California Department of Water Resources Demonstration Dissolved Oxygen Aeration Facility

2008 Operations Performance Report

Prepared for:

California Department of Water Resources
1416 9th Street
Sacramento, CA 94236-0001
Contact: Bill McLaughlin, P.E.
(916) 653-0628

Prepared by:

ICF International
630 K Street, Suite 400
Sacramento, CA 95814
Contact: Russ Brown, Ph.D.
(916) 737-3000

April 2010

ICF International. 2010. *California Department of Water Resources Demonstration Dissolved Oxygen Aeration Facility 2008 Operations Performance Report.* April. (ICF 00902.08). Sacramento, CA. Prepared for: California Department of Water Resources, Sacramento, CA.

Executive Summary

Periods of low dissolved oxygen (DO) concentration have been observed in the Stockton Deep Water Ship Channel (DWSC) downstream from the city of Stockton that have not met the Central Valley Basin Plan water quality objectives for DO. In January 1998, the State Water Resources Control Board (State Water Board) adopted a Clean Water Act (CWA) Section 303(d) list that identified this DO impairment. The Central Valley Regional Water Quality Control Board (Central Valley RWQCB) initiated development of a total maximum daily load (TMDL) that identifies the factors contributing to the DO impairment and apportions responsibility for correcting the low-DO problem.

Since the approval of the TMDL in 2007, two actions have been implemented to alleviate low DO conditions in the DWSC. The City of Stockton added two nitrifying bio-towers and engineered wetlands to the Stockton Regional Wastewater Control Facility (RWCF) to reduce ammonia discharges to the San Joaquin River (SJR). The California Department of Water Resources (DWR) constructed a demonstration aeration facility (Aeration Facility) at Rough and Ready Island (RRI) to determine its effectiveness for improving DO conditions in the DWSC (described in this report).

The Aeration Facility was constructed at the west end of RRI at the Port of Stockton and currently is maintained and operated for testing purposes by DWR. The first period of the demonstration testing began in June 2008 and ended in late September 2008. The demonstration testing phase is anticipated to end by December 2010.

This report describes the 2008 operations of the Aeration Facility and evaluates the performance of the Aeration Facility with respect to increasing the DO concentrations in the DWSC.

Aeration Facility Performance

The performance of the Aeration Facility can be evaluated by its ability to increase DO concentrations in the DWSC and contribute to maintaining DO concentrations above the Basin Plan objective of 5 milligrams per liter (mg/l) (6 mg/l in September–November). The performance evaluation can be summarized by answering the following questions:

1. Can the Aeration Facility be used to meet the DO objectives in the DWSC?

   Based on the available data obtained during the performance testing, the analysis and evaluation in this report indicate that the Aeration Facility can be used in many circumstances to meet the DO objectives in the DWSC. However, it was found that the effectiveness of the Aeration Facility was strongly dependent on various factors, including: natural DO concentrations in the DWSC, surface reaeration, biochemical oxygen demand (BOD) concentrations, algal photosynthesis, river flow, and the tidal cycle. Operating strategies for the Aeration Facility can be developed that will increase the ability of the Aeration Facility to help meet the Basin Plan DO objectives in the DWSC. However, it is not reasonable to expect the Aeration Facility to meet the Basin Plan DO objectives in all situations.

2. Is the RRI monitoring station representative of the "natural" DO concentrations (i.e., without the Aeration Facility operating) in the DWSC, and is it possible to estimate natural DO concentrations while the Aeration Facility is operating?

   Comparison of the RRI DO data with the upstream and downstream DO monitoring stations suggested that the RRI station is near the location of the minimum DO in the DWSC, at least for low-flow conditions such as those observed in 2008. The RRI station is representative of natural DO conditions throughout most of the DWSC upstream of Turner Cut. Because the RRI station is just 0.2 mile downstream of the diffuser, it also shows the greatest response to added DO from the Aeration Facility. Based on the available data, and the analysis and evaluation in this report, it is possible to use the RRI DO data to estimate the natural DO conditions while the Aeration Facility is operating. This is accomplished by subtracting the incremental DO (i.e., DO added to the DWSC by the Aeration Facility) from the measured DWSC monitoring station DO data.

3. Is the Aeration Facility appropriately located to effectively improve the low DO problem?

   Because the RRI station is located near the minimum DO position in the DWSC, the Aeration Facility is located appropriately to increase the DO in the DWSC. Because of tidal movement and mixing, some added DO from the Aeration facility is distributed 1.5 miles upstream and 3 miles downstream. However, the majority of the added DO typically will be observed in the DWSC from about 0.5 mile upstream of the diffuser to about 1.5 miles downstream of the diffuser, because of the net downstream DWSC flow.

Recommendations

The following recommendations are made to improve the performance of the Aeration Facility and obtain more data for developing an Aeration Facility Operational Plan. The Aeration Facility Operational Plan should reduce operational costs while increasing the probability of meeting the Basin Plan DO objectives for the DWSC.

1. Further adjustments in the Aeration Facility should be tested to improve the oxygen gas transfer efficiency and increase the capacity for adding DO to the DWSC.
2. Additional testing of tidal operations during flood tide (i.e., upstream flow) should be made to shift the distribution of the added DO from the Aeration Facility upstream toward Navigation Aid (Light) 48.
3. A long-term monitoring plan should be developed for the DWSC based on the DO monitoring at Light 48, Light 43, RRI, Light 42, and Light 40 stations. RRI could remain the primary monitoring location for evaluating natural DO conditions in the DWSC, effects of the City of Stockton RWCF nitrification facility, and effects of the added DO from the Aeration Facility.
4. An operational strategy for the Aeration Facility should be tested that would involve using upstream flow and water quality monitoring at Mossdale to forecast the DWSC DO profile and the need to operate the Aeration Facility (one or two pumps).

5. The integration of the Port of Stockton aeration facilities at Dock 13 with operation of the Aeration Facility at Dock 20 (RRI) should be evaluated as part of the SJR DO TMDL implementation plan. Procedures for identifying DWSC DO conditions that are not meeting the DO objectives, and estimating the City of Stockton RWCF contributions to improved DO conditions in the DWSC, also should be developed.

Table of Contents

Page

Introduction 1

Aeration Facility Performance Objectives 2

Aeration Facility Description 2

Demonstration Monitoring Plan 3

Demonstration Operational Plan 4

Deep Water Ship Channel Background Data 4

City of Stockton River Water Quality Data 5

2008 Aeration Facility Performance Results 6

Movement and Mixing of Dissolved Oxygen from the Aeration Facility in the Deep Water Ship Channel 7

California Department of Water Resources *San Carlos* Survey Measurements of Dissolved Oxygen in the Deep Water Ship Channel in 2008 10

Dissolved Oxygen at the Deep Water Ship Channel Monitoring Stations 13

University of the Pacific Longitudinal Dissolved Oxygen Profiles in the Deep Water Ship Channel from June to September 2008 18

Comparison of Longitudinal Profiles and Monitoring Station Data 24

Summary of Performance Results 28

San Carlos Deep Water Ship Channel Dissolved Oxygen Boat Surveys in 2004 and 2008 28

Tidal Movement and Dissolved Oxygen Increments 29

Dissolved Oxygen Longitudinal Profile Results 30

Conclusions 31

Recommendations 32

References 33

Appendix A ***San Carlos* Dissolved Oxygen Surveys and the Deep Water Ship Channel Dissolved Oxygen Model**

Appendix B **Monitoring of the Aeration Facility Effects and Calculated Dissolved Oxygen Increments in the Stockton Deep Water Ship Channel**

Tables, Figures, and Photographs

Table **Page**

1 Calculated Dissolved Oxygen Increments in the Deep Water Ship Channel with Reaeration for Maximum Dissolved Oxygen Diffuser Output of 7,500 lb/day 13

Figure **at end of Report**

1 Stockton Deep Water Ship Channel Water Quality Stations

2a Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2001.

b Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2002

c Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2003

d Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2004

e Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2005

f Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2006

g Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2007

h Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2008

3a City of Stockton DO Measurements in the DWSC (R3, R4, R5, and R6) Compared to the Saturated, Minimum, and Maximum DO Concentrations at the DWR RRI Monitoring Station for 2004

b San Joaquin River Inflow BOD Concentration (mg/l) Measured by City of Stockton in 2004

c Weekly DO Concentrations (mg/l) Measured in the DWSC by City of Stockton in 2008

d Weekly River Inflow 10-day BOD Concentrations (mg/l) Measured by City of Stockton in 2008

4a Tidal Elevations and Tidal Movement Calculated for the RRI Station for June 2008

b Tidal Elevations and Tidal Movement Calculated for the RRI Station for July 2008

5a Depth Profiles near the Diffuser before and after Aeration Facility Operation on March 18, 2008

b Longitudinal Profile Measured at the 10-Foot Depth, 20–30 Feet away from the Diffuser on March 18, 2008

6 Lateral Profiles of Dye and Dissolved Oxygen Concentrations Measured near Center of the Diffuser at Higher-High Slack Tide on March 18, 2008

7a Longitudinal Dissolved Oxygen Profiles Measured 15-20 Feet away from Diffuser on April 30, 2008

b Longitudinal Dye and Dissolved Oxygen Concentratioin Profiles along Mid-Channel Measured at the 10-Foot Depth after the First Dye Injection of August 5, 2008

8a Longitudinal Dye Concentration Profiles Measured 1 Tidal Day (25 hr) after Each Dye Injection on August 5, 2008

b Longitudinal Dye Concentration Profiles Measured along the Dock and at Mid-Channel 8–9 Hours after the Low-Low Slack Tide Dye Injection of August 13, 2008

9a Longitudinal Dye Profile Measured near Mid-Channel at High Tide on August 14, 2008, about 18 Hours after Dye Release

b Longitudinal Dye Concentration Profile near Mid-Channel at Low Tide on August 14, 2008, about 25 Hours after Dye Release

10a Measured and Calculated DWSC DO Profile for July 16, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l, and BOD of 10 mg/l

b Measured and Calculated DWSC DO Profile for July 30, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l, and BOD of 10 mg/l

c Measured and Calculated DWSC DO Profile for August 14, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l and BOD of 10 mg/l

d Measured and Calculated DWSC DO Profile for August 28, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l, and BOD of 10 mg/l

11a Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for June 2008

b Daily Average DO Concentrations at the DWSC Monitoring Stations for June 2008

12a Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for July 2008

b Daily Average DO Concentrations at the DWSC Monitoring Stations for July 2008

13a Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for August 2008

b Daily Average DO Concentrations at the DWSC Monitoring Stations for August 2008

14a Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for September 2008

b	Daily Average DO Concentrations at the DWSC Monitoring Stations for September 2008
15a	DWSC DO Profile on August 12, 2008 (Prior to DO Diffuser Operation)
b	DWSC Chlorophyll (Algae) Profile on August 12-16, 2008
c	DWSC DO Profile on August 13, 2008 (1 Day of DO Diffuser Operation)
d	DWSC DO Profile on August 14, 2008 (2 Days of Operation)
e	DWSC DO Profile on August 15, 2008 (3 Days of DO Dffuser Operation)
f	DWSC DO Profile on August 16, 2008 (4 Days of Operation)
16a	DWSC Surface DO Profiles for August 12–16, 2008 with San Carlos Data from August 14, 2008
b	DWSC Bottom DO Profiles for August 12–16, 2008 with San Carlos Data from August 14, 2008
17a	DWSC DO Profile on August 26, 2008 (Prior to DO Diffuser Operation)
b	DWSC Chlorophyll (Algae) Profiles on August 26-September 5, 2008
c	DWSC DO Profile on August 28, 2008 (2 Days of Operation)
d	DWSC DO Profile on August 30, 2008 (4 Days of Operation)
e	DWSC DO Profile on September 1, 2008 (6 Days of Operation)
f	DWSC DO Profile on September 3, 2008 (8 Days of Operation)
g	DWSC DO Profile on September 5, 2008 (10 Days of Operation)
h	DWSC Surface and Bottom Temperature Profiles from August 26 to September 5, 2008
18a	DWSC DO Profile on September 15, 2008 (Prior to DO Diffuser Operation)
b	DWSC Chlorophyll (µg/l) Profiles for September 15 to September 26, 2008 Surveys
c	DWSC DO Profile on September 18, 2008 (2 Days of Operation)
d	DWSC DO Profile on September 20, 2008 (4 Days of Operation)
e	DWSC DO Profile on September 22, 2008 (6 Days of Operation).
f	DWSC DO Profile on September 26, 2008 (10 Days of Operation).
g	DWSC DO Profile on September 29, 2008 (3 Days without Aeration)
h	DWSC DO Profile on October 4, 2008 (8 Days without Aeration)
19a	DO Concentrations at Upstream DO Monitoring Stations for August 11–17, 2008.
b	DO Concentrations at Downstream DO Monitoring Stations for August 11–17, 2008
20a	DO Concentrations at Upstream Monitoring Stations for August 25 to September 5, 2008
b	DO Concentrations at Downstream Monitoring Stations for August 25 to September 5, 2008
21a	DO Concentrations at Upstream Monitoring Stations for September 15 to 26, 2008
b	DO Concentrations at Downstream Monitoring Stations for September 15 to 26, 2008

Photograph		**Follows Page**

1 Aeration Facility 2

2 Upstream DWSC DO Monitoring Stations 4

3 Downstream DWSC DO Monitoring Stations 4

Acronyms and Abbreviations

µg/l	micrograms per liter
Aeration Facility	aeration facility
Af	acre-feet
BOD	biochemical oxygen demand
Central Valley RWQCB	Central Valley Regional Water Quality Control Board
cfs	cubic feet per second
CVP	Central Valley Project
CWA	Clean Water Act
DO	Dissolved Oxygen
DWR	California Department of Water Resources
DWSC	Stockton Deep Water Ship Channel
DWSC DO Model	Stockton Deep Water Ship Channel DWSC) Dissolved Oxygen Model
EC	electrical conductivity
mg/l	milligrams per liter
RRI	Rough and Ready Island
RWCF	Regional Wastewater Control Facility
SJR	San Joaquin River
State Water Board	State Water Resources Control Board
SWP	State Water Project
TMDL	total maximum daily load
USGS	U.S. Geological Survey
VAMP	Vernalis Adaptive Management Plan

Introduction

Periods of low dissolved oxygen (DO) concentration have been observed in the Stockton Deep Water Ship Channel (DWSC) downstream from the city of Stockton that have not met the Central Valley Basin Plan water quality objectives for DO. In January 1998, the State Water Resources Control Board (State Water Board) adopted a Clean Water Act (CWA) Section 303(d) list that identified this DO impairment. The Central Valley Regional Water Quality Control Board (Central Valley RWQCB) initiated development of a total maximum daily load (TMDL) that identifies the factors contributing to the DO impairment and apportions responsibility for correcting the low-DO problem.

Since the approval of the TMDL in 2007, two actions have been implemented to alleviate low DO conditions in the DWSC. The City of Stockton added two nitrifying bio-towers and engineered wetlands to the Stockton Regional Wastewater Control Facility (RWCF) to reduce ammonia discharges to the San Joaquin River (SJR). The California Department of Water Resources (DWR) constructed a demonstration aeration facility (Aeration Facility) at Rough and Ready Island (RRI) to determine its effectiveness for improving DO conditions in the DWSC (described in this report).

The Aeration Facility was constructed at the west end of RRI at the Port of Stockton and currently is maintained and operated for testing purposes by DWR. The first period of the demonstration testing began in June 2008 and ended in late September 2008. The demonstration testing phase is anticipated to end by December 2010.

This report describes the 2008 performance testing of the Aeration Facility and evaluates the performance of the Aeration Facility against several performance objectives (defined in the following section). This report describes the monitoring and measurements collected in 2008 and the analysis methods used to evaluate the performance objectives. The evaluation of the monitoring data and analysis of the Aeration Facility performance are presented in five sections:

1. **Movement and Mixing of Dissolved Oxygen from the Aeration Facility in the Deep Water Ship Channel—**investigates the tidal movement and spreading of added DO from the Aeration Facility diffuser;
2. **California Department of Water Resources Boat Survey Measurements of Dissolved Oxygen in the Deep Water Ship Channel in 2008 (*San Carlos* surveys)—**provides a summary of the DWR DWSC DO measurement surveys conducted by boat (more fully described in Appendix A);
3. **Dissolved Oxygen at the Deep Water Ship Channel Monitoring Stations—**discusses measured DO concentrations at the five DO monitoring stations during 2008 Aeration Facility testing periods (more fully described in Appendix B);
4. **University of the Pacific Longitudinal Dissolved Oxygen Profiles from June to September 2008—**evaluates DO measurements from three depths in the DWSC during the Aeration Facility testing periods in 2008; and
5. **Comparison of Longitudinal Profiles and Monitoring Station Data—**compares DO measurement surveys and monitoring station data.

A summary section with conclusions and recommendations completes the report. Two technical appendices are provided for more detailed information. Appendix A describes the *San Carlos* surveys in the DWSC, and the Stockton Deep Water Ship Channel Dissolved Oxygen Model (DWSC DO Model), which was developed to evaluate the measured DWSC DO conditions. Appendix B describes the monitoring of added DO from the Aeration Facility at the RRI station and the four new stations installed by DWR for this testing program. A second model (DO Increment Model) that was used to estimate the DO increments from the Aeration Facility at each of the DO monitoring stations in the DWSC is presented in Appendix B.

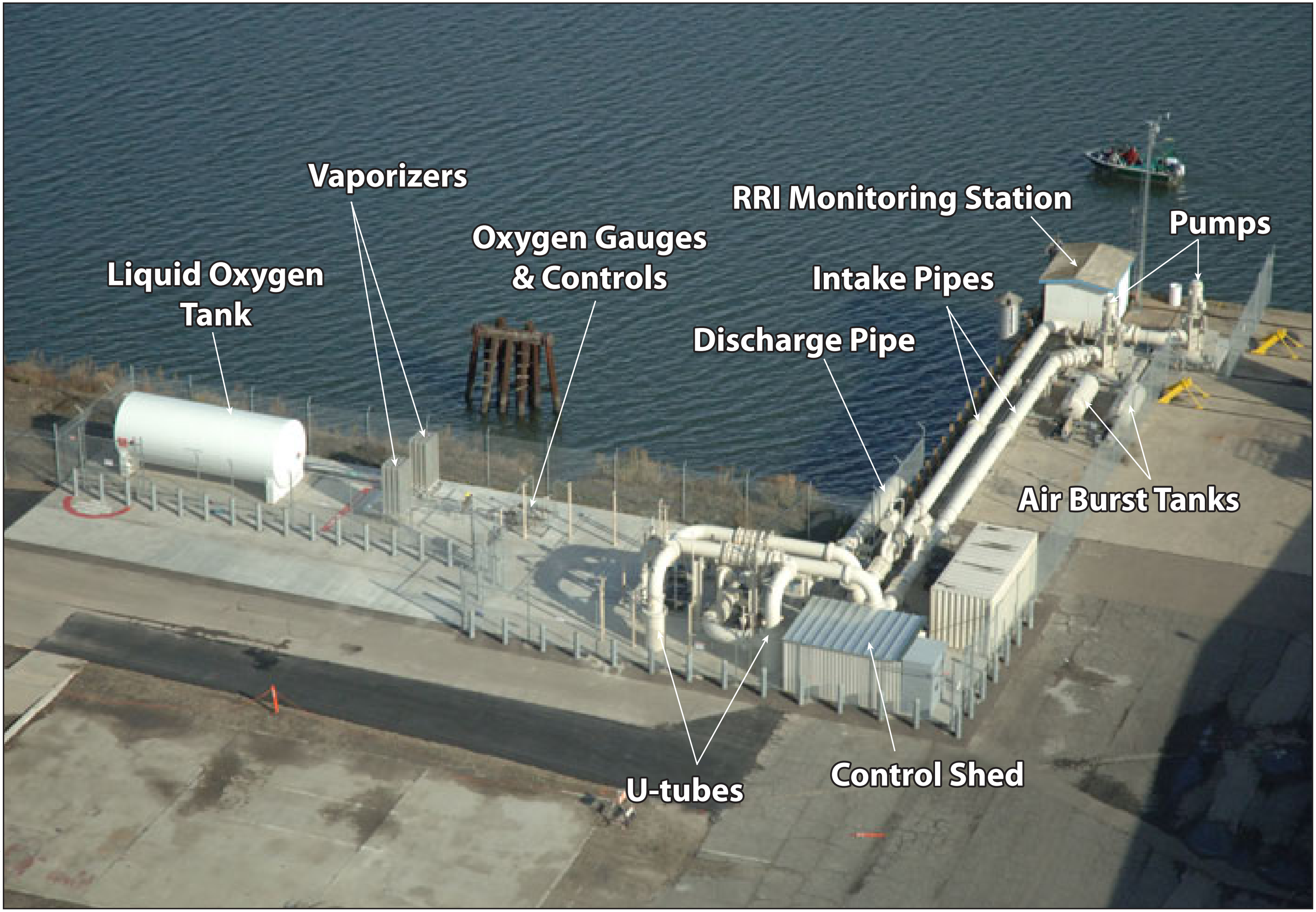
Aeration Facility Performance Objectives

Several performance objectives were established for the DWR Aeration Facility 2008 testing program. Testing of the Aeration Facility capacity and oxygen transfer efficiency was considered in a previous report (ICF Jones & Stokes 2008). The six 2008 performance objectives can be summarized as:

- Determine how well the existing RRI DO monitoring station (at approximately 3-foot [ft] depth) represents natural DO conditions in the DWSC from Turner Cut to Channel Point (natural DO conditions);
- Determine whether the Aeration Facility diffuser location between Dock 19 and Dock 20 is appropriate for adding DO to the DWSC to alleviate the lowest DO conditions (location);
- Determine how much DO could be added to the DWSC from the Aeration Facility under a variety of flows (i.e., 250 cubic feet per second [cfs] to 1,000 cfs) at maximum Aeration Facility capacity (DO increments);
- Determine how much of an effect on DO could be expected along the DWSC at high tide and low tide (tidal spreading);
- Determine the effects of natural surface reaeration on the downstream DO profile and the DO increments from the Aeration Facility (reaeration rate); and
- Determine the ability of the Aeration Facility to maintain DWSC DO above the Basin Plan objectives of 5 milligrams per liter (mg/l) from December 1 through August 31, and 6 mg/l from September 1 through November 30 (DO objectives).

Aeration Facility Description

Photograph 1 provides an aerial view of the Aeration Facility, which was constructed at the west end of RRI at the Port of Stockton and currently is maintained and operated for testing purposes by DWR. The Aeration Facility includes a liquid oxygen storage tank and two identical 200 ft–deep wells consisting of an inner and outer casing forming a "U-tube." Water for each U-tube is drawn from the DWSC through a screened intake using a vertical turbine pump. The water is pumped to the inner of the two concentric casings, gaseous oxygen is injected, and the water then flows down to the bottom through an open space that allows the water to flow up the outer casing. The two outer discharge casings merge into a single pipe that conveys the discharge water to the 200 ft–long DO diffuser located under the dock about 1,000 ft upstream of the U-tubes. This U-tube configuration provides increased contact time and hydrostatic pressure, which increases the gas adsorption rate and raises the DO concentration.



ICF INTERNATIONAL

Photograph 1
Aeration Facility

Photograph 2 shows the DWSC upstream of the Aeration Facility. The location of the diffuser and the upstream DO monitors at Light 43 and Light 48 are indicated. The diffuser is approximately 200 ft long and is mounted along the pilings beneath the dock about 10 ft inside of the edge of the dock (protected from ships). It is positioned such that it remains submerged 10 ft deep at low tide. The water is about 30 ft deep at the diffuser (dredged for ships to dock). The 80 ports on the diffuser have a diameter of 6 inches and are spaced every 2.5 ft. The port alignment alternates between lateral and 45° downward angles. Photograph 3 shows the DWSC downstream of the Aeration Facility. The location of the downstream DO monitors at Light 42 and Light 40 are indicated.

Figure 1 shows a map of the DWSC and the DO monitoring stations. The most upstream monitor is at Light 48, about 1.5 miles upstream of the diffuser. Light 43 is located about 0.2 mile upstream. The RRI monitor is located about 0.2 mile downstream, Light 42 is located about 0.7 mile downstream, and Light 40 is located about 1.6 miles downstream of the diffuser. Locations in the DWSC generally are referenced with the SJR mile or with the numbered Lights. The river stations for the City of Stockton Regional Wastewater Control Facility (RWCF) water quality monitoring program also are shown.

Demonstration Monitoring Plan

As part of the basic monitoring approach described in the *Aeration Technology Feasibility Report for the San Joaquin River Deep Water Ship Channel* (Jones & Stokes 2004), three primary data collection methods were included:

1. The existing RRI water quality monitoring station, operated by DWR, will continue to be the main station for determining the effectiveness of the Aeration Facility. Mid-depth and near-bottom sensors were added at the RRI station by DWR to investigate vertical stratification and DO gradients.

2. Four additional monitoring stations with 15-minute DO monitoring were installed in the DWSC by DWR. Two stations were located upstream of the diffuser (at Lights 48 and 43), and two were located downstream (at Lights 42 and 40). These four stations provide a complete record of the position and extent of the longitudinal DO profile within the DWSC. Measurements are obtained from mid-depth (about 10-ft to15-ft depth) to eliminate the higher DO concentrations often measured during surface stratification.

   Monitoring of the DWSC DO concentrations at the four in-river monitoring stations began in 2007 to provide a full year of background DO monitoring. DWR also added water quality monitoring at mid-depth (10 ft) and near bottom (20 ft) at the RRI station to evaluate the effects of stratification in the DWSC. These data from 2007 and 2008 provide a very complete picture of natural DO variations within the DWSC, as well as the effects of the Aeration Facility on the DWSC DO concentrations.

3. DWSC longitudinal boat surveys were conducted by UOP for near-bottom, mid-depth, and surface measurements of temperature, DO, pH, electrical conductivity (EC), turbidity and algae fluorescence periodically during Aeration Facility operation. These longitudinal surveys provide additional data to understand the movement of the longitudinal DO profiles between high-tide and low-tide conditions.

The monitoring plan suggested that other available data be integrated in the performance testing. In addition to the DWSC longitudinal profiles conducted by UOP, DWR conducted DO monitoring in the

DWSC during the summer and fall months, using the *San Carlos* water quality sampling boat. These data were used to document the variability of DO conditions from Stockton to Turner Cut for 2004 and 2008. These data were useful in comparing DO conditions in the DWSC before and after the Stockton RWCF added nitrification to its treatment processes to reduce the ammonia concentration in the effluent discharge. Water quality sampling in the DWSC by the City of Stockton also was incorporated into this performance evaluation. Weekly mid-depth DO measurements collected in the summer by the City of Stockton from four stations between Channel Point and Turner Cut were compared with the DO monitoring stations and the UOP DWSC longitudinal surveys.

Demonstration Operational Plan

A pulsed operation of the Aeration Facility was suggested in the monitoring plan, because DO added to the DWSC from the Aeration Facility cannot be distinguished from natural DO at the monitoring stations. An operational plan was developed for 2008 that had the Aeration Facility operate for several days and then be turned off for several days. This operational plan was used to measure the increases in the DWSC DO concentrations at the five river monitoring stations, and provide data that were used to determine the amount of added DO from the Aeration Facility at each monitoring station or in the UOP boat survey DO profiles of the DWSC. The natural DO conditions at each monitoring station in the DWSC were observed during the periods when the Aeration Facility was not operating.

Deep Water Ship Channel Background Data

The design capacity for the Aeration Facility (about 10,000 pounds [lb]/day) was originally determined from review of the DWSC flows and DO concentrations for 1995–2001. The aeration capacity needed to meet the DWSC DO objectives was estimated by multiplying the DO concentration deficit (below the DO objective) by the DWSC flow. To demonstrate that flow and DO conditions in the DWSC remain similar to those during 1995–2001, the DWSC flows and DO concentrations measured at the RRI monitoring station for 2001–2008 are discussed below.

These 8 years of daily SJR and DWSC flows and DO concentrations at RRI demonstrate the general influence of flows on the DO in the DWSC. Because the DO was below the 5 mg/l DO objective in each of the years until 2008, the Aeration Facility appears to be needed. Years with higher summer flows have had higher minimum DO concentrations. The DO concentrations in 2007 and 2008 appear to be higher than in previous years with similar flows of less than 500 cfs, indicating good effects on DWSC DO from the Stockton RWCF nitrification facility, installed in 2007.

Figure 2 shows the daily minimum and maximum DO measured at the RRI station (surface monitor) for 2001–2008, together with the daily flow. Each panel shows 1 year of daily SJR flows at Vernalis and daily DWSC flows measured at the Garwood station. The DWSC flows were generally about 50% of the Vernalis flows, although the Central Valley Project (CVP) and State Water Project (SWP) pumping will reduce this flow fraction to less than 50%, and the head of Old River barrier can increase the flow fraction substantially. The saturated DO concentration is shown for reference.

The daily maximum DO can be affected by surface heating (i.e., stratification) that allows increased DO from surface reaeration and algae growth in the summer months. Therefore, the daily minimum DO was used to estimate the average DWSC DO conditions and calculate the needed aeration capacity to increase the daily DO concentration to meet the DO objective. Lower DO concentrations would require more aeration. Higher flows would require more aeration to increase the DO

ICF INTERNATIONAL

Photograph 2
Upstream DWSC DO Monitoring Stations

Graphics/Projects/00902.08 Stockton Aeration Demo Facility/2008 Operations Report (01-10) SS

ICF INTERNATIONAL

Photograph 3
Downstream DWSC DO Monitoring Stations

concentration by 1 mg/l. A combination of low DO (3 mg/l) and relatively high flow (500 cfs) would require the most aeration.

Figure 2a shows the daily average flows and the daily DO concentrations at RRI for 2001. Vernalis flows were less than 1,500 cfs from June through mid-October. The DWSC tidal flows were not available for the summer period, but using 50% of the Vernalis flow as an estimate, flows were likely about 750 cfs from June through September. The DO was less than 5 mg/l from June through September, and the DO was 3–4 mg/l during June–August.

Figure 2b shows the daily average flows and the daily DO concentrations at RRI for 2002. Vernalis flows were less than 1,500 cfs from June through mid-October. The DWSC tidal flows were less than 500 cfs from June through August. The DO was less than 5 mg/l from mid-June through mid-October, and the DO was 2–3 mg/l in July and August.

Figure 2c shows the daily average flows and the daily DO concentrations at RRI for 2003. Vernalis flows were about 2,000 cfs from July through mid-October. The DWSC tidal flows were less than 500 cfs in July and August. The DO was less than 5 mg/l from June through mid-September, and the DO was 3–4 mg/l in July and August.

Figure 2d shows the daily average flows and the daily DO concentrations at RRI for 2004. Vernalis flows were about 1,500 cfs from June through August. The DWSC tidal flows were less than 500 cfs from June through August. The DO was less than 5 mg/l from June through mid-October, and the DO was 2–3 mg/l from July through September.

Figure 2e shows the daily average flows and the daily DO concentrations at RRI for 2005. Vernalis flows were greater than 2,500 cfs all summer. The DWSC tidal flows were higher than 1,000 cfs all summer. The DO was less than 5 mg/l in August and September, and the DO was 4 mg/l in August and September.

Figure 2f shows the daily average flows and the daily DO concentrations at RRI for 2006. Vernalis flows were greater than 3,500 cfs all summer. The DWSC tidal flows were higher than 1,500 cfs all summer. The DO was less than 5 mg/l in July and August, and the DO was 4 mg/l in July and August.

Figure 2g shows the daily average flows and the daily DO concentrations at RRI for 2007. Vernalis flows were about 1,000 cfs from July through mid-October. The DWSC tidal flows were less than 500 cfs in July and September. The DO was less than 5 mg/l from June through August, and the DO was 3–4 mg/l in June and July.

Figure 2h shows the daily average flows and the daily DO concentrations at RRI for 2008. Vernalis flows were less than 1,000 cfs from June through September. The DWSC tidal flows were less than 500 cfs from June through September. The DO was never less than 5 mg/l from June through September. The Aeration Facility was operated about half of the time from mid-June through September.

City of Stockton River Water Quality Data

Evaluation of the City of Stockton water quality data for river water quality changes due to the waste water treatment plant process modifications was part of the monitoring plan. The City of Stockton conducts weekly sampling at nine river stations as part of its discharge permit from the RWQCB. River station R3 is located at Light 48, R4 is located at Light 45, R5 is located downstream of RRI at Light 42, R6 is located at Light 36, R7 is located near Turner Cut at Light 24, and R8 is located at

Light 18. DO concentrations at R7 and R8 are usually high because they are strongly influenced by Sacramento River water. Figure 3 shows the City of Stockton data from stations R3 to R6 for 2004 and 2008 to demonstrate reduction in DWSC biochemical oxygen demand (BOD) as the result of the City of Stockton nitrification facility completed in 2007. The RRI DO data are also shown to demonstrate that the minimum DO in the DWSC often is located near the RRI station.

Figure 3a shows the mid-depth DO concentrations measured at the DWSC stations (R3 to R6) for 2004, compared to the daily DO concentrations from the RRI station. The City of Stockton summer DO data generally were confirmed by the DO concentrations measured at the RRI station. The major decline in the DWSC DO concentrations in 2004 was measured in June as flow decreased after the Vernalis Adaptive Management Plan (VAMP) period. The RRI DO was less than 5 mg/l from early June through early October, and was 2–3 mg/l in July, August, and September. The minimum DO often was measured at stations R4 and R5, located in the vicinity of RRI. This indicates that the minimum DO in the DWSC is often observed in the vicinity of the RRI station.

Figure 3b shows 10-day BOD measurements from the three upstream river stations in 2004. The maximum 10-day BOD concentrations in June, July, and August were about 10–12 mg/l. Because the 30-day BOD is generally about 50% more than the 10-day BOD, the 30-day BOD entering the DWSC in June–August 2004 was about 15–18 mg/l. This was similar (somewhat lower) than the BOD concentrations of 18–20 mg/l estimated to match the DWR *San Carlos* survey DO measurements from the summer of 2004.

Figure 3c shows the City of Stockton weekly DO measurements at the DWSC stations (R3 to R6) for 2008. The DO concentrations in 2008 were higher than DO concentrations in 2004, with daily minimum DO concentrations of about 5–6 mg/l during the summer. The RRI DO data matched the City of Stockton DO measurements, confirming that the DWSC DO generally was above the DO objective of 5 mg/l for June–August and 6 mg/l for September–November. The Aeration Facility was operated about half of the time (with a pulsed on-off schedule) from mid-June through September 2008.

Figure 3d shows the 10-day BOD measurements from the three upstream river stations in 2008. The summer 10-day BOD concentrations in 2008 of about 2–3 mg/l were much lower than those of about 6–12 mg/l in 2004. The reduced ammonia effluent concentrations from the RWCF apparently were effective in reducing the 10-day BOD concentrations entering the DWSC. The City of Stockton data confirm the minimum DO in the DWSC is located near the RRI station, and indicate that the inflow BOD concentrations were much less in 2008 than in 2004, with similar flow conditions.

2008 Aeration Facility Performance Results

The 2008 Aeration Facility performance objectives were evaluated by carefully considering all available measurements of DO conditions in the DWSC and identifying the effects of the added oxygen from the Aeration Facility diffuser on DO concentrations in the DWSC. This summary description of the performance results is presented in five sections.

1. The tidal movement and mixing of the DO added from the Aeration Facility diffuser into the DWSC are very important for understanding the Aeration Facility performance.

2. The DWR *San Carlos* survey measurements of DO in the DWSC provide the framework for understanding the downstream DO profile as a function of the river flow, the inflowing BOD, and the natural surface reaeration.
3. The DO measurements from the five DWSC DO monitoring stations provide the most comprehensive data for evaluating the Aeration Facility performance.
4. The UOP boat surveys of DWSC DO concentrations at three depths upstream and downstream from the diffuser provide a clear picture of the changes in the DWSC DO concentrations caused by the Aeration Facility.
5. The comparison of results from the DO monitoring stations with the UOP boat survey DO profiles demonstrates the successful performance of the Aeration Facility.

Movement and Mixing of Dissolved Oxygen from the Aeration Facility in the Deep Water Ship Channel

Tidal movement and mixing processes are the physical linkages between the water with high DO concentrations discharged from the Aeration Facility and the resulting distribution of increased DO concentrations in the DWSC. Three tidal flow measurement stations have been established along the SJR that can be used to estimate the tidal flows and tidal velocities in the DWSC. The first tidal flow measurements station was established on the SJR at Garwood by the U.S. Geological Survey (USGS) with cooperation from the City of Stockton in 1996. The river channel is about 200 ft wide, the cross section is about 3,000 ft^2, and the tidal velocities are about 1 ft/sec. This tidal flow station has been considered reliable because the measured velocities are relatively high (easy to measure), the depth is relatively shallow, and the width is relatively small (most of the cross section is included in the index velocity measurement). This station is located just upstream of the RWCF discharge of about 50 cfs. Therefore, the net flow in the DWSC is about 50 cfs more than measured Garwood net flow.

The second tidal flow station was established by DWR at the RRI monitoring location, just downstream of the diffuser. This tidal flow station is a more challenging location to measure flow because the channel is so wide (and deep). DWR uses side-scan acoustic Doppler equipment. Because of the equipment design, the index velocity measurement extends only about 100 ft into the channel. Based on these index velocity measurements, average estimates for tidal flow velocities for the entire 16,000 ft^2 channel are calculated. The measured tidal elevation is used to estimate the cross-sectional flow area, and hence the tidal flow is calculated as the average flow velocity multiplied by the cross-sectional area.

The third tidal flow station was established by DWR near Lathrop, about a mile downstream of the head of Old River. This tidal flow measurement station is similar (high velocities with small cross section) to the Garwood station. These tidal flow records at Lathrop generally confirm the Garwood station data.

Figure 4a shows the measured RRI tidal elevation and the estimated RRI tidal movement for June 2008, separated into periods of downstream velocity (i.e., positive velocity during ebb tide) and upstream velocity (i.e., negative velocity during flood tide). The downstream tidal movements are greater because (1) the net flows add to the tidal flows during periods of ebb tides, and (2) the normal tidal variation includes a large ebb-tide variation from higher-high tide to lower-low tide each day. The maximum downstream movement was about 2.5 miles on several days in June 2008, while the maximum upstream tidal movement was about 1.5 miles on a few days in June 2008. The added DO (i.e., DO increments) from operation of the Aeration Facility will move upstream to the Light 48 DO monitoring station only on days with maximum upstream (i.e., flood tide) movement, unless there is longitudinal spreading upstream of the diffuser.

Figure 4b shows the estimated upstream and downstream RRI tidal movement for July 2008. The patterns of upstream and downstream tidal movement appear very similar to the June 2008 patterns. Although the tidal movements are accurately represented, the net movement of DWSC water is generally downstream, and the tidal excursions are greater during spring tide periods and less during ebb tide periods. A more thorough description and evaluation of the tidal movement and mixing in the DWSC for June–September 2008 is included in Appendix B.

Near-Field Diffuser Mixing

The mixing of the DO added from the Aeration Facility into the DWSC begins with the near-field diffuser mixing. Near-field mixing was evaluated with vertical DO and dye profiles at the diffuser, along a lateral cross section in the DWSC perpendicular to the diffuser, and with a longitudinal transect approximately 20 ft away from the diffuser. About 30 lb of dye was metered into the aeration system for 30 minutes on March 18, 2008. The concentration of dye in the diffuser pipeline was calculated to be about 750 micrograms per liter (μg/l). DO profiles were measured with a DO sensor suspended from a 12-foot boom to reach under the dock within a few feet of the diffuser.

Figure 5a shows that prior to aeration, the DO was approximately 8.5 mg/l throughout the profile. The DO profiles collected about 5 ft from the diffuser were relatively uniform, varying from 12 to 13 mg/l throughout the 30-ft depth. These data indicate that mixing of the oxygenated water was very rapid because the discharge DO was 35–40 mg/l. The initial concentration was diluted by a factor of about 8–12, suggesting that the DO increment was reduced to 4–5 mg/l within 10–20 ft of the diffuser.

Figure 5b shows the longitudinal dye and DO concentration profiles measured along the dock about 20–30 ft away from the diffuser at a depth of 10 ft during the dye injection period. As expected, the highest concentrations of dye and DO were measured directly in front of the diffuser.

Figure 6 shows the measured lateral-depth concentration profiles for dye and DO during the near-field survey on March 18, 2008. The diffuser jet velocities were sufficient to push the dyed and oxygenated water about 100 ft into the DWSC. The lateral and downward-angled diffuser ports, together with the bubbles in the diffuser discharge, appear to distribute the dye and DO throughout the water column.

Figure 7a shows longitudinal DO profiles at the surface, at 10-ft and at 25-ft depth measured about 15–20 ft from the dock on April 30, 2008. The added DO from the Aeration Facility diffuser was very uniform at about 5 mg/l above the ambient DO concentration for a distance of about 125 ft. The downward angled ports are effective in distributing the diffuser discharge water deeper in the DWSC.

Tidal Spreading and Dispersion

The tidal flows in the DWSC mix the initial DO increments from the Aeration Facility diffuser across the channel (lateral mixing) and along the channel (longitudinal spreading). A 2002 dye study conducted by UOP from the RRI station (Jones & Stokes 2003) indicated that full lateral and vertical mixing of the dye occurred within a tidal cycle (25 hours).

The longitudinal spreading (distance with about 50% of the maximum measured dye concentration) has been measured previously in the DWSC. This earlier study showed that the longitudinal spreading increased from the initial 1,000 ft of upstream channel dyed during the 45-minute dye release to about 2,000 ft after 6 hours and about 3,000 ft after 24 hours (See Figures 21–23 from Jones & Stokes [2003]).

Two dye studies were conducted in 2008 to evaluate the tidal movement and spreading of water discharged from the Aeration Facility diffuser. The first study was on August 5. About 35 lb of dye was injected for an hour at lower-high tide (elevation 5.8 ft) at 9 a.m., and another 35 lb of dye was injected for an hour at lower-low tide (elevation 2.8 ft) at 4 p.m.

Figure 7b shows the longitudinal dye and DO profile measured 250 ft from the diffuser (near mid-channel) at a depth of 10ft. These measurements were started at the end of the lower-high, slack-tide dye release. The downstream front of the dye and DO profile had almost reached the Aeration Facility intake pumps at Mile 37.9 because of a weak ebb-tide flow. The increased oxygen concentration in the DWSC was correlated with the dye concentration. High concentrations of both dye and DO were measured over a 750-ft distance after only 1 hour of aerator operation. At the profile maximum, the DO was about 3 mg/l higher than ambient concentrations. The maximum dye concentration was 25 μg/l. This suggests a dilution of about 10 from the discharge DO concentration, which was 35 mg/l greater than the ambient DO of 6 mg/l.

Figure 8a presents two longitudinal dye profiles measured approximately 25 hours after each dye injection. The two dye releases were separated by about 1.5 miles of tidal movement (3 ft of tidal elevation), but after 1 day they appear blended into one plume extending about 2 miles. The distance between the peaks measured on August 6 suggests a tidal excursion of about 1.25 miles. These dye profiles suggest that water and oxygen from the diffuser were mixed over about 2 miles of the DWSC after 1 day (i.e., the tidal mixing volume). The dye concentrations extended upstream about 1.5 miles to Light 48 during the higher-high tide profile, and extended downstream about 2 miles to mile 36 (0.5 mile past Light 40) during the lower-low tide profile.

The second tidal dispersion dye study was done on August 13 and 14. About 50 lb of dye was injected over an hour at lower-low tide (2.6 ft elevation) at 8 a.m. on August 13. Several longitudinal profiles were measured along the mid-channel of the DWSC over the next day. Figure 8b shows the longitudinal dye profile at mid-channel and near the diffuser 8 to 9 hours after the end of the dye injection. The plume of dye had been transported upstream by the flood tide following the dye release at lower-low slack tide. A significant residual of dye remained along the RRI dock near the diffuser. Lateral dye profile measurements at mile 38.6 indicated that the highest concentrations of dye were measured between depths of 15 and 20 ft, apparently because the diffuser discharge was slightly cooler than the afternoon surface temperatures.

Figure 9a shows the longitudinal dye profiles from depths of 10 ft and 25 ft, measured on August 14 about 18 hours after the dye release, at higher-high tide. No dye was detected upstream of Light 48. Much more dye was measured at the 25-ft depth. Figure 9b shows the longitudinal dye measurements performed 25 hours after the dye injection at lower-low tide. The maximum dye concentration was about 0.5 mile downstream of the diffuser. This was consistent with the relatively low-flow conditions in the DWSC. The spreading of the dye was measured over about 1 mile, and most of the dye was within about 0.5 mile of the peak. This was less longitudinal spreading of dye than measured in the August 6 longitudinal profile because two dye releases were made on August 5 (at lower-low tide and at higher-high tide), but only one dye release was made on August 13 at lower-low tide.

These tidal dispersion studies indicated that the injected dye was spread over about 1 mile of the DWSC after a full tidal cycle, but that most of the dye was spread only 0.5 mile from the peak concentration near the diffuser location. However, because the tidal movement is about 1.5 miles between lower-low and higher-high tide, DO from the diffuser will be spread over this tidal movement and mixing length, and some additional distance upstream and downstream. Therefore, some DO will be added over about 2.5 miles of the DWSC during each day of Aeration Facility operation.

Stratification and Algal Photosynthesis

Temperature stratification in the DWSC inhibits vertical mixing and may allow the surface DO to increase from reaeration and algae growth (photosynthesis). Stratification therefore will interfere with the vertical mixing of the DO added by the Aeration Facility diffuser and will reduce the vertical mixing caused by tidal movement in the DWSC. Measuring the DO added by the Aeration Facility will be more difficult near the surface because of the effects of temperature stratification on algal photosynthesis (i.e., DO production).

The 15-minute DO measurements at RRI in the summer indicate substantial stratification and algal growth effects in the afternoon. Generally, a daily DO variation (i.e., maximum DO – minimum DO) of more than 1 mg/l suggests stratification and algal growth at the RRI station. Surface temperature stratification may reduce vertical mixing and allow algal photosynthesis to increase the DO in the near-surface layer during sunny afternoons. During stratified periods, the near-surface DO will increase from a combination of reaeration and algal photosynthesis, which will reduce the DO deficit and reduce the surface reaeration source of DO during stratification. This algae growth also will produce additional biomass that may increase the downstream BOD (from decay of the algal biomass).

California Department of Water Resources *San Carlos* Survey Measurements of Dissolved Oxygen in the Deep Water Ship Channel in 2008

DWR has conducted longitudinal boat surveys of the DWSC in the late summer and fall period to document the effects of the head of Old River barrier that has been installed to increase flows and increase DO concentrations in the DWSC, so that conditions for adult Chinook salmon (upstream) migration to tributary spawning areas would be improved. The DWR water quality sampling boat used for these surveys was the *San Carlos*, so these data are often referred to by the boat name. The DWR biweekly boat survey measurements in the DWSC extend from Prisoners Point near the Mokelumne River mouth (SJR mile 24.7) to the Stockton DWSC Turning Basin (mile 41.5). Surface and bottom measurements are collected for DO, temperature, and salinity (EC) collected from about 14 stations.

The DWR boat survey measurements from 2004 to 2008 are described and evaluated in Appendix A, together with other general information about the effects of flow and BOD on the measured longitudinal DO concentration profiles in the DWSC. These five years of DWSC DO data provide a wide range of conditions from before and after the City of Stockton added nitrification to the RWCF tertiary treatment, reducing the effluent ammonia concentrations starting in 2007. This substantially reduced the total BOD concentrations entering the DWSC and increased the observed DO concentrations in the DWSC. A description of the DWSC DO Model that was developed to evaluate the DWSC DO data, is also provided in Appendix A.

The DWR boat survey measurements of DO concentrations in the DWSC provide a framework for understanding the general effects of flow, initial DO and BOD, and natural surface reaeration on the longitudinal (i.e., downstream) DO profiles. The DWSC DO Model was developed to compare the natural DO profile with the DO profile with the Aeration Facility operating (See Appendix A). The Aeration Facility performance can be evaluated from these comparative DWSC DO concentration profiles. Four examples of DWSC DO profiles measured by DWR *San Carlos* surveys in 2008 demonstrate the natural DO conditions in the DWSC and illustrate the general effects of the Aeration Facility.

Figure 10a shows the DO concentrations in the DWSC measured by the DWR *San Carlos* survey on July 16, 2008, with a measured flow of about 250 cfs. The DWSC DO model-calculated natural DO profile (dark blue) and the estimated DO profile with full aeration (light blue) also are shown. The DWSC DO model requires a flow and an inflow BOD concentration to be specified to match the measured DO profile. The estimated inflow BOD concentration that best matched the measured DO profile was 10 mg/l. The minimum natural DO concentration profile was calculated to be about 5 mg/l from mile 38 to mile 35, and the DO was about 6 mg/l at Turner Cut (mile 32.5).

The Aeration Facility was operated with an on-off schedule during July 2008 and had operated for 2 days on July 16. The measured surface and bottom DO at mile 38.2 (Light 43) was about 0.5 mg/l higher than the calculated natural DO profile. The measured DO at mile 37.3 (Light 42) was about 1.5 mg/l higher than the calculated natural DO profile, and the measured DO at mile 36.5 (Light 40) was also about 1 mg/l higher than the natural DO profile. The calculated downstream effects of the Aeration Facility matched the measured DO reasonably well, although the facility had operated for only 2 days (15,000 pounds of oxygen added). Some of the elevated DO in this region might have been from algal photosynthesis.

Figure 10b shows the DO concentrations in the DWSC measured by the DWR *San Carlos* survey on July 30, 2008, with a measured flow of about 250 cfs. The calculated natural DO profile and the estimated DO profile with full aeration also are shown. The estimated inflow BOD concentration that matched the measured DO profile was 10 mg/l. The minimum natural DO was calculated to be about 5 mg/l from mile 38 to mile 35, and the DO was about 6 mg/l at Turner Cut (mile 32.5). The surface and bottom measured DO at mile 38.2 (Light 43) was about 1 mg/l higher than the calculated natural DO profile. The measured DO at mile 37.3 (Light 42) was about 1.5 mg/l higher than the calculated natural DO profile, the measured surface DO at mile 36.5 (Light 40) was also about 2 mg/l higher, and the measured bottom DO was about 1.5 mg/l higher than the natural DO profile. The calculated downstream effects of the Aeration Facility matched the measured DO reasonably well, although the facility had operated for only 2 days.

Figure 10c shows the DO concentrations in the DWSC measured by the DWR *San Carlos* survey on August 14, 2008, with a measured flow of about 250 cfs. The calculated natural DO profile and the estimated DO profile with full aeration also are shown. The estimated inflow BOD concentration was again 10 mg/l. The minimum natural DO was calculated to be about 5 mg/l from mile 38 to mile 35, and the DO was about 6 mg/l at Turner Cut (mile 32.5). The measured bottom DO at mile 38.2 (Light 43) matched the natural DO profile, but the measured surface DO was about 2.5 mg/l higher than the calculated natural DO profile. The measured bottom DO at mile 37.3 (Light 42) was about 1 mg/l higher, and the measured surface DO was 2 mg/l higher than the natural DO profile. The measured surface DO at mile 36.5 (Light 40) was also about 1.5 mg/l higher, and the measured bottom DO was about 1 mg/l higher than the natural DO profile. The calculated downstream effects of the Aeration Facility matched the measured DO reasonably well, although the facility had operated for only 2 days.

Figure 10d shows the DO concentrations in the DWSC measured by the DWR *San Carlos* survey on August 28, 2008, again with a measured flow of 250 cfs. The calculated natural DO profile and the estimated DO profile with full aeration also are shown. The estimated inflow BOD concentration was again10 mg/l. The minimum natural DO was calculated to be about 5 mg/l from mile 38 to mile 35, and the DO was about 6 mg/l at Turner Cut (mile 32.5). The measured bottom DO at mile 38.2 (Light 43) was 0.5 mg/l higher than the natural DO profile, and the measured surface DO was almost 2 mg/l higher than the calculated natural DO profile. The measured surface and bottom DO at mile 37.3 (Light 42) were about 1.5 mg/l higher than the natural DO profile. The measured surface and bottom DO at mile 36.5 (Light 40) was also about 1.5 mg/l higher than the natural DO profile. The calculated DO profile with aeration was about 0.5 mg/l higher than the natural DO at mile 34 and was just 0.1 mg/l higher than the natural DO at Turner Cut.

Table 1 gives a summary of the calculated Aeration Facility performance (i.e., downstream distribution of added DO) for a range of flows between 250 cfs and 1,500 cfs for a capacity of 7,500 lb/day (See Appendix A for a description of the DWSC DO Model used to match the DWR boat survey measurements). The performance is represented by the DO increment from the Aeration Facility at each 0.5-mile distance downstream. The DO increments from the Aeration Facility decrease with distance downstream because of the reduced natural surface reaeration. The percentage of the added DO from the Aeration Facility that is retained in the DWSC between the diffuser and Turner Cut is given as a general performance indicator. Higher flows reduce the travel time and allow more of the added DO to remain in the DWSC upstream of Turner Cut. However, the average DO increments downstream of the diffuser are smaller at higher flows.

Operating strategies for the Aeration Facility can be developed for the range of observed flows, as a function of the inflowing DO and BOD concentrations. When the inflow BOD is high enough to create a low DO concentration in the DWSC (approaching the DO objectives), the Aeration Facility can be operated at some fraction of full capacity, and the effects of the added DO can be estimated from the summary of downstream performance results given in Table 1. Full capacity operation may not be needed if the natural DO conditions are only slightly below the DO objective. When the flows are less than 1,000 cfs, the Aeration Facility DO increments will be greater than 1 mg/l and will persist downstream several miles, over a period of several days.

Table 1. Calculated Dissolved Oxygen Increments in the Deep Water Ship Channel with Reaeration for Maximum Dissolved Oxygen Diffuser Output of 7,500 lb/day

	Flow (cfs)	250	500	750	1,000	1,250	1,500
Maximum Possible DO Increment at Diffuser (mg/l)		5.6	2.8	1.9	1.4	1.1	0.9
Location	San Joaquin River Mile						
	40.0	0.00	0.00	0.00	0.00	0.00	0.00
Light 48	39.5	0.00	0.00	0.00	0.00	0.00	0.00
	39.0	0.00	0.00	0.00	0.00	0.00	0.00
Light 43	38.5	0.51	0.27	0.18	0.14	0.11	0.09
DO Diffuser	38.0	2.55	1.46	1.02	0.78	0.63	0.53
Light 42	37.5	3.24	2.12	1.55	1.22	1.00	0.85
	37.0	2.37	1.82	1.40	1.13	0.94	0.81
Light 40	36.5	1.56	1.48	1.22	1.02	0.87	0.75
	36.0	1.10	1.25	1.09	0.93	0.81	0.71
	35.5	0.77	1.05	0.97	0.86	0.75	0.67
	35.0	0.52	0.87	0.85	0.78	0.70	0.63
	34.5	0.36	0.73	0.76	0.71	0.65	0.60
	34.0	0.22	0.57	0.65	0.63	0.59	0.55
	33.5	0.10	0.39	0.50	0.52	0.51	0.48
	33.0	0.05	0.29	0.42	0.46	0.46	0.44
Turner Cut	32.5	0.03	0.23	0.35	0.40	0.41	0.41
DO Retention to Turner Cut		23%	40%	49%	54%	57%	59%
Travel Time to Turner Cut (days)		19.1	10.1	7.0	5.5	4.6	4.0

Dissolved Oxygen at the Deep Water Ship Channel Monitoring Stations

The five DWSC DO monitoring stations provide the most comprehensive data for evaluating the Aeration Facility performance, by comparing the natural DO concentrations measured during periods with no Aeration Facility operation to the increased DO concentrations measured during Aeration Facility operation.

The DWR Aeration Facility delivered about 7,500 lb of DO per day when operated at full capacity, so about 78 lb were discharged from the diffuser during each 15-minute period (with 96 periods per day). Based on observations made during the 2008 tests and conceptual understanding of the mixing dynamics of the channels; the discharge of oxygenated water from the diffuser will not be immediately mixed laterally or vertically, so more of the DO will remain near the dock and perhaps near the surface because of the bubbles remaining in the discharge. Therefore, the RRI surface monitoring station likely measures a higher DO increment than the fully mixed estimated DO increment. Because the Light 43 DO monitoring station is across the DWSC from the diffuser, the measured DO increments may be less than expected. DO monitoring at Light 42 likely provides the best estimate of the fully mixed effects from the Aeration Facility.

The primary method for testing the performance of the Aeration Facility was monitoring of DO concentrations at RRI and two upstream and two downstream monitoring stations. The DO sensors were placed at a depth of about 10 ft (at low tide) and recorded 15-minute data. The two upstream stations are at Light 43 (0.2 mile upstream and across the channel from the diffuser) and at Light 48 (1.5 miles upstream and just downstream of the SJR inflow to the DWSC at Channel Point). The RRI station (3-ft depth) is about 0.2 mile downstream of the diffuser, and the downstream stations are at Light 42 (0.7 mile downstream) and Light 40 (1.6 miles downstream).

Monitoring during months without any aeration indicated that there were temporal changes during the month and spatial differences between the DO concentrations measured at these DWSC locations (about 3 miles apart). This confirmed substantial variability in the DO conditions in this upstream portion of the DWSC. The suggested monitoring plan strategy for identifying the effects on the DWSC DO was to operate the Aeration Facility for several days, and then turn the Aeration Facility off for several days to allow the DWSC to return to natural DO conditions. The results of this on-off operation and monitoring strategy for determining the performance of the Aeration Facility in June, July, August, and September 2008 are described in the following sections.

The DO Increment Model was developed to help identify the DO increments from the Aeration Facility and calculate the effects of reduced surface reaeration on the downstream DO increments. The expected DO changes at each monitoring station were calculated from the tidal movement in the DWSC. The expected DO changes at each station then were adjusted (reduced) to account for the effects of reduced surface reaeration caused by the DO added by the Aeration Facility. The natural DO conditions then were estimated by subtracting the calculated DO increments from the measured DO concentrations at each monitoring station. These calculated DO increments and natural DO conditions were compared to the measured DO at each monitoring station to estimate (calibrate) the surface reaeration rate that provided the best match with the natural DO measured during periods without Aeration Facility operation. Appendix B provides a description of the DO Increment Model and evaluates the results of comparisons of the measured DO at the five monitoring station with the estimated DO increments and calculated natural DO conditions.

Effects of Port of Stockton Aeration and Natural Surface Reaeration

The Port of Stockton operates two aeration facilities on Dock 13 near Channel Point. One device was installed by the U.S. Army Corps of Engineers in 1992 and uses a water jet to entrain air bubbles (jet-aerator). This device was designed with an aeration capacity of 2,500 lb/day and was tested in 2002 as part of the TMDL studies (Jones & Stokes 2003). The jet aerator was found to have an aeration capacity of about 1,850 lb/day when DO concentrations were about 3 mg/l (DO deficit of 5 mg/l). The capacity would be reduced at higher DO concentrations. A second device using oxygen bubbles discharged from perforated hose suspended about 20 ft below the water surface under Dock 13 was installed by the Port of Stockton in 2007 as required for mitigation of dredging impacts. The aeration capacity for this facility is about 2,000 lb/day. Both of these facilities were operated for most of the summer of 2008 (June 7 through October 13) because DO at Light 48 was often approaching or less than the established operational trigger, which is 5.2 mg/l for June–August and 6.2 mg/l daily average in September–November.

Because the daily source of DO from surface reaeration is the reaeration rate times the DO deficit, the added DO increments will reduce the DO deficit and reduce the surface reaeration downstream of the diffuser. Therefore, the observed DO increments from the Aeration Facility will decrease downstream with time. The higher the reaeration rate, the faster the DO increments from the

Aeration Facility will be reduced downstream. This same effect on natural surface reaeration will reduce the downstream effects from the Port of Stockton aeration facilities. The largest effects are expected at the Light 48 DO monitoring station.

June 2008 Dissolved Oxygen Measurements

The June 2008 DWSC DO monitoring data for the first month of operational testing is described here to evaluate the ability to maintain DO above the water quality objective in the DWSC between Lights 40 and 48. The Aeration Facility was turned on at about noon on Monday, June 16, and operated for 4 days until noon Friday, June 20. The Aeration Facility was turned on again at about noon Monday, June 22. The purpose of this pulsed operation was to allow the DO concentrations at the monitoring stations to return to natural conditions during the 3 days the Aeration Facility was turned off.

Figure 11a shows the 15-minute DO concentrations measured in the DWSC for June 2008. DO measurements at Light 48 were highly variable within each day. DO measurements at RRI were the highest during periods of Aeration Facility operation. Figure 11b shows the daily average DO from each station for June 2008. The measured DO at Light 48 declined from about 5–6 mg/l early in the month to about 4 mg/l during the first period of aeration testing, and were 3–4 mg/l during the second period of aeration testing during June 23–27. This was assumed to be the natural DO at Light 48 because no DO increments from operation of the Aeration Facility were calculated to reach this upstream station.

Some increased DO appeared at Light 43 on the first day of operation, but it took a few days of aeration operation for the maximum DO increments to appear at Light 43; the DO increments were almost gone on the third day of non-operation (see June 22 and June 29). There were lower DO increments at Light 43 during low tides when most of the added oxygen moved downstream of the diffuser.

The maximum increased DO at RRI was about 3 mg/l during ebb tide on a few days. It took about 3 days of operation for the maximum DO increments to appear at the RRI station, and most of the DO increments were gone on the third day of non-operation (June 22 and June 29). The daily variation (from algal photosynthesis) was less than 1 mg/l for June 1–16 and on June 21, 22, and 29 when the Aeration Facility was not operated. This suggests that the majority of the large variations in DO were caused by tidal variations of the DO increments. The RRI station has a floating sensor (at 3-ft depth) and may measure a near-surface DO increment that is greater and passes the monitoring station faster than the fully mixed calculated DO increments.

The measured DO increments at Light 42 were similar to those observed at the RRI station. However, the tidal variations in the DO increments were reduced because water from the diffuser was more fully mixed across the DWSC and in the vicinity of Light 43 most of the day. There likely was more lateral and longitudinal spreading at this station because the tidal movements had more time to spread the added DO.

The measured DO at Light 40 showed very small increases during periods of Aeration Facility operation. A delay in the DO increments at Light 40 was expected, but very little of the DO increments observed at RRI and Light 42 was measured at Light 40. Because each monitoring station is located at different distances from the Aeration Facility diffuser, it is difficult to visually determine the effects of the added DO. Generally the DO was increased at each station while the Aeration Facility was operating. However, the effects at each station are evaluated in more detail in Appendix B.

July 2008 Dissolved Oxygen Measurements

The July 2008 DWSC DO monitoring data for the second month of operational testing is described here to evaluate the ability to maintain DO above the water quality objective in the DWSC between Lights 40 and 48. The Aeration Facility was turned on at about noon on each Monday and operated for 4 days until noon on each Friday, with five operation periods and four non-operation periods measured in July 2008.

Figure 12a shows the 15-minute DO concentrations measured in the DWSC for July 2008. DO measurements at Light 48 were highly variable within each day. DO measurements at RRI were the highest during periods of Aeration Facility operation. Figure 12b shows the daily average DO from each station for July 2008. The measured DO at Light 48 generally varied between about 4 mg/l and 6 mg/l during the month. This was assumed to be the natural DO at Light 48 because no aeration DO increments were assumed to reach this upstream station, although the Port of Stockton was operating the water-jet aeration and the oxygen gas bubble–hose facilities at Dock 13. DO at Light 43 increased during operation periods. It took about 3 days of Aeration Facility operation for the maximum DO increments to appear at Light 43, and the DO increments were not quite gone on the third day of non-operation. The daily average DO at Light 43 was similar to the Light 48 DO during days without operation.

The highest DO concentrations at RRI were measured during the ebb tides on days with Aeration Facility operation. The maximum measured DO was greater than DO saturation (8 mg/l) during operation. The measured DO at Light 42 increased only about half as much as at RRI during aeration operations in July 2008. The DO increments were more uniform with less tidal variation because more of the added DO was mixed across the DWSC at Light 42.

The measured DO at Light 40 was very uniform at about 6–7 mg/l during July 2008, with daily increases of about 1 mg/l from algal photosynthesis or reaeration effects during low tides. A time delay in the DO increments at Light 40 was expected during these low-flow conditions, but very little of the DO increments observed at RRI and Light 42 was measured at Light 40. Because of the low flow, it took about 5 days for the maximum DO increments to appear at Light 40. Generally the DO was increased at each station while the Aeration Facility was operating. However, the effects at each station are evaluated in more detail in Appendix B.

The basic strategy of evaluating the Aeration Facility performance by DO monitoring of pulsed operations was not as effective as planned at the downstream stations during low-flow conditions because DO increments from the diffuser required more days to be transported past Light 42 and Light 40 stations. The effects of the pulsed operation at the downstream stations would be stronger (more complete separation) if the Aeration Facility were operated for a week and then not operated for a week. This change in the operation (i.e., longer pulses) was used in August and September.

August 2008 Dissolved Oxygen Measurements

The August 2008 DWSC DO monitoring data for the third month of operational testing is described here to evaluate the ability to maintain DO above the water quality objective in the DWSC between Lights 40 and 48. The Aeration Facility was operated for three periods during August 2008, with a 4-day period August 4–8, and two longer periods August 12–19 and August 26–September 5 to give a better separation between operation effects on DO and natural DO conditions. It was expected that the longer operation periods would provide more time for the effects of the Aeration Facility to build up at the downstream DO monitoring stations.

Figure 13a shows the 15-minute DO concentrations measured in the DWSC for August 2008. DO measurements at Light 48 were again highly variable within each day. DO measurements at RRI were the highest during periods of Aeration Facility operation. Figure 13b shows the daily average DO at each station for August 2008. The measured DO at Light 48 generally varied between about 5 mg/l and 7 mg/l during the month. There was a daily variation of about 1 mg/l, with some days of 2 mg/l that may have been caused by algal photosynthesis.

The measured DO at Light 43 was more than 7 mg/l, approaching the saturated DO concentration (8 mg/l), during periods of aeration operation. The DO increments at Light 43 were limited to the periods of higher tidal elevations when tidal flow moved at least 0.2 mile upstream of the diffuser. It took about 3 days of Aeration Facility operation for the maximum DO increments of about 3 mg/l to appear at Light 43, and the DO increments were gone on the third day of non-operation.

The highest DO concentrations (some above DO saturation) at RRI were measured during the ebb tides of days with Aeration Facility operation. The measured DO on days without Aeration Facility operation was 5–6 mg/l with a daily variation (from algal photosynthesis) of 1–2 mg/l. This suggests that the majority of the large variations in measured DO at RRI were caused by the added DO from the Aeration Facility during ebb tides when water was moving past the RRI surface monitor before the DO was fully mixed across the channel.

The measured Light 42 DO increased less than at RRI because the Light 42 measurements are taken 10–15 ft below the surface and most of the DO moving past Light 42 on ebb tides has been more fully mixed across the DWSC. The measured DO was 5–6 mg/l during periods of non-operation and matched the measured DO at the upstream stations.

The measured DO at Light 40 was about 6–7 mg/l during August 2008, with the highest DO about 4–5 days after the Aeration Facility operation began. The highest DO concentrations often were associated with the periods of lowest tide elevations, when DO increments from the Aeration Facility were tidally transported downstream to the Light 40 station. The maximum average increase at Light 42 was measured 4–5 days after operation began. Generally, the DO was increased at each station while the Aeration Facility was operating. The effects at each station are evaluated in more detail in Appendix B.

September 2008 Dissolved Oxygen Measurements

The September 2008 DWSC DO monitoring data for the fourth month of operational testing is described here to evaluate the ability to maintain DO above the water quality objective in the DWSC between Lights 40 and 48. The Aeration Facility was operated for just two periods during September 2008—a 5-day period of August 1–5 (continuing from August 26), and a 10-day period from September 16–26 to see if a longer operation period would provide a greater increase in DO concentrations downstream from the diffuser.

Figure 14a shows the 15-minute DO concentrations measured in the DWSC for September 2008. DO measurements at Light 48 were less variable within each day. DO measurements at all of the stations were similar during the longer non-operation periods of September 6–15 and September 27–30. DO measurements at Light 43, RRI, and Light 42 were highest during periods of Aeration Facility operation. Figure 14b shows the daily average DO from each station for September 2008. The DO concentrations at Light 48 increased from 6 mg/l to 7 mg/l during September 4–8. The DO at Light 48 increased from about 6 mg/l on September 15 to more than 7 mg/l during September 20–30, and was almost at DO saturation (8.5 mg/l) on September 23–26. These higher DO concentrations at Light 48 appeared to correspond to the period of aeration operation from September 16 to 26. This apparent influence of the Aeration Facility on the Light 48 DO concentrations was not observed as strongly in the previous 3 months of operation. Measured DO at Light 43 also appeared to increase by about 1–2 mg/l during operation periods.

The measured DO at RRI was above DO saturation during ebb tides on September 2–6 and again September 23–26 during Aeration Facility operation. The measured DO increments at RRI appeared to be greatest at the beginning of ebb tides. This suggests that (1) the surface DO increments measured at RRI were higher because they were not fully mixed as they passed the RRI station , and (2) more DO accumulated upstream of the RRI station during slack tide periods.

The measured DO at Light 42 approached saturated DO during September 1–5 (after 5 days of operation) and September 24–26 (after 8 days of operation). The measured DO at Light 42 did not have much tidal variation when the Aeration Facility was not operating, but the tidal variation of DO was about 2 mg/l during periods of operation. The highest DO increments were associated with ebb tides and middle tide elevations, corresponding to the fully mixed, maximum expected Aeration Facility DO increment.

The measured DO at Light 40 did not have much tidal or daily variation when the Aeration Facility was not operating, but the tidal variation of DO was about 1 mg/l during operation (highest DO at low tide elevations). The measured DO at Light 40 appeared to increase by about 1 mg/l at the beginning of the month, and by almost 2 mg/l during the longer operation periods. The effects at each station are evaluated in more detail in Appendix B.

University of the Pacific Longitudinal Dissolved Oxygen Profiles in the Deep Water Ship Channel from June to September 2008

The distribution of added DO from the Aeration Facility in the DWSC is an important aspect of the performance of the Aeration Facility in order to identify and track the longitudinal effects of the Aeration Facility, beginning with natural DO conditions 1 day prior to operation and continuing for several days while the Aeration Facility was operated. The increase in DO concentrations upstream and downstream of the diffuser when the Aeration Facility was operating was measured with boat surveys conducted by UOP (Litton 2003). The data collected from the UOP boat surveys was used to develop comparative DO profiles which generally identified the magnitude and extent of the DO added from the Aeration Facility operation.

Each boat survey was conducted at either high slack tide or low slack tide. Measurements were collected with an automated monitoring system using three towed DO sensors. One sensor was measuring DO near the surface (5-ft depth), a second DO sensor was suspended at mid-depth of 15 ft, and the third DO sensor was near the bottom (25-ft depth). During a testing period, the DO concentrations were measured between Turner Cut at SJR mile 32.5 and upstream of the DO monitoring station at Light 48 in the river channel at SJR mile 40. The DO profiles were collected every 1–3 days during operation and some non-operation periods to measure the DWSC DO concentration changes in response to the Aeration Facility operation. Measurements collected at low tides showed the downstream extent of the DO effects, and measurements collected at high tides showed the upstream effects between the diffuser and Light 48. The movement of the DO profile position for this section of the DWSC is about 2 miles between high tide and low.

There were four boat survey sequences. The first survey sequence was from August 12 to August 16. The August 12 survey measured the natural DO profile, with the Aeration Facility having been turned off since August 4. The August 16 profile measured the effects after 4 days of aeration. The second survey sequence was from August 26 through September 5. The Aeration Facility had been turned off for 10 days on August 26. The Aeration Facility had been operated for 10 days on September 5. The third measurement sequence was from September 15 through September 26. The Aeration Facility had been turned off for 10 days on September 15 and had been operated for 10 days on September 26. The fourth survey sequence measured the downstream movement and decreases in the DO increments from September 26 (last day of Aeration Facility operation in 2008) through October 19. This fourth survey sequence showed the natural variability in the DWSC DO profiles caused by changes in temperatures, flows, and vertical mixing but is not described here because it did not measure the Aeration Facility performance.

August 12–16 Longitudinal Dissolved Oxygen Surveys

The first series of UOP boat surveys from August 12 to 16 measured the effects of the Aeration Facility on the DWSC DO concentrations during a 4-day operation period. Figure 15 shows the longitudinal DO profiles measured during the first UOP boat survey sequence August 12–16. The first day represents natural DO conditions in the DWSC, and the next 4 days indicate the buildup of DO increments from the Aeration Facility. The net flows in the DWSC were assumed to be about 250 cfs during this operational sequence, so the net downstream water movement was about 0.25 mile per day. The downstream tidal movement from higher-high tide to lower-low tide was about 1.5 to 2 miles during this survey period. It was expected that some added DO from the Aeration Facility would appear at the downstream Light 40 monitoring station at the lower-low tide each day, when the boat surveys were conducted. The upstream tidal movement was estimated to be 0.5 to 1.0 mile, so DO increments from the Aeration Facility were not expected at the upstream Light 48 monitoring station at high tides each day.

Figure 15a shows the DO measurements at the surface, mid-depth (15 ft), and bottom (25 ft) on August 12. The saturated DO concentration was about 8 mg/l. The mid-depth and bottom DO concentrations were about 6 mg/l in the downstream portion of the profile, so the natural DO deficit was about 2 mg/l. There was not much of a DO sag, indicating that the BOD concentration entering the DWSC was relatively low. The surface DO profile was more than 1 mg/l higher than the mid-depth and bottom DO concentrations between mile 37.5 and 38.5 (diffuser is at mile 38), suggesting some algal growth (i.e., photosynthesis). The August 12 survey was conducted at low tide between 10 a.m. and noon.

Figure 15b shows the measured chlorophyll concentration profiles for the August 12–16 surveys. The August 12 survey indicated chlorophyll concentrations were higher than 5 µg/l upstream of SJR mile 37. The highest chlorophyll concentrations were measured on August 15 between 2 p.m. and 3:30 p.m. Temperature measurements indicated a slight stratification between the mid-depth and the surface of about 1^{o}C. Therefore, the surface DO concentrations during August 12–16 were partially the result of algal photosynthesis; this may confound the tracking of the added DO from the Aeration Facility. The major reason that the DO sensors were located at a depth of about 10–15 ft was to avoid this near-surface effect from algal photosynthesis.

Figure 15c shows the DO profiles on August 13 after 1 day of aeration. The mid-depth DO concentrations were increased by about 1.5 mg/l downstream 1 mile (mile 37) and slightly increased almost 2 miles downstream (not quite to mile 36). This was consistent with the 2-mile downstream tidal movement at lower-low tide. The bottom DO concentrations also were increased by about 0.5 mg/l for 1 mile downstream and increased slightly 2 miles downstream. The mid-depth DO from August 12 was used to generally identify the DO increments from the Aeration Facility operation. The surface DO on August 13 upstream of mile 38 (diffuser) cannot have come from the diffuser because the boat survey was made at lower-low tide. The similarity of the DO profiles downstream of the diffuser suggests that vertical mixing from tidal flows was relatively strong, although there was a slight temperature difference between the surface and bottom profiles on August 13 (9:30 to 11:30 a.m.).

Figure 15d shows the DO profiles on August 14 after 2 days of aeration. The surface DO was increased by about 2 mg/l to nearly DO saturation (8 mg/l) between mile 37.5 and 38. The mid-depth DO concentrations were increased by about 1.5 mg/l downstream at mile 37 and were increased somewhat 2 miles downstream (just beyond mile 36). This was consistent with the 2-mile downstream tidal movement at lower-low tide and suggests that this portion of the river channel had been double-dosed by the diffuser. The 25-ft depth DO concentrations were increased by about 2 mg/l at mile 37.5; the 25-ft depth DO increment decreased faster than the mid-depth DO increment and extended downstream to just below mile 36, suggesting that vertical mixing of the added DO was not complete.

Figure 15e shows the DO profiles on August 15 after 3 days of aeration. The surface DO upstream of the diffuser was above saturation, suggesting algal photosynthesis (survey was conducted from 2 to 3:30 p.m.). The downstream surface and mid-depth DO were increased by about 2 mg/l to mile 37. The surface and mid-depth DO concentrations were increased by about 1 mg/l downstream to mile 36 and were increased by about 0.5 mg/l to mile 35.

Figure 15f shows the DO profiles on August 16 after 4 days of aeration. The surface DO upstream of the diffuser was no longer above saturation, suggesting less algal photosynthesis (survey was conducted from 12 noon to 2:15 p.m.). The surface and mid-depth DO were increased by about 2 mg/l to mile 37, were increased by about 1 mg/l downstream to mile 36, and were increased by about 0.5 mg/l for 2.5 miles downstream (mile 35.5).

The simultaneous DO profiles from three depths in the DWSC indicated that there are natural differences in the DO concentrations from temperature stratification and algal photosynthesis, and that the added DO from the Aeration Facility is not completely mixed vertically and not distributed uniformly in the channel. Identifying the DO increments from the Aeration Facility will be uncertain because of these variations in the natural DO concentration and the variations in the longitudinal and vertical distribution of the added DO increments.

Figure 16 shows the surface and bottom DO profiles from the August 12–16 boat surveys. The DWR *San Carlos* survey data from August 14 is shown to indicate that the UOP boat survey data was similar to the *San Carlos* DO measurements. The DO measured in the *San Carlos* survey bottom sample at Light 42 (mile 37.3) was about 6 mg/l, which was lower than measured in the 25-ft depth UOP profile on August 14. The *San Carlos* survey sample was measured 1 ft from the bottom, and the 25-ft depth DO profile measurements may have been increased by the 2 days of aeration.

August 26–September 5 Longitudinal Dissolved Oxygen Surveys

The second series of UOP boat surveys from August 26 to September 5 was done to determine whether a greater increase in DO concentration would be observed in the DWSC with a longer period of Aeration Facility operation. The Aeration Facility had been turned off on August 18, so natural DWSC DO profile conditions were measured at low tide on August 26. The Aeration Facility was operated at full capacity of about 7,500 lb/day for 10 days, with longitudinal DO surveys at three depths done every 2 days.

Figure 17a shows the DO measurements at the surface, mid-depth (15 ft), and near bottom (25 ft) on August 26. The saturated DO concentration was about 8 mg/l. The surface, mid-depth, and bottom DO concentrations were all about 6 mg/l in the DWSC, so the natural DO deficit was very uniform at about 2 mg/l. There was no measured DO sag, indicating that the BOD concentration entering the DWSC was low. Any inflowing BOD effect on the DO profile apparently was eliminated by tidal mixing. The August 26 survey was conducted at low tide between 8 a.m. and 10 a.m.

Figure 17b shows the measured chlorophyll concentration profiles for the August 26 to September 5 surveys. The August 26 survey indicated chlorophyll concentrations were only slightly greater than 5µg/l upstream of mile 38. The highest chlorophyll concentrations were measured on the September 3 survey, conducted between 2:30 p.m. and 4:30 p.m. Temperature measurements indicated fully mixed conditions on August 26. Therefore, the August 26 DO profiles represent ideal natural conditions for tracking subsequent DO increments from the Aeration Facility.

Figure 17c shows the DO profiles on August 28 after 2 days of aeration, surveyed between 10:30 a.m. and 12:30 p.m. The surface DO was increased by about 1 mg/l from mile 36.5 to mile 39. The mid-depth DO concentrations were increased by about 0.5 mg/l downstream to mile 36 and slightly increased upstream to mile 39.5. The bottom DO concentrations also were increased by about 0.5 mg/l for 1 mile downstream and slightly increased for about 2 miles downstream. The downstream DO increases were consistent with the 2-mile downstream tidal movement at low tide. The slight DO differences between the surface, mid-depth, and near-bottom DO measurements indicate that vertical mixing was not quite strong enough to fully mix the DO from the diffuser and not strong enough to mix surface DO from algal photosynthesis.

Figure 17d shows the DO profiles on August 30 after 4 days of aeration, surveyed between 1:30 p.m. and 3:30 p.m. at lower-low tide. The surface DO was increased by about 2 mg/l to DO saturation (8 mg/l) from mile 38 to mile 37 and was increased to about 7 mg/l at mile 36, with some increased DO measured downstream to mile 35. The surface DO was increased by about 1 mg/l upstream to mile 40, which indicates some influence from algal photosynthesis. The mid-depth DO concentrations were increased by about 1.5 mg/l downstream to mile 37 and increased by 1 mg/l at mile 36, with no increase measured downstream of mile 36. The bottom DO concentrations were increased by at least 1 mg/l downstream to mile 37, with decreasing DO increments to mile 36. Only small increases in the mid-depth and bottom DO were measured upstream of the diffuser.

Figure 17e shows the DO profiles on September 1 after 6 days of aeration, surveyed between 2:30 p.m. and 4:30 p.m. The surface, mid-depth, and near-bottom DO profiles were similar downstream of the diffuser, indicating strong vertical mixing. Temperature measurements indicated that stratification was greatest on August 30 and that surface temperatures had cooled from 26°C to 25°C on September 1, producing well-mixed conditions. The DO profiles were increased by about 2 mg/l to DO saturation (8 mg/l) at mile 37, about a mile downstream of the diffuser. This maximum DO increment 1 mile downstream was consistent with the DO increments increasing just downstream of the diffuser, and being reduced farther downstream by the effects of reduced surface reaeration. The DO increments decreased from about 2 mg/l at mile 37 to about 1 mg/l at mile 35, and the DO increment downstream of mile 34 was likely small. The surface cooling and vertical mixing between August 30 and September 1 likely increased the natural DO profile from 6 mg/l to about 6.5 mg/l.

Figure 17f shows the DO profiles on September 3 after 8 days of aeration, surveyed between 2:20 p.m. and 4:20 p.m. The surface DO was increased by more than 1 mg/l compared to the September 1 profile, and was supersaturated at about 9 mg/l from mile 38 to 36, likely indicating algal photosynthesis in addition to effects from the Aeration Facility. The temperature data indicated stratification on September 3. The mid-depth DO profile was similar to the mid-depth DO profile on September 1, but the bottom DO profile was decreased from the September 1 DO profile, apparently because the BOD decay was not being balanced by surface reaeration or diffuser DO during this stratified period. The mid-depth DO increments decreased from about 2 mg/l at mile 37 to about 1 mg/l at mile 35, and the DO increment downstream of mile 34 was small because surface cooling and vertical mixing between August 30 and September 1 likely increased the natural DO profile to about 6.5 mg/l. It therefore is difficult to separate the DO increments caused by operation of the Aeration Facility from natural DO changes.

Figure 17g shows the DO profiles on September 5 after 10 days of aeration, surveyed between 4:20 a.m. and 6:20 a.m. The surface DO and mid-depth DO were increased about 2 mg/l from mile 38 to mile 36.5 by operation of the Aeration Facility and were increased by about 1 mg/l to mile 35.5, compared to the August 26 natural DO. The bottom DO was 6 mg/l at mile 38.5 upstream of the diffuser, increased to a maximum of 7.5 mg/l at mile 36.5, and decreased along with the mid-depth and surface DO to 7 mg/l at mile 35.5. Apparently a slight stratification between mile 36.5 and 38.5 prevented full vertical mixing and reduced the DO effects from the Aeration Facility in the near-bottom water. The surface and mid-depth DO profiles remained similar to the September 1 DO profile downstream of the diffuser. The DO increments decreased from about 2 mg/l at mile 36.5 to about 1 mg/l at mile 35.5, with no DO increments downstream of mile 34. The low-flow conditions did not provide much downstream movement of DWSC water, and the loss of the DO increments from reduced surface reaeration apparently maintained this maximum observed wedge of DO influence from the Aeration Facility in the DWSC.

Figure 17h shows the surface and bottom temperature profiles from August 26 to September 5, indicating that the maximum stratification was observed on August 28 and 30. Temperatures cooled (causing convective mixing) on September 1 and remained mixed on September 3 and 5. Days with a slight stratification allowed the surface DO to increase above the mid-depth DO and bottom DO concentrations because of surface reaeration and algal photosynthesis.

September 15–26 Longitudinal Dissolved Oxygen Surveys

The third series of longitudinal DO profiles was measured with the UOP boat surveys from September 15 to September 26 to determine how much of an increase in DO concentration would be observed upstream of the diffuser at high tide during a 10-day Aeration Facility operation period. These longitudinal surveys were collected at high tide to document the upstream tidal movement and distribution of the added DO (i.e., DO increments) from the Aeration Facility. The Aeration Facility had been turned off September 5, so natural DWSC DO profile conditions were measured at low tide on September 15. The Aeration Facility was operated at full capacity of about 7,500 lb/day for 10 days, with longitudinal DO surveys at three depths done every 2 days, except that the survey on September 24 (day 8) was missed.

Figure 18a shows the DO measurements at the surface, mid-depth (15 ft), and near bottom (25 ft) on September 15 at low tide. The saturated DO concentration was about 8.5 mg/l. The surface, mid-depth, and bottom DO concentrations were all about 6 mg/l in the DWSC from mile 38.5 to mile 35, so the natural DO deficit was very uniform at about 2.5 mg/l. The inflow DO was about 8 mg/l, and the DO downstream at Turner Cut (mile 32.5) was about 7 mg/l. Temperature measurements indicated a slight stratification, and some algal photosynthesis was indicated by the slightly higher surface DO from mile 39 to mile 36.

Figure 18b shows the measured chlorophyll concentration profiles for the September 15 to September 26 surveys. The chlorophyll concentrations were higher than 5µg/l upstream of mile 36.5 on the September 15 survey, conducted between 2 p.m. and 4 p.m. The high inflow DO concentrations on September 15 may have been the result of photosynthesis in the river upstream.

Figure 18c shows the DO profile on September 18 after 2 days of aeration, surveyed between 7 a.m. and 9 a.m. at lower-high tide (elevation 5 ft). The DO profile at each depth was about the same, suggesting strong vertical mixing on September 18. Temperature measurements confirm that cooling of 1°C occurred between the September 15 and September 18 surveys. The DO concentrations were increased about 1 mg/l compared to the September 15 DO concentrations from mile 39 to 37.5, with some DO increments measured to mile 37. These DO measurements suggest that the wedge of DO increments from the Aeration Facility was mixed into about 2 miles of water and extended about 1 mile upstream of the diffuser at lower-high tide after 2 days of aeration with relatively low flow.

Figure 18d shows the DO profiles on September 20 after 4 days of aeration, surveyed between 9 p.m. and 11 p.m. at high tide (elevation 6.5 ft). The surface and mid-depth DO were about 8 mg/l from mile 39 to 38, but the bottom DO was about 7.5 mg/l, suggesting that less DO from the Aeration Facility was mixed into the bottom of the DWSC. The surface and mid-depth DO were increased by about 1 mg/l more than the bottom DO from mile 39 to 38, and the bottom DO was increased above the September 18 profile. The surface, mid-depth, and near-bottom DO profiles were similar downstream of the diffuser, indicating strong vertical mixing. The minimum DO of 6.5 mg/l measured at mile 36.5 was about 0.5 mg/l higher than the minimum DO measured on September 18. The wedge of DO increments from the Aeration Facility was perhaps farther upstream than on September 18, but because the inflow DO and the DO profile in the DWSC also were increased by about 0.5 mg/l, it is difficult to determine the incremental DO effects from the 4 days of aeration.

Figure 18e shows the DO profiles on September 22 after 6 days of aeration, surveyed between 9 p.m. and 11 p.m. (tidal elevation 6 ft). The surface and mid-depth DO was about 8 mg/l from mile 39.5 to 38.5, and the bottom DO was slightly less, again suggesting that less DO from the Aeration Facility was mixed in to the bottom of the DWSC. The surface DO was about 1.5 mg/l higher than the bottom DO upstream of the diffuser at mile 39.5. The near-bottom DO profile was slightly less than the surface and mid-depth DO profiles downstream of the diffuser. The minimum DO of about 6.5 mg/l measured at mile 35.5 was about 0.5 mg/l higher than measured on September 18. Because the DWSC DO concentrations were increased by at least 0.5 mg/l compared to the DO concentrations measured on September 15, it was difficult to determine the downstream influence of the Aeration Facility.

Figure 18f shows the DO profiles on September 26 after 10 days of aeration, surveyed between 1:30 p.m. and 3:45 p.m. (tidal elevation 6 ft). The inflow DO of about 8.5 mg/l was close to DO saturation. The surface and mid-depth DO concentrations were from 8 mg/l to 9 mg/l between mile 39.5 and

38.5. The near-bottom DO was 7 mg/l to 8 mg/l upstream of the diffuser. The DO profiles were similar downstream of the diffuser, with a DO of about 8 mg/l at mile 38 (at the diffuser) and a DO of about 7 mg/l at mile 37, with a minimum DO of 6.5 mg/l at mile 35.5 and increasing DO to about 7 mg/l at mile 34. The wedge of DO increments on September 26, after 10 days of aeration, appeared to be only somewhat greater than the wedge of DO increments measured on September 18 after just 2 days of aeration. The wedge of DO increments was evident upstream of the diffuser because of the differences between the bottom DO profile and the mid-depth or surface DO profiles.

This sequence of DO profiles in the DWSC at high tide suggests that the wedge of DO increments from the Aeration Facility moves upstream about 1mile at high tide, but the downstream magnitude and extent of the wedge are limited by the reduction in surface reaeration caused by the added DO from the Aeration Facility. The maximum effects from the Aeration Facility appeared to be about 2 mg/l in a volume of water extending about 2 miles in the DWSC. The upstream end of this volume of added DO moved about a mile upstream of the diffuser during high tides and moved about a mile downstream of the diffuser during low tides during relatively low flows (250 cfs) observed in September 2008.

Figure 18g shows the DO profiles on September 29 after 3 days without aeration, surveyed between 1:30 p.m. and 4 p.m. at low tide (elevation 3 ft). A *San Carlos* survey also was made in the morning on September 29. The DO profiles measured by the two surveys were similar, although the *San Carlos* survey DO concentrations were slightly lower. This was likely because the *San Carlos* survey bottom measurements were deeper than the UOP boat survey measurements (25 ft), and the surface DO was higher from the UOP survey because it was in the afternoon with more algal photosynthesis. After just 3 days without aeration, there was little evidence of DO increments from the Aeration Facility remaining in the DWSC. With the reaeration coefficient estimated to be about 0.2 day^{-1}, there should have been about 50% of the DO increments remaining. However, the DO increments from the Aeration Facility appear to have vanished in the 3 days without aeration.

Figure 18h shows the DO profiles on October 4 after 8 days without aeration, surveyed between 3 a.m. and 5 a.m. at low tide (elevation 3 ft). The October 4 DO profile in the DWSC was very similar to the September 15 DO profile, except the inflow DO was slightly less and the minimum DO was lower. The natural DO deficit of 2.5–3 mg/l was reestablished in the DWSC at these low-flow conditions of about 250 cfs, suggesting that the inflow BOD was also about the same. Some additional aeration was needed on October 4 because the minimum DO was slightly less than the October objective of 6 mg/l.

Comparison of Longitudinal Profiles and Monitoring Station Data

The purpose of this last section of the performance objectives evaluation is to demonstrate that the DWSC DO monitoring station data and the UOP boat surveys of longitudinal DO profiles provide a consistent description of the overall performance of the Aeration Facility for increasing the DO concentrations in the DWSC in the vicinity of the Aeration Facility.

Comparison of August 12–16 Data

The comparison of the DO data from the monitoring station with the UOP boat survey profiles from August 12–16 demonstrates that the tidal movement in the DWSC shifts the longitudinal distribution of the increased DO (i.e., wedge of DO increments) downstream by about 2 miles between higher-high tide and lower-low tide. This tidal movement of the DO increments from the Aeration Facility also is observed in the data from the DWSC DO monitoring stations.

Figure 19 shows the 15-minute DO measurements from the five DO monitoring stations for August 11–17, which include the first boat-survey DO profile sequence. The Aeration Facility began operation on August 12 at about noon at lower-low tide. Figure 19a indicates the upstream DO monitors showed small DO effects that were correlated with the flood-tide periods and therefore were likely from the Aeration Facility. However, because this was a period with high algal photosynthesis in this upstream portion of the DWSC, the effects from the Aeration Facility were difficult to distinguish from photosynthesis in the afternoons. Some effects from the Port of Stockton's jet aeration and oxygen-bubble devices (located just upstream of Light 48) may be detected after the lower-high tides on some days.

Figure 19b indicates the downstream DO monitoring stations measured no DO effects from the Aeration Facility until after the higher-high tide on August 13. As the tidal elevation began to decrease, there was a sharp increase in DO at the RRI and Light 42 stations, and at Light 40 during lower-low tide each day (tidal elevation below 4 ft). As the tidal elevation increased, the DO increments at Light 40 were reduced because water from downstream (without any DO increment) moved upstream past the Light 40 DO monitor. The Light 42 and RRI DO monitors likely recorded the same DO increments during the flood tide as had been measured during the previous ebb tide (tidal flow reversal with same longitudinal DO increments). The DO at Light 42 and RRI decreased at higher-high tide because water from downstream did not have much of a DO increment, as there was little net downstream movement of the DWSC water. The downstream DO monitoring stations recorded very consistent patterns each day, although a greater increase in the DO increments was expected as the Aeration Facility was operated for multiple days. The UOP boat surveys indicated some buildup of the DO increments with days of operation, but the downstream DO monitoring did not measure much increase in the DO increments with 4 days of operation.

The DO monitoring data indicated that the effects of the Aeration Facility were clearly measured at the RRI and Light 42 stations during ebb tides, and that a build-up in the DO concentrations with days of operation could be detected. Because the sequence of DO increments at each monitoring station were different, the expected downstream wedge of DO increments from the Aeration Facility was difficult to identify. The combination of fixed DO monitoring and longitudinal DO profiles provides the most complete description of the effects of the Aeration Facility on the DWSC DO concentrations.

The amount of added DO in the measured downstream wedge of DO increments can be estimated from the DO increase in each 0.1-mile channel segment at low tide. The mass of DO added by the diffuser in each DWSC channel segment can be estimated as:

DO Content (lb) = 2.72 x Volume (af) x DO concentration change (mg/l)

Because each 0.1-mile segment of the DWSC has a volume of about 175 acre-feet (af) (Table 1), about 500 lb of oxygen is required to increase the DO concentration by 1 mg/l. The volume of water in the DWSC between mile 38 and mile 35 is about 5,000 af at low tide.

On August 13, the mid-depth DO profile indicated the Aeration Facility increments had increased the amount of DO by about 7,500 lb of oxygen after about a day of operation (7,500 lb added). On August 14, the mid-depth DO profile indicated the Aeration Facility increments had increased the oxygen content by about 12,500 lb after 2 days aeration (15,000 lb added). On August 15 the mid-depth DO profile indicated the Aeration Facility increments had increased the oxygen content by about 23,000 lb after 3 days of aeration (22,500 lb added), and on August 16 the mid-depth DO profile indicated the Aeration Facility increments had added about 19,500 lb after 4 days aeration (30,000 lb added). Most of the added oxygen from the Aeration Facility appeared to increase the measured DO profile between mile 38 and 35 during this 4-day period of operation.

Comparison of August 26–September 5 Data

The second period of data comparison demonstrates the tidal movement and build-up of DO concentrations at the DO monitoring stations during a 10-day operation of the Aeration Facility. Figure 20 shows the 15-minute DO measurements from the five DO monitoring stations for August 25–September 5. The Aeration Facility began operation on August 26 at about noon at low tide. Figure 20a indicates the upstream DO monitors showed no obvious DO increases that were correlated with the flood tide periods as would be expected from the Aeration Facility. The Light 43 and Light 48 DO concentrations increased from 5 mg/l to 7 mg/l from August 25 to 27, apparently the result of algal photosynthesis in the upstream portion of the DWSC. Beginning on August 30, the Light 43 DO was about 1 mg/l higher than the Light 48 DO concentrations. However, there were no obvious DO increases during flood tides, suggesting this difference was caused by algal photosynthesis or a slow mixing of DO upstream from the diffuser.

Figure 20b shows that the downstream DO monitors measured the greatest DO effects from the Aeration Facility during the lowest tidal elevations, because the wedge of DO increments from the Aeration Facility was farther downstream at the lowest tides. The DO increments were largest (about 2 mg/l) at the RRI station, and were almost as large (1.5 mg/l) at Light 42 but for shorter periods during each tidal period (usually twice each day) at lower tidal elevations. The DO increments were usually only about 0.5 mg/l at Light 40 because this station is about 1.6 miles downstream from the diffuser. The natural DO at Light 40 (measured at higher tidal elevations) increased by almost 1 mg/l on September 1, apparently caused by surface cooling and mixing. The DO increments at Light 40 during low tides remained about 0.5 mg/l for just a few hours each day. The DO increments observed at the downstream stations indicated that DO effects increased for 3–4 days after the Aeration Facility began operating but did not continue to increase during the remainder of the 10-day operation period.

Both the UOP boat surveys and the downstream DO monitoring indicated that the wedge of DO increments was established in the 2-mile tidal mixing volume within a few days of aeration operations, and was maintained as a dynamic balance between the influence of the Aeration Facility adding DO into the tidal mixing volume and the loss of the DO increments from reduced surface reaeration in the downstream portion of the DWSC.

On August 28, the added DO from the Aeration Facility had increased the DO content between mile 38 and 35 by about 7,000 lb after 2 days of aeration (15,000 lb added). On August 30, the DO content was increased by about 15,000 lb between mile 38 and 35 after 4 days of aeration (30,000 lb added). On September 1 the DO content was increased by about 25,000 lb after 6 days of aeration (45,000 lb added). On September 3 the DO content was increased by about 23,000 lb after 8 days of aeration (60,000 lb added), and on September 5 the DO content was increased by about 28,000 lb between mile 38 and 35 after 10 days of aeration (75,000 lb added). The maximum wedge of DO increments observed during these 10 days of operation therefore was about 25,000 lb of oxygen between mile 38 and 35. This maximum observed increase in the DO content represents about 3–4 days of added

DO from the Aeration Facility, with an average DO increment of about 1.75 mg/l in this 3-mile segment downstream of the diffuser.

Comparison of September 15–26 Data

The third period of data comparison demonstrates the tidal movement and build-up of DO concentrations at the DO monitoring stations during a 10-day operation of the Aeration Facility. The results from the UOP boat surveys at higher-high tide were consistent with the DO data from the monitoring stations. Figure 21 shows the 15-minute DO measurements from the five DO monitoring stations for September 15–September 26. The Aeration Facility began operation on September 16 at about noon during ebb tide. Figure 21a indicates the upstream DO monitoring stations showed no obvious DO increases that were correlated with the high-tide periods as would be expected from the Aeration Facility. The Light 43 and Light 48 DO concentrations increased from 6 mg/l to 8 mg/l during this 12-day period, apparently the result of increased inflow DO. From September 17 to September 22, the Light 43 DO was about 0.5 mg/l higher than the Light 48 DO concentrations. However, there were no obvious DO peaks at higher tides, suggesting this difference may have been caused by a more general mixing of DO upstream from the diffuser.

Figure 21b shows that the downstream DO monitors measured the greatest DO effects from the Aeration Facility during the lowest tidal elevations because the wedge of DO increments from the Aeration Facility was farther downstream at the lowest tides. The measured DO increments were largest (about 1.5 to 2 mg/l) at the RRI station, and were almost as large (1 to 1.5 mg/l) at Light 42 but for shorter periods during each tidal period. The DO increments at Light 40 were usually about 0.5 to 1 mg/l at lower tides because this station is about 1.6 miles downstream from the diffuser. The natural DO at Light 40 (measured at higher tidal elevations) increased from 6 mg/l on September 17 to about 7 mg/l on September 21, apparently caused by surface cooling and mixing (with surface reaeration). The DO increments at Light 40 during low tides were about 0.5 to 1 mg/l for just a few hours each day during low tides.

These comparisons between the UOP boat surveys and the DO monitoring stations led to the general performance evaluation conclusion. The DO increments observed at the downstream stations indicated that DO effects from the Aeration Facility increased for 3–4 days after the diffuser began operating but did not increase substantially during the remainder of the 10-day operation period. This was consistent with the UOP boat surveys of the DWSC DO profiles, which indicated that a wedge of DO from the Aeration Facility developed within a 2-mile tidal movement zone but did not move farther downstream with a longer operation period.

The zone of influence for the added DO from the Aeration Facility appeared to represent about 4 days of DO discharge capacity (about 25,000 lb of oxygen) distributed in a volume of about 5,000 af (2.5 miles of DWSC) with an average DO increment of 1.75 mg/l. The location of the wedge of DO increments was shifted 1 mile upstream of the diffuser at high tides and 1 mile downstream of the diffuser at low tides, but the length of the zone of Aeration Facility influence did not appear to extend beyond about 2.5 miles for the relatively low flows (250 cfs) observed in 2008. The consistent measurement of a maximum wedge of added DO in the DWSC after about 4 or 5 days of Aeration Facility operation at lower-low tide each day confirms the maximum downstream movement of the added DO increments and the reduction of the DO increments from the Aeration Facility caused by the effects of the added DO on the natural surface reaeration.

Summary of Performance Results

This report has described the results of implementing the monitoring plan and the pulsed operations of the Aeration Facility to test the performance objectives and evaluate the effects on DWSC DO concentrations (i.e., DO increments). The primary evaluation methods were analysis of the 15-minute DO monitoring from upstream and downstream monitoring stations, and the detailed longitudinal UOP boat survey profiles of DO from surface, mid-depth, and near-bottom DO sensors. Comparison of the DWR *San Carlos* surveys from 2004 and 2008 also was used to analyze the effects of the Aeration Facility on the DWSC DO concentrations for a range of flows from 250 cfs to 1,000 cfs. The results from these performance evaluation methods are summarized in this section, along with general conclusions and recommendations for additional performance testing.

Limited operation of the Aeration Facility likely would have been needed to meet the DO objective of 5 mg/l in June, July, and August of 2008, and more operation likely would have been needed in September 2008 to meet the higher DO objective of 6 mg/l. To evaluate Aeration Facility performance, pulsed operation, rather than operation in response to actual DO conditions in the DWSC, was used in order to compare natural DO conditions and aerated conditions during June, July, August, and September 2008.

San Carlos Deep Water Ship Channel Dissolved Oxygen Boat Surveys in 2004 and 2008

The longitudinal DO profile measured by the DWR *San Carlos* surveys in the DWSC is governed by the balance between the decay of BOD materials in the water (decreasing the DO) and the source of DO from algal photosynthesis and surface reaeration (increasing the DO). The DO decline in the DWSC is the result of BOD and ammonia loads from the Stockton RWCF and river loads of algae and detritus that enter the DWSC. The sources of BOD and ammonia in the DWSC change seasonally and with river flow. The DWR *San Carlos* survey DO profiles in the DWSC provide many years of summer and fall longitudinal profiles that can be used to evaluate the range of observed DO conditions (See Appendix A).

The DWSC longitudinal DO profiles are most sensitive to the flow, the inflow DO and BOD concentration, and the surface reaeration rate. The DWSC DO Model was used to match the measured *San Carlos* survey DO data for a range of flows, BOD concentrations, and reaeration values for 2004 and 2008. The range of flows evaluated was 250 cfs to 1,000 cfs because low DO conditions rarely have been measured when the DWSC flows were higher than 1,000 cfs. The *San Carlos* surveys indicate that the position of the minimum DO in the DWSC moves upstream with a lower flow and downstream with a higher flow. The minimum DO concentration does not change substantially with flow because the minimum DO is controlled by the inflow BOD concentration and the relative balance between the daily BOD decay and the daily surface reaeration. A natural surface reaeration rate of 20% per day was found to match the *San Carlos* survey DO data profiles for 2004 and 2008.

The DWSC DO Model also was used to show the general performance of the Aeration Facility for a range of flows. The natural DO profile and the added DO increment at the Aeration Facility diffuser and downstream in the DWSC were calculated for each flow. Table 1 gives these Aeration Facility performance calculations for flows of 250 cfs to 1,500 cfs. The Aeration Facility performance can be summarized as DO increments expected at downstream locations for each flow condition. At full capacity of 7,500 lb/day, the Aeration Facility would increase the DWSC DO concentrations by about 1 mg/l over a distance of about 2–3 miles for flows of 250–1,000 cfs. At low flows of 250 cfs or 500 cfs, there is no measurable DO increment at Turner Cut because the travel time is relatively long. At higher flows of 750 cfs or 1,000 cfs, a small DO increment of about 0.25 mg/l will persist to Turner Cut, about 5.5 miles downstream from the diffuser. At flows of 1,250 cfs or 1,500 cfs the maximum DO increment is less than 1 mg/l but the DO increment at Turner Cut would be almost 0.5 mg/l because the travel time is less than 5 days.

Tidal Movement and Dissolved Oxygen Increments

The primary method of testing the performance of the Aeration Facility was the 15-minute DO monitoring at the existing RRI station, and at two upstream and two downstream stations that were installed by DWR for this testing program. The RRI station uses a near-surface DO sensor and is closest to the diffuser, about 0.2 mile downstream. The other installed DO monitoring stations use a DO sensor located at a depth of about 10–15 ft so that DO measurements would not be as strongly influenced by surface algae growth as the surface DO monitor at RRI would be. The DO monitoring station at Light 48 is located about 1.5 miles upstream from the diffuser, and the station at Light 43 is about 0.2 mile upstream from the diffuser. The DO monitoring station at Light 42 is about 0.7 mile downstream from the diffuser, and the station at Light 40 is about 1.6 miles downstream from the diffuser.

The DO monitoring indicated that the maximum DO increments were observed at the RRI station, which was expected because of its location just 1,000 ft downstream of the diffuser on the same side of the channel. The RRI DO increments were larger than the DO increments observed farther downstream at Light 42 and Light 40. The measured DO increments at Light 42 (0.7 mile downstream) were likely the best indication of the fully mixed DO added from the Aeration Facility. Much lower DO increments are measured at Light 40 because it is farther downstream (1.6 miles downstream of the diffuser). The DO increments upstream at Light 48 station were small and infrequent because only rarely does the flood tide movement extend 1.5 miles upstream from the diffuser. It generally took about 2 days of Aeration Facility operation for the maximum DO increments to appear at Light 43, located just 0.2 mile upstream but across the DWSC from the diffuser.

Each of the four DO monitoring stations added to test the performance of the Aeration Facility provided valuable information for the performance assessment. The Light 48 DO data indicated the variable upstream conditions, largely unaffected by the Aeration Facility. The Light 43 DO data indicated the lateral spreading of the added DO from tidal movement, showing a gradual increase during operation of the Aeration Facility. The RRI DO data provided a clear signal during operation periods, having a very large DO increment during all ebb tides when the Aeration Facility was on. Light 42 DO data provided the best estimate of the average (i.e., fully mixed) DO increment from the Aeration Facility. The Light 40 DO data provided a very strong tidal signal during operation, with a relatively large DO increment at low tide (i.e., downstream tidal movement) and a much smaller DO increment at high tide (i.e., upstream tidal movement).

The physical factors of geometry and tidal flows were used to estimate the DO increments in the DWSC and at the DO monitoring station resulting from operation of the Aeration Facility (See Appendix B). When operated at full capacity, the Aeration Facility diffuser discharges about 7,500 lb/day of added DO into the DWSC. The average daily DO increment from the Aeration Facility (measured at Light 42, 0.7 miles downstream) depends on the net daily flow moving downstream past the diffuser. For a flow of 250 cfs, the average DO increment from the Aeration Facility would be about 5.6 mg/l. For a flow of 500 cfs, the average DO increment would be about 2.8 mg/l; for a flow of 750 cfs the average DO increment would be 1.9 mg/l; and for a flow of 1,000 cfs, the average DO increment would be 1.4 mg/l.

Because the daily source of DO from surface reaeration in the DWSC depends on the reaeration rate and the DO deficit, the added DO from the Aeration Facility reduces the natural reaeration source of DO in the DWSC. The added DO from the Aeration Facility reduces the DO deficit and thereby reduces the surface reaeration downstream of the diffuser. Therefore, the measured DO increment from the Aeration Facility will decrease with time (and distance downstream). The measured changes in the DO at Light 40 (1.6 miles downstream) were therefore less than the measured changes in DO at Light 42 (0.7 mile downstream) during periods of Aeration Facility operation. Appendix A provides more background information about this surface reaeration effect.

Because there were no previous surface reaeration rate measurements for the DWSC, a range of values was tested with the DO Increment Model and compared with the DO monitoring data. The DO monitoring data indicated that the best estimate for the reaeration rate was about 20% per day, suggesting that the initial DO increment will decrease by about 20% each day. This relatively high natural surface reaeration rate in the DWSC limits the downstream extent of the added DO effects of the Aeration Facility (See Table 1).

Dissolved Oxygen Longitudinal Profile Results

The performance of the Aeration Facility also was measured by boat surveys of longitudinal DO concentration profiles conducted by UOP. Measurements were collected using three DO sensors near the surface, at mid-depth, and near the bottom. The purpose of the UOP boat surveys was to identify and track the longitudinal effects of the Aeration Facility beginning with natural DO conditions 1 day prior to operation, and continuing for several days while the Aeration Facility was operated. Measured DO profiles at mid-depth were used to estimate the added DO from the Aeration Facility compared to the natural DO profile measured prior to Aeration Facility operation. Measurements at low tides showed the downstream extent of the DO effects, and measurements at high tides showed the upstream effects between the diffuser and Light 48.

The multiple DO profiles from three depths in the DWSC indicated that there are natural differences in the DO concentrations resulting from temperature stratification and algal photosynthesis. The added DO from the Aeration Facility diffuser was not completely mixed vertically and was not distributed uniformly in the channel. The vertical differences and the day-to-day changes in DO concentrations along the DWSC make the identification of the Aeration Facility effects on the DWSC DO somewhat uncertain. However, the consistent measurements of a wedge of increased DO concentrations in the DWSC at low tide each day during operation confirmed the slow downstream movement (because of the low flows) during summer 2008. These DO longitudinal profiles also confirmed that the added DO increments decreased downstream (with time) because of the effects of the added DO on the natural surface reaeration in the DWSC. The maximum amount of increased DO in the DWSC measured with the UOP boat surveys was about 4 days of Aeration Facility capacity (i.e., 4 x 7,500 = 30,000 lb), suggesting that the surface reaeration rate of 20% per day will limit the maximum amount of DO that can be added to the DWSC.

Conclusions

The six performance objectives were tested and evaluated in the 2008 demonstration period. Each of the DWSC monitoring methods (DO monitoring, UOP longitudinal DO profiles, and DWR *San Carlos* surveys) contributed to testing and evaluating these performance objectives. The six performance objectives are as follows:

- Determine how well the existing RRI DO monitoring station (at approximately 3-ft depth) represents natural DO conditions in the DWSC from Turner Cut to Channel Point (natural DO conditions).

  Comparison of the RRI 15-minute DO data with the upstream and downstream DO monitoring station data suggested that the RRI station is near the location of the minimum DO in the DWSC, at least for the flow conditions measured in 2008. Based on this data, the RRI station is representative of natural DO conditions throughout most of the DWSC upstream of Turner Cut. Because the RRI station is just 0.2 mile downstream of the diffuser, it also shows the greatest response to added DO from the Aeration Facility. It should be possible to evaluate the natural DO conditions while the Aeration Facility is operated by estimating and subtracting the incremental DO effects from the RRI monitoring DO records.

- Determine whether the Aeration Facility diffuser location between Dock 19 and Dock 20 was appropriate for adding DO to the DWSC to alleviate the lowest DO conditions (location).

  Because the RRI station is located near the minimum natural DO concentrations in the DWSC, the construction of the DWR Demonstration Aeration Facility at RRI, with the diffuser between Docks 19 and 20, was an appropriate location to increase the minimum DO in the DWSC. Because of tidal movement and mixing, some added DO from the Aeration facility is distributed upstream of the diffuser, between Light 43 and Light 48. The majority of the added DO was observed from slightly downstream of the diffuser to Light 42. Some added DO from the Aeration Facility was observed downstream at Light 40.

- Determine how much DO could be added to the DWSC from the Aeration Facility under a variety of flows (i.e., 250 cfs to 1,000 cfs) at maximum Aeration Facility capacity (DO increments).

  The DWSC DO Model was calibrated with measured DWR San Carlos surveys and used to demonstrate the downstream effects of the Aeration Facility for a range of flows between 250 cfs and 1,000 cfs (Table 1). The incremental DO effects depend on only the Aeration Facility capacity (7,500 lb/day) and the natural surface reaeration rate. The average DO increment downstream of the diffuser will be greater with lower flows, but DO increments will move farther downstream with higher flow. The average DO increment at a flow of 250 cfs will be about 3 mg/l and will be about 0.5 mg/l at mile 35 (3 miles downstream). The average DO increment at a flow of 1,000 cfs will be about 1.25 mg/l and will be about 0.5 mg/l at mile 33 (5 miles downstream).

- Determine how much of an effect on DO could be expected along the DWSC at high tide and low tide (tidal spreading).

  Results of the dye studies, the measured DO longitudinal profiles, and DO monitoring station data indicate that the tidal movement of the added DO from the Aeration Facility can be estimated accurately. The tidal dispersion studies indicated that dye was spread over about 1 mile of the DWSC after a full tidal cycle. Therefore, because the tidal movement is about 1.5

miles between low tide and high tide, added DO from the Aeration Facility will be spread by the tidal movement and mixed some additional distance upstream and downstream. The added DO from the Aeration Facility each day therefore will be tidally mixed in a volume extending about 2.5 miles in the DWSC.

- Determine the effects of natural surface reaeration on the downstream DO profile and the DO increments from the Aeration Facility (reaeration rate).

  Results from DO longitudinal profiles measured by the UOP boat surveys suggest that a maximum of about 30,000 lb of oxygen can be added to the DWSC with the Aeration Facility (about 4 days' DO discharge capacity). Continuous operation would be needed to maintain this added DO wedge because the added DO increments are reduced at about 20% per day. The maximum amount of added DO from the Aeration Facility observed in the DWSC is limited by the reduction in the natural surface reaeration caused by the added DO.

- Determine the ability of the Aeration Facility to maintain DWSC DO above the Basin Plan objectives of 5 mg/l from December 1 through–August 31, and 6 mg/l from September 1 through November 30 (DO objectives).

  Operating strategies for the Aeration Facility to help meet the Basin Plan DO objectives in the DWSC can be developed for the range of observed inflows, as a function of the inflowing DO and BOD concentrations. When the BOD is high enough to cause the minimum DO in the DWSC to approach the DO objective, the Aeration Facility can be operated to help maintain the minimum DO in the DWSC above the DO objectives. However, it is not reasonable to expect the added DO from the Aeration Facility to be sufficient to meet the Basin Plan DO objectives in all situations.

Recommendations

The testing of the Aeration Facility performance objectives provides the basis for an operational strategy that can be developed for the Aeration Facility to help meet the Basin Plan DO objectives in the DWSC. The Aeration Facility will be operated only when the natural DO concentrations in the DWSC decrease to the DO objectives of 5 mg/l (6 mg/l from September 1 to November 30). The Aeration Facility likely will not be operated when DWSC flows are greater than 1,000 cfs. A permanent DO monitoring strategy also can be implemented, based on the results from the four DO monitoring stations installed by DWR at Lights 40, 42, 43, and 48. Specific recommendations are:

1. Some adjustments in the Aeration Facility should be tested to improve the oxygen gas transfer efficiency and increase the DO discharge capacity.
2. Some additional testing of Aeration Facility operation during flood tide should be made to shift the distribution of the added DO increments upstream of the diffuser toward Light 48.
3. A long-term monitoring plan should be developed for the DWSC based on the DO monitoring at Light 48, Light 43, RRI, Light 42 and Light 40 stations. RRI could remain the primary monitoring location for evaluating natural DO conditions in the DWSC, effects of the City of Stockton RWCF nitrification facility, and effects of the added DO from the Aeration Facility.
4. An operational strategy for the Aeration Facility should be developed that would involve upstream flow and water quality monitoring at Mossdale to forecast the expected DWSC DO profiles and the need to operate the Aeration Facility (with one or two pumps).

5. The possible integration of the Port of Stockton aeration facilities at Dock 13 with operation of the DWR Aeration Facility at Dock 20 (RRI) should be evaluated as part of the SJR DO TMDL implementation plan. Procedures for identifying DWSC DO conditions that are not meeting the DO objectives, as well as estimating the City of Stockton RWCF contributions to improved DO conditions in the DWSC, also should be developed.

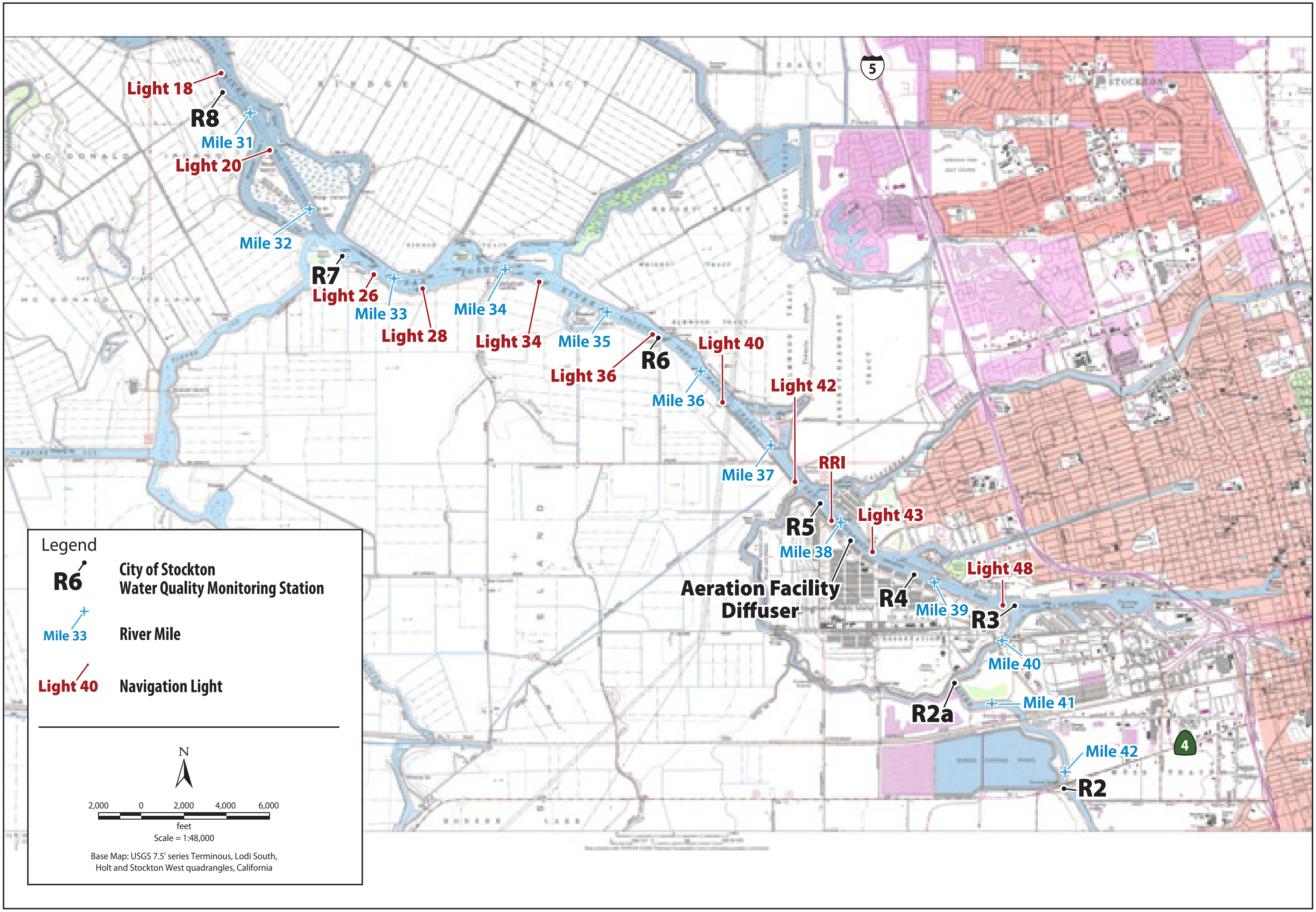
References

ICF Jones & Stokes. 2008. Testing of the DWR aeration facility efficiency and capacity. Sacramento, CA. Prepared for: California Department of Water Resources, Bay-Delta Office.

Jones & Stokes. 2003. Evaluation of aeration technology for the deep water ship channel. Prepared for: California Bay-Delta Authority. February 2003.

Jones & Stokes. 2004. Aeration technology feasibility report for the San Joaquin River deep water ship channel. Prepared for: California Bay-Delta Authority. August 2004.

Litton, Gary M. 2003. Deposition rates and oxygen demands in the Stockton Deep Water Ship Channel of the San Joaquin River *June–November 2001*. Prepared for the San Joaquin River Dissolved Oxygen TMDL Technical Committee and CALFED. University of the Pacific, Department of Civil Engineering. Stockton, CA.



Graphics/Projects/00902.08 Stockton Aeration Demo Facility/208 Operations Report (rev04-10) SS

ICF INTERNATIONAL

Figure 1
Stockton Deep Water Ship Channel Water Quality Stations

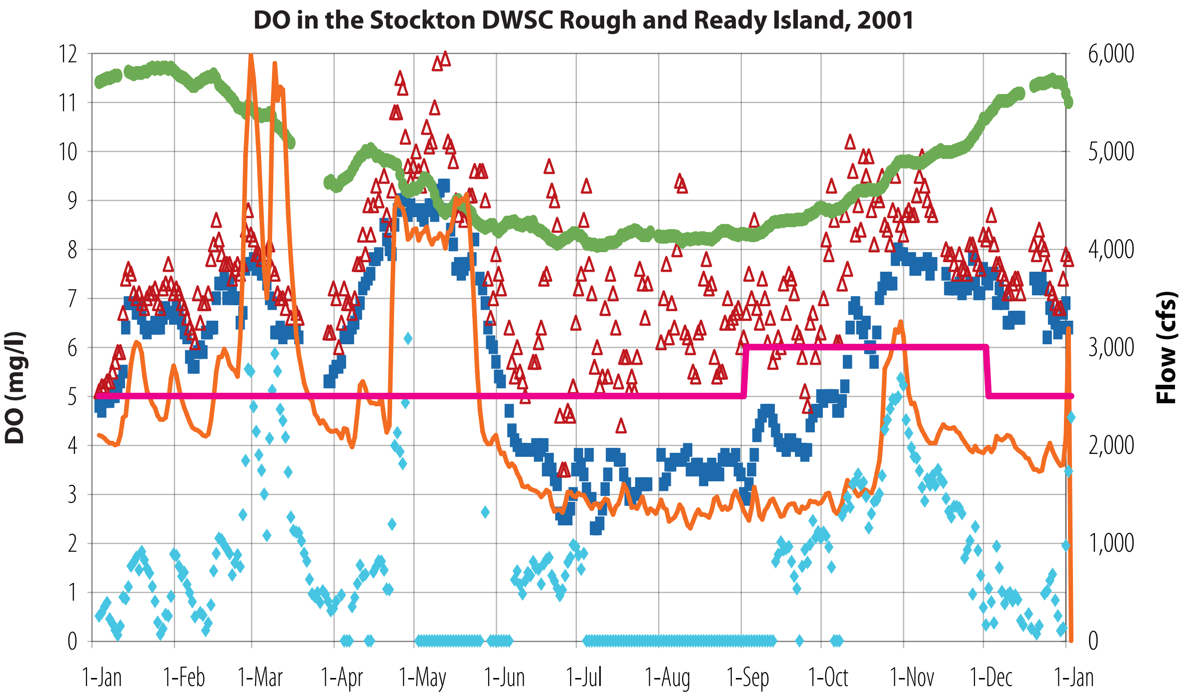


Figure 2a: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2001.

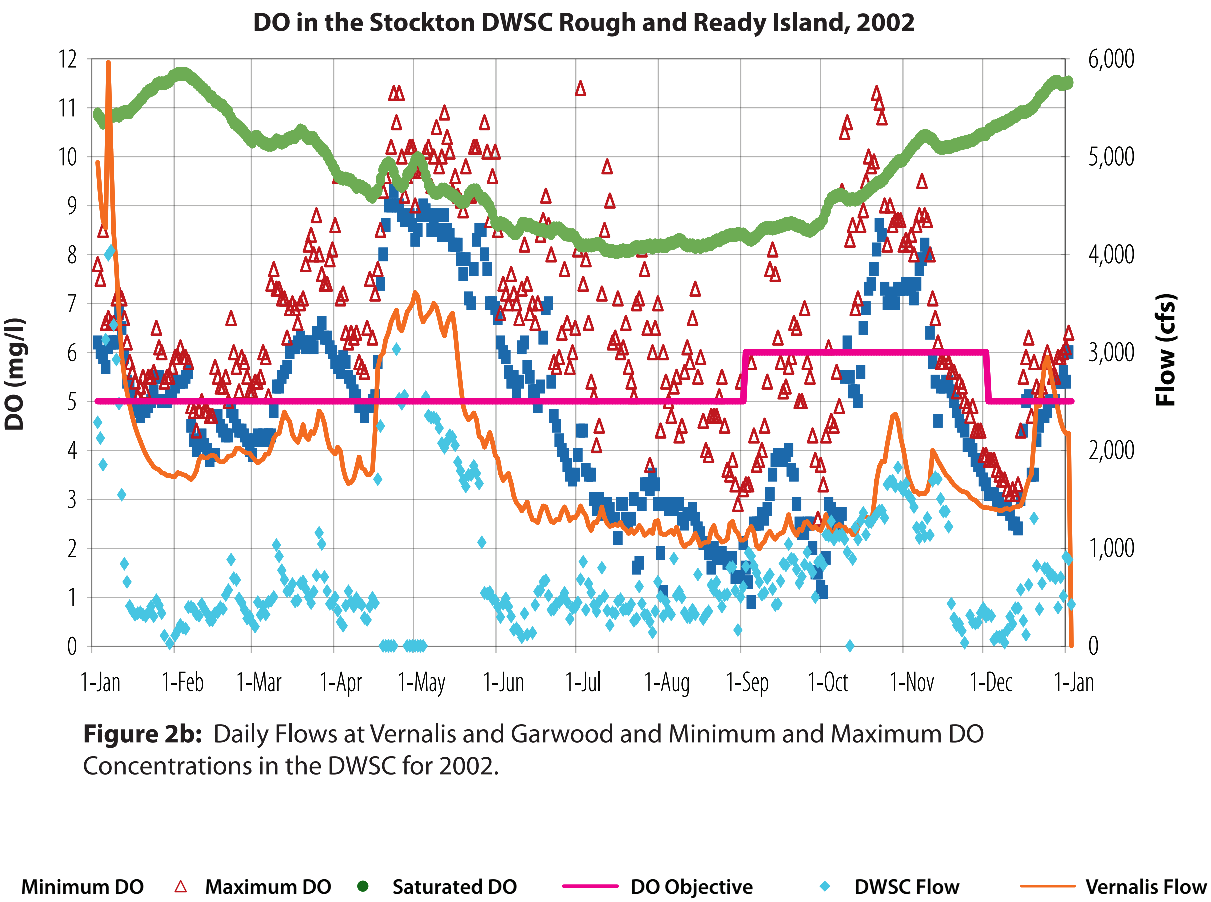


Figure 2b: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2002.

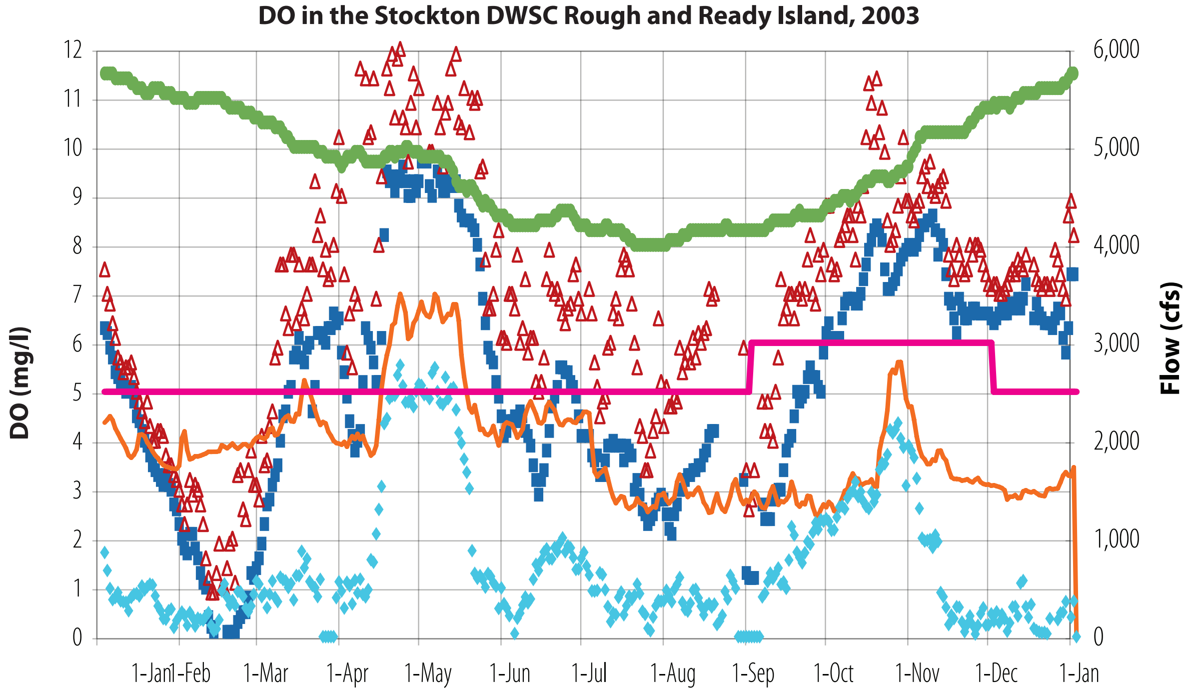


Figure 2c: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2003.

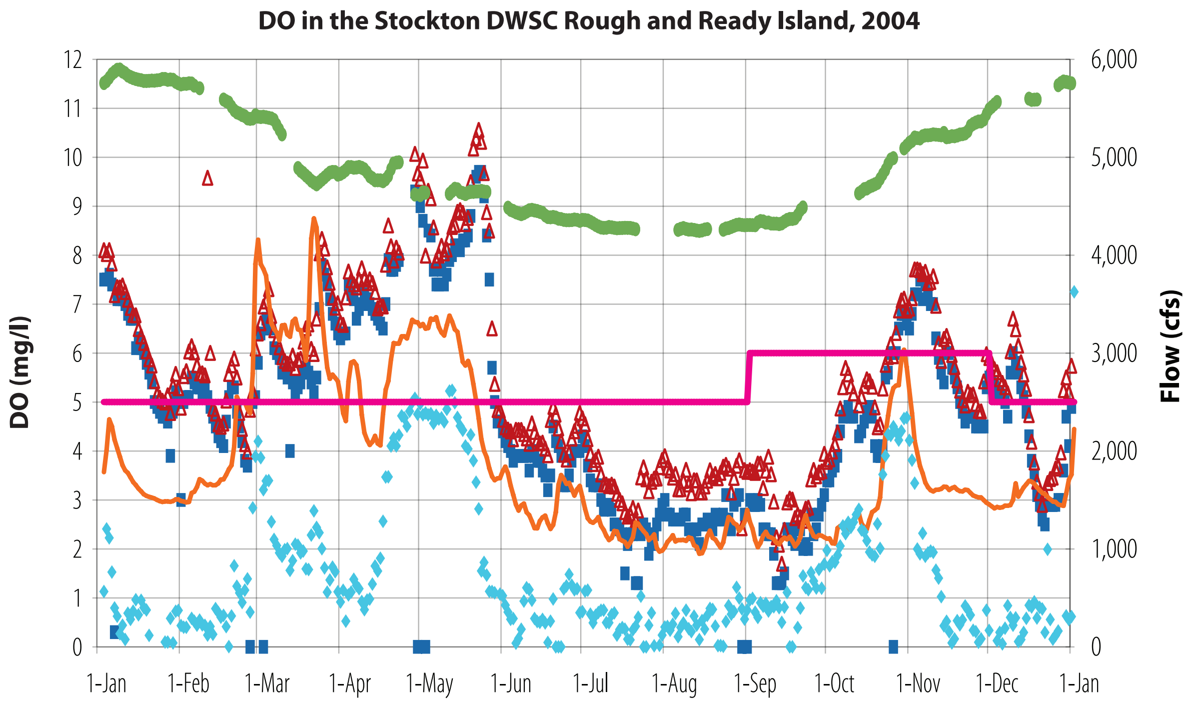


Figure 2d: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2004.

Minimum DO | Maximum DO | Saturated DO | DO Objective | DWSC Flow | Vernalis Flow

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

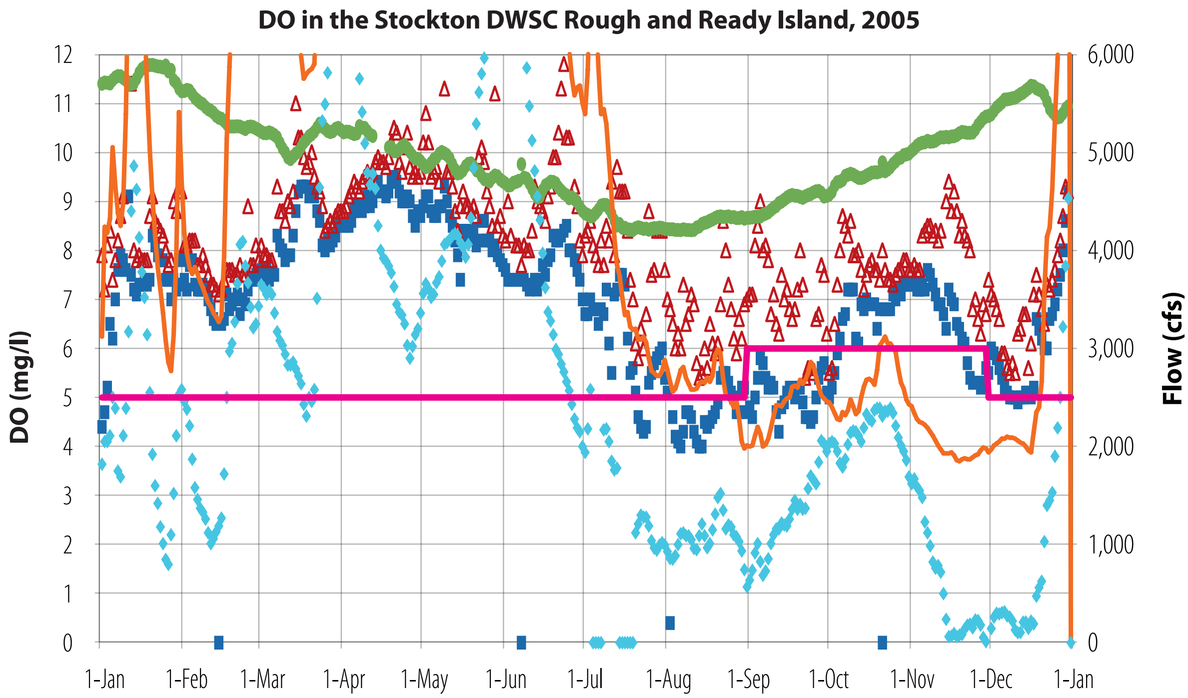


Figure 2e: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2005.

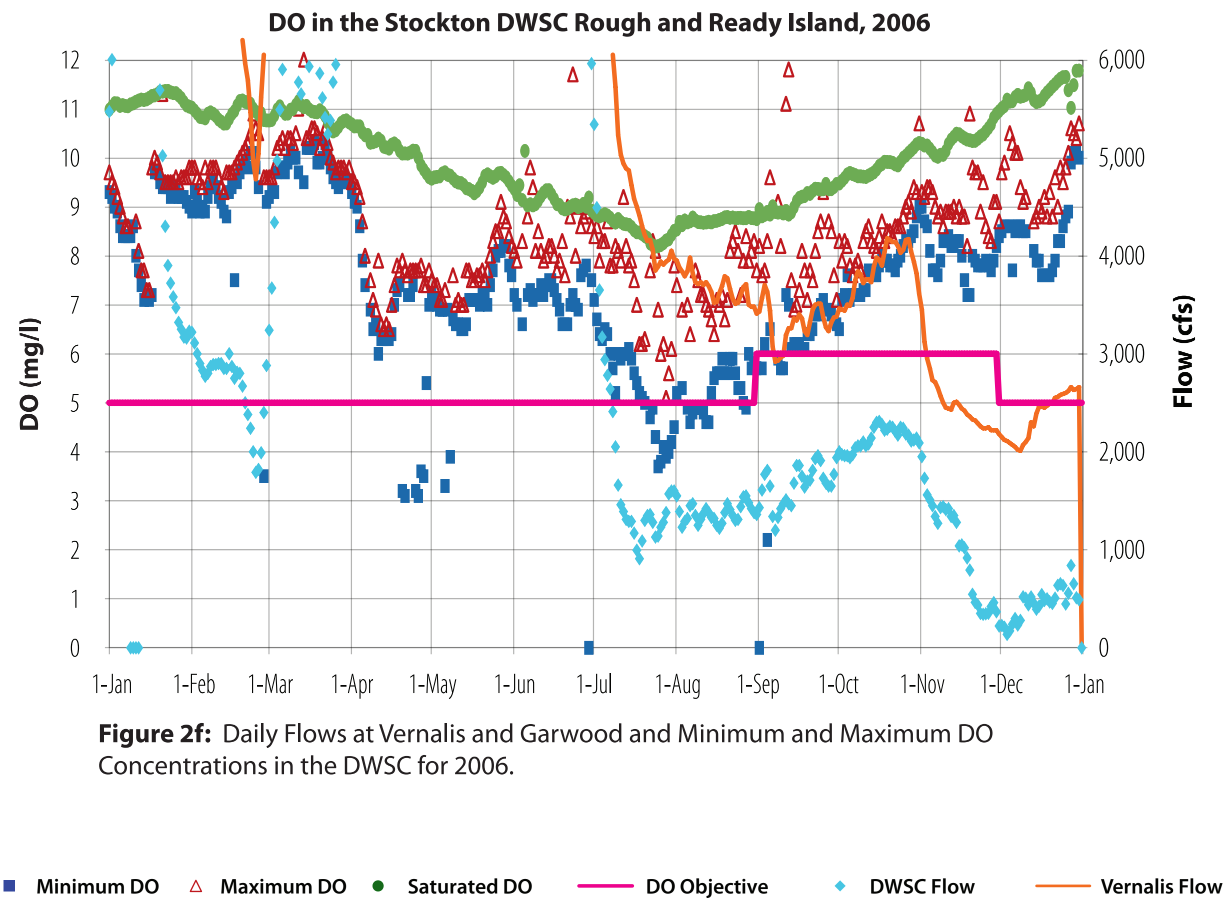


Figure 2f: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2006.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 2 (continued)

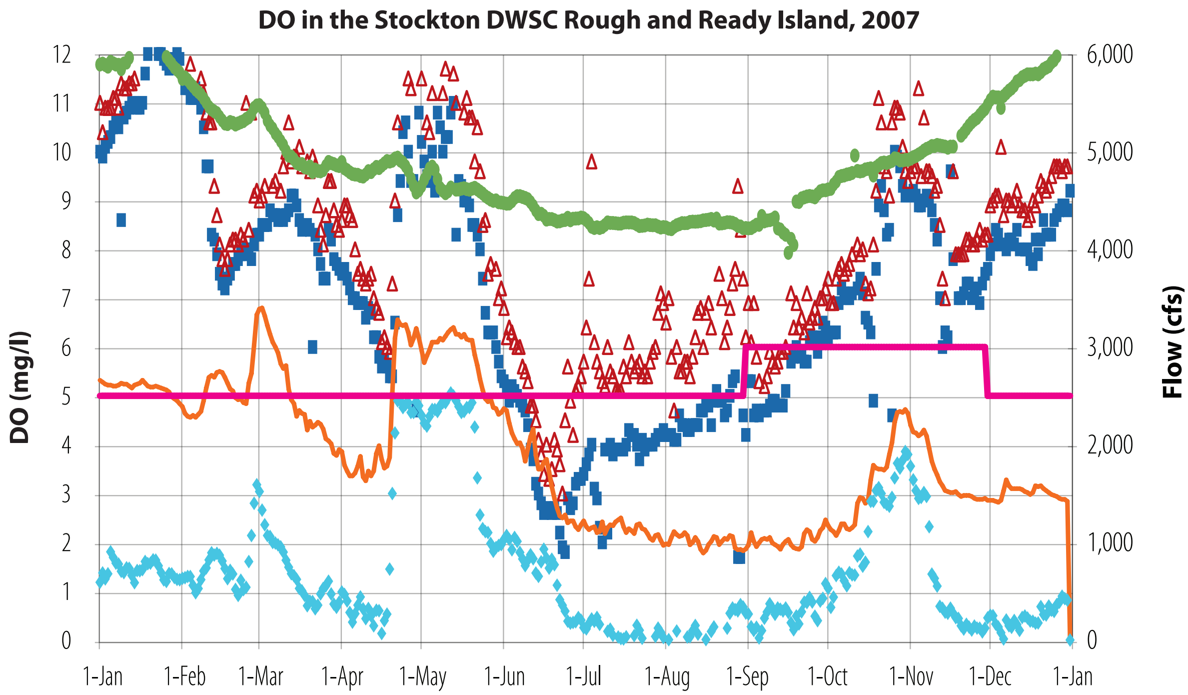


Figure 2g: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2007.

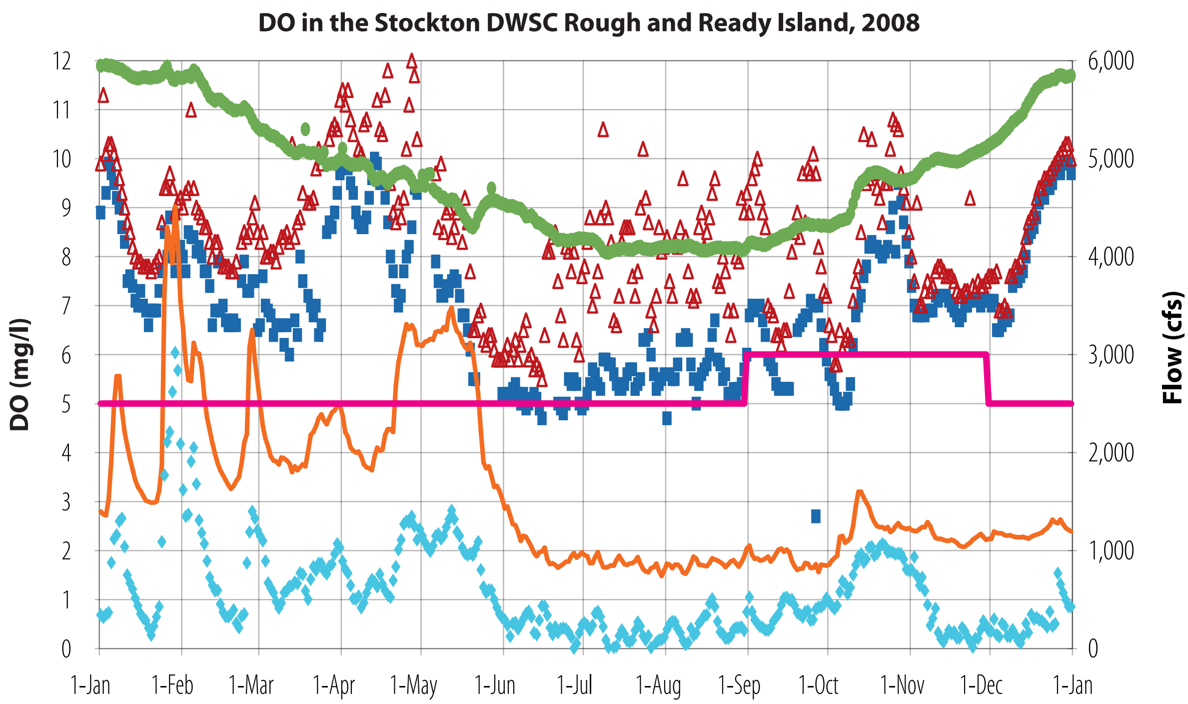


Figure 2h: Daily Flows at Vernalis and Garwood and Minimum and Maximum DO Concentrations in the DWSC for 2008.

ICF INTERNATIONAL

Figure 2 (continued)

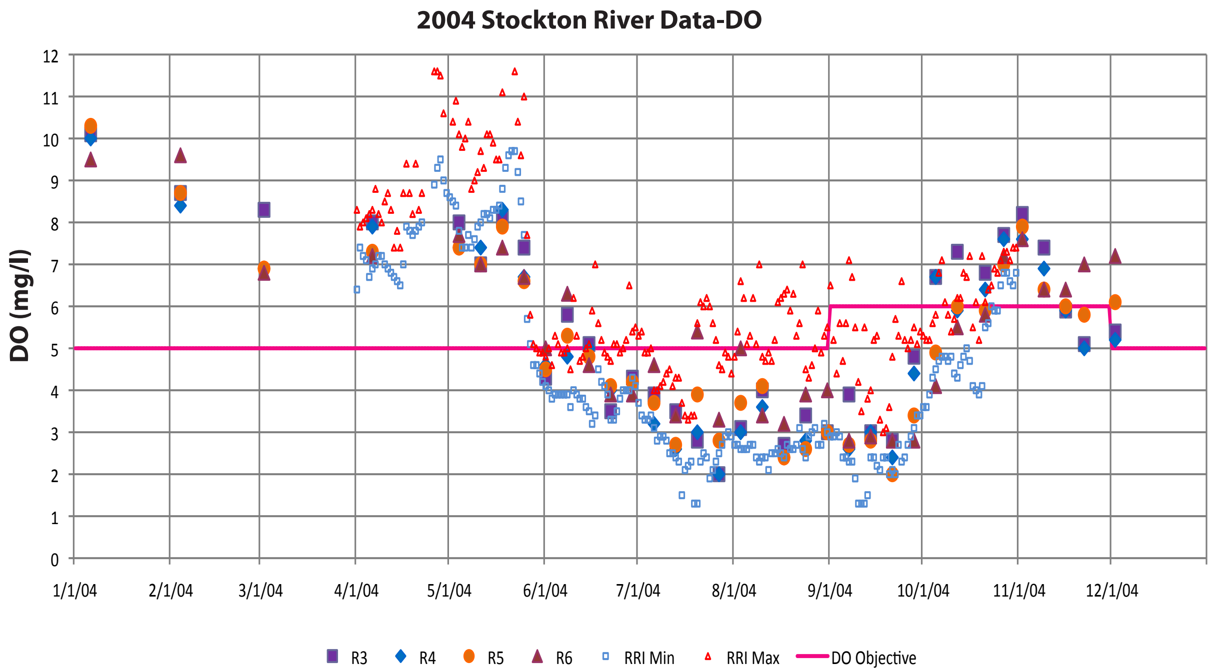


Figure 3a: City of Stockton DO Measurements in the DWSC (R3, R4, R5, and R6) Compared to the Saturated, Minimum and Maximum DO Concentrations at the DWR RRI Monitoring Station for 2004.

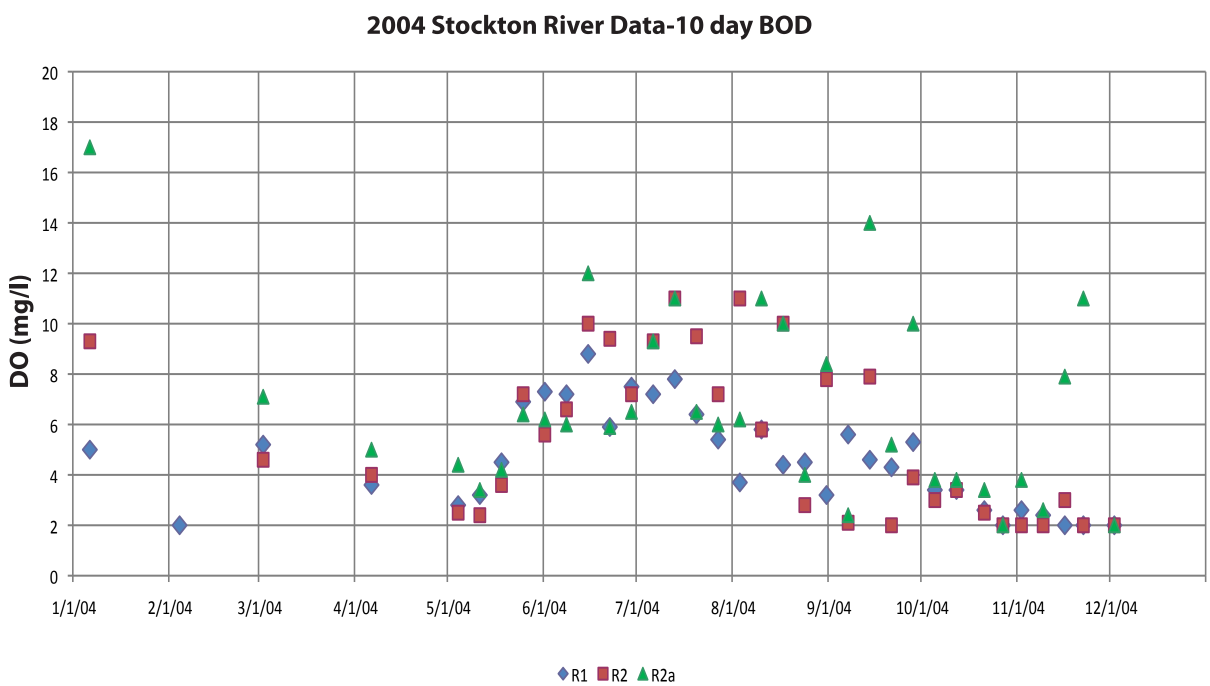


Figure 3b: San Joaquin River Inflow BOD Concentration (mg/l) Measured by City of Stockton in 2004.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 3

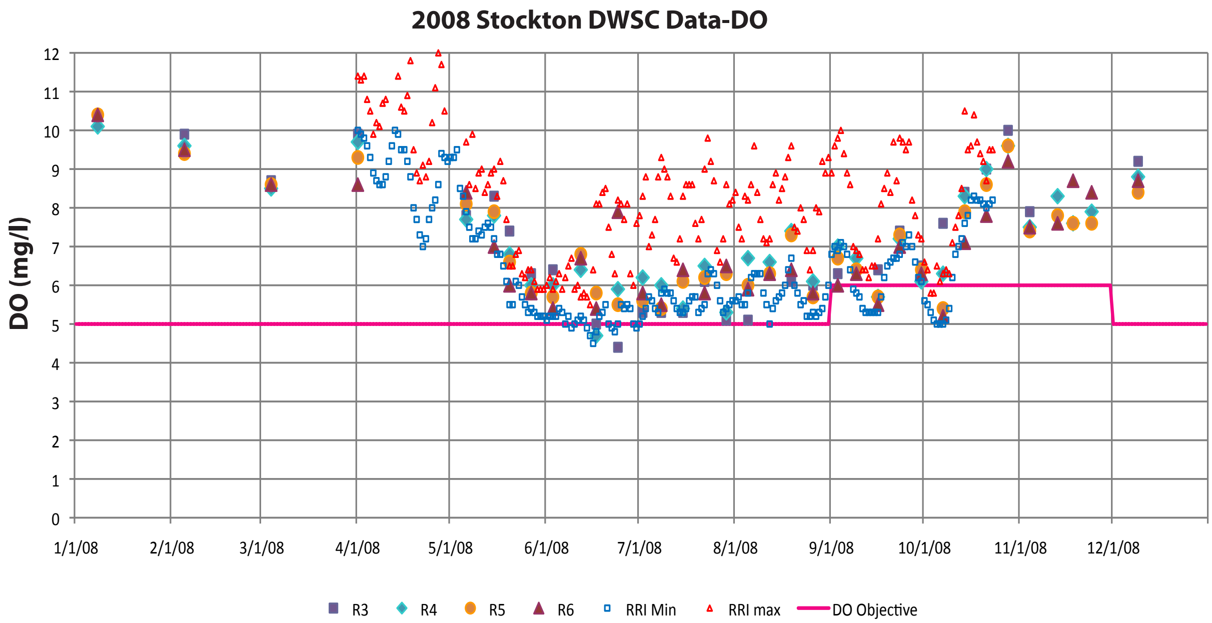


Figure 3c: Weekly DO Concentrations (mg/l) Measured in the DWSC by City of Stockton in 2008

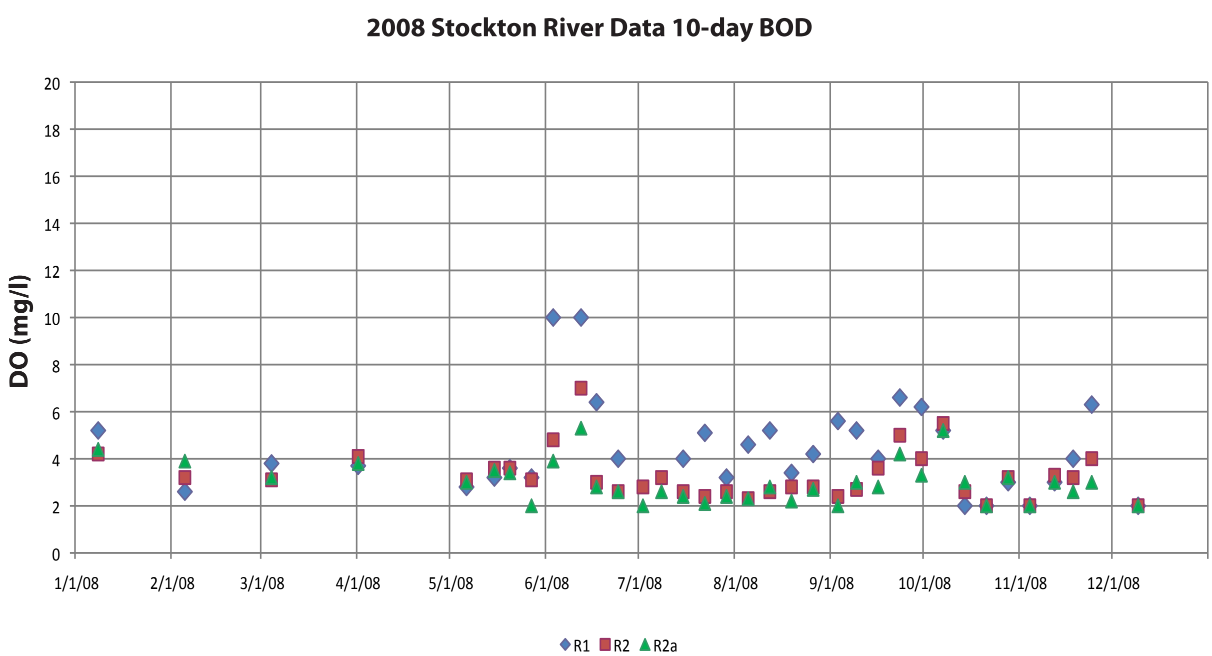


Figure 3d: Weekly River Inflow 10-day BOD Concentrations (mg/l) Measured by City of Stockton in 2008

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 3 (continued)

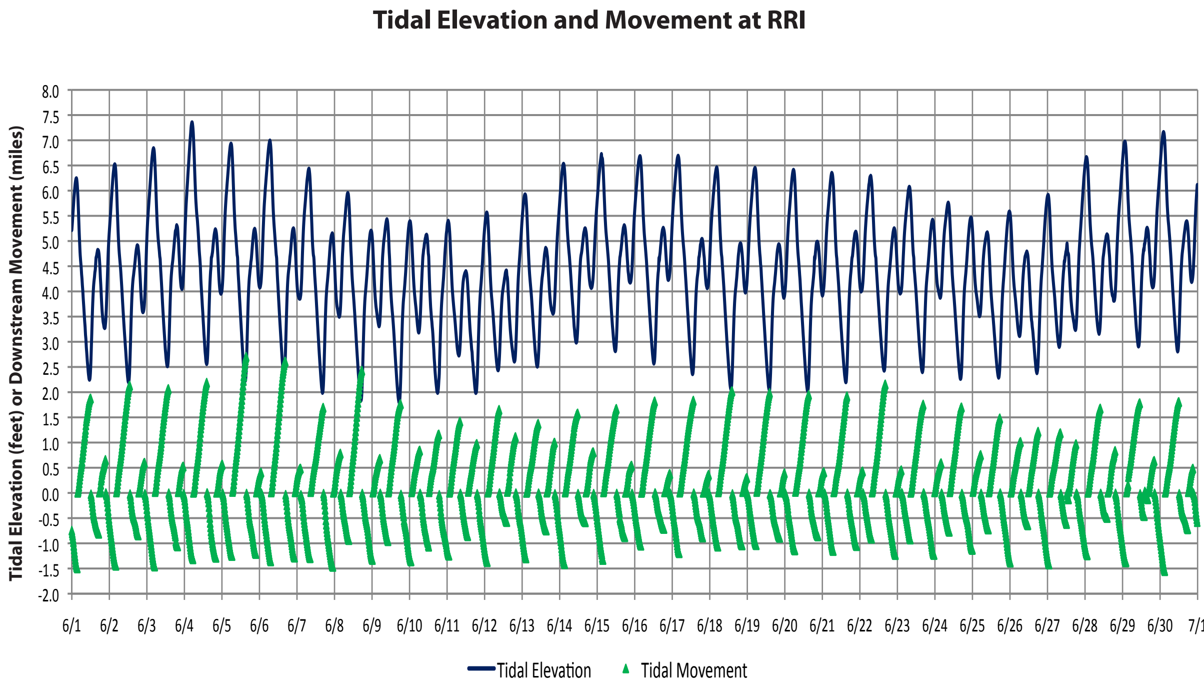


Figure 4a: Tidal Elevations and Tidal Movement Calculated for the RRI Station for June 2008.

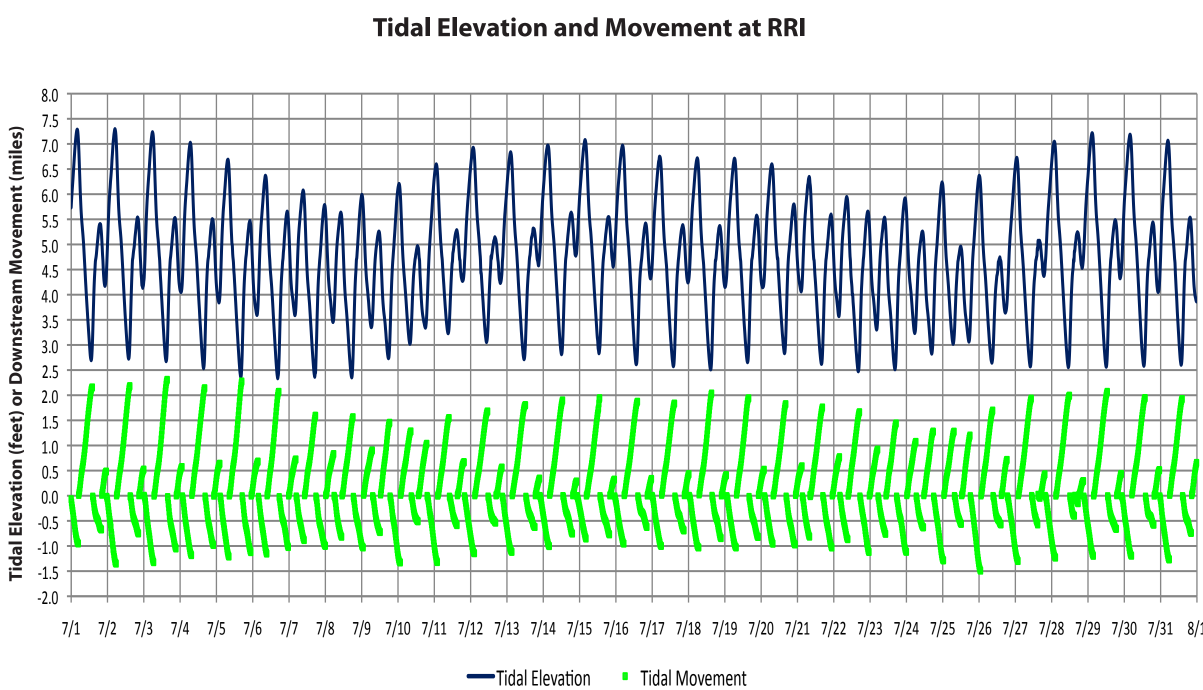


Figure 4b: Tidal Elevations and Tidal Movement Calculated for the RRI Station for July 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 4

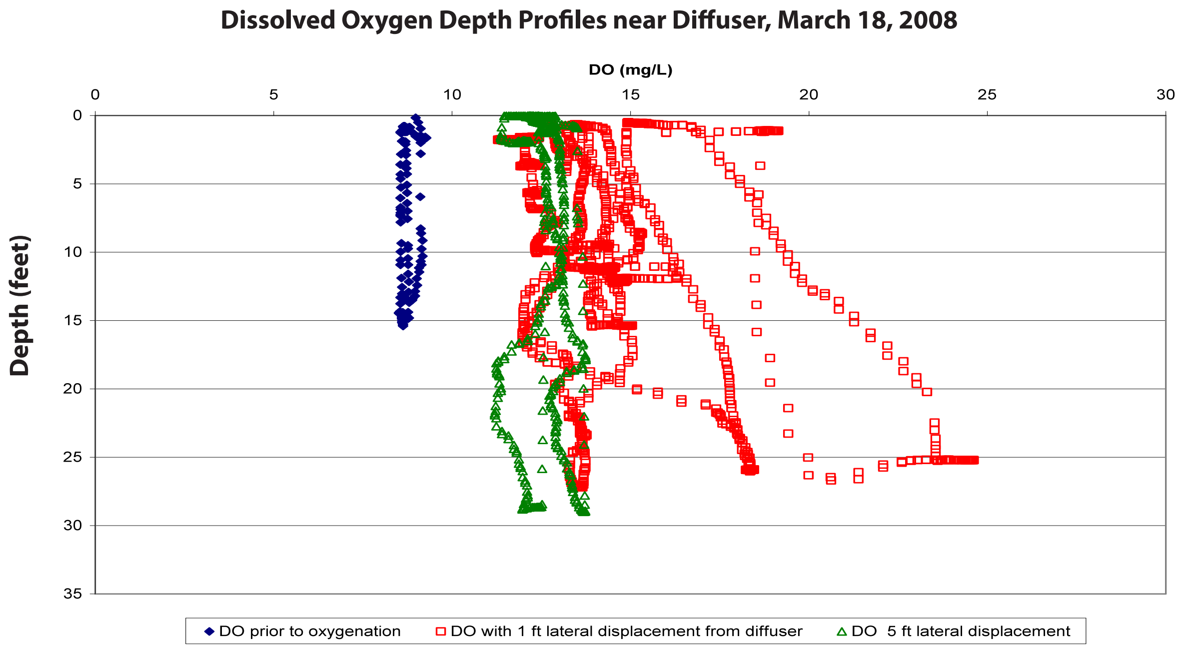


Figure 5a: Depth Profiles near the Diffuser before and after Aeration Facility Operation on March 18, 2008.

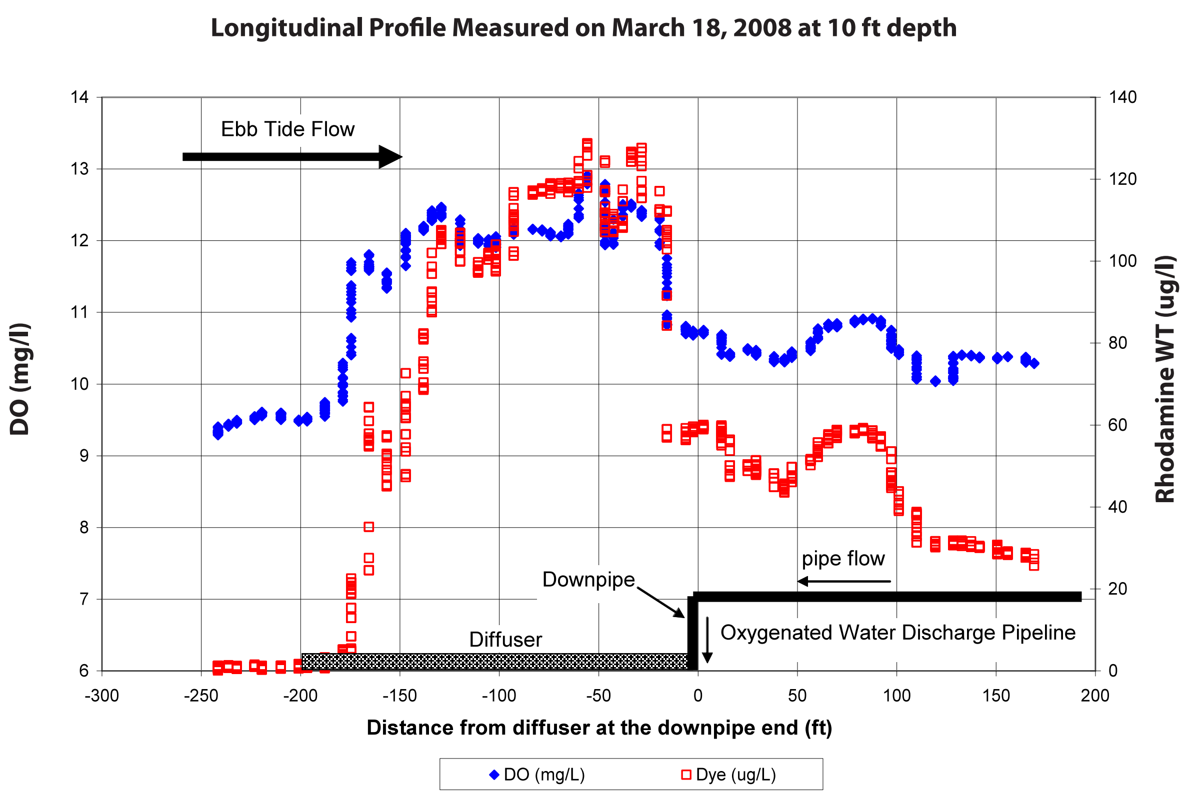


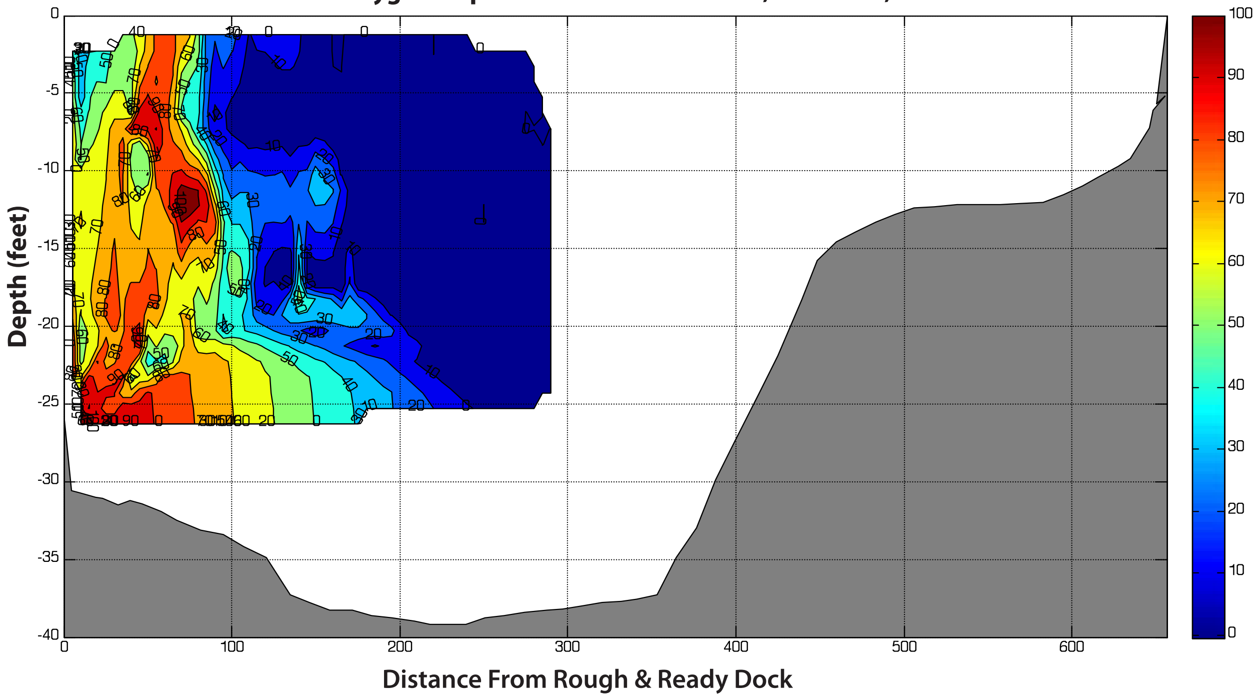
Figure 5b: Longitudinal Profile Measured at the 10-Foot Depth, 20-30 Feet away from the Diffuser on March 18, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

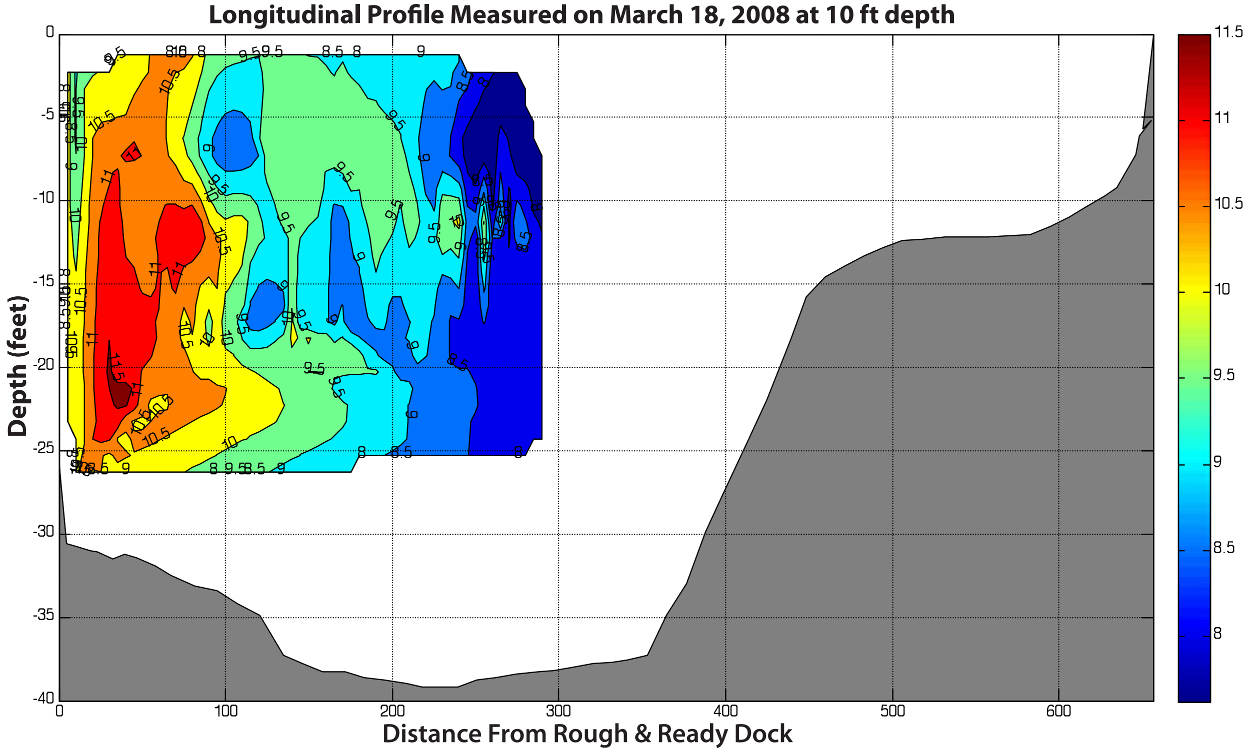
ICF INTERNATIONAL

Figure 5

Dissolved Oxygen Depth Profiles near Diffuser, March 18, 2008



Longitudinal Profile Measured on March 18, 2008 at 10 ft depth



Lateral Profiles of Dye and Dissolved Oxgen Concentrtions
Measured Near Center of the Diffuser at Higher-High Slack Tide on March 18, 2008

ICF INTERNATIONAL

Figure 6

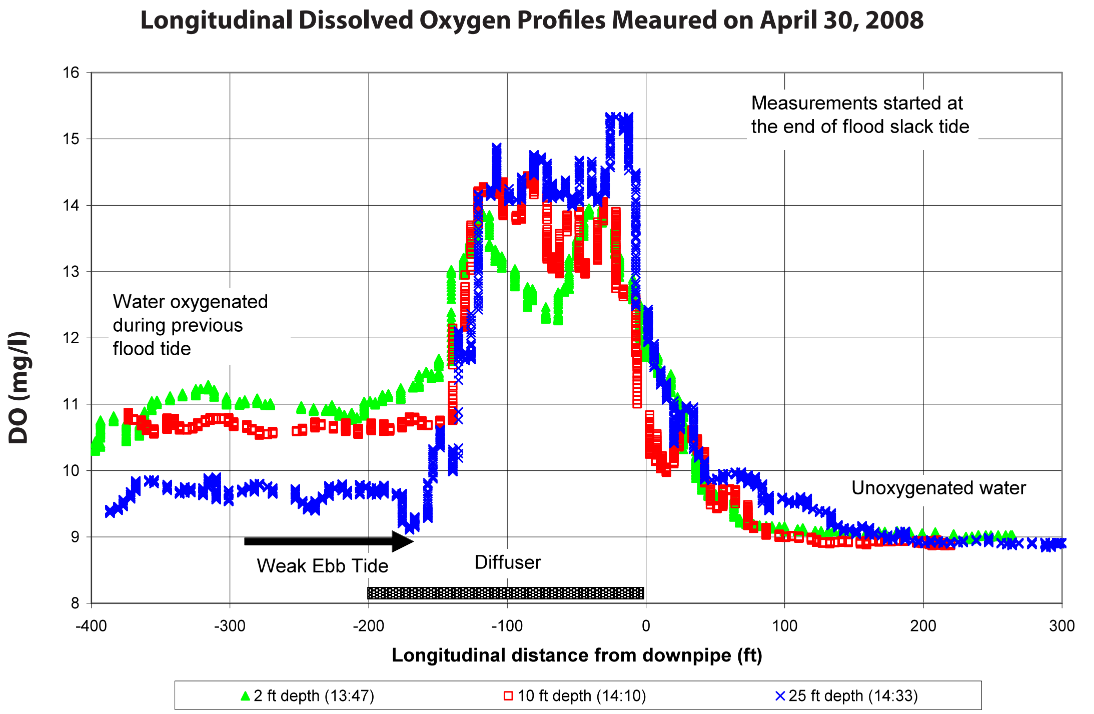


Figure 7a: Longitudinal Dissolved Oxygen Profiles Measured 15-20 Feet away from Diffuser on April 30, 2008.

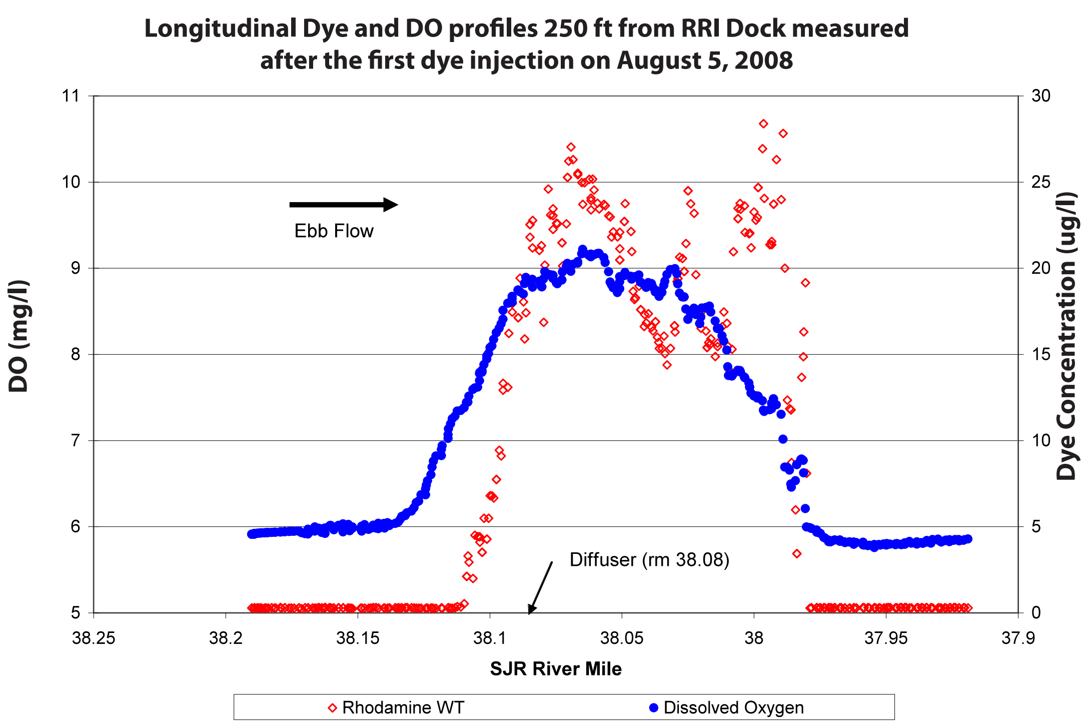


Figure 7b: Longitudinal Dye and Dissolved Oxygen Concentration Profiles along Mid-Channel Measured at the 10-Foot Depth after the First Dye Injection of August 5, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 7

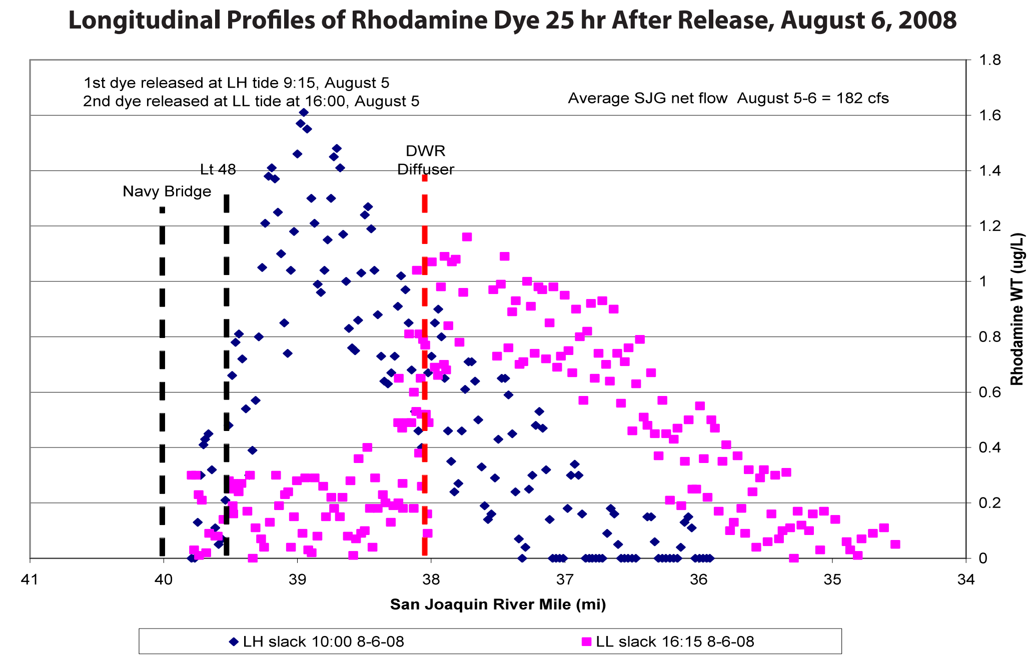


Figure 8a: Longitudinal Dye Concentration Profiles Measured 1-Tidal Day (25 hr) after Each Dye Injection on August 5, 2008.

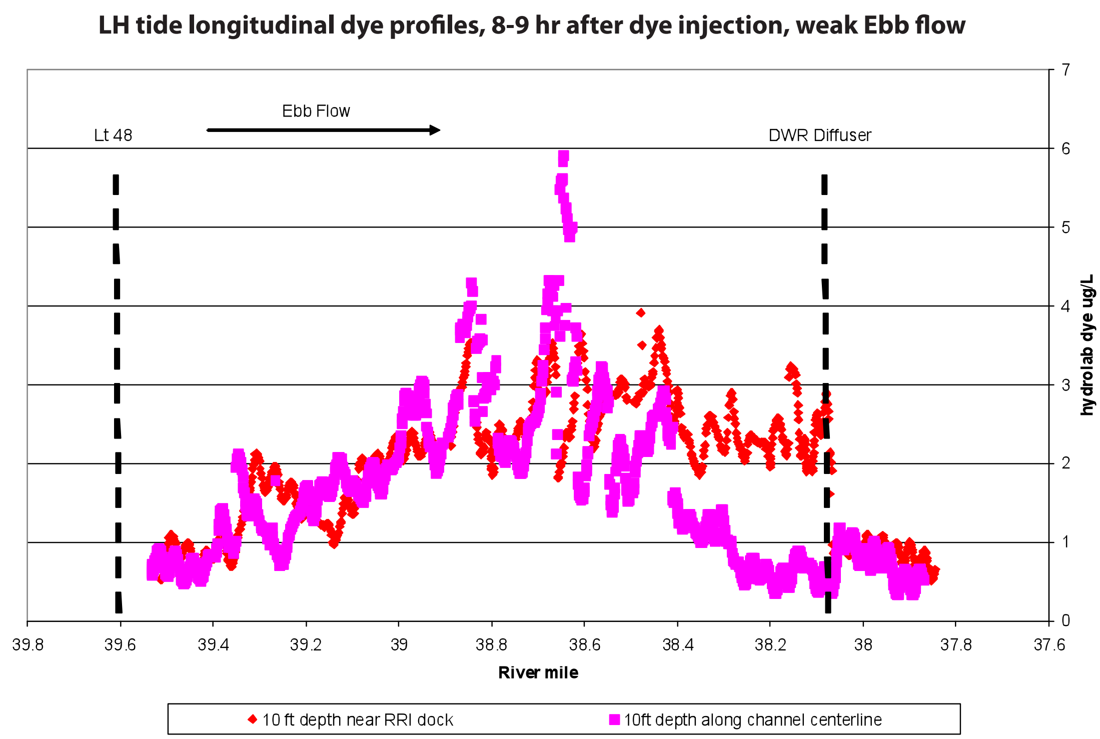


Figure 8b: Longitudinal Dye Concentration Profiles Measured along the Dock and at Mid-Channel 8-9 Hours after the Low-Low Slack Tide Dye Injection of August 13, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 8

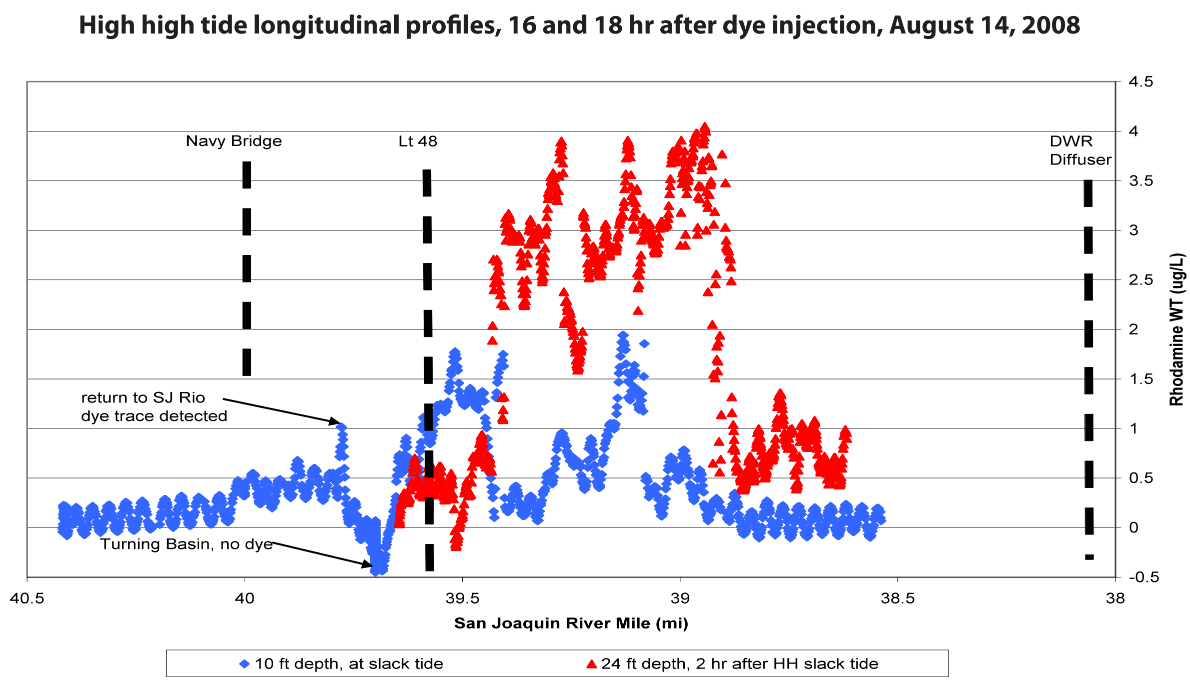


Figure 9a: Longitudinal Dye Profile Measured near Mid-Channel at High Tide on August 14, 2008, about 18 Hours after Dye Release.

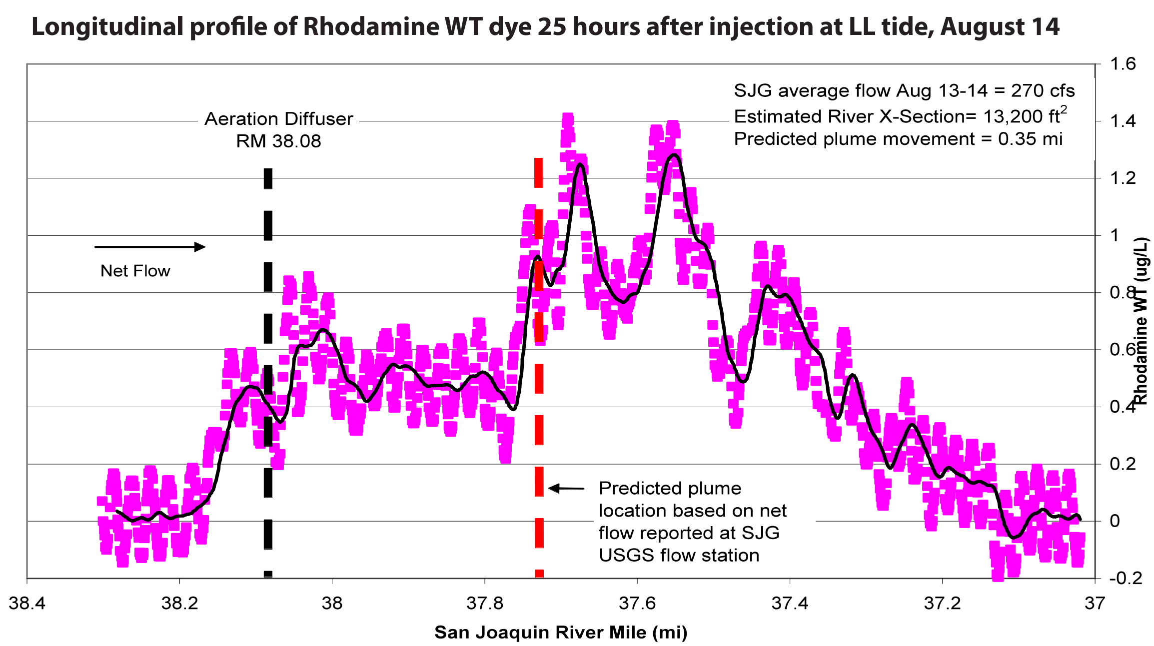


Figure 9b: Longitudinal Dye Concentration Profile near Mid-Channel at Low Tide on August 14, 2008, about 25 Hours after Dye Release.

Figure 9

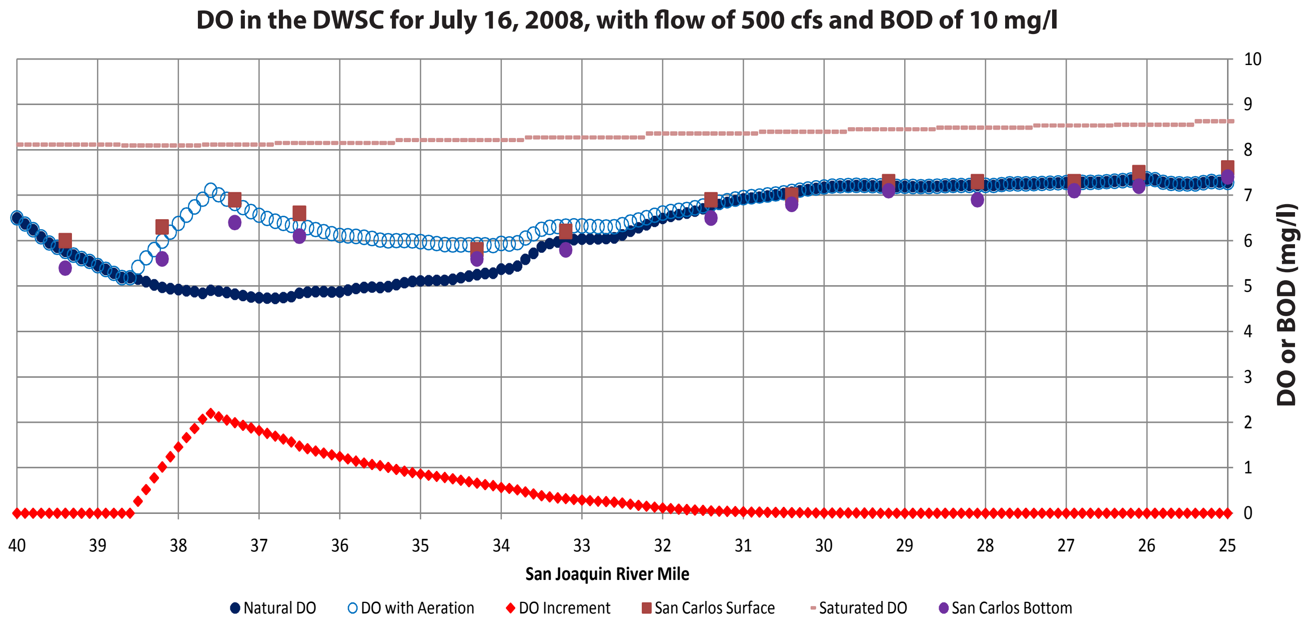


Figure 10a: Measured and Calculated DWSC DO Profile for July 16, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l and BOD of 10 mg/l.

Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

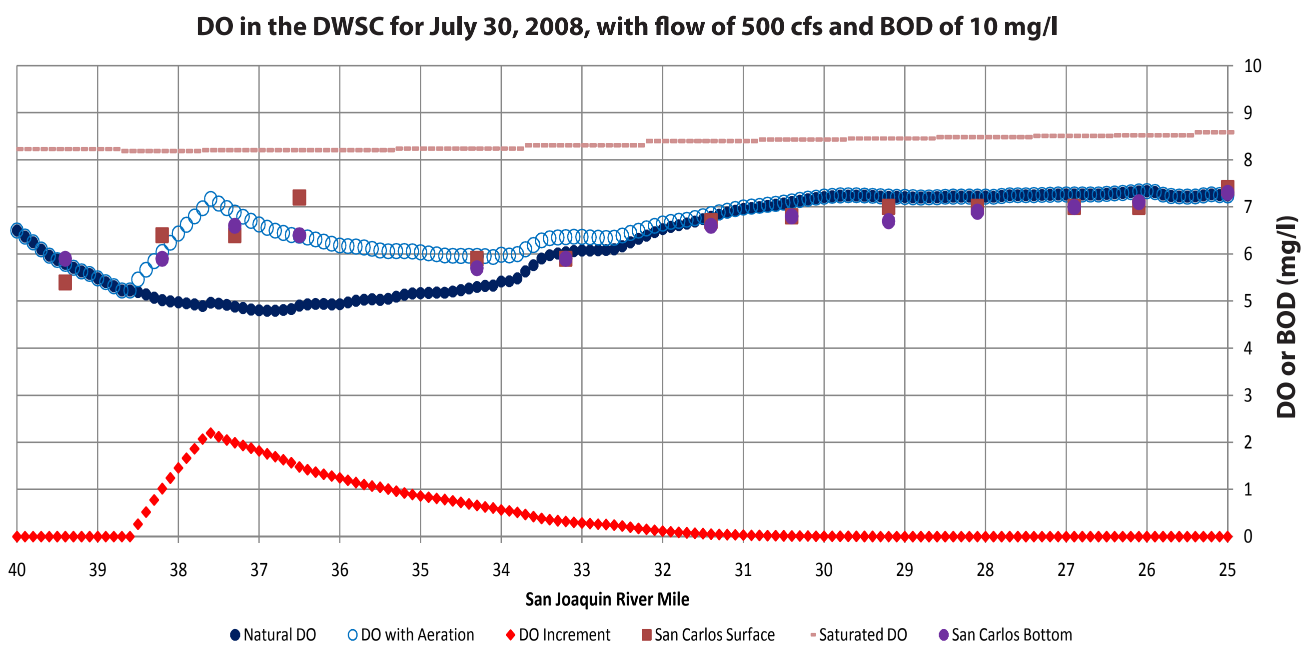


Figure 10b: Measured and Calculated DWSC DO Profile for July 30, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l and BOD of 10 mg/l.

Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 10

DO in the DWSC for August 14, 2008, with flow of 500 cfs and BOD of 10 mg/l

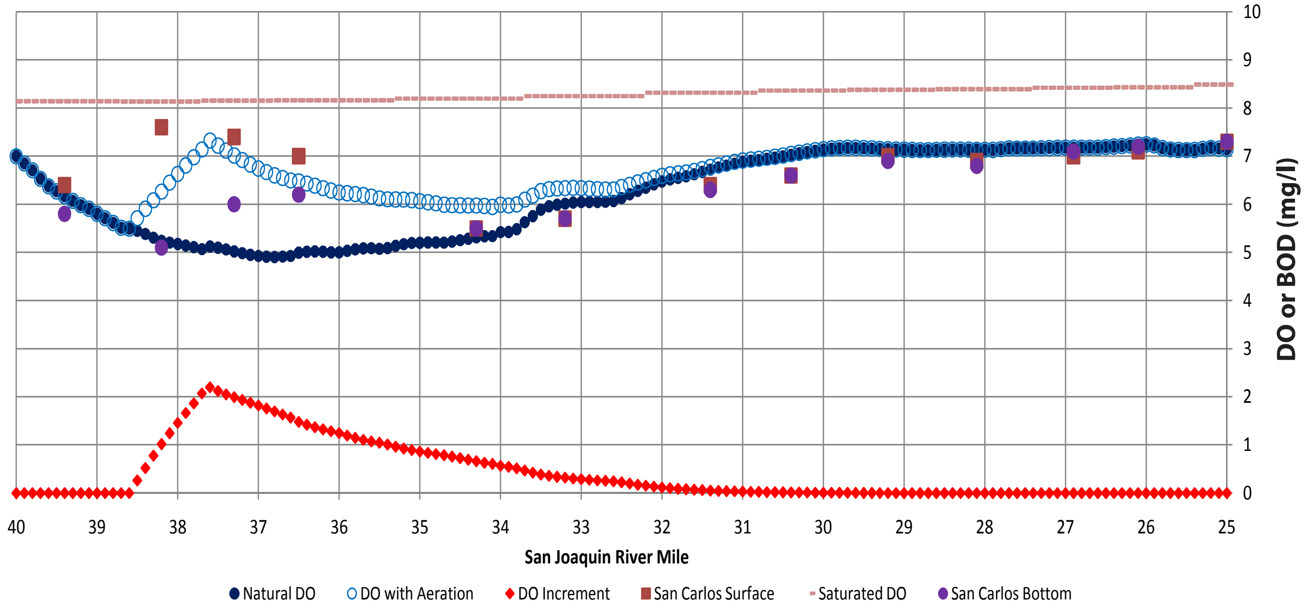


Figure 10c: Measured and Calculated DWSC DO Profile for August 14, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l and BOD of 10 mg/l.

Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

DO in the DWSC for August 28, 2008 with flow of 500 cfs and BOD of 10 mg/l

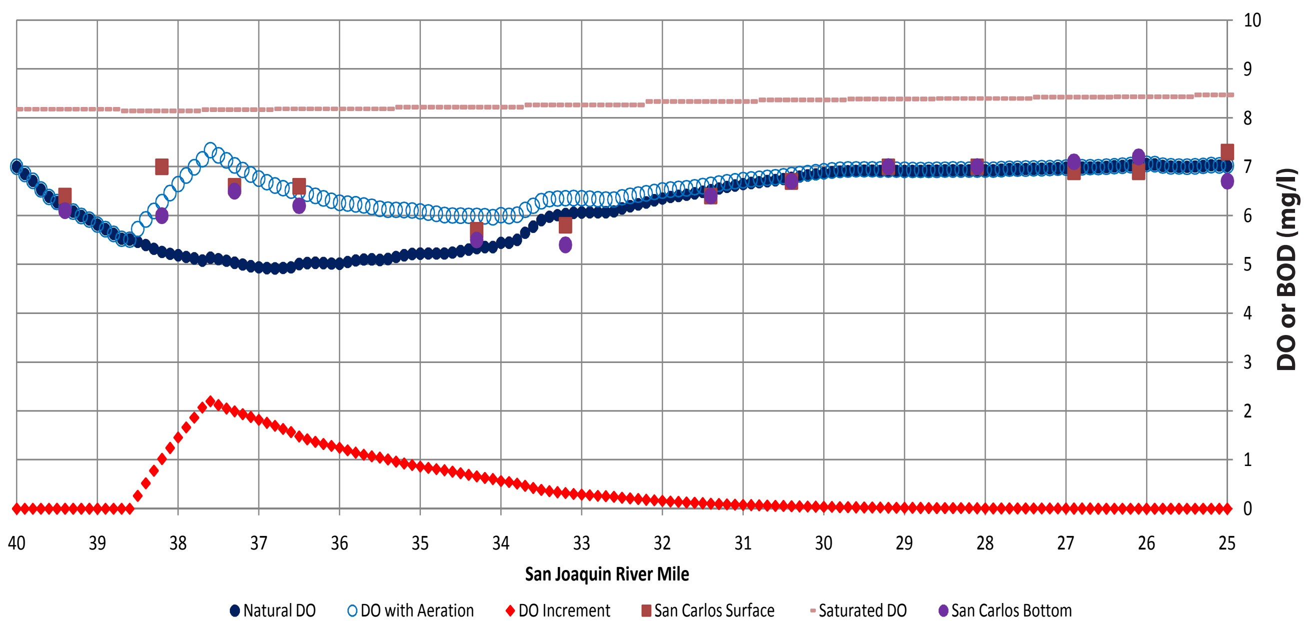


Figure 10d: Measured and Calculated DWSC DO Profile for August 28, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l and BOD of 10 mg/l.

Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

Figure 10 (continued)

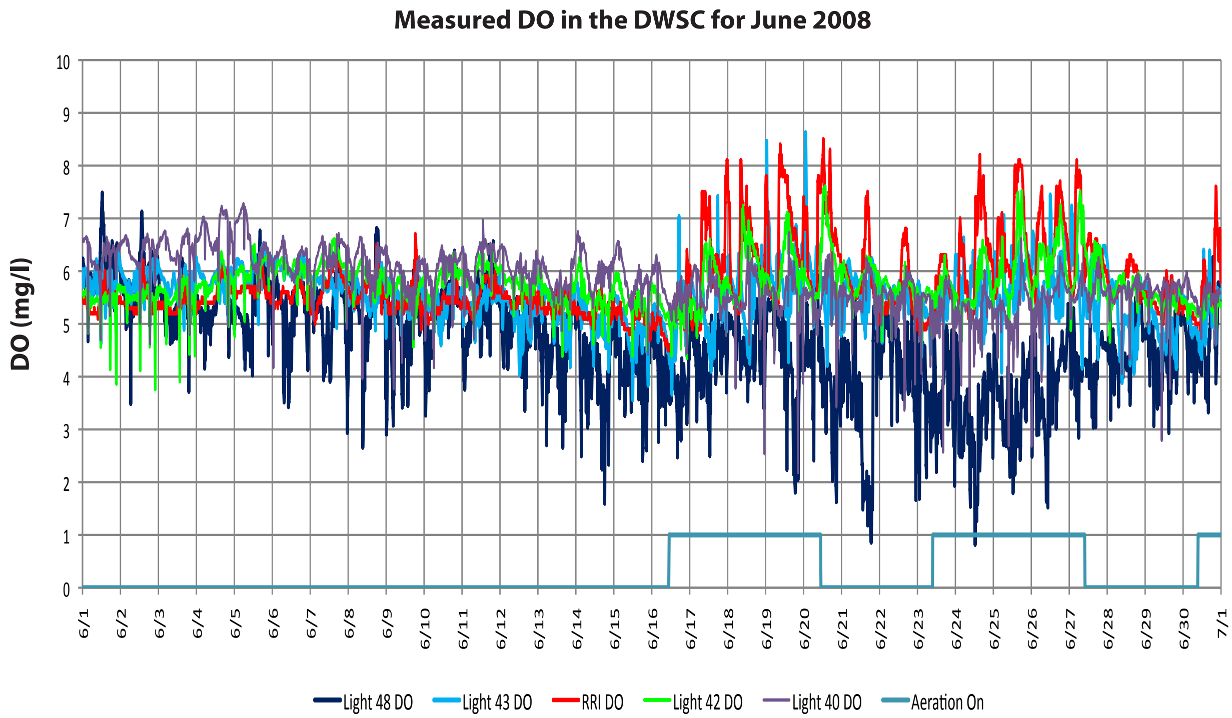


Figure 11a: Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for June 2008.

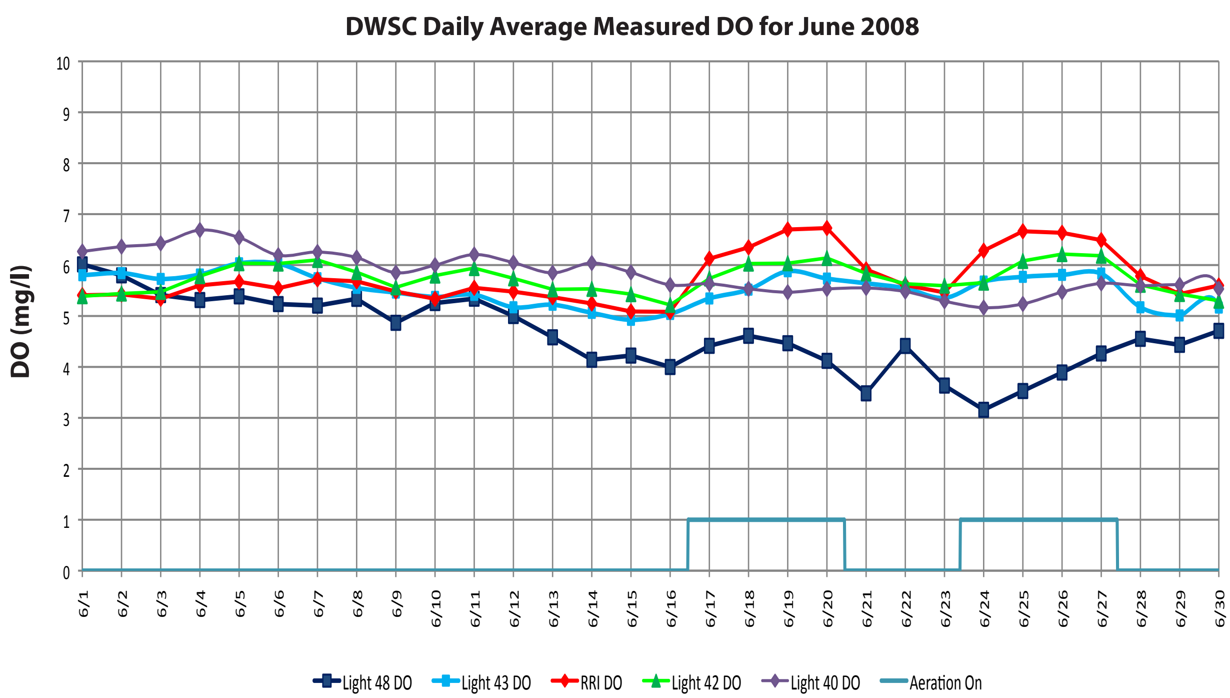


Figure 11b: Daily Average DO Concentrations at the DWSC Monitoring Stations for June 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 11

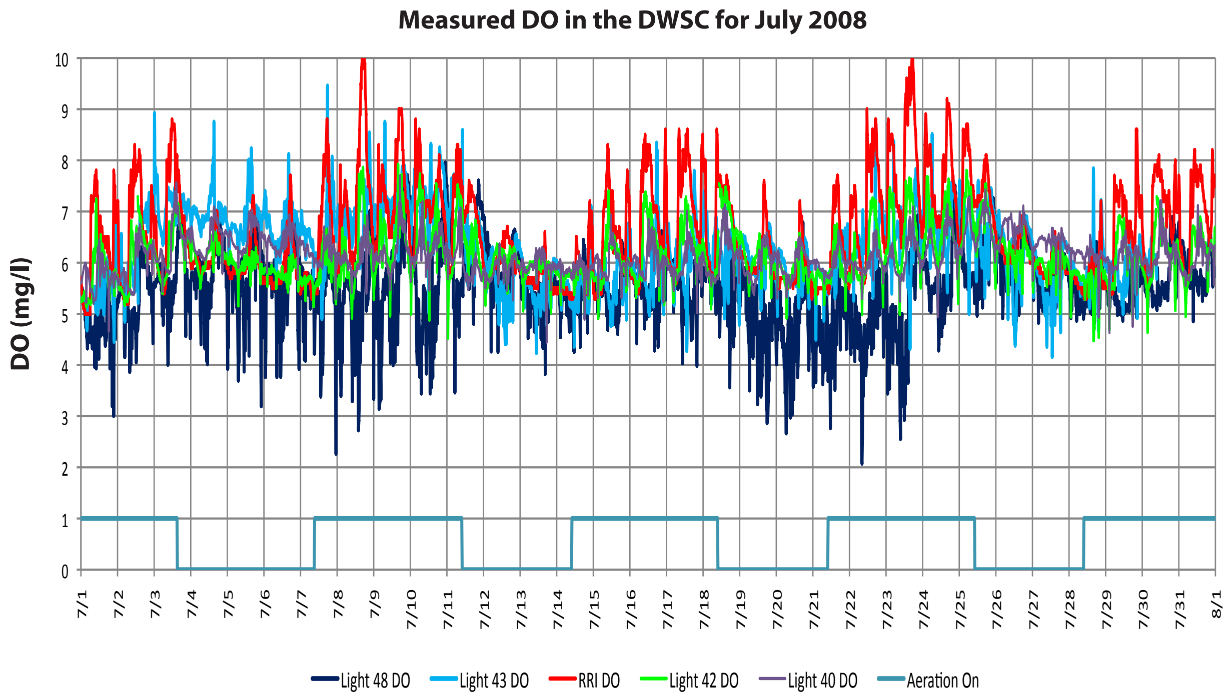


Figure 12a: Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for July 2008.

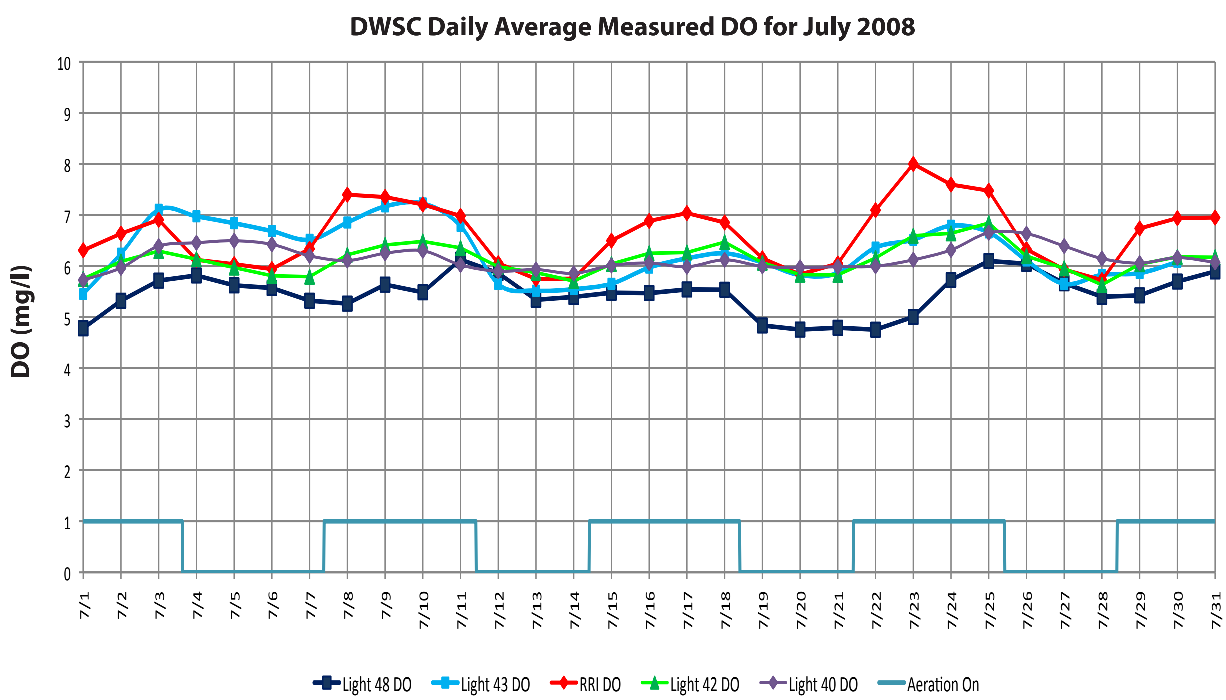


Figure 12b: Daily Average DO Concentrations at the DWSC Monitoring Stations for July 2008.

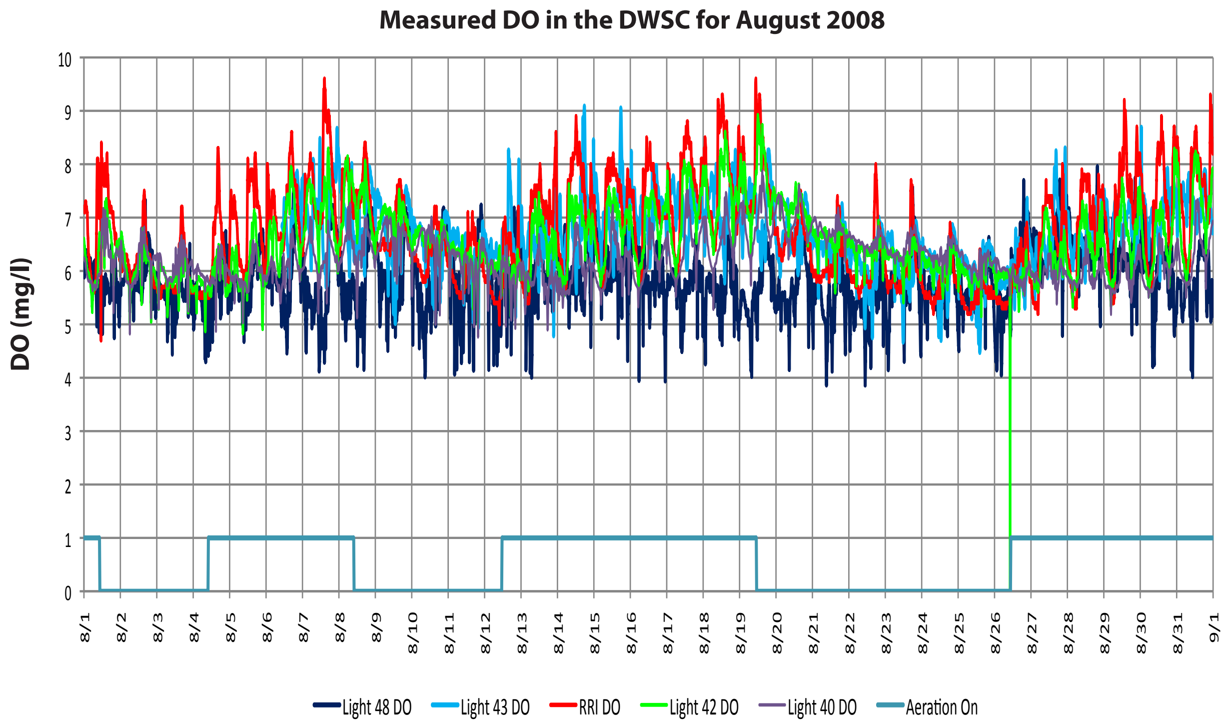


Figure 13a: Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for August 2008.

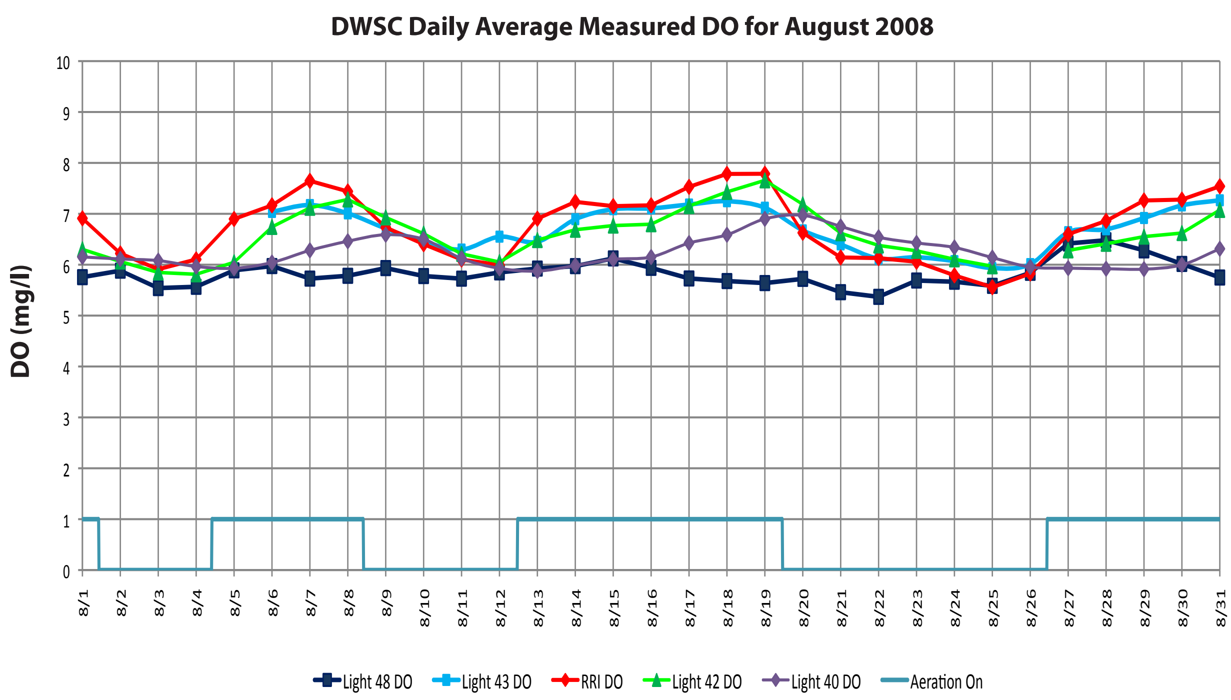


Figure 13b: Daily Average DO Concentrations at the DWSC Monitoring Stations for August 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 13

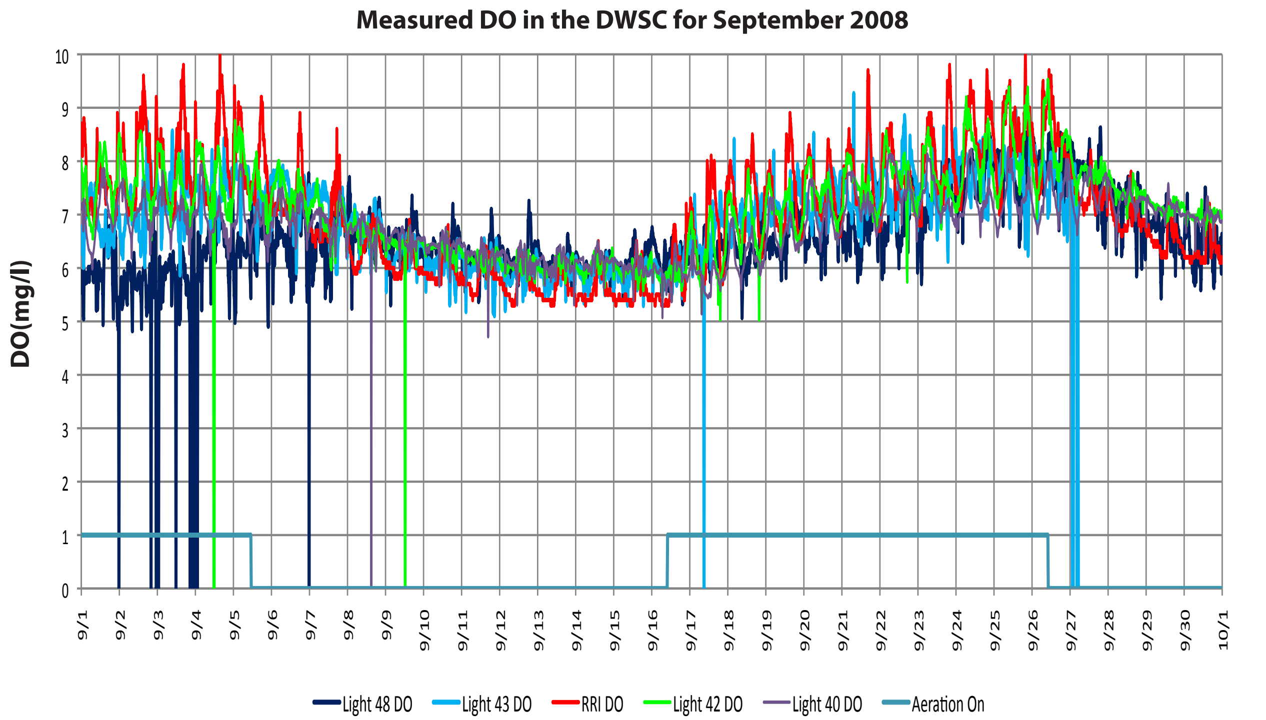


Figure 14a: Measured 15-minute DO Concentrations at the DWSC Monitoring Stations for September 2008.

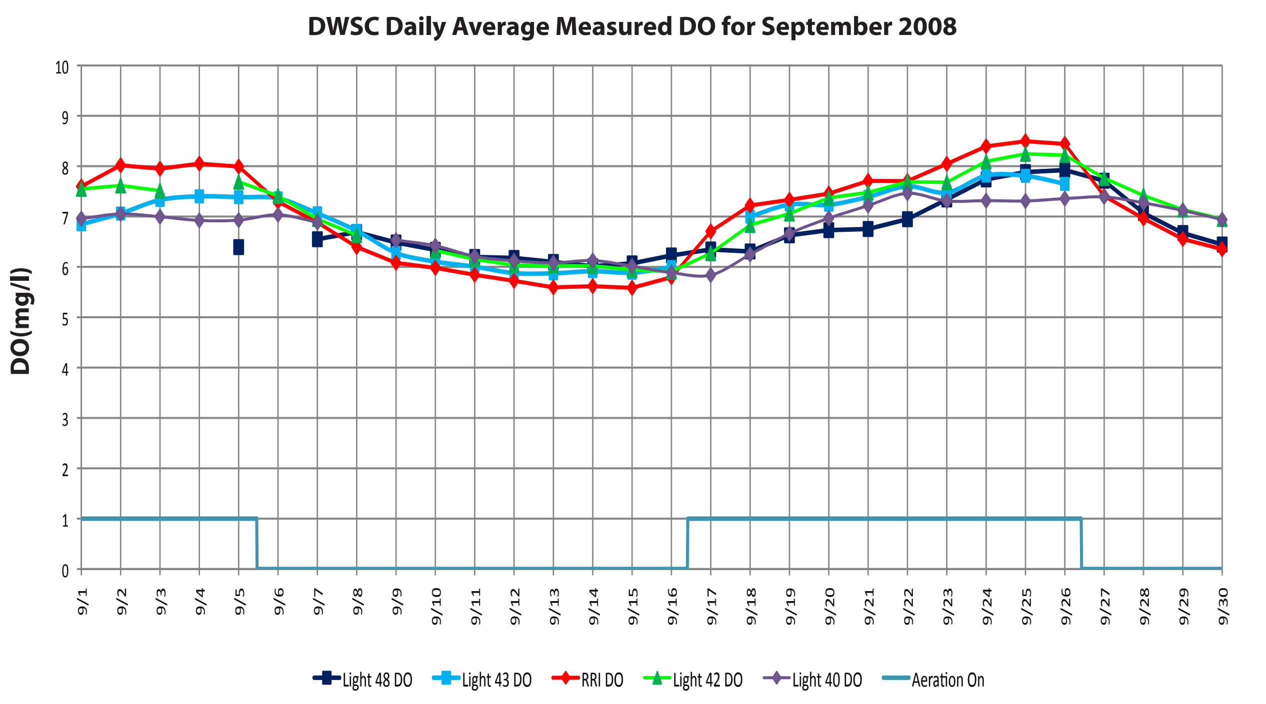


Figure 14b: Daily Average DO Concentrations at the DWSC Monitoring Stations for September 2008.

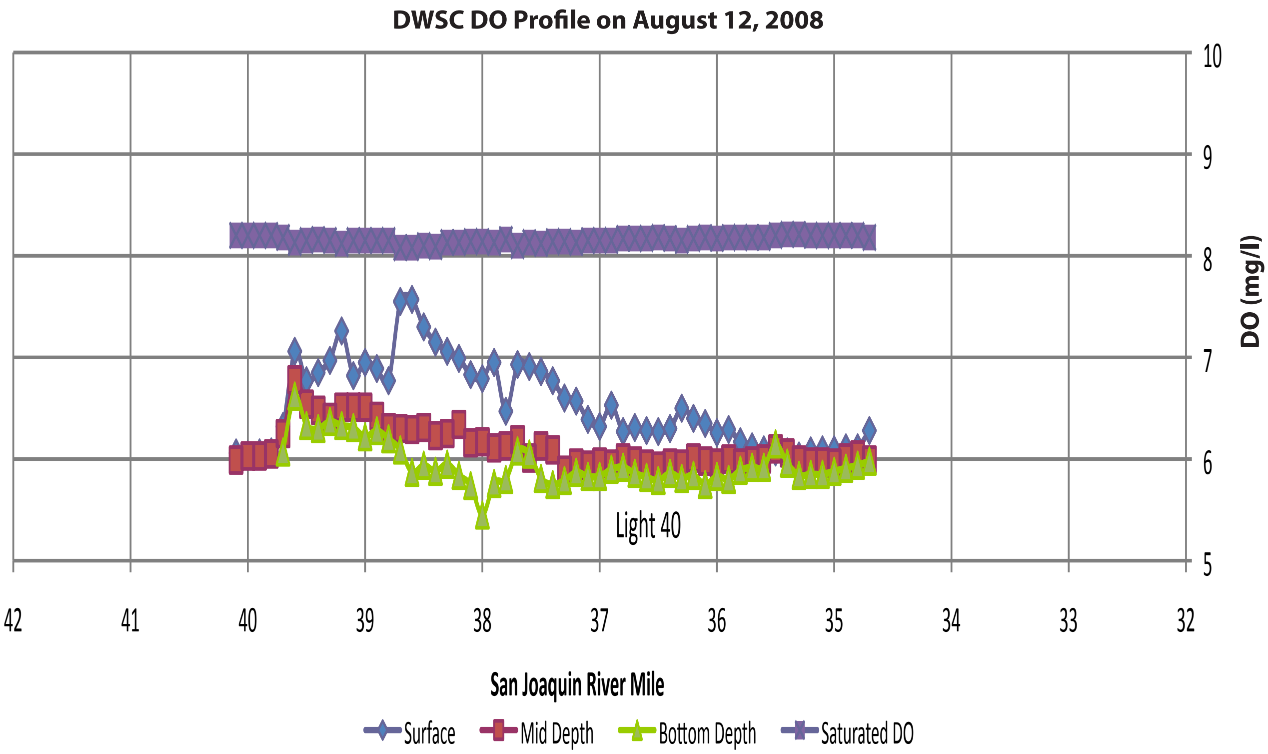


Figure 15a: DWSC DO Profile on August 12, 2008 (Prior to DO Diffuser Operation).

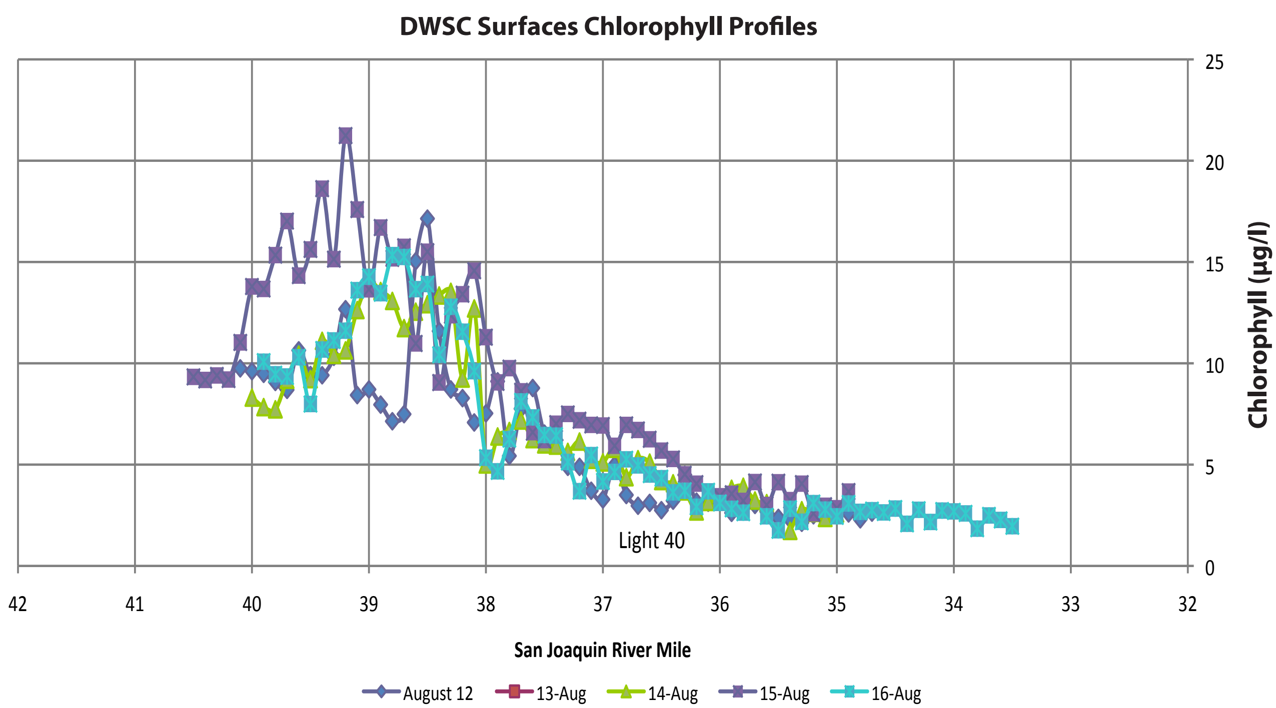


Figure 15b: DWSC Chlorophyll (Algae) Profiles on August 12-16, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 15

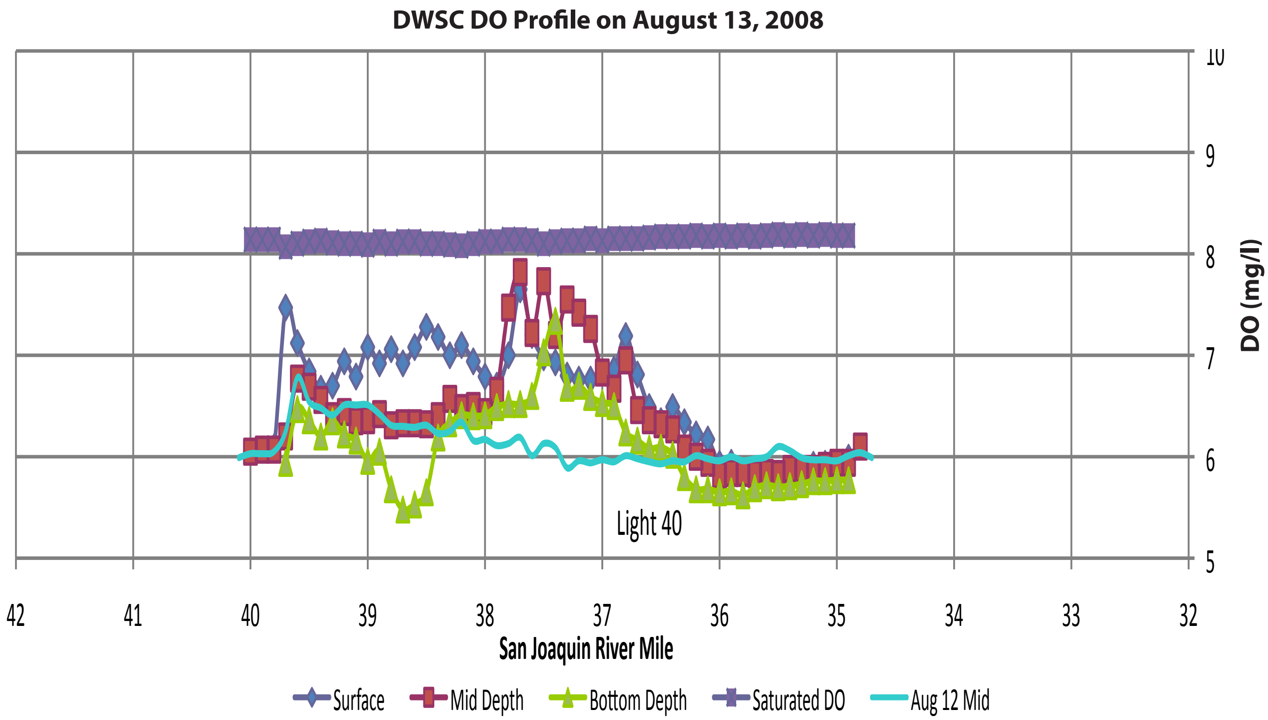


Figure 15c: DWSC DO Profile on August 13, 2008 (1 Day of DO Diffuser Operation).

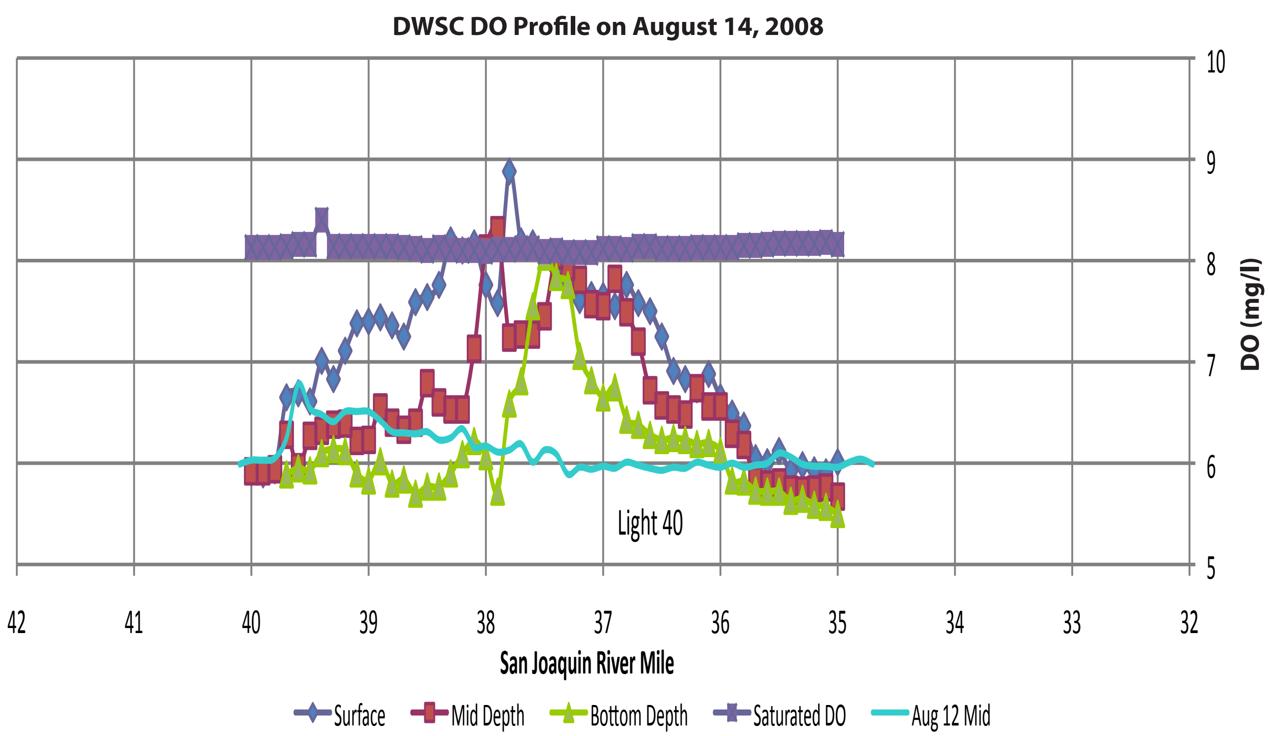


Figure 15d: DWSC DO Profile on August 14, 2008 (2 Days of Operation).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

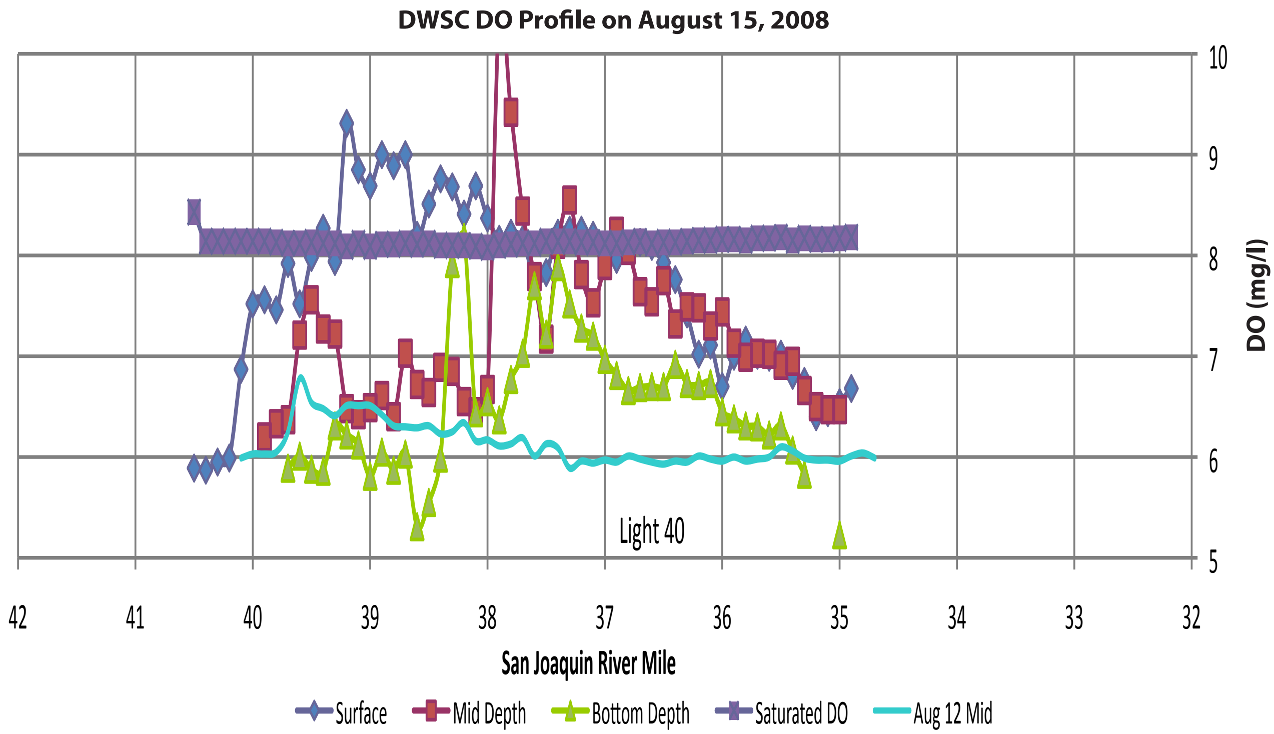


Figure 15e: DWSC DO Profile on August 15, 2008 (3 Days of DO Diffuser Operation).

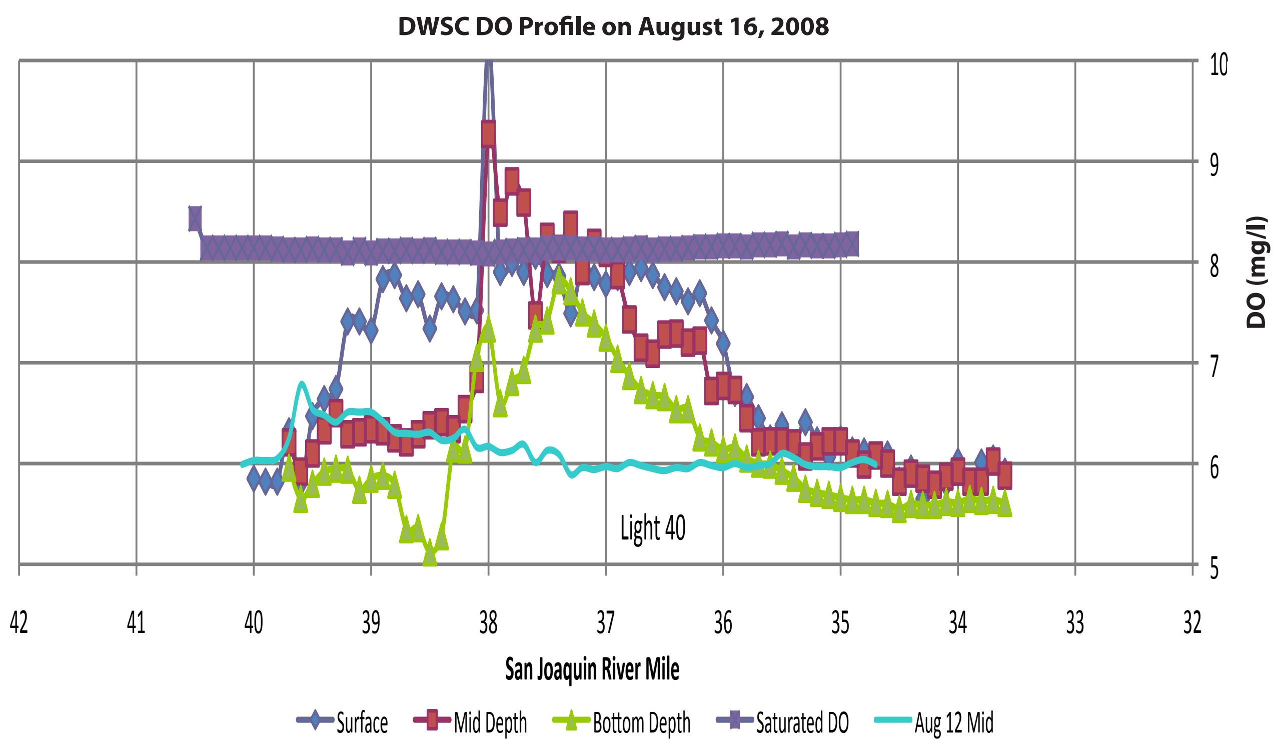


Figure 15f: DWSC DO Profile on August 16, 2008 (4 Days of Operation).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 15 (continued)

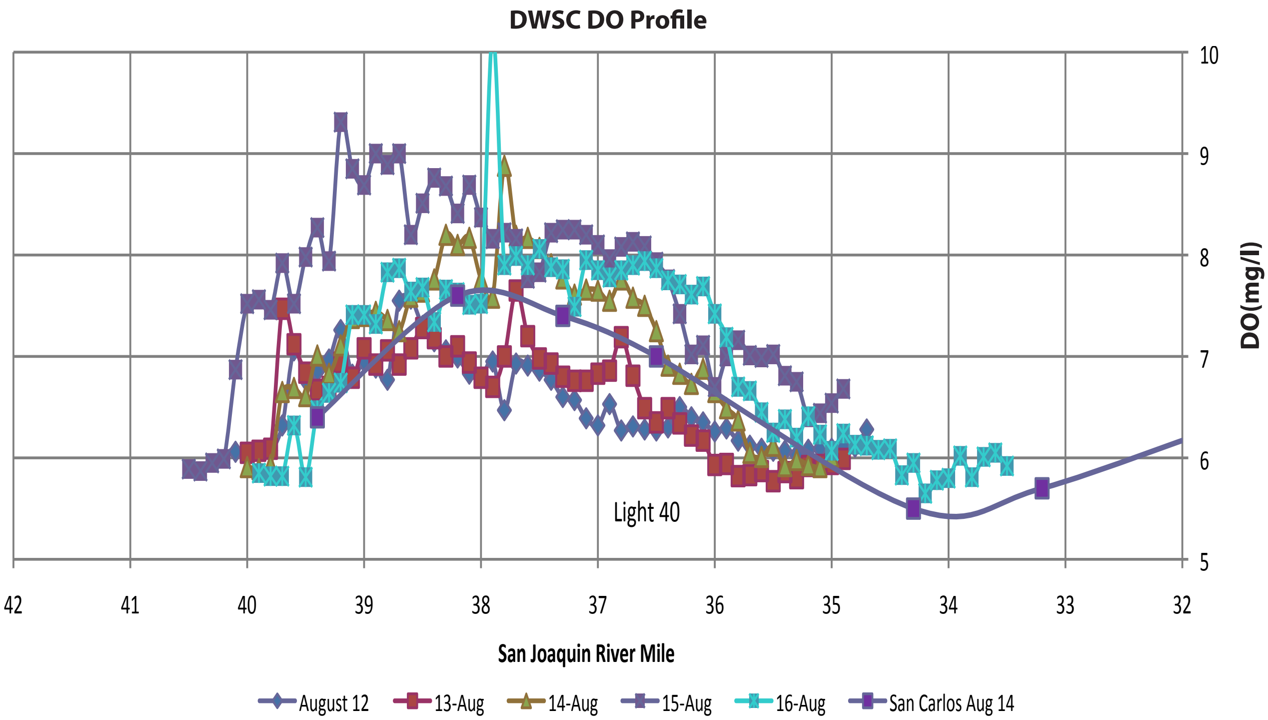


Figure 16a: DWSC Surface DO Profiles for August 12-16, 2008 with San Carlos Data from August 14, 2008.

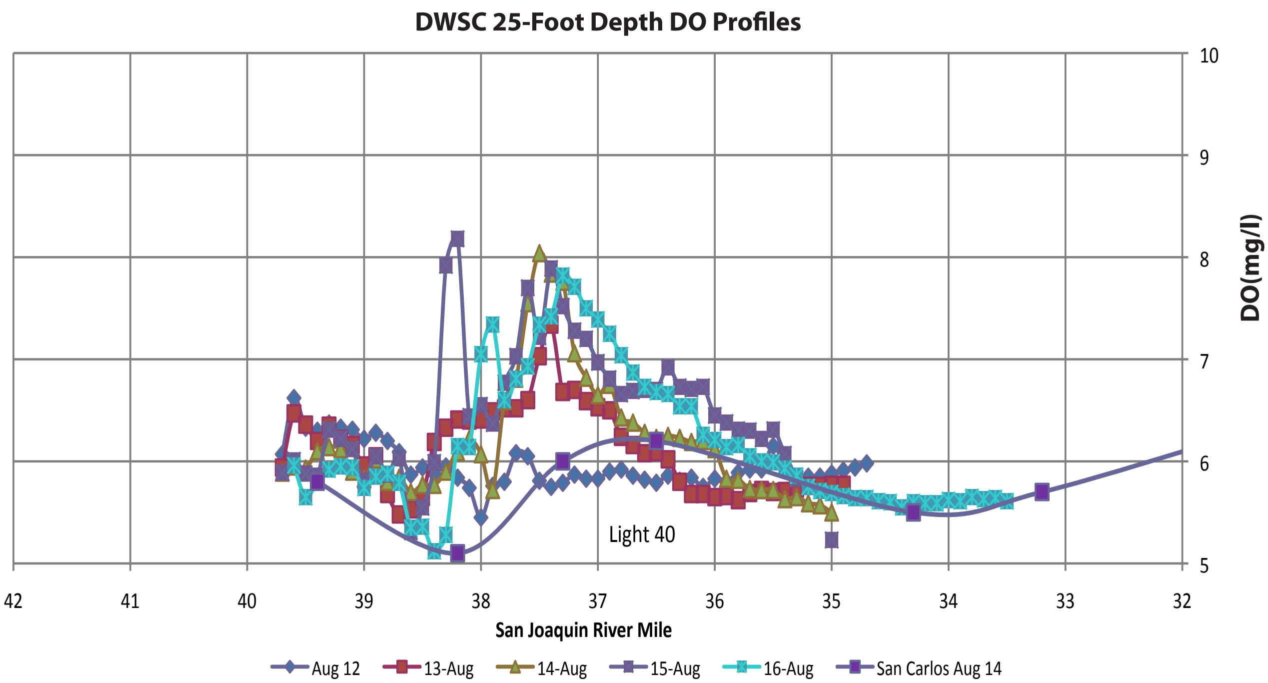


Figure 16b: DWSC Bottom DO Profiles for August 12-16, 2008 with San Carlos Data from August 14, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 16

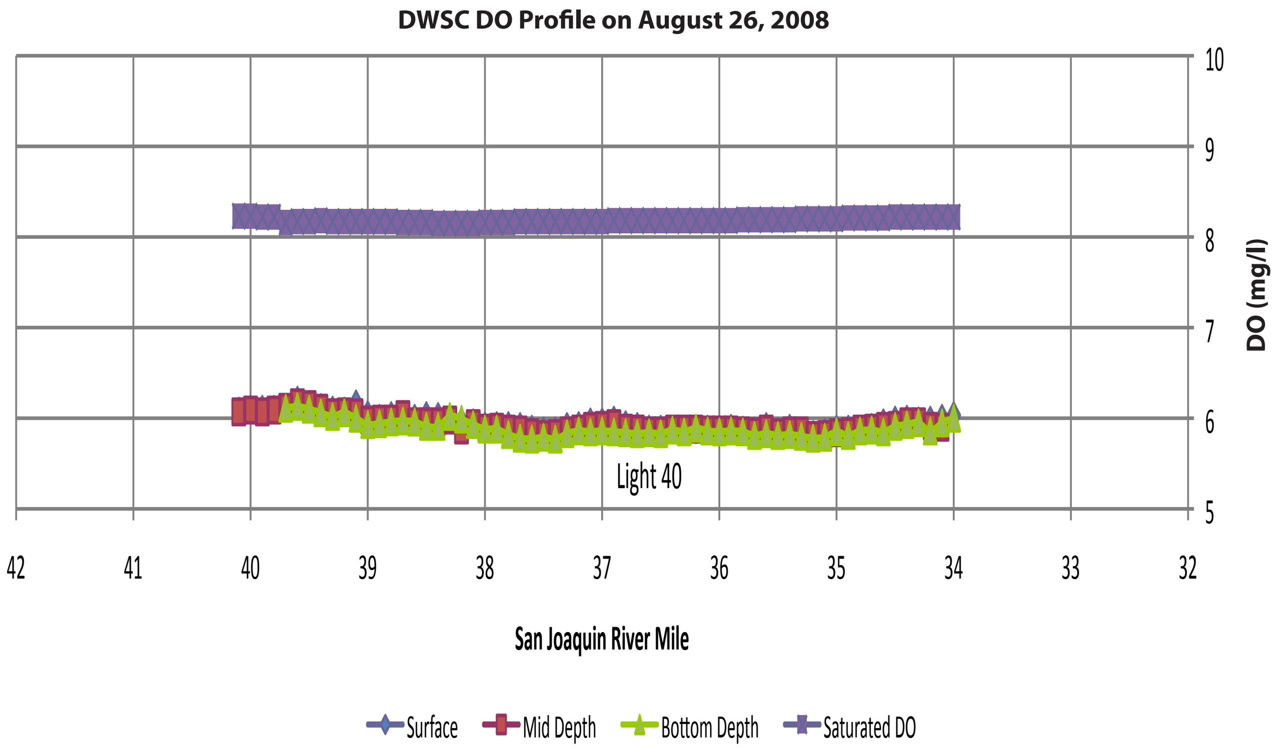


Figure 17a: DWSC DO Profile on August 26, 2008 (Prior to DO Diffuser Operation).

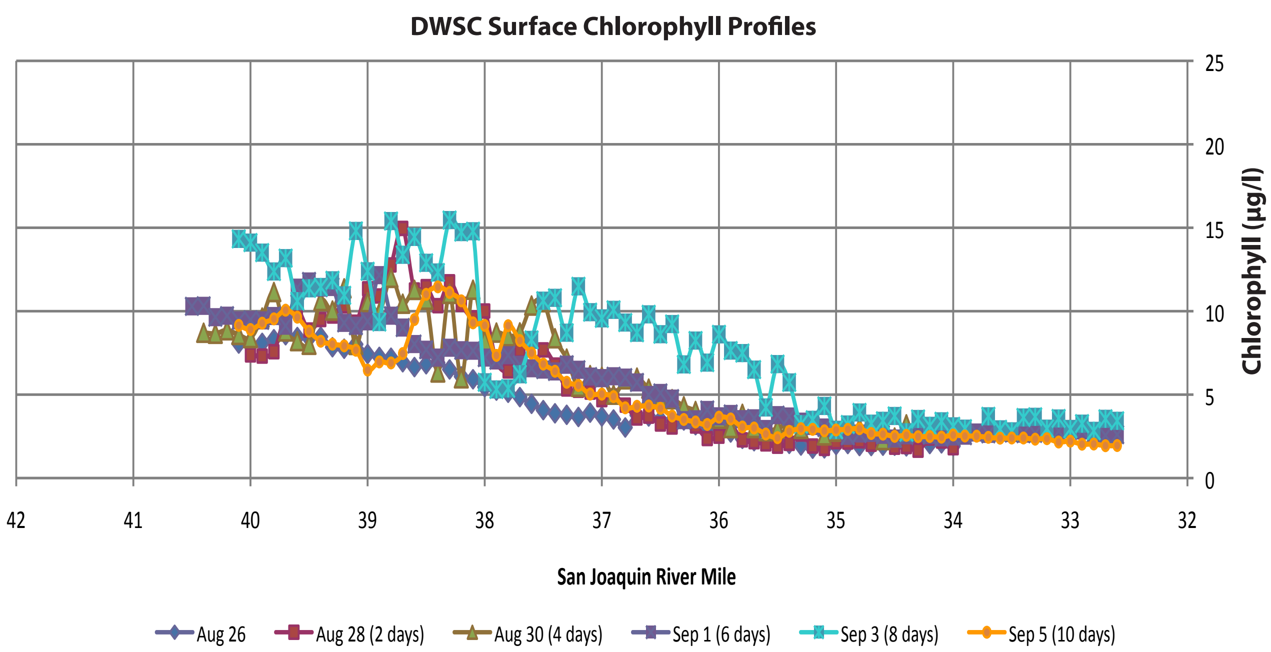


Figure 17b: DWSC Chlorophyll (Algae) Profiles on August 26-September 5, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 17

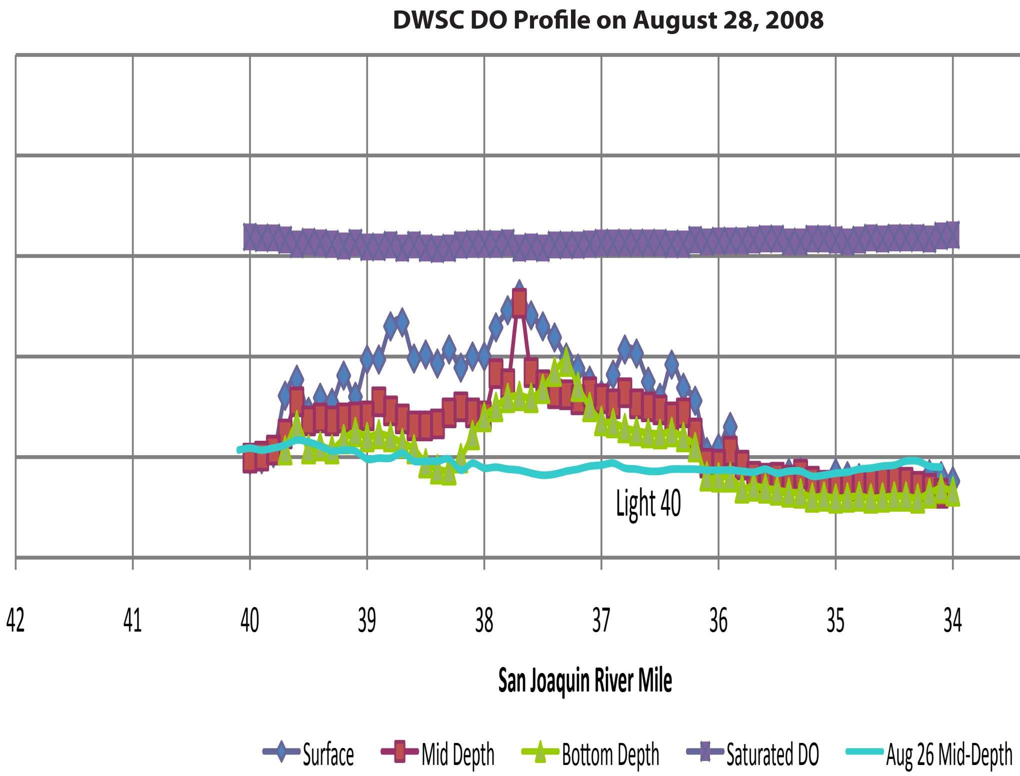


Figure 17c: DWSC DO Profile on August 28, 2008 (2 Days of Operation).

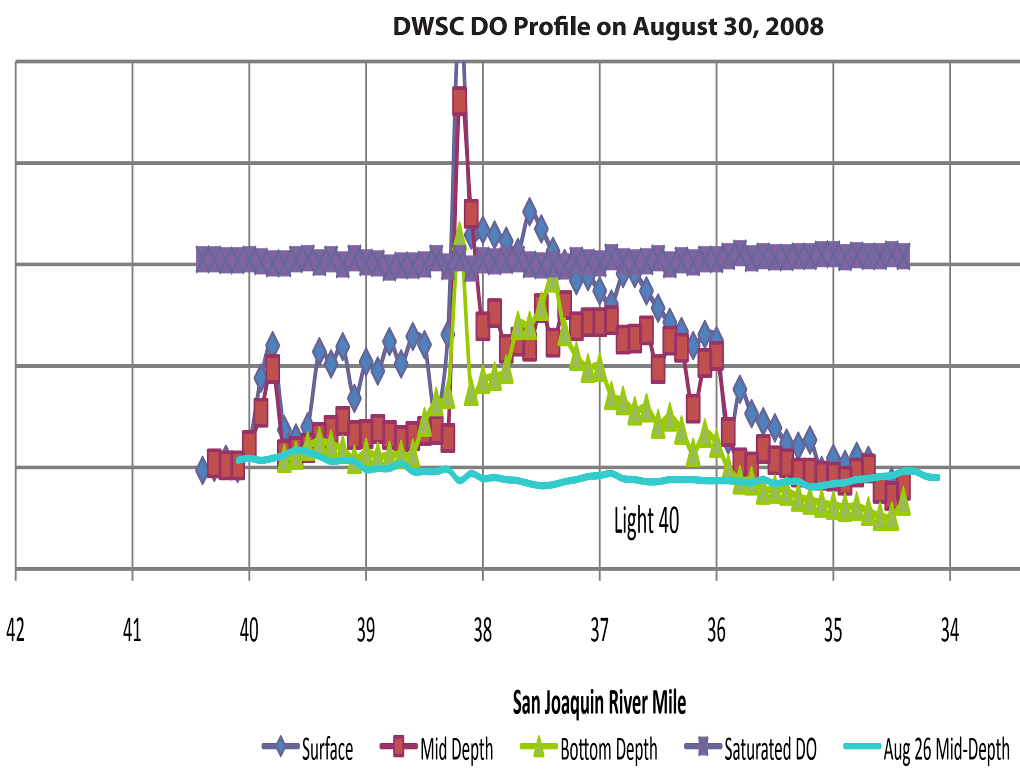


Figure 17d: DWSC DO Profile on August 30, 2008 (4 Days of Operation).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 17 (continued)

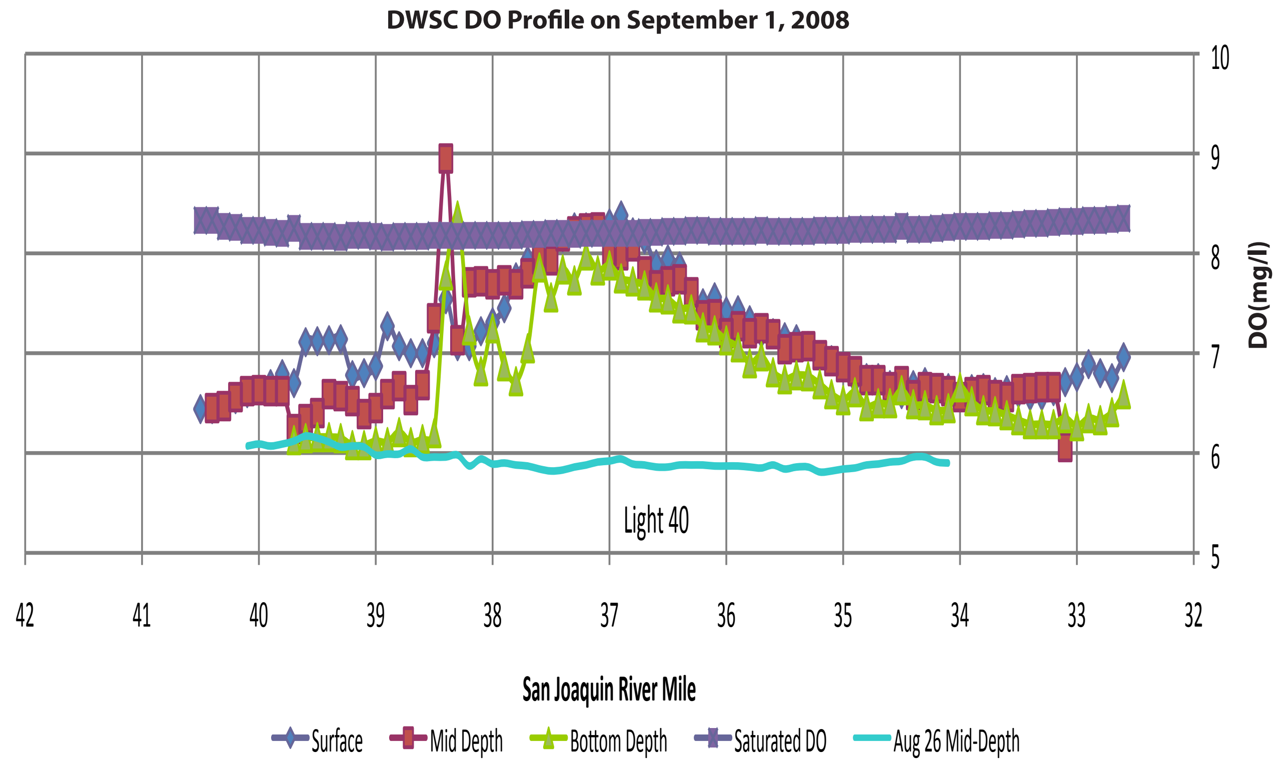


Figure 17e: DWSC DO Profile on September 1, 2008 (6 Days of Operation).

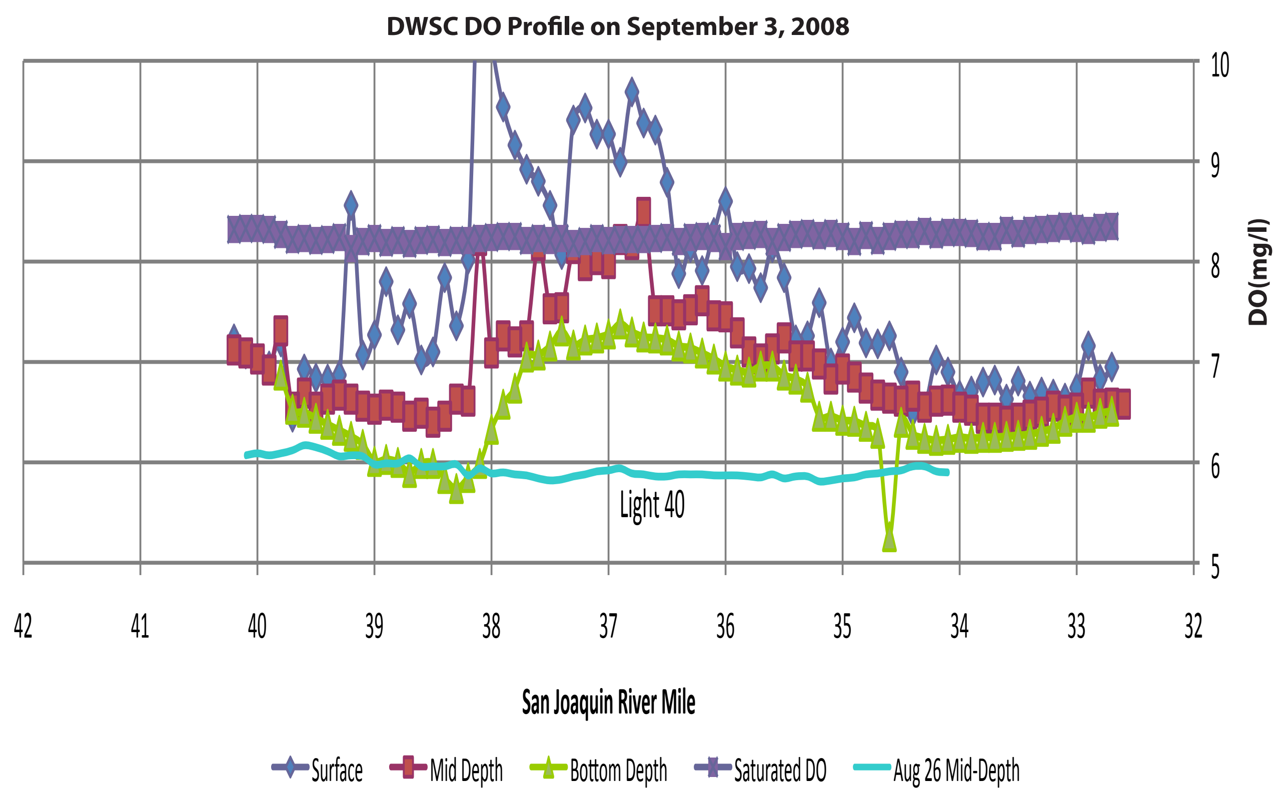


Figure 17f: DWSC DO Profile on September 3, 2008 (8 Days of Operation).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

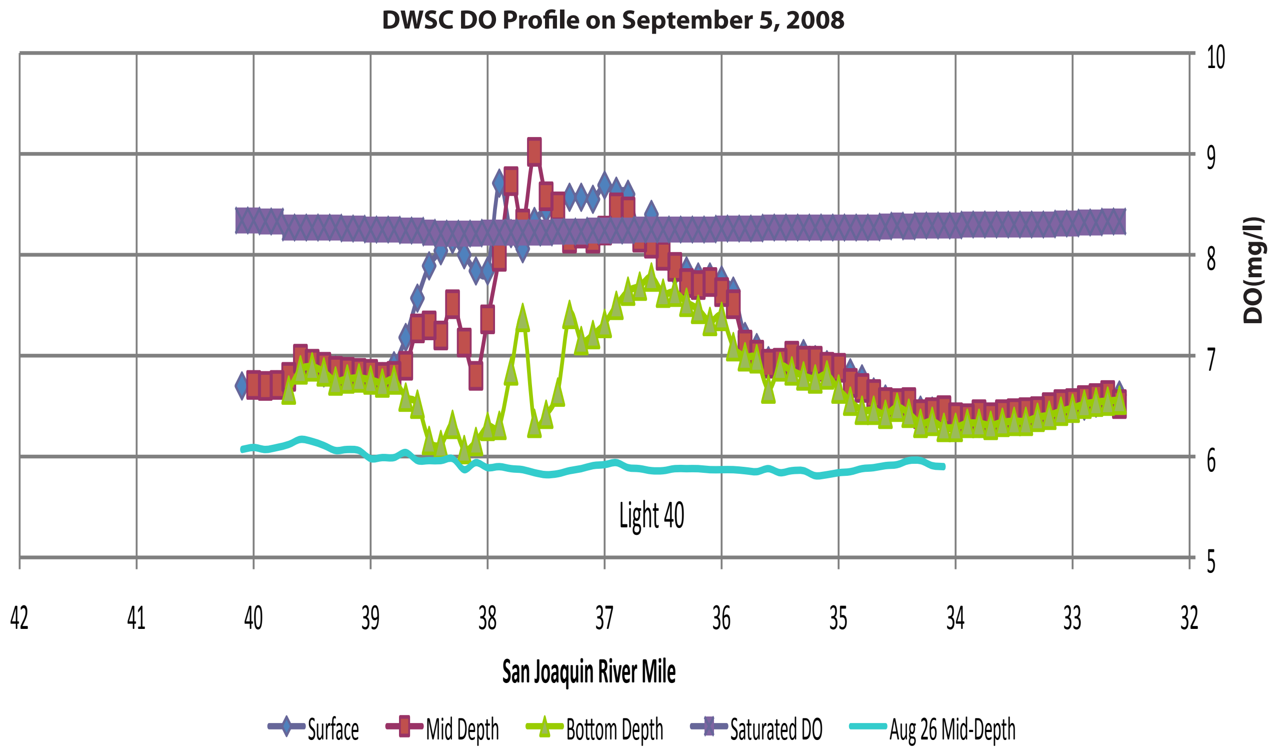


Figure 17g: DWSC DO Profile on September 5, 2008 (10 Days of Operation).

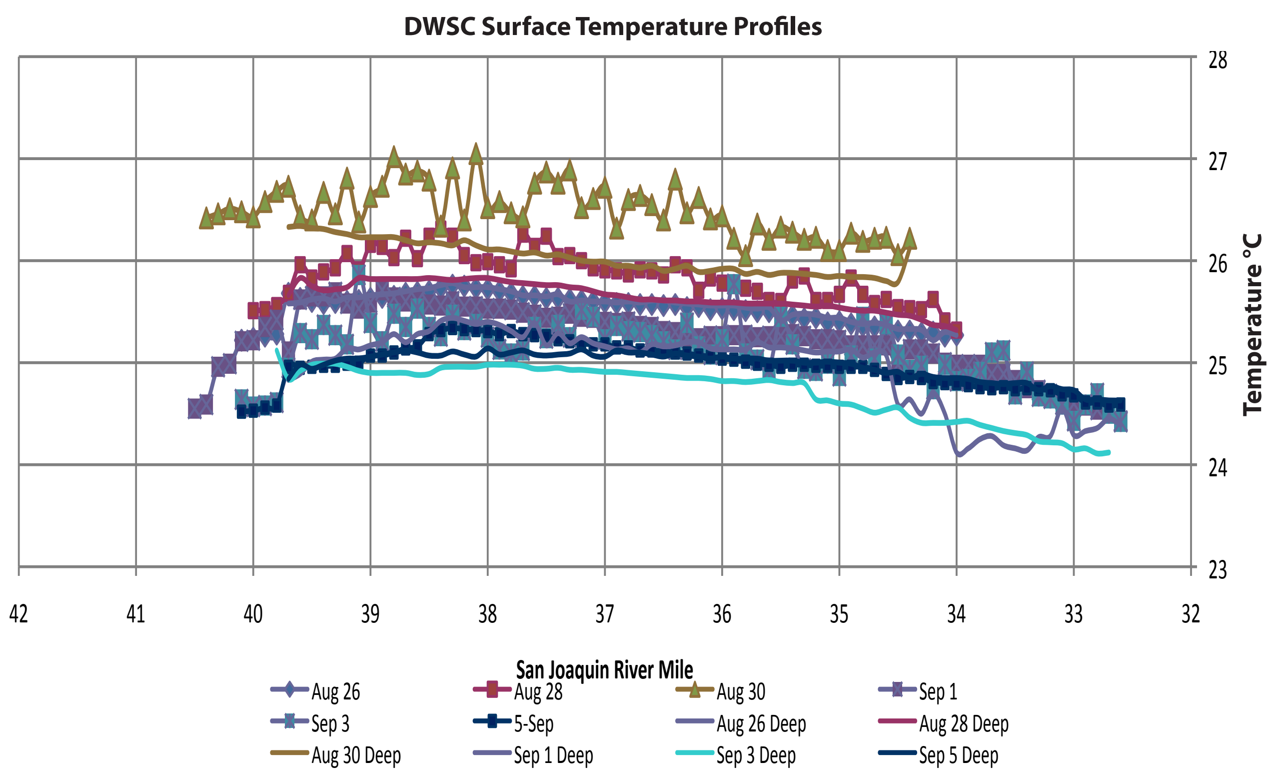


Figure 17h: DWSC Surface and Bottom Temperature Profiles from August 26 to September 5, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

Figure 17 (continued)

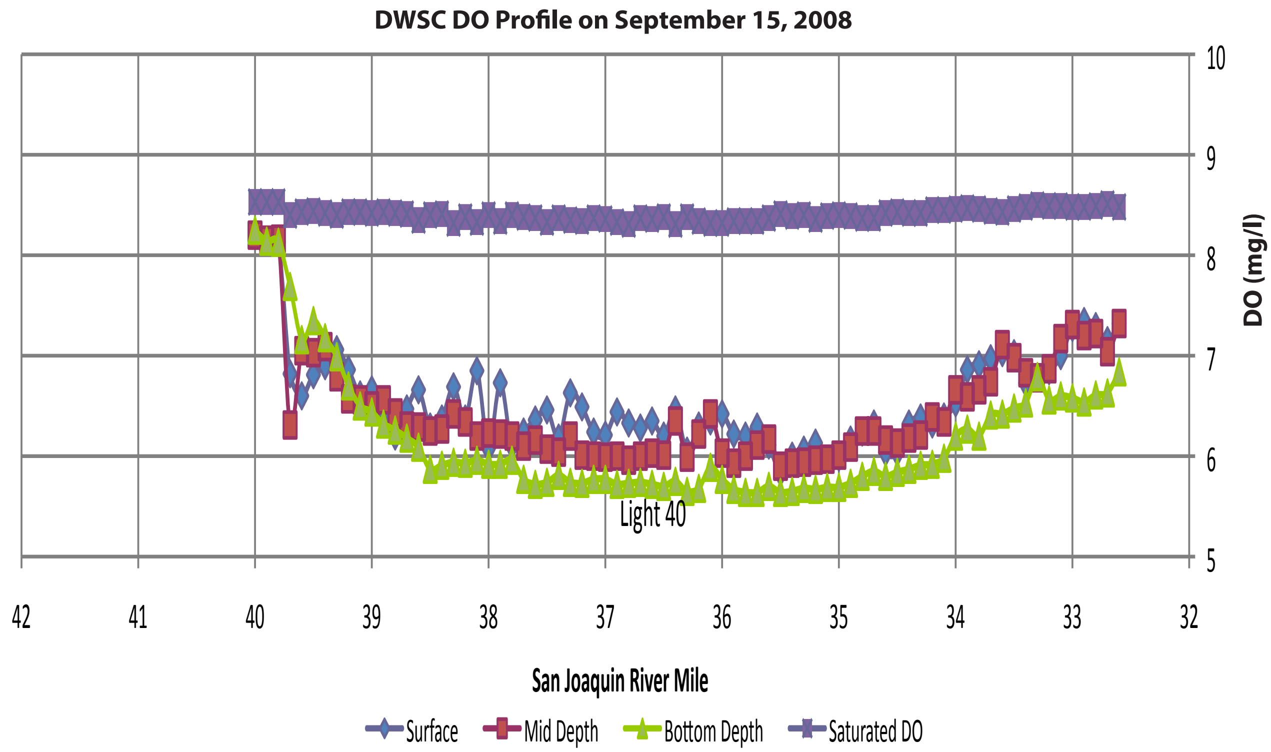


Figure 18a: DWSC DO Profile on September 15, 2008 (Prior to DO Diffuser Operation).

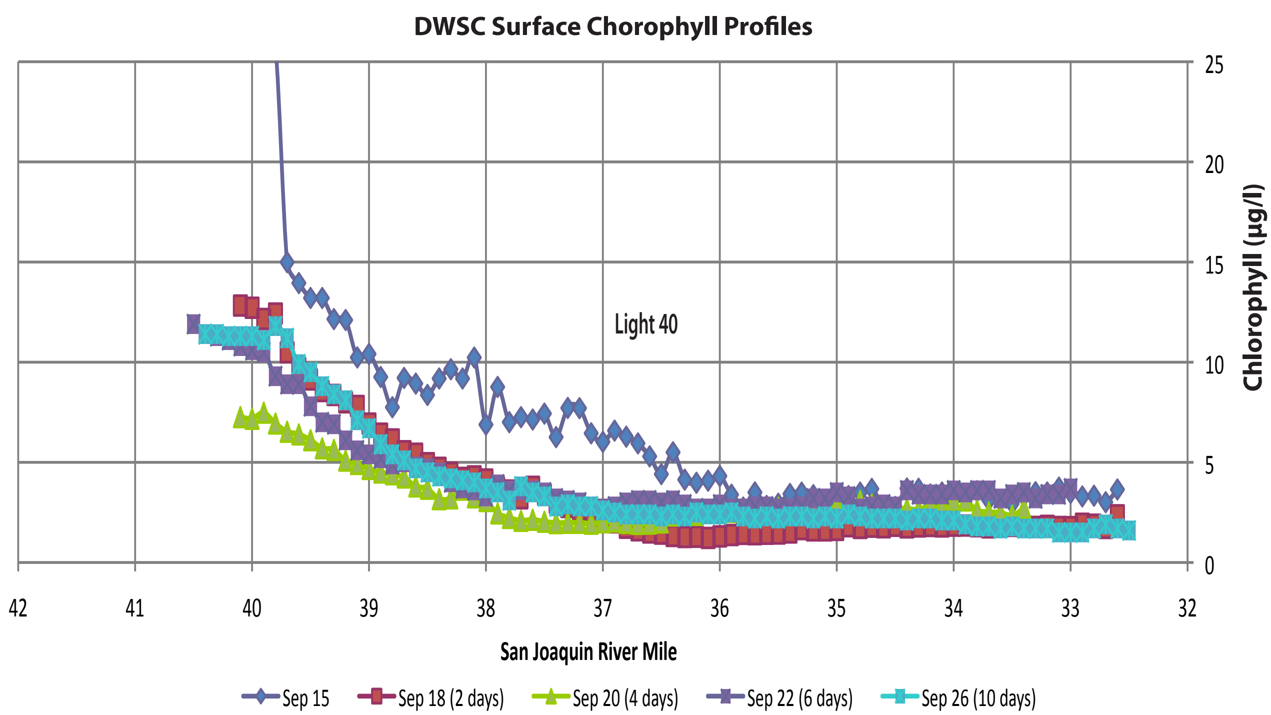


Figure 18b: DWSC Chlorophyll (µg/l) Profiles for September 15 to September 26, 2008 Surveys.

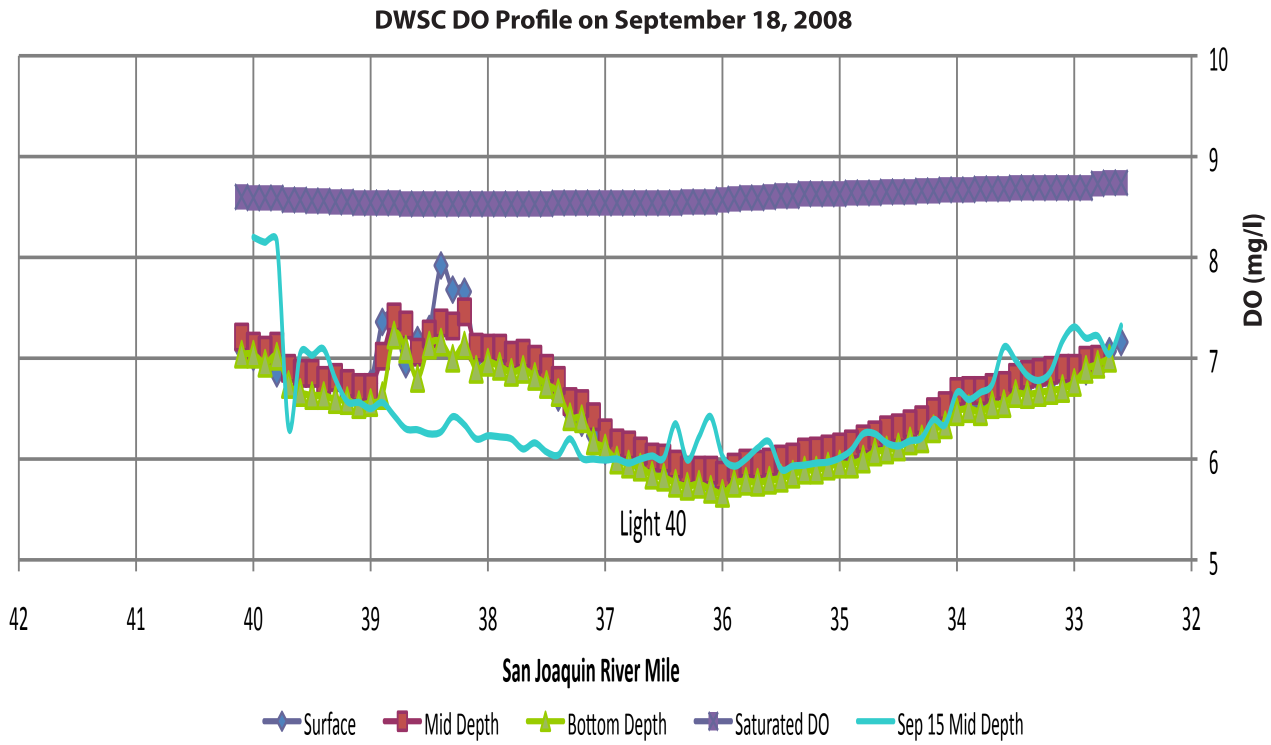


Figure 18c: DWSC DO Profile on September 18, 2008 (2 Days of Operation).

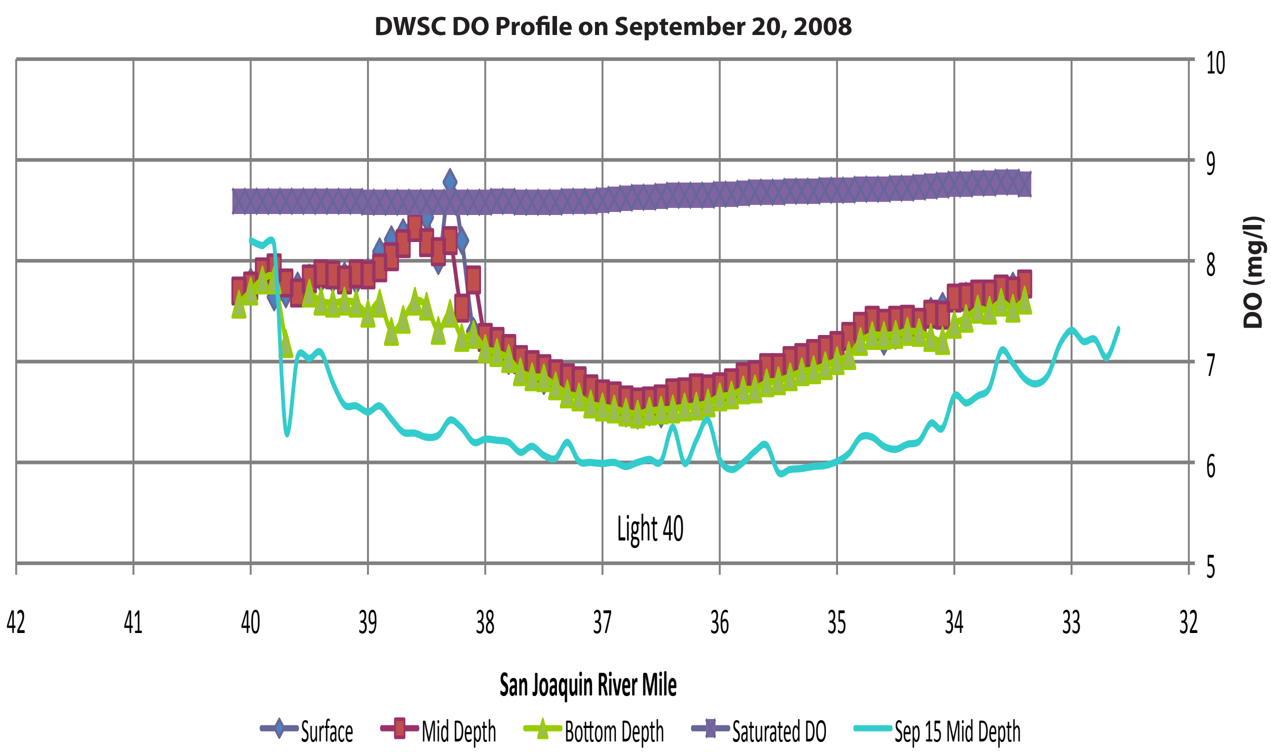


Figure 18d: DWSC DO Profile on September 20, 2008 (4 Days of Operation).t

Figure 18 (continued)

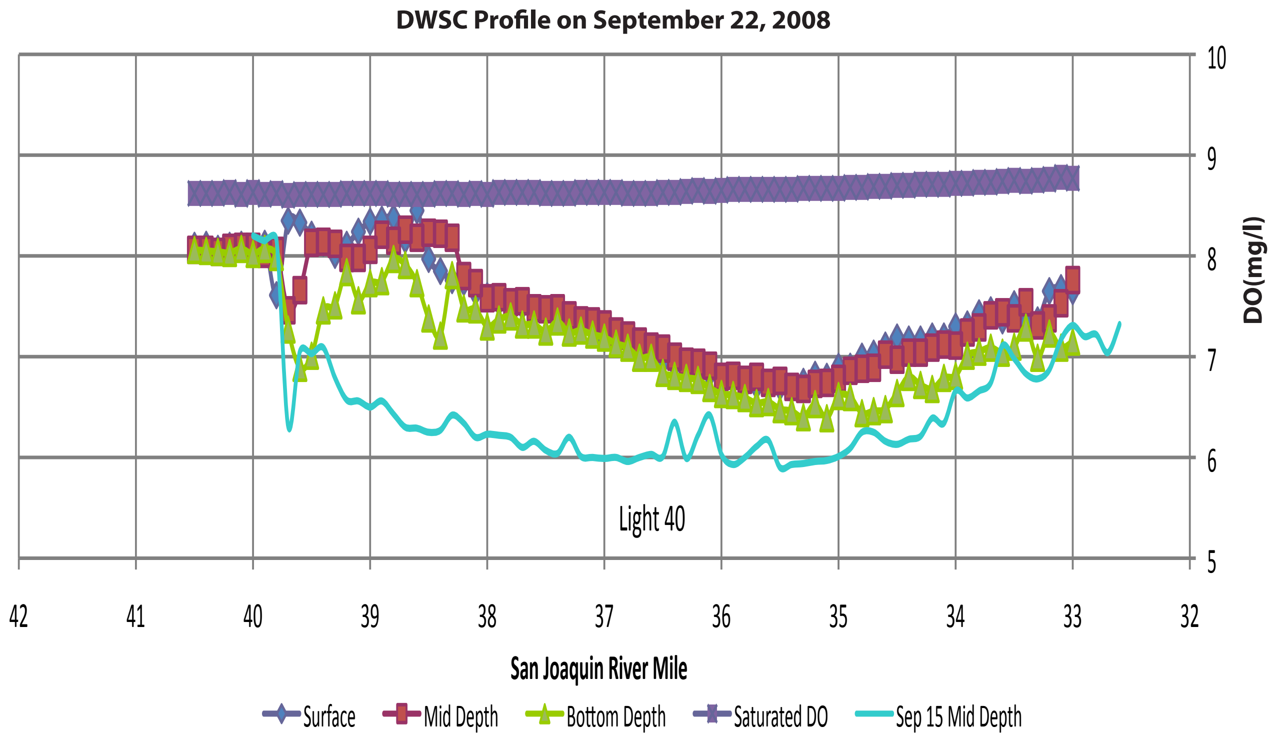


Figure 18e: DWSC DO Profile on September 22, 2008 (6 Days of Operation).

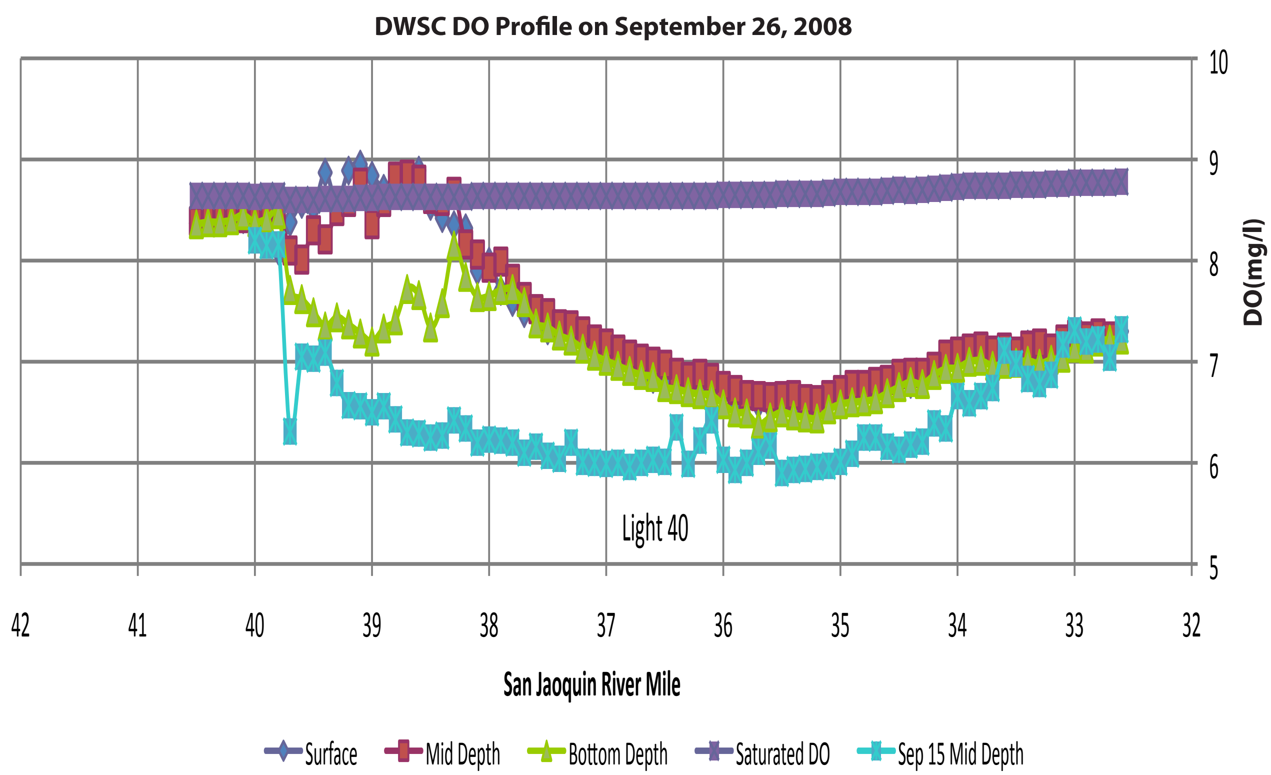


Figure 18f: DWSC DO Profile on September 26, 2008 (10 Days of Operation).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 18 (continued)

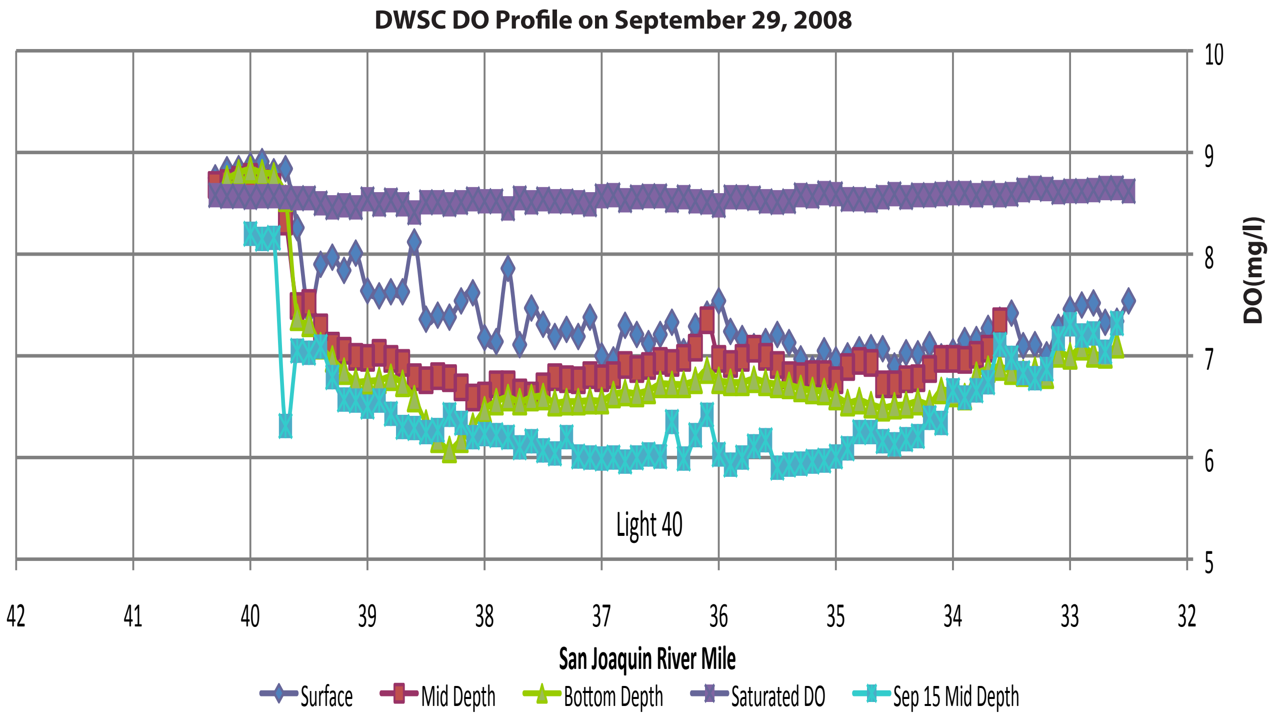


Figure 18g: DWSC DO Profile on September 29, 2008 (3 Days without Aeration).

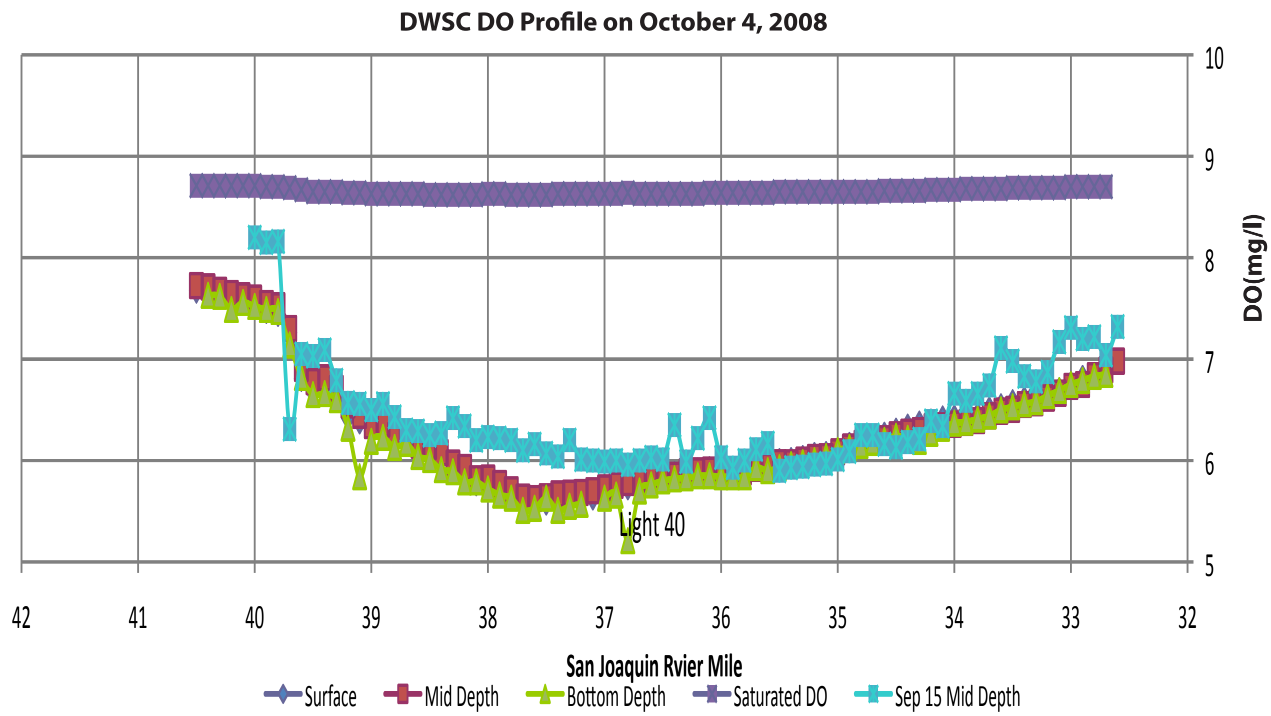


Figure 18h: DWSC DO Profile on October 4, 2008 (8 Days without Aeration).

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 18 (continued)

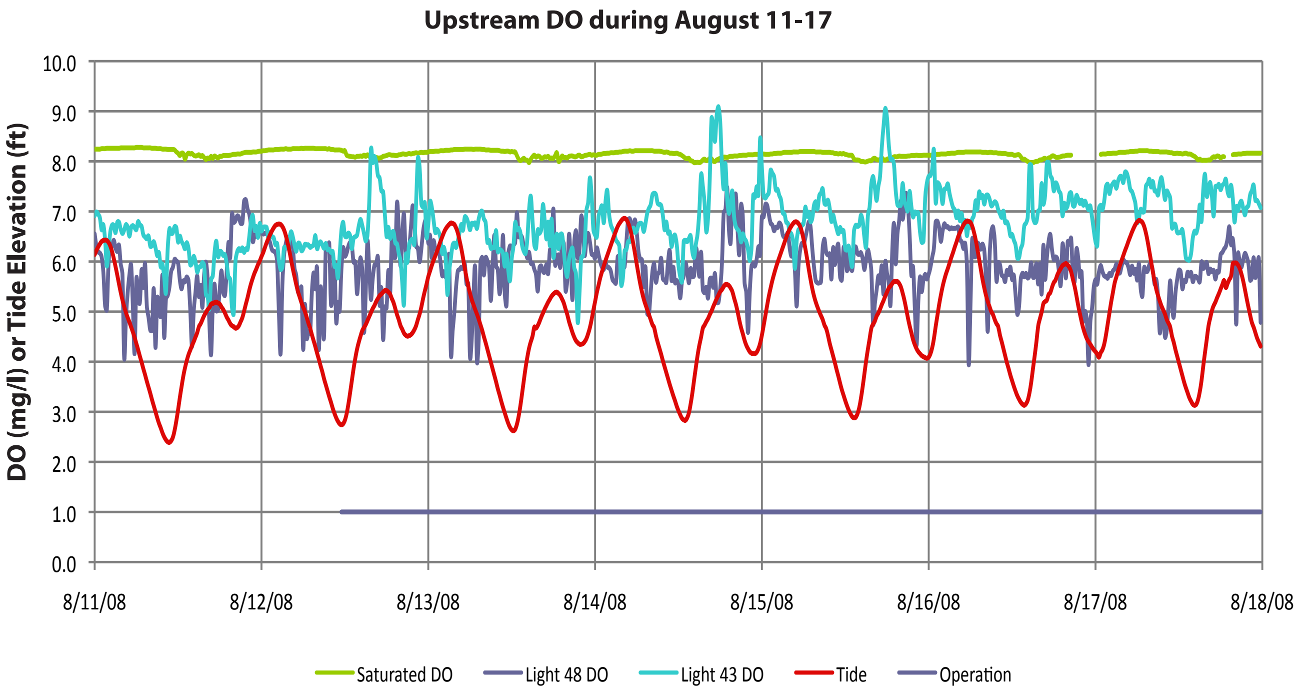


Figure 19a: DO Concentrations at Upstream DO Monitoring Stations for August 11–17, 2008.

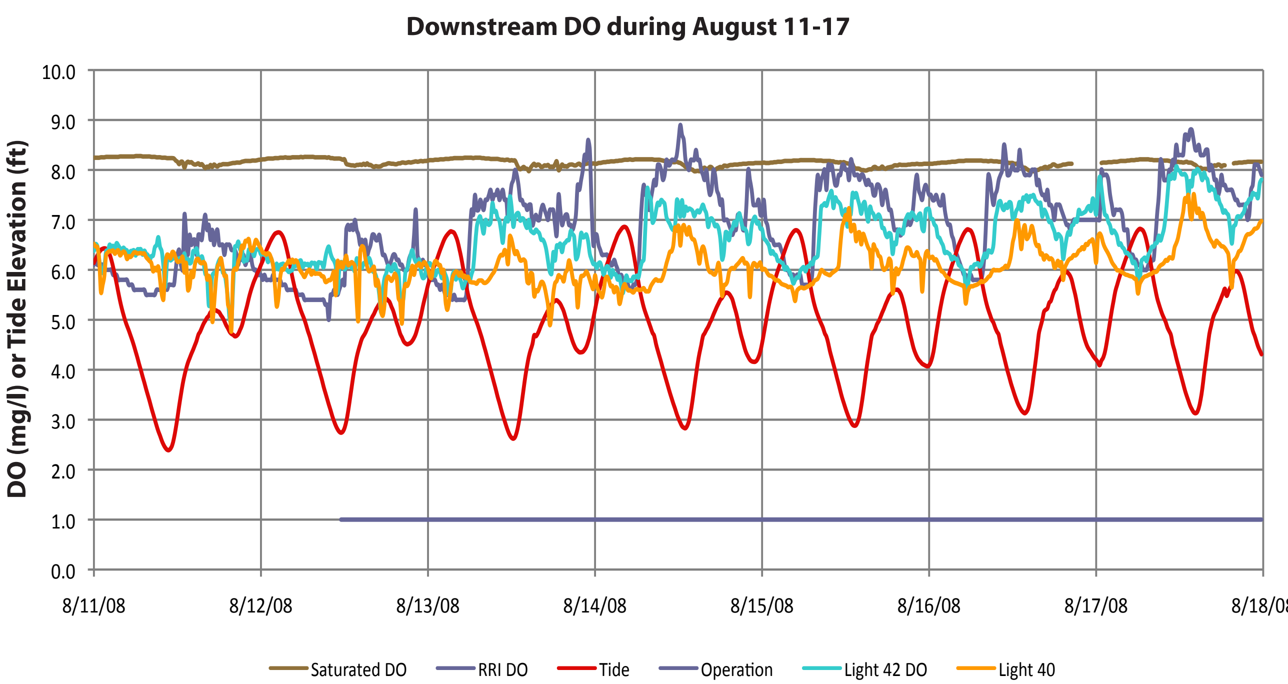


Figure 19b: DO Concentrations at Downstream DO Monitoring Stations for August 11–17, 2008.

ICF INTERNATIONAL

Figure 19

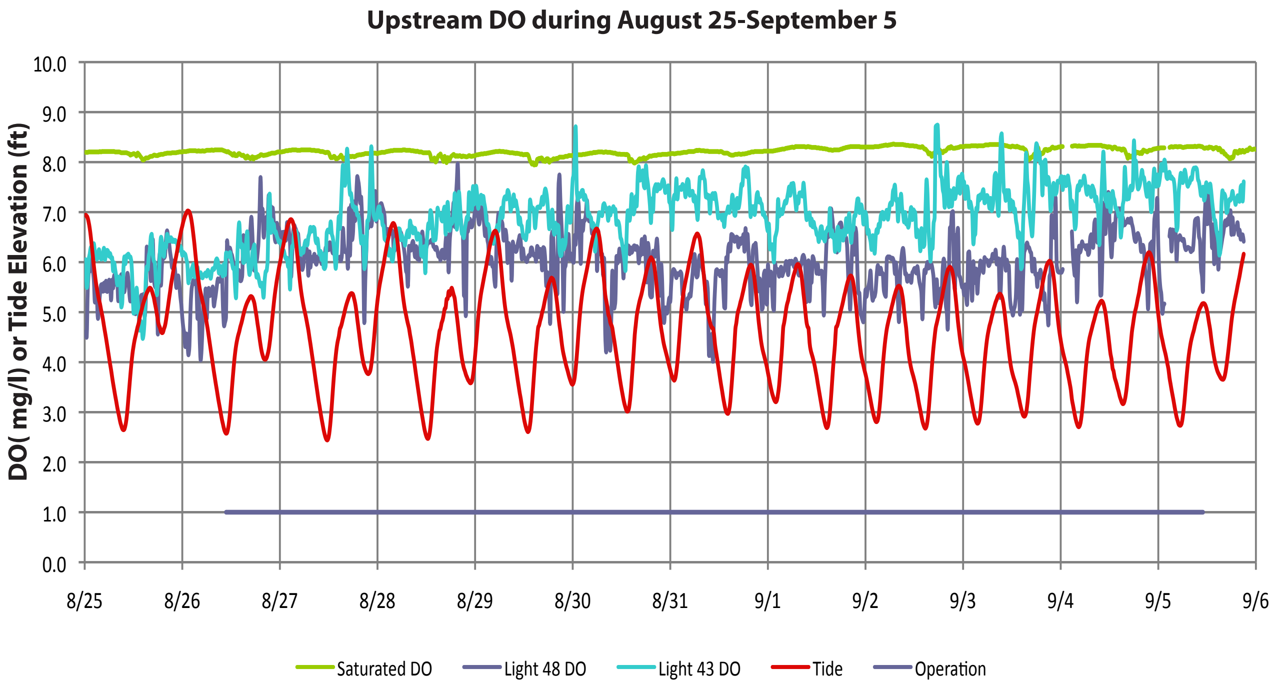


Figure 20a: DO Concentrations at Upstream Monitoring Stations for August 25 to September 5, 2008.

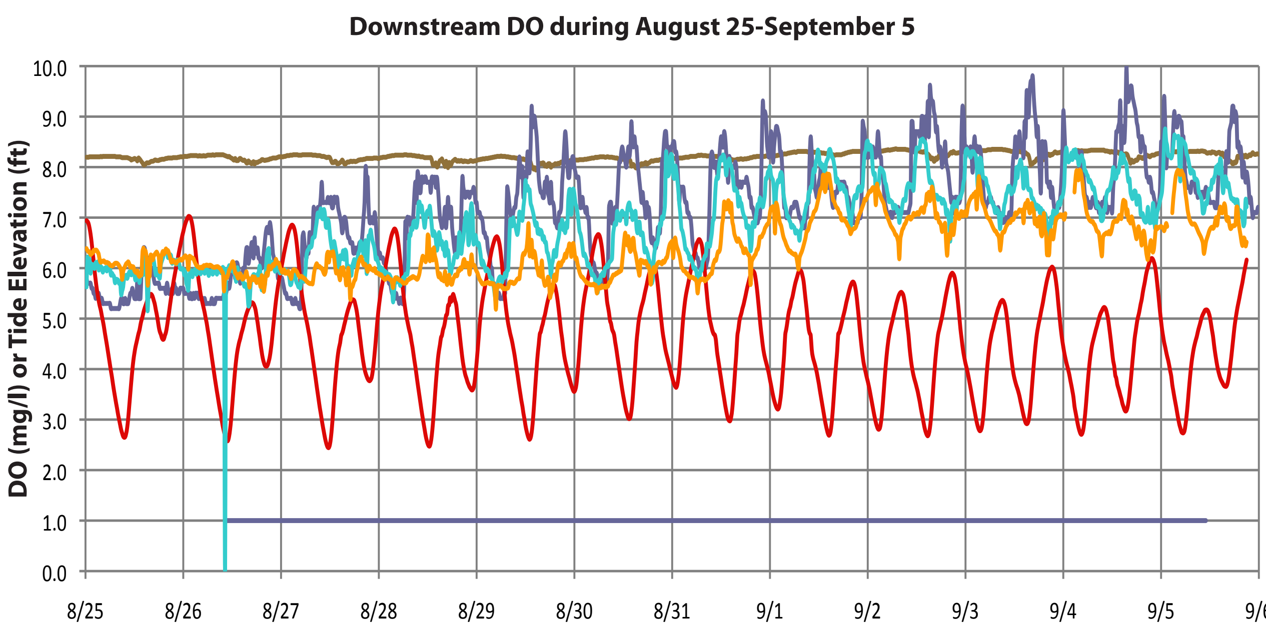


Figure 20b: DO Concentrations at Downstream Monitoring Stations for August 25 to September 5, 2008.

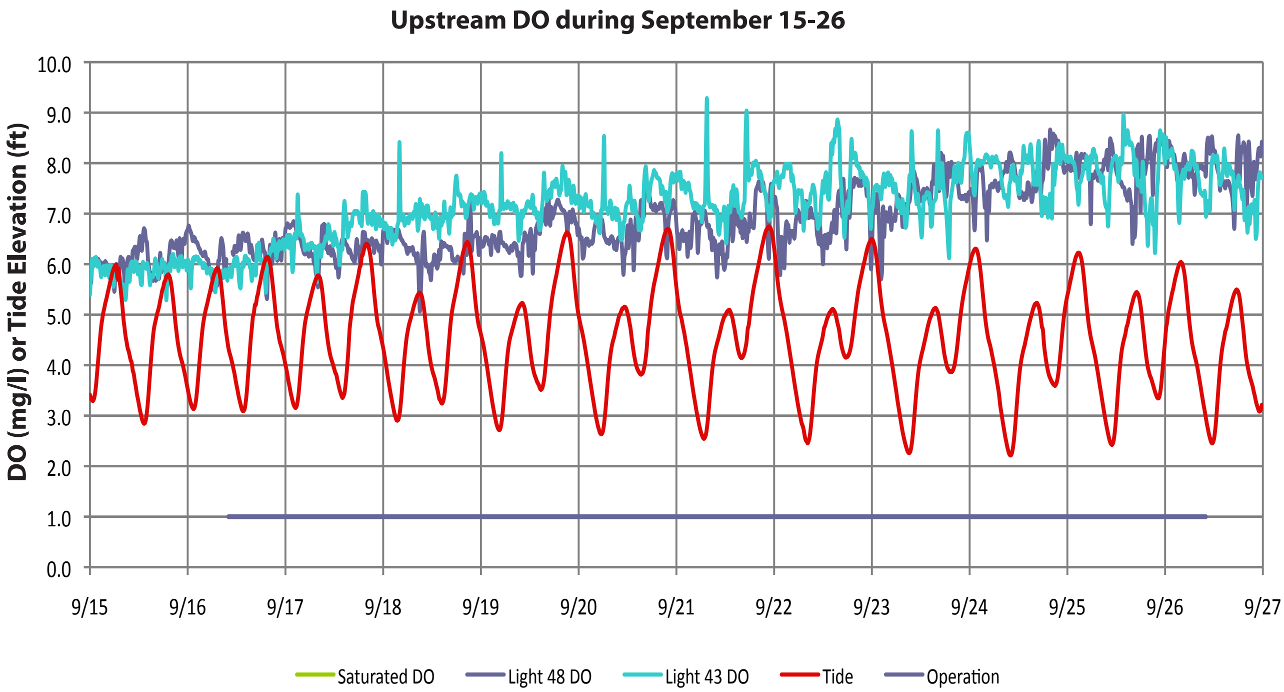


Figure 21a: DO Concentrations at Upstream Monitoring Stations for September 15 to 26, 2008.

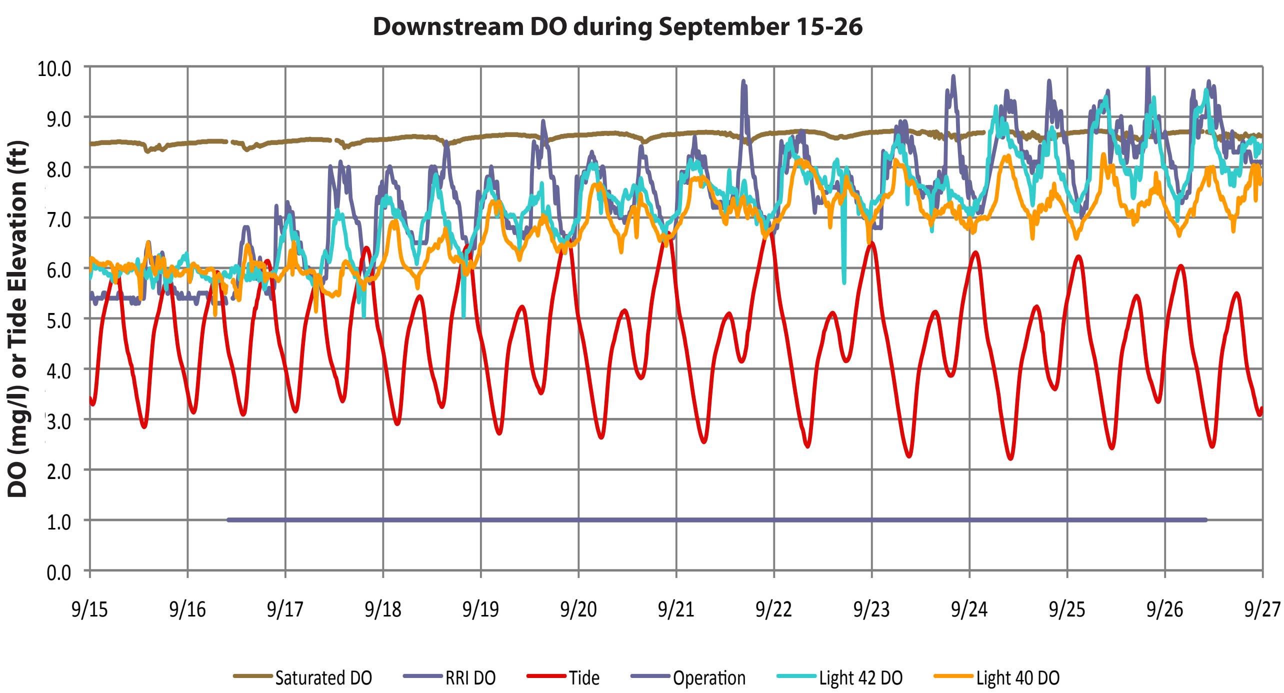


Figure 21b: DO Concentrations at Downstream Monitoring Stations for September 15 to 26, 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report

ICF INTERNATIONAL

Figure 21