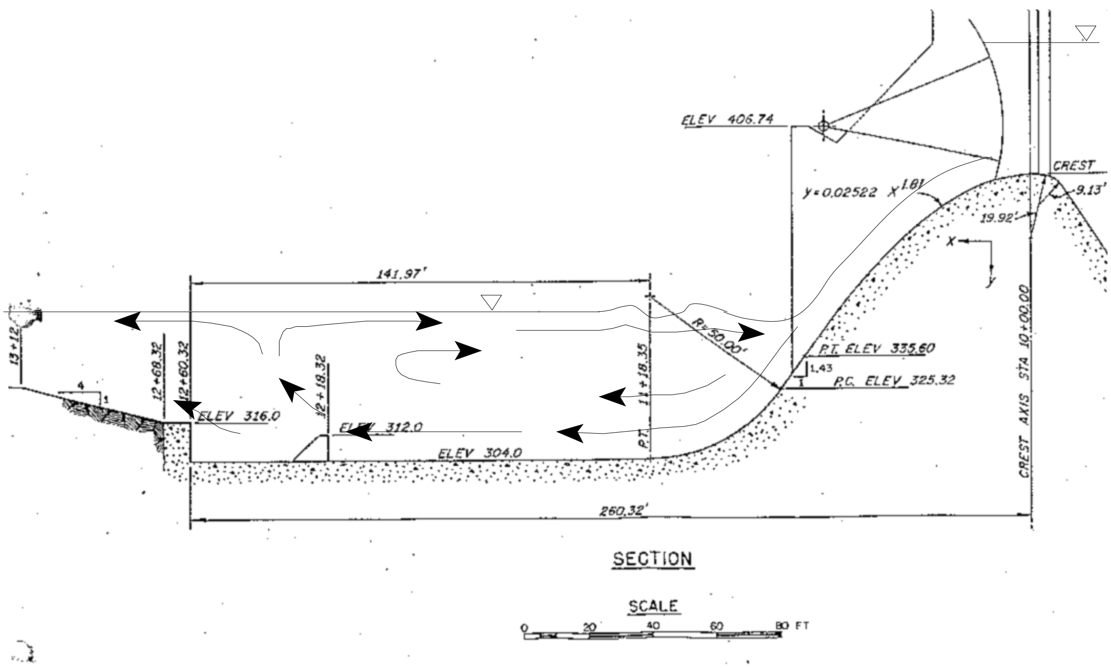

Figure 2. Ice Harbor Dam Spillway and Stilling Basin, Profile View

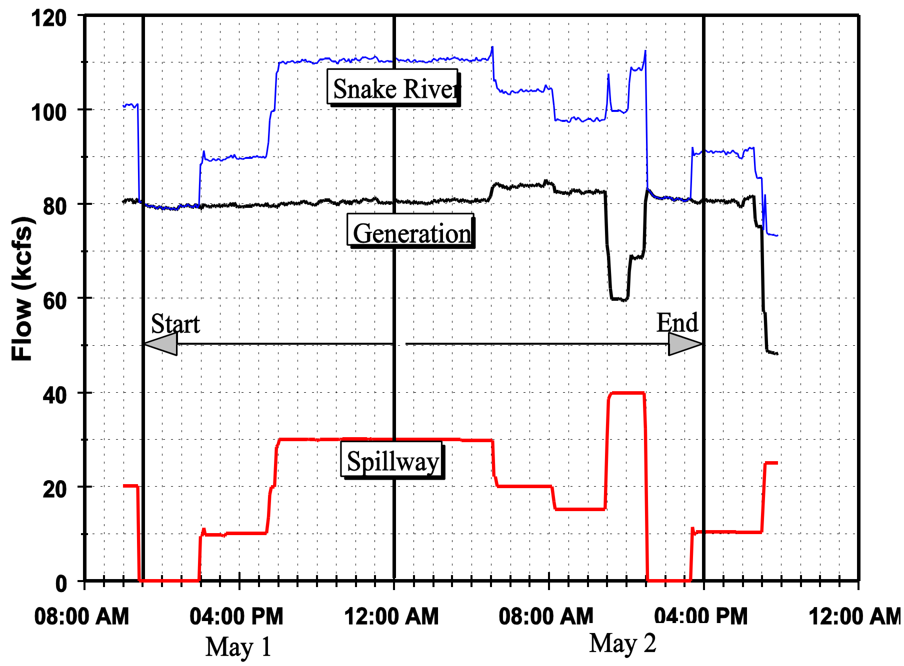

Figure 3. Ice Harbor Project Discharge on May 1-2, 1996

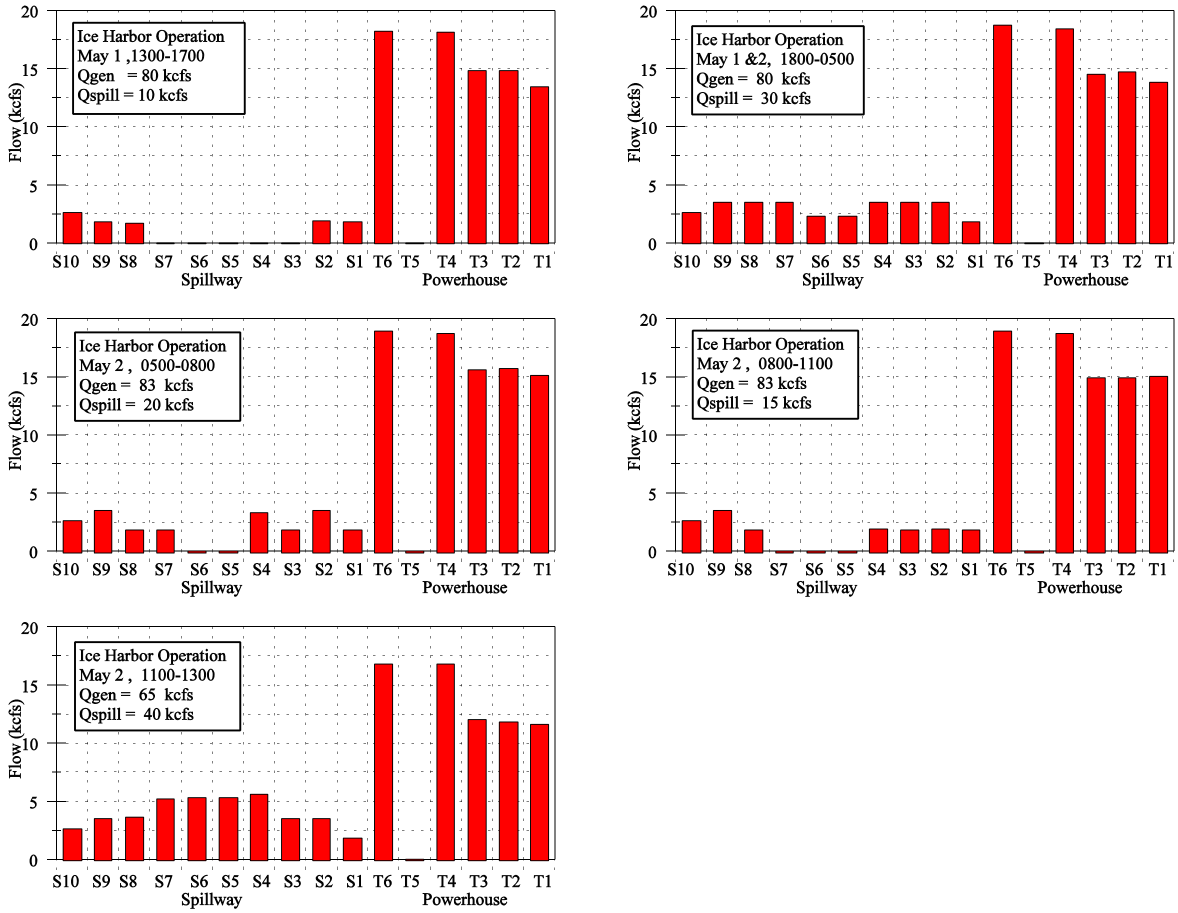

Figure 4. Spill Pattern and Turbine Unit Discharge for May 1-2, 1996

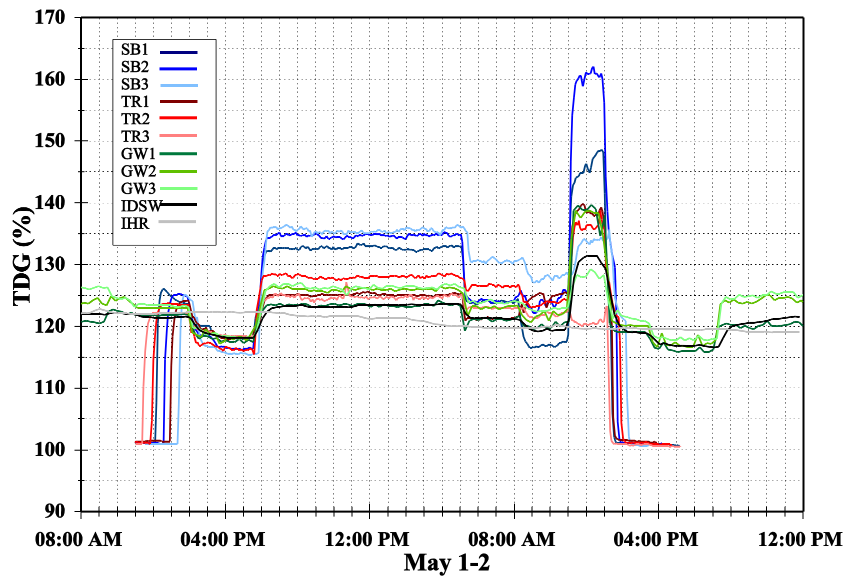

Figure 5. TDG Levels in the Ice Harbor Tailwater on May 1-2, 1996.

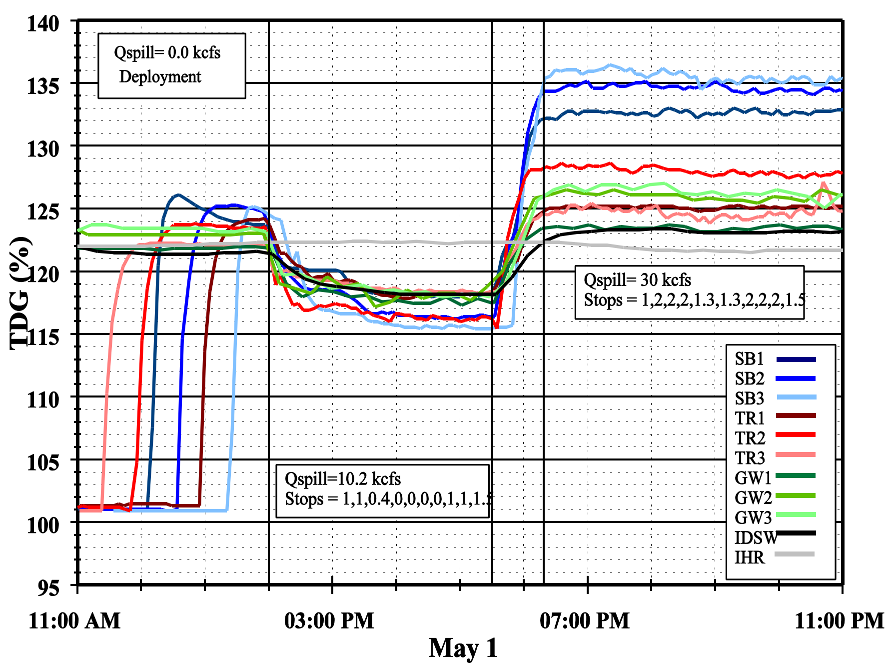

Figure 6. TDG at Ice Harbor Tailwater, 1100-2300, May 1, 1996

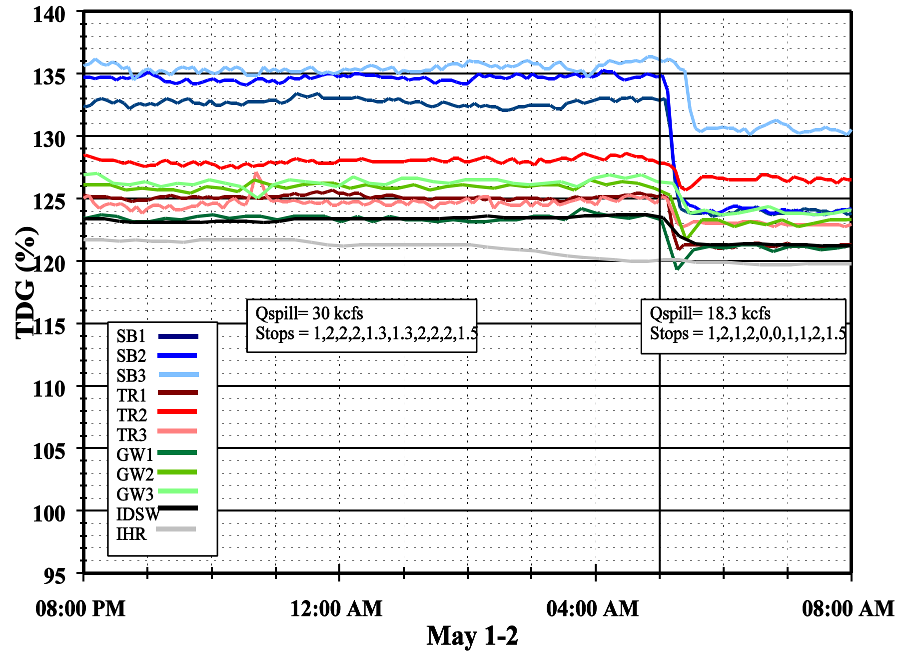

Figure 7. TDG at Ice Harbor Tailwater, 2000-0800, May 1-2, 1996

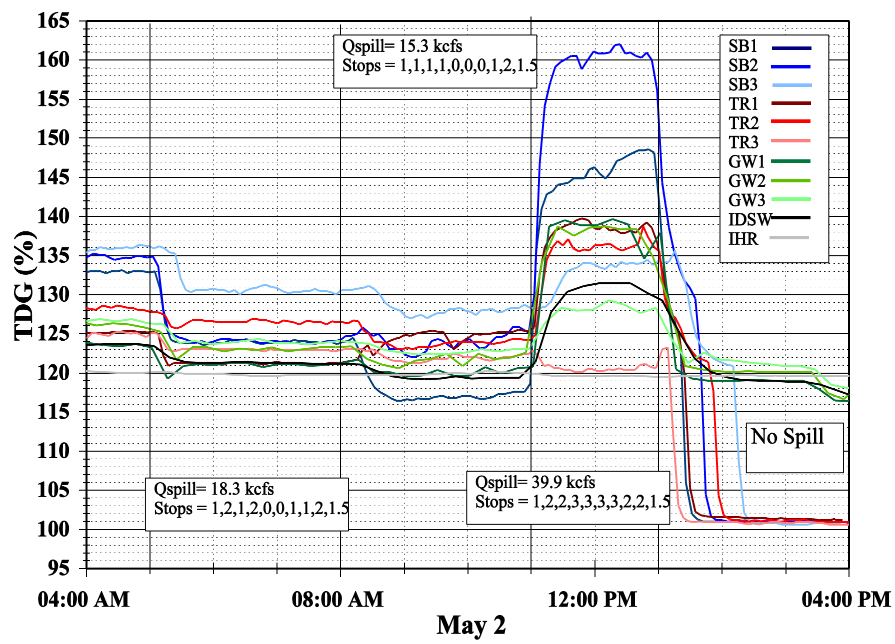

Figure 8. TDG at Ice Harbor Tailwater, 0400-1600, May 2, 1996

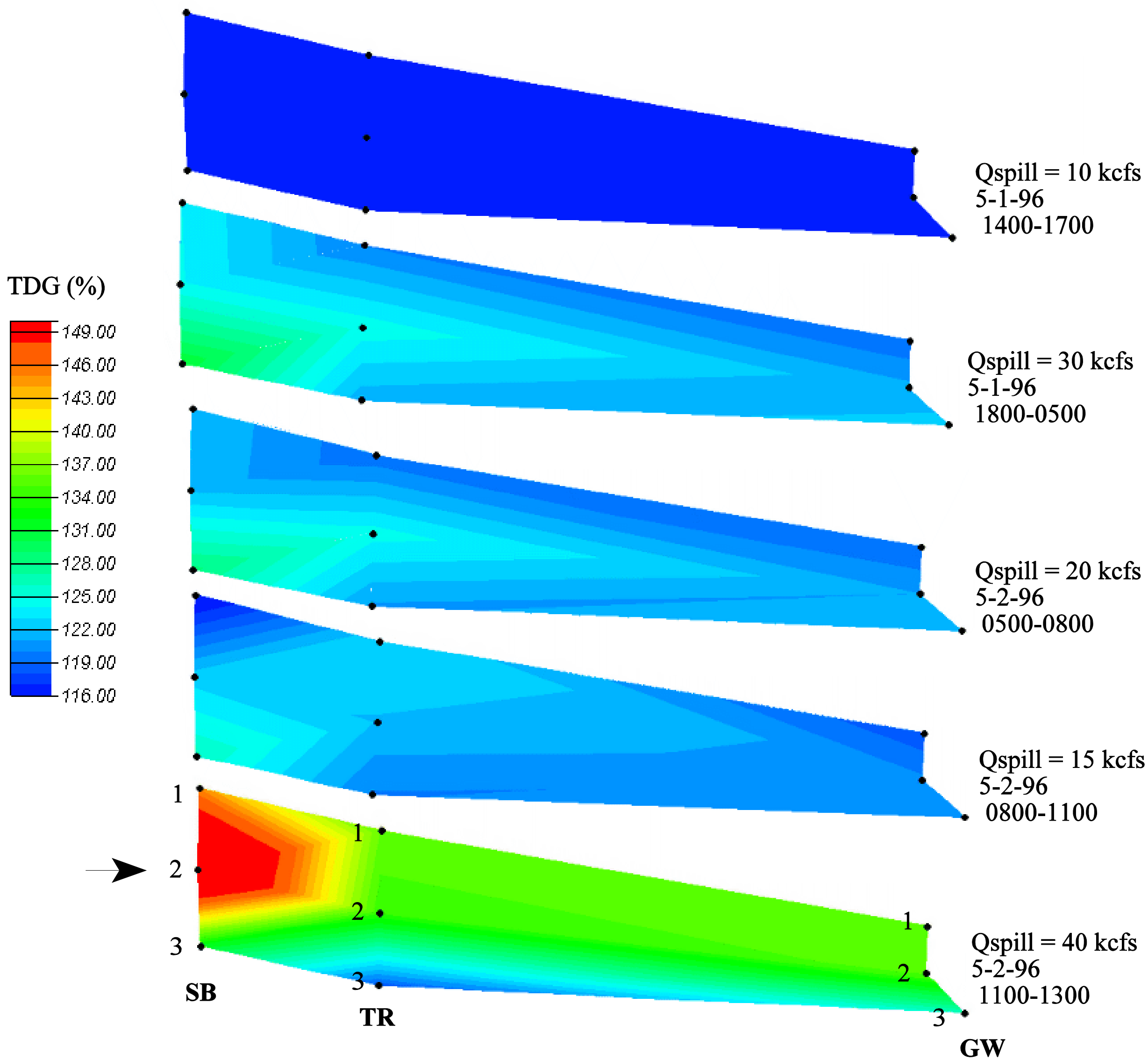

Figure 9. Contours of TDG Levels Downstream of Ice Harbor Dam, May 1-2, 1996 (Plan View)

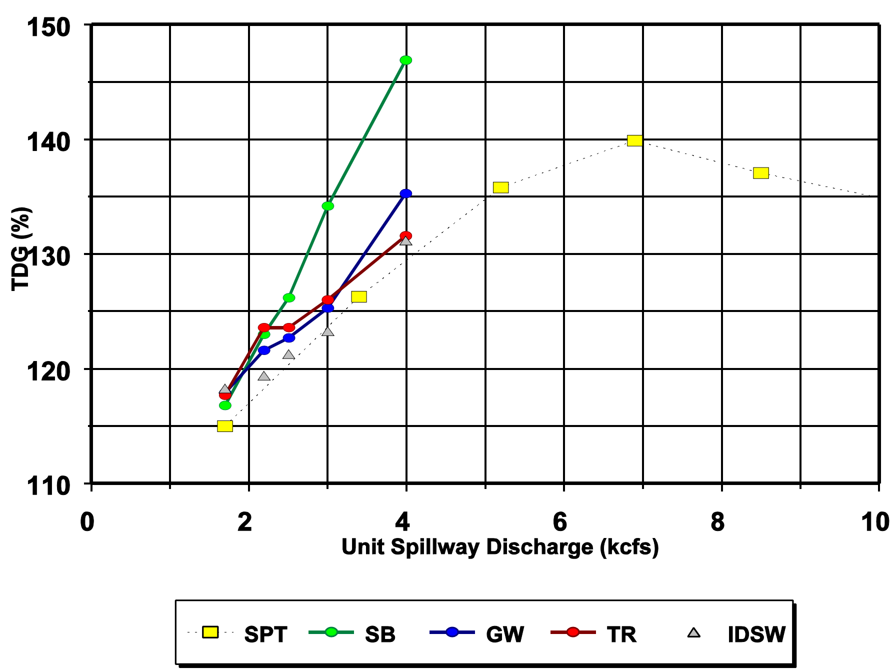

Figure 10. TDG Levels versus Unit Spillway Discharge for the Spillway
Performance Test and May 1996 Tailwater Study at Ice Harbor Dam

Appendix A: Discussion of Near-Field Hydrodynamics

A1. To gain a better understanding of circulation patterns in the stilling basin and adjoining tailwater channel, flow conditions in the Ice Harbor general model were studied. The operating conditions during the 40 kcfs spillway discharge were set up in the 1:40-scale physical model located in Vicksburg MS, at the Waterways Experiment Stations. A considerable degree of flow concentration or focusing occurred in the stilling basin for the observed flow conditions. The shear flow that develops in the stilling basin creates a large entrainment flow. This entrainment flow is supplied by water released from adjacent bays. If the unit discharge from adjacent bays is unequal, the focusing of flow becomes more pronounced. The effective discharge from the bay with the greater flow increases and at the expense of flow from the bay with lesser unit flow. The splitter walls located in the stilling basin between bays 9 and 10 and bays 1 and 2 significantly reduce the lateral exchange of water between units.

A2. The velocity distribution exiting the stilling basin was highly non-uniform for the 40 kcfs spillway event simulated in the physical model. The water released from bays 2 and 9 (2 stops) did not immediately exit the stilling basin. The flow downstream from these bays at the end sill, was directed at the dam. This water ultimately contributed to a lateral entrainment flows feeding discharges from adjacent bays. The main flow downstream of bays 3 and 8 (2 stops) did exit the stilling basin, but at a modest rate. The highest velocities exiting the stilling basin were located in the middle of the spillway downstream of bays 4 and 5 (3 stops). Most of the spillway discharge from units 1 and 10 (1 and 1.5 stops respectively) were quickly flushed from the stilling basin aided by the training walls.

A3. The flow observed in the physical model along transect SB, was directed downstream at all instrument locations. The trajectory of the flow was generally directed normal to the dam. Other general observations of flow patterns in the physical model for the 40 kcfs discharge are as follows:

a. An eddy was located directly downstream of the adult fish entrance next to spill bay 10 causing slow flow and long detention times in this area.

b. The spillway discharge from bay 1 entrains surface water from the powerhouse..

c. The lateral zone of influence of water discharged from a spill bay grows rapidly as the flow is transported downstream due to high levels of turbulence.

d. The spill pattern will greatly influence which bays contribute to flow at a fixed point in the tailwater channel.

A4. The flow patterns in the stilling basin can significantly influence the TDG pressures of spillway releases. The flow patterns can change considerable for relatively small changes in the spill pattern. The detention time for water released from bays providing lateral entrainment flows to adjacent units can be considerably longer than water that is efficiently transported through and out of the stilling basin. The entrainment flow may be pulled into recirculation cells and exposed to entrained air for long durations resulting in high levels of TDG. This may explain why the highest TDG pressures were experienced at station SB2 and not SB1. The instrument located at station SB2 was downstream of spillbay 7. A significant amount of water influencing TDG pressures at station SB2 may have originated from bays 8 and 9. The longer detention times associated with discharge from these bays may have resulted in elevated TDG pressures recorded at station SB2.

Appendix B: Memorandum for Record Subject: Documentation and Preliminary Analysis of the Near-Field Ice Harbor Tailwater Study, 27–28 June 1996

CEWES-CS-L 27 January 1997

MEMORANDUM FOR RECORD

SUBJECT: Documentation and Analysis of the Near-Field Ice Harbor Tailwater Study, June 27-28, 1996

1. Introduction. The purpose of the Dissolved Gas Abatement Study (DGAS) is to develop structural and operational alternatives that reduce the dissolved gas levels produced during spillway operations on the Snake and Columbia Rivers. The assessment of DGAS alternatives will be conducted through analysis of historic data from fixed monitoring stations, site specific prototype field studies, physical models, and analytical investigations of gas exchange at hydraulic structures. Two previous field studies at Ice Harbor have shown the project to be a high gas producer with dissolved gas levels of nearly 140 percent exiting the project area (Wilhelms 1995). A near-field tailwater study in May 1996 (Schneider 1996) showed measured TDG above 160 percent exiting the stilling basin on the channel bottom, which raised questions regarding the presence and extent of vertical gradients in TDG. Questions also arose regarding the processes that would produce these high concentrations. Thus, several instruments were modified to determine if bubble impingement on the instrument sensors produced the high observed values, rather than actual dissolved gas. Lastly, the range of spillway discharges and spill patterns tested during the May study were somewhat limited, thus further testing with higher discharges was warranted. This document summarizes the results of a field study conducted in the tailwater channel at Ice Harbor Dam during the period of June 27-28, 1996.

2. Objectives and Scope. The purpose of this study was to quantify dissolved gas exchange downstream of the spillway at Ice Harbor Dam and identify the dominant processes responsible for dissolved gas transfer during spillway releases. Specifically, vertical, lateral, and longitudinal gradients in total dissolved gas (TDG) levels downstream of the spillway were investigated. The measurements were made downstream of the north end of the spillway between the stilling basin endsill and the downstream end of the lock guide wall. Fifteen logging multi-parameter instruments were deployed along three longitudinal profiles forming three lateral transects as shown in Figure 1. TDG levels were sampled on a regular interval throughout the study period. Spillway discharge and spill pattern were systematically varied over a 24 hr period with spillbay discharges ranging from about 1,800 cfs to 10,400 cfs and total spill up to 60,000 cfs. Generation discharges were not controlled as part of the field study and ranged from about 30,000 cfs up to 77,000 cfs. These measurements can provide estimates of the mass flux of dissolved gas moving past a given transect. The comparison of mass flux estimates at each transect will indicate the relative importance of gas exchange processes within the stilling basin and the tailwater channel downstream.

3. Project Description. The powerhouse at Ice Harbor Dam consists of 6 hydroturbines with a combined capacity of 105 kcfs. The spillway at Ice Harbor Dam has a total width of 590 feet and consists of 10 gate-controlled bays. There were no spillway deflectors at Ice Harbor Dam. The horizontal apron-type stilling basin at Ice Harbor Dam is about 210 ft. long with an invert elevation of 304 ft. The depth of flow in the stilling basin was over 40 ft. during the entire testing period on June 27 and 28. One row of baffle blocks 8 ft. high and an end sill 12 ft. high

provide for energy dissipation in the stilling basin. A training wall extending over two-thirds the length of the stilling basin separates bays 10 and 1 from interior bays. The tailwater channel downstream of
the stilling basin is generally above elevation 320 ft with the exception of a large depression located upstream of the end of the lock guide wall.

4. Hydrodynamics. The main spillway flow at Ice Harbor, plunges and moves through the stilling basin as a highly turbulent shear flow. A bottom current directs flow out of the stilling basin, while a surface roller returns toward the plunge point. This general pattern of circulation is broken up at the baffle blocks and end sill, which direct flow vertically. The spillway discharge from bays 1 and 10 are partially separated from the flow from interior bays by training walls that extend over three-fourths of the length of the stilling basin. The tailwater channel downstream of the powerhouse is shallow causing generation and spillway discharges to converge to the navigation channel on the north side of the Snake River.

5. TDG Instrument Array. A sampling array, consisting of nine stations, was established downstream of the spillway at Ice Harbor Dam to measure the TDG pressures during spillway discharge. Three lateral transects were located 40, 240, and 1100 ft downstream of the end of the stilling basin. Three stations were located along each transect as shown in Figure 1. Instruments manufactured by Common Sensing and Hydrolab were used in this test. The parameters measured by the Common Sensing instruments were water temperature, total dissolved gas pressure, and dissolved oxygen. Hydrolab instruments measured water temperature, total dissolved gas pressure, instrument depth, dissolved oxygen concentration, pH, and conductivity. All instruments logged data on a 5-minute interval.

6. The first transect (SB) was located about 40 feet downstream of the stilling basin end sill in about 25 ft of water. Common Sensing TDG instruments were deployed on the channel bottom at three stations located downstream of spillway bays 5, 7, and 9. The instruments were located downstream of the northern section of the spillway to reduce the potential for dilution from generation releases. Common Sensing TDG instruments were encased between two 30-inch-long steel rails for ballast and to protect the instrument. This housing also reduced the flow velocities past the instrument and limited instrument exposure to entrained air bubbles. To further reduce the exposure of the instrument to air bubbles, a Nitex[1] mesh with a spacing of 335 μm was placed around the TDG membrane as shown in Figure 2**.** A redundant Common Sensing TDG instrument, without mesh, was attached to the outside of the iron rail housing at Station SB2. This instrument was added to the experiment to determine the influence of instrument housing on observed pressures.

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[1]Nitex is a registered trademark for a fine-pore cloth-like material with filtering capabilities

7. The instruments along Transect SB were secured to 500-ft-long steel cables attached to the railing on the trunnion deck of a spillway pier. This cable restricted instrument movement and aided instrument recovery. Two additional instruments (Hydrolab DS4's with Nitex mesh) were deployed at an intermediate depth at stations SB1 and SB2. These instruments provided estimates of vertical gradients in TDG pressures. The depth of the instruments deployed above the bottom of the channel varied as a function of the local flow conditions, which caused the instrument to rise and fall over a 5-6 ft range.

8. The second transect (TR) was located about 240 ft downstream of the end of the stilling basin. Station TR3 was located about 100 ft closer to the stilling basin than TR1 and TR2 because the cable snagged on the channel bottom. A TDG instrument was located on the channel bottom and at an intermediate depth at each of the three stations on transect TR. Common Sensing instruments were deployed on the channel bottom at stations TR1 and TR2 with protective mesh and housed between iron rails. A Hydrolab instrument was sited near the channel bottom at station TR3 housed in a PVC stilling chamber with protective Nitex mesh. All three instruments were deployed on the channel bottom in about 20-25 feet of water. The lateral position of the instruments corresponded to the north piers adjacent to spillbays 6, 8, and 10. The depth of the intermediate-depth instruments varied throughout the testing period between mid-depth to within 4 ft of the water surface.

9. The third transect (GW) was located about 1100 ft downstream of the end of the stilling basin at the end of the lock guide wall. The transect was selected because it represents the downstream extent of bubbly flow during high spillway discharge. The TDG pressure at each station was measured by a single Hydrolab instrument located at an intermediate depth. The stations GW1 and GW2 were located 40 ft apart in depths ranging from 24 to 30 ft. The station GW3 was positioned 80 ft to the lock side of station GW2 in shallower water. This instrument was positioned at a depth of 15 to 18 ft throughout the testing period All three Hydrolab instruments were tethered on a 50 ft long cable between a surface float and a bottom anchor.

10. Additional TDG levels were measured in the forebay and at the tailwater fixed monitoring stations. A fixed TDG monitor (IHR) was located on the upstream face of the powerhouse to provide an estimate of TDG levels passing through the turbines. Measurements were made at the fixed monitoring station (ISDW), which is located about 3.6 miles downstream of Ice Harbor Dam along the north channel bank. This instrument was located on the north bank of the Snake River to capture TDG associated with spillway releases. The parameters measured at the fixed monitoring stations include water temperature, barometric pressure, total dissolved gas pressure, and dissolved oxygen pressure.

11. Operating Conditions. The spillway flow was halted at 1130 on June 27 to enable the deployment of instruments within the restricted access area. The spillway releases were restarted at 1400 and were changed every two hours throughout the 24 hour testing. Five uniform spill patterns and seven standard spill patterns were studied. The uniform spill patterns of two hour

duration were scheduled on June 27 in the following order: 25 kcfs, 30 kcfs, 40 kcfs, 50 kcfs, and 60 kcfs. A standard spill pattern was used during spillway releases on June 28 with spillway flow decreasing in the following order: 60 kcfs, 50 kcfs, 40 kcfs, 30 kcfs, 25 kcfs, 20 kcfs, and 10 kcfs as shown in Figure 3. The generation discharge decreased during high spill periods and increased during low spill periods to maintain relatively constant total river flow rates. Total river flow ranged from 60 kcfs during instrument deployment to 104 kcfs during the morning hours of June 28. The tailwater stage ranged from 343.6 ft during the lowest river flow to a high water level of 346.9 ft during the higher flow events. The discharge for the 10 spillway bays and six turbine are shown graphically in Figure 4 for the entire study period.

12. The spillway gate settings for all bays were equal during the uniform spill pattern test on June 27. The gate settings ranged from 1.5 stops or 2.5 kcfs/bay during the 25 kcfs release to 3.5 stops or 6.0 kcfs/bay during the 60 kcfs spill. The standard spill pattern calls for a non-uniform distribution of discharge across the spillway. The standard 60 kcfs spill pattern calls for unit spillway releases ranging from 10.4 kcfs (6.2 stops) to 1.7 kcfs (1 stops). The spill pattern transitions from a convex-shaped distribution at higher flow rates to a concave distribution for spills less than 30 kcfs. The operation of 6 turbine units and 10 spillway bays were also recorded on a 5 minute interval throughout the study period. This information was averaged for each hour of the study and is listed Appendix A, Table A1.

13. Results. The TDG pressures recorded by the instrument array downstream of Ice Harbor Dam, were converted to percent saturation by dividing by the local barometric pressure as determined by a reference barometer at the fixed monitoring station. The observed data are presented in several time history plots and discussed in detail in the following paragraphs. An hourly summary of TDG data at each station has been tabulated in Tables A2-A4. Several general observations regarding this study are as follows:

a. Changes in TDG corresponded closely with operational changes.

b. The TDG saturation levels resulting from the uniform spill pattern were generally less than the corresponding TDG pressures generated for the same total spill discharge using the standard spill pattern.

c. TDG levels were generally highest at Transect SB, just downstream of the stilling basin, and decreased with distance downstream.

d. Vertical gradients in TDG were greatest at Transect SB, just downstream of the stilling basin, for the higher discharges during the standard spill pattern.

e. Lateral gradients in TDG saturation levels were much more pronounced on stations closest to the dam during the standard spill discharges.

f. The variability of TDG levels for a specific instrument was generally small for constant operating conditions.

g. The range of TDG levels measured at the tailwater fixed monitoring stations were generally smaller than values observed at the near-field stations.

14. Transect SB - Uniform Spill. The TDG saturation levels measured on Transect SB with a uniform spill pattern are shown in Figure 5 from 0800 to 2400 on June 27. The instrument located at an intermediate depth on Station SB1 malfunctioned 3 hours into the test period and was not included in the plot. The maximum TDG saturation measured for the uniform spill pattern was 152 percent and occurred during the 60,000 cfs release. The minimum TDG saturation measured for a uniform spill pattern was 122 percent with a spill of 25,000 cfs, only slightly higher than forebay TDG levels. The average TDG saturation along Transect SB for a uniform 25,000 cfs release was 122.3 percent (Table 1). For a 60,000 cfs uniform spill, the mean TDG level was 149.3 percent leaving the stilling basin (Table 1). The variability in measured TDG saturation levels at any station for constant operating conditions was generally quite small, less than 1-2 percent. Lateral and vertical gradients in TDG were generally small for the uniform spill releases, less than 5-6 percent. The average TDG levels measured on transect SB were highly correlated with spillway discharge for the 5 uniform spill patterns monitored during the testing period.

Table 1. Average TDG Saturation by Transect for Ice Harbor Tailwater on June 27-28, 1996

Spillway Discharge (kcfs)	Average TDG Saturation Transect SB		Average TDG Saturation Transect TR		Average TDG Saturation Transect GW	
	Uniform	Standard	Uniform	Standard	Uniform	Standard
10	NA	115.4	NA	115.1	NA	116.1
20	NA	124.8	NA	122.1	NA	120.8
25	122.3	125.8	119.3	123	M	120.9
30	128.2	132.6	122.9	125.5	121.4	122.9
40	138.8	145.2	130.8	135.9	128.1	133.1
50	145.1	149.8	136.6	143.5	132.7	135.4
60	149.3	154.2	139.6	143.6	135.3	136.1
M - Missing Data.		NA - Not Applicable				

16. The average TDG pressure measured on transect SB was also highly correlated with spillway discharge for the 7 standard spill patterns monitored during the testing period (Table 1). The range in TDG pressures measured across transect SB was considerable, indicating both

strong lateral and vertical TDG gradients. The vertical gradients in saturation were as high as 20 percentage points (160 percent at SB2 bot compared to 140 percent at SB2 top) during the 50,000 cfs standard spill. Lateral gradients were as high as 30 percentage points (162 percent at SB2 bot compared to 132 percent at SB3 bot) during the 40,000 cfs standard spill. TDG saturation remained relatively constant on station SB2 for spills of 40,000 cfs and greater despite a reduction in unit discharge from spillbays 4, 5, and 6. The TDG saturation dropped dramatically at stations SB1 and SB2, when the standard spill was reduced from 40,000 to 30,000 cfs. The significant reduction in unit discharge from spillbays 4, 5, and 6 may have accounted for this reduction in TDG.

17. Two Common Sensing instruments were located at station SB2 to study the influence of instrument housing on observed TDG pressures. The instrument identified by station label “SB2 bot” was a standard Common Sensing design except that a Nitex mesh cover was installed around the pressure membrane. The instrument was placed between two steel rails for ballast and protection (Figure 2). The second instrument, identified by the station label “SB2 bot*”, was a standard instrument attached to the outside of the steel rails. The TDG levels measured by these two instruments were nearly identical throughout the testing period on June 27 and June 28 up through the hour 0300. The unprotected instrument “SB2 bot*” experienced a pressure drop shortly after 0300, but higher TDG pressures quickly returned. After this pressure disturbance, the unprotected instrument recorded TDG pressures slightly greater than or less than (± 3%) its companion instrument. It is possible that the exposed instrument was slightly damaged during the 50 kcfs standard spill event resulting in the slight difference in TDG pressures recorded on the channel bottom at station SB2 after 0300 on June 28. However, this evidence suggests that measured pressures were not significantly influenced by entrained air bubbles coming into contact with the pressure sensing membrane.

18. <u>Transect TR - Uniform Spill</u>. The measurements of TDG along Transect TR are shown in Figure 6. The minimum TDG saturation measured was 117 percent for a uniform spill pattern of 25,000 cfs , slightly less than forebay TDG levels. The maximum TDG saturation measured for the uniform spill pattern was 144 percent at stations TR1 bot and TR2 bot and occurred during the 60,000 cfs spill. The maximum average TDG saturation reached as high as 139.6 percent during the uniform 60,000 cfs release (Table 1). The average TDG saturation for the uniform 25,000 cfs release was 119.3 percent, essentially equal to forebay levels (Table 1). The average TDG pressure measured on transect TR increased with unit spillway discharge during uniform spill conditions. The lateral and vertical gradients in TDG pressure were generally small throughout the uniform spill releases. The gradients in TDG increased as spillbay discharge increased, although the TDG measured on the six Transect SB instruments was within ±5 percentage points throughout the uniform spill testing period (Figure 6). The TDG was generally greater near the channel bottom and downstream of central section of the spillway.

19. <u>Transect TR - Standard Spill</u>. Figure 6 shows that the spill pattern and unit spillbay discharge were both important determinants of the average TDG pressure measured on transect

TR. The TDG pressures peaked during the 50,000 cfs standard spill at stations TR3 and TR2 with a maximum TDG saturation of 157 percent occurring at station TR2 bot. The lateral variation in TDG pressures increased significantly with the implementation of standard spill patterns on June 28. The lateral range in TDG was greatest during the 40,000 and 50,000 cfs standard spill. The vertical gradients in TDG pressures were moderate with the largest pressures occurring near the channel bottom. The average TDG saturation for the standard 10,000 cfs release was 115.0 percent, which was below forebay levels (Table 1). The TDG cross-sectional average for the other flows was a weak function of total spillway discharge, although there was a significant decrease in the average when spill was reduced from 40,000 to 30,000 cfs. The sudden decrease of TDG at station TR1 for the 30,000 cfs spill was likely caused by the reduction in discharge through bays 4 and 5.

20. Transect GW- Uniform Spill. The observed TDG along Transect GW is shown in Figure 7. The instrument at station GW2 failed early in the test and could not be included in this analysis. For the uniform spill pattern, the minimum TDG level of about 120 percent occurred during the 30,000 cfs spill test. Measurements, however, were unavailable for the 25,000 cfs spill, which would likely produce slightly smaller levels of TDG. The maximum TDG level of nearly 137 percent occurred during the 60,000 cfs spill test at Stations GW1 top. Lateral variation in TDG increased slightly with increasing spillbay discharge. Observations at station GW1 suggest that it was located close to the interface between generation and spillway releases during low spill events. Vertical gradients in TDG could not be determined on this transect. The average conditions at Transect GW were generally computed from observations of 2 instruments located above the channel bottom. The average TDG pressure measured on transect GW were slightly less than conditions observed on transect TR, indicating slight degassing (Table 1).

21. Transect GW - Standard Spill. For the standard spill pattern, the maximum TDG along Transect GW of 138 percent occurred with the 60,000 cfs spill release. The minimum TDG of about 116 percent, slightly below forebay level, occurred with the 10,000 cfs spill. The lateral variation between GW1 and GW3 was greater with the Standard spill pattern than with the uniform spill pattern. The average TDG pressure on transect GW did not exceed 139 percent during the standard spill events (Table 1). The TDG decreased significantly when the spill reduced from 40,000 to 30,000 cfs as shown in Figure 7. The time history of TDG pressures observed at the fixed tailwater monitoring station (IDSW) downstream of Ice Harbor closely reflected TDG pressures observed at station GW3, although lagged by about one hour. This suggests that the tailwater monitor, located on the north bank of the Snake River provides a reasonable estimate of TDG in the spill release.

22. Flow Path 1. Test results along longitudinal flow Path 1 are shown in Figure 8. TDG consistently decreased from Stations SB1 to TR1 to GW1. It appears that most of the reduction in TDG takes place between stations SB and TR. The TDG measurements from the instruments above the channel bottom on transect TR1 were identical to the measurements at station GW1 with the exception of the 60,000 cfs standard spill. This analysis suggests that little reduction in

TDG occurs between stations TR and GW for most spill flows. For lower spill discharges, the TDG measurements at each station were at similar saturation levels, indicating that any gas absorption or desorption was occurring upstream of the first station.

23. Flow Path 2. The TDG measurements along longitudinal flow path 2 (SB2, TR2, and GW2) are presented in Figure 9. The highest dissolved gas levels consistently occurred at the stilling basin endsill (Station SB2). TDG was measured at about 165 percent at SB2 with a 60,000 cfs standard spill pattern. Significant degassing apparently occurs between the stilling basin station SB and the tailrace station TR. The instrument at Station GW2 malfunction early in the 24-hr test period and data for GW2 are unavailable for much of the longitudinal comparison. However, the TDG measured at Station GW1 is very similar to that at GW2. Using these data for comparison, most of the reduction in TDG pressures, once again, takes place between the stilling basin endsill (Transect SB) and the tailrace transect (Transect TR).

24. Flow Path 3. Figure 10 shows the TDG pressure along Flow Path 3 (SB3, TR3, and GW3). Like the other longitudinal profiles, TDG along Flow Path 3 also decreased in a downstream direction during most flow conditions. The TDG saturations along this flow path were more variable during steady spill releases than flow path 1 or 2. The peak TDG levels occurred during the 60,000 cfs uniform spill releases since there is a higher unit discharge on the outside bays compared to the standard spill pattern, which distributes more spill to the interior bays. Once again, the TDG saturation at Station TR3 was nearly identical to the measured TDG at Station GW3 during the uniform spill test. This suggests that only modest degassing downstream of transect TR on flow path 3 during uniform spill conditions. The TDG saturation drops off significantly during the operational change from 50,000 to 40,000 cfs and from 20,000 to 10,000 cfs (Figure 10). The fixed monitoring station (IDSW) provides another set of data to analyze changes in TDG pressures. The TDG levels observed at station IDSW (lagged 1 hour) were only slightly less (up to 2 percentage points) than TDG saturation observed at GW3 during the spill tests.

25. Discussion. The three objectives of this investigation were to (a) identify dominant processes and quantify dissolved gas exchange downstream of the spillway at Ice Harbor Dam, (b) extend the range of previously tested spill discharge, and (c) assess the reliability of the instruments in bubbly flow. By measuring TDG along the three lateral transects and three longitudinal flow paths discussed in the previous paragraphs, the vertical, lateral, and longitudinal gradients in total dissolved gas could be estimated. With these observations as a basis, regions of gas absorption and desorption were identified. Relationships between TDG production and discharge could be developed and verified. Discharges ranged up to about 6,000 cfs per spillbay for a uniform spill pattern and over 10,000 cfs on the central spillbay for the standard spill pattern. The side-by-side measurements of TDG with a protected and unprotected instruments clearly showed the effects of bubble flow. All of these objectives were accomplished and are discussed in the following paragraphs.

26. Assessment of Instruments in Bubbly Flow. The last objective must be discussed first to ascertain the validity of the observations in this study. During the conduct of the May 1996 near-field study at Ice Harbor (Schneider 1996), the validity of the extremely high measured levels of TDG at the stilling basin endsill were questioned. It was suggested that the observed data were not representative of total dissolved gas, but were biased by exposure to entrained air under 25 ft of hydrostatic pressure. It was conjectured that if bubbly flow was in constant contact with the membrane of the TDG monitor, the pressure readings could reflect both the dissolved gas pressure in the water and the hydrostatic pressure in the entrained air bubbles. The resulting levels of TDG would be biased toward the extremely high hydrostatic pressure in the bubbles. Thus, in this near-field study, a protected instrument and an unprotected instrument were deployed side-by-side to determine if bubbles could bias the observations.

27. As previously described, the protected instrument had been wrapped in a fine-mesh, inserted in a steel housing, and placed between two rails that served as ballast and protection. The mesh and the steel housing served to reduce the velocity in the vicinity of the TDG pressure membrane, letting buoyancy move the bubbles away from the membrane. The unprotected instrument was a standard design mounted on the outside of the rail. Figure 11 shows a time history of the two instruments at Station SB2 bot. Clearly, during the uniform spill pattern tests and even through the 60,000 and 50,000 cfs standard spill, the instruments were identical. Their readings diverged toward the end of the 50,000 cfs standard spill and for the remainder of the testing, they differed by about 3 percentage points. Close examination of Figure 11 will show that the lower TDG level was recorded by the unprotected instrument. If bubbles were in contact with the unprotected membrane, higher TDG readings should have been recorded. Thus, this comparison validates the observations in the bubbly flow. We would conclude that the measured levels of TDG are correct and that entrained air bubbles have no significant effect on TDG measurements. An identical conclusion was reach in a separate study that is summarized in the attached CEWES-HS-L memorandum dated August 14, 1996, entitled “Field Experiments to Assess Effects of Entrained Air on TDG Measurements.”

28. Description of Dominant Gas Exchange Processes. Accepting the validity of the TDG measurements at the stilling basin endsill leads us to the conclusion that extremely high rates of gas absorption take place in the stilling basin. From field and physical model observations, air that is entrained at the plunge point in the stilling basin will be transported to the bottom of the stilling basin, where the exchange of gas from entrained air bubbles to the flow is greatly accelerated because of the high local pressures. The observed data show higher concentrations of dissolved gas near the bottom compared to mid-depth or near-surface measurements. Although entrained air is transported throughout the flow in the stilling basin, it is not unreasonable to find
higher TDG levels at the bottom of the stilling basin, where the discharge jet and entrained air are concentrated. These vertical gradients seem to quickly dissipate as turbulence mixes the spillway flow as it moves downstream. Due to the complex 2- and 3-dimensional circulation patterns, the pressure history and exposure time of a parcel of air-entrained water may vary

considerably along the length and width of the stilling basin. These flow patterns, together with variations in the amount of entrained air, could account for much of the temporal and lateral variation in TDG pressures observed along the stilling basin endsill.

29. Measurements in the tailrace area immediately downstream of the endsill show a consistent decrease in TDG saturation from that measured near the endsill. Two processes could contribute to this decrease: degassing, where TDG is lost to the atmosphere or dilution by hydropower releases of lower TDG concentration. For dilution to be the dominant process, lateral and vertical gradients of TDG would have to be present in the vicinity of the mixing to be a source of lower TDG water. The data from the matrix of monitors do not support this hypothesis, inasmuch as the measured vertical and lateral gradients do not seem to be sufficient to provide the dilution required for the reduction in TDG. Thus, it seems likely that degassing is the dominant process in the tailrace causing the reduction in TDG. A highly air-entrained flow with supersaturated TDG levels exiting a deep stilling basin has the potential to degas the water. If bubbles are transported to depths greater than the "compensation depth," which is the depth where hydrostatic pressure equals the TDG pressure, there will be a net mass transfer from those air bubbles to the water. However, the buoyancy of the air bubbles will cause the bubbles to rise resulting in higher bubble concentrations in the water column. Since these bubble are above the compensation depth, there will be a net mass transfer of gas from the water to the bubbles. With the enormous surface area available for mass transfer, like the absorption in the stilling basin, there is significant desorption of TDG in the tailrace region. As bubbles are lost to the atmosphere, then the rate of gas loss is greatly reduced.

30. Prior to the findings of this field study, it was assumed that TDG levels increased cumulatively downstream of the spillway. The TDG pressures were assumed to reach a given level in the stilling basin and continue to increase as bubbly flow extended beyond the stilling basin. This conceptual model is obviously inconsistent with data from this study. The data indicates a rapid and extensive absorption of gas in the stilling basin followed by a rapid and extensive desorption of dissolved gas in the tailwater channel. This alternative model of gas exchange has significant implications for the effectiveness of structural and operational alternatives for dissolved gas reduction.

31. The gas transfer processes at Ice Harbor Dam were found to be related to both spillway discharge and spill pattern. TDG increased throughout the range of spillway discharges. TDG produced with the standard spill pattern was consistently greater than TDG produced with the uniform spill pattern. Figure 12 shows the average TDG saturations along Transect SB as a function of spillway discharge, indicating the TDG production in the Ice Harbor stilling basin. Also shown, validating the observations, are the measurements from the May 1996 near-field study (Schneider 1996). Clearly, TDG production is related to spillway discharge and seems to experience marginal increases with larger discharges. Figure 13 shows the average TDG levels from transect SB, TR and GW for the uniform spill distribution. From this plot, the degassing in the tailrace is evident. Dissolved gas levels decrease from nearly 150 percent at the stilling basin

endsill to approximately 135 percent at the lock guide wall for a 60,000 cfs uniform spill (6,000 cfs per spillbay). Figure 14 shows the average TDG observed at Transect GW and at the fixed monitor for this study, from Transect GW in the May 1996 study (Schneider 1996), and from the previously-conducted spillway performance tests (Wilhelms 1995). The comparison validates the measurements from the May study and shows that the fixed monitor is only slightly less than the observed levels at Transect GW. The results of the spillway performance tests are slightly greater than, but compare closely to the observations from this near-field test.

32. In the foregoing analysis, the mass flux was estimated by computing a simple average of TDG levels on each transect. This analysis presumes a consistent volume of water was being sampled, TDG observations at the channel bottom were representative of bulk flow conditions, and uniform flow existed across each transect. Obviously, the heterogeneities in both the flow and TDG fields preclude a rigorous accounting of the mass flux. However, these average levels provide an adequate first approximation for analysis, comparison, and description of gas transfer.

33. In the May 96 study, a maximum spill discharge of 40,000 cfs was tested with a standard spill pattern, for which the maximum gate opening was set at 3 stops. For this study, the maximum spill discharge was 60,000 cfs. With a standard spill pattern, the maximum gate opening in the center gate was 14 stops. Figure 15 shows the average TDG at Transect GW, at the fixed monitor and the results of the spillway performance tests for a uniform spill pattern compared to similar observations with the standard spill pattern. Like the production characteristics of the stilling basin (shown in Figure 12), the standard spill pattern consistently resulted in higher TDG than the uniform pattern. The relationships shown in Figure 15 represent the best estimates for TDG based on total spill and spill pattern.

34. Conclusions. This study of dissolved gas levels in the immediate tailwater at Ice Harbor Dam, successfully measured temporal and spacial variations in TDG levels during May 1-2, 1996. This study demonstrated the capability to remotely monitor TDG levels in high velocity flow near the end of the stilling basin and adjoining tailwater channel. The general conclusions from this study are as follows:

a. The TDG pressures measured by the instruments in bubbly flow reflect the effects of dissolved gases. Side-by-side comparison between protected and unprotected instruments showed that entrained air had no measurable effect on the recorded level of TDG.

b. The variability of TDG levels for a specific instrument was generally small for constant operating conditions.

c. Changes in TDG corresponded closely with operational changes. Higher unit spillway discharges resulted in higher levels of TDG on all transects.

d. The TDG saturation levels resulting from the uniform spill pattern were generally less than the corresponding TDG pressures generated for the same total spill discharge using the standard spill pattern.

e. TDG levels were generally highest at Transect SB, just downstream of the stilling basin, and decreased with distance downstream.

f. The data support the conclusion that gas absorption occurs in the stilling basin, while degassing occurs in the tailrace area.

g. Vertical gradients in TDG were greatest at Transect SB, just downstream of the stilling basin, for the higher discharges during the standard spill pattern.

h. Lateral gradients in TDG saturation levels were much more pronounced on stations closest to the dam during the standard spill discharges.

i. The TDG levels measured at the tailwater fixed monitoring stations were slightly lower than those observed at the most downstream near-field stations. The range of TDG at the fixed monitor was likewise smaller than the range of saturations observed at the near-field stations.

j. The observed levels of TDG at the end of the lock guide wall (transect GW) and 240 ft downstream of the stilling basin (transect TR) were generally consistent with observations from the Spillway Performance Tests (Wilhelms 1995) and the fixed monitor.

k. The similarity of TDG levels on transects TR and GW imply little additional change in dissolved gas levels outside of 240 feet of the stilling basin.

l. The relationships shown in Figure 15 represent the best estimates for TDG based on total spill and spill pattern.

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CEWES-CS-L 27 January 1997

SUBJECT: Total Dissolved Gas Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater, June 27-28, 1996

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References

Wilhelms, S. C. 1995. "Final Letter Report, Data Documentation and Preliminary Analysis: Field Study at Columbia and Snake River Spillways," CEWES-HS-L Memorandum for Record dated 11 May 1995, US Army Waterways Experiment Station, Vicksburg, MS.

Schneider, M. L. 1996. "Total Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater," CEWES-HS-L Memorandum for Record dated 13 June 1996, US Army Waterways Experiment Station, Vicksburg, MS.

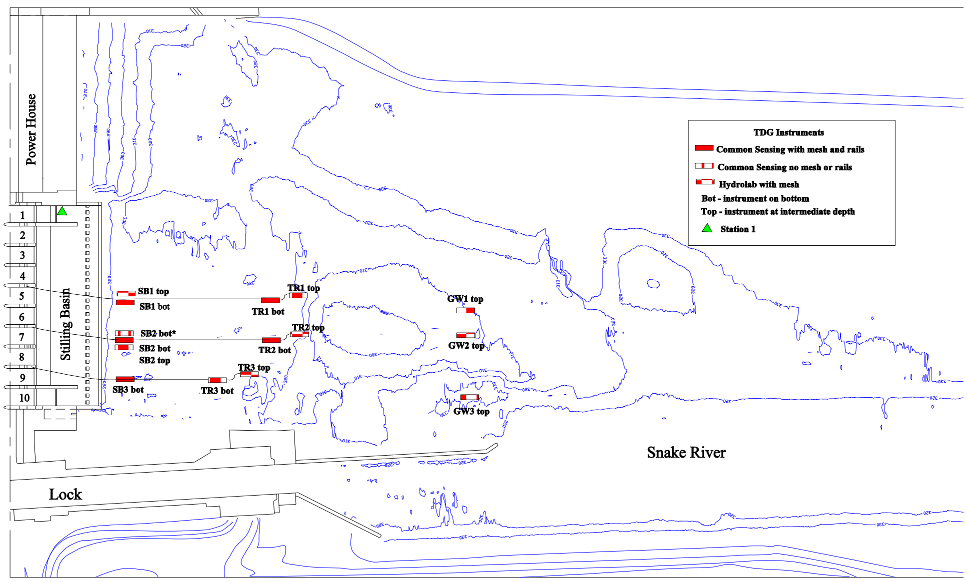

Figure 1. TDG Instrument Layout at Ice Harbor Tailwater, June 27-28, 1996.

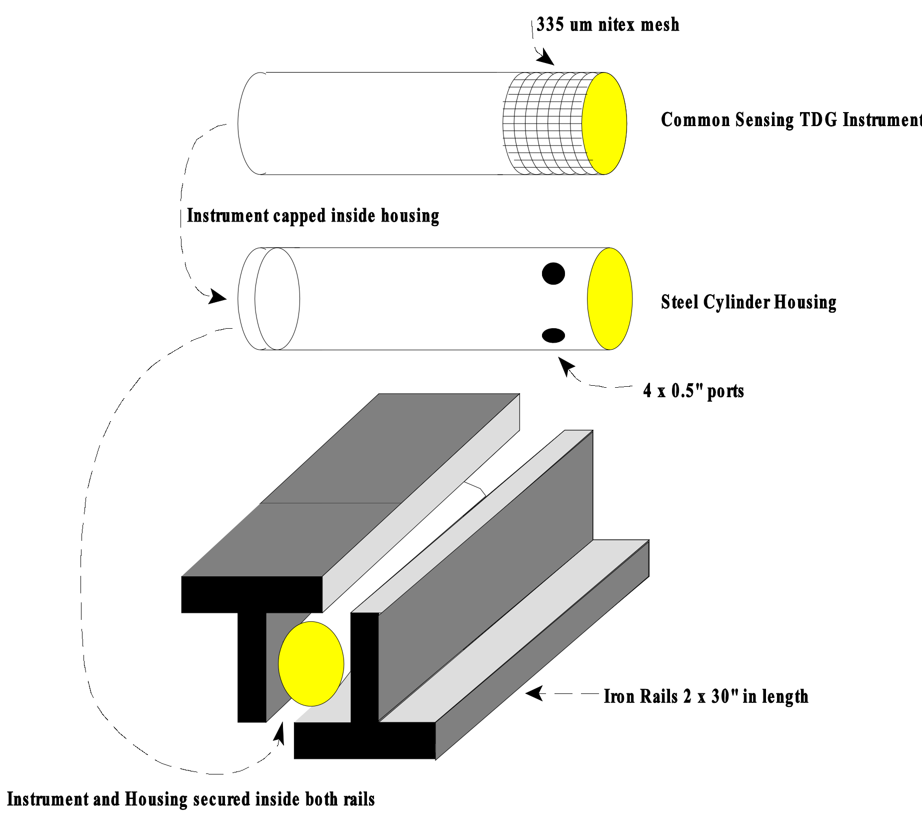

Figure 2. Common Sensing Instrument Enclosure.

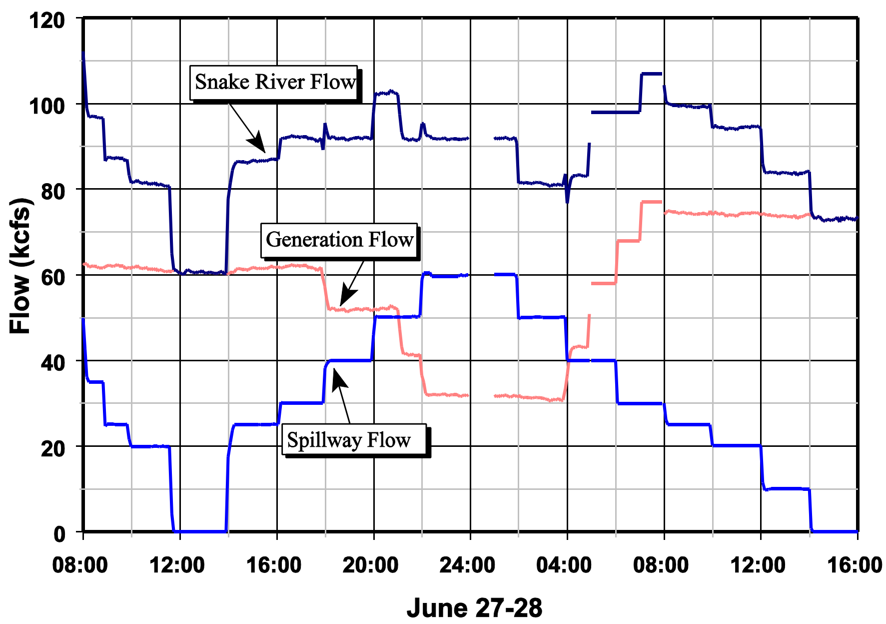

Figure 3. Ice Harbor Project Operation During June 27-28, 1996.

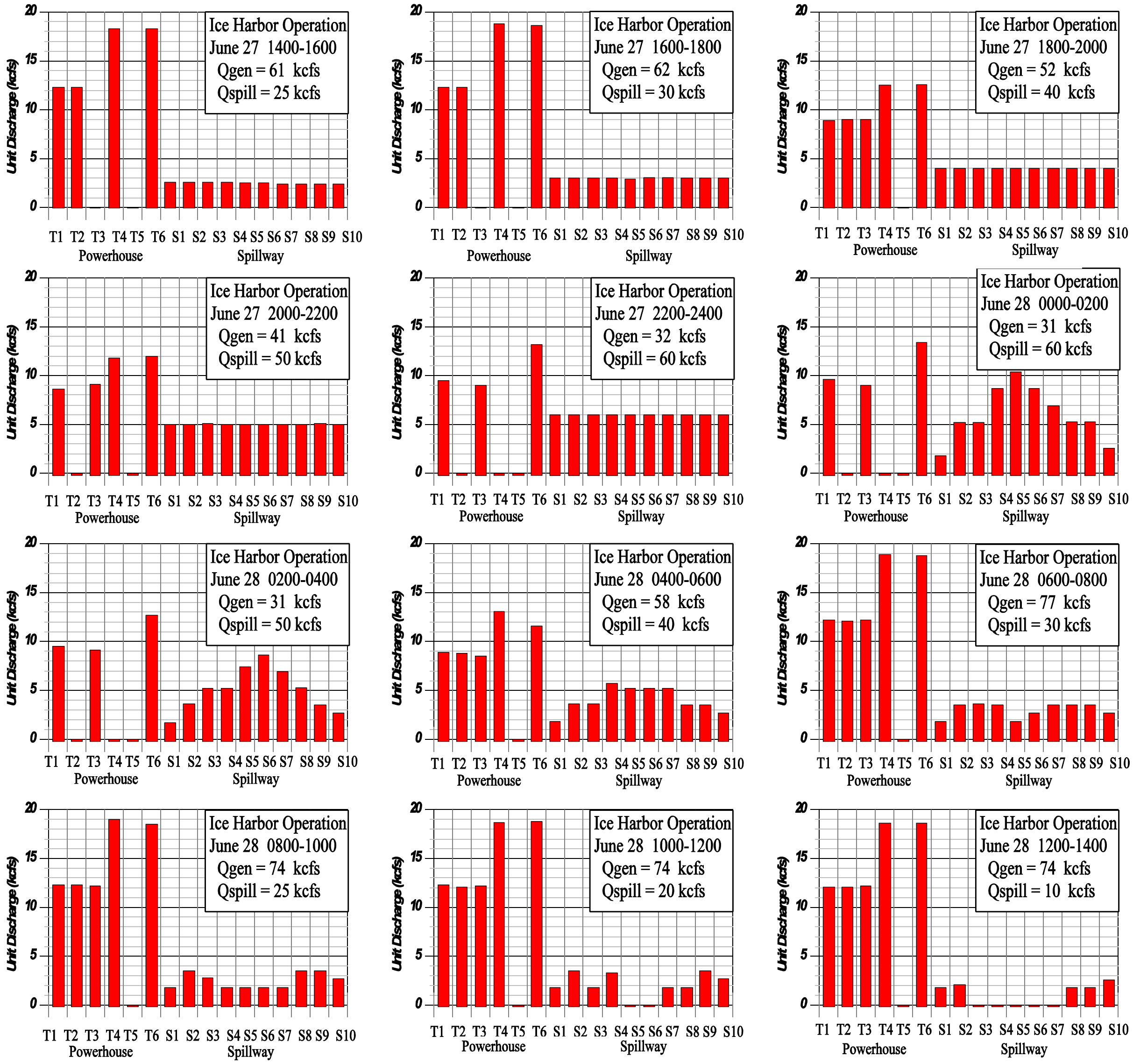

Figure 4. Turbine and Spillway Operation at Ice Harbor Dam on June 27-28, 1996.

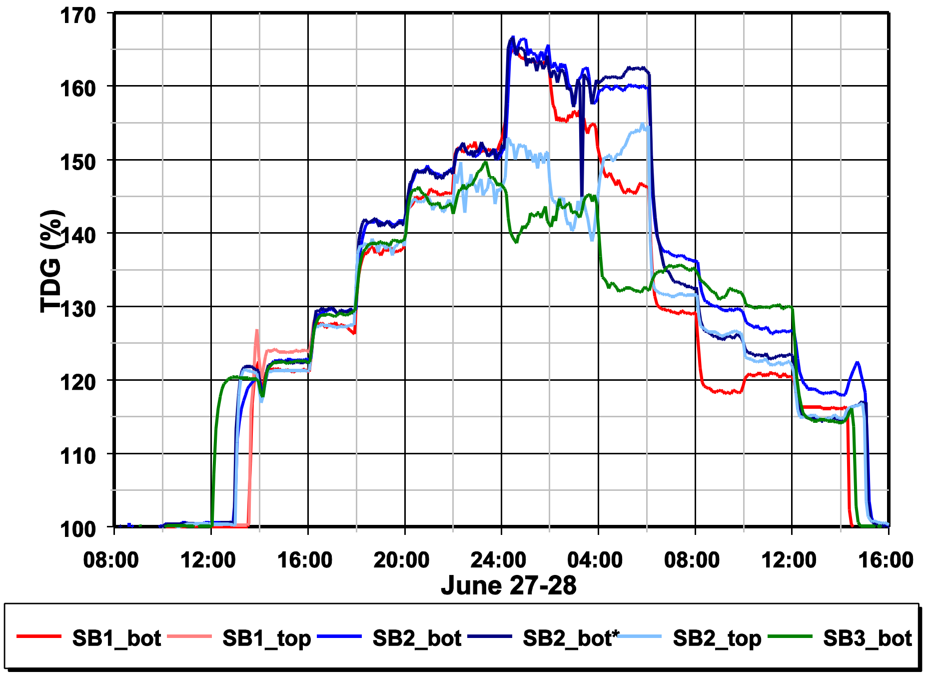

Figure 5. TDG levels along Transect SB

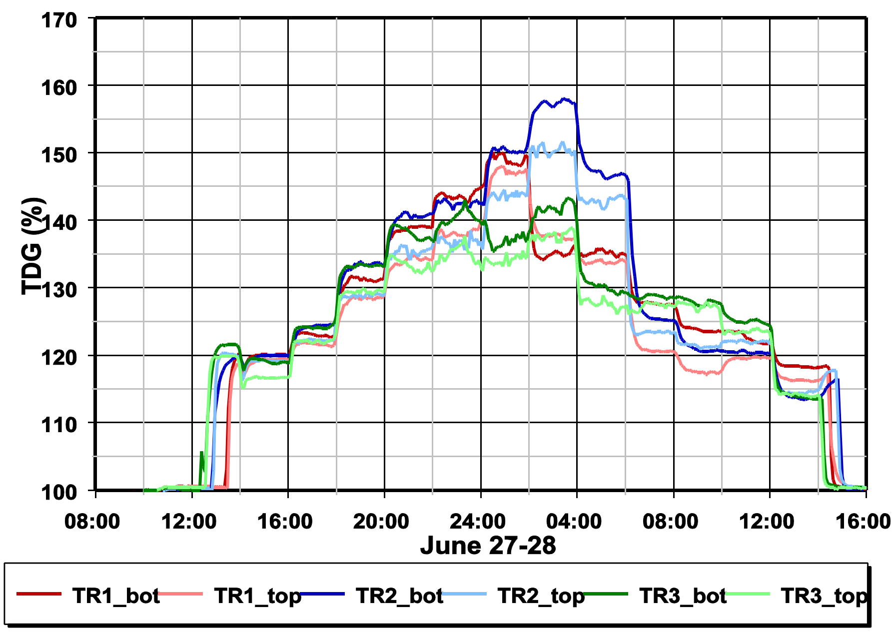

Figure 6. TDG measured at across Transect TR.

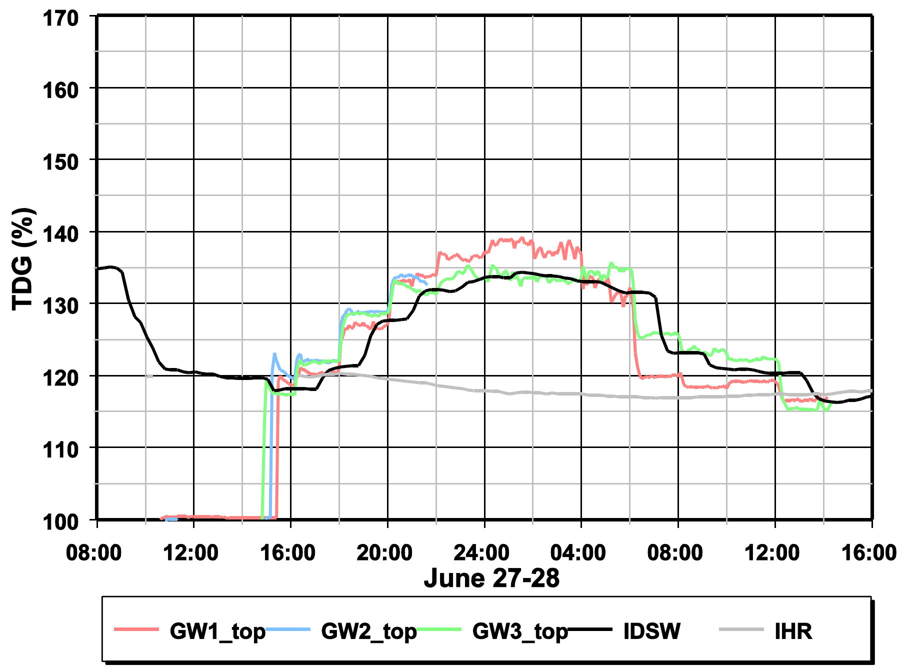

Figure 7. TDG at Transect GW and at the Fixed Monitor below Ice Harbor Dam

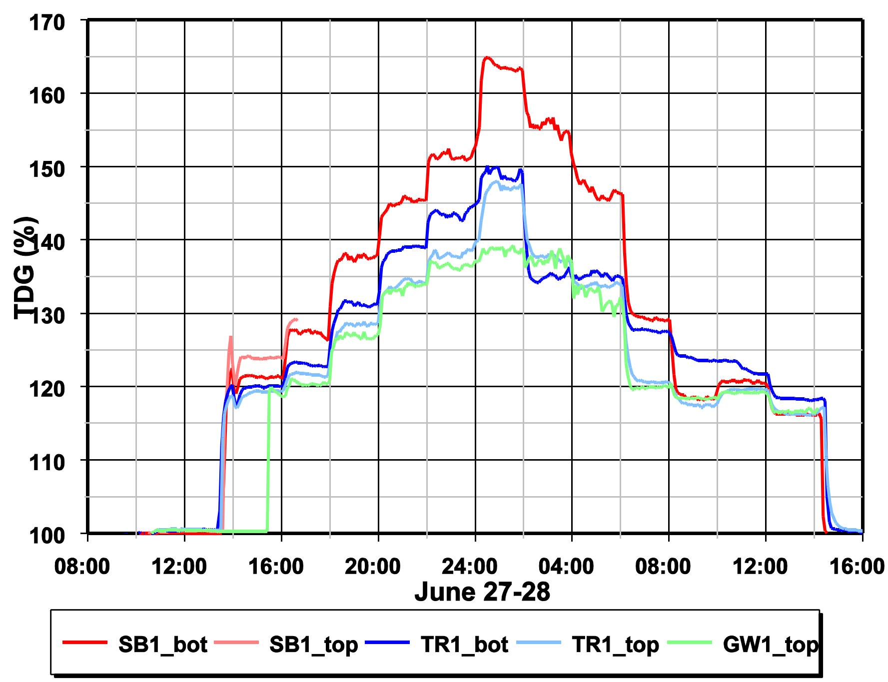

Figure 8. TDG Saturation on Flow Path 1 in the Ice Harbor Tailwater, June 27-28, 1996

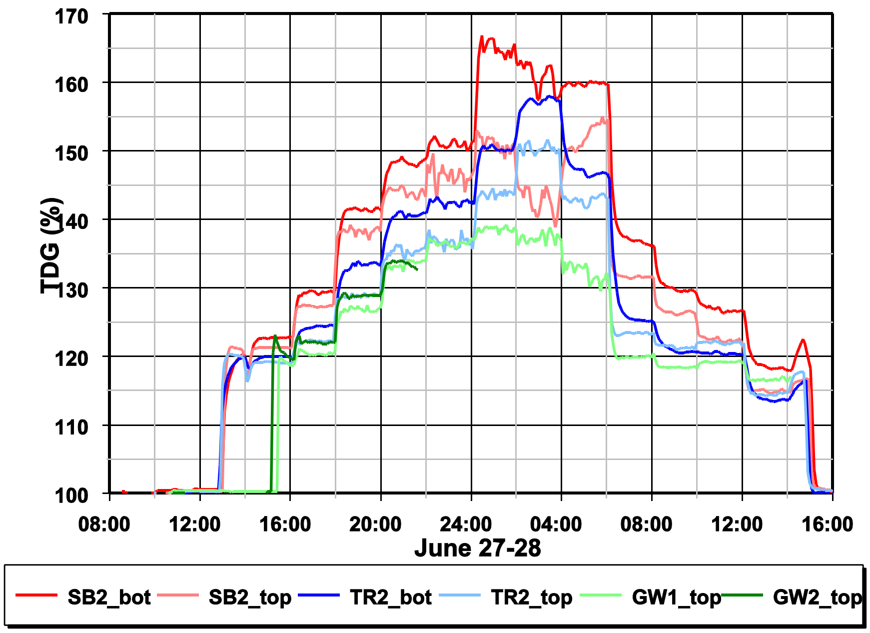

Figure 9. TDG Saturation on Flow Path 2 for Ice Harbor Tailwater, June 27-28, 1996

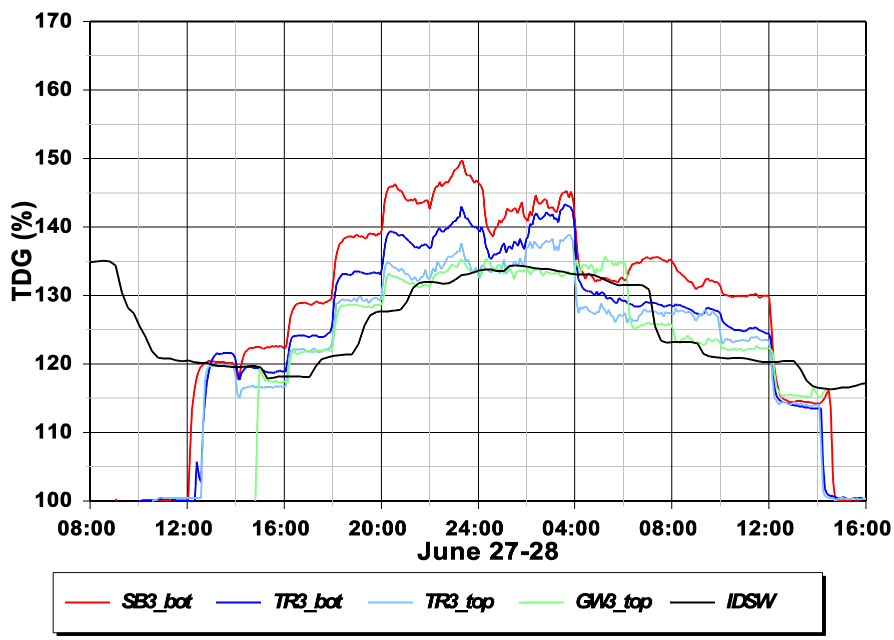

Figure 10. TDG Saturation on Flow Path 3 at Ice Harbor Dam, June 27-28, 1996.

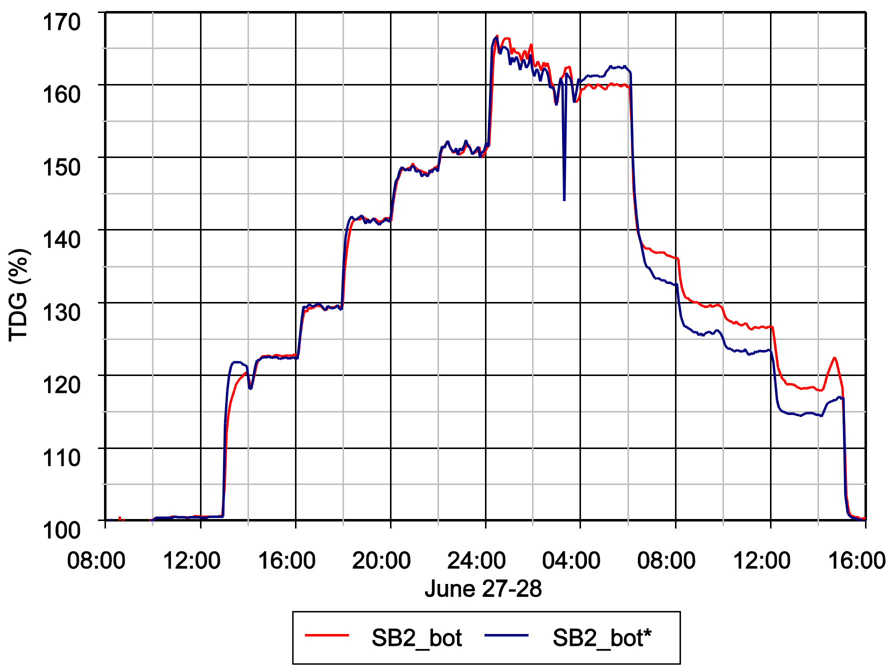

Figure 11. Comparison of Protected and Unprotected TDG Monitors in Bubbly Flow

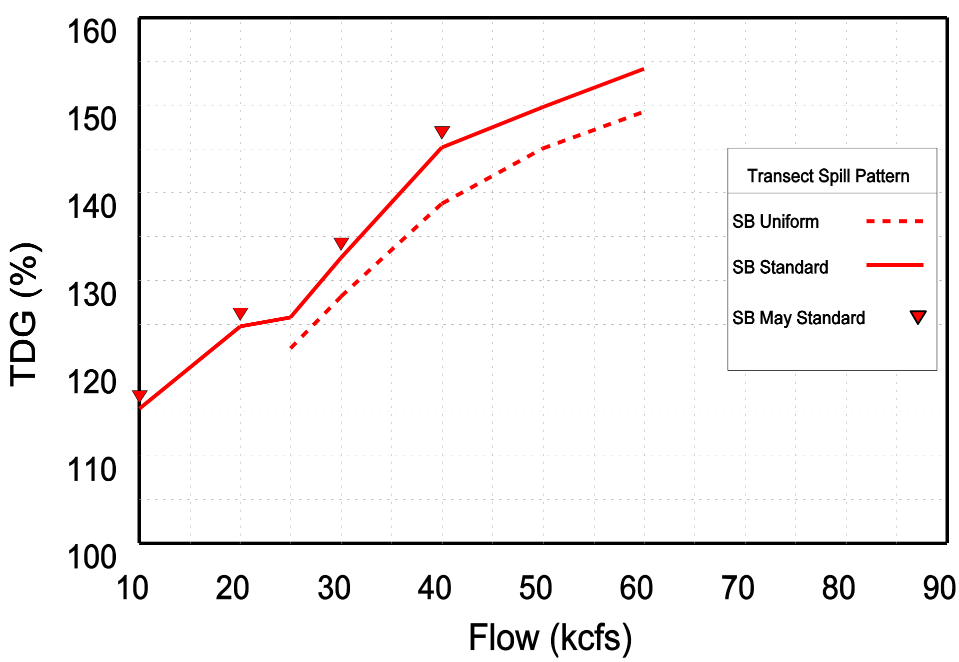

Figure 12. TDG versus Spill Discharge on Transect SB for Uniform, Standard and the May 1996 Standard Tests

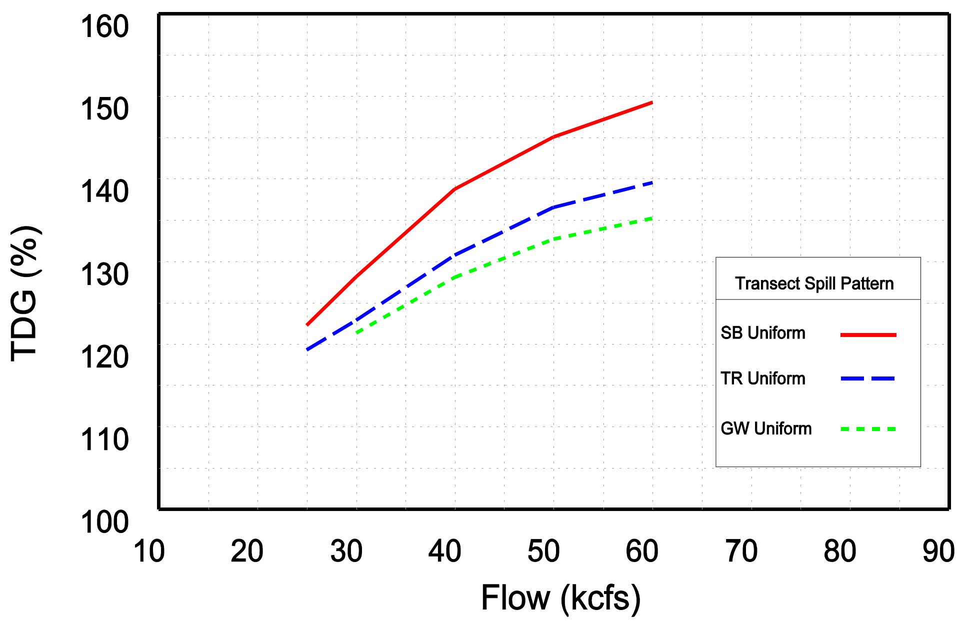

Figure 13. TDG versus Spill Discharge for Transects SB, TR, and GW Uniform Spill Distribution

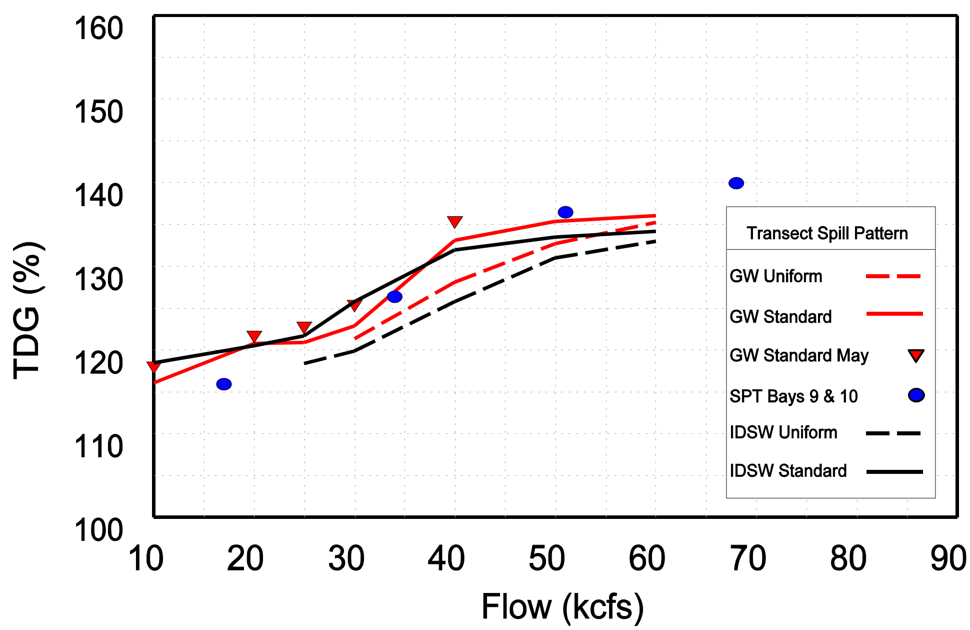

Figure 14. Average TDG at Transect GW and at the Fixed Monitor for the May and June 1996 Near Field Tests and the February 1995 Spillway Performance Test

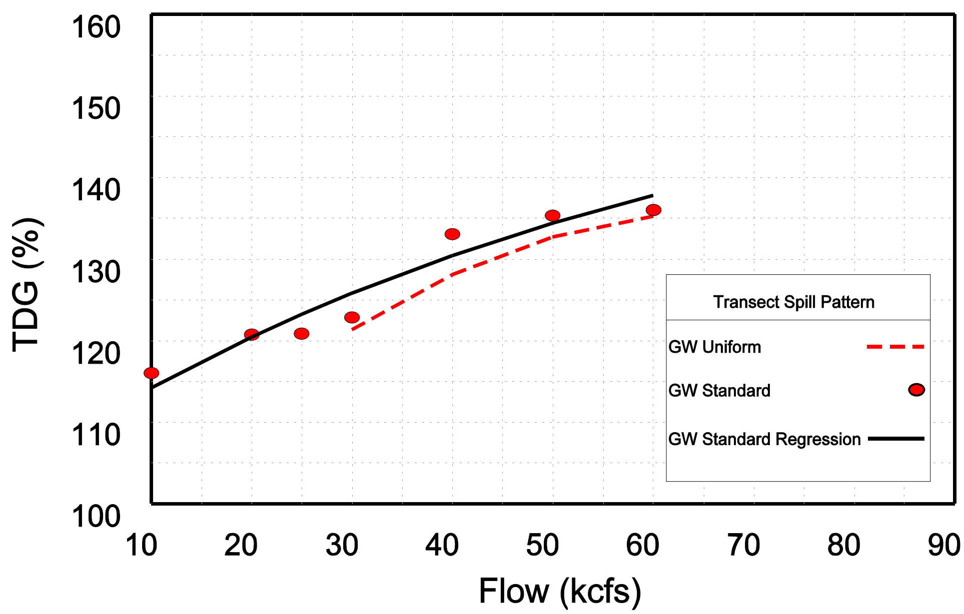

Figure 15. TDG Estimates for Standard and Uniform Spill Patterns

Appendix C: Memorandum for Record Subject: Documentation and Analysis of the Ice Harbor Near-Field Study, March 1998, Post-Deflector Installation

CEWES-CR-F November 27, 1998

MEMORANDUM FOR RECORD

SUBJECT: Documentation and Analysis of the Ice Harbor Near-Field Tailwater Study, March 1998, Post-Deflector Installation

1. Introduction. The purpose of the Dissolved Gas Abatement Study (DGAS) is to develop structural and operational alternatives that reduce the dissolved gas levels produced during spillway operations on the Snake and Columbia Rivers. The assessment of DGAS alternatives has been conducted through analysis of historical data from fixed monitoring stations (FMS), site-specific prototype field studies, physical models, and analytical investigations of gas exchange at hydraulic structures. Previous field studies at Ice Harbor Dam (Wilhelms 1995, Schneider 1996, Schneider and Wilhelms, 1997) have shown the project to be a high gas producer with measured total dissolved gas (TDG) levels above 160 percent exiting the stilling basin and nearly 140 percent exiting the project area. Studies at Lower Monumental, Little Goose, and Lower Granite, have clearly shown that spillway deflectors significantly reduce TDG production compared to that produced by a traditional spillway and stilling basin. Because of their lower TDG production, deflectors were installed on eight of the ten bays at Ice Harbor. As part of the DGAS effort, the US Army Engineer Waterways Experiment Station (WES) was tasked with evaluating the effects of the deflectors at Ice Harbor. The following paragraphs outline the objective and approach for the field study and document the observed data and our preliminary analysis.

2. Objective and Scope. The objective of the field study was to determine the gas exchange characteristics of the Ice Harbor Dam spillway, stilling basin, and tailrace after installation of eight deflectors on the spillway (deflectors were not installed on the two outside bays). TDG within the stilling basin and throughout the tailwater channel was measured with an array of dissolved gas instruments. The array of instruments provided direct assessment of the vertical, lateral, and longitudinal gradients in TDG levels. The mixing between powerhouse and spillway releases was also investigated, since this interaction is important to the total flux of TDG introduced into the Snake River. The influence of the tailwater depth on the exchange of gas during spillway operation was also investigated during this study by controlling hydropower releases. At selected cross sections, TDG was monitored and velocities were measured with an acoustic doppler current profiler (ADCP) to allow TDG flux computations.

3. TDG instruments were deployed downstream of the spillway at Ice Harbor Dam from the stilling basin end sill to the fixed monitoring station (FMS), approximately 3-1/2 miles downstream. These instruments were placed along five longitudinal profiles forming six lateral transects. Auxiliary instruments were located in the forebay, in the tailwater off the powerhouse deck, at the north entrance to the adult fish ladder, in the McNary forebay, and in the Columbia River upstream of the confluence with the Snake River. The TDG instruments logged data on a 15-minute interval throughout the duration of the testing period. Spillway discharge, spill pattern, and hydropower discharge were systematically varied during the study. Spillbay discharges ranged from about 1,500 cfs per bay up to nearly 9,400 cfs per bay during a maximum spill of 75,000 cfs. The spill pattern was varied from the Juvenile Pattern, which is a

uniform setting across the eight deflectored bays, to the Adult Pattern, which uses all ten bays. Generation discharges ranged from zero to a maximum of about 60,000 cfs.

4. Project Description. The powerhouse at Ice Harbor Dam consists of 6 hydroturbines with a combined capacity of 105 kcfs as shown in Figure 1. The spillway at Ice Harbor Dam has a total width of 590 ft and consists of 10 gate-controlled bays. The horizontal apron-type stilling basin at Ice Harbor Dam is about 210 ft long with an invert elevation of 304 ft. With normal tailwater at el 344, the depth in the stilling basin was about 40 ft. One row of 8-ft-high baffle blocks and a 12-ft end sill provide energy dissipation in the stilling basin. The eight central bays have the "Type II" spillway deflectors (Data Report - Ice Harbor Section Study 1996), which is 12.5 ft long horizontally with a 15-ft radius toe curve (Figure 2). All of the deflectors are located at el 338[1]. The interior piers were extended to the downstream end of the deflector to reduce surface turbulence and air entrainment. A splitter wall separates non-deflectored exterior bays 1 and 10 from the interior bays. The tailwater channel downstream of the stilling basin is generally above elevation 320 ft with the exception of a large depression located upstream of the end of the lock guide wall as shown in Figure 3. Beyond the immediate vicinity of the tailrace, the river is generally shallow except for the navigation channel, which was excavated on the northern side of the thalway providing depths of 25-30 ft.

5. Hydrodynamics. The main spillway flow from the central bays at Ice Harbor jets across the stilling basin tailwater surface. The surface jet violently interacts with the tailwater creating a great deal of turbulence. There is a clear demand for entrainment water, since releases from the powerhouse and Gate 1 are pulled laterally across the spillway into the stilling basin (Figure 4). This entrainment flow interferes with the surface jets from bays 2-4, limiting their reach downstream. Although smaller in scale, similar action occurs on the north side of the spillway with release flows from Gate 10 and the fishladder. For lower spill discharges and relatively high powerhouse flows, velocities in the entire tailrace are generally in a downstream direction. However, for the higher spillway discharges of 60,000 cfs and 75,000 cfs, the entrainment into the stilling basin causes a large horizontal circulation cell to form on the south side of the tailrace. Contributing to the formation of this cell is the shallowness of the tailwater channel downstream of the powerhouse, which causes power and spillway discharges to naturally converge to the navigation channel on the north side of the river thalway.

6. TDG Instrument Array. A sampling array, consisting of 41 instruments, was established to measure the TDG pressures. Six lateral transects (T1-T6) were located 40, 240, 540, 1100, 7400, and 19000 ft downstream of the end of the stilling basin. Three to seven stations were located along each transect as shown in Figure 5 and 6. Instruments manufactured by Hydrolab and YSI were used in this test. In general, the measured parameters were water temperature, total dissolved gas pressure, and dissolved oxygen (DO). Some instruments also included instrument depth, pH, and conductivity. All instruments logged data on a 15-minute interval. The instrument name used in this report reflects the location of the instrument in the sampling array. The first two characters of the instrument name refer to the lateral sector (L1-L7), the second two

[1]All elevations are in reference to the National Geodetic Vertical Datum.

characters refer to the longitudinal transect (T1-T6), and the last character refers to the vertical position in the water column (B-bottom, U-upper, P-intermediate). The instrument referred to as L4T1B was located on the L4 lateral sector, T1 longitudinal transect, and was deployed on the channel bottom as shown in Figure 5.

7. The instruments making up the first three transects T1-T3 were deployed along five 750-ft-long steel cables attached to the railing on the trunnion deck of a spillway piers. This cable restricted instrument movement and aided instrument recovery. These cables define the five lateral sectors (L1-L5) below the spillway. The cables were attached to the spillway piers between bays 1 and 2 (L1), bays 3 and 4 (L2), bays 5 and 6 (L3), bays 7 and 8 (L4), and bays 9 and 10 (L5). Transects T1 was located about 40 ft downstream of the stilling basin end sill in about 10-20 ft of water. Transect T2 was located about 240 ft downstream of the end of the stilling basin at similar depths. Transect T3 was located at the end of the cables about 540 ft downstream of the stilling basin end sill. The depth of flow across transect T3 was from 5 to 15 deeper than transects T1 and T2. Most of the TDG instruments were deployed on the channel bottom on transects T1 and T2. These instruments were encased in a 4-in-diameter steel pipe with added steel for ballast (total weight of 150 lbs). Three instruments were deployed in the upper half of the water column on transect T1 to provide estimates of the vertical gradients in TDG pressure exiting the stilling basin. All instruments deployed above the channel bottom were encased in a 4-in-diameter PVC pipe for protection. However, the depth of the instruments deployed above the bottom of the channel varied as a function of the local flow conditions, which caused the instrument to rise and fall over a 3-6 meter range. Both casings were vented with holes to allow a sufficient flow of water through the sampling chamber.

8. Transects T4 was located near the end of the lock guide wall located 1100 ft downstream of the stilling basin end sill. A total of five instruments were deployed across the entire width of the channel with depths ranging from less than 10 ft to over 30 ft. These instruments were deployed in 4-in-diameter PVC pipe for protection, and anchored with a 150-lb concrete anchors. Transect T5 was located about ½ mile downstream of Ice Harbor at Navigation Buoy No. 18. A total of seven instruments were deployed across the channel terminating at Goose Island. Transect T6 was located about 3.6 miles downstream of Ice Harbor at the fixed monitoring station (FMS) and consisted of 3 stations. The station near the north bank on transect T6 consisted of the tailwater fixed monitor instrument and a redundant instrument deployed nearby. These instruments were deployed in 4-in-diameter PVC pipe for protection, anchored with 150-lb concrete blocks.

9. Additional stations were sited in the Ice Harbor forebay and at important locations below the dam. A TDG instrument (ICEFBAYP) was located on the upstream face of the powerhouse to supplement data collected from the forebay FMS (IHR) to provide an estimate of TDG pressures upstream of the powerhouse. Two instruments (DTD1 and DTD2) were deployed in the tailrace channel from the decking of the powerhouse at units 2 and 4, to measure the TDG pressures above the turbine draft tube exits. A station was sited near the entrance of the north adult fishway and consisted of a pair of instruments (FISHATK1 and FISHATK2) deployed at the same depth. Monitors were placed on the Columbia River upstream of the confluence with the Snake at the railroad bridge in Pasco Washington and in the McNary forebay.

10. Operating Conditions. Spillway discharge was halted at 0830 on March 4 to allow access to the restricted access area for deploying cables, instruments, and anchors. With two boats and crews, about 6 hours were required to place the instruments in the restricted area. An additional 2-3 hours were needed to place the monitors at Transects T4 and T5 and on the Columbia River. Normal spillway operation was restarted at 1500. Beginning at 0330 on March 5, the first set of conditions was set and was changed every 2-1/2 hours until the conclusion of the daily test schedule at 1600. Each test day was scheduled in the same fashion.

11. The spillway discharge was increased from 15,000 cfs to 75,000 cfs (15,000 cfs increments) with a uniform spill distribution and a standard spill pattern with and without powerhouse discharges. The powerhouse discharge was held constant during test conditions on March 5 and March 9 at 34,000 and 60,000 cfs, respectfully. Test conditions are summarized in Table 1. The operating conditions for the 20 different test conditions are shown in Figure 7. Hourly operations data are given in Table A1, Appendix A.

Table 1. Test Conditions for Ice harbor Near-Field Study - March 1998

Date	Spill Discharge Range	Spill Pattern	Powerhouse Discharge
March 5	15,000-75,000 cfs	Standard	34,000 cfs
March 6	15,000-75,000 cfs	Standard	zero
March 7	15,000-75,000 cfs	Uniform	zero
March 9	15,000-75,000 cfs	Uniform	60,000 cfs

12. Results. The local barometric pressure as measured at the tailwater FMS was used to calculate the TDG saturation during the study period. The variability of the barometric pressure is shown in Figure 8 along with the project operation. The minimum barometric pressure of 750 mm Hg occurred on March 5 and increased to a maximum pressure of 757 mm Hg on March 9. The water temperature ranged from 5.0 to 5.7 C during the testing period. The TDG saturation in Lake Sakajawea remained nearly constant during the testing period ranging from a maximum level of 103 percent during March 5 to a minimum saturation of 99 percent on March 9. The tailwater elevation, as measure near the south end of the powerhouse, ranged from a low of 338.5 feet to a high of 347.5 ft during the largest Snake River flows on March 9 as shown in Figure 9. The tailwater elevation was highly correlated to the total river flow during this study period. The range in tailwater elevation enabled the investigation of TDG exchange over a range of different flow deflector submergences and tailwater depths.

13. The data presented in this memorandum were scrutinized for reliability and accuracy given their locations and the flow conditions under investigation. In our examination of the observed TDG data, it was obvious that some instruments had malfunctioned. The dissolved gas sensor failed to perform properly as a result of torn, punctured, or clogged membranes, or broken

stirrers. In some cases, the data may be a total loss or it may be difficult to distinguish between a damaged or slowly responding sensor.

14. In general, with both TDG and DO sensors working properly, the TDG pressure is highly correlated to the partial pressure or concentration of dissolved oxygen. The functional relationship between DO and TDG was determined for all instruments in the study. The data from instruments with a standard error less then 7 mm Hg were pooled and a linear regression (Equation 1) was derived from this data set (with an r^2 of 0.95 and standard error of 10.4 mm):

$$TDG_{est} = 58.5DO_{obs} + 95.5 \qquad (1)$$

where TDG_{est} is the estimated dissolved gas pressure, mm HG; and DO_{obs} is the measured oxygen concentration, mg/l. This equation was used to estimate TDG pressure from dissolved oxygen where TDG measurements were missing or erroneous and dissolved oxygen records were judged to be accurate. Five instruments showed symptoms of a malfunctioning or of a slow-responding TDG probe: L1T5P, L2T5P, L5T4B, L6T5P, and L7T5P. The TDG levels for these instruments are represented in this analysis with symbols in the time-history plots and the letter ‘c’ indicating corrected values was appended to the instrument name (L7T5Pc).

15. The results are divided into four sets of daily operations. Each set of observed data is presented in several time-history plots with an analysis and discussion of the results. Hourly TDG data at each station has been tabulated in Table A2 – A7, Appendix A. The latter samples of each test period represent when steady-state or quasi-steady state conditions have been established. The discussion below is based on the observed TDG levels without regard to the actual flux of dissolved gas being delivered to the river. A TDG flux analysis, based on observed TDG and velocities, is presented in subsequent paragraphs.

16. March 5, 1998 (Standard Spill Pattern - 10 Bays; 34,000 cfs Hydropower Flow). The observed TDG levels for these conditions are shown in Figures 10-13. These plots show the time histories of TDG across Transects T1-T4, respectively, which reflect TDG levels in the immediate vicinity of the structure. The level of TDG production by the stilling basin was directly related to the spillbay discharge. At 132 percent, the highest TDG saturation on Transect T1 occurred consistently on the L3 longitudinal profile, which is along the centerline of the spillway. For Transects T2-T4, the peak TDG decreased with distance downstream. On Transect T4, the maximum TDG was about 118 percent on the L4 longitudinal profile, which is just north of the spillway centerline, but near the center of spillway flow. There was significant lateral variation in TDG levels in the immediate tailrace. The lateral variation is likely due to lateral entrainment or mixing caused by 3-dimensional flow effects or to the different TDG production level of bays 1 and 10.

17. Figures 14-15 show the lateral TDG variation across the river channel at Navigation Buoy 18 (Transect T5), about ½ mile downstream of the guide wall, and at the FMS, which is about

3.6 miles downstream of the structure (Transect T6). Peak TDG saturation of about 117 percent occurred across both transects. Lateral variation of TDG was significant, with as much as 5-6 percentage points, indicating that lateral mixing of hydropower releases and spillway releases was not complete, even at the FMS. Figure 16 shows the auxiliary TDG monitors, including Ice Harbor forebay, powerhouse deck, and north fish ladder. With generation at 34,000 cfs, forebay and turbine deck instruments track each other very well, except for the higher spillway flows of 60,000 and 75,000 cfs. Consistent with the visual observation of the flow field, there appears to be a circulation cell transporting a small amount of entrained spillway releases back to the turbine deck instruments. The fish-ladder instruments show TDG levels from spillway 10, which explains the large immediate rise at the beginning of the test period and the relatively small variation through the spillway flow range.

18. Of particular interest are the longitudinal gradients in TDG, which show the degassing characteristics of the tailrace. Figures 17-21 show the TDG along Longitudinal Profiles L1-L5. The TDG saturation in the L1 profile is influenced by powerhouse releases, with TDG rising only 3-percentage points above forebay levels. The L5 profile clearly shows interference from lateral flows from Spillbay 10. The L2 profile is initially responsive to changes in spillway flow at Transect T2, but suffers lateral entrainment from hydropower releases by the time the flow reaches Transect T3. For the two upstream stations, the L4 profile also appears to reflect an influence from the Bay 10 operation, which actually reduces TDG levels because of the lower TDG production from Bay 10 (maximum discharge of 3,400 cfs). Based on observations of the general flow field, the two downstream stations are likely measuring the effects of the central portion of the spillway. Profile L3 shows a dramatic drop in TDG from the 132 percent peak to 125 percent at Transect T2. However, because of the convergence of the flow field, the TDG measurements at Stations L3T3 and L3T4 were likely tainted by lateral entrainment from the powerhouse. Thus, the production characteristics of the spillway alone should be described by the observations along Stations L3T1-L1T2 and Stations L4T3-L4T4, which ranged from 132 percent down to 119 percent.

19. <u>March 6, 1998 (Standard Spill Pattern - 10 Bays; Zero Hydropower Flow)</u>. The time histories of TDG in the immediate tailrace for five spillway discharge over all 10 bays without hydropower operation are shown in Figures 10-13 for Transects T1-T4, respectively. TDG production was directly related to the spillbay discharge. The highest TDG saturation at 132 percent, occurred at Station L3T1, which is along the centerline of the spillway. For Transects T2-T4, the peak TDG decreased with distance downstream. Some of the highest TDG pressures were observed near the entrance to the north adult fishway during the lower spillway releases. On Transect T4, the maximum TDG was about 117 percent, with less than a 2-percentage point variation across the transect. The water recirculating downstream of the powerhouse achieve TDG pressures equal to or greater than TDG pressures observed in the spillway releases on Transect T4. There was significant lateral variation in TDG levels in the immediate tailrace. Without the hydropower releases, the lateral variation was minimal at Transect T4. The mixing zones downstream of Spillbays 1 and 10 are clearly shown by the reduced TDG at stations on the L1 and L5 longitudinal profiles.

20. Figures 14-15 show the lateral TDG variation across the river channel at Navigation Buoy 18, and at the FMS. Peak TDG saturation of about 117 percent occurred at both transects with very little lateral variation. The TDG monitors on the south side of the river on Transects T5 and T6 seem slow to respond at the beginning of the test period. This, however, is simply caused by the low velocities and longer time of travel to these sampling stations. With higher discharges, the response time becomes similar to the other instruments. Figure 16 shows the auxiliary TDG monitors, including Ice Harbor forebay, powerhouse deck, and north fish ladder. With zero generation, the forebay instrument shows a consistent level at 101 percent. The turbine deck instruments show the effects of the circulation cell downstream of the powerhouse transporting spillway releases back to the turbine deck instruments. The maximum TDG saturation outside of the bubbly flow was observed next to the powerhouse at station DTD1 where levels approached 124 percent. The water captured in this flow feature maybe exposed to aerated conditions multiple times leading to the elevated TDG pressures. The TDG at the instruments in the north fish ladder releases are essentially identical to TDG levels from the tests conducted on March 5, tracking the TDG production of Spillbay 10.

21. The longitudinal gradients in TDG are shown in Figures 17-21 for Profiles L1-L5, respectively. The L1 profile shows a mix of flows from the deflectored bays and Bay 1, producing less than 116 percent TDG saturation. The effects of the Bay 10 release decreases as the spill discharge increases. Along the L5 profile, lateral flows from spillbay 10 are evident in the high TDG levels at the T1B location. The L2 profile shows the reduced TDG effects of lateral entrainment from Bay 1 and the horizontal circulation cell on the south for the higher spillway discharges. Profile L3 shows a dramatic drop in TDG from the 132 percent peak to 125 percent at Transect T2. However, because of the convergence of the flow field, the TDG measurements at Stations L3T3 and L3T4 were possibly tainted by lateral entrainment from Bay 1 and the circulation cell. Thus, the production characteristics of the spillway alone are likely described by the observations along Stations L3T1-L1T2 and Stations L4T3-L4T4, which ranged from 131 percent down at the end sill to 116 percent at the end of the guide wall.

22. <u>March 7, 1998 (Uniform Spill Pattern- 8 Bays; Zero Hydropower Flow)</u>. The observed TDG levels for Transects T1-T4 are shown in Figures 10-13 for uniform spill over the 8 deflectored spillway bays. These plots show the time histories of TDG in the immediate vicinity of the structure. The level of TDG production by the stilling basin was directly related to the spillbay discharge. At 130 percent, the highest TDG saturation on Transect T1 occurred at Station L3T1 with 75,000 cfs spillway flow. Peak TDG decreased with distance downstream to about 117 percent on Transect T4. The lateral variation in TDG levels in the immediate tailrace was less for the uniform 8-bay flow distribution than for the standard spill pattern. However, the entrainment of lower TDG water from the horizontal circulation cell on the south side of the river is clearly seen at the monitors along the southerly edge of the spillway flow (Stations L1T1, L1T2, and L1T3) in the tailrace. When the flow exits the tailrace area (Transect T4), the lateral distribution of TDG is essentially uniform. The TDG saturation downstream of the south side of the stilling basin was not influenced greatly by the entrainment of water.

23. Figures 14-15 show the lateral TDG variation across the river channel at Navigation Buoy 18, and at the FMS. Peak TDG saturation of about 117 percent occurred across both transects.

Lateral variation of TDG was relatively small, indicating that transverse mixing was nearly uniform with only a small lag in mixing along the south shore. Figure 16 shows the auxiliary TDG monitors, including Ice Harbor forebay, powerhouse deck, and north fish ladder. The forebay shows a consistent TDG level of about 101 percent. With zero generation and uniform 8-bay spill distribution, the turbine deck instruments track each other very well, showing TDG levels just slightly lower than those observed at T4, T5, and T6. The fishladder instruments are likewise identical, but show higher TDG. This is likely stilling basin TDG production mixed with fish ladder flows in a small circulation cell.

24. Figures 17-21 show the TDG along the Longitudinal Profiles L1-L5. The L1 profile is clearly influenced by both spillway releases and the circulation cell on the south side of the river. The L2 profile likewise suffers lateral entrainment from the circulation cell, evident in its reduced TDG levels. The L5 profile shows the TDG production level of the stilling basin for each of the spillway flows with a maximum of about 130 percent, which decreases to about 115 percent at T4. The vertical TDG gradient is particularly evident between the observations at Stations L5T1U and L1T5B, with as much as a 10-percentage point gradient from bottom to mid-depth. Profiles L3 and L4 show a similar response to TDG levels with production at nearly 130 percent (T1) and degassing to approximately 117 percent at T4.

25. <u>March 9, 1998 (Uniform Spill Pattern - 8 Bays; 60,000 cfs Hydropower Flow)</u>. The operating conditions on March 9 corresponded with the both highest river flows and tailwater elevations observed during the testing period. The observed TDG levels for Transects T1-T4 are shown in Figures 10-13. As in the previous observations, the level of TDG production by the stilling basin was directly related to the unit spillbay discharge. Peak TDG saturation was 132 percent and occurred on Transect T1 on the L4 longitudinal profile, which is just north of the spillway centerline. There was significant lateral variation in TDG levels in the immediate tailrace. On Transect T1, TDG levels ranged from 132 percent on the L4 profile to approximately 101 percent on the L1 profile, which is in the mixing zone between spillway and powerhouse flows. Similar lateral gradients occur for all the transects. Transects T2-T4 show decreasing TDG with distance downstream from the maximum of 132 percent on Transect T1 to 120 percent on Transect T4. The lateral variation is due to lateral entrainment of hydropower flows.

26. Figures 14-15 show the lateral TDG variation across the river channel at Navigation Buoy 18 and at the FMS. Peak TDG saturation of about 118 percent occurred across both transects. Lateral variation of TDG on Transect T5 ranged from about 105 percent up to 117 percent. Figure 16 shows the auxiliary TDG monitors, including Ice Harbor forebay, powerhouse deck, and fish ladders. The forebay and turbine deck instruments show a consistent TDG level of about 100 percent for the entire day's testing. With 60,000 cfs generation, the circulation cell to the turbine deck, so easily discernible in previous time-histories, was not evident. The fish ladder instruments are identical and responsive to changes in project operation. The TDG levels for each spill flow are slightly higher than those observed at T4, which is likely caused by stilling basin TDG production mixed with fish ladder flows in a small circulation cell.

27. Figures 17-21 show the TDG along the longitudinal profiles L1-L5. The L1 profile shows only the powerhouse releases, because the lateral impingement of hydropower flow on the spillway jet causes the jet to become focused toward the north shore, leaving Profile L1 exposed only to turbine releases. Profile L2 is likewise influenced by the hydropower release; only the L2T2B instrument shows TDG generated by spill. The L3 profile is much more responsive to changes in spillway flow, but with reduced TDG levels compared to Profile L4. Profile L4 shows the least impact from hydropower flows. Peak TDG ranges from 132 percent on T1 to 120 percent on T4. TDG levels on the L5 profile are only slightly reduced from the L4 profile, ranging at its maximum from 129 percent to 117 percent.

28. Planview TDG Patterns. The spatial variation of TDG saturation across the sampling array can help to identify areas of dissolved gas absorption, desorption, transport, and mixing. The two-dimensional TDG saturation field for the highest spillway flow conditions tested during this study are shown in Figures 22-25. The horizontal distributions of dissolved gas in the immediate tailrace were similar for the 10-bay spill pattern with and without power flows and for the 8-bay spill pattern with and without power discharges. For the 10-bay patterns (Figures 22 and 23), the highest TDG was located in the center of the spillway downstream of bays 5 and 6. For the 8-bay patterns (Figures 24 and 25), the highest TDG was skewed toward the north end of the spillway downstream of bay 8. The lateral exchange of flow between spillbay discharges is typically toward the center bays, which tends to increase the unit discharge toward the center and result in the "focusing" of flow. The higher unit discharge in this area is likely responsible for the higher dissolved gas pressures. The longer travel time associated with these flows may also contribute to higher levels of TDG saturation. Lateral entrainment, particularly from the powerhouse, significantly shapes the distribution of TDG in the tailrace. For these field tests, the TDG pressures generally decreased in a downstream direction with the absorption of dissolved gas taking place in the stilling basin.

29. TDG in the powerhouse releases ranged from 99 to 102 percent saturation. It mixed with spillway flows during the higher spillway discharge events because of entrainment (near-field) and lateral turbulent mixing and dispersion (far-field). The data suggest that some powerhouse flow was being entrained into the aerated flow in the stilling basin and contributed to the dissolved gas flux into the Snake River.

30. The effects of lateral entrainment from the powerhouse side are clearly illustrated in all of the figures. In Figures 22 and 25, the TDG downstream of bays 1-3 was significantly less than the TDG in the northern portion of the tailrace. For the high spill (75 kcfs) and relatively low powerhouse flows (34 kcfs) in Figure 22, the high entrainment of flows causes a very weak counter-clockwise horizontal circulation cell downstream of the powerhouse. With the higher powerhouse flow (60 kcfs) in Figure 25, the circulation cell was not observed on-site, nor is it indicated by the data. Without powerhouse flow, the circulation cell in Figures 23 and 24 is indicated by the high TDG levels (~116 percent) in the powerhouse tailrace. The non-deflectored discharges from bay 1 were masked by the entrainment of flow from powerhouse releases. The non-deflectored discharges from bay 10 did not result in elevated TDG pressures at local tailwater stations downstream. The surface jets from adjacent deflectored bays also entrained this flow.

31. The TDG saturation on Transect T5 and T6 (FMS) exhibited significant lateral gradients ranging from as low as 102 percent up to 118 percent (Figures 22 and 25) during powerhouse and spill releases. The variation in TDG pressures on this transect was caused by differential mass exchange during spillway releases and mixing between powerhouse and spillway flows. Figures 23 and 24 show nearly uniform lateral TDG levels without powerhouse releases. There was no discernible difference in TDG production between the spill patterns except that explained by a higher discharge per spillbay. The TDG pressures at the fixed monitoring station were nearly identical to the pressures observed on the northern-most instruments on Transects T5 and T4.

32. Discussion. The objective of this field investigation was to quantify the dissolved gas exchange downstream of the spillway at Ice Harbor Dam. The vertical, lateral, and longitudinal gradients in total dissolved gas are shown in the measurements along the four lateral transects and five longitudinal profiles discussed in the previous paragraphs. With these observations as a basis, regions of gas absorption and desorption can be identified. Relationships between TDG production and discharge can be developed. The influence of flow deflector submergence and depth of flow on TDG exchange can also be evaluated.

33. Dominant Gas Exchange Processes. The TDG measurements along Transect T1, at the stilling basin end sill, compared to the downstream transects, leads us to the conclusion that gas absorption takes place in the stilling basin. From field and physical model observations, large volumes of air are entrained due to turbulence in the spillway jet and when the spillway jet collides with the tailwater. Some of this air will be transported to depths where the exchange of gas from the air bubbles is greatly accelerated because of the high local pressures. The observed data show higher saturation of dissolved gas near the bottom compared to mid-depth or near-surface measurements, which seems reasonable to expect, where local pressures are highest near the bottom. These vertical gradients seem to quickly dissipate as turbulence mixes the flow as it moves downstream. Due to the complex 2- and 3-dimensional circulation patterns, the pressure history and exposure time of a parcel of air-entrained water may vary considerably along the length and width of the stilling basin. These flow patterns, together with variations in the amount of entrained air, account for the temporal and lateral variation in TDG pressures observed along the stilling basin end sill.

34. Measurements in the tailrace area immediately downstream of the end sill show a consistent decrease in TDG saturation from that measured near the end sill. Two processes could contribute to this decrease: degassing, where TDG is lost to the atmosphere or dilution by hydropower releases of lower TDG saturation. Dilution seems to be a localized process as indicated by instruments in the mixing zone between hydropower and spillway releases. The maximum TDG saturation delivered to the river was strongly dependent on the specific spillway discharge and weakly a function of the depth of flow. Thus, it seems likely that degassing is the dominant process in the tailrace causing the reduction in TDG. Since the entrained air in the surface jet is likely above the compensation depth, there will be a net mass transfer of gas from the water to the bubbles. With the enormous surface area available for mass transfer, there is

significant desorption of TDG in the tailrace. As bubbles are lost to the atmosphere, the rate of gas loss is greatly reduced.

35. Description of Gas Transfer. The gas transfer at Ice Harbor Dam with spillway deflectors was related to unit spillway discharge and, to a lesser degree, tailwater depth. In general, TDG production in the stilling basin and the TDG delivered to the river increased throughout the range of spillway discharges. The rate of increase in TDG saturation diminished with increasing unit discharge as shown in Figure 26 at station L4T4P and Figure 27 at the FMS (L3T6P). The difference in TDG saturation between the 8 bay (deflectored only) and 10 bay patterns outside of the aerated flow region was indistinguishable. The operations with hydropower generation generated slightly higher TDG levels than the corresponding operations without generation discharge. At station L4T4P, the 75 kcfs spill with generation flows of 60 kcfs resulted in TDG levels about 3 percentage points greater than the same spillway operations without generation flows (Figure 26). The tailwater stage was highly correlated with total river flows resulting in greater tailwater channel depths and deflector submergences with generation discharge. The larger depths were probably responsible for the higher TDG saturation during the generation releases.

36. The presence of flow deflectors greatly reduced the TDG saturation exiting the stilling basin. Figure 28 shows the TDG saturation exiting the stilling basin and downstream of the aerated flow region for the June 1996 field test without flow deflectors and the March 1998 field test with flow deflectors on 8 of the 10 bays. The TDG saturation exiting the stilling basin was reduced in half for the 6 kcfs/bay discharge from 150 percent to 125 percent. All of the curves converge for the smaller unit discharges. The pressure gradient in the tailwater channel was greater for the pre-deflector conditions as compared to the post-deflector conditions. The reduction in TDG saturation for the 6 kcfs/bay event was about 15 percentage point in 1996 and about 10 percentage points in 1998. The TDG pressure delivered to the Snake River was significantly reduced by the addition of flow deflectors. At 6 kcfs/bay the reduction in TDG pressure downstream of the highly aerated flow regime was about 20 percentage points. At 4 kcfs/bay the reduction in TDG saturation was about 15 percentage points. The amount of improvement in TDG saturation does eventually decrease for the higher unit discharges as the deflectors become less effective during larger river flows and higher submergences.

37. The reduction in TDG saturation downstream of the stilling basin favors an exponential decay. Figure 29 shows the maximum TDG levels from Transects T1-T5 for the March 6 operation with the standard spill distribution and no hydropower releases. The maximum and average TDG pressures by transect are listed in Table 2. The degassing in the tailrace channel is evident with dissolved gas levels decreasing from a peak of 132 percent at the stilling basin end sill (Transect T1) to approximately 116 percent at the lock guide wall (Transect T4) for a 75,000 cfs spill. Similar results were evident from the test conditions on the other days. An examination of the average TDG levels across each transect (Figures 30) gives a similar impression of the degassing in the tailrace. However, good judgment must be exercised in using the average TDG levels, because this type of analysis inherently assumes that a consistent volume of water was being sampled, TDG observations at the channel bottom were representative of bulk flow conditions, and uniform flow existed across each transect.

Obviously, the heterogeneities in both the flow field and TDG distribution preclude a rigorous accounting of the mass flux. In spite of this limitation, average levels provide an interesting analysis for comparison and description of gas transfer. A detailed evaluation of the degassing properties observed during this test is described in "Ice Harbor Raised Tailrace Channel TDG Estimates", (Schneider and Wilhelms, 1998).

38. TDG Production The variation in total river discharge for the same spillway operations enabled the investigation of tailwater stage on gas exchange during project releases. The influence of tailwater elevation will determine the submergence of flow deflectors and the characteristics of the surface skimming flow introduced into the stilling basin. Conversely, the tailwater elevation will determine the depth of the tailwater channel, the effective depth of bubbles, turbulence intensity, and time of travel throughout this region.

39. The experimental design of the spillway performance test included the opportunity to measure the influence of gas exchange for the same spillway discharge and pattern under two different tailwater elevations. The variation in the tailwater stage for a given spillway discharge was achieved through varying the powerhouse flow. The tailwater stage ranged from a minimum of 338.5 ft during a 15 kcfs spill without powerhouse flow to a maximum of 347.6 ft during the highest total river flow associated with a 75 kcfs spill and a 60 kcfs powerhouse release as shown in Figure 31. The tailwater stage during combined project releases on March 5 using all 10 spillbays were generally from 2.8 to 3.0 feet higher than the tailwater stage for the same spillway discharge conducted on March 6 (Figure 31). The combined project operation on March 9, using only the 8 deflectored spillbays, resulted in tailwater elevations which were from 4.9 to 5.1 feet higher than the tailwater stage for the same spillway discharge conducted on March 7 (Figure 31). The submergence of the spillway deflectors ranged from 0.5 to 5.0 ft during the test conditions without powerhouse releases on March 6 and 7, from 3.5 to 7.5 ft during the test conditions with a powerhouse discharge of 34 kcfs on March 5, and from 5.5 to 9.5 ft during powerhouse discharge of 60 kcfs on March 9.

Table 2. Average and Maximum Transect TDG					
Average Transect TDG, March 5, 1998					
Transect	15 kcfs	30 kcfs	45 kcfs	60 kcfs	75 kcfs
T1	108.21	112.97	114.34	118.26	121.04
T2	106.72	109.84	112.97	115.45	118.08
T3	106.37	109.55	111.54	112.61	114.64
T4	105.10	106.70	108.67	110.49	112.30
T5	104.83	108.44	110.63	112.54	114.11
Maximum Transect TDG, March 5, 1998					
T1	116.50	122.76	122.27	127.59	132.28
T2	111.58	114.39	120.27	124.24	126.68
T3	109.99	110.67	118.28	119.32	122.55
T4	110.65	111.67	114.56	116.68	118.28
T5	108.94	111.36	114.12	115.88	116.85
Average Transect TDG, March 6, 1998					
Transect	15 kcfs	30 kcfs	45 kcfs	60 kcfs	75 kcfs
T1	109.42	116.57	118.69	121.54	123.58
T2	107.26	111.34	113.87	117.66	120.46
T3	106.80	111.32	112.77	115.03	117.46
T4	106.91	111.23	112.56	114.02	115.84
T5	102.89	111.05	113.54	114.54	115.83
Maximum Transect TDG, March 6, 1998					
T1	116.63	121.60	125.27	127.59	132.00
T2	110.37	116.29	118.49	122.54	124.55
T3	108.24	112.63	115.30	119.22	121.36
T4	110.04	111.86	113.58	114.97	116.31
T5	107.47	112.25	115.47	115.33	116.71

Table 2. Average and Maximum Transect TDG continued.					
Average Transect TDG, March 7, 1998					
Transect	15 kcfs	30 kcfs	45 kcfs	60 kcfs	75 kcfs
T1	108.62	114.78	118.23	120.64	124.13
T2	107.44	112.41	116.08	118.23	120.95
T3	107.53	111.10	113.55	115.94	118.23
T4	107.45	111.13	113.35	114.93	116.51
T5	102.53	110.46	113.49	114.80	116.15
Maximum Transect TDG, March 7, 1998					
T1	112.04	119.34	124.96	129.48	129.98
T2	109.39	116.32	119.53	122.18	125.73
T3	108.46	113.41	115.95	119.13	122.41
T4	107.98	111.69	113.70	115.34	117.62
T5	107.14	112.65	116.11	116.01	117.36
Average Transect TDG, March 9, 1998					
Transect	15 kcfs	30 kcfs	45 kcfs	60 kcfs	75 kcfs
T1	104.19	109.83	114.47	117.42	119.93
T2	104.50	109.20	111.90	114.47	116.42
T3	107.53	111.10	113.55	115.94	118.23
T4	102.91	105.11	106.69	108.18	109.37
T5	102.23	104.85	107.28	109.46	111.65
Maximum Transect TDG, March 9, 1998					
T1	107.75	117.58	123.00	126.88	131.51
T2	107.62	115.01	119.84	124.94	129.26
T3	108.46	113.41	115.95	119.13	122.41
T4	107.28	112.10	115.22	117.76	119.88
T5	105.89	110.84	113.17	114.80	116.12

40. The tailwater gage below Ice Harbor Dam is located on the south side of the powerhouse, well removed from most of the water quality sampling stations used during this study. The depth sensor of a floor mounted water quality instrument was compared with the 5-minute tailwater stage records to determine how representative gage records were of flow conditions downstream of the spillway. The records from the depth sensor on the Hydrolab DS4 at station L3T2B (450-ft downstream spillbays 5 and 6) were compared with the tailwater gage. The instrument depth was highly correlated (R^2=0.96) to the reading at the tailwater gage throughout the duration of the test, with a standard error of about 0.4 feet. The observed tailwater elevation at the powerhouse was used in subsequent analyses to quantifying the influence of this parameter on gas exchange.

41. The TDG saturation was found to be highly correlated to the unit spillway discharge throughout the testing period. The TDG saturation of spillway releases exiting the stilling basin and downstream of the bubbly flow were found to be highly correlated to a logarithmic function of the unit spillway discharge. The TDG saturation at station L4T1B, L4T4P, and L3T6P are show as a function of the unit specific discharge in Figure 32 for all 20 test conditions. The difference between the two data grouping shown in this figure represents the amount of TDG stripped from the water column during passage over the shallow tailwater channel. The similarity in TDG saturation between stations on Transect 4 (L4T4P) and the FMS (L3T6P) infers little exchange in TDG over this river reach.

42. The data also indicates a consistent and identifiable relationship between the tailwater stage and the TDG production at Ice Harbor Dam. The higher tailwater stage conditions resulted in slightly higher TDG saturation produced over much of the northern half of the spillway. The consistent pattern of higher TDG levels for higher tailwater elevation appears to develop over the tailwater channel and not emanate from conditions in the stilling basin.

43. The observed TDG saturation were studied on a series of sampling stations located below the north side of the spillway and at the FMS station located 3.6 miles below the dam. The comparison of TDG pressures below the southern half of the stilling basin were not used for comparison purposed because of the influence of water entrained from the region downstream from the powerhouse. The influence of the variation in tailwater stage was examined by comparing observations between March 5 and 6 for the 10 bay pattern, and March 7 and 9 for the 8 bay spill pattern. The eight bay spill pattern generated higher TDG saturation than the ten bay pattern at station L4T1B, which was located 40 ft downstream the end of the stilling basin endsill below spillbays 7 and 8, as shown in Figure 33. These higher levels of saturation were probably the result of the higher unit discharges utilized during the 8 bay spills. The TDG pressures for the same spill pattern with and without hydropower generation, were similar except for the 75 kcfs spill over 8 bays and the 15 kcfs spill over 10 bays (Figure 33). The data from this station suggests there were no consistent pattern of higher TDG pressures exiting the stilling basin during the higher tailwater channel conditions experienced on March 5 and 9 during hydropower discharges. However, the limited number of observations and range of tailwater stage prevents a rigorous statistical validation of this conclusion.

44. A consistent pattern of higher TDG pressures associated with higher tailwater stage conditions developed below the northern side of the stilling basin. The TDG saturation

throughout the testing period at stations L4T4B, located near the end of the lock guide wall are shown in Figure 34. The TDG pressures on March 9 were consistently equal to or higher than the pressures observed for the same spillway discharge on March 7 except for the 15 kcfs 8 bay spill. The influence of the processes in the tailwater channel which cause a net desorption of dissolved gasses, may diminish during the lower unit discharges because of the smaller concentration of bubbles reaching the tailwater channel. The 10 bay spill pattern also resulted in equivalent or higher TDG pressures during the higher tailwater stage conditions on March 5 when compared to conditions on March 6. The TDG saturation at the FMS were very similar to conditions observed at station L4T4P.

45. A nonlinear multivariate regression was developed between the TDG pressure gradient (TDG pressure minus barometric pressure), the specific discharge, and the tailwater depth. The form of this relationship is shown in Equation 2.

$$\Delta P = c_1 * D_w * \ln(qs) + c_2 \qquad (2)$$

The dependent variable was defined as the difference between the TDG pressure and the atmospheric pressure in millimeters of Hg ($P=P_{tdg}-P_{bar}$), D_w is the tailwater channel depth in feet as determined be the difference in the tailwater elevation and the average elevation of the tailwater channel (327 ft), q_s is the unit spillway discharge with units of kcfs/bay, and c_1 and c_2 are regression coefficients. The form of equation 2 was determined for five instruments located downstream from the north end of the spillway using results from the 20 test conditions. The finding from the nonlinear regression are shown in Table 3. In all cases, the coefficients were significant to within the 95 percent confidence interval.

46. The exchange of TDG at Ice Harbor dam as represented by Equation 2 is highly responsive to the specific spillway discharge and weakly responsive to tailwater depth during moderate to low spillway discharges. The response surface for Equation 2 at station L4T4P is shown in Figure 35. The weak response of TDG production to tailwater depth at low specific discharges is consistent with the view that the region of bubbly flow does not extent into the tailwater channel to a significant degree during these flow conditions. During high spillway releases, the change in the depth of the tailwater channel can result in a significant increase in TDG production. Under the high flow conditions, the region of aerated flow extents well into the tailwater channel where the depth of flow plays a prominent role in the exchange of TDG. The dependence of TDG exchange on both specific discharge and tailwater elevation provides a direct linkage between powerhouse operation and the TDG content of spillway releases. This also means that it will be difficult to identify a single spillway discharge that will result in exceedence of tailwater quality criteria for TDG compliance. The production relationships shown in Table 3 are applicable only for the range of flow conditions tested. The limited variation in tailwater depth during the testing period introduced considerable uncertainty into the influence of this parameter. This range of flow conditions does not include the forced spill that will occur at higher Snake River flows.

Table 3 Nonlinear regression results using Equation 2 for all test conditions, March 5-9 1998.

Station	Observation n	Correlation r^2	Standard Error of Estimate (mm Hg)	C_1	C_2
L4T1B	20	0.91	19.52	5.24 (0.40)*	18.62 (10.50)
L4T2B	20	0.96	14.76	4.55 (0.30)	24.62 (7.94)
L4T3P	20	0.85	16.72	3.39 (0.34)	30.92 (9.00)
L4T4P	20	0.95	6.46	2.46 (0.13)	41.51 (3.47)
L3T6P	16	0.89	9.49	2.51 (0.24)	33.48 (7.02)

* Standard coefficient error.

47. TDG Loading. The velocities across Transects T4, T5, and T6 were measured with an Acoustic Doppler Current Profiler (ADCP)[2] during the daylight hours of this near-field study. The two objectives of these measurements were to (a) estimate the flux or total mass of dissolved gas being delivered to the Snake River and (b) determine the fate of powerhouse flows entrained by spillway releases. Velocity and depth were measured at a regular interval during a bank to bank cruise, in which the survey boat would "crab" sideways across the transect, taking several minutes to complete a lateral survey. These data were collected for several spill and generation conditions. The flow conditions were allowed to stabilize for about 2 hours after each operational change before starting data collection across the transect.

40. The velocity measurements along Transect T5 provided the best opportunity to meet the objectives of this part of the field study. The river bottom was relatively smooth in the navigation channel and between the navigation channel and Goose Island on the south side of the river. Because of the shallow depth south of the island, velocities were not measured with the ADCP equipment. A few velocity and depth measurements, made with a Price current meter, showed that a very small percentage of flow (less than 3 percent) was passing through the shallow south channel. The quality of the velocity measurements on Transect T4 was degraded during the higher spillway flows, because of entrained air preventing the collection of a continuous data record required for the TDG loading analysis. Although velocity measurements were made at Transect T6, the depth was highly variable and very shallow across the south half of the river. With only 3 water quality monitors across the transect, calculations of TDG loading were highly uncertain. Additionally, the lag-time between operational changes and arrival of that water for the lower discharges limited the usefulness of the Transect T6 measurements.

[2] The ADCP measures the Doppler shift in sound waves traveling through the flow field to estimate the three-dimensional velocity field beneath the sampling vessel.

41. The three-dimensional velocity field was depth-averaged and integrated across the transect to develop estimates of cumulative discharge. The depth-averaged velocity transects T4 and T5 are shown during the March 9 spillway discharge of 75 kcfs in Figure 36. Several velocity transects were selected for analysis based on the completeness of their data (in some cases, shallow water prevented a bank-to-bank survey and velocities were measured only in the navigation channel). Table 4 lists the operational conditions for the transects in this analysis.

42. In Figures 37-41 the vertically-averaged velocity, depth, and normalized cumulative discharge for the velocity transects listed in Table 4 are plotted against distance from north bank of the Snake River. The highest velocities and majority of flow were found in the navigation channel on the north side of the river. In general, the total discharge estimated during ADCP transecting was generally 20-25 percent lower than the Snake River flow recorded at the powerhouse. It is not clear why the measured discharge was consistently less than the recorded flow.

Table 4. Operational Conditions for Velocity Transects used in Analysis

Transect No.	Date of Collection	Powerhouse Discharge, kcfs	Spillway Discharge, kcfs	Number of Spillbays
25	3/5/98	35.5	75.0	10
70	3/9/98	60.8	29.8	8
71	3/9/98	61.1	29.8	8
72	3/9/98	61.2	29.8	8
75	3/9/98	61.2	45.1	8
85	3/9/98	61.7	60.1	8
93	3/9/98	62.4	74.7	8

43. The lateral locations of the water quality monitors are given in Table 5. Each monitor “serviced” a specific width of river and, for this analysis, we assumed that the measured TDG value was representative of the TDG level across the serviced width. Thus, Transect T5 was dissected into 7 segments, each with a monitor located at its midpoint. A normalized cumulative width distribution for the instruments is also shown in Table 5.

Table 5. Lateral Location of Monitors Across Transect T5

Distance from North Bank, ft	Width of river serviced by monitor, ft	Cumulative Service Width, ft	Normalized Cumulative Service Width
80	161	161	0.15
241	161	302	0.30
302	161	463	0.45
468	170	633	0.61
693	200	833	0.80
828	150	983	0.94
936	65	1048	1.00

44. To compute the flux of TDG delivered to the Snake River, for each transect, the percentage of flow was determined for each of the water quality sampling stations. This was accomplished by matching the normalized lateral location of each monitor's "service width" with the normalized lateral distribution of discharge and taking the difference in the cumulative normalized discharge on each side of the "service width." The flow-weighted average TDG saturation was then computed with Equation 3.

$$TDG_{avg}^{T5} = \sum TDG_i * \frac{P_i^Q}{100} \qquad (3)$$

where TDG_{avg}^{T5} is the flow-weighted average TDG level entering the Snake River, TDG_i is the observe TDG level at monitor "i," and P_i^Q is the percentage of discharge flowing through the "service width" for monitor "i." The results of applying Equation 3 to the discharge distributions used in this analysis are shown in Table 6. Based on this analysis, the TDG measured at the tailwater FMS and at Station L7T5P generally overestimates the average TDG levels. The degree of overestimation increases as the percentage of total river flow from hydropower operation increases. From this analysis, we have concluded that the north-bank measurements are more indicative of the spillway, but should not be used to represent the total mass of dissolved gas delivered to the Snake River.

45. The fate of powerhouse flows entrained in the stilling basin by the surface jet can be investigated by comparing the flux of TDG passing Transect T5 and the TDG flux assuming no entrainment, $(TDG_{avg}^{no\,ent})$. Equation 4 shows the computation of the average TDG saturation assuming no entrainment of powerhouse releases into the aerated spillway discharge. Under these assumptions, the flow-weighted average saturation was estimated by adding the powerhouse loading, the product of forebay dissolved gas saturation(TDG_{FB}) and generation releases (Q_{power}), and the spillway loading as determined by the product of the tailwater TDG saturation below the north side of the spillway(Station L7T5P) and the spillway discharge (Q_{spill}).

$$TDG_{avg}^{no\ ent} * (Q_{spill} + Q_{power}) = Q_{spill} * TDG_{spill} + Q_{power} * TDG_{FB} \qquad (4)$$

The results of solving this equation for $TDG_{avg}^{no\ ent}$ are also shown in Table 6. In every instance, the average TDG saturation at Transect T5 was greater than the TDG saturation without entrainment. This strongly supports observations in the field and laboratory that powerhouse flows were being entrained into the stilling basin and absorbing dissolved gas. As a consequence, the amount of TDG delivered to the Snake River is greater, than if entrainment were prohibited.

46. Equation 5 provides a means to estimate the minimum entrainment rate[3].

$$Q_{ent} = \frac{TDG_{avg}^{T5} * (Q_{spill} + Q_{power}) - Q_{spill} * TDG_{spill} - Q_{power} * TDG_{FB}}{(TDG_{spill} - TDG_{FB})} \qquad (5)$$

where $Q_{spill}^{eff} = Q_{spill} + Q_{ent}$ is the "effective" spill discharge required to produce the average TDG saturation at Transect T5 (TDG_{avg}^{T5}). The difference between the effective spill discharge and the actual spill is the amount of powerhouse discharge entrained by the spill. These estimates show that, at a minimum, entrainment of powerhouse flows ranged from a low of 26 kcfs up to nearly 40 kcfs, but averaged around 32.5 kcfs. Obviously, for some flow conditions, the entrainment flow will be limited by the availability of powerhouse releases. However, these mass-balance calculations conclusively show that a substantial portion of the powerhouse discharge becomes entrained into aerated spillway flow absorbing TDG in the tailrace region.

Table 6. Results of Flux and Entrainment Analysis

Velocity Transect number	Q_{spill} (kcfs)	TDG_{spill} (%)	Q_{power} (kcfs)	TDG_{FB} (%)	TDG_{avg}^{T5} (%)	$TDG_{avg}^{no\ ent}$ (%)	Q_{ent} (kcfs)	Q_{spill}^{eff} (kcfs)
25	75.0	116.3	35.5	103.0	115.2	112.0	26.4	101.4
70	29.8	110.8	61.3	99.8	107.1	103.3	30.7	60.5
71	29.8	110.8	61.3	99.8	107.3	103.3	32.3	62.1
72	29.8	110.8	61.3	99.7	106.7	103.3	27.7	57.5
75	45.1	113.2	60.9	99.8	109.8	105.8	34.0	79.1
85	60.0	114.5	61.7	99.8	111.7	107.0	38.5	98.5
93	75.0	116.5	61.5	99.7	113.0	108.7	33.1	108.1

[3] The rate is minimum in this formulation since we implicitly assume that entrained flows are "gassed" to the level of spillway flows.

47. Conclusions. The general conclusions from this study are as follows:

a. Spillway deflectors significantly reduced the TDG supersaturation delivered to the Snake River by over 50 percent. The maximums pre-deflector TDG levels of nearly 140 percent were reduced to 120 percent with deflectors, as measured at the FMS. The magnitude of enhancement associated with the deflectors may be partially attributed to the flat spill pattern and lower tailwater elevations maintained during this study.

b. The high levels of TDG absorption in the stilling basin were reduced from as high as 170 percent to 132 percent as a result of the flow deflectors. Thus, the reduction in delivery of TDG to the Snake River is likely due to reduced absorption in the stilling basin.

c. TDG saturation were highest at Transect T1, just downstream of the stilling basin, and decreased with distance downstream. The data support the conclusion that gas absorption occurs in the stilling basin, while degassing occurs in the tailrace area. The degassing of spillway releases can be approximated as exponential decay.

d. The TDG production was found to be primarily a function of the unit specific discharge and secondarily to the tailwater channel depth of flow. The regression model generated from this study is applicable only over the limited range of flow conditions tested. The dependence of TDG exchange on both unit discharge and tailwater elevation provides a direct linkage between powerhouse operation, pool elevation in McNary reservoir, and the TDG content of spillway releases. The concept of a single spillway capacity make little sense in light of the dual dependency of spillway TDG pressures on tailwater depth and unit spillway discharge.

e. The lateral entrainment of hydropower releases is evident in visual observations and in the measurements in the immediate tailrace. The similar TDG production relationships suggest that some of the entrained hydropower water is subjected to gas absorption. The flux calculations based on data from Transect T5 clearly show that between 26 - 40 kcfs is being entrained and “gassed” to near spillway levels. Under some test conditions, all the powerhouse flows were entrained and recirculating flow was apparent downstream of the powerhouse. The entrainment of powerhouse flow resulted in a significant increase in the TDG loading delivered to the Snake River during this study.

f. The operation of Spillbays 1 and 10 had no apparent influence on the TDG measured at the FMS. The small discharge from the non-deflectored bays contributed to minimal impacts in TDG saturation downstream of the highly aerated flow. Their effects were much more pronounced in the immediate tailrace and can be seen directly below the north end of the stilling basin for the lower spillway discharge.

g. The TDG pressure in areas of recirculating flow can achieve TDG levels significantly greater than observed in the main spillway release. These regions occur below the north fishway entrance and below the powerhouse during operations where most of the river is spilled.

h. Lateral gradients in TDG saturation at the FMS were greatest during hydropower operation with high spillway releases. This occurrence is the result of incomplete mixing of powerhouse and spillway releases.

i. Changes in TDG corresponded closely with operational changes. Higher unit spillway discharges resulted in higher levels of TDG on all transects. Larger total river flows associated with hydropower operation also resulted in slightly higher TDG pressures.

j. Vertical gradients in TDG were greatest at Transect T1, just downstream of the stilling basin, for the higher discharges during the standard spill pattern.

k. Lateral gradients in TDG saturation levels were much more pronounced at stations closest to the dam on the south end of the spillway, due to the lateral entrainment of powerhouse flows. On the north side of the spillway, lateral and some longitudinal TDG variation could be attributed to the operation of spillbay 10.

l. Based on the TDG observations in the tailrace, the bulk of degassing occurs within the first 240 ft of the stilling basin. Only minor reductions in TDG occurred in the next 300 ft.

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References

CEWES-HS-S 1996. "Data Report - Ice Harbor Section Study," Memorandum dated 18 March 1996, US Army Waterways Experiment Station, Vicksburg, MS.

Wilhelms, S. C. 1995. "Final Letter Report, Data Documentation and Preliminary Analysis: Field Study at Columbia and Snake River Spillways," CEWES-HS-L Memorandum for Record dated 11 May 1995, US Army Waterways Experiment Station, Vicksburg, MS.

Schneider, M. L. 1996. "Total Dissolved Gas Data Documentation and Preliminary Analysis: Near-Field Study of the Ice Harbor Tailwater," CEWES-HS-L Memorandum for Record dated 13 June 1996, US Army Waterways Experiment Station, Vicksburg, MS.

Schneider, M. L. and Wilhelms, S. C. 1997. "Documentation and Analysis of the near-Field Ice Harbor Tailwater Study," CEWES-CS-L Memorandum for Record dated 27 January 1997, US Army Waterways Experiment Station, Vicksburg, MS.

Schneider, M. L. and Wilhelms, S. C. 1998. "Proposed Ice Harbor Raised Tailrace Channel – Total Dissolved Gas Estimates," CEWES-CS-L Memorandum for Record dated 26 October 1998, US Army Waterways Experiment Station, Vicksburg, MS.

Figure 1. Ice Harbor Dam – aerial photograph.

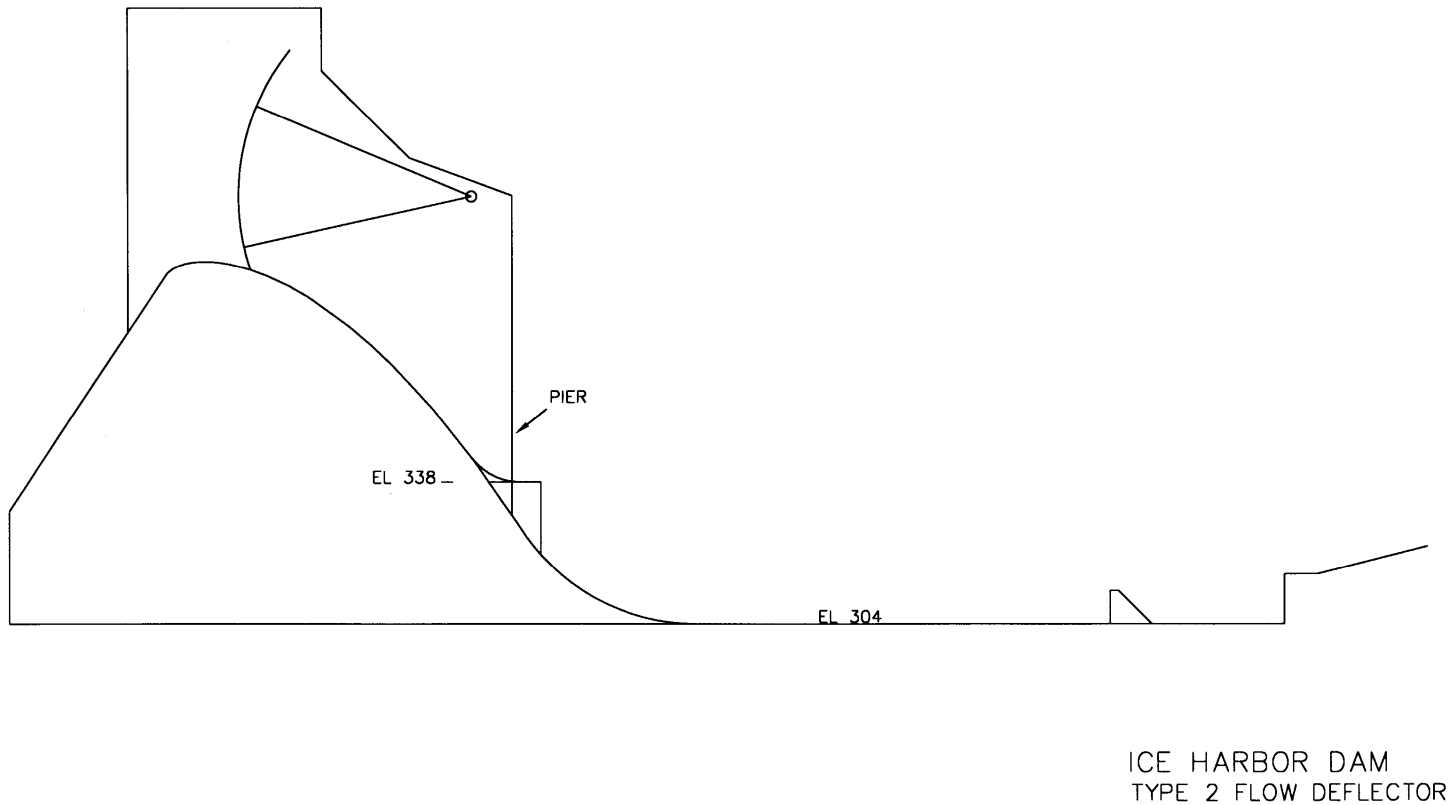

Figure 2. Ice Harbor Dam – Spillway Elevation View

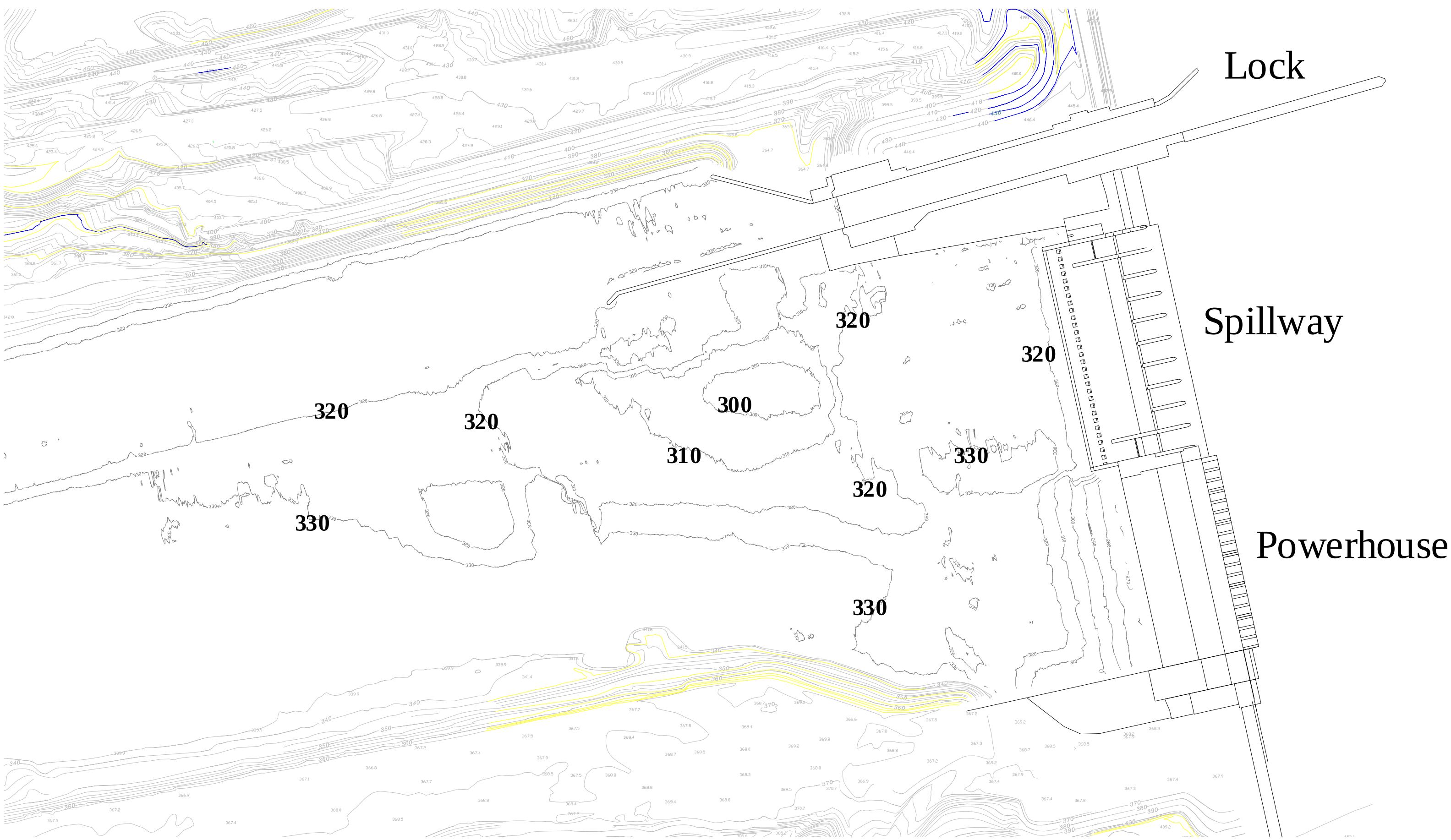

Figure 3. Ice Harbor Dam and tailwater channel bathymetry.

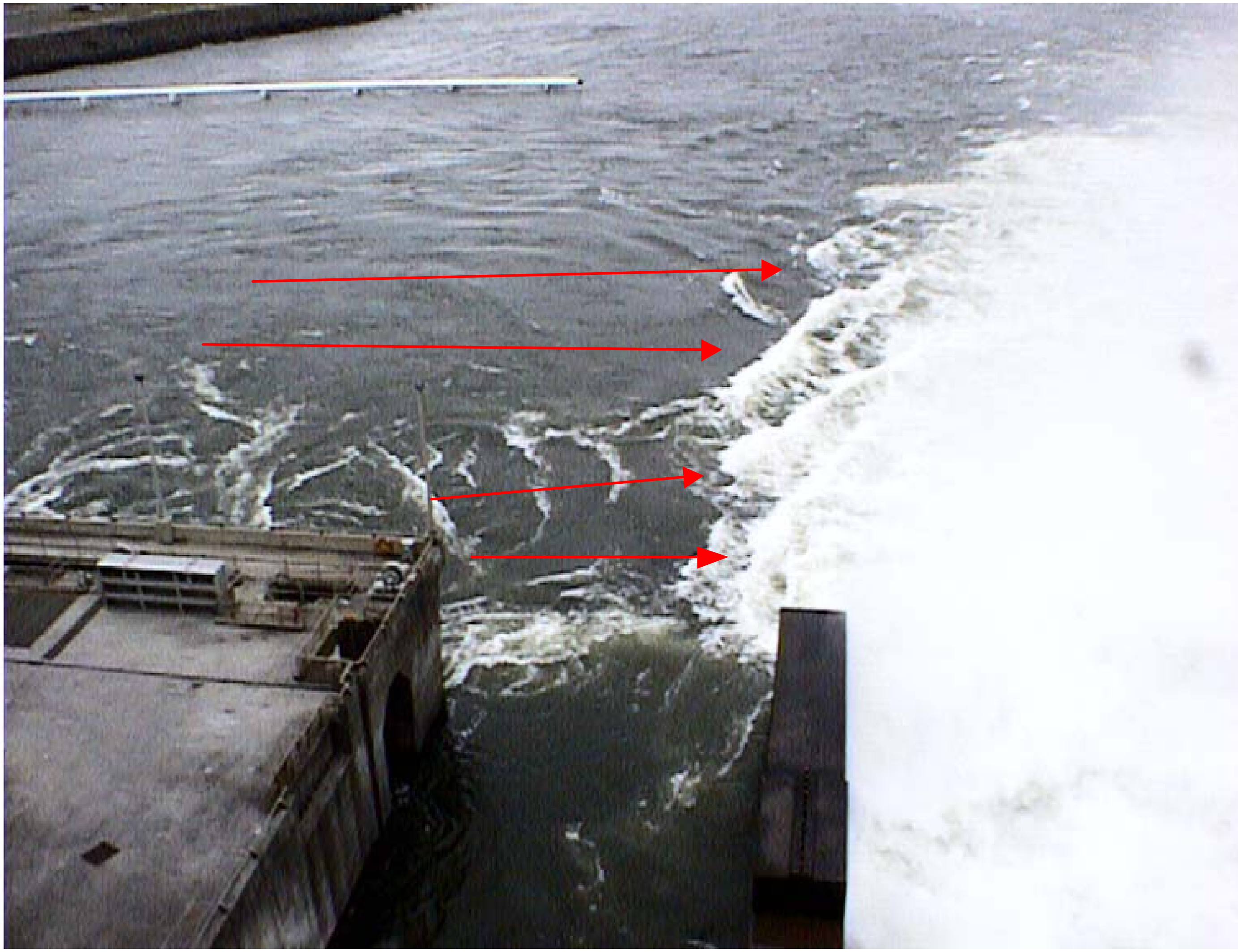

Figure 4. Entrainment of Hydropower Releases into Spillway Flow.

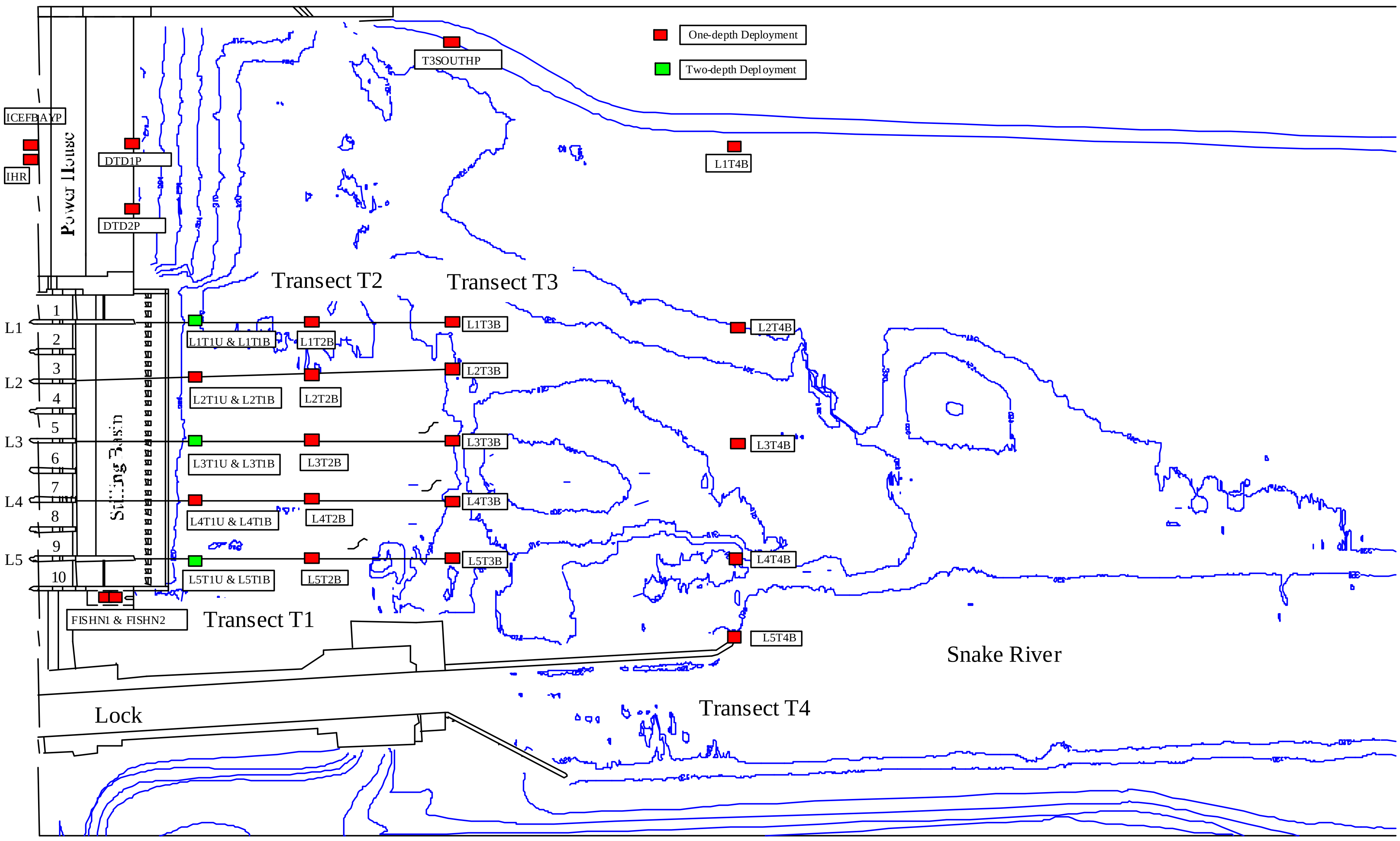

Figure 5. TDG Instrument Layout at Ice Harbor Tailwater, March 1998.

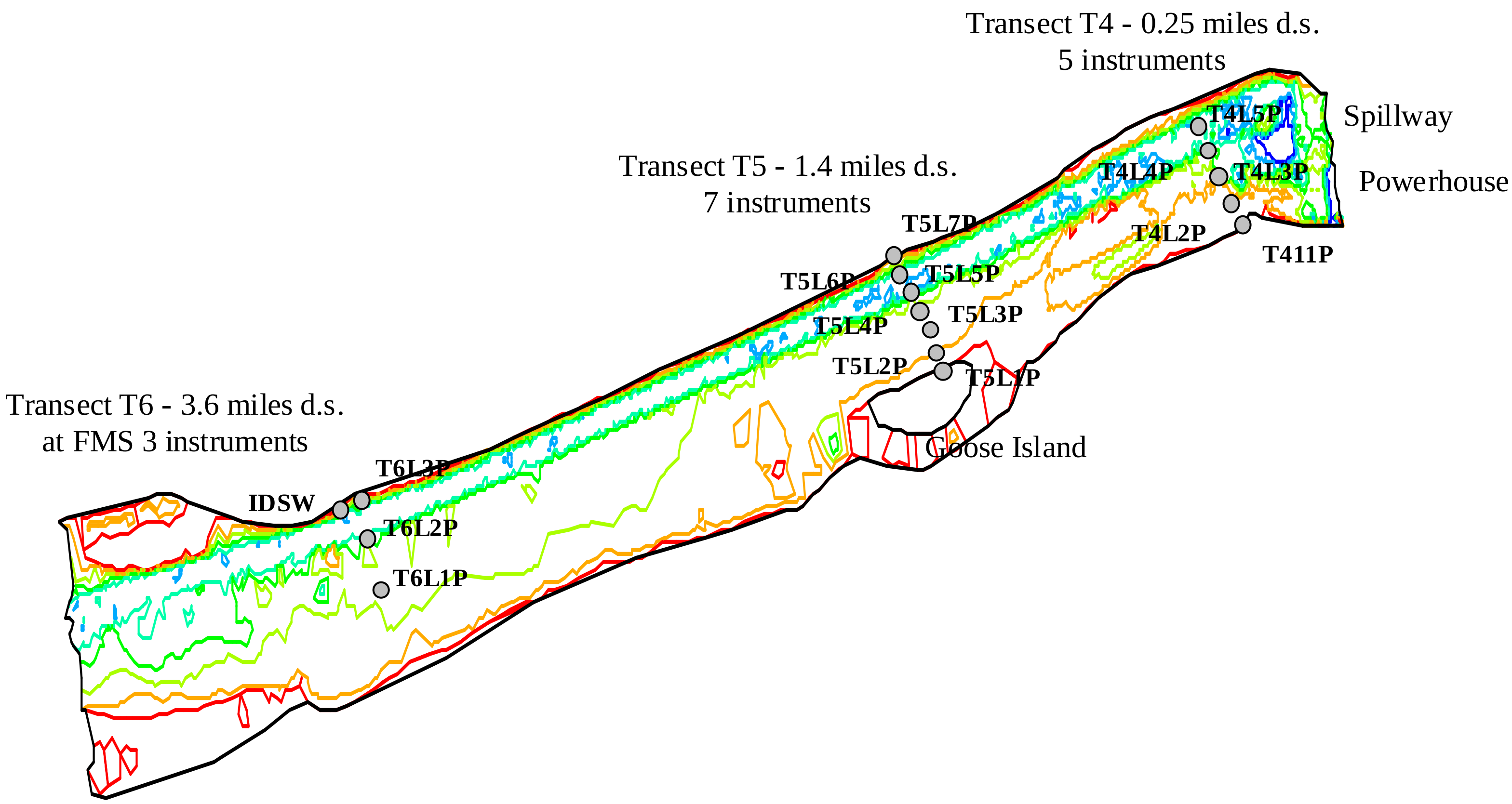

Figure 6. Locations of Downstream TDG sampling array, March 1998.

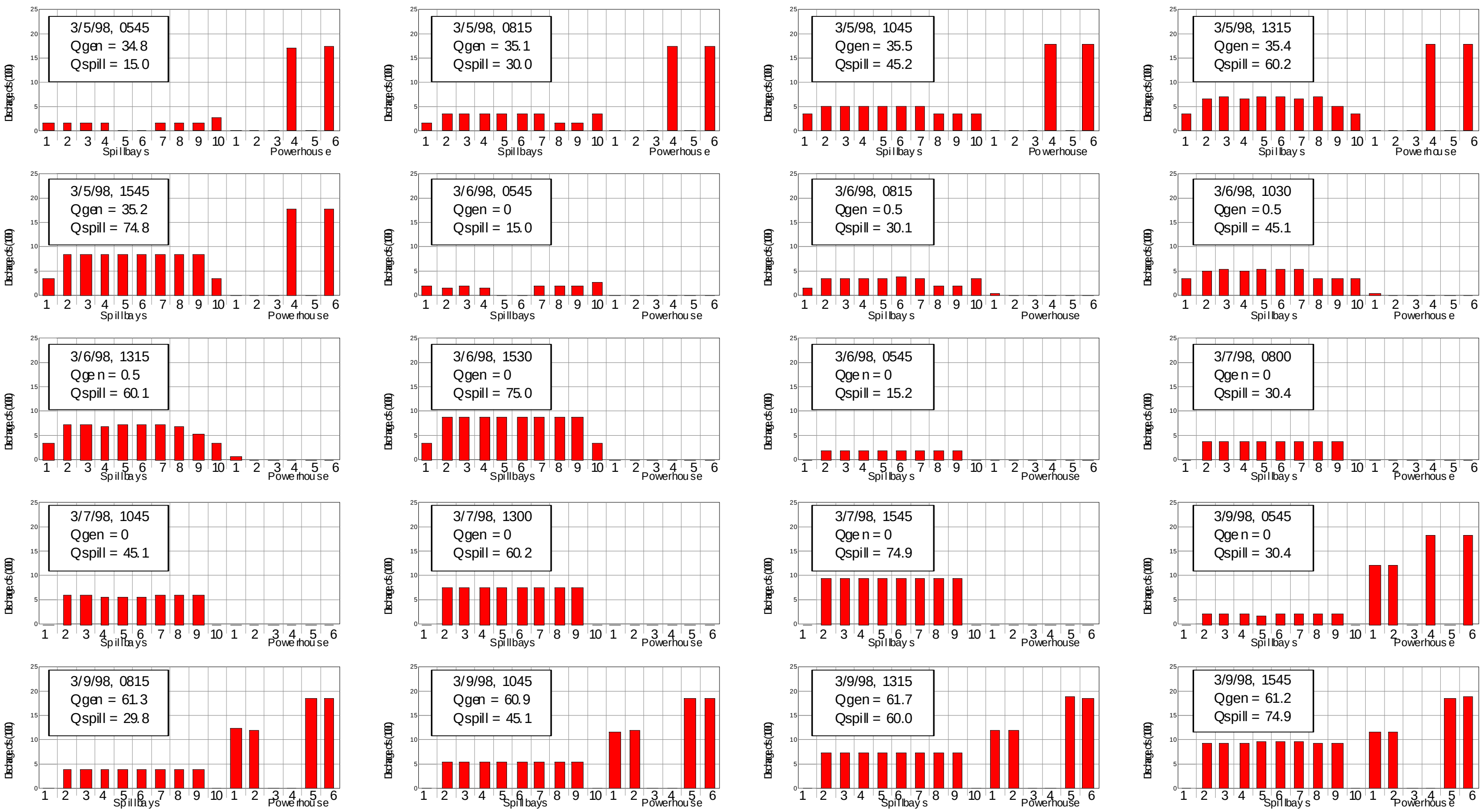

Figure 7. Turbine and Spillway Operation at Ice Harbor Dam, March 1998.

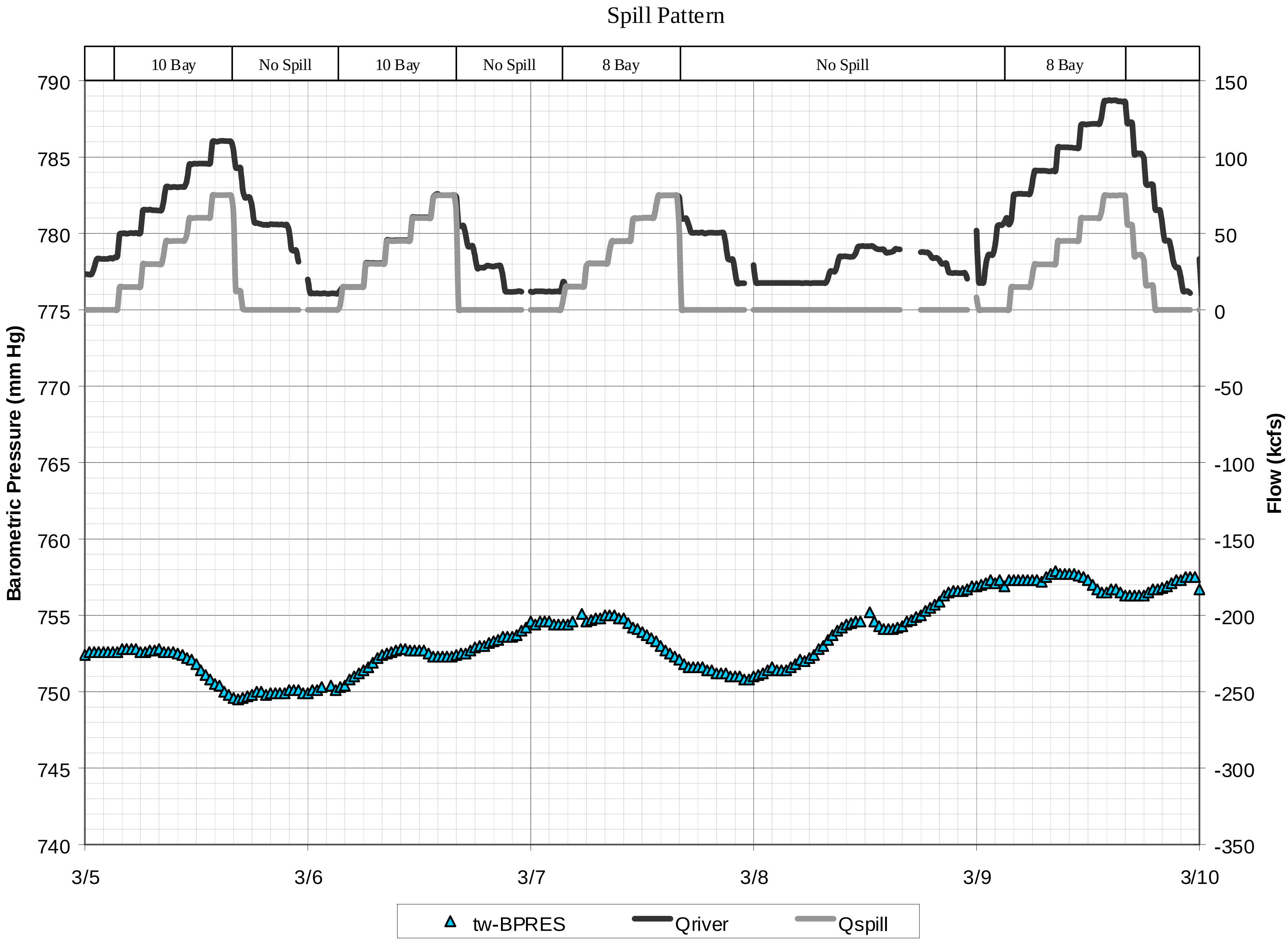

Figure 8. Project operation and barometric pressure at the Ice Harbor tailwater fixed monitoring station, March 5-9, 1998.

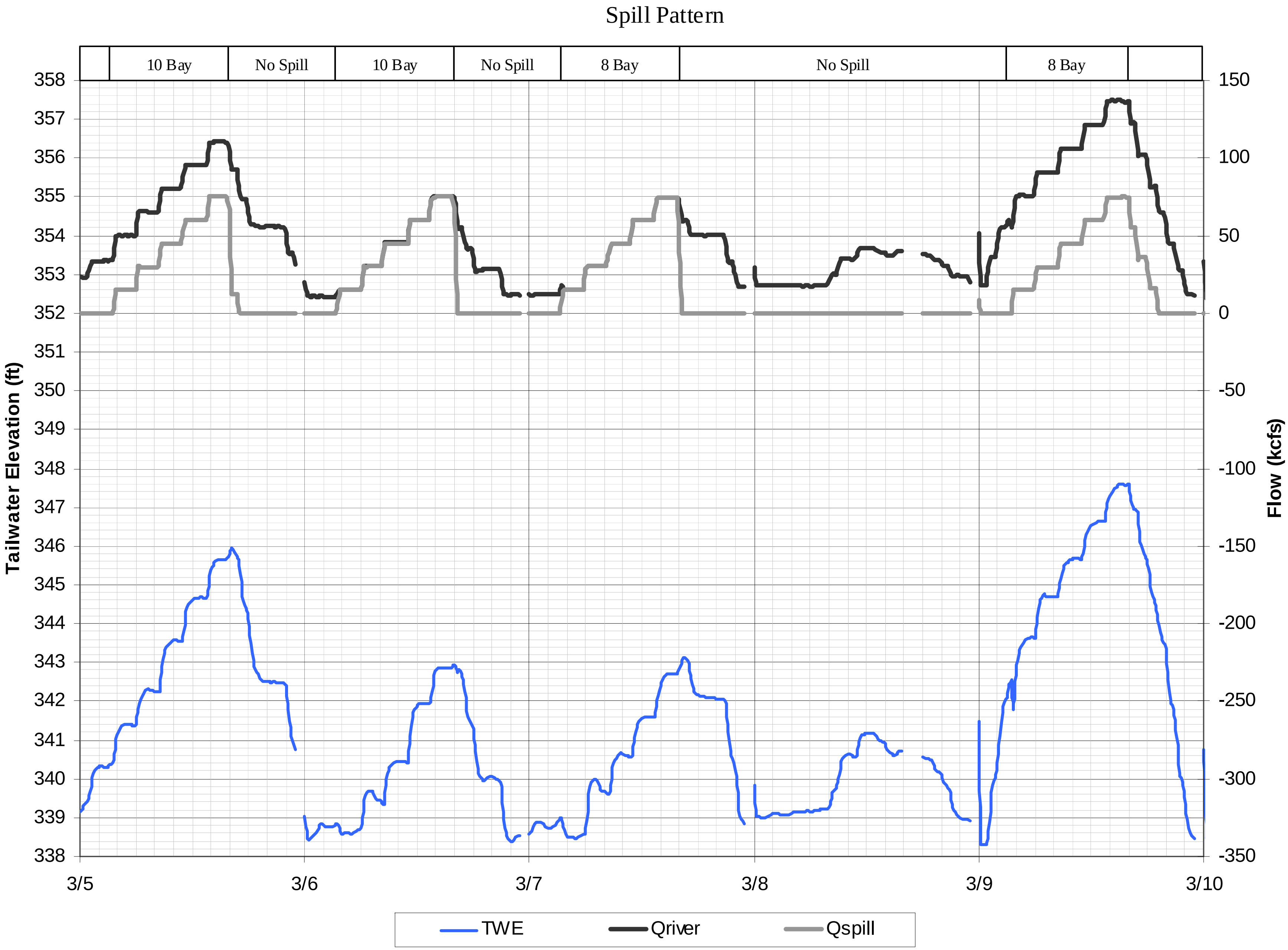

Figure 9. Project operation and tailwater elevation at Ice Harbor Dam, March 5-9, 1998.

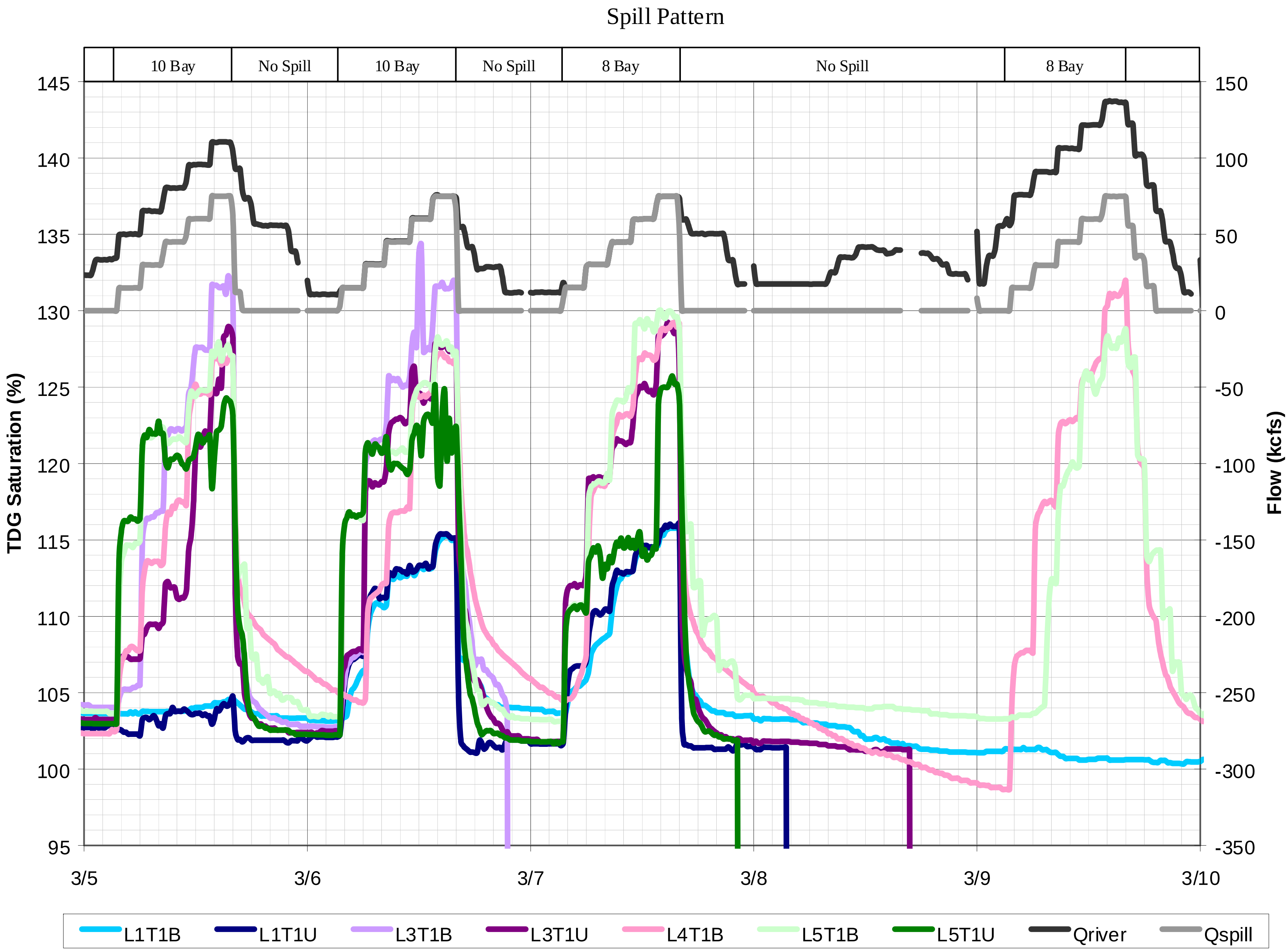

Figure 10. TDG Saturation along Transect T1, March 1998

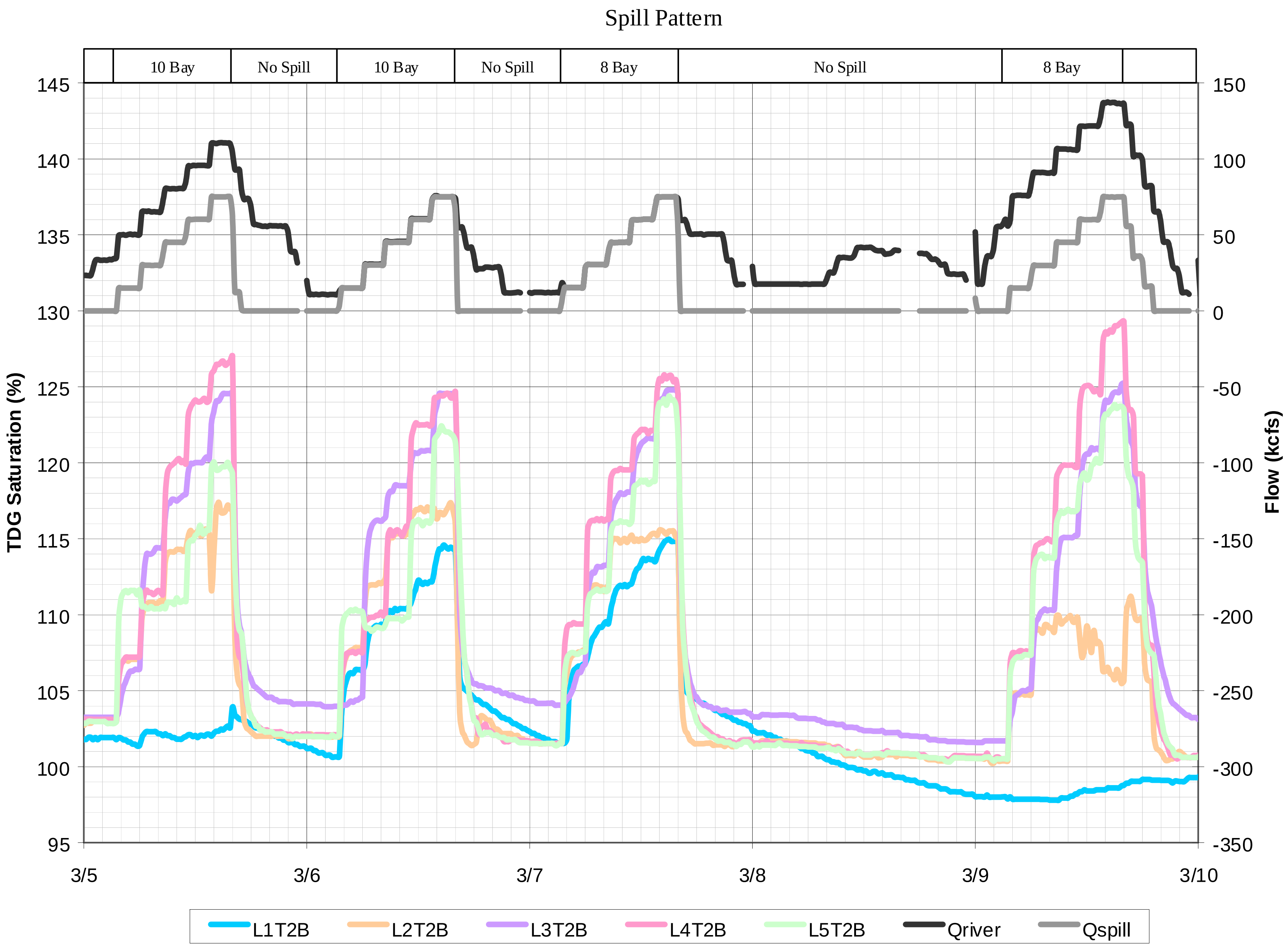

Figure 11. TDG Saturation along Transect T2, March 1998

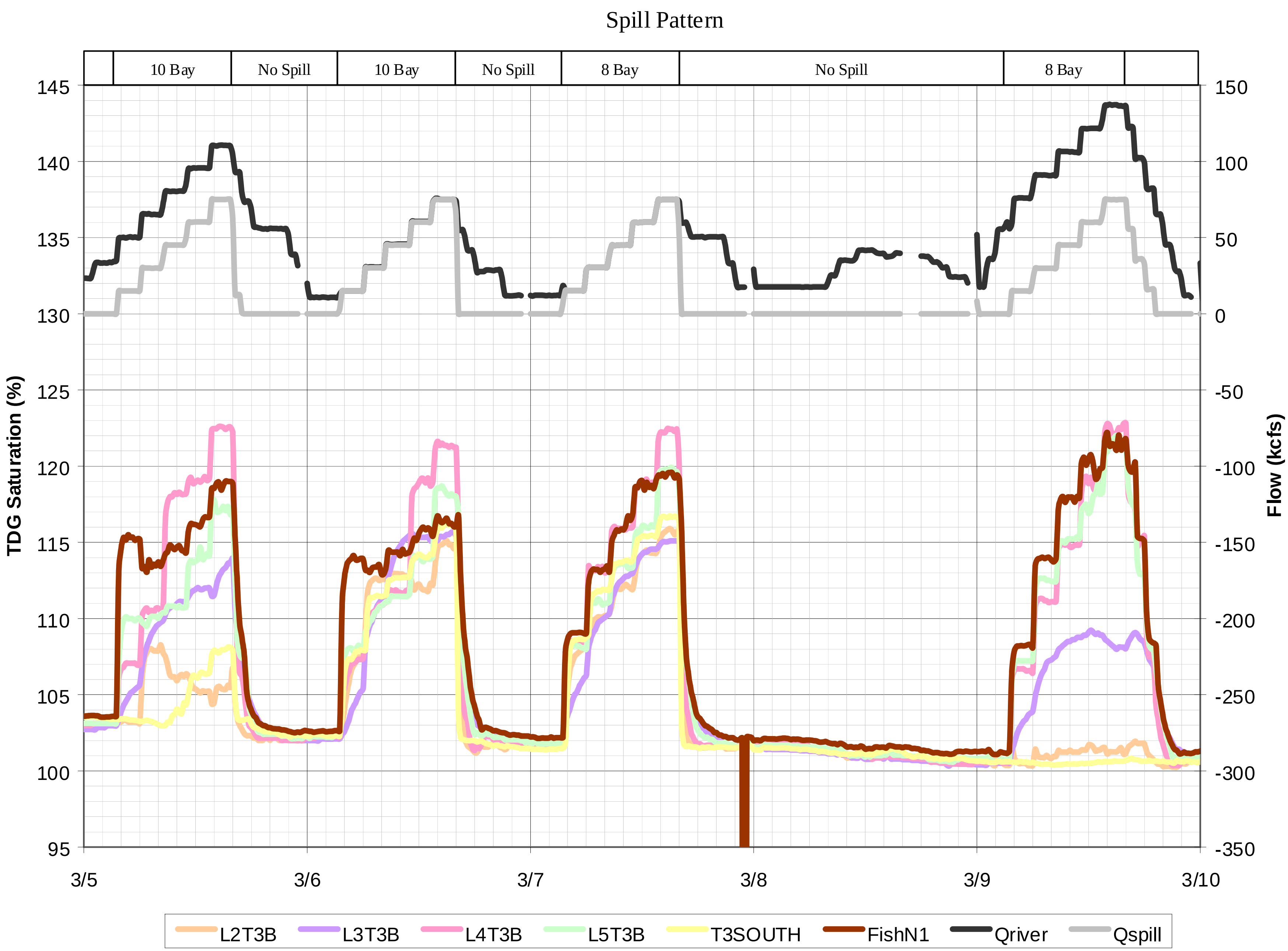

Figure 12. TDG Saturation along Transect T3, March 1998

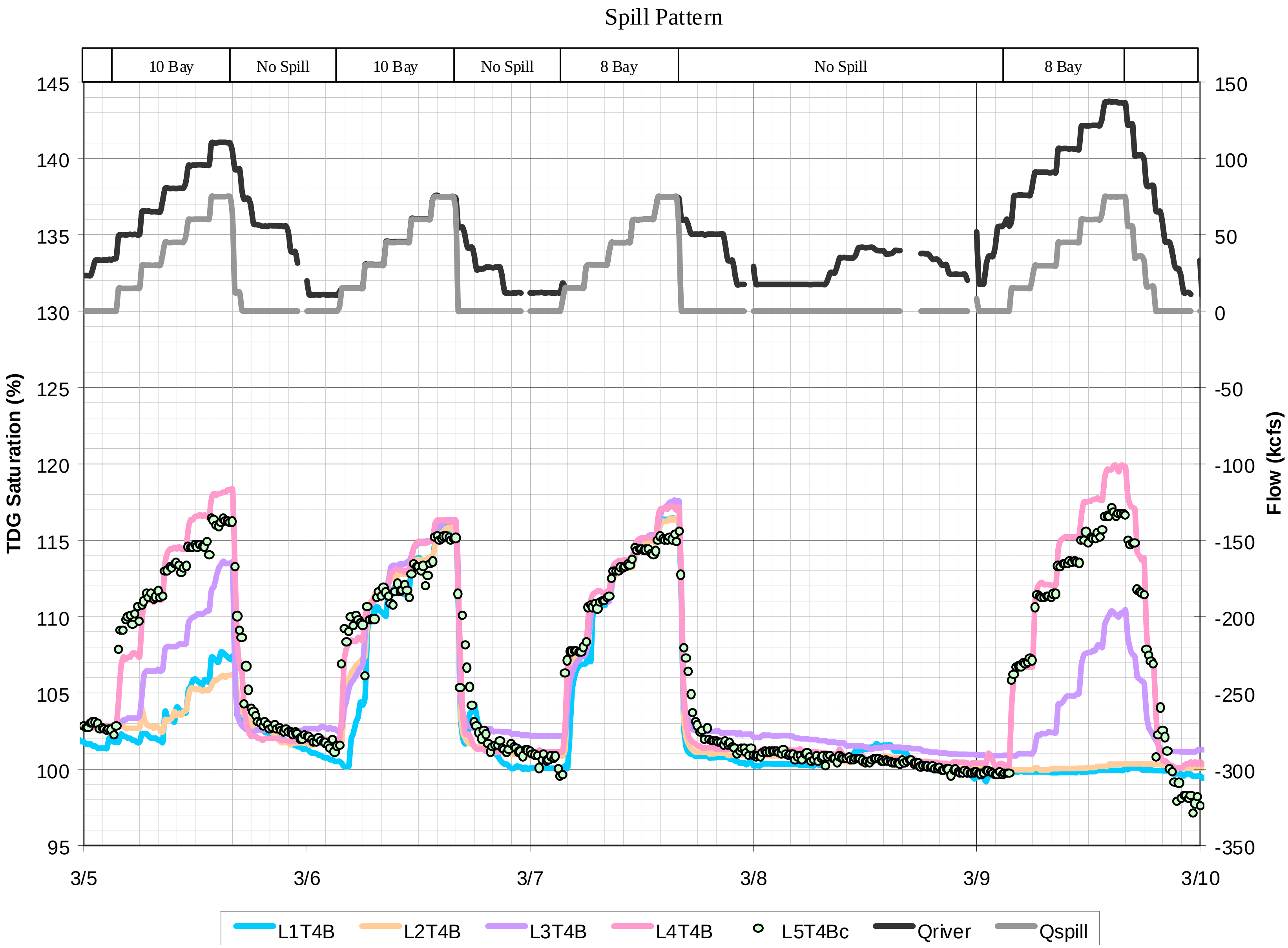

Figure 13. TDG Saturation along Transect T4, March 1998

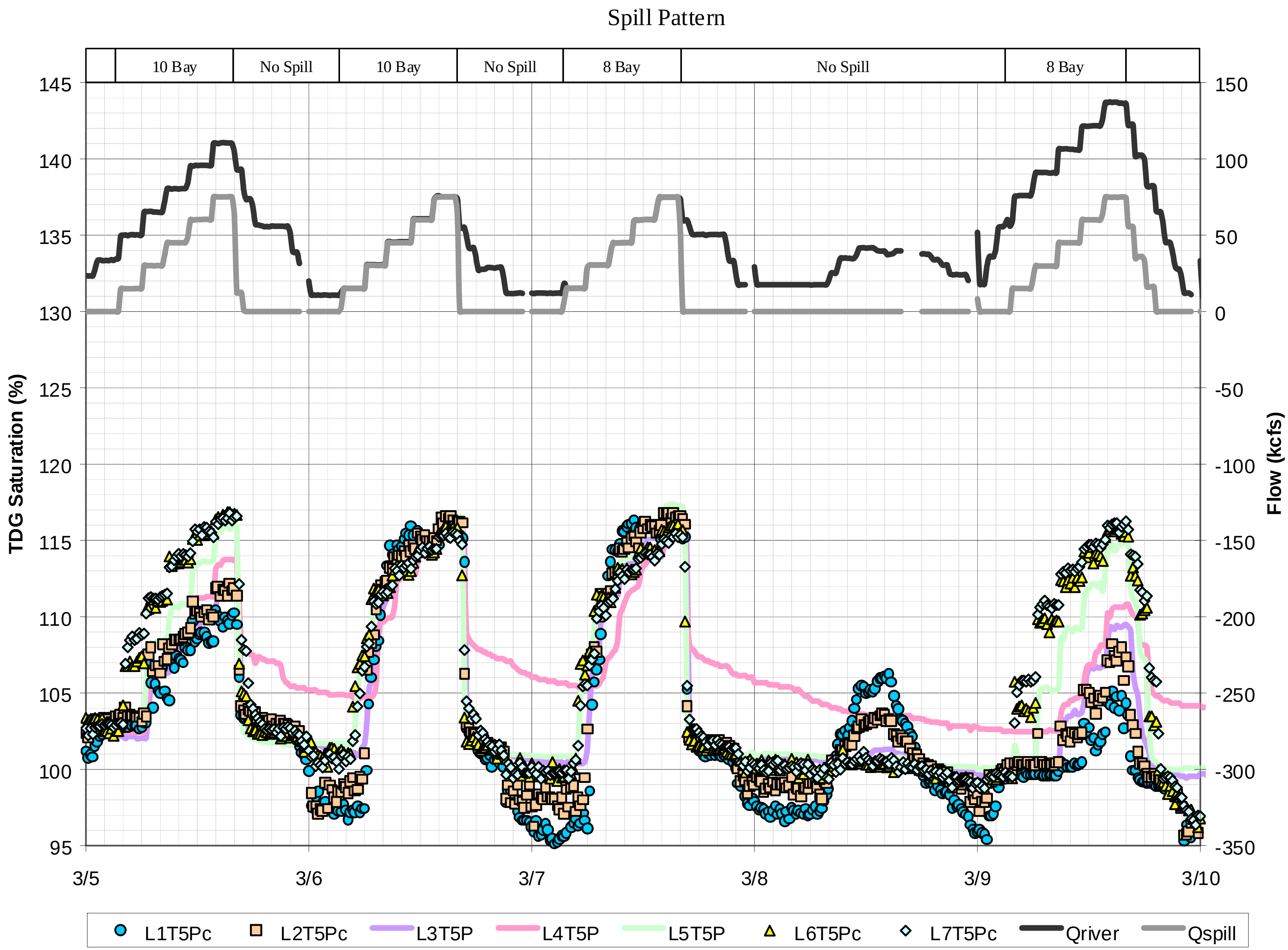

Figure 14. TDG Saturation along Transect T5, March 1998

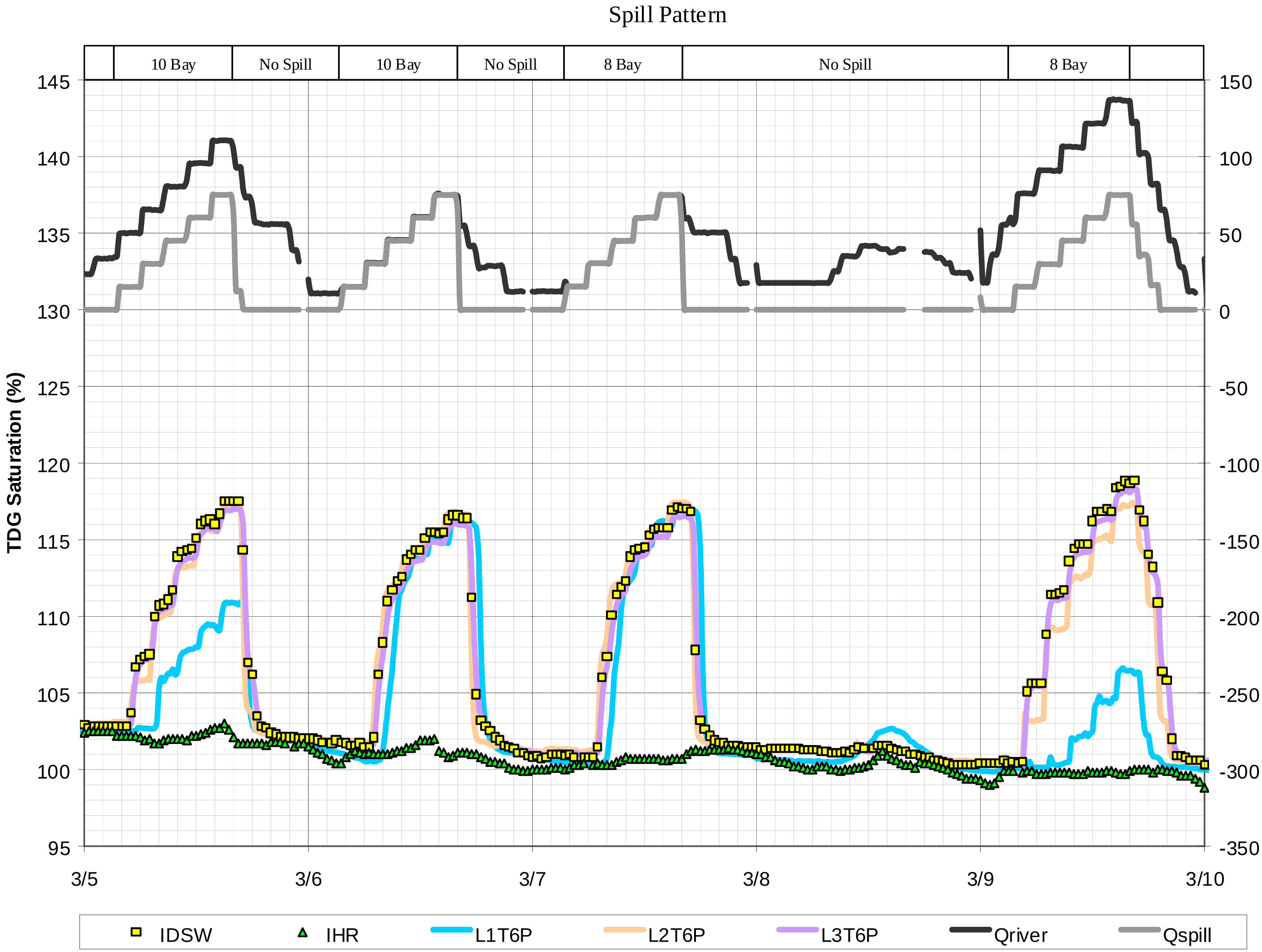

Figure 15. TDG Saturation along Transect T6, March 1998

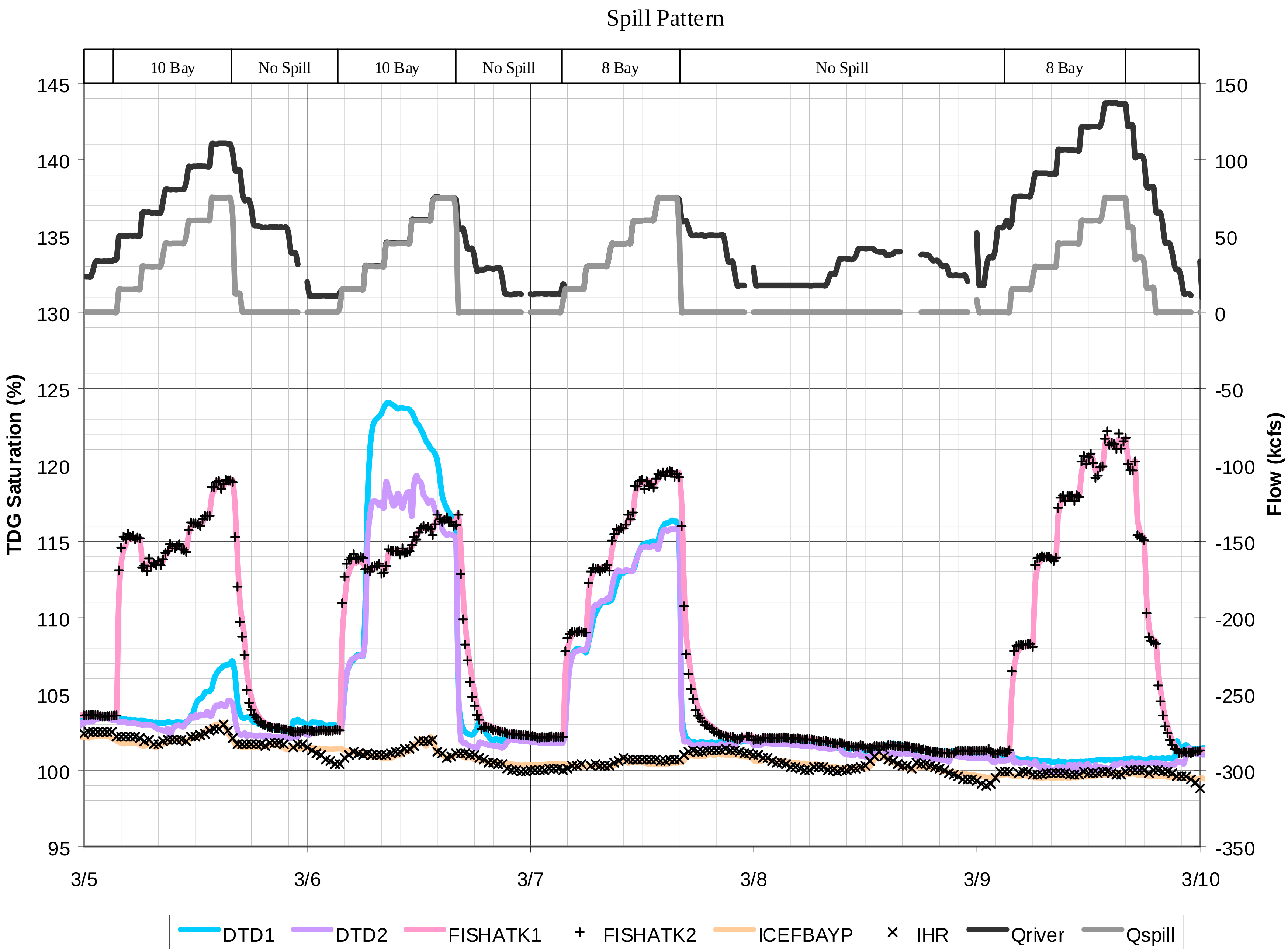

Figure 16. TDG Saturation along the Auxiliary Monitors, March 1998

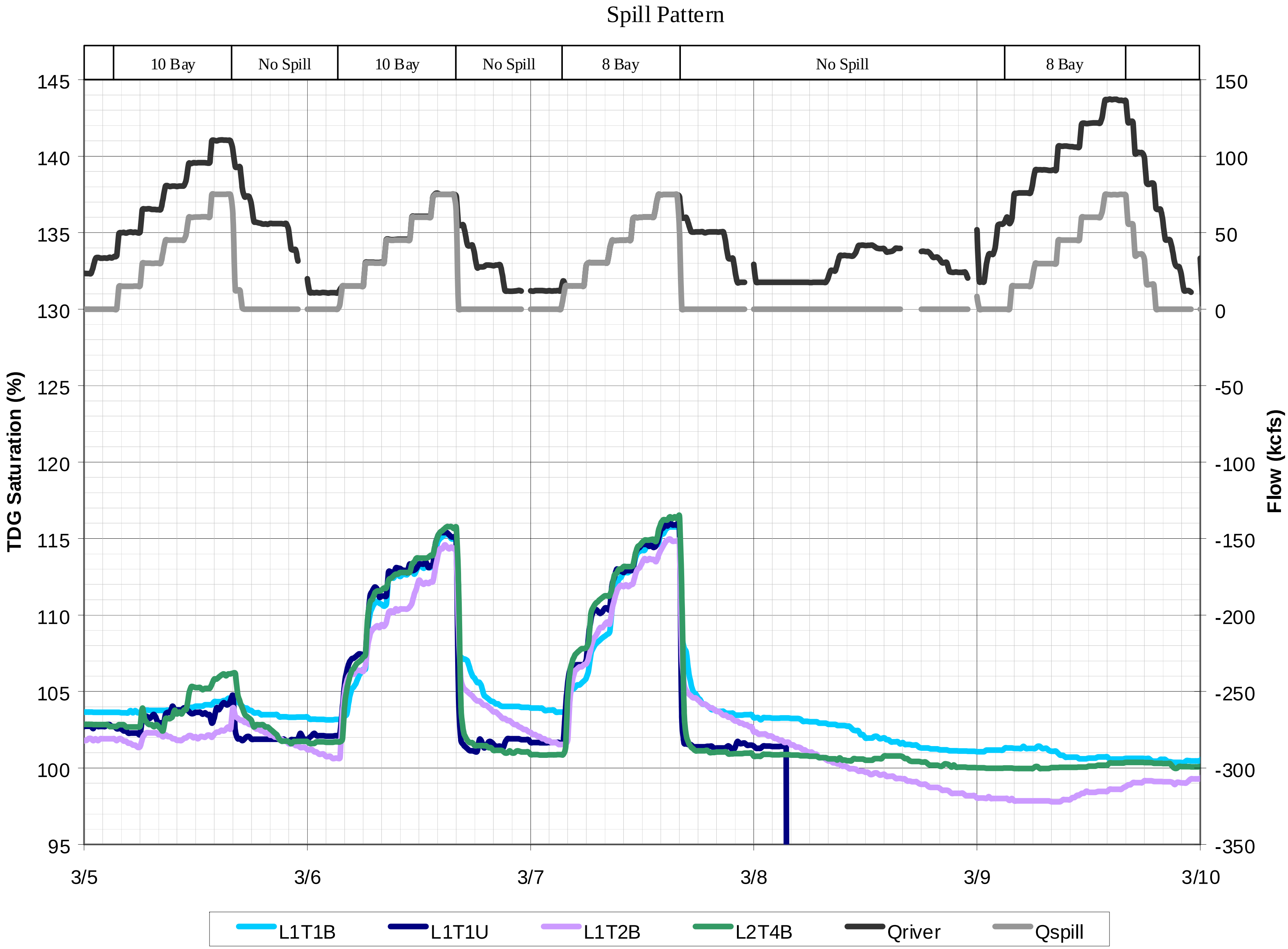

Figure 17. TDG Saturation along Longitudinal Profile, L1, March 1998

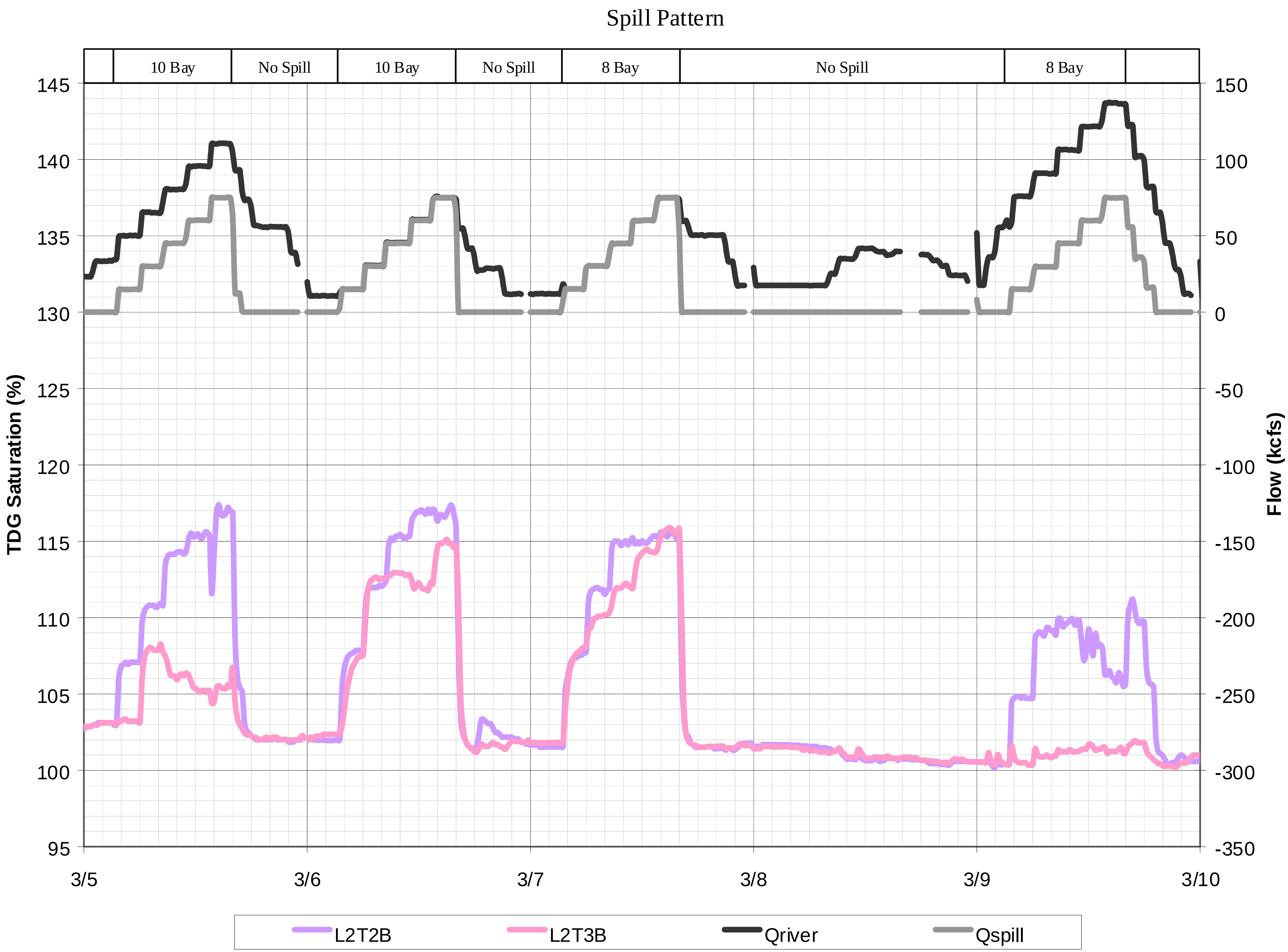

Figure 18. TDG Saturation along Longitudinal Profile L2, March 1998

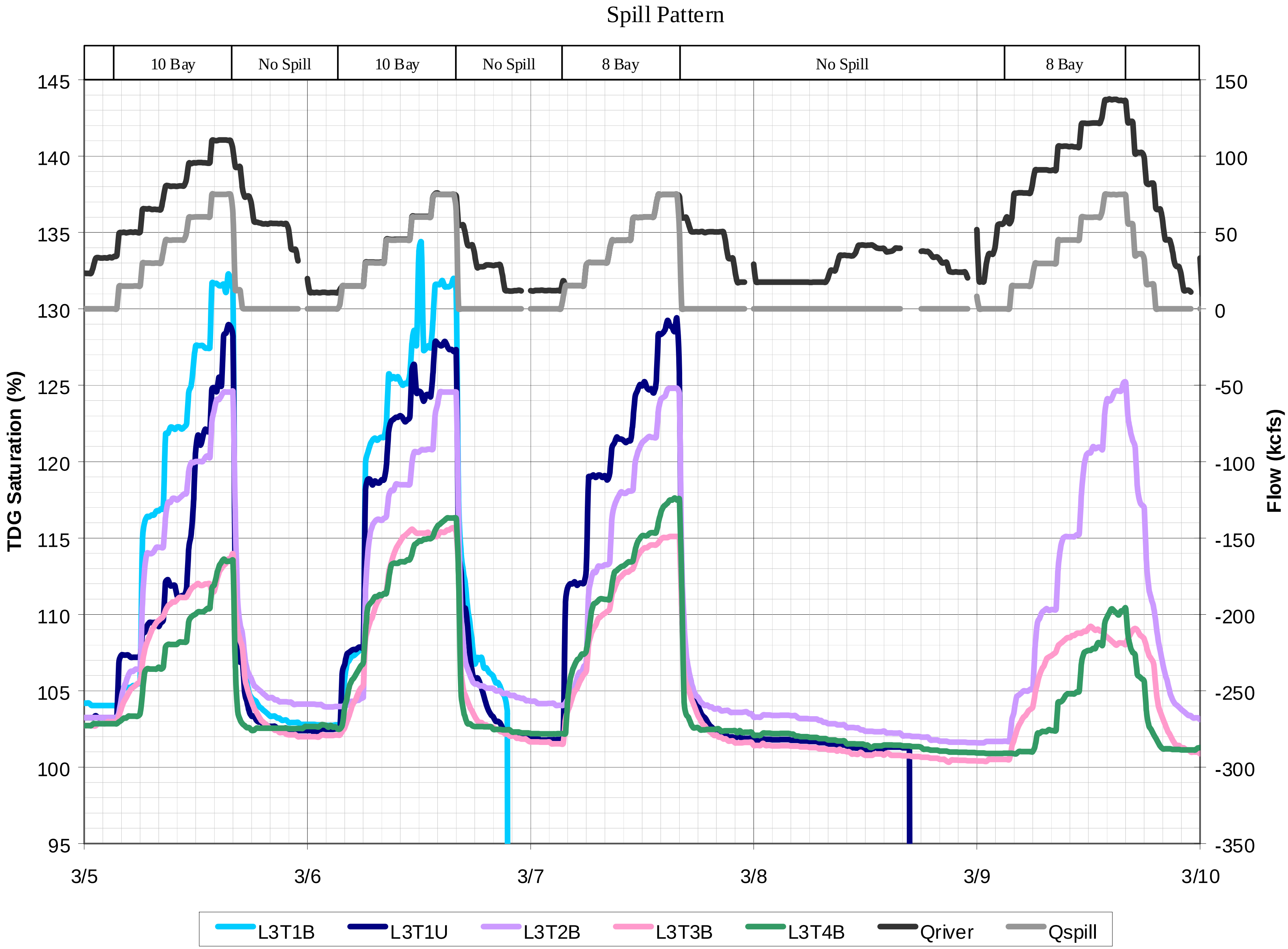

Figure 19. TDG Saturation along Longitudinal Profile L3, March 1998

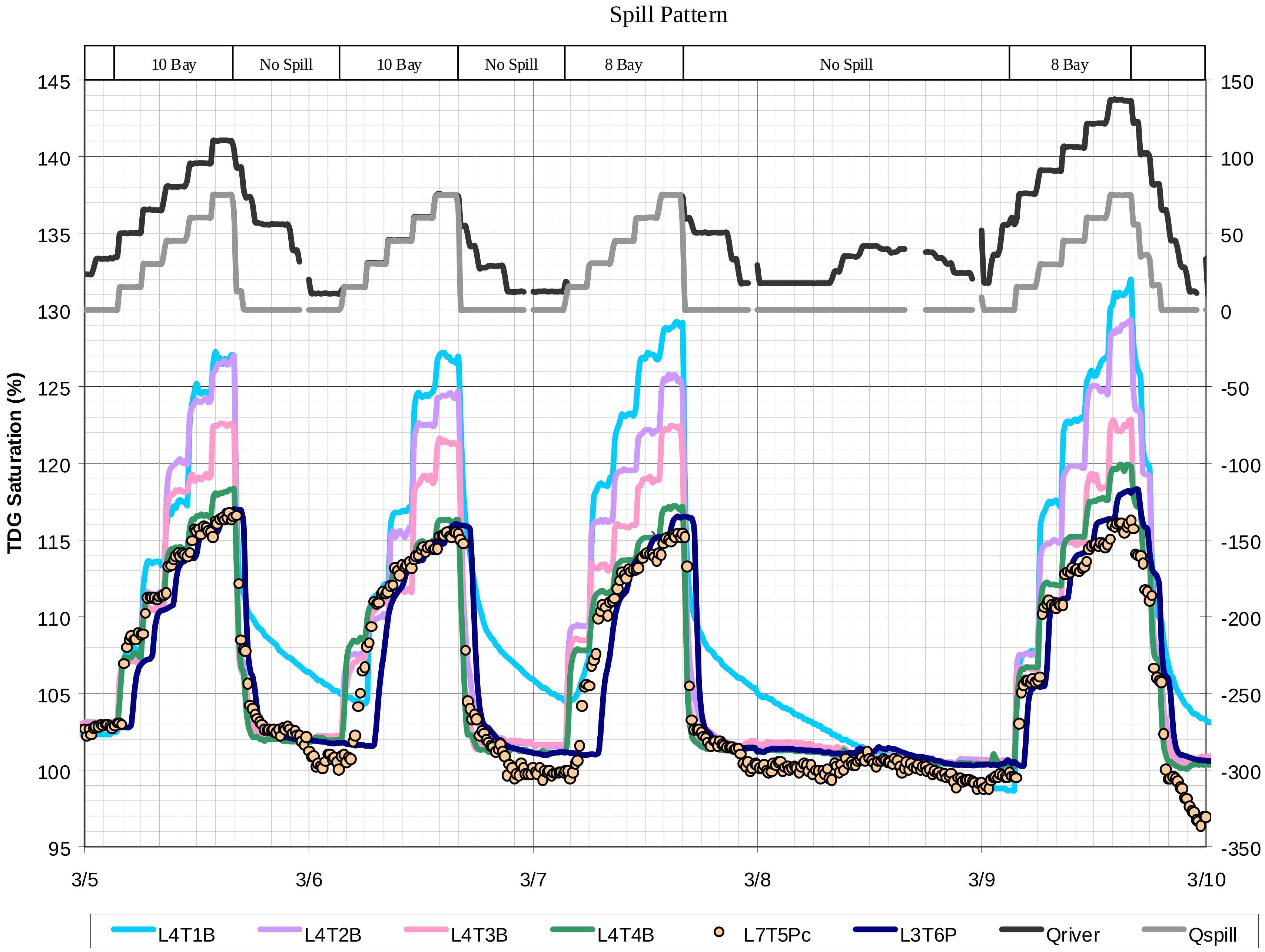

Figure 20. TDG Saturation along Longitudinal Profile L4, March 1998

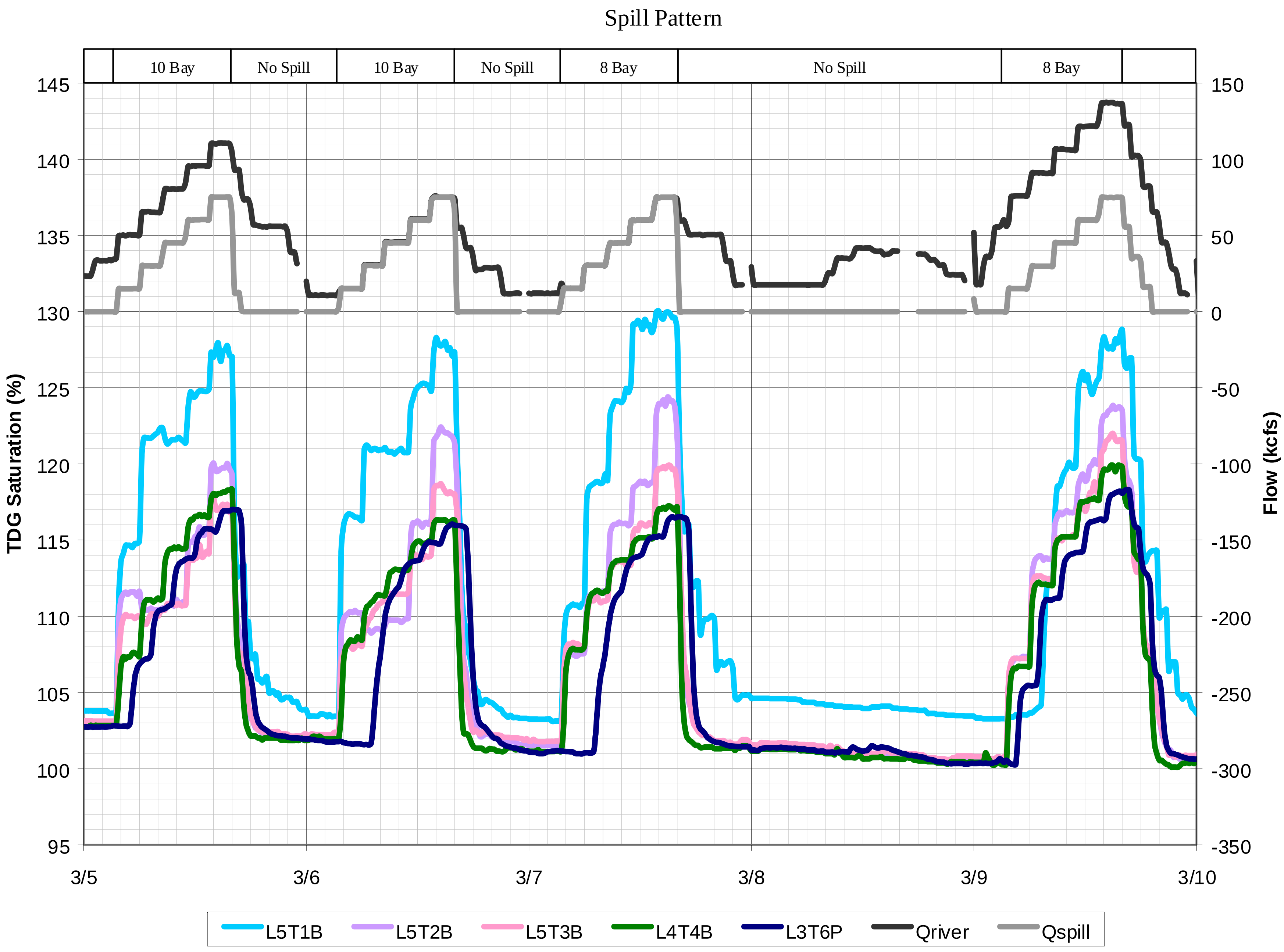

Figure 21. TDG Saturation along Longitudinal Profile L5, March 1998

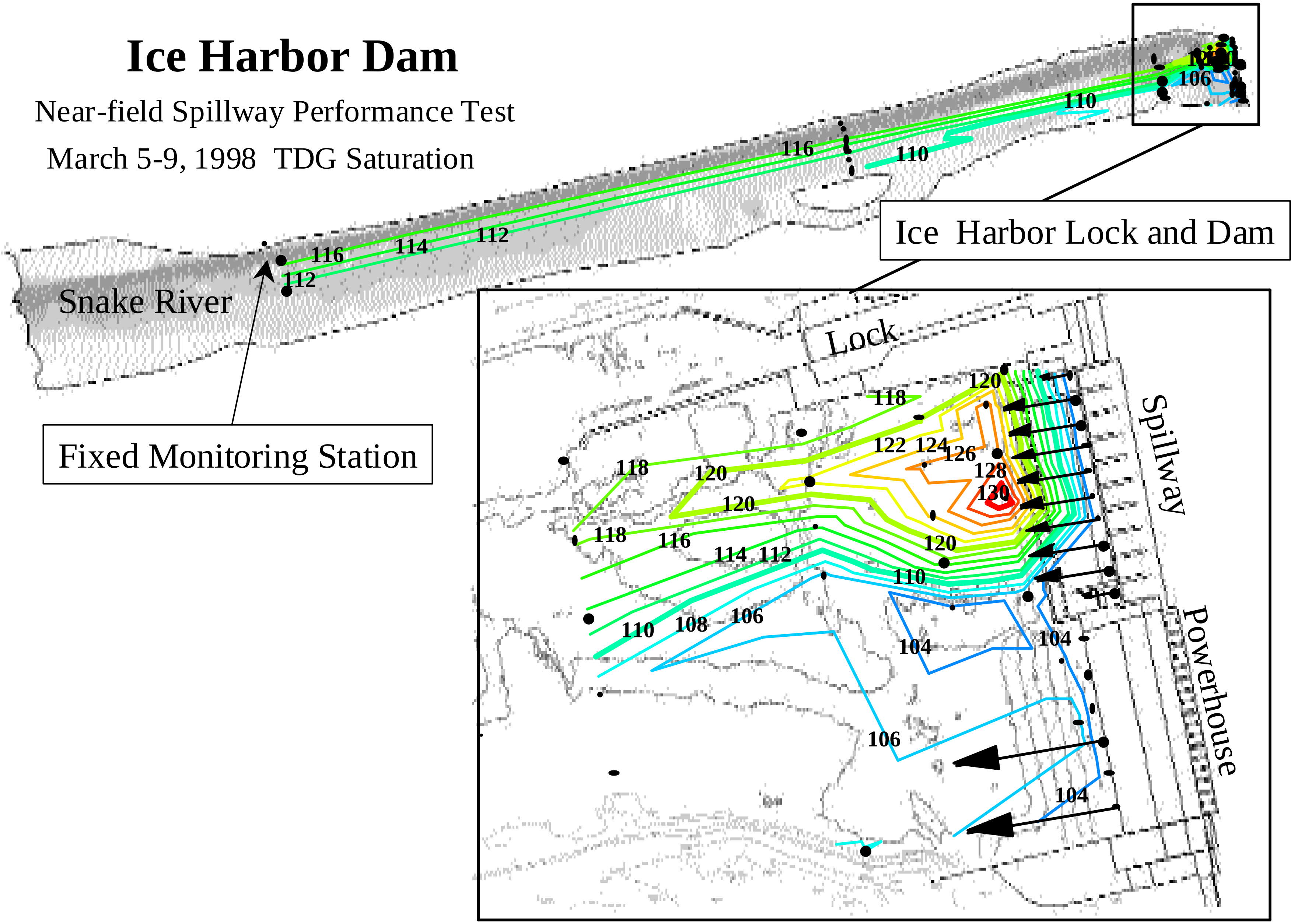

Figure22. March 5, 1998, 10-Bay Pattern, Qspill = 75 kcfs, Qpower = 34 kcfs.

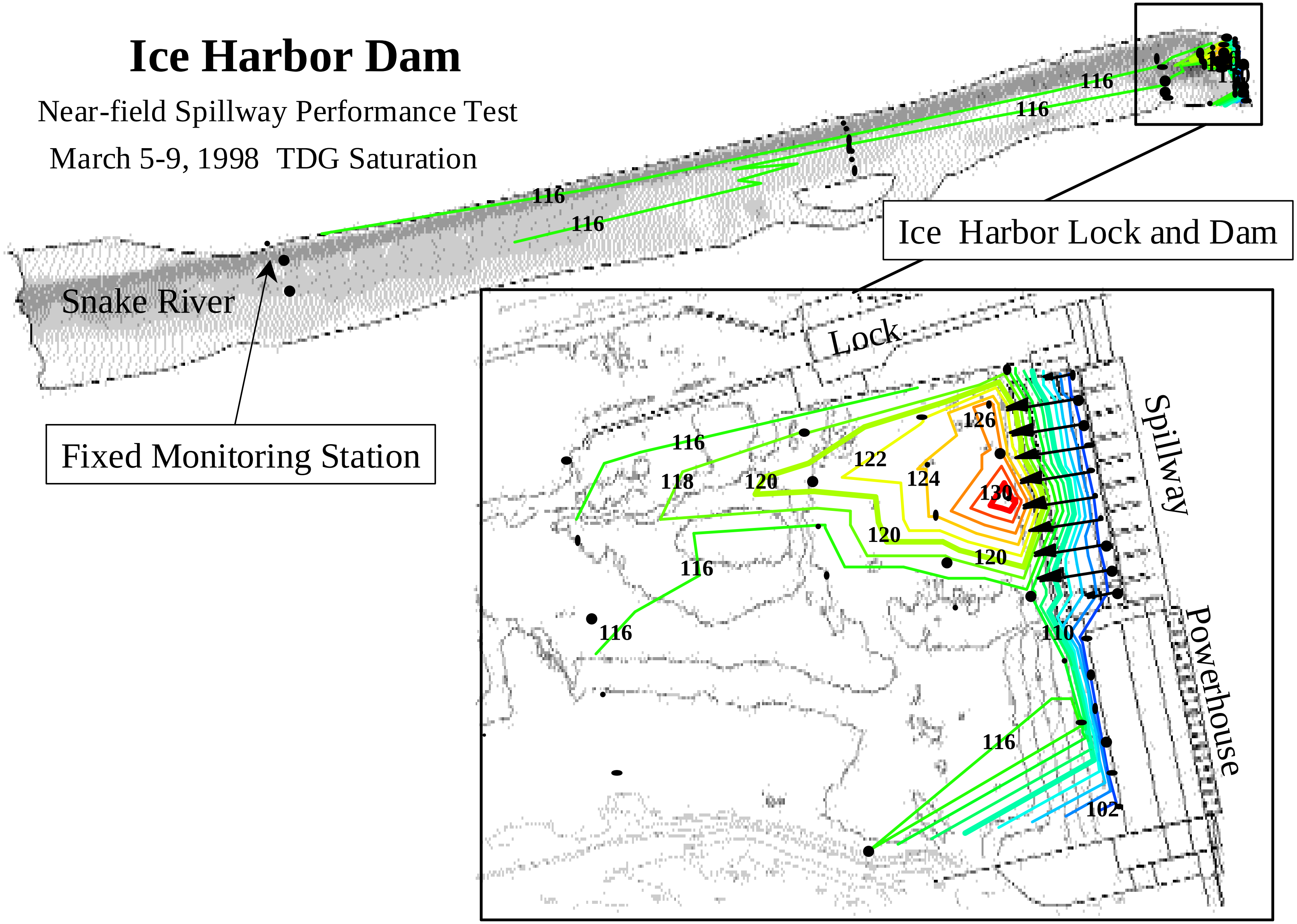

Figure 23. March 6, 1998, 10-Bay Pattern; Qspill = 75 kcfs; Qpower = 0

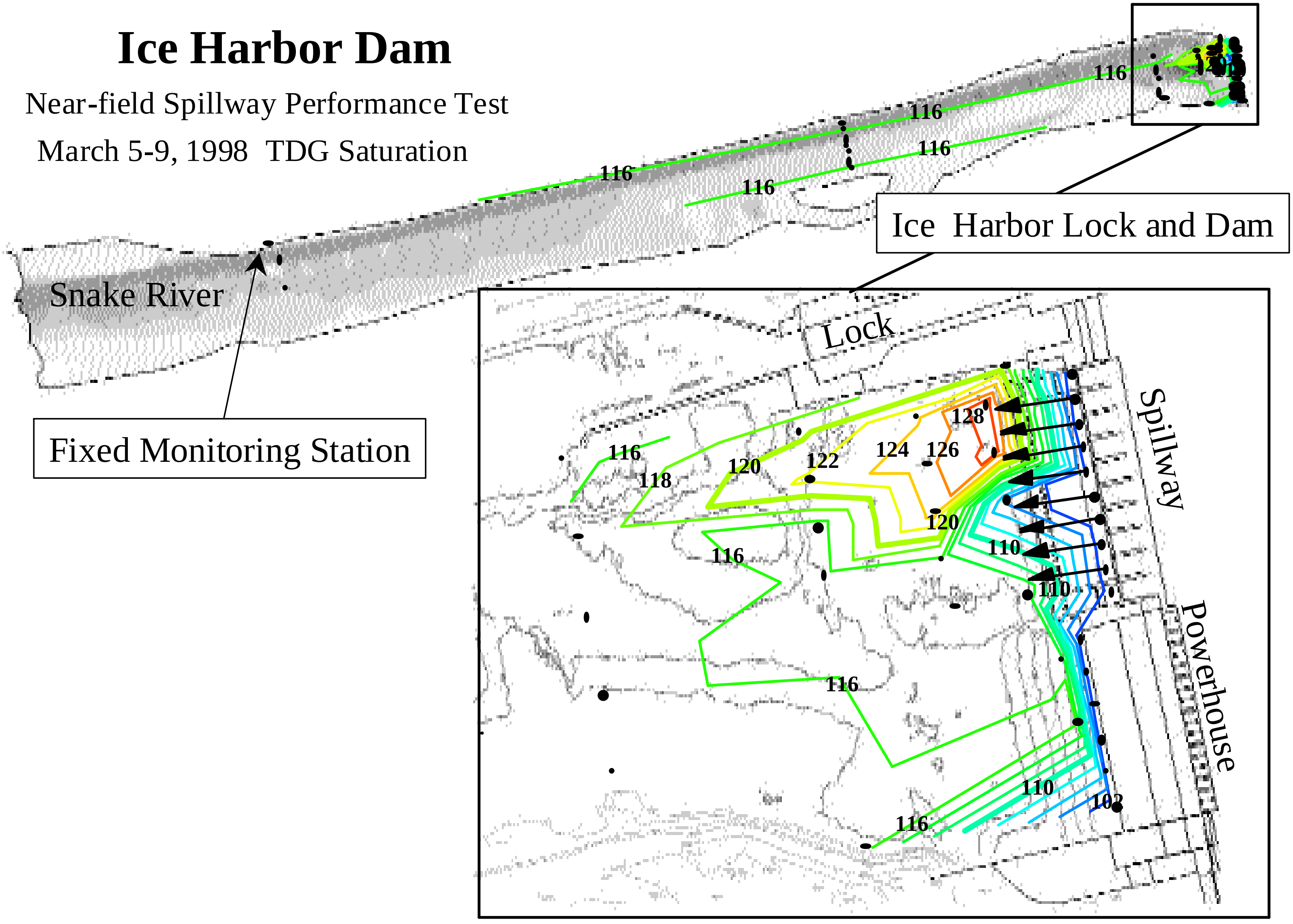

Figure 24. March 7, 1998; 8-Bay Uniform Pattern; Qspill = 75 kcfs; Qpower = 0 kcfs

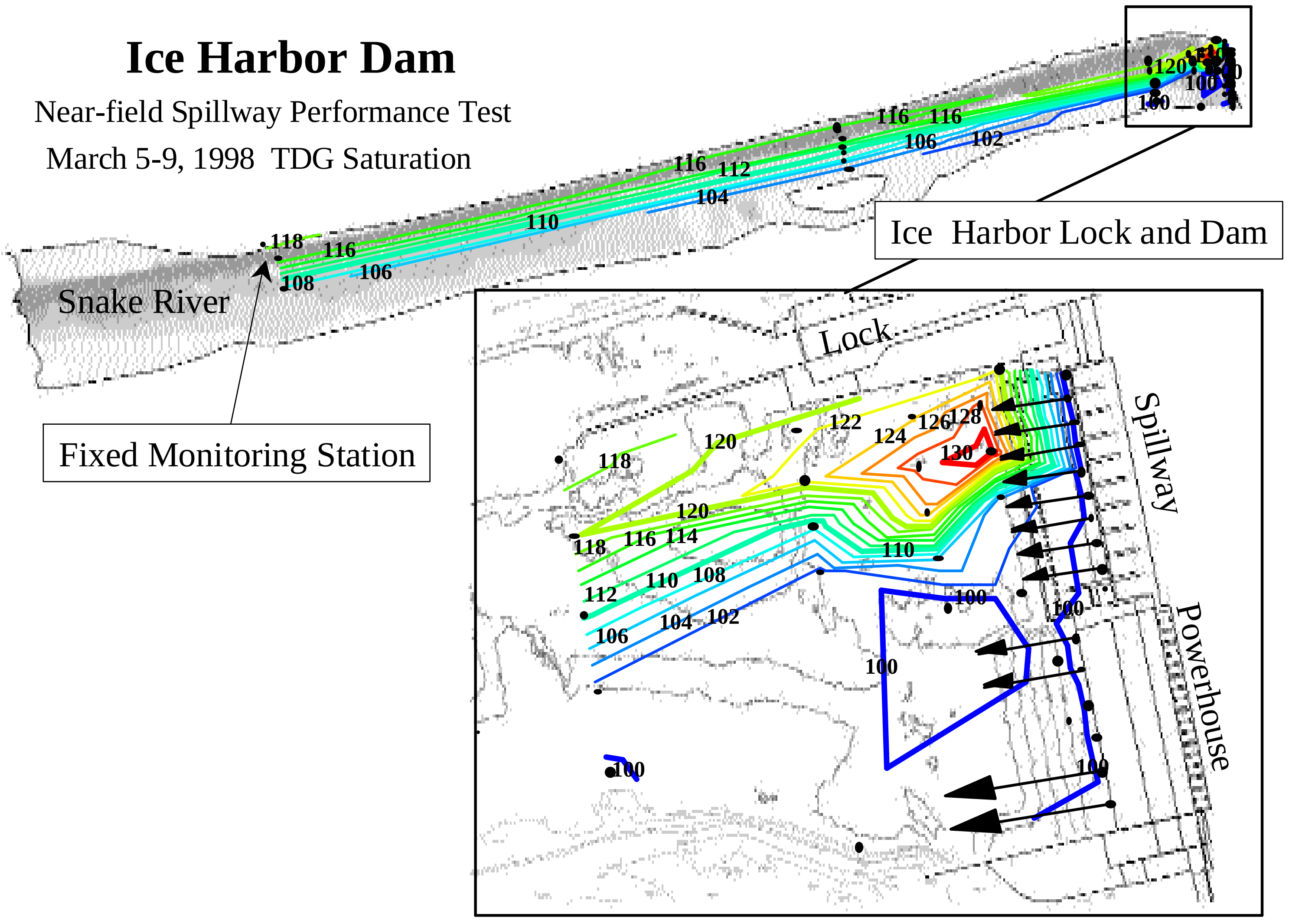

Figure 25. March 9, 1998; 8-Bay Uniform Pattern; Qspill = 75 kcfs; Qpower = 60 kcfs

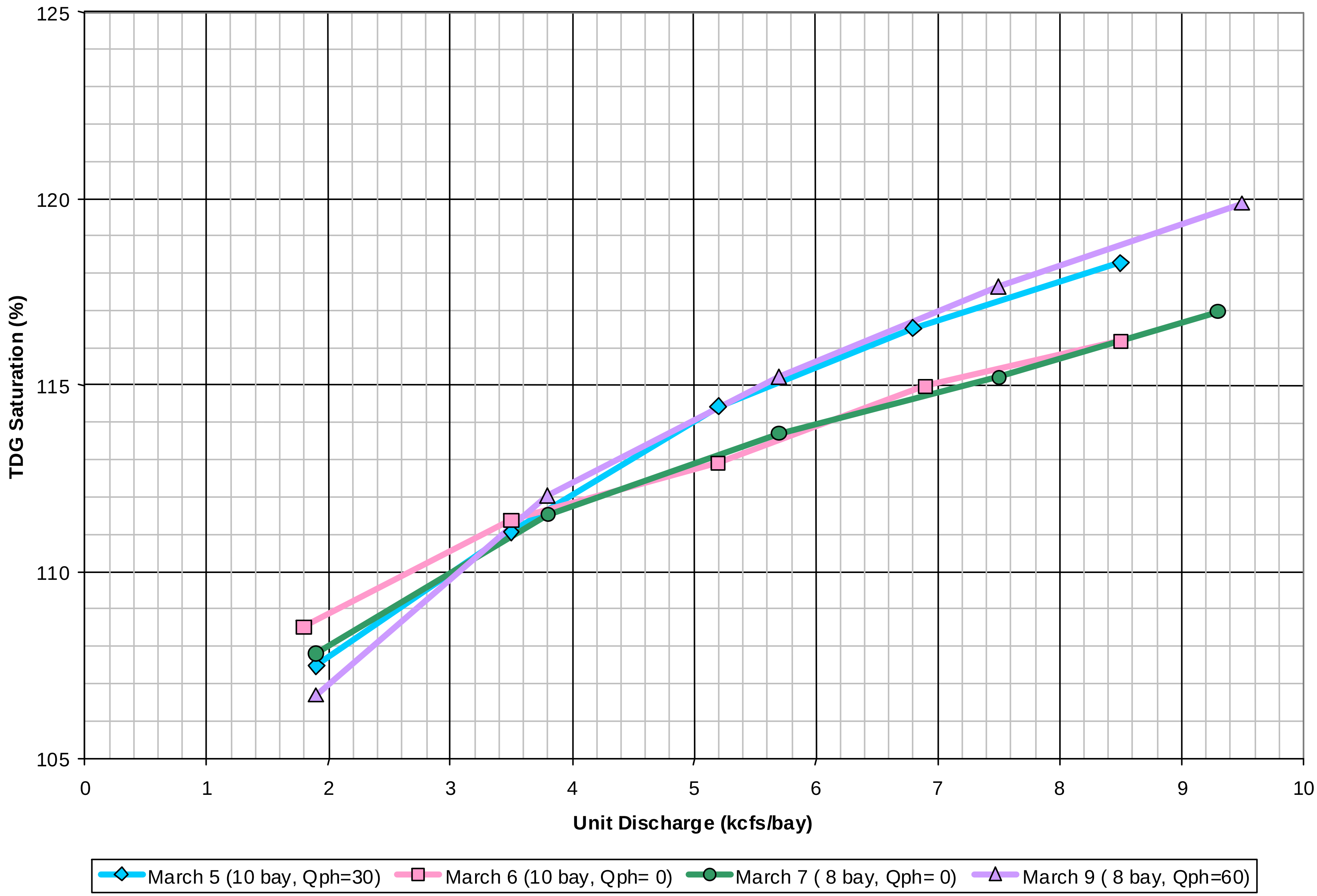

Figure 26. TDG Saturation versus Unit Spillway Discharge on Station L4T4P, March 5-9, 1998.

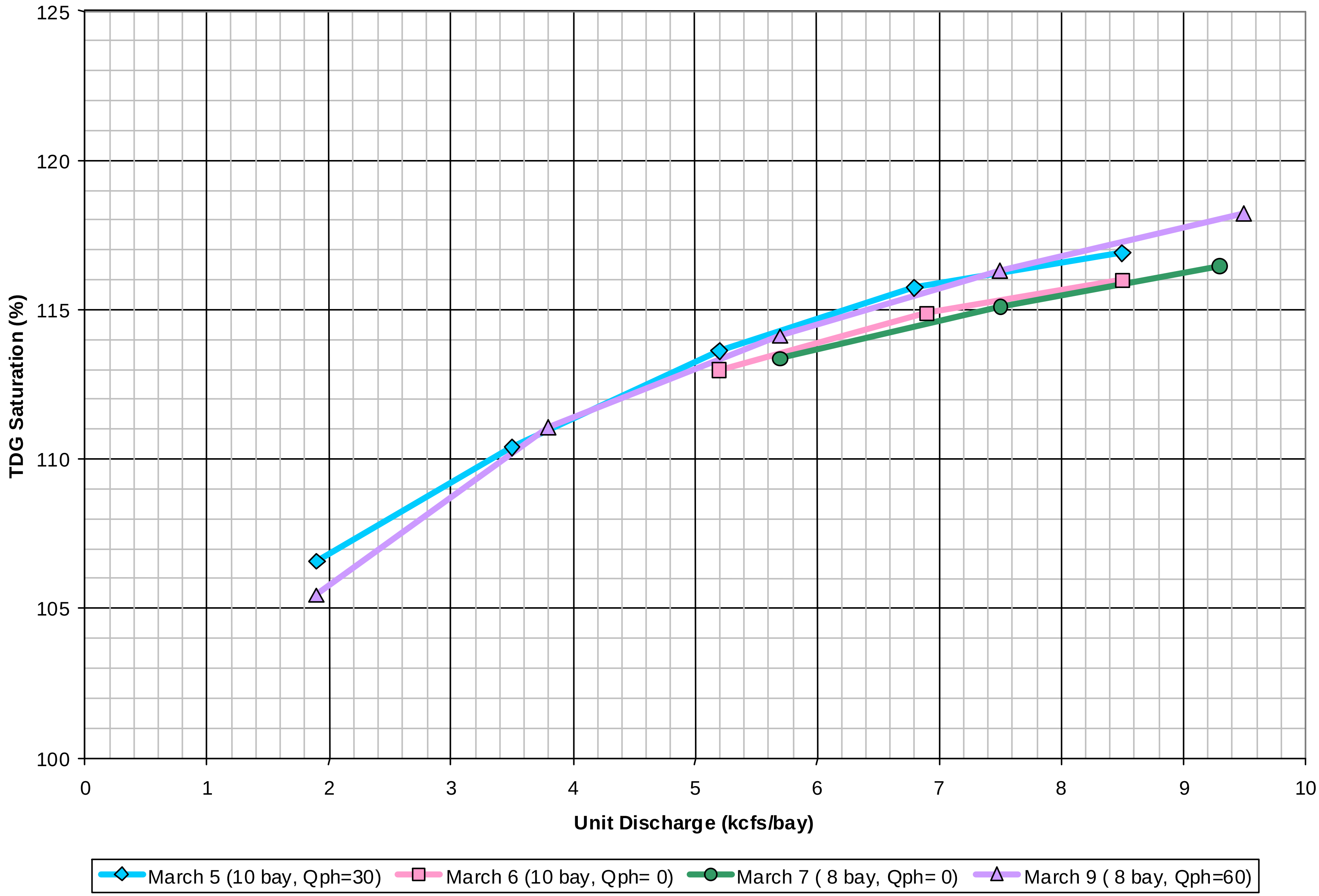

Figure 27. TDG Saturation versus Unit Spillway Discharge on Station L3T6P, March 5-9, 1998.

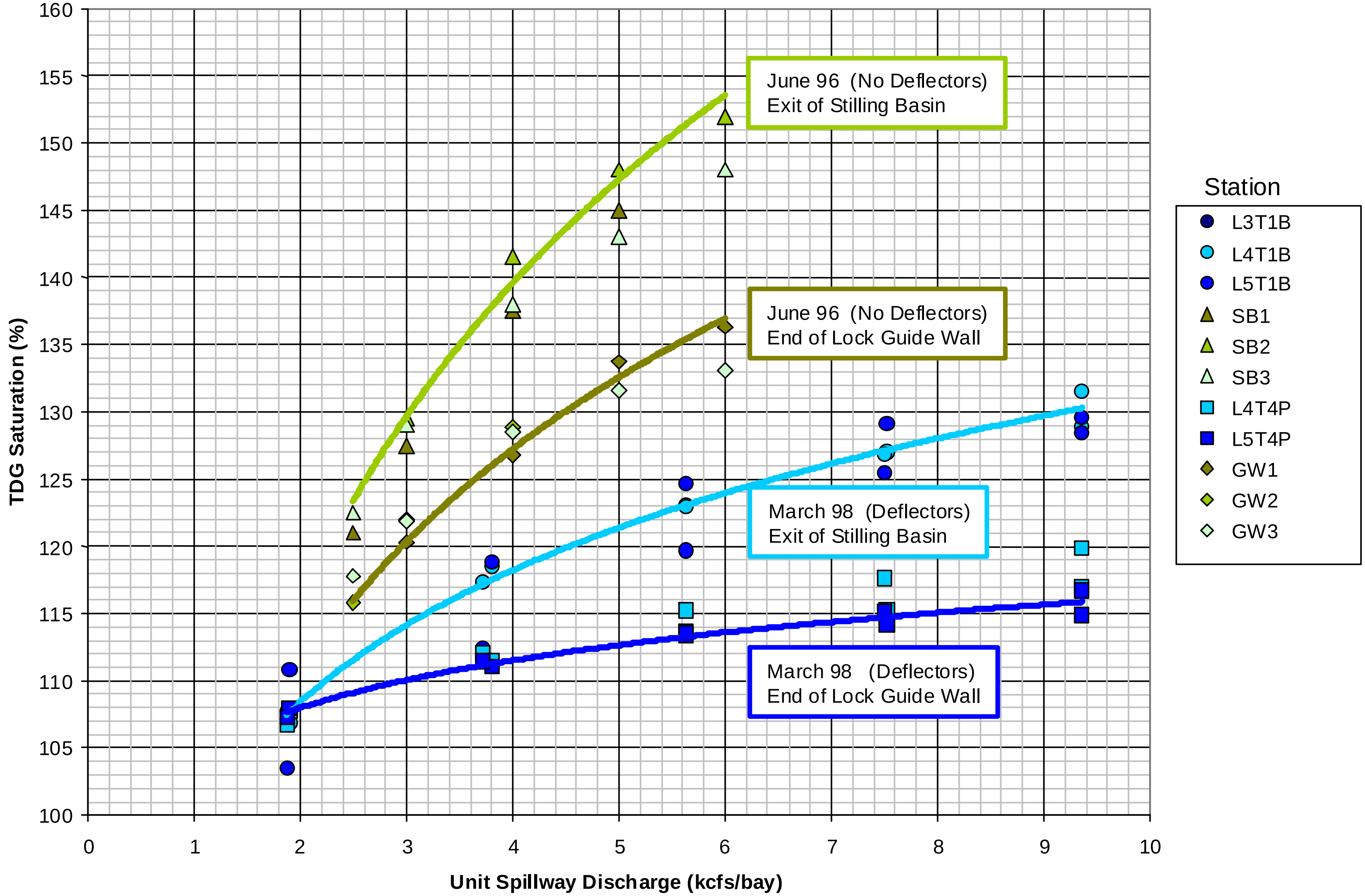

Figure 28. Pre-Deflector and Post-Deflector TDG Saturation below Ice Harbor Dam.

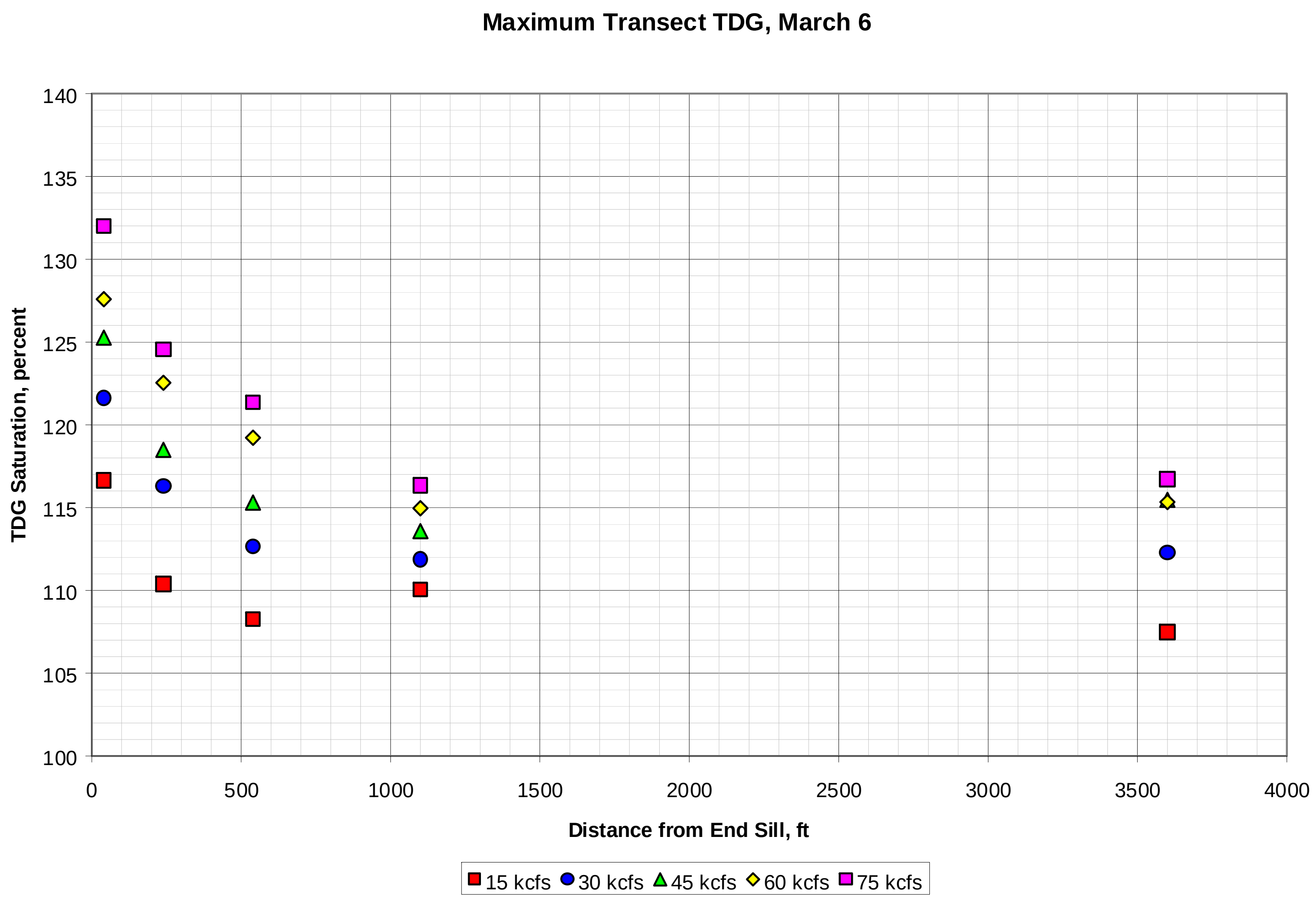

Figure 29. Peak TDG versus Discharge for Transects T1 – T5, March 6 1998

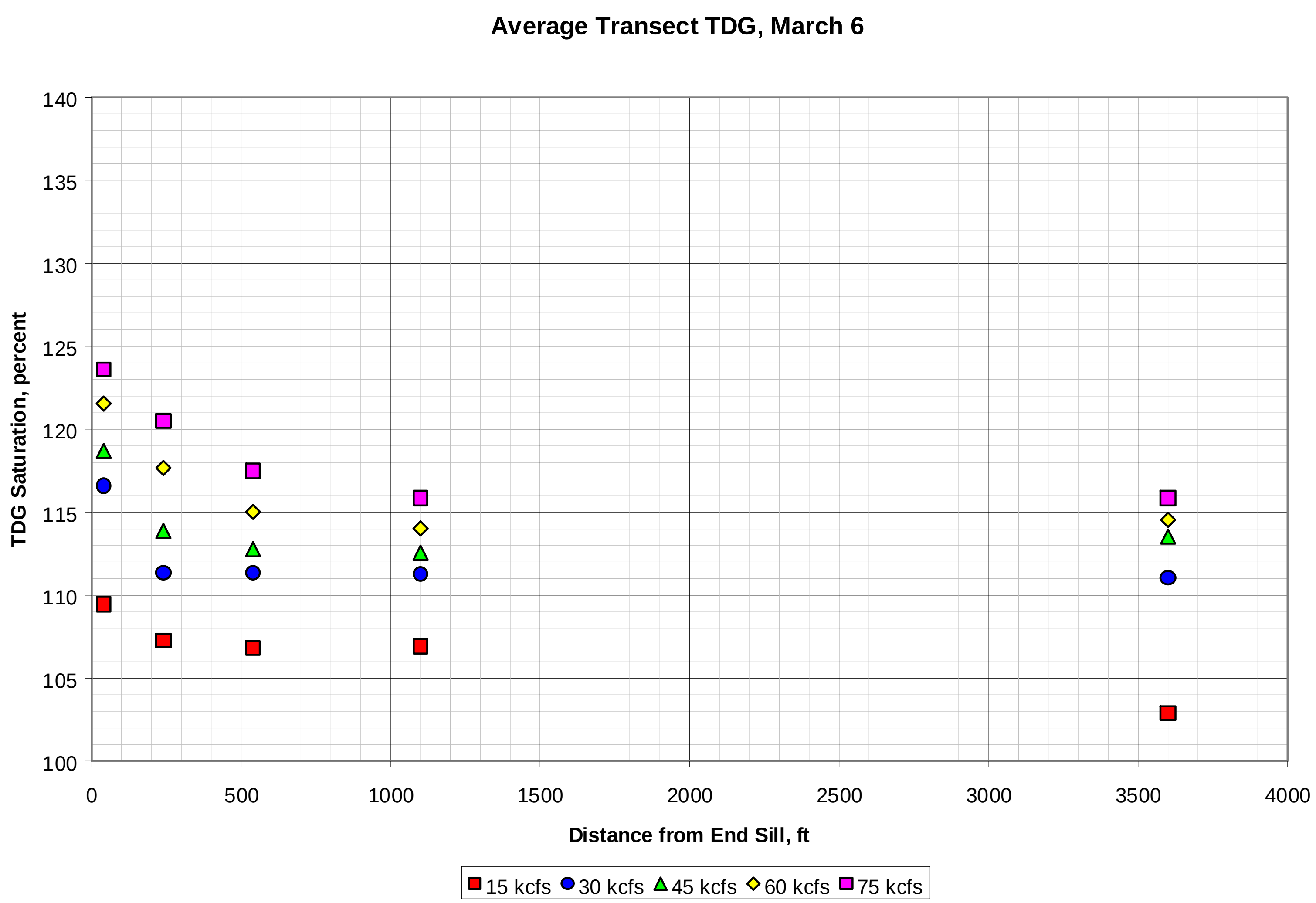

Figure 30. Average TDG versus Discharge for Transects T1 – T5, March 6, 1998

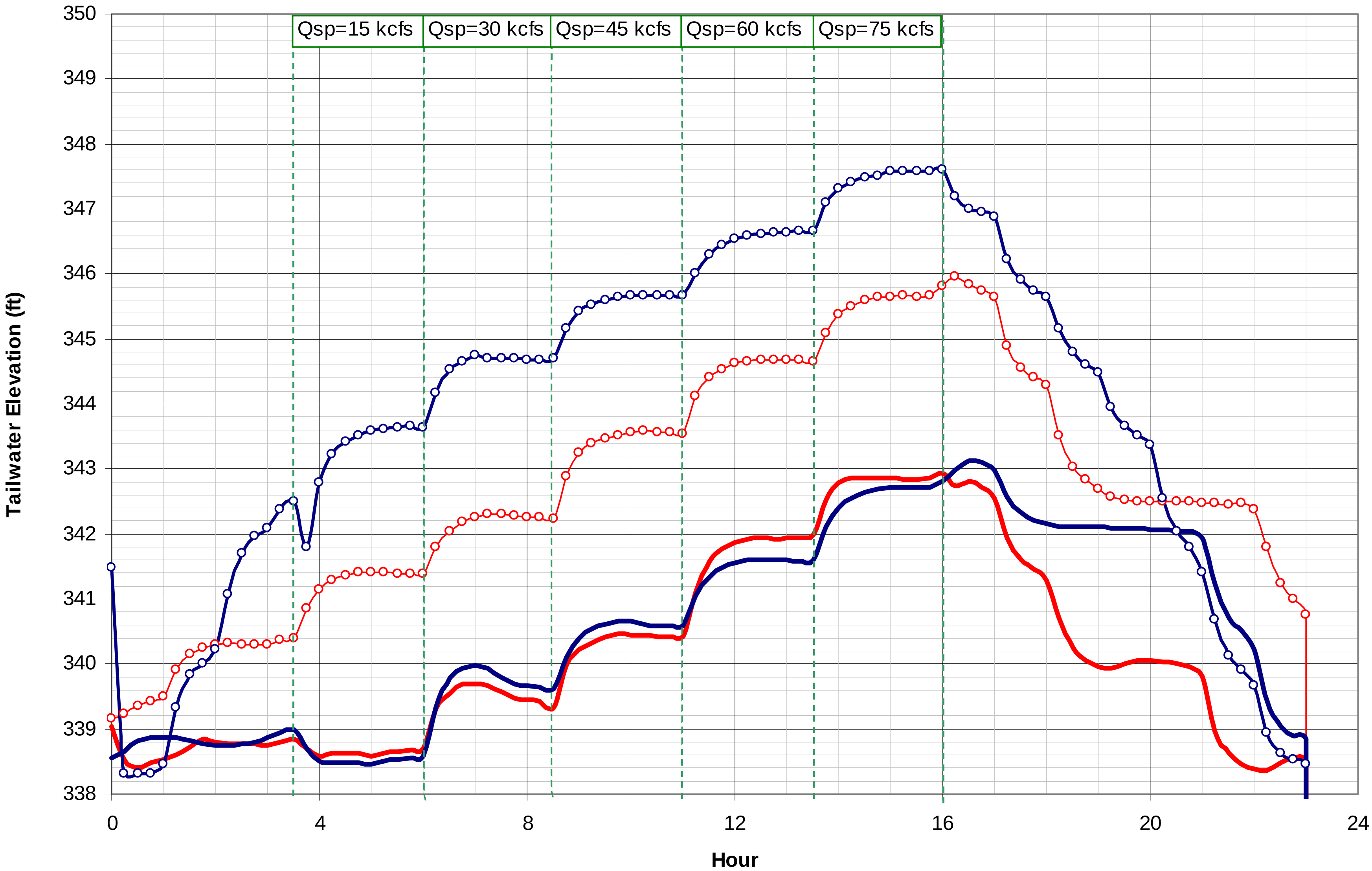

Figure 31. Tailwater Elevation at Ice Harbor Dam, March 5-9, 1998.

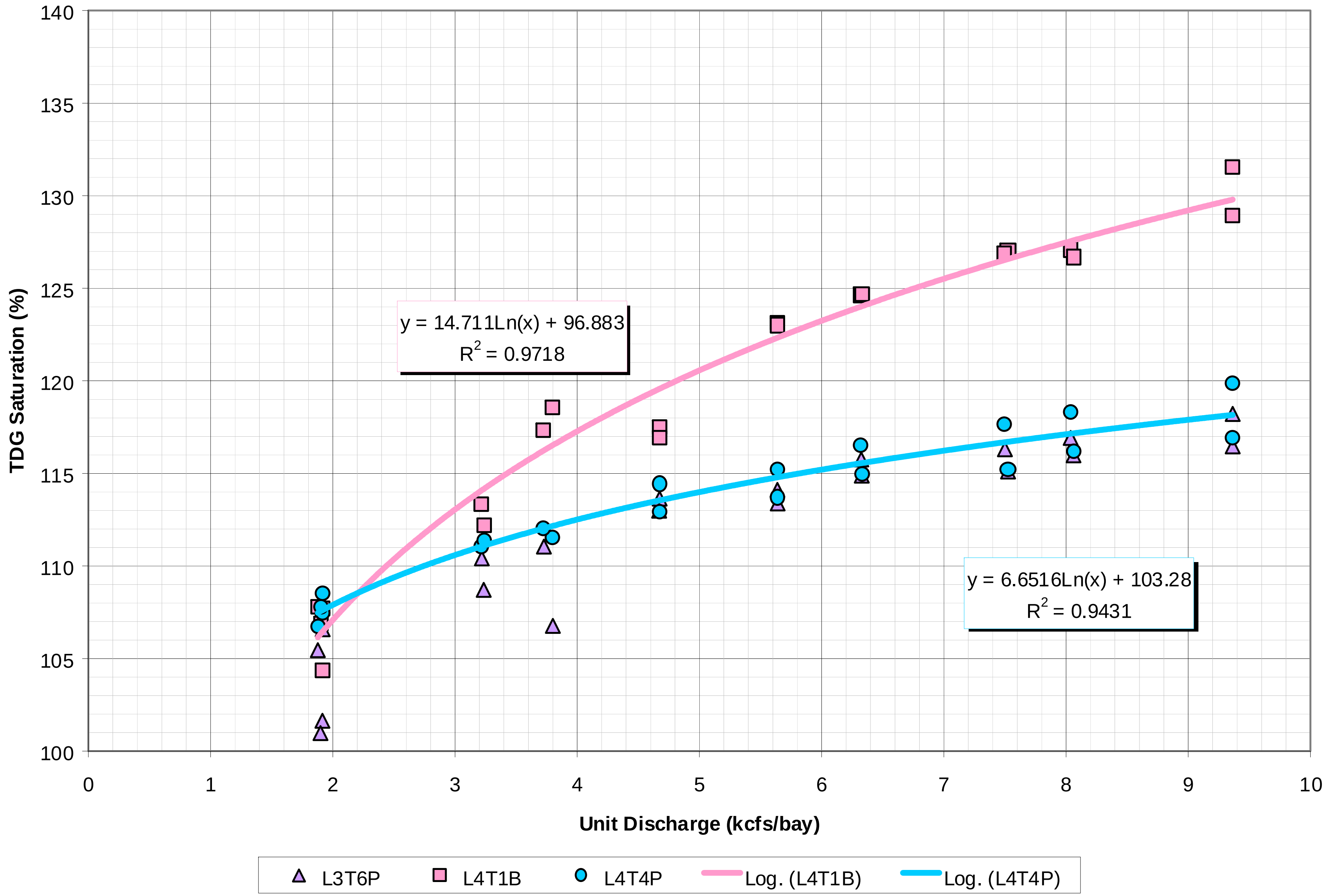

Figure 32. Total Dissolved Gas Saturation versus Unit Spillway Discharge at Stations L4T1B, L4T4P, and L3T6P, at Ice Harbor Dam, March 5-9, 1998.

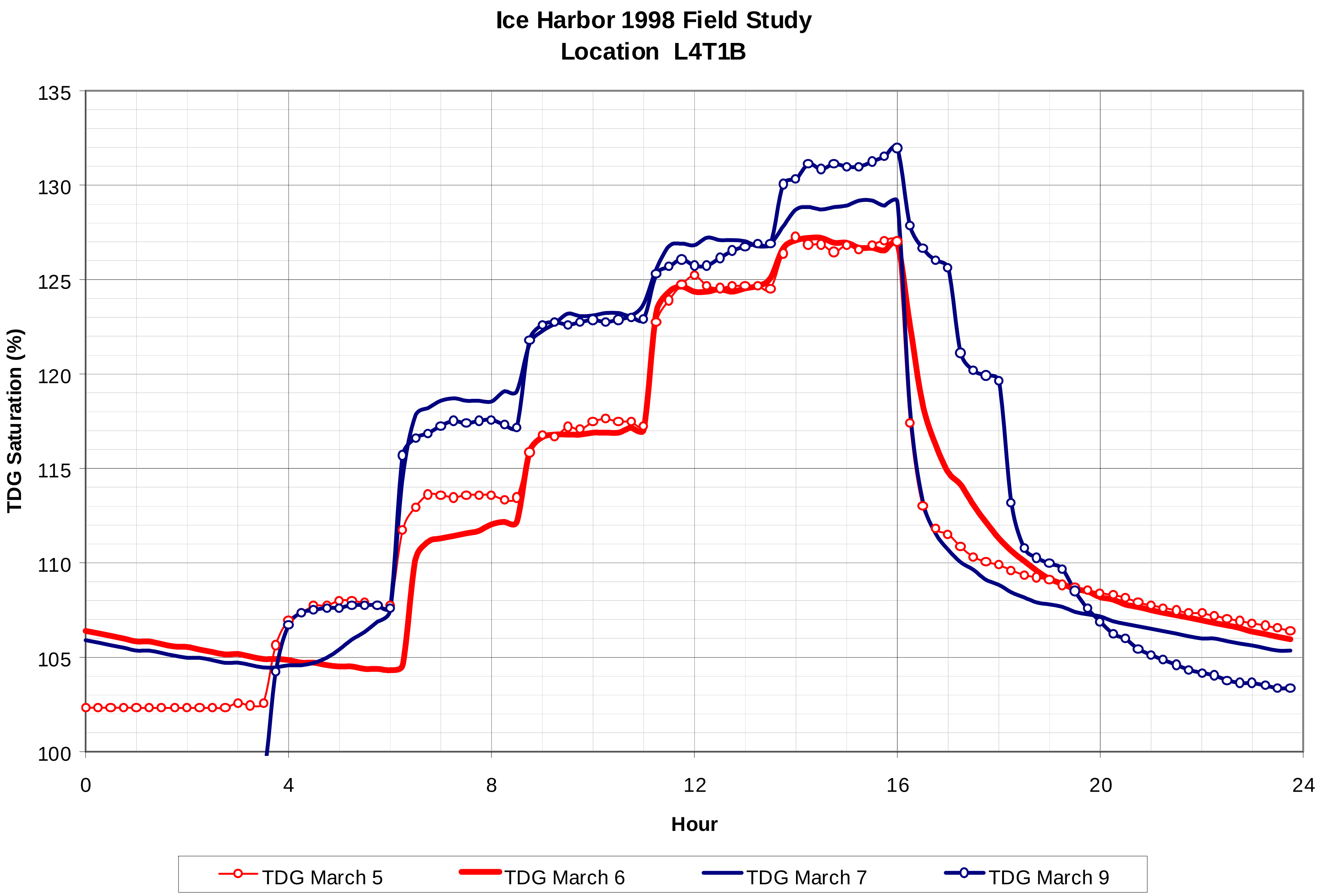

Figure 33. Total Dissolved Gas Saturation at Station L4T1B at Ice Harbor Dam, March 5-9, 1998.

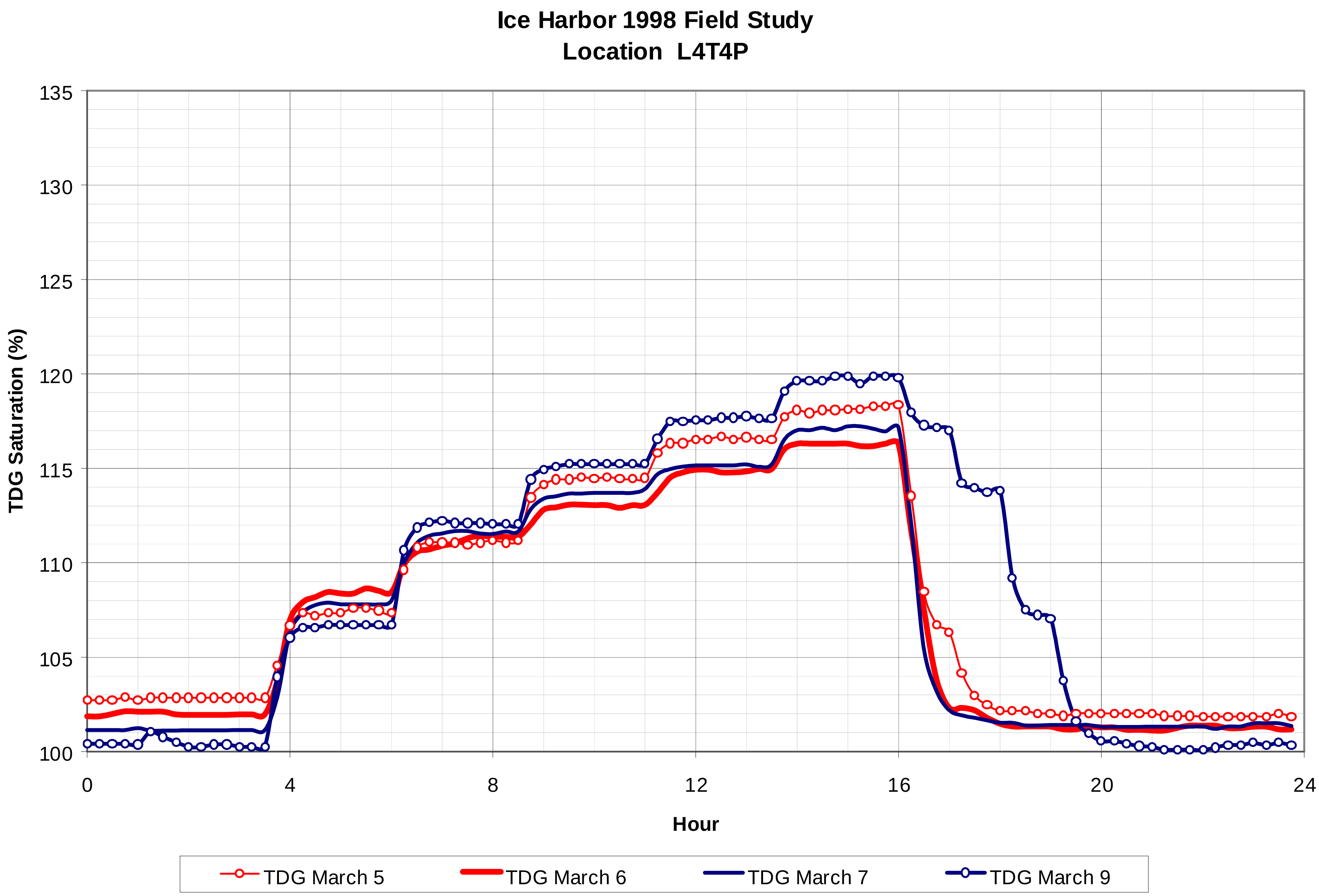

Figure 34. Total Dissolved Gas Saturation at Station L4T4P at Ice Harbor Dam, March 5-9, 1998.

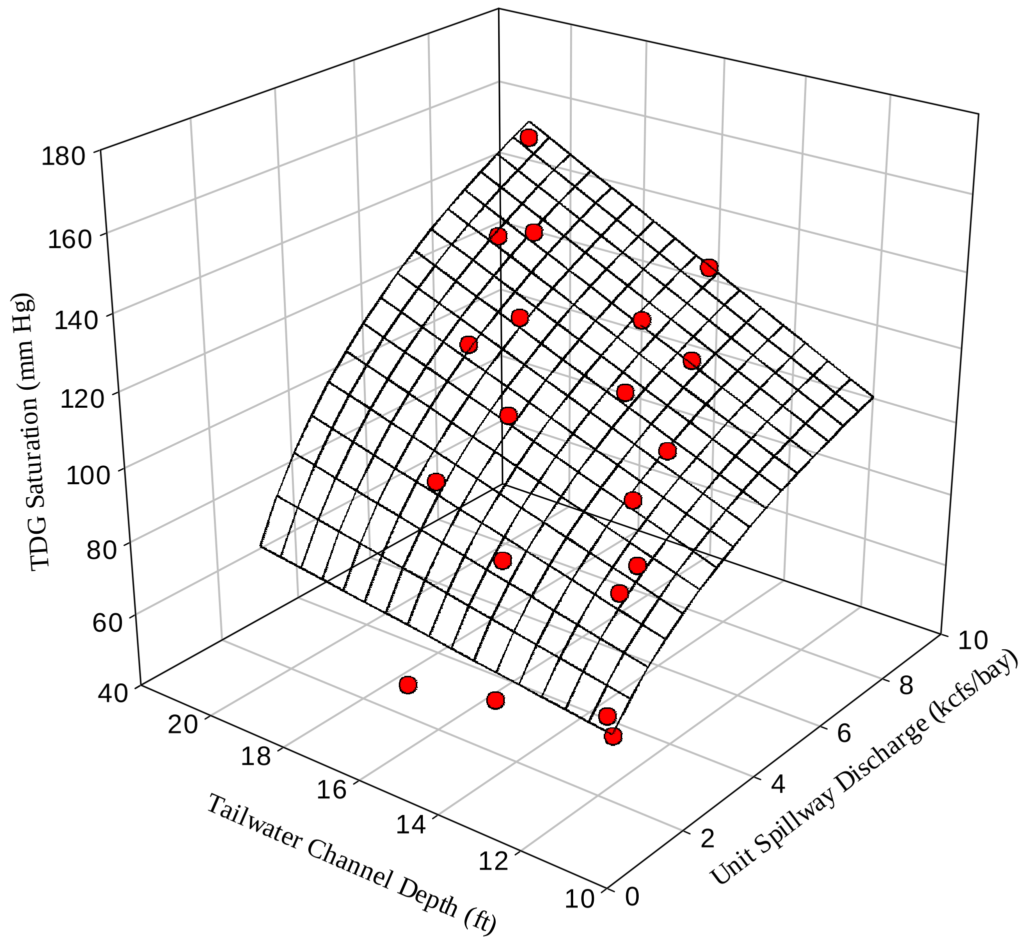

Figure 35. Total Dissolved Gas Pressure Response Surface at Station L4T4P at Ice Harbor Dam, March 5-9, 1998.

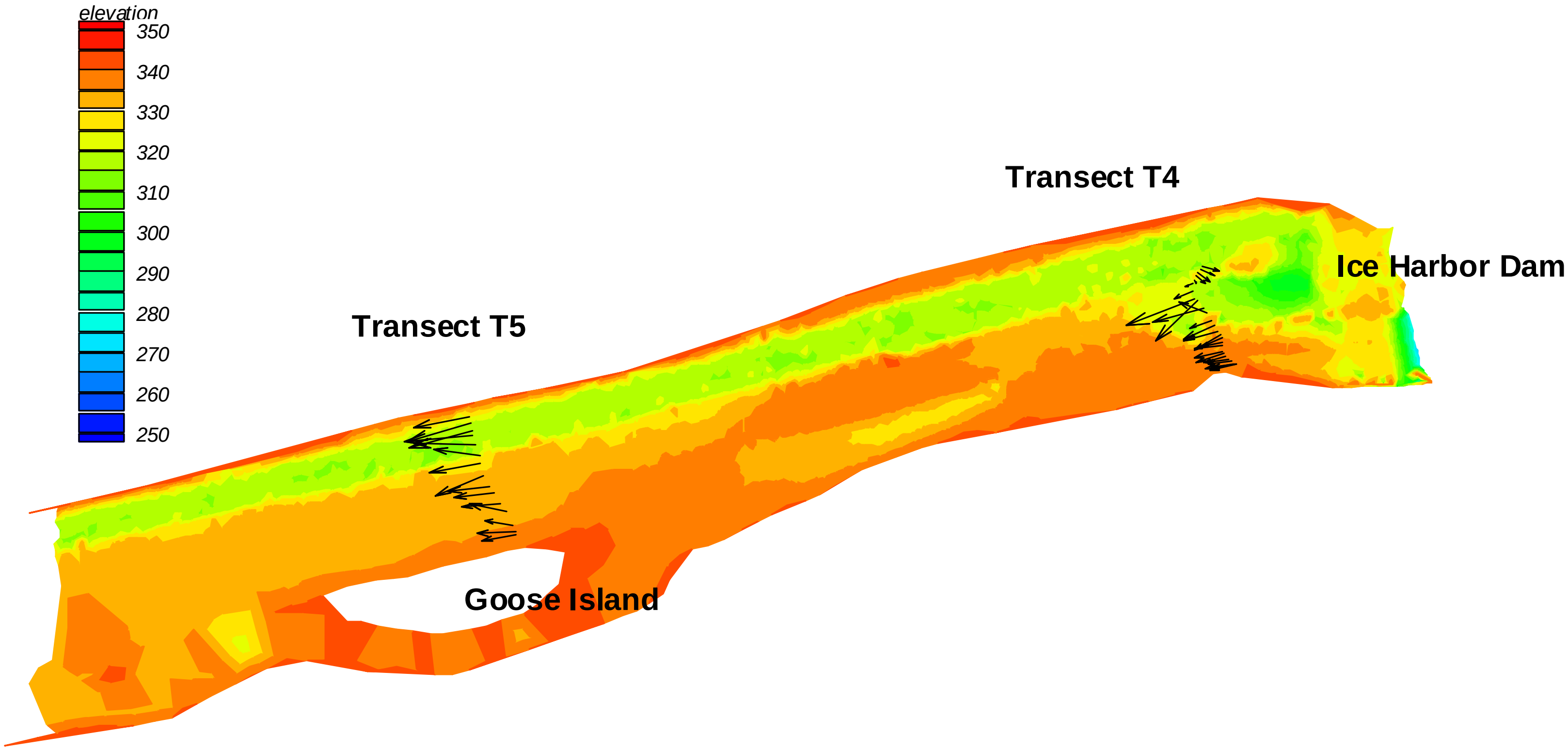

Figure 36. Depth-Averaged Velocity Field on Transects T4 and T5 during 135 kcfs Snake River Flow, March 9, 1998.

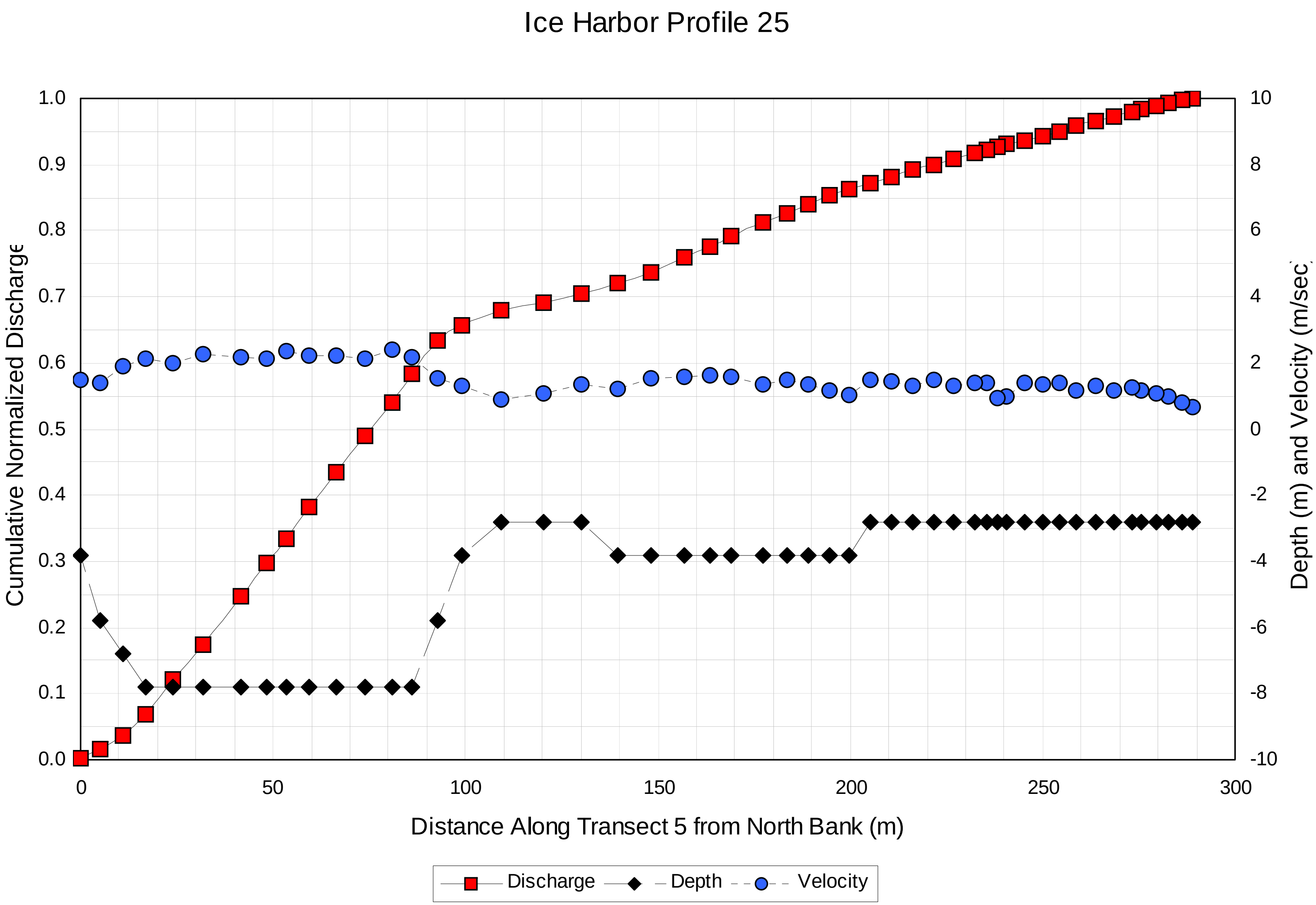

Figure 37. Velocity, Depth, and Cumulative Normalized Discharge Across Transect T5
March 5, 1998; 10-bay, Qspill = 75 kcfs, Qpower = 35.5 kcfs.

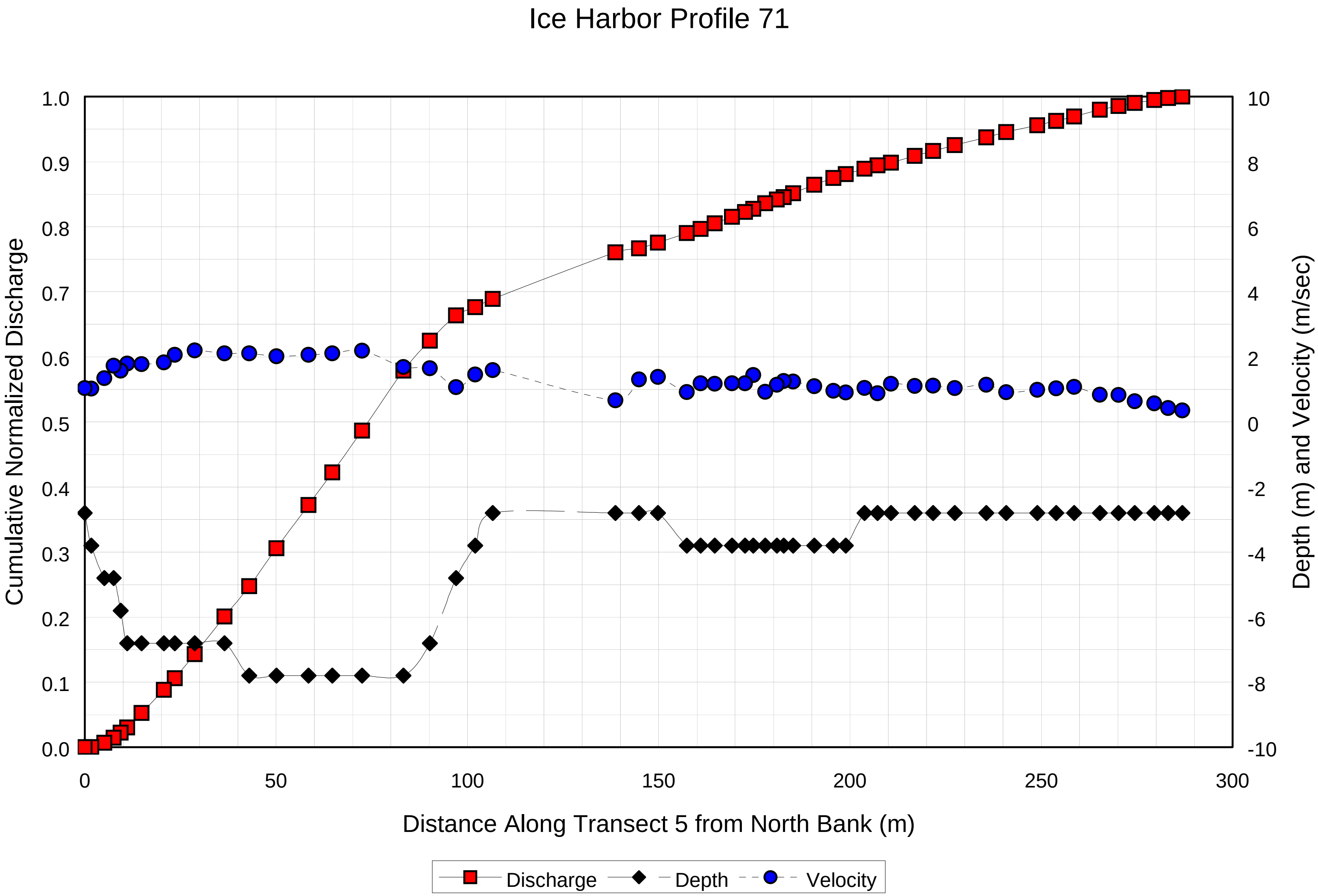

Figure 38. Velocity, Depth, and Cumulative Normalized Discharge Across Transect T5
March 9, 1998; 8-bay, Qspill = 29.8 kcfs, Qpower = 61.3 kcfs

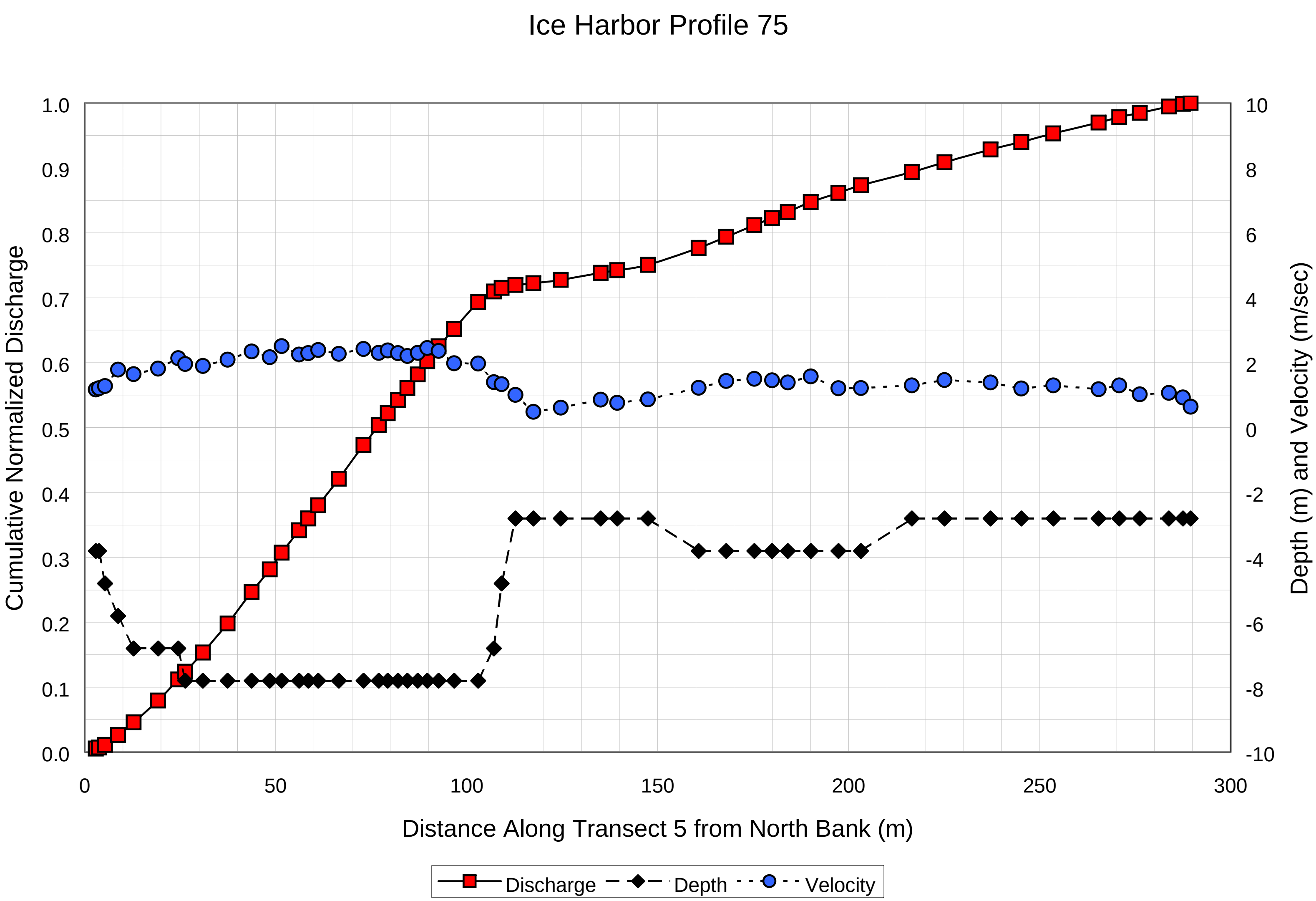

Figure 39. Velocity, Depth, and Cumulative Normalized Discharge Across Transect T5
March 9, 1998; 8-bay, Qspill = 45.1 kcfs, Qpower = 60.9 kcfs

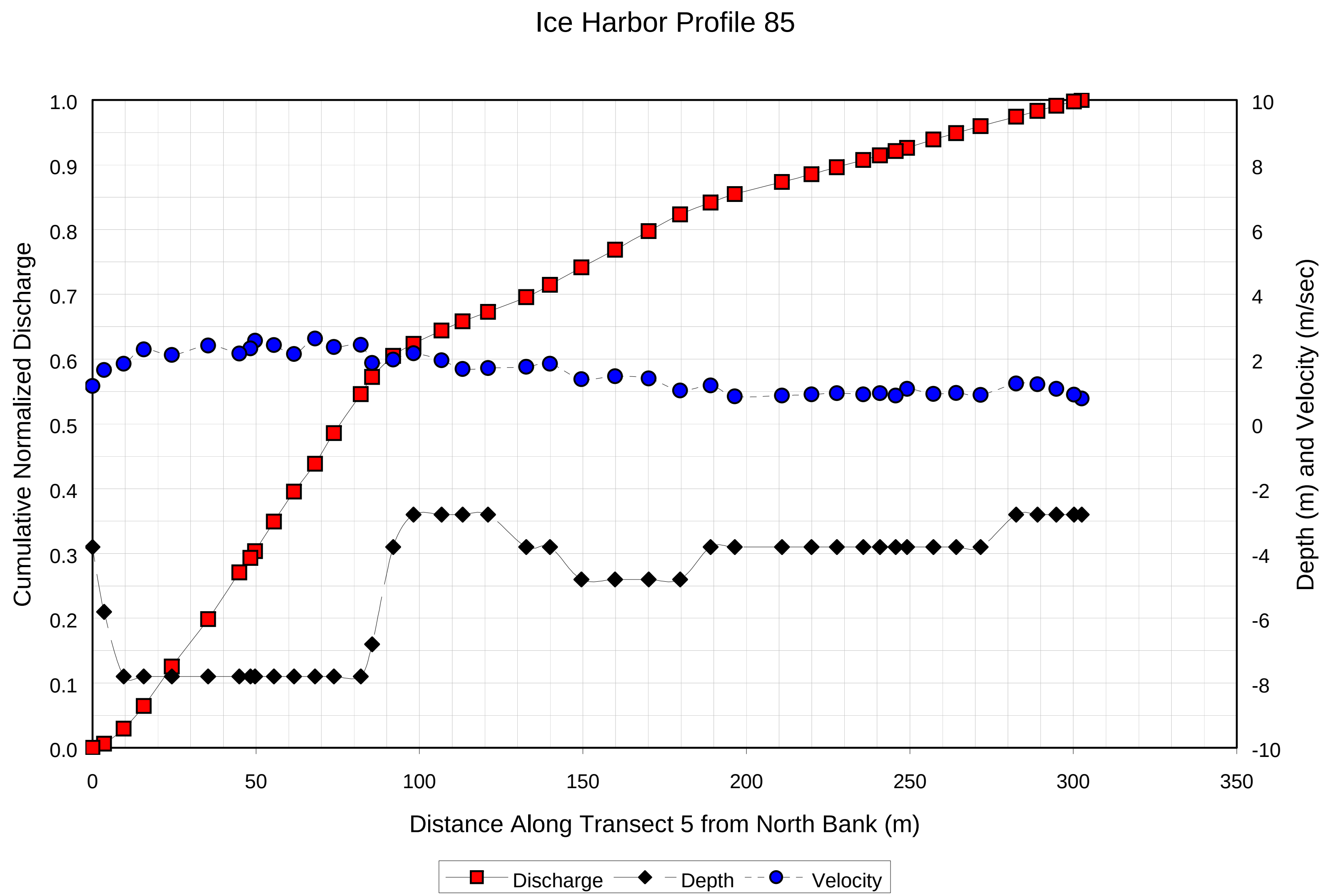

Figure 40. Velocity, Depth, and Cumulative Normalized Discharge Across Transect T5
March 9, 1998; 8-bay, Qspill = 60.0 kcfs, Qpower = 61.7 kcfs

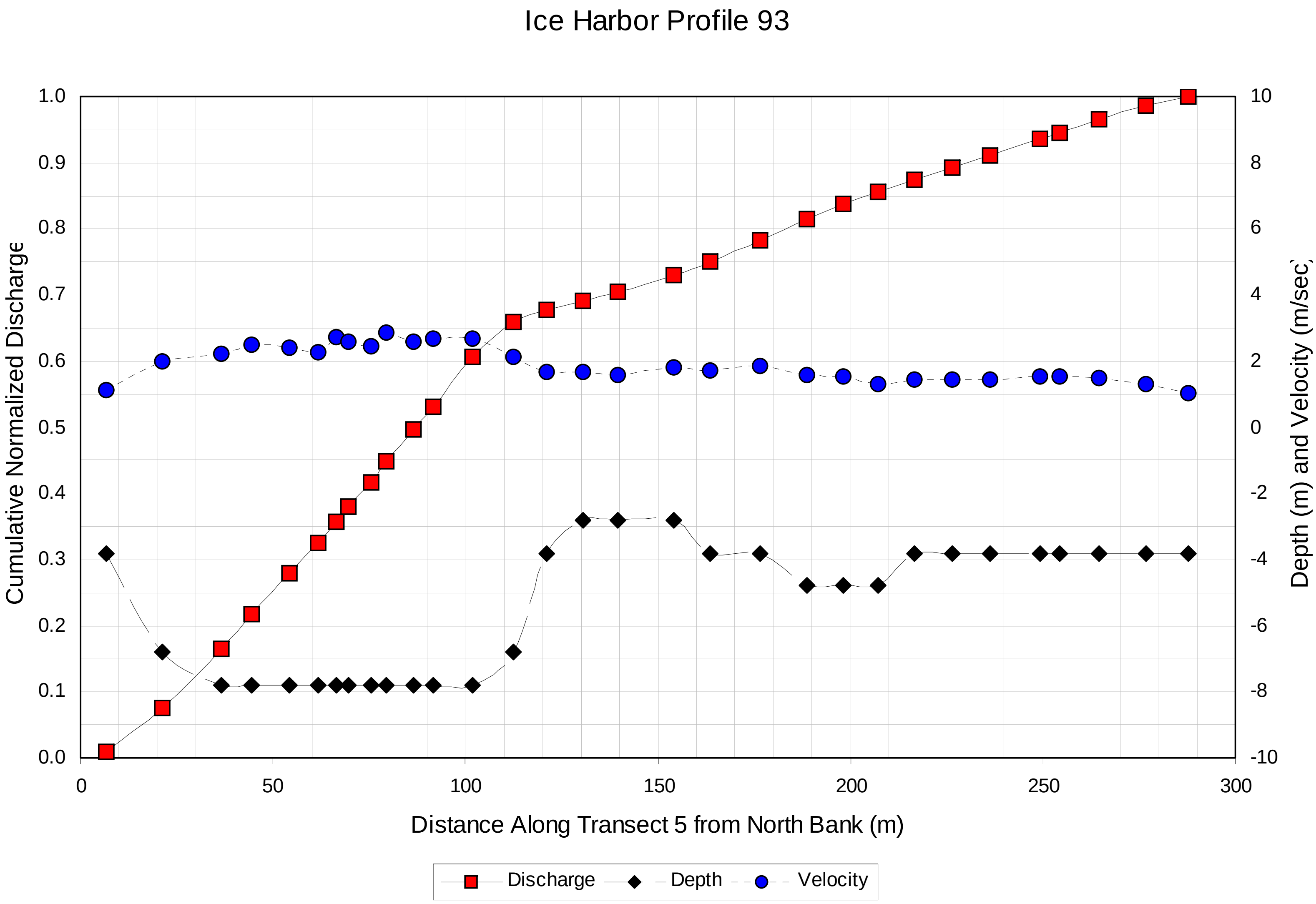

Figure 41. Velocity, Depth, and Cumulative Normalized Discharge Across Transect T5
March 9, 1998; 8-bay, Qspill = 75.0 kcfs, Qpower = 61.5 kcfs

Appendix A. Tabulated Hourly Operations and Measured Data

Table A1. Ice Harbor Project Hourly Operations Summary

March 5, 1998, 10-Bay Spill Pattern

		Project Discharge (kcfs)			Spillway Bay Discharge (kcfs)										Powerhouse Discharge (kcfs)						Water Surface (ft)	
Date	Hour	Total Flow	Generation	Spillway Flow	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	T1	T2	T3	T4	T5	T6	FBE	TWE
3/5/98	4	49.95	35.05	14.90	1.70	1.70	1.80	1.70	0.00	0.00	1.88	1.80	1.73	2.60	0.00	0.00	0.00	17.50	0.00	17.55	439.07	341.31
3/5/98	5	50.13	35.18	14.95	1.70	1.70	1.80	1.70	0.00	0.00	1.90	1.80	1.75	2.60	0.00	0.00	0.00	17.58	0.00	17.60	439.18	341.39
3/5/98	6	61.58	35.30	26.28	1.70	2.98	3.08	3.13	2.78	2.65	3.10	1.80	1.80	3.28	0.00	0.00	0.00	17.68	0.00	17.63	439.25	341.86
3/5/98	7	65.23	35.28	29.95	1.73	3.40	3.50	3.60	3.63	3.58	3.50	1.73	1.80	3.50	0.00	0.00	0.00	17.70	0.00	17.58	439.24	342.29
3/5/98	9	80.40	35.33	45.08	3.40	5.18	5.20	5.20	5.20	5.20	5.20	3.50	3.50	3.50	0.00	0.00	0.00	17.65	0.00	17.68	439.13	343.41
3/5/98	10	80.48	35.35	45.13	3.43	5.20	5.20	5.20	5.20	5.20	5.20	3.50	3.50	3.50	0.00	0.00	0.00	17.68	0.00	17.68	439.15	343.57
3/5/98	11	92.83	35.35	57.48	3.50	6.58	6.70	6.55	6.65	6.58	6.48	6.05	4.90	3.50	0.00	0.00	0.00	17.65	0.00	17.70	438.92	344.16
3/5/98	12	95.73	35.50	60.23	3.50	6.80	6.90	6.80	6.90	6.90	6.83	6.90	5.20	3.50	0.00	0.00	0.00	17.78	0.00	17.73	438.81	344.66
3/5/98	13	99.30	35.35	63.95	3.50	7.23	7.30	7.23	7.30	7.30	7.25	7.33	6.03	3.50	0.00	0.00	0.00	17.70	0.00	17.65	438.79	344.78
3/5/98	14	110.35	35.35	75.00	3.40	8.50	8.50	8.50	8.50	8.50	8.50	8.60	8.50	3.50	0.00	0.00	0.00	17.70	0.00	17.65	438.49	345.53
3/5/98	15	110.33	35.33	75.00	3.40	8.50	8.48	8.48	8.50	8.58	8.50	8.60	8.50	3.48	0.00	0.00	0.00	17.68	0.00	17.65	438.37	345.66

Table A1. Ice Harbor Project Operations Summary
March 6, 1998, 10 – Bay Spill Pattern

		Project Discharge (kcfs)			Spillway Bay Discharge (kcfs)										Powerhouse Discharge (kcfs)						Water Surface (ft)	
Date	Hour	Total Flow	Generation	Spillway Flow	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	T1	T2	T3	T4	T5	T6	FBE	TWE
3/6/98	4	15.00	0.00	15.00	1.80	1.70	1.80	1.70	0.00	0.00	1.80	1.80	1.80	2.60	0.00	0.00	0.00	0.00	0.00	0.00	438.59	338.62
3/6/98	5	15.00	0.00	15.00	1.80	1.70	1.80	1.70	0.00	0.00	1.80	1.80	1.80	2.60	0.00	0.00	0.00	0.00	0.00	0.00	438.58	338.64
3/6/98	6	26.73	0.38	26.35	1.75	2.98	3.08	3.15	2.70	2.78	3.10	1.80	1.80	3.23	0.38	0.00	0.00	0.00	0.00	0.00	438.84	339.32
3/6/98	7	30.63	0.50	30.13	1.70	3.40	3.50	3.60	3.60	3.80	3.50	1.80	1.80	3.43	0.50	0.00	0.00	0.00	0.00	0.00	438.92	339.61
3/6/98	8	38.10	0.50	37.60	2.53	4.25	4.33	4.35	4.43	4.53	4.20	2.58	2.55	3.88	0.50	0.00	0.00	0.00	0.00	0.00	439.00	339.55
3/6/98	9	45.48	0.50	44.98	3.40	5.10	5.20	5.10	5.30	5.30	5.13	3.50	3.50	3.45	0.50	0.00	0.00	0.00	0.00	0.00	438.99	340.36
3/6/98	10	45.60	0.50	45.10	3.40	5.10	5.20	5.10	5.30	5.30	5.20	3.50	3.50	3.50	0.50	0.00	0.00	0.00	0.00	0.00	439.14	340.44
3/6/98	11	56.80	0.50	56.30	3.40	6.40	6.48	6.38	6.50	6.50	6.48	5.98	4.70	3.50	0.50	0.00	0.00	0.00	0.00	0.00	439.05	341.22
3/6/98	12	60.60	0.50	60.10	3.40	6.90	6.90	6.80	6.90	6.90	6.90	6.80	5.10	3.50	0.50	0.00	0.00	0.00	0.00	0.00	439.06	341.92
3/6/98	13	67.40	0.50	66.90	3.40	7.68	7.70	7.65	7.73	7.80	7.65	7.68	6.18	3.45	0.50	0.00	0.00	0.00	0.00	0.00	438.96	342.10
3/6/98	14	75.20	0.23	74.98	3.40	8.50	8.50	8.50	8.50	8.68	8.50	8.50	8.50	3.40	0.23	0.00	0.00	0.00	0.00	0.00	438.71	342.85
3/6/98	15	75.00	0.00	75.00	3.40	8.50	8.50	8.50	8.50	8.70	8.50	8.50	8.50	3.40	0.00	0.00	0.00	0.00	0.00	0.00	438.70	342.85

Table A1. Ice Harbor Project Operations Summary

March 7, 1998, 8 – Bay Spill Pattern

		Project Discharge (kcfs)			Spillway Bay Discharge (kcfs)										Powerhouse Discharge (kcfs)						Water Surface (ft)	
Date	Hour	Total Flow	Generation	Spillway Flow	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	T1	T2	T3	T4	T5	T6	FBE	TWE
3/7/98	4	15.20	0.00	15.20	0.00	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.68	338.49
3/7/98	5	15.20	0.00	15.20	0.00	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.71	338.52
3/7/98	6	29.95	0.00	29.95	0.00	3.80	3.80	3.78	3.75	3.75	3.70	3.73	3.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.59	339.41
3/7/98	7	30.40	0.00	30.40	0.00	3.80	3.80	3.80	3.80	3.80	3.80	3.80	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.70	339.86
3/7/98	8	36.13	0.00	36.13	0.00	4.63	4.63	4.50	4.48	4.48	4.50	4.58	4.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.74	339.76
3/7/98	9	44.90	0.00	44.90	0.00	5.70	5.78	5.40	5.40	5.43	5.70	5.80	5.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.53	340.55
3/7/98	10	45.08	0.00	45.08	0.00	5.70	5.80	5.45	5.40	5.50	5.70	5.80	5.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.73	340.61
3/7/98	11	59.78	0.00	59.78	0.00	7.50	7.55	7.45	7.43	7.33	7.53	7.60	7.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.46	341.12
3/7/98	12	60.15	0.00	60.15	0.00	7.50	7.50	7.50	7.48	7.50	7.50	7.60	7.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.39	341.59
3/7/98	13	65.88	0.00	65.88	0.00	8.28	8.28	8.25	8.25	8.23	8.18	8.23	8.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	439.31	341.73
3/7/98	14	74.85	0.00	74.85	0.00	9.30	9.30	9.48	9.48	9.40	9.30	9.30	9.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	438.96	342.58
3/7/98	15	74.90	0.00	74.90	0.00	9.30	9.30	9.50	9.50	9.40	9.30	9.30	9.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	438.96	342.72

Table A1. Ice Harbor Project Operations Summary

March 9, 1998, 8 – Bay Spill Pattern

		Project Discharge (kcfs)			Spillway Bay Discharge (kcfs)										Powerhouse Discharge (kcfs)						Water Surface (ft)	
Date	Hour	Total Flow	Generation	Spillway Flow	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	T1	T2	T3	T4	T5	T6	FBE	TWE
3/9/98	4	75.73	60.73	15.00	0.00	1.90	1.90	1.90	1.70	1.90	1.90	1.90	1.90	0.00	12.33	12.33	0.00	18.00	0.00	18.08	439.04	343.24
3/9/98	5	75.90	60.90	15.00	0.00	1.90	1.90	1.90	1.70	1.90	1.90	1.90	1.90	0.00	12.15	12.35	0.00	18.18	0.00	18.23	439.13	343.62
3/9/98	6	88.95	61.00	27.95	0.00	3.58	3.60	3.43	3.38	3.40	3.53	3.55	3.50	0.00	10.13	10.13	0.00	15.30	10.30	15.15	439.20	344.25
3/9/98	7	90.93	61.13	29.80	0.00	3.80	3.80	3.60	3.60	3.60	3.80	3.80	3.80	0.00	11.53	11.43	0.00	3.58	17.28	17.33	439.14	344.71
3/9/98	8	94.73	61.10	33.63	0.00	4.25	4.28	4.13	4.08	4.08	4.28	4.28	4.28	0.00	12.20	12.05	0.00	0.00	18.40	18.45	439.20	344.80
3/9/98	9	106.43	61.35	45.08	0.00	5.60	5.70	5.70	5.50	5.48	5.70	5.70	5.70	0.00	12.23	12.03	0.00	0.00	18.50	18.60	439.26	345.54
3/9/98	10	106.13	61.03	45.10	0.00	5.60	5.70	5.70	5.50	5.50	5.70	5.70	5.70	0.00	11.98	12.03	0.00	0.00	18.50	18.53	439.25	345.67
3/9/98	11	117.43	61.10	56.33	0.00	7.03	7.05	7.05	7.05	7.00	7.05	7.05	7.05	0.00	12.00	11.98	0.00	0.00	18.58	18.55	439.13	346.10
3/9/98	12	121.60	61.58	60.03	0.00	7.50	7.53	7.50	7.50	7.50	7.50	7.50	7.50	0.00	12.13	11.95	0.00	0.00	18.73	18.78	439.00	346.59
3/9/98	13	126.85	61.83	65.03	0.00	8.15	8.15	8.13	8.18	8.13	8.13	8.10	8.08	0.00	12.20	11.95	0.00	0.00	18.85	18.83	438.84	346.76
3/9/98	14	137.00	62.13	74.88	0.00	9.30	9.30	9.30	9.53	9.40	9.45	9.30	9.30	0.00	12.05	11.93	0.00	0.00	19.08	19.08	438.47	347.43
3/9/98	15	136.55	61.68	74.88	0.00	9.20	9.30	9.30	9.50	9.53	9.48	9.30	9.28	0.00	11.95	11.95	0.00	0.00	18.88	18.90	438.11	347.58

Table A2. Ice Harbor Dam Hourly TDG Summary – Transect T1

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T1B	L1T1U	L3T1B	L3T1U	L4T1B	L5T1B	L5T1U
3/5/98	4	49.95	35.05	14.90	103.61	102.42	105.17	107.33	107.43	114.50	116.00
3/5/98	5	50.13	35.18	14.95	103.68	102.28	105.34	107.20	107.90	115.00	116.00
3/5/98	6	61.58	35.30	26.28	103.74	103.04	113.21	108.49	111.51	120.00	120.25
3/5/98	7	65.23	35.28	29.95	103.76	103.33	116.55	109.47	113.56	122.00	122.00
3/5/98	8	70.68	35.13	35.55	103.76	103.00	118.11	110.10	114.06	122.00	121.75
3/5/98	9	80.40	35.33	45.08	103.77	103.77	122.11	111.98	116.93	121.50	120.00
3/5/98	10	80.48	35.35	45.13	103.79	103.83	122.23	111.20	117.52	121.75	120.25
3/5/98	11	92.83	35.35	57.48	103.90	103.67	124.61	114.67	122.15	123.50	120.00
3/5/98	12	95.73	35.50	60.23	104.04	103.61	127.59	121.27	124.77	124.75	121.50
3/5/98	13	99.30	35.35	63.95	104.13	103.37	128.50	122.71	125.04	125.50	121.00
3/5/98	14	110.35	35.35	75.00	104.34	103.77	131.59	124.99	126.86	127.50	121.50
3/5/98	15	110.33	35.33	75.00	104.48	104.25	131.68	128.62	126.82	127.25	124.00

Table A2. Ice Harbor Dam – Transect T1

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T1B	L1T1U	L3T1B	L3T1U	L4T1B	L5T1B	L5T1U
3/6/98	4	15.00	0.00	15.00	104.12	106.45	106.68	107.31	104.72	116.50	116.50
3/6/98	5	15.00	0.00	15.00	105.78	107.34	107.51	107.78	104.45	116.25	116.75
3/6/98	6	26.73	0.38	26.35	107.98	108.92	117.30	115.90	107.55	119.75	120.00
3/6/98	7	30.63	0.50	30.13	110.73	111.56	121.47	118.61	111.50	121.00	121.00
3/6/98	8	38.10	0.50	37.60	111.14	111.64	122.87	119.84	113.06	121.00	121.00
3/6/98	9	45.48	0.50	44.98	112.57	112.90	125.49	122.80	116.75	121.00	120.00
3/6/98	10	45.60	0.50	45.10	112.61	112.91	125.13	122.81	116.96	121.00	119.75
3/6/98	11	56.80	0.50	56.30	112.93	113.06	127.44	124.95	122.33	123.50	121.50
3/6/98	12	60.60	0.50	60.10	113.16	113.36	130.70	124.35	124.39	125.00	122.00
3/6/98	13	67.40	0.50	66.90	113.40	113.54	128.95	125.56	125.23	125.50	123.50
3/6/98	14	75.20	0.23	74.98	115.01	115.31	131.63	127.71	127.11	128.00	121.50
3/6/98	15	75.00	0.00	75.00	115.11	115.21	131.63	127.38	126.71	127.50	121.50

Table A2. Ice Harbor Dam – Transect T1 March 7, 1998, 8-Bay Spill Pattern											
Date	Hour	River Flow	Generation	Spillway Flow	L1T1B	L1T1U	L3T1B	L3T1U	L4T1B	L5T1B	L5T1U
3/7/98	4	15.20	0.00	15.20	104.90	106.30		111.96	104.71	110.75	110.50
3/7/98	5	15.20	0.00	15.20	105.52	106.74		112.01	106.14	111.00	110.50
3/7/98	6	29.95	0.00	29.95	106.90	108.92		117.50	114.49	116.50	113.00
3/7/98	7	30.40	0.00	30.40	108.31	110.23		119.04	118.61	119.00	113.75
3/7/98	8	36.13	0.00	36.13	109.14	110.79		119.50	119.57	120.00	113.50
3/7/98	9	44.90	0.00	44.90	112.00	112.80		121.44	122.80	124.00	114.75
3/7/98	10	45.08	0.00	45.08	112.80	112.87		121.35	123.17	124.50	114.50
3/7/98	11	59.78	0.00	59.78	113.70	113.90		124.15	125.74	128.00	114.75
3/7/98	12	60.15	0.00	60.15	114.35	114.59		124.93	127.06	129.00	114.00
3/7/98	13	65.88	0.00	65.88	114.58	114.61		125.70	127.12	129.25	116.75
3/7/98	14	74.85	0.00	74.85	115.46	115.76		128.68	128.78	130.00	125.00
3/7/98	15	74.90	0.00	74.90	115.76	115.93		128.89	129.05	130.00	125.25

Table A2. Ice Harbor Dam – Transect T1 March 9, 1998, 8-Bay Spill Pattern											
Date	Hour	River Flow	Generation	Spillway Flow	L1T1B	L1T1U	L3T1B	L3T1U	L4T1B	L5T1B	L5T1U
3/9/98	4	75.73	60.73	15.00	101.28				107.29	103.50	
3/9/98	5	75.90	60.90	15.00	101.31				107.72	104.00	
3/9/98	6	88.95	61.00	27.95	101.35				114.19	104.00	
3/9/98	7	90.93	61.13	29.80	101.24				117.42	106.75	
3/9/98	8	94.73	61.10	33.63	101.05				118.47	113.25	
3/9/98	9	106.43	61.35	45.08	100.77				122.67	119.00	
3/9/98	10	106.13	61.03	45.10	100.70				122.87	120.00	
3/9/98	11	117.43	61.10	56.33	100.59				124.98	124.25	
3/9/98	12	121.60	61.58	60.03	100.64				126.03	125.25	
3/9/98	13	126.85	61.83	65.03	100.71				127.64	126.00	
3/9/98	14	137.00	62.13	74.88	100.61				130.85	128.00	
3/9/98	15	136.55	61.68	74.88	100.58				131.18	128.00	

Table A3. Ice Harbor Dam – Transect T2

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T2B	L2T2B	L3T2B	L4T2B	L5T2B
3/5/98	4	49.95	35.05	14.90	101.75	106.93	105.34	107.00	111.25
3/5/98	5	50.13	35.18	14.95	101.49	107.07	106.34	107.20	111.75
3/5/98	6	61.58	35.30	26.28	101.95	109.49	111.02	110.15	111.00
3/5/98	7	65.23	35.28	29.95	102.30	110.77	114.12	111.43	110.25
3/5/98	8	70.68	35.13	35.55	102.13	111.50	114.89	113.03	110.25
3/5/98	9	80.40	35.33	45.08	101.98	114.10	117.46	119.72	111.00
3/5/98	10	80.48	35.35	45.13	101.83	114.26	117.68	120.14	111.00
3/5/98	11	92.83	35.35	57.48	102.04	115.07	119.29	122.65	114.00
3/5/98	12	95.73	35.50	60.23	102.02	115.32	120.01	124.07	115.25
3/5/98	13	99.30	35.35	63.95	102.07	114.52	120.88	124.54	116.75
3/5/98	14	110.35	35.35	75.00	102.34	116.26	123.96	126.39	120.00
3/5/98	15	110.33	35.33	75.00	102.55	116.92	124.55	126.58	120.00

Table A3. Ice Harbor Dam – Transect T2

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T2B	L2T2B	L3T2B	L4T2B	L5T2B
3/6/98	4	15.00	0.00	15.00	105.72	107.28	104.15	107.31	110.00
3/6/98	5	15.00	0.00	15.00	106.31	107.81	104.38	107.54	110.00
3/6/98	6	26.73	0.38	26.35	107.42	110.51	111.28	109.15	109.25
3/6/98	7	30.63	0.50	30.13	109.17	111.99	116.08	109.90	109.00
3/6/98	8	38.10	0.50	37.60	109.58	112.83	116.65	111.30	109.25
3/6/98	9	45.48	0.50	44.98	110.28	115.23	118.32	115.46	110.00
3/6/98	10	45.60	0.50	45.10	110.39	115.30	118.49	115.47	110.00
3/6/98	11	56.80	0.50	56.30	111.10	116.31	119.93	120.53	114.25
3/6/98	12	60.60	0.50	60.10	112.13	116.91	120.73	122.49	116.00
3/6/98	13	67.40	0.50	66.90	112.34	116.99	121.38	122.94	117.25
3/6/98	14	75.20	0.23	74.98	114.25	116.58	124.35	124.39	122.00
3/6/98	15	75.00	0.00	75.00	114.38	117.04	124.55	124.42	122.00

Table A3. Ice Harbor Dam – Transect T2

March 7, 1998, 10-Bay Spill Pattern
(incomplete)

Date	Hour	River Flow	Generation	Spillway Flow	L1T2B	L2T2B	L3T2B	L4T2B	L5T2B
3/7/98	4	15.20	0.00	15.20	104.54	106.86	104.77	109.31	107.00
3/7/98	15	74.90	0.00	74.90	114.87	115.40	124.80	125.56	124.00

Table A3. Ice Harbor Dam – Transect T2

March 9, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T2B	L2T2B	L3T2B	L4T2B	L5T2B
3/9/98	4	75.73	60.73	15.00	97.85	104.78	104.45	107.52	107.00
3/9/98	5	75.90	60.90	15.00	97.85	104.75	105.01	107.55	107.00
3/9/98	6	88.95	61.00	27.95	97.85	107.85	108.05	112.54	112.00
3/9/98	7	90.93	61.13	29.80	97.84	109.10	110.25	114.84	114.00
3/9/98	8	94.73	61.10	33.63	97.78	109.26	110.98	115.93	114.50
3/9/98	9	106.43	61.35	45.08	97.89	109.64	114.85	119.70	117.00
3/9/98	10	106.13	61.03	45.10	98.06	109.71	115.12	119.80	117.00
3/9/98	11	117.43	61.10	56.33	98.34	108.31	118.28	123.26	118.50
3/9/98	12	121.60	61.58	60.03	98.40	108.57	120.75	124.94	119.50
3/9/98	13	126.85	61.83	65.03	98.47	107.65	121.46	125.50	120.75
3/9/98	14	137.00	62.13	74.88	98.57	106.23	124.17	128.60	123.25
3/9/98	15	136.55	61.68	74.88	98.63	105.90	124.77	129.10	124.00

Table A4. Ice Harbor Dam – Transect T3

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L2T3B	L3T3B	L4T3B	L5T3B	T3SOUTHP
3/5/98	4	49.95	35.05	14.90	103.28	104.38	106.90	109.75	103.40
3/5/98	5	50.13	35.18	14.95	103.21	105.27	107.03	110.00	103.32
3/5/98	6	61.58	35.30	26.28	106.07	107.06	109.59	109.75	103.28
3/5/98	7	65.23	35.28	29.95	107.94	109.04	110.50	110.00	103.21
3/5/98	8	70.68	35.13	35.55	107.85	109.87	112.10	110.00	102.98
3/5/98	9	80.40	35.33	45.08	106.40	110.72	117.96	111.00	103.42
3/5/98	10	80.48	35.35	45.13	106.15	111.07	118.18	111.00	104.04
3/5/98	11	92.83	35.35	57.48	105.96	111.51	118.83	113.00	105.35
3/5/98	12	95.73	35.50	60.23	105.24	111.93	119.01	114.25	106.29
3/5/98	13	99.30	35.35	63.95	105.00	111.86	119.98	115.00	106.70
3/5/98	14	110.35	35.35	75.00	105.20	112.37	122.53	117.25	107.85
3/5/98	15	110.33	35.33	75.00	105.45	113.45	122.52	117.00	108.04

Table A4. Ice Harbor Dam – Transect T3

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L2T3B	L3T3B	L4T3B	L5T3B	T3SOUTHP
3/6/98	4	15.00	0.00	15.00	105.42	103.22	106.28	108.00	107.02
3/6/98	5	15.00	0.00	15.00	107.24	104.71	107.21	108.00	107.78
3/6/98	6	26.73	0.38	26.35	110.25	108.05	109.02	109.00	109.42
3/6/98	7	30.63	0.50	30.13	112.56	110.50	110.60	110.25	111.44
3/6/98	8	38.10	0.50	37.60	112.60	111.70	111.17	111.00	111.74
3/6/98	9	45.48	0.50	44.98	112.90	114.00	111.77	111.00	112.63
3/6/98	10	45.60	0.50	45.10	112.85	115.07	111.72	111.00	112.69
3/6/98	11	56.80	0.50	56.30	112.30	115.45	116.68	113.25	113.62
3/6/98	12	60.60	0.50	60.10	112.00	115.32	119.04	114.00	114.10
3/6/98	13	67.40	0.50	66.90	112.44	115.16	119.48	115.00	114.41
3/6/98	14	75.20	0.23	74.98	114.81	115.31	121.46	118.75	116.03
3/6/98	15	75.00	0.00	75.00	114.85	115.58	121.29	118.00	116.12
3/6/98	16	59.68	43.68	16.00	108.28	109.91	112.23	113.50	105.93
3/6/98	17	43.53	43.53	0.00	101.65	104.14	102.61	104.50	101.99

Table A4. Ice Harbor Dam – Transect T3

March 7, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L2T3B	L3T3B	L4T3B	L5T3B	T3SOUTHP
3/7/98	4	15.20	0.00	15.20	106.63	104.31	108.38	108.00	107.63
3/7/98	5	15.20	0.00	15.20	107.87	105.65	108.46	108.00	108.62
3/7/98	6	29.95	0.00	29.95	109.12	108.00	112.10	110.00	110.09
3/7/98	7	30.40	0.00	30.40	110.06	109.70	113.31	111.00	111.80
3/7/98	8	36.13	0.00	36.13	110.40	110.46	113.77	111.50	112.08
3/7/98	9	44.90	0.00	44.90	111.87	112.13	115.94	113.75	113.62
3/7/98	10	45.08	0.00	45.08	112.10	112.77	115.88	113.50	113.76
3/7/98	11	59.78	0.00	59.78	113.14	113.54	117.98	115.00	114.68
3/7/98	12	60.15	0.00	60.15	114.35	114.35	118.96	116.00	115.41
3/7/98	13	65.88	0.00	65.88	114.38	114.58	119.62	116.75	115.54
3/7/98	14	74.85	0.00	74.85	115.59	115.00	122.27	120.00	116.63
3/7/98	15	74.90	0.00	74.90	115.70	115.10	122.38	120.00	116.68

Table A4. Ice Harbor Dam – Transect T3

March 9, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L2T3B	L3T3B	L4T3B	L5T3B	T3SOUTHP
3/9/98	4	75.73	60.73	15.00	100.62	102.47	106.66	107.00	100.58
3/9/98	5	75.90	60.90	15.00	100.42	103.53	106.60	107.00	100.56
3/9/98	6	88.95	61.00	27.95	100.92	105.08	109.93	111.25	100.50
3/9/98	7	90.93	61.13	29.80	100.91	106.85	111.18	112.50	100.44
3/9/98	8	94.73	61.10	33.63	101.02	107.55	111.97	112.75	100.40
3/9/98	9	106.43	61.35	45.08	101.23	108.29	114.89	115.00	100.43
3/9/98	10	106.13	61.03	45.10	101.26	108.62	114.76	115.00	100.45
3/9/98	11	117.43	61.10	56.33	101.35	108.84	117.88	116.50	100.48
3/9/98	12	121.60	61.58	60.03	101.57	109.09	118.77	117.50	100.52
3/9/98	13	126.85	61.83	65.03	101.44	108.88	119.38	119.00	100.59
3/9/98	14	137.00	62.13	74.88	101.21	108.31	122.42	121.50	100.61

3/9/98	15	136.55	61.68	74.88	101.31	108.08	122.46	121.75	100.63

Table A5. Ice Harbor Dam – Transect T4

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T4B	L2T4B	L3T4B	L4T4B	L5T4Bc
3/5/98	4	49.95	35.05	14.90	102.00	103.00	103.00	107.00	109.50
3/5/98	5	50.13	35.18	14.95	102.00	103.00	103.00	107.50	110.00
3/5/98	6	61.58	35.30	26.28	102.00	103.25	105.25	109.75	111.00
3/5/98	7	65.23	35.28	29.95	102.00	103.00	106.00	111.00	111.25
3/5/98	8	70.68	35.13	35.55	102.50	102.75	107.00	111.50	111.75
3/5/98	9	80.40	35.33	45.08	103.00	103.25	108.00	114.25	113.00
3/5/98	10	80.48	35.35	45.13	104.00	104.00	108.00	114.25	113.00
3/5/98	11	92.83	35.35	57.48	105.00	104.75	109.50	115.50	114.00
3/5/98	12	95.73	35.50	60.23	106.00	105.00	110.00	117.00	115.00
3/5/98	13	99.30	35.35	63.95	106.25	105.00	110.50	117.25	115.00
3/5/98	14	110.35	35.35	75.00	107.25	106.00	112.75	118.00	116.00
3/5/98	15	110.33	35.33	75.00	107.25	106.00	113.25	118.00	116.00

Table A5. Ice Harbor Dam – Transect T4

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T4B	L2T4B	L3T4B	L4T4B	L5T4Bc
3/6/98	4	15.00	0.00	15.00	100.50	105.25	104.75	107.75	109.00
3/6/98	5	15.00	0.00	15.00	103.00	107.00	106.25	108.50	109.75
3/6/98	6	26.73	0.38	26.35	107.00	108.75	109.25	110.00	109.00
3/6/98	7	30.63	0.50	30.13	110.25	111.50	111.00	111.00	110.75
3/6/98	8	38.10	0.50	37.60	110.50	112.00	111.25	111.25	111.50
3/6/98	9	45.48	0.50	44.98	111.75	112.75	113.00	113.00	111.50
3/6/98	10	45.60	0.50	45.10	111.75	113.00	113.25	113.00	112.00
3/6/98	11	56.80	0.50	56.30	113.00	113.25	114.50	114.25	112.50
3/6/98	12	60.60	0.50	60.10	114.00	114.00	115.00	115.00	112.75
3/6/98	13	67.40	0.50	66.90	114.25	114.25	115.00	115.25	113.75

3/6/98	14	75.20	0.23	74.98	116.00	115.50	116.00	116.00	115.00
3/6/98	15	75.00	0.00	75.00	116.00	116.00	116.00	116.00	115.00

Table A5. Ice Harbor Dam – Transect T4 March 7, 1998, 8-Bay Spill Pattern									
Date	Hour	River Flow	Generation	Spillway Flow	L1T4B	L2T4B	L3T4B	L4T4B	L5T4Bc
3/7/98	4	15.20	0.00	15.20	103.25	106.25	105.75	107.25	107.75
3/7/98	5	15.20	0.00	15.20	106.75	108.00	107.00	108.00	108.00
3/7/98	6	29.95	0.00	29.95	107.75	109.25	109.50	110.00	110.25
3/7/98	7	30.40	0.00	30.40	110.75	111.00	111.00	112.00	111.00
3/7/98	8	36.13	0.00	36.13	111.25	111.25	111.25	112.25	111.25
3/7/98	9	44.90	0.00	44.90	113.00	113.00	113.00	113.75	113.00
3/7/98	10	45.08	0.00	45.08	113.00	113.00	113.00	114.00	113.00
3/7/98	11	59.78	0.00	59.78	114.25	114.00	114.50	114.75	114.00
3/7/98	12	60.15	0.00	60.15	115.00	115.00	115.00	115.00	114.00
3/7/98	13	65.88	0.00	65.88	115.00	115.00	115.25	115.50	114.25
3/7/98	14	74.85	0.00	74.85	116.00	116.00	117.00	117.00	115.00
3/7/98	15	74.90	0.00	74.90	116.00	116.00	117.25	117.00	115.00

Table A5. Ice Harbor Dam – Transect T4 March 9, 1998, 8-Bay Spill Pattern									
Date	Hour	River Flow	Generation	Spillway Flow	L1T4B	L2T4B	L3T4B	L4T4B	L5T4Bc
3/9/98	4	75.73	60.73	15.00	100.00	100.00	101.00	106.75	106.75
3/9/98	5	75.90	60.90	15.00	100.00	100.00	101.00	107.00	107.00
3/9/98	6	88.95	61.00	27.95	100.00	100.00	101.50	110.50	110.00
3/9/98	7	90.93	61.13	29.80	100.00	100.00	102.00	112.00	111.00
3/9/98	8	94.73	61.10	33.63	100.00	100.00	102.50	112.50	111.50
3/9/98	9	106.43	61.35	45.08	100.00	100.00	104.50	115.00	113.00
3/9/98	10	106.13	61.03	45.10	100.00	100.00	105.00	115.00	114.00
3/9/98	11	117.43	61.10	56.33	100.00	100.00	106.75	116.50	115.00
3/9/98	12	121.60	61.58	60.03	100.00	100.00	108.00	118.00	115.00
3/9/98	13	126.85	61.83	65.03	100.00	100.00	108.25	118.25	116.00

3/9/98	14	137.00	62.13	74.88	100.00	100.00	110.00	120.00	117.00
3/9/98	15	136.55	61.68	74.88	100.00	100.00	110.00	119.75	117.00

Table A6. Ice Harbor Dam – Transect T5

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T5Pc	L2T5Pc	L3T5P	L4T5P	L5T5P	L6T5Pc	L7T5Pc
3/5/98	4	49.95	35.05	14.90	103.00	103.50	102.00	102.00	103.50	106.25	106.50
3/5/98	5	50.13	35.18	14.95	103.00	103.00	102.00	102.00	103.50	107.00	108.75
3/5/98	6	61.58	35.30	26.28	104.00	104.25	102.50	103.25	105.50	108.75	109.75
3/5/98	7	65.23	35.28	29.95	105.25	107.00	105.50	107.00	108.00	111.00	111.00
3/5/98	8	70.68	35.13	35.55	105.50	107.00	106.00	107.00	108.25	111.00	111.25
3/5/98	9	80.40	35.33	45.08	106.50	108.00	107.25	108.25	110.50	113.50	113.50
3/5/98	10	80.48	35.35	45.13	107.25	108.75	108.00	109.00	111.00	113.75	114.00
3/5/98	11	92.83	35.35	57.48	108.50	109.75	108.25	109.75	112.00	114.50	114.75
3/5/98	12	95.73	35.50	60.23	109.00	110.00	109.50	111.00	113.50	115.25	115.75
3/5/98	13	99.30	35.35	63.95	108.25	110.00	110.00	111.00	114.00	115.50	115.75
3/5/98	14	110.35	35.35	75.00	109.75	111.75	111.50	113.25	115.50	116.50	116.00
3/5/98	15	110.33	35.33	75.00	110.00	111.75	112.00	114.00	116.00	117.00	116.25

Table A6. Ice Harbor Dam – Transect T5

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T5Pc	L2T5Pc	L3T5P	L4T5P	L5T5P	L6T5Pc	L7T5Pc
3/6/98	4	15.00	0.00	15.00	97.00	98.75	101.00	105.00	102.00	101.75	101.25
3/6/98	5	15.00	0.00	15.00	97.25	99.25	101.00	105.00	105.25	106.50	104.25
3/6/98	6	26.73	0.38	26.35	101.75	105.75	104.00	105.00	108.00	109.00	108.00
3/6/98	7	30.63	0.50	30.13	108.25	110.50	108.25	107.50	111.50	112.00	111.00
3/6/98	8	38.10	0.50	37.60	113.00	112.25	111.25	110.00	112.00	111.75	111.75
3/6/98	9	45.48	0.50	44.98	114.25	113.75	112.25	111.50	113.00	113.00	112.75
3/6/98	10	45.60	0.50	45.10	115.00	114.25	113.00	113.00	114.00	113.00	113.25
3/6/98	11	56.80	0.50	56.30	115.50	114.50	113.25	113.25	114.25	113.75	113.75
3/6/98	12	60.60	0.50	60.10	115.00	115.00	114.00	114.00	115.00	114.00	114.25
3/6/98	13	67.40	0.50	66.90	115.00	115.00	114.00	114.00	115.00	114.00	114.25

3/6/98	14	75.20	0.23	74.98	115.75	116.25	115.25	115.50	116.75	115.75	115.00
3/6/98	15	75.00	0.00	75.00	115.25	116.25	116.00	116.00	117.00	115.75	115.25

Table A6. Ice Harbor Dam – Transect T5

March 7, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T5Pc	L2T5Pc	L3T5P	L4T5P	L5T5P	L6T5Pc	L7T5Pc
3/7/98	4	15.20	0.00	15.20	96.50	98.25	100.00	106.00	101.00	100.25	100.00
3/7/98	5	15.20	0.00	15.20	96.50	98.25	100.25	105.00	105.00	106.00	104.25
3/7/98	6	29.95	0.00	29.95	101.25	106.50	104.50	105.00	108.25	108.25	106.75
3/7/98	7	30.40	0.00	30.40	108.50	110.25	109.00	105.75	111.75	111.00	110.50
3/7/98	8	36.13	0.00	36.13	113.00	111.75	111.00	107.25	112.00	111.00	110.75
3/7/98	9	44.90	0.00	44.90	114.75	113.50	111.75	109.00	113.25	112.75	112.50
3/7/98	10	45.08	0.00	45.08	116.00	114.50	113.50	111.50	114.00	113.00	112.75
3/7/98	11	59.78	0.00	59.78	115.75	114.75	114.00	112.25	114.50	113.50	113.50
3/7/98	12	60.15	0.00	60.15	116.00	116.00	115.00	113.50	115.00	114.50	114.00
3/7/98	13	65.88	0.00	65.88	115.75	115.75	115.00	114.00	115.00	114.00	114.00
3/7/98	14	74.85	0.00	74.85	115.75	116.75	116.00	115.25	117.00	116.00	115.00
3/7/98	15	74.90	0.00	74.90	115.75	116.50	117.00	116.00	117.00	116.00	115.00

Table A6. Ice Harbor Dam – Transect T5 March 9, 1998, 8-Bay Spill Pattern											
Date	Hour	River Flow	Generation	Spillway Flow	L1T5Pc	L2T5Pc	L3T5P	L4T5P	L5T5P	L6T5Pc	L7T5Pc
3/9/98	4	75.73	60.73	15.00	100.00	100.00	100.00	102.00	100.75	104.50	105.00
3/9/98	5	75.90	60.90	15.00	99.75	100.00	100.00	102.00	100.00	103.75	106.00
3/9/98	6	88.95	61.00	27.95	100.00	100.50	100.25	102.00	102.25	107.00	108.25
3/9/98	7	90.93	61.13	29.80	100.00	100.00	100.00	102.25	105.00	109.75	111.00
3/9/98	8	94.73	61.10	33.63	100.00	100.00	100.00	103.00	105.00	110.00	111.00
3/9/98	9	106.43	61.35	45.08	100.25	102.25	102.75	104.00	108.75	112.00	113.00
3/9/98	10	106.13	61.03	45.10	100.00	102.00	103.75	105.00	109.00	112.50	113.00
3/9/98	11	117.43	61.10	56.33	101.25	103.50	104.75	105.75	110.25	113.25	114.00
3/9/98	12	121.60	61.58	60.03	102.00	104.50	107.00	107.25	112.00	114.00	115.00
3/9/98	13	126.85	61.83	65.03	102.00	105.00	107.00	108.00	112.25	114.25	114.75
3/9/98	14	137.00	62.13	74.88	104.25	107.25	108.75	110.25	114.50	116.00	116.00
3/9/98	15	136.55	61.68	74.88	104.25	107.25	109.00	111.00	114.75	115.50	116.00

Table A7. Ice Harbor Dam – Transect T6

March 5, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T6P	L2T6P	L3T6P
3/5/98	4	49.95	35.05	14.90	102.50	103.00	103.00
3/5/98	5	50.13	35.18	14.95	102.75	105.25	105.25
3/5/98	6	61.58	35.30	26.28	103.00	106.00	107.00
3/5/98	7	65.23	35.28	29.95	103.00	108.50	108.50
3/5/98	8	70.68	35.13	35.55	105.75	110.00	110.25
3/5/98	9	80.40	35.33	45.08	106.25	111.00	111.25
3/5/98	10	80.48	35.35	45.13	107.25	113.00	113.50
3/5/98	11	92.83	35.35	57.48	108.00	113.00	114.00
3/5/98	12	95.73	35.50	60.23	108.50	115.25	115.00
3/5/98	13	99.30	35.35	63.95	109.25	116.00	116.00
3/5/98	14	110.35	35.35	75.00	109.25	116.50	116.25
3/5/98	15	110.33	35.33	75.00	111.00	117.00	117.00
3/5/98	16	95.68	70.90	24.78	111.00	117.00	117.00

Table A7. Ice Harbor Dam – Transect T6

March 6, 1998, 10-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T6P	L2T6P	L3T6P
3/6/98	4	15.00	0.00	15.00	101.00	102.00	102.00
3/6/98	5	15.00	0.00	15.00	101.00	102.00	102.00
3/6/98	6	26.73	0.38	26.35	101.00	102.00	102.00
3/6/98	7	30.63	0.50	30.13	101.00	106.25	104.00
3/6/98	8	38.10	0.50	37.60	103.00	111.00	109.25
3/6/98	9	45.48	0.50	44.98	109.25	112.00	111.50
3/6/98	10	45.60	0.50	45.10	112.25	113.75	112.50
3/6/98	11	56.80	0.50	56.30	113.75	114.00	113.75
3/6/98	12	60.60	0.50	60.10	114.00	114.75	114.25
3/6/98	13	67.40	0.50	66.90	115.00	115.00	115.00
3/6/98	14	75.20	0.23	74.98	115.00	115.75	115.00
3/6/98	15	75.00	0.00	75.00	115.75	117.00	116.00
3/6/98	16	59.68	43.68	16.00	116.00	117.00	116.00

Table A7. Ice Harbor Dam – Transect T6

March 7, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T6P	L2T6P	L3T6P
3/7/98	4	15.20	0.00	15.20	100.00	101.00	101.00
3/7/98	5	15.20	0.00	15.20	100.00	101.00	101.00
3/7/98	6	29.95	0.00	29.95	100.00	101.00	101.00
3/7/98	7	30.40	0.00	30.40	100.25	106.00	103.75
3/7/98	8	36.13	0.00	36.13	103.00	111.00	108.50
3/7/98	9	44.90	0.00	44.90	109.00	112.00	111.00
3/7/98	10	45.08	0.00	45.08	112.25	113.75	112.50
3/7/98	11	59.78	0.00	59.78	114.00	114.00	114.00
3/7/98	12	60.15	0.00	60.15	115.00	115.25	114.50
3/7/98	13	65.88	0.00	65.88	115.75	116.00	115.00
3/7/98	14	74.85	0.00	74.85	116.00	116.25	115.25
3/7/98	15	74.90	0.00	74.90	116.75	117.00	116.25
3/7/98	16	63.23	50.28	12.95	117.00	117.00	116.75

Table A7. Ice Harbor Dam – Transect T6

March 9, 1998, 8-Bay Spill Pattern

Date	Hour	River Flow	Generation	Spillway Flow	L1T6P	L2T6P	L3T6P
3/9/98	4	75.73	60.73	15.00	100.00	101.25	100.50
3/9/98	5	75.90	60.90	15.00	100.25	103.00	104.75
3/9/98	6	88.95	61.00	27.95	100.00	103.00	105.00
3/9/98	7	90.93	61.13	29.80	100.25	108.75	109.75
3/9/98	8	94.73	61.10	33.63	100.00	109.00	111.00
3/9/98	9	106.43	61.35	45.08	100.75	110.50	111.75
3/9/98	10	106.13	61.03	45.10	102.00	112.50	114.00
3/9/98	11	117.43	61.10	56.33	102.00	113.00	114.00
3/9/98	12	121.60	61.58	60.03	103.75	115.00	115.75
3/9/98	13	126.85	61.83	65.03	104.25	115.00	116.00
3/9/98	14	137.00	62.13	74.88	105.00	116.25	116.75
3/9/98	15	136.55	61.68	74.88	106.25	117.00	118.00
3/9/98	16	125.83	65.48	60.35	106.00	117.00	118.00

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Based on the results of the Dissolved Gas Abatement Studies, spillway deflectors were adopted for Ice Harbor as a measure to reduce the total dissolved gas (TDG) production during spill operations. Three field studies were conducted at the Ice Harbor Spillway on the lower Snake River to characterize the effects of spill operations on TDG in the Snake River. The first two studies examined TDG production for the original spillway design. The third study characterized TDG production with flow deflectors installed on the spillway face. TDG was significantly reduced for nearly all spill operations with deflectors in place. TDG near the stilling basin was reduced from approximately 150% to approximately 124%. TDG at end of the navigation guide wall was reduced from 135% to 114% for similar operating conditions.

15. SUBJECT TERMS (see reverse)

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** **Steve Wilhelms**
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15. SUBJECT TERMS (concluded)

Dissolved Gas
Spillway Deflectors
Spillways
Stilling basins
Supersaturation
Total Dissolved Gas
Columbia River
Snake River (Wyo.-Wash.)
Nitrogen supersaturation
Water--Dissolved oxygen
Hydraulic structures
Spillways
Stilling basins
Water--Air entrainment
Tailwater ecology
Ice Harbor Dam