Final Report

Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility Project

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

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Acronyms and Abbreviations

µg/l	micrograms per liter
Aeration Facility	aeration facility
af	acre-feet
BA	biological assessment
BML	Bodega Marine Laboratory
BMPs	best management practices
BOD	biochemical oxygen demand
CBDA	California Bay-Delta Authority
CDEC	California Data Exchange Center
CEQA	California Environmental Quality Act
cfs	cubic feet per second
CVRWQCB	Central Valley Regional Water Quality Control Board
CWA	Clean Water Act
CWC	California Water Code
DES	DWR Division of Environmental Services
DFG	California Department of Fish and Game
DO	dissolved oxygen
DWR	California Department of Water Resources
DWSC	Stockton Deep Water Ship Channel
EC	electrical conductivity
EPA	U.S. Environmental Protection Agency
ERP	Ecosystem Restoration Program
ft/sec	feet per second
HDPE	high density polyethylene
IS-MND	Initial Study–Mitigated Negative Declaration
lb	pounds
lb/day	pounds per day
LOX	Liquid oxygen supply
MAD	median of the absolute deviation of the median
mg/l	milligrams per liter
mgd	million gallons per day

Mile	San Joaquin River mile
NA	Navigational Aid
NMFS	National Marine Fisheries Service
NPDES	National Pollutant Discharge Elimination System
ORP	oxidation reduction potential
PLC	Programmable Logic Controller
PRC	Public Resources Code
psi	Pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
ROS	reactive oxygen species
RRI	Rough and Ready Island
RWCF	Stockton Regional Wastewater Control Facility
SC	Steering Committee
scfh	standard cubic feet per hr
SJR	San Joaquin River
SL	side-looking acoustic
SR	State Route
State Water Board	State Water Resources Control Board
TAC	Technical Advisory Committee
TMDL	total maximum daily load
TMDL Staff Report	Staff Report for the Total Maximum Daily Load for Low Dissolved Oxygen in the San Joaquin River
UOP	University of the Pacific
USACE	United States Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UVM	ultrasonic velocity meter
VAMP	Vernalis Adaptive Management Plan
WARMF	Watershed Analysis Risk Management Framework
WDRs	waste discharge requirements

Summary

Aeration Facility Background and Purpose

Periods of low dissolved oxygen (DO) concentrations have historically been observed in the San Joaquin River's (SJR's) Stockton Deep Water Ship Channel (DWSC), which is located downstream from Stockton, California. The majority of these low DO concentrations have been observed in the summer and fall months upstream of Turner Cut. These low concentrations have violated the Central Valley Basin Plan (Basin Plan) water quality objectives for DO. In January 1998, the State Water Resources Control Board (State Water Board) adopted the Clean Water Act (CWA) Section 303(d) list that identified this DO impairment, and the Central Valley Regional Water Quality Control Board (CVRWQCB) initiated development of a total maximum daily load (TMDL) to identify factors contributing to the DO impairment and assign responsibility for correcting the low-DO problem.

Since the approval of the SJR DO TMDL Basin Plan Amendment in 2005, two actions have been implemented to alleviate low-DO conditions in the DWSC. First, the City of Stockton added engineered wetlands and two nitrifying bio-towers to the Stockton Regional Wastewater Control Facility (RWCF) to reduce ammonia discharges to the SJR. Second, the California Department of Water Resources (DWR) constructed the Demonstration Dissolved Oxygen Aeration Facility (Aeration Facility) at Rough and Ready Island (RRI) to determine its applicability for improving DO conditions in the DWSC.

This report describes the background, design, and construction of the Aeration Facility, and details the testing of the physical operation of the facility (performance) and the evaluation of its ability to increase DO concentrations in the DWSC (effectiveness).

Constructed between 2006 and 2007 at the west (downstream) end of RRI at the Port of Stockton Dock 20, the Aeration Facility is maintained and operated for testing purposes by DWR. In 2008 demonstration testing began in June and ended in late September. In 2009 testing was not possible until September because of State Bond funding issues. Operational testing of flood tide aeration and nighttime aeration was conducted in September 2009. Additional operational testing and DWSC monitoring were conducted during the summer of 2010. The demonstration phase will end in December 2010, and long-term operation of the facility by the SJR DO TMDL stakeholders is expected to begin in 2011.

Description of Aeration Facility and Monitoring Stations

Figure S-1 shows a schematic illustration of the Aeration Facility. The Aeration Facility includes a 9,000-gallon liquid oxygen storage tank and two identical 200-foot-deep wells, each consisting of an inner and outer casing forming a concentric *U-tube*. The U-tubes are distinguished from each other as U-tube A and U-tube B. Water for each U-tube is pumped from the DWSC through a screened intake using a vertical turbine pump and gaseous oxygen is injected. This U-tube configuration provides increased contact time and hydrostatic pressure, which together increase the gas dissolution rate and the DO concentration. The water is discharged to the DO diffuser located under the dock about 1,000 feet upstream of the U-tubes.

The diffuser is approximately 200 feet long and is mounted along the pilings beneath the dock at a depth of about 10 feet at low tide. There are a total of eighty 6-inch-diameter ports on the diffuser. As part of the monitoring network for the study, DWR installed four DO monitoring stations at Navigation Aids (NAs) 40, 42, 43, and 48 along the DWSC in December 2006. Two of these stations are upstream of the diffuser (NA 43 is 0.2 mile upstream and NA 48 is 1.5 miles upstream), and two are downstream of the diffuser (NA 42 is 0.7 mile downstream, and NA 40 is 1.7 miles downstream). These monitoring stations supplemented an existing station at RRI, which is located 0.2 mile downstream of the diffuser. Figure S-2 is an aerial view of the DWSC that shows the location of the Aeration Facility diffuser and the NA monitoring stations.

Aeration Facility Testing and DWSC Monitoring Program Objectives

Several objectives were established for the Aeration Facility operational testing and DWSC monitoring program. The Aeration Facility's capacity and gas-transfer efficiency were tested, and the distribution and retention of the added DO in the DWSC was monitored. The major operational performance and effectiveness objectives are summarized as follows.

1. **Capacity and efficiency**. Determine the gas-transfer efficiency and capacity (pounds per day [lb/day] of DO delivered to the DWSC) of the Aeration Facility with a range of gas injection rates (percentage of water flow) for one-pump and two-pump operations.
2. **DWSC DO profile.** Determine how well the existing RRI monitoring station (with its near-surface DO sensor) represents DO conditions in the DWSC from Turner Cut to Channel Point.
3. **Natural DO conditions**. Determine whether the RRI DO measurements can be adjusted while the Aeration Facility is operating to estimate the DWSC DO concentrations without the added DO from the Aeration Facility.
4. **Diffuser location**. Determine whether the Aeration Facility diffuser location between Dock 19 and Dock 20 is appropriate for alleviating low-DO conditions.
5. **DO increments**. Determine how much DO could be added to the DWSC from the Aeration Facility under a variety of SJR flows (i.e., 250 cfs–1,000 cfs) at maximum Aeration Facility capacity.
6. **Tidal spreading**. Determine how tidal flows distribute the added DO from the Aeration Facility along the DWSC at high tide and low tide.
7. **Reaeration effects**. Because reaeration causes the added DO increments to decrease with time, determine the effects of natural surface reaeration on the downstream DO increments added by the Aeration Facility.
8. **DO objectives compliance**. Determine the ability of the Aeration Facility to maintain DWSC DO above the Basin Plan criteria of 5 milligrams per liter (mg/l) from December through August and 6 mg/l from September through November.
9. **Operational strategy**. Evaluate the ability to anticipate low-DO conditions in the DWSC and estimate the necessary amount of DO to add from the Aeration Facility.
10. **Implementation methods**. Recommend potential methods for identifying responsibility for low-DO conditions and for efficient operations of the Aeration Facility as part of the SJR DO TMDL implementation program.

Aeration Facility Performance and Effectiveness

Aeration Facility performance and effectiveness were evaluated by carefully considering all available measurements of DO conditions in the DWSC and identifying the tidal distribution of the added DO from the Aeration Facility diffuser. A previous report described the results of the 2008 operations (testing) of the Aeration Facility (ICF International 2010). This report describes the monitoring and measurements collected in 2008–2010 and the methods used to evaluate the above-listed objectives. A conclusion and recommendation section completes this report. Appendix A provides more information about potential TMDL "accounting procedures" for determining the effects of DWSC geometry, reduced flows, upstream river algae, and treated wastewater discharges during periods of low-DO conditions in the DWSC. The potential TMDL accounting procedures could be used for identifying and allocating stakeholder responsibility for operating the Aeration Facility to alleviate future low-DO periods in the DWSC.

Performance (Efficiency and Capacity)

Results of extensive testing showed that the measured oxygen delivery capacity at full water flow of about 45 cubic feet per second (cfs) with an oxygen gas supply to water flow (gas flow/water flow ratio) of about 4% (i.e., 6,480 standard cubic feet per hour [scf/hr]) was about 8,000 pounds per day (lb/day). This was less than the design capacity of 10,000 lb/day. The full water flow was less than the design flow of 50 cfs. The measured DO concentration in the U-tube discharge was about 32–34 mg/l higher than the inlet DO concentrations. The oxygen gas-transfer efficiency of the U-tubes was about 60% at a gas/water ratio of 4%.

The gas-transfer efficiency testing included sparger designs with more holes, and with smaller holes, to provide a greater area with reduced gas velocities to allow smaller bubble formation. However, the only observed changes in gas-transfer efficiencies were associated with changes in the gas/water ratio, as summarized in Table S-1. The gas-transfer efficiency was high (90%) at a gas/water ratio of 1% and declined as the gas/water ratio was increased. The efficiency was reduced to about 50% at a gas/water ratio of 6%. The amount of oxygen that can be added from the diffuser during a day of operation and be tidally distributed is shown in Table S-1 for a range of gas/water ratios from 2–6%. Because the gas-transfer efficiency is reduced at higher gas/water ratios, it is more efficient to operate at 3% or 4%, although the maximum capacity will be achieved with the highest gas/water ratio of 6%. Using one pump is less expensive than using two pumps, so two pumps should only be operated when one pump cannot deliver the amount of oxygen needed to meet the DO objective.

Table S-1. Summary of Aeration Facility Efficiency and Capacity

	Gas/Water Flow Ratio					
	1%	**2%**	**3%**	**4%**	**5%**	**6%**
Gas Supply with 1-pump (scf/hr)	900	1,800	2,700	3,600	4,500	5,400
Gas Supply with 2-pumps (scf/hr)	1,620	3,240	4,860	6,480	8,100	9,720
Assumed Efficiency	90%	75%	65%	58%	53%	50%
DO Increment (mg/l)	12	20	25	30	34	39
DO Delivery Capacity with 1-pump (lbs. at 25 cfs)	1,580	2,633	3,422	4,072	4,651	5,265
DO Delivery Capacity with 2-pumps (lbs. at 45 cfs)	2,843	4,739	6,160	7,329	8,371	9,477

Effectiveness (DO Increments in the DWSC)

The effectiveness of the Aeration Facility to help maintain DO concentrations above the Basin Plan objectives of 5 mg/l (or 6 mg/l from September through November) can be summarized with answers to two basic questions:

1. Is the Aeration Facility in the right location to address the low-DO problem?

   Yes. Because the RRI monitoring station and the Aeration Facility diffuser are located near the minimum DO position in the DWSC, the construction of the Aeration Facility at RRI, with the diffuser located between Docks 19 and 20, was an appropriate location to increase the minimum DO in the DWSC. Because of tidal movement and mixing in the DWSC, some added DO from the Aeration Facility is distributed upstream of the diffuser, between NA 43 and NA 48. The majority of the added DO was observed slightly downstream of the diffuser near NA 42.

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

   Not always. Operating strategies for the Aeration Facility can be developed for a range of DWSC flows, as a function of the inflowing DO and BOD concentrations. When the inflow BOD is high enough (>8 mg/l) to cause the DO in the DWSC to potentially approach and/or drop below the DO objective, the Aeration Facility can be operated to maintain the DWSC DO concentration above the DO objective. However, if the inflow BOD concentration is high enough to cause the daily DO deficit below the DO objective to be greater than the capacity of the Aeration Facility (10,000 lb/day), DO concentrations in some portions of the DWSC may remain below the DO objective.

   Table S-2 provides a summary of the expected distribution of the DO increments from the Aeration Facility for a range of net flows between 250 cfs and 1,000 cfs. A flow of 250 cfs will provide a net downstream movement of about 0.25 miles per day and will allow the largest DO increments from the Aeration Facility. The expected DO increment upstream 0.5 miles would be about 0.5 mg/l. The expected DO increment at the diffuser (or at RRI) would be about 2.5 mg/l, and the expected DO increment at NA 40 would be about 1.5 mg/l. For many of the DWSC DO profiles observed since the nitrification facility was completed in 2006, the DO increments from the Aeration Facility would be sufficient to meet the DO objective downstream of the diffuser.

Table S-2. Summary of Longitudinal Distribution of Added DO from the Aeration Facility

	SJR Mile	DWSC Flow (cfs)			
		250	500	750	1000
	40.0	0.00	0.00	0.00	0.00
NA 48	39.5	0.00	0.00	0.00	0.00
	39.0	0.00	0.00	0.00	0.00
NA 43	38.5	0.51	0.27	0.18	0.14
DO Diffuser	38.0	2.55	1.46	1.02	0.78
NA 42	37.5	3.24	2.12	1.55	1.22
	37.0	2.37	1.82	1.40	1.13
NA 40	36.5	1.56	1.48	1.22	1.02
	36.0	1.10	1.25	1.09	0.93
	35.5	0.77	1.05	0.97	0.86
	35.0	0.52	0.87	0.85	0.78
	34.5	0.36	0.73	0.76	0.71
	34.0	0.22	0.57	0.65	0.63
	33.5	0.10	0.39	0.50	0.52
	33.0	0.05	0.29	0.42	0.46
Turner Cut	32.5	0.03	0.23	0.35	0.40
Added DO Upstream of Turner Cut (lbs)		32,500	30,000	26,000	22,500

Recommendations for Future Operations

Based on the successful operational testing of the Aeration Facility from 2008–2010, there are three general recommendations for the future long-term operations of the Aeration Facility. These three recommendations are briefly discussed below.

(1) The Aeration Facility could be a major component of the TMDL implementation plan for achieving the Basin Plan DO objective in the DWSC when the river flow and inflow DO and BOD concentrations would have resulted in low-DO conditions. An operating strategy that would use the measured DO in the DWSC and upstream water quality monitoring to forecast periods of reduced DO in the DWSC could be helpful for the long-term operation of the Aeration Facility as part of the SJR-DO TMDL implementation plan. The possible consolidation of the Port of Stockton aeration facilities at Dock 13 with the Aeration Facility could be evaluated as part of the SJR DO TMDL implementation plan. Procedures for identifying the relative contributions from the possible causes of low DO in the DWSC (i.e., reduced flows, upstream algae, RWCF effluent, and DWSC geometry) could be developed as part of the TMDL implementation plan. Possible accounting procedures are described in Appendix A of this report. Operation of the Aeration Facility during periods of reduced DO concentrations will likely to be the most cost-effective approach for long-term TMDL implementation.

(2) A long-term TMDL monitoring strategy should be developed to identify periods when the Aeration Facility should be operated, based on the DWSC DO measurements and upstream SJR flow

and water quality monitoring at Mossdale or Vernalis to forecast the DWSC DO profile. The monitoring strategy should also provide data necessary to confirm that the added DO was sufficient to achieve the DWSC DO objective. The historic RRI DO data may be representative of minimum DO conditions in the DWSC upstream of Turner Cut. It should be possible to evaluate the natural DO conditions while the Aeration Facility is operating by estimating and subtracting the incremental DO effects from the RRI records. The TMDL monitoring strategy should include the City of Stockton's river sampling stations and should provide all data needed for the TMDL accounting procedures.

(3) Several modifications to the Aeration Facility should be further evaluated to increase the capacity to deliver DO to the DWSC or to improve the distribution of DO upstream of the diffuser. For example, the diffuser performance might be improved if about half of the ports were closed to produce a higher jet velocity and better lateral mixing. Another possible improvement would separate the discharges from the two U-tubes with a second discharge line and diffuser that would extend about a half a mile upstream of the existing diffuser to distribute more DO upstream.

These recommendations for an operating strategy, a monitoring strategy, and possible improvements to the Aeration Facility should be considered for the future operation of the Aeration Facility to help meet the SJR DO TMDL objective.

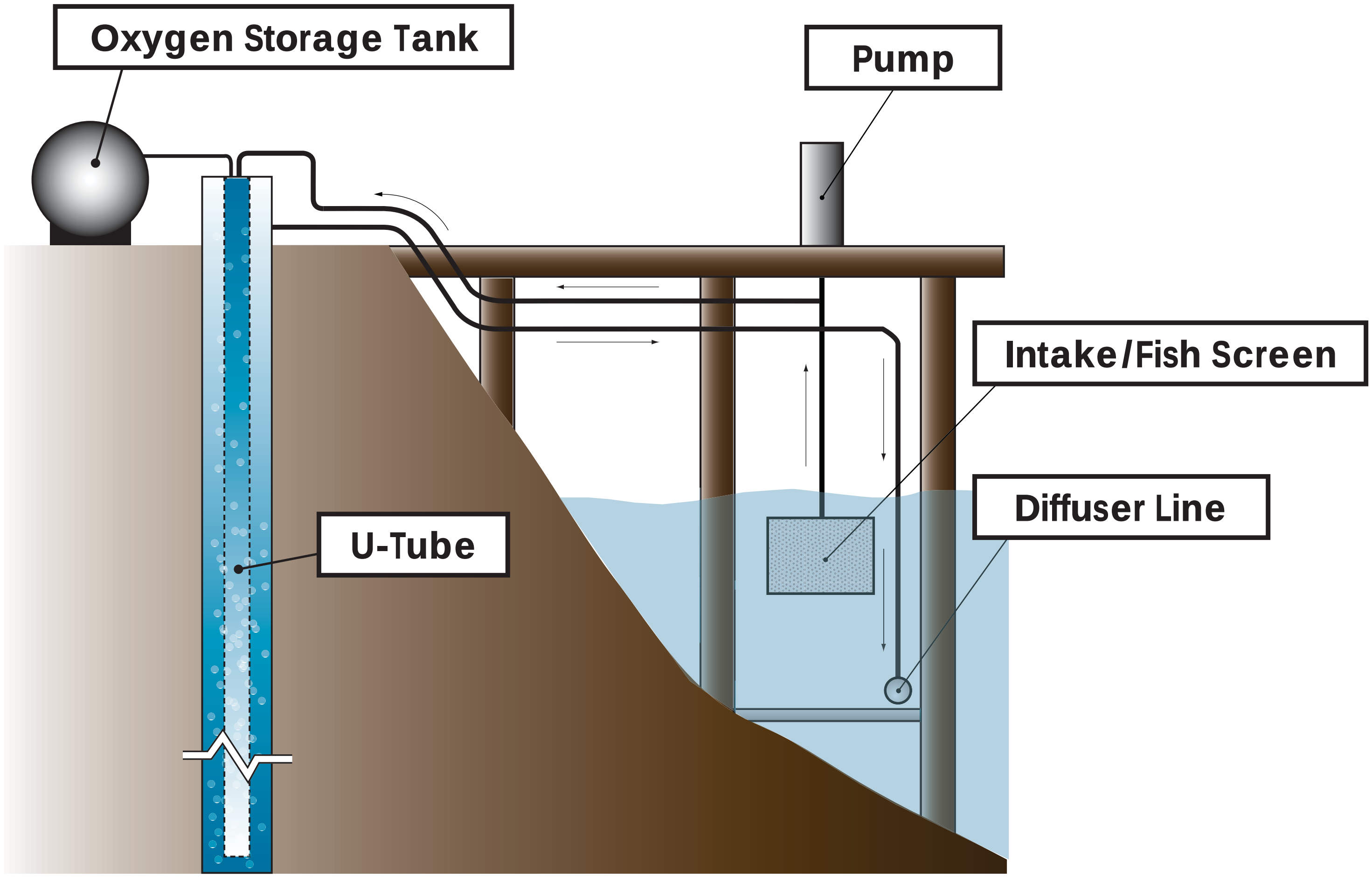

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Figure S-1
Schematic of the DWR Demonstration Aeration Facility

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Figure S-2
Aerial View of the Project Area and the DWSC Monitoring Stations

Introduction

This section of the final report describes the history of the San Joaquin River Dissolved Oxygen Total Maximum Daily Load (TMDL) study and implementation efforts, which included the design, construction, and testing of the Department of Water Resources (DWR) Demonstration Dissolved Oxygen Aeration Facility (Aeration Facility). The physical features of the Aeration Facility are fully described so that the testing and effectiveness of the operations, as discussed in subsequent sections, can be clearly understood.

The project was funded through the Proposition 13 Safe Drinking Water, Clean Water, Watershed Protection, and Flood Protection Act of 2000. The project was an *eligible project* for funding as defined in the act and promulgated in the California Water Code (CWC), Chapter 4, Article 3. Bay-Delta Multipurpose Water Management Program, Section 79190.(c), (d)(1) and (d)(2)(A)(ii). The CWC requires that the project be a CALFED stage 1 action as identified in the CALFED environmental impact report / environmental impact statement (EIR/EIS). The Clean Water Act (CWA) also requires that the project be a demonstration project, subject to the CALFED adaptive management principle, which constructs facilities to control waste discharges that contribute to low dissolved oxygen (DO) and other water quality problems in the lower San Joaquin River (SJR) and the South Delta.

History of San Joaquin River Dissolved Oxygen Total Maximum Daily Load Efforts

The Stockton Deep Water Ship Channel (DWSC) experiences periods of low DO concentrations. These periods are most prolonged and acute from June through October, but they have also been observed in other months. The geographic area of interest is from Channel Point, where the SJR meets the DWSC, to Turner Cut (Figure 1).

The low DO concentrations may stress resident aquatic life and may prevent (i.e., delay) the upstream migration of fall-run Chinook salmon (Hallock et al. 1970). The Basin Plan for the Sacramento–San Joaquin Bay Delta estuary contains a water quality objective requiring that oxygen levels be maintained above 6 mg/l between September 1 and November 30 and above 5 mg/l at all other times. The 6 mg/l objective was adopted to protect the upstream migration of fall-run Chinook salmon by the State Water Resources Control Board (State Water Board) in 1991.

The State of California placed the San Joaquin River (SJR) on the 303(d) list in 1994 because of low DO levels. In 1998 the problem was classified as a high priority for correction and the State committed to delivering a technical TMDL document to the U.S. Environmental Protection Agency (EPA) by June of 2003. Furthermore, a commitment was made to develop and present an implementation plan to the Central Valley Regional Water Quality Control Board (CVRWQCB) for its consideration as a Basin Plan Amendment in the fall of 2004.

The Bay Protection and Toxic Cleanup Plan, adopted by the State of California in 1999, laid out a strategy for developing the technical elements of the SJR DO TMDL and the associated implementation plan. A key element of the plan was the formation of a Steering Committee (SC) composed of local interests to oversee the development of the TMDL, including the allocation of loads (and responsibility) and the development and financing of the implementation plan. The SC formed a Technical Advisory Committee (TAC) to advise them on the sources and causes of the DO impairment and to help develop a cost effective control plan.

As owner of the Stockton Regional Wastewater Control Facility (RWCF), which discharges into the SJR, the City of Stockton (City) began additional water quality sampling for the TMDL in the summer of 1999. The City also conducted a preliminary feasibility study on the SJR's low-DO conditions (Jones & Stokes 1998). The TMDL SC/TAC organized and received funding for a series of studies in 2000 and 2001. These studies included additional sampling of the City effluent and at the City's river water quality stations, studies by University of the Pacific (UOP) on the sedimentation and sediment oxygen demands and biochemical oxygen demand (BOD) decay rates in the DWSC, and studies by DWR on algae concentration and photosynthesis in the DWSC. Upstream measurements of nutrients, algae concentrations (chlorophyll), and BOD in the SJR and tributary streams also were included in these studies. Water quality modeling studies were included to calibrate and evaluate the major factors causing the low DO in the DWSC.

Numerous monitoring and research studies were performed by various agencies, academic institutions, and interest groups to better understand the causes of the DO impairment. Most of these studies were peer-reviewed by an independent science panel convened by CALFED in June 2002 and subsequently summarized in a synthesis report (Lee and Jones-Lee 2003).

The conceptual model developed by CVRWQCB for low DO in the DWSC showed that there are at least three primary factors or processes influencing oxygen concentrations. The first factor is the SJR flow through the DWSC. Increased flows can increase the load of upstream BOD but also increase dilution of RWCF effluent and reduce water residence time. The second is the DWSC volume itself. Deepening the river decreased the efficiency of both atmospheric reaeration (transfer of oxygen gas from the atmosphere to become dissolved in water) and algal photosynthesis and increased water residence time, allowing a larger fraction of the imported organic material to be oxidized. The third factor is the BOD and ammonia discharged from the RWCF. Upstream BOD concentrations (from algae biomass) are largest in the summer and decline in the fall and winter as the RWCF historically discharged high concentrations of ammonia. Prior to the TMDL funded studies, there was little information on the oxygen-requiring substances, sources, and driving forces of low DO in the DWSC.

In 2003 the CVRWQCB issued the *Staff Report for the Total Maximum Daily Load for Low Dissolved Oxygen in the San Joaquin River* (TMDL Staff Report). The report concluded that although there is adequate scientific understanding to support a general allocation of responsibility to the three main contributing factors, there was inadequate understanding at that time to support more detailed waste load or load allocations to specific point and nonpoint sources of oxygen-demanding substances and their precursors. To address oxygen-demanding substance loads and their precursors, the CVRWQCB concluded that those entities responsible for the various sources must complete scientific studies to obtain information for more detailed allocations and eventual implementation of alternate measures. This was the motivation for the upstream studies that were approved by the CALFED Ecosystem Restoration Program (ERP) (State Bond–funded).

These upstream studies included measurements of flows and nutrient and algae concentrations in 2005–2007. Additional modeling of the watershed and river water quality also was initiated, using a TMDL model called Watershed Analysis Risk Management Framework (WARMF). Studies by UOP of the "transition zone" between the river conditions at Vernalis and Mossdale and the water quality entering the DWSC were included. The ERP separately funded two DWSC multi-dimensional modeling efforts, based on recommendations from the 2002 peer review by the independent science panel convened by CALFED.

DWSC geometry and reduced flows through the DWSC, the two nonpoint-related contributing factors to the low DO levels, are not BOD loads for which mass or concentration limits can be assigned. Instead, these factors reduce the capacity of the DWSC to assimilate loads of oxygen-demanding substances (load capacity). The capacity of the DWSC to assimilate oxygen demand exerted by incoming loads of oxygen-demanding substances is a function of the flow rate through the DWSC and of temperature. The CVRWQCB found that each of the three main contributing factors is equally responsible for reducing the excess net oxygen demand exerted in the DWSC.

In 2005 the CVRWQCB released the final Basin Plan Amendments (Central Valley Regional Water Quality Control Board 2005). The report contained the evaluation of alternatives and technical support for adoption of an amendment to the Basin Plan to formally establish the DO TMDL. Appendix A of this report summarizes the TMDL implementation plan and describes possible procedures for long-term operation of the Aeration Facility as part of the TMDL implementation. A complete history of the TMDL hearings and CVRWQCB documents (drafts, comments, responses, revisions, and final) are available at the following web address:

http://www.waterboards.ca.gov/centralvalley/water_issues/tmdl/central_valley_projects/san_joaquin_oxygen/index.shtml

Additional information about the DWSC DO conditions and upstream river flows and algae biomass (chlorophyll) concentrations, as well as copies of many of the TMDL technical reports made for the 2000–2001 and the 2005–2007 upstream studies (measurements and modeling) are available at the San Joaquin River DO TMDL Technical Working Group website:

http://www.sjrdotmdl.org/index.html

Additional information and contacts for the Aeration Facility can be found at the DWR Bay-Delta Office website:

http://baydeltaoffice.water.ca.gov/sdb/af/index_af.cfm

Table 1 provides a timeline of the development of the DO TMDL as it relates to the Aeration Facility.

Table 1. DO TMDL and Aeration Facility Timeline

1994—SJR placed on CWA Section 303(d) list for low-DO impairment.
1998—DO TMDL requirement placed on the DWSC by the CVRWQCB.
1999—SJR DO impairment identified in Bay Protection and Toxic Cleanup Plan by the State Water Board.
1999—Stakeholders formed a steering committee to participate in the development of the DO TMDL.
2000—SJR DO impairment listed in CALFED Record of Decision as an ERP-directed action. CALFED funded studies (in 2000 and 2001) to support the DO TMDL.
2002—CVRWQCB issued “strawman” source and linkage analysis. Synthesis report is released describing results from the 1999–2001 CALFED DWSC studies.
2003—SC recommends phased DO TMDL implementation with additional upstream studies and Aeration Facility demonstration. CVRWQCB issued draft TMDL report providing an overview of the DO TMDL and implementation program.
2004—Feasibility report prepared for DWR evaluating DWSC aeration facility alternatives.
2004—U-tube design selected as the preferred option for Aeration Facility.
2005—CVRWQCB adopted Basin Plan Amendment for SJR DO TMDL.
2006—Construction of the Aeration Facility began on Dock 20. City of Stockton completed construction of RWCF nitrification facility. Four additional water quality monitoring stations along the DWSC were installed.
2007—Upstream studies funded by CBDA (ERP) began. Aeration Facility construction completed. City of Stockton begins operation of nitrification bio-tower—effluent ammonia concentration reduced to <2 mg/l.
2008—Testing of Aeration Facility occurred from June to September.
2009—Testing of Aeration Facility occurred in September and October
2010—Testing of Aeration Facility completed.

Effects of Deep Water Ship Channel Low Dissolved Oxygen on Fish

A conceptual model for the effects of low DO on fish in the DWSC was developed by California Bay-Delta Authority (CBDA) as one of several Delta ecosystem conceptual models for the CALFED ERP (now administered by Department of Fish and Game [DFG]). The involvement of the CBDA was based on the CALFED 2000 Programmatic Record of Decision, which contains a commitment to address low-DO conditions in the DWSC. Since 1999, stakeholders and other agencies have been working with the CVRWQCB and CBDA to develop and implement a TMDL. This conceptual model was developed to assist in that effort.

Jones & Stokes, as the CBDA contractor, developed a web-based model in 2005 that allows links and cross-references between the SJR river segments and the DWSC and included information about the physical and chemical (water quality) processes as well as information about the biological (fish response) processes. The DWSC DO conceptual model is linked to the TWG website:

http://sjrdotmdl.org/concept_model/index.htm

For questions about the model or other items from the TWG, please contact the DWR Bay-Delta Office.

The model has two parts. The Physical and Chemical Processes Conceptual Model provides a basic understanding of what causes low DO concentrations in the DWSC. This part of the model answers the following questions about DO in the DWSC:

- What is the range of DO concentrations in the DWSC?
- Why are DO concentrations in the DWSC important?

Data on DO concentrations in the DWSC have been collected since 1984. These data have been summarized in graphic form for the Biological and Ecological Effects Model. Low DO episodes have occurred every month of the year but are most common in the summer and fall (June–October). DO concentrations frequently fall below the regulatory minimum set in the Basin Plan and have sometimes been below 2 mg/l. As described in this model, DO concentrations in the DWSC are affected by upstream SJR conditions (flow and algae biomass) as well as the channel geometry. .

United States Fish and Wildlife Service (USFWS) and DFG studies have identified low-DO conditions in the DWSC as a possible stressor on resident and anadromous fishes in the Delta. These conditions are thought to block the downstream migration of juvenile salmonids and to lead to other adverse effects on fish. The Biological and Ecological Effects Model describes the conditions that lead to adverse effects on fish and describes in detail what is known about how low-DO conditions affect eight fish species.

DWR environmental scientists summarized historic findings of adverse effects of low DO levels on salmon and steelhead, and described the potential benefits of raising DO levels for those species (Newcomb et al 2010). Potential effects of low DO and increased temperatures on salmonids (steelhead and Chinook) that were previously described in the DWSC DO Conceptual Model, and the most likely direct effects of low DO on adult Chinook upstream migration in September and juvenile Chinook downstream migration in June were reviewed. Comparisons of the daily RRI DO and adult Chinook passing the fish weir installed on the Stanislaus River at Riverbank (downstream end of the spawning reach) for the months of September and October for 2003-2008 were shown.

As previously described by DFG (Hallock et al. 1970), the upstream migration timing (or delay) of Chinook may be influenced by the date, river flow, water temperature, or DO concentrations. Although only a small fraction (<5%) of adult Chinook typically reach the Stanislaus weir in September, the temperatures are often above 70 F and the DO is usually below 6 mg/l in September. Because the Aeration Facility could help increase the DO concentration to 6 mg/l in September, operations could potentially benefit adult Chinook by allowing an earlier migration (in September) and thereby allow earlier spawning, with earlier fry emergence and growth in the spring. However, if warmer temperatures were controlling (delaying) either adult Chinook migration through the DWC or spawning in the upstream tributaries, the fish benefits from the increased DO concentrations in the DWSC from the Aeration Facility may be limited (Newcomb et al 2010).

Total Maximum Daily Load Implementation

Since the adoption of the TMDL in 2005, several actions have been implemented to alleviate low-DO conditions in the DWSC. Among them are waste discharge requirements (WDRs) that were issued to the City of Stockton placing more stringent effluent limits on oxygen-demanding substances. To comply with those requirements, the City of Stockton added engineered wetlands and two nitrifying bio-towers to the RWCF to reduce ammonia discharges to the SJR. WDRs also were issued to the Port of Stockton for its 2006 dredging project. The WDRs require the addition of oxygen to the

DWSC to mitigate additional DO deficits associated with increasing the channel volume and chemical oxygen demand.

Because the United States Army Corps of Engineers (USACE) is responsible for any channel deepening or maintenance dredging in the DWSC, CVRWQCB requested USACE to submit a technical report identifying and quantifying the various mechanisms by which oxygen-demanding substances are converted to oxygen demand and the impact that the DWSC has on reaeration and other mechanisms that affect DO concentration in the water column. Modeling studies of the effects of potential deepening of the DWSC on DO are underway by USACE. Additionally, DWR constructed the Aeration Facility at RRI to determine its effectiveness for improving DO conditions in the DWSC (described in this report).

Stockton Regional Wastewater Control Facility Nitrification

The City of Stockton constructed a nitrification facility in 2006 that dramatically reduced the amount of ammonia in the RWCF effluent. The ammonia-N is converted to nitrate-N in a nitrifying bio-tower, and the ammonia concentration from the oxidation ponds is (now) discharged to the river as nitrate (with no remaining oxygen demand). This removal of ammonia-N concentration (now measured as the effluent nitrate-N concentration) represents a TMDL BOD reduction credit for the City of Stockton.

Port of Stockton Aeration Facilities (Dock 13)

The Port of Stockton operates two aeration facilities on Dock 13 near Channel Point where the SJR enters the DWSC. The USACE constructed the aerator platform in 1992, using a design that was recommended by Sacramento District staff of the USACE to provide aeration outside of ship traffic lanes in the DWSC. In the 1980s, the Sacramento District deepened the DWSC by 5 feet to its current depth of approximately 35 feet at average low water flows. To resolve regulatory agency concerns that the deepening would decrease DO concentrations, the USACE performed a water quality modeling study that indicated that the deepening would decrease the DO concentrations and increase the DO deficit by about 0.2 mg/l. Results from the modeling indicated that a maximum of about 2,500 lb/day of oxygen would need to be dissolved in the DWSC, when the river's net flow was 2,000 cubic feet per second (cfs), to maintain the pre-deepening longitudinal DO profile. Smaller amounts of oxygen would be needed at lower flows.

Because the migration of adult fall-run Chinook salmon has likely been affected by low-DO conditions in the DWSC, the USACE agreed to mitigate the potential effects on DO concentrations in the fall months (September 1 through November 30), whenever DO concentrations dropped below 6 mg/l (i.e., per the Basin Plan objective). The USACE device 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. The capacity likely would be reduced at higher DO concentrations. In 2003 the USACE turned over ownership of the facility to the Port of Stockton who now operates and maintains it on behalf of the USACE during the September–November period.

A second device was installed by the Port of Stockton in 2007 as required for mitigation of dredging impacts. That system uses pure oxygen bubbles discharged from a perforated hose suspended about

20 feet below the water surface under Dock 13 on the Port of Stockton's East Complex. The aeration capacity for this facility is about 2,000 lb/day.

The Port of Stockton operates the aerators in months outside the September–November period to fulfill a separate mitigation measure associated with dredging actions at its West Complex and as a participant in the SJR DO TMDL. The Port of Stockton has committed to supplying (i.e., dissolving) about 4,000 lb/day of oxygen into the DWSC using aerators whenever DO concentrations approach the objective levels. Both of these aerators were operated for most of summer 2008 (June 7–October 13) because DO at NA 48 often was approaching or less than the established operational trigger, which is 5.2 mg/l daily average for June–August and 6.2 mg/l daily average for September–November. The Port of Stockton aerators at Dock 13 were also operated periodically in 2009 and 2010. Added DO from these aerators travels upstream in the SJR during flood tide and downstream toward the DWR Aeration Facility diffuser during ebb tide. After a few days of tidal mixing, it is presumed that the added DO from the Port of Stockton aerators and from the DWR Aeration Facility mix and increase DO concentrations in the DWSC, but the source of the DO cannot be easily identified. Identifying the DO from the Port of Stockton aerators was not an objective of the DWR Aeration Facility monitoring; however, it is reasonable to assume that some portion of the DO added by the Port of Stockton is measured at the NA 48 monitoring station. Therefore, DO added by the Port of Stockton aerators was considered part of the baseline DO conditions. The DWR Aeration Facility monitoring and testing strategy was designed to distinguish only the DO added by the Aeration Facility from all other DO (including that added by the Port of Stockton aerators) in the DWSC.

Background of the Stockton Deep Water Ship Channel Demonstration Dissolved Oxygen Aeration Facility Project

The Aeration Facility project has been a multiple-year study of the effectiveness of elevating DO concentrations in the DWSC. DO concentrations in the channel have dropped as low as 2 to 3 mg/l during warmer and lower water–flow periods in the SJR. The low DO levels can adversely affect aquatic life, including the health and migration of anadromous fishes (e.g., salmon). The objective of the study is to maintain DO levels above the minimum recommended levels specified in the Basin Plan for the Sacramento River and SJR Basins. The Basin Plan water quality objectives for DO are 6.0 mg/l in the SJR between Turner Cut and Stockton, September 1 through November 30, and 5.0 mg/l for the remainder of the year.

The project comprises a full-scale aeration system, including two 200-foot-deep U-tubes, two vertical turbine pumps capable of pumping more than 11,000 gallons per minute each, a liquid to gas oxygen supply system, and ancillary equipment and control systems. The system has been sized to deliver approximately 10,000 lb/day of oxygen into the DWSC. The aeration system is anticipated to be operated only when DWSC DO levels are below the Basin Plan DO water quality objectives (up to 100 days per year). The Aeration Facility study included an ongoing assessment of DO levels in the DWSC and vicinity and a study of potential adverse effects of oxygen on salmon.

Project Funding

The funding for planning, construction, and testing of the full-scale Aeration Facility was from the Proposition 13 Safe Drinking Water, Clean Water, Watershed Protection, and Flood Protection Act of 2000. The Aeration Facility qualified for funding as defined in the act and promulgated in the

California Water Code (CWC), Chapter 4, Article 3. Bay-Delta Multipurpose Water Management Program, Section 79190(c), (d)(1), and (d)(2)(A)(ii). The CWC requires that the project be a CALFED stage 1 action as identified in the CALFED EIR/EIS, be a demonstration project subject to the CALFED adaptive management principle, and construct facilities to control waste discharges that contribute to low DO and other water quality problems in the lower SJR and the south Delta.

Feasibility Study Alternatives

Methods for mechanically oxygenating waters in the project area are presented in the *Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel* (Jones & Stokes 2003) and in the *Aeration Technology Feasibility Report for the San Joaquin River Deep Water Ship Channel* (Jones & Stokes 2004). Results of the implementation analysis study recommended that three technologies be considered for further evaluation and possible implementation: the U-tube, Speece cone, and bubble plume aeration. The *San Joaquin River Dissolved Oxygen Aeration Project: Draft Engineering Feasibility Study*, prepared in June 2004 by HDR Engineering (HDR Engineering 2004), evaluated these treatment technologies and their ability to transfer 10,000 lb/day of oxygen to the channel. Based on that evaluation and additional in-situ testing, the U-tube was selected as the most feasible option for implementation (Jones & Stokes 2004).

Environmental Analysis and Permitting

The California Public Resources Code (PRC) Sections 21000–21177 and the California Environmental Quality Act (CEQA) Guidelines provide the statutory requirements for evaluating environmental impacts of proposed projects. CEQA requires that state and local agencies, when making a discretionary action, follow a protocol of analysis and public disclosure of the potential environmental impacts of development projects. As such DWR conducted an initial study to analyze potential effects. In addition, Section 7 of the Endangered Species Act, 16 U.S.C. Section 1536(a)(2), requires all federal agencies to consult with the National Marine Fisheries Service (NMFS) for marine and anadromous species, or the USFWS for fresh-water fish and wildlife, if they are proposing an action that may affect listed species or their designated habitat. For local governments, any project that requires a federal permit or receives federal funding is subject to Section 7. While this was not required for this project, DWR acted in good faith to allay concerns by the NMFS and prepared a biological assessment. Both of the aforementioned reports are described below.

Initial Study–Mitigated Negative Declaration

An initial study/mitigated negative declaration (IS/MND) was prepared in 2005 to assess the Aeration Facility's potential effects on the environment and the significance of those effects (Jones & Stokes 2005). Potentially significant impacts were identified for biological resources, hydrology and water quality, and noise. However, the study concluded that the proposed project would have no potentially significant impacts on the environment because mitigation and conservation measures would be implemented. Mitigation measures implemented to reduce impacts to a less-than-significant level were as follows.

- Construction air emission controls.
- Best management practices (BMPs) for contaminant spill control.
- Surveys for Swainson's hawk and burrowing owl nests in the immediate vicinity of the project area prior to construction activity.

- Screens to avoid impingement and entrainment impacts on fish.
- Noise mitigation measures to conform to city, state, and federal standards.

Biological Assessment

The DWSC is used as a migration corridor by juvenile and adult salmonids; thus a biological assessment of the potential effects of the Aeration Facility on listed fish species was prepared for USFWS and the National Marine Fisheries Service (NMFS) by DWR (Jones & Stokes 2007a). The direct effects of the operation of the project may include attraction of juvenile and adult salmonids to the diffuser, and whether being close to the diffuser could be harmful to these fish species through exposure to reactive oxygen species (ROS) and/or exposure to oxygen-supersaturated water.

The evaluation of direct effects focused on the effects of the test operation phase of the project. Specifically, NMFS staff voiced concerns that the operation of the project could attract juvenile salmon or steelhead to areas of the water column that are supersaturated with oxygen, and if so attracted, they could be exposed to oxygen at concentrations or ROS that could be harmful. Conversely, project operations could have beneficial effects on these species by increasing DO concentrations within the DWSC from Turner Cut to Stockton, a distance of approximately 7 miles. The potential for effects on fish from the fish screens or from supersaturated oxygen discharged from the project are relatively low for a variety of reasons that were fully discussed in the biological assessment.

Sacramento winter-run Chinook salmon, Central Valley spring-run Chinook salmon, and green sturgeon are very unlikely to occur in the vicinity of the project because these fish spawn and rear in the Sacramento River. They will likely occur only in the lower SJR if there were some kind of attractant flow emanating from the SJR. The likelihood of these fishes traveling upriver 38 miles to the project site is very small.

The presence of juvenile Central Valley steelhead is likely, depending on when the operation of the project is initiated each year. Juvenile steelhead are expected to occur in low numbers following the peak of the outmigration and during the bulk of the period of project operations.

Juvenile salmonids present in the DWSC are not expected to actively seek the highest oxygen concentrations. As indicated in studies outlined above, fish are expected to occupy intermediate oxygen concentrations as long as these concentrations meet their metabolic needs. Because the diffuser is expected to completely mix DO through the width and length of the channel to concentrations appropriate for migrating smolts, juvenile salmonids are not be expected to "need" to seek more oxygen-rich environments.

Juvenile salmonids could not remain in the plumes of supersaturated oxygen exiting the Aeration Facility ports because their critical swim speeds are less than the velocities of the jets in the area of super-saturation. If a juvenile salmon were to somehow swim into a hyperoxic plume, within a second or two the flow would eject the fish from the area to areas with highly mixed waters.

Injecting oxygen into water is relatively common in intensive salmonid aquaculture operations. Juvenile salmonids exposed to hyperoxic waters and allowed to return to normoxic fresh water have not, with the exception of one 20-day exposure with extremely high saturation (328%), shown any mortality or long-term ill effect. During exposure there are changes in ion and acid-base exchange to adapt to higher CO_2 in the blood, and antioxidant reactions to defend against damage at the cellular level as a result of oxidative stress (the effect of ROS). All physiologic effects appear reversible if the fish is allowed 24 hours before another longer-term (12 hour or greater) exposure to hyperoxic water or before it enters saltwater.

The biological assessment concluded that the long-term effects of the project would be beneficial for those fish present in the DWSC during project operations. The project is expected to increase the DO concentrations throughout the DWSC to levels considered safe for salmonids during the spring and summer months.

Basis of Design and Division of Engineering Final Design

Jones & Stokes (now ICF International) contracted with HDR to complete a draft engineering feasibility Study (completed July 2004) that analyzed alternatives for the Aeration Facility. The final feasibility report by Jones & Stokes recommending a full-scale U-tube facility was completed in October 2004.

A basis of design technical memorandum was also completed by HDR per Jones & Stokes in December 2004.

DWR's Division of Engineering began final design of the full-scale U-tube Aeration Facility in January 2005. Final design was completed in July 2005, and the project was advertised for construction bids shortly after.

Construction

DWR requested construction bids in October 2005 for the full-scale demonstration project. The construction contract was awarded to Clyde G. Stegall Inc. of Loomis, California, and the notice to begin construction was given in December 2005. Construction of the facility began in January 2006. Installation of the discharge and diffuser pipe occurred in January 2006, with the construction of the two 200-foot-deep U-tubes completed in April 2006. The aboveground components of the construction, including the concrete pad, piping, pumps, and appurtenances, were completed by September 2006.

Issues with procuring a contract to lease the oxygen system portion of the facility necessitated that the oxygen system instead be designed, put out to bid, and constructed. BOC was awarded the contract, completed design and construction of the oxygen portion of the system in August 2007, and provided safety and system operation training in September 2007. Construction was officially completed in October 2007, and operations began in early 2008. The total cost for construction of the Aeration Facility was $3.7 million. Table 2 provides a description of the various system components.

Table 2. Aeration Facility Design/Construction Elements

Element	Description
Fish screens	Two Johnson-type barrel fish screens feeding two intake headers. Intake headers connected to pump intakes. Screens are self-cleaning using air scour.
Pumps and valves	Two vertical turbine pumps with 200 horsepower electrical motors. Water pumped to U-tube contactor (well) and discharged to a multi-port diffuser. Pump operates ON/OFF through a dedicated control panel for each pump. Flow can be reduced using a throttling valve in a set position. Isolation valves can isolate flows from one pump or the other to one U-tube or the other via crossover piping.
Liquid oxygen supply (LOX)	9,000 gallon liquid oxygen storage tank, vaporizing equipment, and feed lines with valves and piping located onsite. Storage volume sized such that refilling intervals are not to exceed one refill per week. Maximum feed rate sized by considering a minimum 80% transfer rate at design conditions. LOX storage and distribution equipment to the feed control equipment shall be vendor supplied.
U-tube contactor	Two identical 200-foot-deep U-tube assembly contactor wells are specified. Outer casing constructed of welded steel capable of resisting corrosion from the surrounding soil. The bottom of each U-tube shall be sealed with concrete to eliminate the potential for groundwater interaction. Inner casing constructed of alternate material such as high density polyethylene (HDPE) or polyvinyl chloride (PVC) to reduce weight and minimize support structure requirements. Centering supports/guides attached to the inner pipe can be used to guide and stabilize the inner piping. Each U-tube will be designed to provide a minimum of 5,000 lb/day of oxygen.
Multi-port diffuser	A 30-inch discharge pipe is used to transmit effluent (oxygenated water) from the U-tubes 1,000 feet upstream to a single liquid diffuser lateral, mounted along the piers beneath Dock 20. The diffuser lateral is affixed to individual piers with fabricated pipe supports at the deepest possible installation point. The installation must be as deep as possible to guard against effervescence.
Instrumentation and control	Influent valves with manual adjustment. Oxygen feed automated with motorized valves and set point. Onsite readout display of operating parameters (pressure, flow, DO concentration). Communication equipment required to upload data to a remote point. A programmable logic controller (PLC) for data logging, communication, and motor control where needed. A local control panel for operation of fish screen air burst system. Dedicated control panel for onsite ON/OFF startup for pumps.
Site Features	
Site work	Concrete foundations are required for the oxygen supply tank, evaporators, regulation, and refilling equipment. Refilling occurs over concrete pavement. Drilling in the dock structure will be necessary for installing pumping and piping equipment. Chain link fencing used to enclose and secure the pump and oxygen supply equipment.

Source: HDR and Jones & Stokes 2004.

Aeration Facility Description

The facility layout is illustrated in Photograph 1. The Aeration Facility was constructed at the west end of Dock 20, RRI, on the Port of Stockton's West Complex. The facility is composed of two nearly identical systems that operate side-by-side (referenced as Tube A and Tube B). Water is drawn from the DWSC through screened intakes using two vertical turbine pumps that supply a combined water flow of approximately 45 cfs. The screens are installed around the two pump intakes between the piers that support Dock 20 and were designed such that none of the project infrastructure interferes with shipping traffic. The pumping columns are mounted through the dock structure where the pump discharge headers and pump motors are located. The pumps convey the river water via 30-inch piping to two 200-foot-deep wells consisting of an inner and outer casing forming U-tubes. This U-tube configuration provides increased contact time and hydrostatic pressure, which together increase the gas adsorption rate and raises the DO concentration. This is discussed in detail in HDR's 2005 report, *Basis of Design Technical Memorandum*.

Gaseous oxygen is injected through stainless steel spargers at the point just above where water flows down the U-tubes. The oxygen source is a 9,000-gallon LOX tank. The LOX is converted to gas in a vaporizer before being introduced to the process water. The oxygenated water exiting the U-tubes is commingled and routed through approximately 1,000 feet of piping back to the DWSC through a diffuser upstream from the pump intakes. The diffuser is approximately 200 feet long and is mounted along the pilings beneath the dock about 10 feet inside of the edge of the dock (where it is protected from ships) at a depth of 10 feet at low tide. The water is about 30 feet deep at low tide at the diffuser (dredged for ships to dock). There are a total of eighty 6-inch-diameter ports on the diffuser. Half of the ports are spaced every 5 feet along the centerline of the diffuser pointing laterally towards the DWSC. The other half of the ports are installed between the forty lateral ports, and are pointed down at a 45° angle to distribute the oxygenated water deeper in the DWSC. The portion of the facility atop the dock is secured with an 8-foot chain link fence and gate.

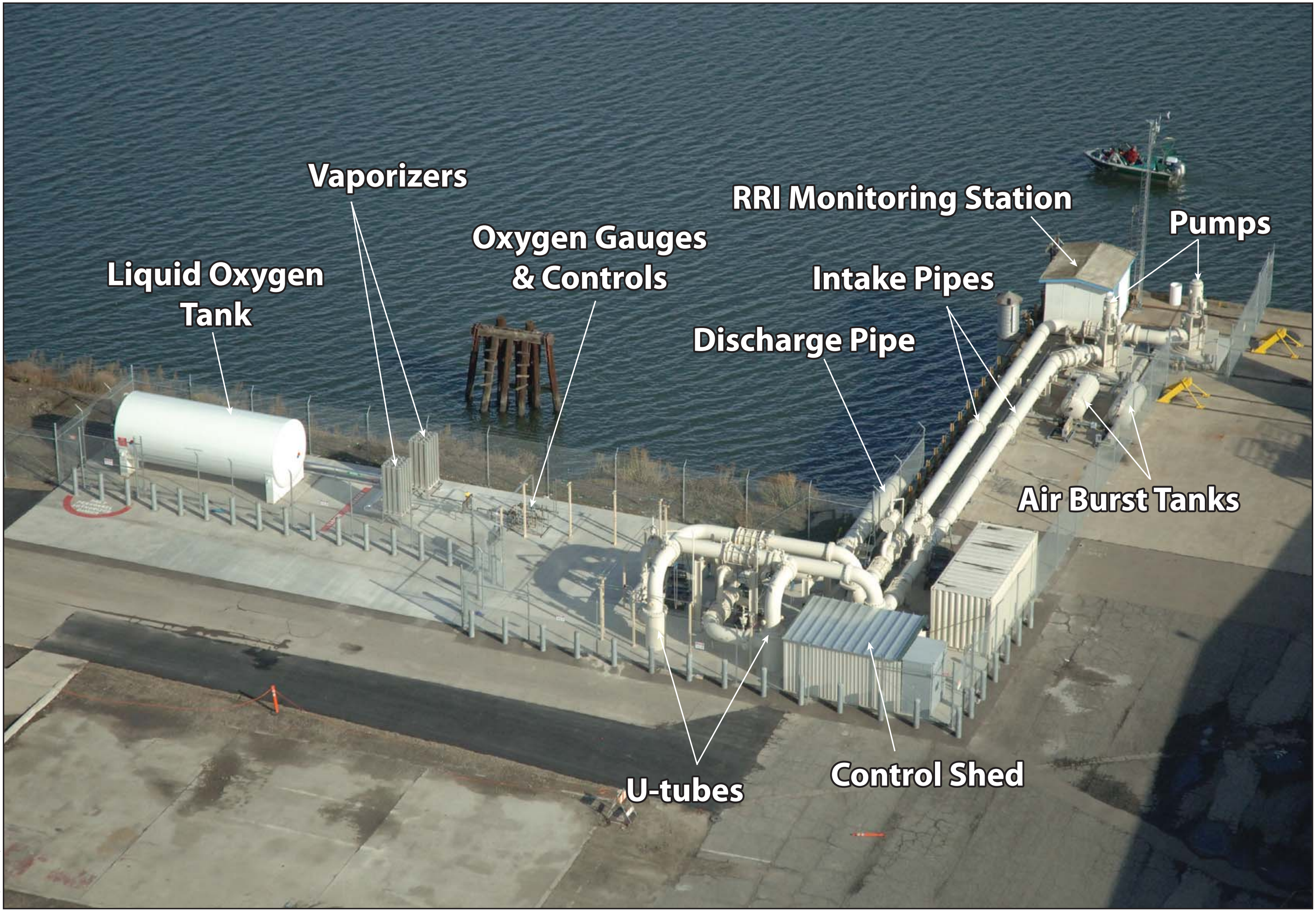
Photograph 2 shows the DWSC upstream of the Aeration Facility. The location of the diffuser and the upstream DO monitors at NA 43 and NA 48 are indicated. Photograph 3 shows the DWSC downstream of the Aeration Facility. The locations of the downstream DO monitors at NA 42 and NA 40 are indicated.

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

Monitoring of Aeration Facility and Deep Water Ship Channel Conditions

A monitoring plan for evaluating the performance of the Aeration Facility and the effects on DO conditions in the DWSC was developed as part of the feasibility report in 2004 (Jones & Stokes 2004). The monitoring strategy included the following components.

- Measurement parameters for U-tube device operations.
- Discrete sampling and continuous monitoring locations.
- Lateral and longitudinal boat surveys of the DWSC with multi-parameter monitoring probes.



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

Photograph 1
Aeration Facility

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

ICF INTERNATIONAL

Photograph 2
Upstream DWSC DO Monitoring Stations

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ICF INTERNATIONAL

Photograph 3
Downstream DWSC DO Monitoring Stations

- Methods for detecting incremental effects from operation of the U-tube oxygenation device.

Previous Deep Water Ship Channel Monitoring and Sampling

The historical records for temperature, DO, electrical conductivity (EC), and pH have been measured since 1986 at the DWR water quality monitoring station at the western end of RRI (Dock 20), the location of the Aeration Facility. Measurements of temperature, DO, pH, and EC are made every 15 minutes using a pump and flow-through monitoring devices. The separate monitoring devices were replaced with a multi-parameter YSI probe in about 2000. The pump intake is located at a depth of about 3 feet within a perforated 12-inch-diameter stilling well. The water depth is about 15–20 feet at the RRI monitoring location. The 15-minute tidal elevation has been measured by DWR at the RRI station. The tidal flows in the SJR about 2 miles upstream of the DWSC have been measured at the U.S. Geological Survey (USGS) Stockton (Garwood Bridge) station since 1995 (originally an ultrasonic velocity meter [UVM] device, now a side-looking acoustic [SL] device).

The City of Stockton is required as part of its National Pollutant Discharge Elimination System (NPDES) permit and associated WDRs and to collect mid-depth weekly grab sample data from several stations in the DWSC during the summer and early fall. Water quality monitoring stations used by the City for its NPDES permit were incorporated into the sampling plan during the first year following device implementation. Weekly grab samples are collected by the City from stations R2a, R3, R4, R5, and R6 for many water quality parameters. Station R2a is located on the SJR upstream of Channel Point (i.e., the confluence with the DWSC) at Burns Cutoff. R3 and R4 stations are upstream of the oxygen diffuser, and R5 and R6 are downstream (see Figure 1). The sampling is conducted weekly from May 1 through November 30.

DWR samples for minerals, nutrients, phytoplankton, zooplankton, and benthos upstream at Vernalis and in the DWSC at Buckley Cove (P-8), located about 1 mile downstream of the Calaveras River mouth and 1.25 miles downstream of the RRI water quality monitoring station. These two stations provide a long-term record of SJR water quality entering the tidal delta and in the DWSC. These monthly samples were required by State Water Board as part of the D-1485 (1978) and D-1641 (2000) compliance and baseline monitoring program.

DWR also collects surface and bottom temperature, DO, EC, turbidity, and fluorescence (chlorophyll *a*) measurements from the San Carlos water quality sampling boat during the June–November period, prior to and after the installation of the fall temporary barrier at the head of Old River. The monitoring is designed to determine the changes in DO caused by installing the head of Old River barrier, which increases the flow past Stockton. Samples are collected biweekly from 14 locations at low slack water from Prisoners Point (on Venice Island) upstream to the Turning Basin. The longitudinal gradient in temperature, DO, EC, turbidity, and fluorescence indicates the general mixing between SJR water and Sacramento River water that occurs at about Turner Cut. Some differences between surface and bottom measurements are observed in the DWSC upstream of Turner Cut. Changes in DO are difficult to interpret because flow, temperature, and algal biomass are all changing during this summer and fall period.

Deep Water Ship Channel Monitoring Approach

The monitoring approach to determine the effectiveness of the Aeration Facility was developed after reviewing the available information from previous DWSC measurements. The basic monitoring approach can be summarized as three primary tasks.

- The existing RRI water quality monitoring station, operated by DWR, will continue to be the main station for judging the effectiveness of the Aeration Facility. The station is equipped with a pump intake that is floating at a depth of 1 meter within a stilling-well pipe that is perforated along its depth (about 15 feet). The existing monitor measures maximum temperatures and DO in the late afternoon of many summer days, suggesting the influence of surface stratification on algae growth and DO. The daily minimum DO, which usually occurs in the early morning hours, will continue to be used to indicate the average daily DO in the DWSC.
- Four new stations with continuous (15-minute) DO monitoring will be installed along the DWSC. Two stations will be located upstream of the oxygen device diffuser (at NAs 48 and 43), and two will be located downstream (at NAs 42 and 40). These four stations will provide a record of the position and extent of the longitudinal DO sag within the DWSC. Existing navigation light pilings will be used for these monitoring stations. Measurements will be obtained from mid-depth (8–12 feet) to eliminate the higher DO measured during surface stratification in the afternoon.
- Longitudinal boat surveys in the DWSC for near-bottom (25 feet), mid-depth (15 feet), and surface (5 feet) measurements of temperature, DO, pH, EC, turbidity, and algae fluorescence will be obtained at the end of each “on” and “off” period within the operational testing cycle to provide a more complete record of the longitudinal gradients for high-tide and low-tide conditions.

To provide a baseline for comparison with the primary RRI monitoring station, monitoring of the DWSC DO concentrations at the four new stations began in 2007 prior to operation of the Aeration Facility. Because of the relatively large variations in the DO measured at the RRI station and the similar variations expected at the additional monitoring locations, it will be difficult to separate natural variations from the additional DO supplied by the oxygenation device. Therefore, the basic experimental design proposed to estimate the performance of the Aeration Facility in raising the minimum DO in the DWSC is to operate the device with an on-off cycle. The device is expected to raise the DO by about 1 mg/l within the tidal zone of the DWSC (2,500 acre-feet [af] tidal volume) after a day of operation. A 3-day operational period should raise the DO by about 3 mg/l, depending on the downstream flow that will transport the added DO. The natural reaeration also will cause the downstream increment of DO to be reduced slowly back toward the natural DO (reaeration balancing the rate of BOD decay). When the device is shut off, the DO profile in the DWSC will return to the natural conditions (without the Aeration Facility). The basic objective of this on-off operation is to produce a clearly identified “ramping signal” that can be separated from the natural DO fluctuations in the DWSC. The DWSC residence time (i.e., flow) and BOD concentration will control the days needed for the DO concentration profile to return to natural conditions.

Goals of the Demonstration Aeration Facility

The goals for the Aeration Facility were to test the physical operation of the facility (performance) and to evaluate its ability to increase the DO concentrations in the DWSC (effectiveness). The testing and evaluation results are presented as three major topics in this report.

- Performance of Aeration Facility for capacity and gas-transfer efficiency.
- Effectiveness of Aeration Facility for increasing DO in the DWSC.
- Operational costs and strategies for long-term TMDL implementation.

Several performance and effectiveness objectives were established for the Aeration Facility. The six Aeration Facility performance objectives can be summarized as listed below.

1. Determine the Aeration Facility water flow rates with one-pump and two-pump operations.
2. Determine the maximum gas flow rate for a range of operating pressures.
3. Determine the gas-transfer efficiency for a range of gas/water ratios with a variety of sparger (gas injection device) designs.
4. Determine the capacity of the Aeration Facility (pounds per day of dissolved oxygen delivered to the DWSC) with one-pump and two-pump operations for a range of gas/water ratios.
5. Determine the possible loss of DO concentrations in the discharge line when the outlet DO concentrations are greater than the oxygen saturation (about 40 mg/l).
6. Determine the most cost-effective operating regime for a range of required DO delivery rates (lb/day).

The six Aeration Facility effectiveness objectives can be summarized as listed below.

1. Determine how well the existing RRI DO monitoring station (at an approximate 3-foot depth) represents natural DO conditions in the DWSC from Turner Cut to Channel Point (natural DO conditions).
2. 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).
3. Determine how much DO could be added to the DWSC from the Aeration Facility under a variety of flows (i.e., 250 cfs–1,000 cfs) at maximum Aeration Facility capacity (DO increments).
4. Determine the distribution of added DO in the DWSC at high tide and low tide (tidal spreading).
5. Determine the effects of natural surface reaeration on the downstream DO profile and the DO increments from the Aeration Facility (reaeration rate).
6. 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).

Testing and Monitoring Methods

This section of the final report describes the methods that were used to test the performance of the Aeration Facility (gas-transfer efficiency and capacity) for both one-pump and two-pump operations with a range of gas/water ratios, and to evaluate the effectiveness of the Aeration Facility for adding DO into the DWSC for a range of flows and natural DO conditions.

Aeration Facility Testing Procedures

The goal of Aeration Facility testing was to measure the flows and the increase in DO concentration from the inlet to the outlet of the U-tubes under normal operation and to calculate the gas-transfer efficiency and the DO-delivery capacity. Various gas sparger designs were tested for a range of gas/water ratios. The basic steps for the field testing are summarized below.

- Operate one or two pumps to provide flow (25 cfs for one, 45 cfs for both) to the U-tube(s).
- Add oxygen gas at a selected gas/water flow ratio (volume) of between 1% and 6%.
- Measure the change in DO concentration between the U-tube inlet and outlet.
- Calculate the gas-transfer efficiency for the U-tube and the delivery capacity for the Aeration Facility.
- Determine whether DO in the discharge line between the U-tube outlet and the diffuser is increasing (additional gas dissolution) or decreasing (if the outlet DO is above saturation).

Water Flow, Dissolved Oxygen Concentration, and Gas Supply Measurements

The Aeration Facility was designed to have inlet and outlet DO sensors for each U-tube. However, the selected probes were not installed until 2009, so for the first year of testing two temporary YSI-6600 DO sondes (sensor probes) were installed in flow-through chambers by UOP to measure the outlet DO in each U-tube. The inlet DO was estimated either from the nearby DWR RRI monitoring station surface sensor or from the YSI probes in the U-tubes when the oxygen gas was shut off between tests. The YSI sensors were calibrated and placed in the flow-through cells and connected with hoses from the outlet ports on each U-tube.

Water samples were collected from the outlet ports by UOP for modified (for high DO concentrations) Winkler titrations to verify and adjust the DO sensor measurements. Several titrations were used to estimate the necessary adjustments in the YSI probe readings at relatively high outlet DO concentrations (above 20 mg/l).

The gas flow rates were determined by visual readings from the gas flow meters, and the water flow rates were determined by visual reading of the water flow meters. Because all of these measurements were variable, there was some uncertainty in the DO increment, the water flow, the gas supply, and the resulting estimates of gas-transfer efficiency and DO-delivery capacity. Measurements taken under similar conditions yielded gas-transfer efficiencies and capacities that were usually within 5% of previous measurements. Therefore, the general performance parameters for the Aeration Facility can be described accurately based on these measurements.

A PLC records data while the system is in operation. The date and time, water flows (cfs), inlet DO (mg/l), outlet DO (mg/l), and oxygen gas feed rates (scf/hr) are recorded on a compact flash card at a 15-minute interval. In addition to data being stored electronically, data were recorded manually on a hard copy whenever the facility was started or stopped or when a daily check was made during operations. These data were used to monitor operations, analyze system performance, and analyze operational costs. These daily data records included the following.

- Date and time.
- Pump start and stop times.
- Air burst cycle times of the fish screens.
- Water flows (cfs) and totalizer (million gallons).
- Water pressure (psi).
- Electricity usage readings (kilowatt-hour [kWh] and kilowatt [kW]).
- Oxygen system start and stop times (date and time).
- Inlet and outlet DO (mg/l).
- Oxygen gas flow rate (scf/hr) and totalizer (scf).
- Oxygen supply pressure (psi).
- Oxygen tank pressure and remaining product (psi and percent).
- Oxygen level (inches of water).
- Vaporizer in use (1 or 2).
- Ship activity in front of the diffuser.

Aeration Facility Test Conditions

A series of tests were conducted in 2008 with the objective of identifying ways to increase the gas-transfer efficiency of the U-tubes. The only variables within the investigators' control were water flow rates, gas flow rates, and gas injection method. As such experiments were conducted using combinations of those variables. The underlying hypothesis of many of the tests was that lower gas exit velocity would result in smaller, more numerous bubbles due to the shearing action of the water flow and that this increase in bubble surface area would result in greater oxygen transfer. Initial testing on March 13 and 18, 2008, used the original sparger in both U-tubes, with a range of gas supply rates, with the gas supply regulator set at 45 psi. The original sparger, constructed by BOC, consisted of a ¾-inch-inside-diameter stainless steel tube with ten ⅛-inch-diameter holes placed in two rows at 2-inch spaces across the pipe (with a 90° angle between the rows), that extended across the middle 8 inches of the 20-inch-diameter inner U-tube. Full water flow (45 cfs) with a 4% gas/water supply ratio is the full capacity design condition. Reduced gas supply rates of 3% and 2% also were tested. An increased gas supply ratio of 5% could not be achieved, because of limited gas delivery tubing capacity, with the gas supply pressure of 45 psi.

Testing on May 22 and May 28, 2008, was conducted at full water flow with two pumps to compare the gas-transfer efficiency for a variety of sparger designs. The maximum gas supply rate (at 45 psi) was about 3,600 scf/hr or about 1 standard cubic foot per second (scf/sec) of gas into each U-tube (with 22.5 cfs of water flow in each). This represents a gas/water flow ratio of 4.4%. The testing goal was to compare different numbers (area) and sizes of holes for the sparger. However, before testing could begin, the pump controls for U-tube A malfunctioned, and the pump was not operational. Testing was conducted with just U-tube B. The single pump provided a maximum water flow of 25 cfs because there was less head loss through the (shared) diffuser pipeline. The oxygen gas supply rate was adjusted to 4% and 3% for testing on May 22. Testing of the alternative sparger holes in U-tube B continued on May 28, 2008. A second sparger design increased the number of holes to 40, with ten ⅛-inch holes in four rows around the sparger pipe. This reduced the gas exit velocity from 1,000 feet per second (ft/sec) for the original sparger to about 300 ft/sec. The third sparger design used one hundred sixty 1/16-inch holes to retain the 300 ft/sec gas exit velocity but potentially allowed smaller bubbles to be formed with the smaller holes. A fourth sparger design used the open end of the ¾-inch-inside-diameter stainless steel pipe with a gas exit area that was similar to the area of the 40-hole sparger and 160-hole sparger.

A fifth sparger design was tested on July 7, 2008, using four 30-foot-long sections of the aeration hose similar to what is used at the Port of Stockton oxygen gas bubbler system at Dock 13. The outside diameter of the hose is 1 inch and the inside diameter is 0.5 inch. The bubbles form at "pores" on the surface of the hose, which has an estimated porosity of about 20%. The gas exit velocity was likely much less than with the drilled holes in the sparger pipe and was estimated to be only 0.2 ft/sec. The 30-foot sections of hose were hung down into the U-tube, in parallel, and attached to a manifold placed at the normal location of the sparger. Test results showed no significant increase in transfer efficiency. It is suspected that the increasing hydrostatic pressure in the U-tube may inhibit the flow of gas through the lower portion of the 30-foot sections of aeration hose effectively shortening the aeration hoses by some unknown amount.

Testing of alternative sparger designs resumed on July 30, 2008. The factor being evaluated was the gas supply pressure at the sparger. The high pressure of the gas supply line (45 psi) was thought to be limiting the formation of small bubbles. The pressure regulator was reduced to 35 psi. However, this reduced the gas delivery to a maximum of 2,400 scf/hr with the spargers and allowed a maximum gas/water ratio of about 3% with full water flow of 22.5 cfs. Testing with a reduced gas supply pressure was conducted again on September 22 and 25, 2008. Both gas supply lines were connected to a single sparger. This allowed a higher gas ratio to be delivered at a reduced pressure. Additional testing of the aeration hose and the open-ended pipe sparger was conducted at 1% to 6% gas/water ratios. Transfer efficiencies were compared at the original pressure of 45 psi and reduced pressures of between 25 and 35 psi.

Aeration Facility operations were limited in 2009 because all State Bond–funded projects were suspended. No testing of the Aeration Facility was conducted in 2009, although the Aeration Facility was operated for effectiveness monitoring in September and October 2009.

Aeration Facility testing was resumed on June 23, 2010. The main objectives were to measure the water pressures in the system with one pump and two pumps operating and determine the effects of increased gas pressure on gas delivery. Several water pressure gauges were installed, and both gas and water pressures were measured in a series of tests with different regulated gas pressures. Additional pressure readings were taken at the diffuser to determine the actual pressure drop through the Aeration Facility for one-pump and two-pump operations. The head loss measurements for the discharge pipeline for one-pump (25 cfs) and two-pump (45 cfs) operations were helpful in describing the basic hydraulic performance of the Aeration Facility.

The maximum gas delivery in 2008 and 2009 operations with a regulated pressure of 45 psi was about 4% gas. This corresponds to a gas flow of about 3,250 scf/hr to each U-tube, with a water flow of 22.5 cfs in each U-tube. It was found that by loosening the "check nut" on the pressure regulator thumb screw valve, a much higher regulated gas supply pressure could be obtained. Discussion with the gas flow meter vendor indicated that the flow gauge is properly adjusted at a wide range of operating pressures, so that the gas flow meter reading in standard cubic feet of gas per hour was accurate at any gas supply pressure between 20 psi and 100 psi. An 8% gas/water ratio could be supplied with the gas flow valve fully opened at a pressure of 85 psi.

The exit DO concentration with the same gas flow rate at two different gas pressures was compared to confirm that the flow meters provided accurate measurements for this range of pressures. Both U-tubes were operated with the gas flow set at 3,250 scf/hr, to give a 4% gas to water ratio with the measured water flow of 22.5 cfs. With a gas pressure of 45 psi, the exit DO for U-tube A was 43.5 mg/l and the exit DO for U-tube B was 40 mg/l. The gas pressure was increased to 85 psi and the flow valve was adjusted slightly to give the same gas flow of 3,250 scf/hr. The U-tube A exit DO remained at 43.5 mg/l, and the U-tube B exit DO was increased slightly to 41 mg/l. Because there are fluctuations in the gas flow rate and the valve is very sensitive, these exit DO measurements were assumed to be essentially the same at both gas pressures. It was concluded that the gas flow meters give accurate gas flow measurements at either pressure.

The main objective for the testing on July 6, 2010 was to determine the size distribution of the bubbles by obtaining underwater photographs (video) of the bubbles forming at the sparger. The test hypothesis was that larger-than-expected bubbles were forming at the sparger, or perhaps coalescing in the inner "down" tube, reducing the transfer surface area of the gas bubbles. The assumed size in the design modeling was 3–4 millimeters (about ⅛ inch). The transfer efficiency was expected to be about 80% but was measured at only 60%. Unfortunately, the standard pipe inspection camera that was available did not have enough light intensity and did not have nearly fast enough image capture (i.e., digital shutter speed) to render the bubbles. Only a vague image could be seen on the screen with the camera located about 2 feet above the sparger. The image showed a spreading "mist" of bubbles extending about 6–8 inches away from four ⅛-inch holes (two each direction) that were visible. It had also been hypothesized that an air pocket might be forming on the lip of the inner tube immediately below the sparger, but observers were unable to see any evidence of this using the camera.

The second testing objective on July 6, 2010, was to determine the effects of reduced water velocity on the gas transfer efficiency. Operating one pump and splitting the flow between the two U-tubes was used to test the effects of reduced velocity in the U-tubes. The split flow would double the travel time from 40 seconds (i.e., 400 feet at 10 ft/sec) to 80 seconds (i.e., 400 feet at 5 ft/sec) and was expected to increase the gas-transfer efficiency. Operating the Because the water flow meter is mounted on the supply line, the difference in the manometer readings (pressure drop) at orifice plates in the discharge lines was used to regulate the one pump "split flow" operation to equalize the water flow in each U-tube. The one pump split flow conditions in each tube were difficult to resolve, and the reduced velocity did not appear to improve the gas transfer efficiency.

The possible loss of DO in the discharge line to the diffuser was evaluated with Winkler titrations on July 8, 2010. Both pumps were operating with a combined flow of 45 cfs, so the travel time in the 30-inch-diameter discharge line was about 2 minutes (1,200 feet at 10 ft/sec). With just one pump the travel time would be twice as long. Measurements were made at 2%, 3%, 4%, and 6% gas/water ratios.

The Aeration Facility testing was continued on July 20, 2010. An open-ended pipe (with no sparger) was tested to see if reduced gas velocity would allow smaller bubbles and increased gas-transfer efficiency. The initial results looked promising because the exit DO concentrations were higher than previously measured with the Oxyguard DO probes. Unfortunately, it was discovered later in the week (July 26) that the Oxyguard probes were reading very high during this testing. A calibration curve was developed, and the DO measurements with the open pipe were adjusted to yield very similar transfer efficiency values as previously measured with all the different spargers. The Oxyguard DO probes were cleaned, and the membranes were replaced. The Oxyguard DO measurements then were found to match the Winkler titration DO values. This suggests that the open pipe (no sparger) conditions of low gas velocity did not increase the DO transfer efficiency.

The second objective for the July 20, 2010, testing was to increase the water velocity past the sparger. Both pumps were turned on and the connection valve between U-tube A and U-tube B was opened. The inlet valve to U-tube A then was closed to force all of the water into U-tube B. The additional back pressure of about 17 feet of head (20 psi at the sparger rather than 12.5 psi with normal two-pump operation) reduced the combined flow through U-tube B to about 36 cfs rather than 22.5 cfs for normal two-pump operation. The water velocity at the sparger was increased from 7.5 ft/sec to about 12 ft/sec (60% higher), and the travel time in the U-tube was reduced from 40 seconds to about 25 seconds.

Another possible improvement in the oxygen gas-transfer efficiency was tested on August 8, 2010. A gas heating apparatus that has proved helpful for increasing the dissolving of carbon dioxide gas at soda bottling plants was tested at the Aeration Facility. The increased temperature potentially would increase the gas-transfer velocity and thereby increase the rate of gas transfer from the gas bubbles into the water in the U-tube. The gas heater consists of a trailer-mounted boiler and heat exchanger tubes that pass through a bath of heated water. Oxygen was taken from the end of the stainless steel delivery pipe, run through the heater, and returned to the U-tube sparger. The device was turned on and allowed to heat for several hours prior to running the test. The oxygen gas temperature was increased from 95°F (without heating) to about 120°F (with heating). Because this heating would require additional energy, a relatively large increase in the gas-transfer efficiency would be necessary for this approach to be considered for the long-term operations of the Aeration Facility. The results of these various facility testing procedures will be described and evaluated in the next section of the report.

Tidal Flow and Dissolved Oxygen Concentration Monitoring in the Deep Water Ship Channel

Tidal elevation, tidal flow, and tidal velocities in the DWSC were measured at the RRI station and upstream at the Garwood Bridge. The net flow moving through the DWSC was estimated from a comparison with the upstream river flow at Vernalis, as well as the tidal-day averages of the 15-minute tidal flows at RRI and Garwood. DO monitoring was continued at the RRI station, and mid-depth DO measurements were made at the four new monitoring stations. UOP conducted boat survey longitudinal profile monitoring of DO and other water quality parameters at either high-tide or low-tide conditions, and the City of Stockton conducted weekly sampling for DO and other water quality parameters. Finally, DWR conducted *San Carlos* boat surveys for DO and other water quality parameters in the DWSC during the summer and fall. Each of these DWSC tidal flow and DO monitoring methods is summarized below.

Tidal Elevation and Tidal Flow Monitoring

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.

In 1996 the first tidal flow measurements station was established on the SJR at Garwood by the USGS with cooperation from the City of Stockton. The river channel is about 200 feet wide, the cross section is about 3,000 square feet, 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). The Garwood monitoring station is located on the SJR near Garwood Bridge (State Route [SR] 4), approximately 1.7 miles upstream (Mile 41.6) of the DWSC. The Garwood tidal flow measurement station is maintained and operated by USGS and data are reported thorough California Data Exchange Center (CDEC) on a 15-minute basis. The Garwood tidal flow data can be used for estimating tidal movement and DO mixing processes in the DWSC. In addition to tidal flow data (elevations, velocity, flow), temperature, turbidity, EC, and fluorescence data are now collected at the Garwood monitoring station. 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 the measured Garwood net tidal 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 feet into the channel. Based on these index velocity measurements, average estimates for tidal flow velocities for the entire 16,000-square-foot 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 to the Garwood station (i.e., high velocities with small cross section). These tidal flow records at Lathrop generally confirm the Garwood station data.

Dissolved Oxygen Concentration Monitoring

As part of the monitoring network for the study and in addition to the existing RRI monitoring station, DWR installed four water quality monitoring stations at NAs 40, 42, 43, and 48 along the DWSC in December 2006 (Figure 1). The equipment was mounted on existing United States Coast Guard Light posts. Each mount included metal brackets, a PVC stilling well (a pipe section open at the top and bottom), safety cable, and a tidal flotation device that maintained sampling at a constant depth. The units included a battery-operated YSI unit (sonde) complete with DO, temperature, oxidation reduction potential (ORP) (from December 2006 through July 2008), depth, EC, and pH probes. The most upstream monitoring point is at NA 48, which is about 1.5 miles upstream of the diffuser. NA 43 is located about 0.2 mile upstream of the diffuser, NA 42 is located about 0.7 mile downstream, and NA 40 is located about 1.6 miles downstream. Figure 1 shows the diffuser location and the four monitoring locations along the DWSC as well as the existing RRI station.

Water quality data from the four remote NA stations were recorded on a 15-minute basis at a depth of 10–12 feet. Two of the four YSI 600 XLM sondes were upgraded to YSI model 6600 V2 sondes in July 2007 (remote stations NA 42 and NA 43). Routine sonde calibration was conducted weekly or biweekly, given the constraints of weather and logistical factors, from December 2006 through the end of the study. All probes and meters used for water quality measurements were calibrated in the laboratory according to manufacturers' specifications. In addition to the remote monitoring station data, handheld monitoring checks were conducted by using a Hach LDO meter during deployment of the freshly calibrated sondes at each monitoring station. Handheld monitoring checks were used for quality assurance purposes and to observe possible differences between sonde readings and handheld Hach LDO meter readings. A field data recording form/checklist was developed and was completed during each monitoring event. The purpose of the form was to guide field staff in performing all the monitoring procedures in a systematic and consistent manner during each monitoring event.

Collected water quality monitoring data were analyzed and processed for quality assurance and quality control (QA/QC) by using Modified Z-Score test to screen data for outliers. The Modified Z-Score test employs the median and the median of the median absolute deviation (MAD) to detect outliers. The collected data for all monitoring stations were used for assessing natural conditions and the performance of Aeration Facility under different operational conditions.

Rough and Ready Island Dissolved Oxygen Monitoring Station

The RRI monitoring station is the only monitoring station in the DWSC with more than 10 years of historical DO records reported through the CDEC. The RRI monitoring station is located about 0.2 mile downstream of the Aeration Facility diffuser and is maintained and operated by DWR's Division of Environmental Services (DES).

RRI monitoring station data are recorded on a 15-minute basis at a depth of approximately 3 feet. In addition to DO data, temperature, flow, velocity, stage, turbidity, EC, and pH data also are collected at the RRI monitoring station. DWR also added water quality monitoring at mid-depth (10 feet deep at low tide) and near the bottom (20 feet deep at low tide) at the RRI station to evaluate the effects of stratification in the DWSC for the Aeration Facility study. The mid-depth and near-bottom data were obtained from DES, as the data are not reported through the CDEC. RRI station data were also screened for outliers using a Modified Z-Score test.

The RRI data were used for assessing natural conditions and the performance of the Aeration Facility under different operational conditions. In addition, the RRI data were used in monthly data reports summarizing DO conditions beginning in January 2007.

California Department of Water Resources Boat Surveys of Deep Water Ship Channel Dissolved Oxygen (*San Carlos*)

DWR's DES 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*, and 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 (SJR Mile 41.5). Surface and bottom measurements are collected for DO, temperature, and salinity (EC) from 14 stations (Figure 1).

The DWR boat survey measurements from 2004 to 2008 were described and evaluated in Appendix A of the 2008 Operations Report (ICF International 2010), together with other general information about the effects of flow and BOD on the measured longitudinal DO concentration profiles in the DWSC. These 5 years of DWSC DO data provided a wide range of conditions from before and after 2007, the year that the City of Stockton added nitrification to the RWCF's tertiary treatment process, thus reducing the effluent ammonia concentrations of its discharge. This substantially reduced the total BOD concentrations entering the DWSC and increased the observed DO concentrations in the DWSC.

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 of ICF International 2010). The Aeration Facility performance can be evaluated from these comparative DWSC DO concentration profiles.

University of the Pacific Boat Survey Dissolved Oxygen Profiles

The distribution of added DO from the Aeration Facility in the DWSC is an important aspect of the performance of the Aeration Facility in identifying and tracking 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 were used to develop comparative DO profiles that generally identified the magnitude and extent of the DO added from Aeration Facility.

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-foot depth), a second sensor was suspended at mid-depth (15-

foot depth), and the third sensor was near the bottom (25-foot depth). During a testing period, the DO concentrations were measured between Turner Cut at Mile 32.5 and upstream of the DO monitoring station at NA 48 in the river channel at 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 NA 48. The movement of the DO profile position for this section of the DWSC is about 2 miles between high and low tide.

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. On August 26 the Aeration Facility had been turned off for 10 days; on September 5 the Aeration Facility had been operating for 10 days. The third measurement sequence was from September 15 through September 26. On September 15 the Aeration Facility had been turned off for 10 days; on September 26 it had been operating for 10 days. 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.

Stockton Regional Wastewater Control Facility Discharge and River Monitoring

Evaluation of the City of Stockton water quality data 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 CVRWQCB. Station R1 is upstream at Brant Bridge, station R2 is at the Garwood Bridge, and station R2a is at Burns Cut (Navy Bridge). Station R3 is located at NA 48, R4 is located at NA 45, R5 is located downstream of RRI at NA 42, R6 is located at NA 36, R7 is located near Turner Cut at NA 24, and R8 is located at NA 18 (Figure 1). DO concentrations at R7 and R8 are usually high because they are strongly influenced by Sacramento River water. Data from these river sampling stations from 2004 and 2008 was compared to demonstrate the reduction in the DWSC BOD as the result of the City of Stockton nitrification facility completed in 2007.

Evaluation of Testing and Monitoring Results

This section of the report describes the results of the testing of the Aeration Facility performance (efficiency and capacity) and of the monitoring and field surveys in the DWSC that were conducted to determine the effectiveness of the Aeration Facility to increase the minimum DO concentrations in the DWSC. A brief summary of the methods used to analyze the testing and monitoring data will provide a "road map" for understanding and comparing these methods and for considering the overall evaluation of the Aeration Facility performance and effectiveness. Some recommendations for long-term operations of the Aeration Facility as part of the TMDL implementation plan will be presented in the next section, based largely on these testing and monitoring results.

Most of the data analysis methods were developed and described in two appendices in the *California Department of Water Resources Demonstration Dissolved Oxygen Aeration Facility 2008 Operations Performance Report* (2008 Operations Report) (ICF International 2010). Appendix A of the 2008 operational testing report described the longitudinal surveys of DO profiles in the DWSC and the DO-BOD model used to interpret these DWR measurements for 2004 and 2008. Appendix B of the 2008 operational testing report described the 15-minute monitoring results during periods of Aeration Facility testing and the monthly model used to estimate DO increments at the five continuous DO monitoring stations during periods of Aeration Facility operations. Boat surveys conducted between Turner Cut and Channel Point at high tide or low tide confirmed the movement of the distribution of the incremental DO from the Aeration Facility caused by tidal water movement in the DWSC. This final report includes the 2008 monitoring and testing results as well as the 2009 and 2010 testing and monitoring results.

Aeration Facility Efficiency and Capacity

Data Analysis Methods

To estimate the gas-transfer efficiency of the Aeration Facility and the ability of the facility to add DO to the DWSC, the supply of oxygen gas is compared against the difference in DO levels between the U-tube inlet and outlet. The gas supply for each U-tube is measured as scf/hr. The supply of oxygen gas for a specified gas/water flow ratio can be calculated as:

Oxygen gas supply (scf/hr) = 36 x gas/water volume ratio (%) x water flow (cfs) [equation 1]

Where 36 is 3600 sec/day divided by 100 %. Because each standard cubic foot of oxygen weighs 0.0831 pound (atmospheric pressure at 70°F), the oxygen gas supply per day can be (conveniently) calculated as:

Oxygen gas supply (lb oxygen/day) = 0.0831 lb/scf x gas flow (scf/hr) x 24 hours/day

= 2 x gas flow (scf/hr) [equation 2]

The Aeration Facility delivered DO oxygen capacity (lb/day) can be calculated by determining the added DO increment achieved with a certain gas supply rate and a measured water flow rate. The delivered capacity equation is:

Oxygen capacity (lb/day) = 28.317 l/cf x (lb /4.536 x 10^5 mg) x 86,400 sec/day x DO increment (mg/l) x water flow (cfs)

= 5.4 x DO increment (mg/l) x water flow (cfs) [equation 3]

Where added DO increment = [measured U-tube outlet DO concentration – measured RRI mid-depth DO concentration]. The Aeration Facility efficiency as a percent will be calculated as the delivered capacity divided by the daily supply:

Efficiency (%) = 5.4 x DO increment (mg/l) x flow (cfs)/[2 x gas flow (scf/hr)] x 100 [equation 4]

Where 5.4 is a conversion factor (see equation 3). The general capacity of the Aeration Facility can be estimated from these equations. For the measured two-pump flow of 45 cfs with a 5% gas/water ratio, the gas supply rate would be about 8,100 scf/hr (4,050 scf/hr for each U-tube). The daily gas supply would be 16,200 lb/day, and with an assumed efficiency of 50% the capacity to add DO to the DWSC would be 8,100 lb/day. A higher efficiency would allow a greater Aeration Facility capacity. Higher efficiencies are expected with lower gas/water ratios, but this would reduce the capacity to add DO to the DWSC.

Evaluation of Efficiency Results

Results of the Aeration Facility testing have been presented in three previous reports. The initial testing in spring 2008 measured the basic performance parameters (ICF Jones & Stokes 2008a). Additional testing of several different sparger designs was performed in the summer of 2008 (ICF Jones & Stokes 2008b). The 2008 operations report also described the Aeration Facility performance (ICF International 2010). The results of testing in 2010 therefore will be emphasized in this section.

Field testing of the Aeration Facility in 2008–2010 showed that the best measured oxygen delivery capacity at full water flow of 45 cfs (with both pumps) and with a 4% gas/water ratio was about 8,000 lb/day. This was somewhat less than the design capacity of 10,000 lb/day. The full water flow was about 20% less than the design flow of 50 cfs. This maximum flow rate cannot be increased because it is a function of the selected pumps and the hydraulic head loss through the Aeration Facility pipes, valves, and the diffuser. The measured DO concentration increase in the U-tubes was about 32–34 mg/l for a 4% gas/water ratio. The measured oxygen transfer efficiency of the facility U-tubes was about 60%. The target design efficiency for oxygen gas transfer (i.e., dissolution) in the U-tubes was about 80%, although this was understood to be controlled by the gas bubble size and specific hydraulic conditions within the U-tubes.

Table 3 gives a summary of the more than 20 test conditions that were evaluated during the demonstration testing program in 2008–2010. The main results from these tests showed that the gas-transfer efficiency was highest at a gas/water ratio of 1% and was reduced as the gas/water ratio was increased. The measured efficiency for 1% gas/water ratio was about 90%, but the capacity would be only about 2,850 lb/day. The efficiency for 2% gas/water ratio would be about 75%, and the capacity would be 4,750 lb/day. The efficiency for a 3% gas/water ratio would be about 65%, and the capacity would be about 6,150 lb/day. The efficiency for a 4% gas/water ratio would be about 58%, and the capacity would be about 7,350 lb/day. The efficiency for a 5% gas/water ratio would be about 53%, and the capacity would be about 8,375 lb/day. The efficiency for a 6% gas/water ratio would be about 50%, and the capacity would be 9,475 lb/day.

The most likely cause for the efficiency increase with lower gas supply rates was a smaller average gas bubble size (with less coalescing of bubbles) in the U-tubes.

Although the efficiency is improved with lower gas supply, the capacity to increase the DO concentration in the DWSC is increased with a higher gas supply rate (higher gas/water ratio). Therefore, the Aeration Facility should be operated at whatever gas/water ratio is necessary to add the required amount of oxygen to the DWSC. The cost to operate the Aeration Facility will be described at the end of this section of the report.

Table 3 indicates that the results from all of the sparger designs were similar. For all of the spargers tested (including open pipe and aeration hose), the gas-transfer efficiency decreased as the gas supply rate increased. The various spargers with different size holes were compared to aeration hose that was attached to the sparger (in four 30-foot sections). The test results were not much different from the drilled-hole spargers. The gas exit velocity is not likely a strong factor in bubble size formation. The aeration hose efficiency with a 3% gas/water ratio was 65%. The efficiency dropped with higher gas/water ratios of 4%, 5%, and 6%, to 60%, 56%, and 52%, respectively. The most likely explanation for the reduced efficiency with higher gas/water supply ratio is that bubble coalescence increases with a higher ratio, forming larger bubbles in the U-tube with the higher gas supply rate. Water travel time and pressure in the U-tube would be identical for these various gas supply ratios.

The gas/water flow ratio was found to be the most important parameter. This was not anticipated, because the gas velocity and other hydraulic parameters were expected to change the average gas bubble size and the corresponding gas-transfer efficiency in the U-tubes. Several tests were made to reduce the water flow in the U-tubes to reduce the velocity and increase the travel time in the U-tubes. However, this did not appear to change the basic relationship between the gas/water ratio and the gas-transfer efficiency. The gas supply pressure was increased in 2010 to allow higher gas/water ratios of 5% and 6%. It was confirmed that the gas pressure did not change the gas supply meter (scf/hr) readings. The higher pressure was needed for the reduced U-tube flow tests because the flow was reduced by closing the U-tube outlet valve, which increased the water pressure at the sparger.

Testing on May 28, 2008, was conducted with a variety of spargers. The 40-hole sparger efficiency at a 4% gas supply ratio was only about 43%. This is much lower than for the original 10-hole sparger. The 160-hole sparger at 4% gas flow had an efficiency of about 48%. The efficiency of both spargers decreased by about 5% at the higher gas supply rates of about 6% of the water flow.

Table 3. Summary of Aeration Facility Test Conditions for Evaluation of Gas Transfer Efficiency and Capacity (pounds of DO added to DWSC)

Date	Sparger Type	U-Tube	Water Flow (cfs)	Gas Flow (scf/hr)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O_2/day)	Gas Supply (lb-O_2/day)	Efficiency (%)
	Two-Pump Operation										
3/13/2008	10-hole	A	22.5	3,230	4.0%	9.0	41.0	32.0	3,888	6,460	60%
3/13/2008	10-hole	A	22.5	2,450	3.0%	9.0	35.0	26.0	3,159	4,900	64%
3/13/2008	10-hole	A	22.5	1,620	2.0%	9.0	27.5	18.5	2,248	3,240	69%
3/13/2008	10-hole	A	22.5	3,400	4.2%	9.0	41.0	32.0	3,888	6,800	57%
3/13/2008	10-hole	B	22.5	3,270	4.0%	9.0	43.0	34.0	4,131	6,540	63%
3/13/2008	10-hole	B	22.5	2,440	3.0%	9.0	35.0	26.0	3,159	4,880	65%
3/13/2008	10-hole	B	22.5	1,540	1.9%	9.0	27.0	18.0	2,187	3,080	71%
3/13/2008	10-hole	B	22.5	3,400	4.2%	9.0	43.0	34.0	4,131	6,800	61%
3/18/2008	10-hole	A	22.5	3,400	4.2%	9.1	45.5	36.4	4,423	6,800	65%
7/30/2008	10-hole	B	22.5	2,315	2.9%	8.7	36.8	28.1	3,414	4,630	74%
6/22/2010	10-hole	B	22.5	3,300	4.1%	8.0	39.5	31.5	3,827	6,600	58%
6/22/2010	10-hole	B	22.5	4,000	4.9%	8.0	44.0	36.0	4,374	8,000	55%
6/22/2010	10-hole	B	22.5	5,400	6.7%	8.0	53.0	45.0	5,468	10,800	51%
6/22/2010	10-hole	B	22.5	6,300	7.8%	8.0	58.0	50.0	6,075	12,600	48%
6/22/2010	10-hole	B	22.5	5,280	6.5%	8.0	50.0	42.0	5,103	10,560	48%
6/22/2010	10-hole	B	22.5	5,400	6.7%	8.0	52.6	44.6	5,419	10,800	50%
6/22/2010	10-hole	B	22.5	7,250	9.0%	8.0	62.0	54.0	6,561	14,500	45%
6/22/2010	10-hole	B	22.5	4,050	5.0%	8.0	47.0	39.0	4,739	8,100	59%
7/6/2010	10-hole	A	22.5	4,000	4.9%	6.0	40.2	34.2	4,155	8,000	52%
7/6/2010	10-hole	B	22.5	4,230	5.2%	5.0	35.3	30.3	3,681	8,460	44%
7/20/2010	10-hole	A	22.5	1,650	2.0%	6.3	29.4	23.1	2,806	3,300	85%
7/20/2010	10-hole	A	22.5	2,480	3.1%	6.3	36.9	30.6	3,712	4,960	75%
7/20/2010	10-hole	A	22.5	3,310	4.1%	6.3	38.5	32.2	3,911	6,620	59%
7/20/2010	10-hole	A	22.5	4,140	5.1%	6.3	44.2	37.9	4,600	8,280	56%

Table 3. Continued

Date	Sparger Type	U-Tube	Water Flow (cfs)	Gas Flow (scf/hr)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O_2/day)	Gas Supply (lb-O_2/day)	Efficiency (%)
7/20/2010	10-hole	A	22.5	3,300	4.1%	6.3	39.8	33.5	4,065	6,600	62%
7/20/2010	10-hole	B	22.5	2,480	3.1%	7.3	29.9	22.6	2,752	4,960	55%
7/20/2010	10-hole	B	22.5	3,310	4.1%	7.3	37.3	30.0	3,642	6,620	55%
7/20/2010	10-hole	B	22.5	4,190	5.2%	7.3	41.8	34.5	4,195	8,380	50%
7/20/2010	10-hole	B	22.5	3,200	4.0%	7.3	38.6	31.3	3,804	6,400	59%
7/7/2008	Hose	B	22.5	2,480	3.1%	6.0	32.1	26.1	3,171	4,960	64%
7/7/2008	Hose	B	22.5	3,300	4.1%	6.0	38.5	32.5	3,949	6,600	60%
7/7/2008	Hose	B	22.5	5,470	6.8%	6.0	50.3	44.3	5,382	10,940	49%
7/7/2008	Hose	B	22.5	3,770	4.7%	6.0	41.0	35.0	4,253	7,540	56%
7/7/2008	Hose	B	22.5	4,970	6.1%	6.0	47.9	41.9	5,091	9,940	51%
7/7/2008	Hose	B	22.5	4,140	5.1%	6.0	43.1	37.1	4,508	8,280	54%
7/30/2008	Hose	B	22.5	2,500	3.1%	8.4	37.0	28.6	3,475	5,000	69%
7/30/2008	Hose	B	22.5	500	0.6%	8.2	16.0	7.8	948	1,000	95%
9/22/2008	Hose	A	22.5	3,340	4.1%	7.9	45.5	37.6	4,568	6,680	68%
9/22/2008	Hose	A	22.5	2,480	3.1%	7.9	37.2	29.3	3,560	4,960	72%
9/22/2008	Hose	A	22.5	1,650	2.0%	7.9	30.2	22.3	2,709	3,300	82%
9/22/2008	Hose	A	22.5	900	1.1%	7.7	21.8	14.1	1,713	1,800	95%
7/30/2008	Open Pipe	A	22.5	2,500	3.1%	8.4	36.0	27.6	3,353	5,000	67%
9/22/2008	Open Pipe	A	22.5	3,340	4.1%	7.9	45.7	37.8	4,593	6,680	69%
9/22/2008	Open Pipe	A	22.5	2,480	3.1%	7.9	38.0	30.1	3,657	4,960	74%
9/22/2008	Open Pipe	A	22.5	3,340	4.1%	7.9	44.6	36.7	4,459	6,680	67%
9/22/2008	Open Pipe	A	22.5	3,340	4.1%	7.7	43.4	35.7	4,338	6,680	65%
9/22/2008	Open Pipe	A	22.5	2,480	3.1%	7.7	37.0	29.3	3,560	4,960	72%
9/25/2008	Open Pipe	A	22.5	1,656	2.0%	9.4	31.6	22.2	2,700	3,312	82%
9/25/2008	Open Pipe	A	22.5	828	1.0%	9.4	22.7	13.3	1,618	1,656	98%
9/25/2008	Open Pipe	A	22.5	3,312	4.1%	9.3	45.1	35.8	4,344	6,624	66%

Table 3. Continued

Date	Sparger Type	U-Tube	Water Flow (cfs)	Gas Flow (scf/hr)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O_2/day)	Gas Supply (lb-O_2/day)	Efficiency (%)
9/25/2008	Open Pipe	A	22.5	2,484	3.1%	9.3	37.8	28.5	3,465	4,968	70%
9/25/2008	Open Pipe	A	22.5	1,656	2.0%	9.2	31.6	22.4	2,724	3,312	82%
9/25/2008	Open Pipe	A	22.5	900	1.1%	9.1	23.2	14.1	1,713	1,800	95%
7/20/2010	Open Pipe	B	22.5	1,645	2.0%	6.3	24.8	18.5	2,244	3,290	68%
7/20/2010	Open Pipe	B	22.5	2,480	3.1%	6.3	30.5	24.2	2,942	4,960	59%
7/20/2010	Open Pipe	B	22.5	3,310	4.1%	6.3	36.6	30.3	3,680	6,620	56%
7/20/2010	Open Pipe	B	22.5	4,140	5.1%	6.3	40.9	34.6	4,202	8,280	51%
7/20/2010	Open Pipe	B	22.5	4,970	6.1%	6.3	45.3	39.0	4,739	9,940	48%
	Single Pump Operation										
5/22/2008	10-hole	B	25.0	3,580	4.0%	7.0	37.0	30.0	4,050	7,160	57%
5/22/2008	10-hole	B	25.0	2,440	2.7%	7.0	32.5	25.5	3,443	4,880	71%
5/28/2008	10-hole	B	25.0	3,730	4.1%	7.0	35.0	28.0	3,780	7,460	51%
5/28/2008	40-hole	B	25.0	5,660	6.3%	7.0	40.0	33.0	4,455	11,320	39%
5/28/2008	40-hole	B	25.0	3,600	4.0%	7.0	30.0	23.0	3,105	7,200	43%
5/28/2008	160-hole	B	25.0	3,750	4.2%	7.0	33.0	26.0	3,510	7,500	47%
5/28/2008	160-hole	B	25.0	5,400	6.0%	7.0	33.0	26.0	3,510	10,800	33%
7/27/2010	Open Pipe	B	25.0	2,405	2.7%	5.8	32	26.2	3,537	4,810	74%
7/28/2010	Open Pipe	B	25.0	2,380	2.6%	6.1	31.6	25.5	3,443	4,760	72%
7/29/2010	Open Pipe	B	25.0	2,330	2.6%	6.3	31.4	25.1	3,389	4,660	73%
7/30/2010	Open Pipe	B	25.0	2,330	2.6%	6.3	31.2	24.9	3,362	4,660	72%
8/9/2010	Open Pipe	B	25.0	2,500	2.8%	6.1	30.2	24.1	3,254	5,000	65%
8/10/2010	Open Pipe	B	25.0	2,490	2.8%	6.2	29.2	23.0	3,105	4,980	62%
8/11/2010	Open Pipe	B	25.0	2,490	2.8%	6.6	30.5	23.9	3,227	4,980	65%
8/12/2010	Open Pipe	B	25.0	2,500	2.8%	6.1	29.6	23.5	3,173	5,000	63%
8/16/2010	Open Pipe	B	25.0	2,450	2.7%	6.4	31.1	24.7	3,335	4,900	68%

Table 3. Continued

Date	Sparger Type	U-Tube	Water Flow (cfs)	Gas Flow (scf/hr)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O_2/day)	Gas Supply (lb-O_2/day)	Efficiency (%)
8/17/2010	Open Pipe	B	25.0	2,490	2.8%	6.3	31.5	25.2	3,402	4,980	68%
8/18/2010	Open Pipe	B	25.0	2,500	2.8%	6.2	31.5	25.3	3,416	5,000	68%
9/7/2010	Open Pipe	B	25.0	4,150	4.6%	5.5	44.1	38.6	5,211	8,300	63%
9/8/2010	Open Pipe	B	25.0	4,165	4.6%	6.5	44.1	37.6	5,076	8,330	61%
9/9/2010	Open Pipe	B	25.0	4,140	4.6%	7.6	45.1	37.5	5,063	8,280	61%
9/10/2010	Open Pipe	B	25.0	4,090	4.5%	6.8	44.2	37.4	5,049	8,180	62%
9/13/2010	Open Pipe	B	25.0	4,030	4.5%	6.9	40.4	33.5	4,523	8,060	56%
9/14/2010	Open Pipe	B	25.0	4,040	4.5%	6.8	44.4	37.6	5,076	8,080	63%
	Two Pumps to One U-tube										
7/20/2010	Open Pipe	B	36.0	2,550	2.0%	6.3	27.6	21.3	4,143	5,100	81%
7/20/2010	Open Pipe	B	36.0	4,000	3.1%	6.3	33.1	26.8	5,211	8,000	65%
7/20/2010	Open Pipe	B	36.0	5,320	4.1%	6.3	38.2	31.9	6,194	10,640	58%
7/20/2010	Open Pipe	B	36.0	6,680	5.2%	6.3	43.2	36.9	7,177	13,360	54%
7/20/2010	10-hole	B	36.0	2,650	2.0%	7.2	28.0	20.8	4,041	5,300	76%
7/20/2010	10-hole	B	36.0	4,000	3.1%	7.2	33.3	26.1	5,073	8,000	63%
7/20/2010	10-hole	B	36.0	5,300	4.1%	7.2	38.7	31.5	6,118	10,600	58%
7/20/2010	10-hole	B	36.0	6,700	5.2%	7.2	43.3	36.1	7,027	13,400	52%
	Reduced Flow with Outlet Valve										
3/13/2008	10-hole	A	18.0	3,740	5.8%	9.0	51.0	42.0	4,082	7,480	55%
3/13/2008	10-hole	B	17.3	3,770	6.1%	9.0	51.0	42.0	3,924	7,540	52%
3/13/2008	10-hole	A	11.8	2,210	5.2%	9.0	29.0	20.0	1,274	4,420	29%
3/13/2008	10-hole	B	11.4	2,560	6.2%	9.0	37.0	28.0	1,724	5,120	34%
7/30/2008	10-hole	B	16.5	2,300	3.9%	8.7	43.0	34.3	3,056	4,600	66%
7/30/2008	Hose	B	17.5	2,450	3.9%	8.0	41.0	33.0	3,119	4,900	64%

Table 3. Continued

Date	Sparger Type	U-Tube	Water Flow (cfs)	Gas Flow (scf/hr)	Gas Ratio (%)	Inlet DO (mg/l)	Outlet DO (mg/l)	DO Increment (mg/l)	DO Delivery (lb-O_2/day)	Gas Supply (lb-O_2/day)	Efficiency (%)
7/30/2008	Open Pipe	A	17.5	2,450	3.9%	8.0	41.0	33.0	3,119	4,900	64%
7/6/2010	10-hole	A	20.0	3,600	5.0%	6.0	39.1	33.1	3,575	7,200	50%
7/6/2010	10-hole	A	16.0	2,880	5.0%	6.0	30.0	24.0	2,074	5,760	36%
7/6/2010	10-hole	A	12.0	2,160	5.0%	6.0	29.2	23.2	1,503	4,320	35%
7/6/2010	10-hole	A	12.0	1,730	4.0%	6.0	23.4	17.4	1,128	3,460	33%
7/6/2010	10-hole	A	12.0	1,280	3.0%	6.0	20.5	14.5	940	2,560	37%
7/6/2010	10-hole	A	12.0	865	2.0%	6.0	16.1	10.1	654	1,730	38%
7/6/2010	10-hole	B	20.0	3,600	5.0%	5.0	32.0	27.0	2,916	7,200	41%
7/6/2010	10-hole	B	16.0	2,880	5.0%	5.0	26.0	21.0	1,814	5,760	32%
7/6/2010	10-hole	B	12.0	2,160	5.0%	5.0	21.0	16.0	1,037	4,320	24%
7/6/2010	10-hole	B	12.0	1,730	4.0%	5.0	19.0	14.0	907	3,460	26%
7/6/2010	10-hole	B	12.0	1,280	3.0%	5.0	16.5	11.5	745	2,560	29%
7/6/2010	10-hole	B	12.0	865	2.0%	5.0	13.1	8.1	525	1,730	30%
7/6/2010	10-hole	A	12.0	2,200	5.1%	6.0	28.5	22.5	1,458	4,400	33%
7/6/2010	10-hole	B	12.0	2,200	5.1%	5.0	32.0	27.0	1,750	4,400	40%

Figure 2a shows the results for the 2008 testing of various drilled spargers. Figure 2b shows the 2008 test results for the aeration hose. Figure 2c shows the 2008 results from the open-ended pipe sparger. The measured efficiency at 4% gas/water ratio was about 66% for the open-ended pipe sparger. The measured efficiency for the aeration hose with a 4% gas/water ratio ranged from 61% to 70%. These values might be averaged to estimate an efficiency of about 65% for a 4% gas/water ratio. The efficiency for both the open pipe and the aeration hose increased to between 65% and 73%, with an average of about 70% for a 3% gas/water ratio. The efficiency was increased to about 80% with a 2% gas/water ratio and was about 90% with a 1% gas/water supply ratio. The efficiency of the aeration hose was reduced to about 55% for 5% gas/water ratio and to about 50% for the 6% gas/water ratio. Only the aeration hose could be tested at these higher gas/water ratios because the gas supply pressure of 45 psi was not enough to supply this much gas through the drilled spargers. These results suggest that the gas/water ratio was the only major factor controlling the U-tube efficiency at maximum water flow rates of 25 cfs for one tube and 45 cfs for both tubes operating.

2010 Efficiency and Capacity Testing Results

The Oxyguard DO probes were installed at the U-tube inlets and outlets during 2009 and were used for the facility testing in 2010. The gas supply pressure was increased to 85 psi, which allowed the spargers to be tested at gas/water ratios of 5% and 6%. All of the spargers (including the open-ended pipe and the aeration hose) gave a similar efficiency at each gas/water ratio. The Aeration Facility could be operated with an 8% gas/water ratio to give a capacity of more than 12,500 lb/day with the gas flow valve fully opened at a pressure of 85 psi. However, the gas-transfer efficiency would be only about 45% at this high oxygen delivery rate. In addition, as described below, the exit DO concentrations would be higher than 40 mg/l, and some of the added DO would be lost in the discharge line.

The head loss measurements for the discharge pipeline for one pump (25 cfs) and two pump (45 cfs) operations were helpful in describing the basic hydraulic performance of the Aeration Facility. These measurements indicated that the pressure drop through the diffuser with one pump (25 cfs) was about 4.1 feet, and the pressure drop was increased only to 4.3 feet with two pumps (45 cfs). The pressure drop through the diffuser did not increase as much as expected with twice the flow. Perhaps not all the jets were flowing with the one-pump operation, or there may be some head loss that is not proportional to the assumed port velocity-squared. This small change in head loss suggests that blocking more of the ports would not likely cause much of a change in back-pressure along the discharge line or at the U-tubes. The 1,000-foot discharge line (27.14-inch inside diameter) head loss was 7.1 feet with one pump (25 cfs) and increased to 17.1 feet with two pumps (45 cfs). If the head loss followed the assumed velocity-squared relationship, the head loss with one pump should have been just 5.3 feet (measured 7.1 feet). Some portion of the head loss may be constant and not change with flow.

The testing of reduced flow in each U-tube with manometers at the orifice plates indicated the head loss across the orifice plate was slightly greater in U-tube B, suggesting slightly higher flow in U-tube B than in U-tube A. The acoustic water flow meters indicated the same water flow of about 22.5 cfs in each U-tube. However, the slightly lower exit DO for U-tube B (of 40 mg/l rather than 43.5 mg/l) indicated that the flow might have been slightly higher in U-tube B. A rating curve for each discharge pipe was obtained by reducing the water flow by closing the discharge valves. The flow was reduced in increments of 2 cfs to a minimum flow of 12 cfs (half flow rate). This would be equivalent to the flow expected with the one-pump split flow operations. The manometer readings were about 3 feet head loss for U-tube B and about 2.5 feet for U-tube A at the full flow of 22.5 cfs in each tube.

Exit DO measurements were made with a 4% gas/water ratio for flows of 22.5 cfs (full capacity), 20 cfs, 16 cfs, and 12 cfs. The flow was adjusted with the discharge valves, and the gas flow rate was adjusted to 4% gas/water ratio at each water flow. The results of this testing are shown in Table 3. The reduced flows did not correspond to increased gas transfer efficiencies. At a gas/water ratio of 5%, the efficiency was about 50% for U-tube A and about 45% in U-tube B. Reducing the flow actually reduced the efficiency. At a flow of 12 cfs, the efficiency was reduced to about 35% in U-tube A and 25% in U-tube B. The water velocity at the sparger was reduced from about 7.5 ft/sec to about 4 ft/sec. A possible explanation for this reduced efficiency at lower flows could be that the initial bubble size was controlled by the water velocity at the sparger. The reduced flow and reduced velocity may have allowed larger bubbles to form, which reduced the gas-transfer efficiency, even with a longer travel time in the U-tube.

The revised hypothesis after the reduced flow testing was that the water velocity at the sparger may be the dominant efficiency factor (not the travel time in the U-tube). Therefore, the best performance might be at full flow (with highest water velocity of 7.5 ft/sec at the sparger). To further test this hypothesis, both pumps were turned on, and the connection valve between U-tube A and U-tube B was opened. The inlet valve to U-tube A then was closed to force all of the water into U-tube B. The additional back pressure of about 17 feet of head (20 psi at the sparger rather than 12.5 psi with normal two-pump operation) reduced the combined flow through U-tube B to about 18 cfs for each pump rather than 22.5 cfs for normal two-pump operation. The 3% gas ratio gave an exit DO of 33 mg/l with an efficiency of about 65% for the open pipe (no sparger). The 4% gas ratio gave an exit DO of 38 mg/l with an efficiency of about 58% for the open pipe. The original 10-hole sparger also was tested for the increased water velocity conditions of two pumps with flow in one U-tube. The exit DO was about 33 mg/l with an efficiency of 63% for the 3% gas ratio. The exit DO was about 39 mg/l with an efficiency of 58% for the 4% gas ratio. These values were similar to what was previously measured for all other gas spargers with normal two-pump operations and normal water velocities of about 7.5 ft/sec at the sparger. This suggested that there would not be much improvement in the gas-transfer efficiency for an increased water velocity at the sparger.

The possible loss of DO in the discharge line to the diffuser was evaluated with Winkler titrations on July 8, 2010. Both pumps were operating with a combined flow of 45 cfs, so the travel time in the 30-inch-diameter discharge line was about 2 minutes (1,200 feet at 10 ft/sec). With just one pump, the travel time would be twice as long. Measurements were made at 2%, 3%, 4%, and 6% gas/water ratios. The exit DO was 27 mg/l, and the diffuser DO was 27 mg/l for the 2% gas/water ratio, indicating that no DO was lost along the discharge line. The exit DO was 37 mg/l, and the diffuser DO was 35 mg/l with a gas ratio of 3%, suggesting that about 2 mg/l was lost along the discharge line. The exit DO was 42 mg/l and the diffuser DO was 38 mg/l with a gas/water ratio of 4%, suggesting that 4 mg/l was lost. The exit DO was 50.5 mg/l, and the diffuser DO was 44 mg/l with a 6% gas/water ratio, suggesting that about 6.5 mg/l was lost along the discharge line. Because the saturated DO (with 100% oxygen gas) was about 40 mg/l in the discharge pipe (near atmospheric pressure at the diffuser), the loss of DO was expected to increase when the exit DO was greater than about 40 mg/l.

These discharge pipe DO measurements indicated that increasing the gas/water ratio above 4% would not be effective in increasing the delivered DO to the DWSC. The most effective gas/water ratio would be about 3% so that the exit DO would be about 37 mg/l and the discharge DO would be about 35 mg/l. This would correspond to an overall supply/discharge DO efficiency of about 60%. A slightly higher exit DO of 42 mg/l can be achieved with a 4% gas ratio, but some (10%) of this DO will be lost in the discharge line, so the discharge DO would be about 38 mg/l and the overall supply/discharge DO efficiency would be reduced to about 50%.

A gas heating apparatus was tested at the Aeration Facility in 2010. Increased gas temperature potentially could increase the gas-transfer velocity and thereby increase the rate of gas transfer in the U-tubes. Table 4 shows that exit DO concentration differences were not any greater than the normal measurement uncertainties caused by variations in the gas flow rate and the exit DO concentrations. Because this heating would require additional energy, it does not appear to be a useful approach for improving the gas-transfer efficiency or reducing the operational costs of the Aeration Facility.

Table 4. Results of Testing the Effects of Heated Oxygen Gas on Gas Transfer Efficiency

Gas Flow (scf/hr)	Oxygen Temp. (°F)	DO (mg/l) at Ambient Oxygen Temp. (94°F)	DO (mg/l) after Heating
4970 (6%)	124.4	46.1	46.9
2480 (3%)	118.0	32.2	32.6
3312 (4%)	119.1	37.0	37.1

The general results of the Aeration Facility testing indicate that regardless of the sparger design (open-ended pipe, small holes in pipe, or aeration hose) the efficiency of the gas transfer (i.e., dissolution) appears to decline with higher gas/water ratios. The overall performance of the facility can be summarized by the increment of DO in the outlet pipe carrying the oxygenated water to the DWSC. To achieve the design capacity of about 10,000 lb/day with the maximum water flow of 45 cfs, the DO increment would need to be about 41 mg/l. However, this DO increment was achieved in only a few tests with the gas/water ratio increased to about 6%. The gas-transfer efficiency at a 6% gas/water ratio was only about 50%. This gas/water ratio is approaching the point of maximum capacity because increasing the gas flow reduces the efficiency, and the DO increment does not increase substantially.

Table 5 summarizes the measured performance of the Aeration Facility for one U-tube operating (25 cfs) and for both U-tubes operating (45 cfs) with a range of gas/water ratios of 2–6%. The capacity will increase with increasing gas/water ratios, from about 1,750 lb/day for a single U-tube with 1% gas/water ratio, to about 5,250 lb/day for one U-tube with a 6% ratio. The DO delivery capacity for operation of both U-tubes increases from about 3,150 lb/day with a 1% gas/water ratio to about 9,500 lb/day with a 6% gas/water ratio. Because the gas-transfer efficiency declines as the gas/water ratio increases, it will be more cost-effective to operate one or both U-tubes at the lowest possible gas/water ratio. The Aeration Facility should not be operated with an exit DO concentration above 40 mg/l because the loss of DO in the discharge line will increase. This will limit the normal operation to a 4% gas/water ratio.

Table 5. Aeration Facility DO Increment, Efficiency, and DO Delivery Capacity (lb/day) for a Range of Operations

			Gas/Water Ratio						
			1%	2%	3%	4%	5%	6%	
Gas Supply for 1-pump (scf/hr)			900	1,800	2,700	3,600	4,500	5,400	
Gas Supply (for each tube) with 2-pumps (scf/hr)			810	1,620	2,430	3,240	4,050	4,860	
Maximum DO Increment (mg/l)			13	26	39	52	65	78	
Assumed Efficiency			90%	75%	65%	58%	53%	50%	
DO Increment (mg/l)			12	20	25	30	34	39	
DO Delivery with 1 pump (25 cfs)			1,580	2,633	3,422	4,072	4,651	5,265	
DO Delivery with 2 pumps (45 cfs)			2,843	4,739	6,160	7,329	8,371	9,477	
									Pumps only
Cost for 1-pump operation			$816	$991	$1,167	$1,342	$1,518	$1,693	$640
Cost for 2-pump operation			$1,596	$1,912	$2,228	$2,544	$2,860	$3,175	$1,280
Cost/lb for 1-pump operation			$0.52	$0.38	$0.34	$0.33	$0.33	$0.32	
Cost/lb for 2-pump operation			$0.56	$0.40	$0.36	$0.35	$0.34	$0.34	
Assumed Power Cost	0.16	$/kWh	166 kW pumps (220 hp) require 4,000 kWh per day of operation						
Assumed Oxygen Cost	0.10	$/lb							

Notes:

Assumed costs were calculated using 2010 rates for oxygen and electricity.

The most cost-effective operation is higher gas/water ratio because the pumping costs are fixed.

Aeration Facility Effectiveness Results

The 2008–2010 Aeration Facility effectiveness 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. These analysis methods were introduced in the 2008 Operations Report (ICF International 2010). This summary description of the effectiveness 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 effectiveness.
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, inflowing BOD, and natural surface reaeration.
3. The City of Stockton water quality sampling station data provide a more detailed record of the river water quality upstream and downstream of the RWCF discharge and in the DWSC.
4. The DO measurements from the five DWSC DO monitoring stations provide the most comprehensive data for evaluating Aeration Facility effectiveness.
5. The UOP boat surveys of DWSC DO concentrations at three depths upstream and downstream of the diffuser provide a clear picture of the changes in the DWSC DO concentrations caused by the Aeration Facility.

The effectiveness of the Aeration Facility is demonstrated by the analysis of data from these individual data sources as well as the comparison of results from the DWR DO monitoring stations, the DWR (*San Carlos*) and UOP boat survey DO profiles, and the City of Stockton water quality sampling stations.

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

The measured RRI tidal elevation and the estimated RRI tidal movement for each month were the basis for estimating the 15-minute incremental DO from the Aeration Facility at each monitoring station in the DWSC. Periods of downstream velocity (i.e., positive velocity during ebb tide) move the DO from the diffuser downstream past the RRI, NA 42, and NA 40 stations. Periods of upstream velocity (i.e., negative velocity during flood tide) move the DO from the diffuser upstream past NA 43 and sometimes to NA 48. 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 each month, while the maximum upstream tidal movement was about 1.5 miles on a few days each month. A more thorough description and evaluation of the tidal movement and mixing in the DWSC for June–September 2008 was included in Appendix B of the 2008 Operations Report (ICF International 2010).

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 feet away from the diffuser. About 30 pounds 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. Prior to aeration, the DO was approximately 8.5 mg/l throughout the profile. The DO profiles collected about 5 feet from the diffuser were relatively uniform, varying from 12 to 13 mg/l throughout the 30-foot 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 feet of the diffuser.

Figure 3a shows longitudinal DO profiles at 2-foot, 10-foot, and 25-foot depths measured about 15–20 feet from the diffuser 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 feet. The downward angled ports are effective in distributing the diffuser discharge water deeper in the DWSC. Figure 3b shows the longitudinal dye and DO profile measured 250 feet from the diffuser (near mid-channel) at a depth of 10 feet. These measurements were started at the end of a 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-foot 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 to about 10% of the discharge DO concentration, which was 35 mg/l greater than the ambient DO of 6 mg/l.

The tidal dispersion studies in the DWSC conducted by UOP 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 1.5–2.0 miles of the DWSC during each day of Aeration Facility operation. A more complete description and analysis of the various dye studies in the DWSC was provided in the 2008 Operations Report (ICF International 2010).

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. 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. 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). For this reason, the DO probes at the monitoring stations were placed at a low tide depth of about 10 feet.

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

The longitudinal DO profiles measured by the DWR *San Carlos* boat surveys in the DWSC are 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 upstream portion of 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* boat 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. A more thorough discussion of these longitudinal DO surveys in the DWSC appears in Appendix A of the 2008 Operations Report (ICF International 2010).

The DWSC longitudinal DO profiles are most sensitive to the flow, inflow DO, inflow BOD concentration, and surface reaeration rate. The DWSC DO Model was developed to match the measured *San Carlos* survey DO data for a range of flows, BOD concentrations, and reaeration values. The range of flows evaluated was 250–1,000 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 DWSC DO Model results were used to show the general effectiveness 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.

Figure 4a shows the estimated DO concentrations in the DWSC with an assumed inflow BOD concentration of 12 mg/l and an inflow DO concentration of 6 mg/l during the summer when the saturated DO is about 8 mg/l. The minimum DO with a flow of 250 cfs would be about 4 mg/l, and the minimum DO would be observed at about Mile 38.5 (just upstream of the diffuser) at low tide. The minimum DO would remain about 4 mg/l but would be located downstream at about Mile 37 with a flow of 500 cfs at low tide. With a flow of 750 cfs, the minimum DO would be about 4.5 mg/l and would be located downstream at about Mile 36 at low tide. With a flow of 1,000 cfs, the minimum DO would be about 4.5 mg/l and would be located near Mile 34 at low tide. These sensitivity results indicate that the minimum DO is controlled largely by the inflow BOD and the reaeration rate, and only the location of the minimum DO moves downstream with higher flow.

Figure 4b shows the estimated DO concentrations in the DWSC for an assumed BOD concentration of 16 mg/l. The minimum DO with a flow of 250 cfs would be about 3 mg/l, and the minimum DO would be observed at about Mile 38.5 at low tide. The minimum DO would remain about 3 mg/l but would be located downstream at about Mile 37 with a flow of 500 cfs at low tide. With a flow of 750 cfs, the minimum DO would be about 3.5 mg/l and would be located downstream at about Mile 36 at low tide. With a flow of 1,000 cfs, the minimum DO would be about 3.5 mg/l and would be located near Mile 34 at low tide. The additional 4 mg/l of BOD would increase the initial daily BOD decay by 0.4 mg/l, and the daily reaeration would be higher. The net effect of the additional 4 mg/l of BOD during the 5 days until the minimum DO was reached would be to reduce the minimum DO by about 1 mg/l for any assumed DWSC flow.

Figure 4c shows the estimated DO concentrations in the DWSC for an assumed BOD concentration of 20 mg/l. The minimum DO with a flow of 250 cfs would be about 2 mg/l, and the minimum DO would be observed at about Mile 38.5 at low tide. The minimum DO would remain about 2 mg/l but would be located downstream at about Mile 37 with a flow of 500 cfs at low tide. With a flow of 750 cfs, the minimum DO would be about 2.5 mg/l and would be located downstream at about Mile 36 at low tide. With a flow of 1,000 cfs, the minimum DO would be about 2.5 mg/l and would be located near Mile 34 at low tide. The additional 8 mg/l of BOD would increase the daily BOD decay by 0.8 mg/l, and the daily reaeration would be higher. The net effect of the additional 8 mg/l of BOD would be to reduce the minimum DO by about 2 mg/l for any assumed DWSC flow.

Figure 4d shows the estimated DO concentrations in the DWSC for an assumed BOD concentration of 24 mg/l. The minimum DO with a flow of 250 cfs would be about 1 mg/l, and the minimum DO would be observed at about Mile 38.5 at low tide. The minimum DO would remain about 1 mg/l but would be located downstream at about Mile 37 with a flow of 500 cfs at low tide. With a flow of 750 cfs, the minimum DO would be about 1.5 mg/l and would be located downstream at about Mile 36 at low tide. With a flow of 1,000 cfs, the minimum DO would be about 1.5 mg/l and would be located near Mile 34 at low tide. The additional 8 mg/l of BOD would increase the daily BOD decay by 0.8 mg/l, and the daily reaeration would be higher. The net effect of the additional 8 mg/l of BOD would be to reduce the minimum DO by about 2 mg/l for any assumed DWSC 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, which is proportional to the DO deficit (below saturation). A natural surface reaeration rate of 20% per day was found to match the *San Carlos* survey DO data profiles. The surface reaeration rate also controls the downstream DO increments from the Aeration Facility. Because the added DO will reduce the DO deficit (below saturation), the surface reaeration will be reduced compared to the natural conditions, and the downstream DO with the Aeration Facility will slowly approach the natural DO profile. This effect is similar to the downstream temperature effects from a heated discharge, which will approach the natural equilibrium temperature. These results also indicate that an inflow BOD concentration of less than 8 mg/l will not likely cause the DWSC DO concentrations to decline below 5 mg/l. An inflow BOD of 12 mg/l caused a minimum DO of about 4 mg/l and an inflow BOD of 16 mg/l caused a minimum DO of about 3 mg/l. Therefore, an inflow BOD of about 8 mg/l would likely cause a minimum DO of about 5 mg/l, for an assumed inflow DO of 6 mg/l.

Table 6 gives a summary of the calculated Aeration Facility effectiveness (i.e., downstream distribution of added DO) for a range of flows between 250 cfs and 1,500 cfs with an Aeration Facility capacity of 7,500 lb/day. The effectiveness 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 indicator of effectiveness. 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. The DWSC DO Model does not calculate the DO concentration profile for zero net flow. With zero net flow, the added DO from the Aeration Facility will be distributed in the tidal mixing zone that is assumed to extend 1.5 miles upstream and 1.5 miles downstream. Because of the effects from natural surface reaeration on the DO increments added from the Aeration Facility, only about 4 days of added DO (30,000 lbs) will remain in the DWSC during periods of zero net flow. The 30,000 pounds of DO will be distributed in a triangular shape centered at the diffuser, as shown in Table 6.

Operating strategies for the Aeration Facility can be developed from this table for the range of possible DWSC 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 DO effects given in Table 6. Full capacity operation may not be needed if the inflowing DO and BOD concentration will result in a natural DO profile that is 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 6. Calculated DO Increments in the DWSC with Reaeration for Maximum DO Diffuser Output of 7,500 lb/day

	Flow (cfs)	0	250	500	750	1,000	1,250	1,500
	Maximum Possible DO Increment at Diffuser (mg/l)	**na**	**5.6**	**2.8**	**1.9**	**1.4**	**1.1**	**0.9**
Location	**San Joaquin Mile**							
	40.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NA 48	39.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	39.0	1.25	0.00	0.00	0.00	0.00	0.00	0.00
NA 43	38.5	2.50	0.51	0.27	0.18	0.14	0.11	0.09
DO Diffuser	38.0	3.75	2.55	1.46	1.02	0.78	0.63	0.53
NA 42	37.5	2.50	3.24	2.12	1.55	1.22	1.00	0.85
	37.0	1.25	2.37	1.82	1.40	1.13	0.94	0.81
NA 40	36.5	0.00	1.56	1.48	1.22	1.02	0.87	0.75
	36.0	0.00	1.10	1.25	1.09	0.93	0.81	0.71
	35.5	0.00	0.77	1.05	0.97	0.86	0.75	0.67
	35.0	0.00	0.52	0.87	0.85	0.78	0.70	0.63
	34.5	0.00	0.36	0.73	0.76	0.71	0.65	0.60
	34.0	0.00	0.22	0.57	0.65	0.63	0.59	0.55
	33.5	0.00	0.10	0.39	0.50	0.52	0.51	0.48
	33.0	0.00	0.05	0.29	0.42	0.46	0.46	0.44
Turner Cut	32.5	0.00	0.03	0.23	0.35	0.40	0.41	0.41
Added DO in the DWSC (lbs)			32,500	30,000	26,000	22,500	20,000	18,000
DO Retention to Turner Cut		na	23%	40%	49%	54%	57%	59%
Travel Time to Turner Cut (days)		na	19.1	10.1	7.0	5.5	4.6	4.0

City of Stockton River Water Quality Data

The only measurements of the BOD concentrations entering the DWSC are from the City of Stockton river water quality sampling surveys. The City traditionally collected 5-day BOD samples, but for the period 2004–2009 it collected 10-day BOD samples to provide a lower measurement level (detection threshold). Because the reporting limit for BOD measurements is 2 mg/l, it is difficult to measure ultimate BOD concentrations of less than 5 mg/l (i.e., ultimate BOD = 2.5 x 5-day BOD). The DO and BOD data from 2004 (prior to nitrification facility operation) and from 2008 (after nitrification facility operation) will be compared here to show the reduction in the inflow BOD that was measured in recent years (2007–2010).

Figure 5a shows the mid-depth DO concentrations measured at the City's stations in the DWSC (R3–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 of April 15 to May 15. 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 of about 3 mg/l would be consistent with an inflow BOD of about 16 mg/l, according to the DWSC DO Model (described above). 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 5b 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 from June through August 2004 was about 15–18 mg/l. This was consistent with the inflow BOD concentrations of 18–20 mg/l estimated to match the DWR *San Carlos* survey DO measurements from the summer of 2004.

Figure 5c shows the City of Stockton weekly DO measurements at the DWSC stations (R3–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 through August and above 6 mg/l for September through November. The Aeration Facility was operated about half of the time (with a pulsed on-off schedule) from mid-June through September 2008.

Figure 5d 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.

Dissolved Oxygen at the Deep Water Ship Channel Monitoring Stations

The five DWSC DO monitoring stations at NAs 40, 42, 43, 48, and RRI provide the most comprehensive data for this study (Figure 1). Aeration Facility performance can be evaluated by comparing measurements of natural DO concentrations to measurements of increased DO concentrations observed during periods of Aeration Facility operation. The DWSC DO monitoring data from June–September 2008 were previously shown and described in the 2008 Operations Report (ICF International 2010). The changes in the DWSC DO concentrations at the five monitoring stations were evaluated during periods of Aeration Facility operations in June–September 2008 (see Figures 11–14 from the 2008 Operations Report). The DWSC DO monitoring data from 2007, 2009, and 2010 are shown and evaluated in the following sections.

DO Monitoring Analysis Methods

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

The Aeration Facility delivered about 7,500 lbs/day of DO when operated at full capacity with a 4% gas/water ratio, so about 78 pounds were discharged from the diffuser during each 15-minute period (with 96 periods per day). Based on observations made during the 2008 diffuser dye tests, the discharge of oxygenated water from the diffuser will not be immediately mixed laterally or vertically. Therefore, the RRI surface monitoring station likely measures a higher DO increment than the fully mixed estimated DO increment. Because the NA 43 monitoring station is across the DWSC from the diffuser, the measured DO increments may be less than expected for fully mixed conditions. DO monitoring at NA 42 likely provides the best estimate of the fully mixed effects from the Aeration Facility.

Monitoring during months without any Aeration Facility operation 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 were described in the 2008 Operations Report (ICF International 2010) and are summarized here. The DO monitoring results from the 2009 and 2010 testing periods are described with more detail in the following sections.

A DO Increment Model was developed to help identify the DO increments in the DWSC from the Aeration Facility and calculate the effects of reduced surface reaeration on the DO increments from the Aeration Facility as the net flow moved downstream in the DWSC. 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 of the 2008 Operations Report provided a description of the DO Increment Model and an evaluation of the results of comparisons of the measured DO at the five monitoring stations with the estimated DO increments and calculated natural DO conditions.

Subsequent to the 2008 Operations Report, a new method for evaluating the 15-minute DO monitoring data was developed and added to the DO Increment Model calculations. This new method compares the longitudinal DO pattern from the five monitoring stations on a selected day by using the tidal movement in the DWSC to position the DO data from each station measured during the day at where this water would be at the low tide elevation of 3 feet or at the high tide elevation of 6 feet. This new method allowed the UOP boat profile DO measurements to be compared to the estimated longitudinal profiles based on the five DO monitoring stations. The tidal movement of water in the DWSC past the DO monitoring stations can be used to estimate the longitudinal DO profile in the DWSC. The water movement near each station can be referenced to the RRI tide elevation. The tidal movement between low tide (3 feet) and high tide (6 feet) at NA 40 was estimated to be about 1.5 miles. The tidal movement at NA 48 was estimated to be about 1.2 miles because of the smaller upstream area. Table 7 shows the movement of water from high tide (6 feet) to low tide (3 feet) for each DO monitoring station.

Table 7. Longitudinal Position of DO Data for Low-tide Profiles

Station	NA 40	NA 42	RRI	NA 43	NA 48
Upstream area (ac)	930	900	850	825	715
Location (Mile)	36.3	37.3	37.9	38.3	39.4
Tidal excursion (miles)	1.5	1.45	1.35	1.3	1.2
Downstream position of water starting at NA at 6 feet tide (Mile)	34.8	35.85	36.55	37	38.2

The DO profiles at low-tide elevation (3 feet) on a given day can be estimated by considering the tidal movement of water compared to the monitoring station location. For each day, the relative position of DO data from each monitoring station collected during the day can be estimated from the 15-minute RRI tide elevation. For example, DO data recorded at NA 48 when the tide elevation was 3 feet would be positioned at the monitoring station. DO data that was recorded when the tide elevation was 6 feet would be positioned downstream at Mile 38.2 (1.2 miles downstream) for estimating the low tide DO profile. A similar procedure is used to estimate the high tide DO profile.

Although there are other sources of variation in the DO data (e.g., algal photosynthesis during the day), this estimation of the tidal movement during the day provides a way to understand some of the variations in the monitoring station DO data. The DO profiles on days without aeration are generally flat or uniform DO concentrations for each of the DO monitoring stations. The DO profiles are humped with increased DO downstream of the diffuser on days with the Aeration Facility operating. Separating the effects of the Aeration Facility from the natural variations in DWSC DO concentrations is the basic reason that the testing schedules always include an on-off comparison.

Figure 6a shows an example of this data analysis method for the high-tide DO profile on September 11, 2009, after 4 days of flood-tide operations. Although both pumps were operated, the DO was added only during half that time, so the capacity was about 4,000 lb/day. All of the added DO would be located upstream of the diffuser at high tide, and most of the added DO would move downstream of the diffuser at low tide. The 15-minute monitoring data from the five stations cover about 4.5 miles of the DWSC from Mile 36.5 to Mile 41. The UOP boat survey of DO at high tide corresponds well with the profile estimated from the monitoring data. Figure 6b shows the estimated DO increments from the DO Increment Model at low tide on this same day (after 4 days of flood-tide operation). The maximum DO increment was about 1 mg/l. The gold dots in the figures show the relative tidal positioning of DO data recorded at the RRI station.

Summary of Natural DO Concentrations in 2007

The existing RRI station (surface sensor) and the four new DO monitoring stations (at 10 foot depths at low tide) were operated during 2007 without any Aeration Facility operations (was not yet completed) and are reviewed here to illustrate the natural variations and patterns in the DWSC DO concentrations. The DO concentrations are often highly variable at the upstream station (NA 48) and are less variable at the downstream station (NA 40). Sometimes there is a strong daytime DO pattern caused by surface stratification and algae photosynthesis. Sometimes there is a strong tidal variation when a longitudinal DO gradient moves back and forth past a DO station. Sometimes a characteristic “sag” pattern was observed with the minimum DO near the RRI station. Because the natural DO patterns are fluctuating over time, the basic approach for testing the effectiveness of the Aeration Facility was to use an on-off testing schedule, as more fully described in the 2008 Operations Report (ICF International 2010).

Figures 7a to 7d show the 15-minute DO data collected at the five DWSC DO monitoring stations for June–September 2007. The San Joaquin River inflow enters the DWSC just upstream of NA 48 (Mile 39.5). Figure 7a shows the DWSC DO data for June 2007. The DO data at NA 48 (Mile 39.5) had a very large daily variation that appears to be highest in the late afternoon during the evening low tide (downstream flow), suggesting high algae growth (photosynthesis) in the river upstream of the DWSC. The daily variation in the NA 48 DO data (blue line) was about 4 mg/l, ranging from 6 mg/l to 10 mg/l for June 1–12 (NA 48 DO data from June 13 to 26 was lost). The DO data at NA 43 (Mile 38.2) was less than the NA 48 data, but was higher than the other DO stations and suggested that the high DO from the SJR was influencing NA 43 DO data (purple line). The daily DO variation was about 2 mg/l, ranging from 6 mg/l to 8 mg/l during the first 10 days of June. The NA 43 DO data decreased to about 4 mg/l by June 20 (NA 43 DO data from June 20 to June 26 was lost). The DO data from the RRI (surface sensor) was generally the lowest DO measured in June 2007. The RRI DO (black line) was about 6 mg/l at the beginning of the month and decreased to 5 mg/l on June 10 and to 4 mg/l on June 14, was about 3 mg/l from June 16 to June 22, and was 2 mg/l on June 22 and 23. However, the RRI station DO was recalibrated on June 23 and the DO was 3–4 mg/l for the remainder of the month, so the minimum DO of 2 mg/l may not be accurate. The DO data from the two stations located downstream of the diffuser were similar. The DO data at NA 42 (Mile 37.3) was about 6 mg/l at the beginning of June, decreased to about 5 mg/l by June 12, and was about 4 mg/l from June 15 to the end of the month (brown line). The DO at NA 40 (Mile 36.4) was the most stable during June 2007 with a daily variation of only about 1 mg/l. By the end of June, DO data from all five monitoring stations averaged about 4 mg/l with a daily variation between 3 mg/l and 5 mg/l. The DO concentrations of about 4 mg/l at the end of June were about 4 mg/l below the DO saturation (of about 8 mg/l). As described in Appendix A of the 2008 Operations Report (ICF International 2010), the DO deficit reflects a balance between BOD decay and surface reaeration. Therefore a higher DO deficit indicates a higher BOD concentration.

Figure 7b shows the DWSC DO data for July 2007. The NA 48 DO data had the largest daily range of about 4 mg/l (from 3 mg/l to 7 mg/l) during the first 10 days of July and a daily range of about 2 mg/l for the remainder of the month. The NA 43 DO data had a smaller variation than the NA 48 DO data. The RRI DO data and the downstream DO data at NA 42 and NA 40 were relatively constant throughout July 2007, with most values between 4 mg/l and 5 mg/l. The DO variation appeared to be from algae photosynthesis in the surface layer, although the NA 42 and NA 40 DO data is collected at a depth of about 10 feet (at low tide). Vertical mixing at the end of each day (i.e., surface cooling) apparently mixed the higher surface DO to the mid-depth probes. An example of a tidal variation DO pattern can be seen in the NA 40 and NA 42 data from July 11 to 17. The highest DO corresponds to periods of higher tide. This suggests that the DO concentration was increasing downstream, and that the high tide transported this higher DO water upstream to the NA 40 and NA 42 stations. At the end of July, the DO concentrations at all of the DWSC DO monitoring stations were generally between 4 mg/l and 5 mg/l.

Figure 7c shows the DWSC DO data for August 2007. The NA 48 DO data had a smaller daily range of about 2 mg/l in August. The average DO at NA 48 was about 5 mg/l at the beginning of August and increased to about 6 mg/l August 20–28 and then decreased to about 5 mg/l at the end of the month. This same variation in average DO was observed at the other DWSC stations. The RRI DO data in August was generally the lowest, and the minimum daily values were between 4 mg/l and 5 mg/l for the first half of the month and increased to about 5 mg/l for the second half of August. The DO data from NA 42 and NA 40 were very stable through August, with a daily variation of only about 1 mg/l. The average daily DO was about 5 mg/l for the first half of the month and about 5.5 mg/l in the second half of August.

Figure 7d shows the DWSC DO data for September 2007. The DO data from all of the DWSC monitoring station were between 5 mg/l and 6 mg/l for the first 10 days of September and then increased to about 6 mg/l for the second half of September. Water temperatures cooled in the second half of September; accordingly DO saturation increased from about 8 mg/l to 9 mg/l. The DO concentrations at NA 48 increased to about 7 mg/l in mid-September and were between 6 mg/l and 7 mg/l for the remainder of September, apparently influenced by higher river DO concentrations.

Daily Average DO Concentrations at the DWSC DO Monitoring Stations

Figure 8a shows the daily average DO concentrations for the five DWSC DO monitoring stations for the summer of 2007. The daily average DWSC flow, measured at the USGS Garwood tidal flow station is shown for reference. The daily flows were reduced at the end of June from about 1,000 cfs to about 250 cfs. The flows declined to less than 250 cfs from early July to late August, and were about 250 cfs in September. Although the 15-minute DO data allows the variation within each day to be identified, the daily average DO data from the five monitoring stations provides a good summary of the overall DO conditions in the DWSC. The daily DO concentrations were highly variable in June, and the DO concentrations decreased to less than 5 mg/l in the middle of June, while the flows were still high (750 cfs). The high DO concentrations in the first 10 days of June at the upstream stations (NA 48 and NA 43) suggests high algae biomass (BOD) from the upstream river likely caused to low DO in the second half of June. The low flows in July and August indicate that very little river algae BOD was entering the DWSC. The DO concentrations slowly increased from about 4 mg/l to 6 mg/l in July and August. The DO conditions in September were about 5 mg/l for the first 10 days and then increased to about 6 mg/l at the end of the month. The variations in the DO concentrations in summer 2007 were apparently related to upstream algae concentrations, DWSC flows, and seasonal water temperatures. The Aeration Facility was not yet operational in 2007, but the Port of Stockton operated the two aeration devices located just upstream of NA 48 (at Dock 13) from June 11 through October 23. Although the Port of Stockton aeration devices added DO to the upstream end of the DWSC, the effects were constant during the summer months and did not contribute to the variations in DO concentrations observed during 2007.

Figure 8b shows the daily average DO concentrations at the five DWSC monitoring stations for the summer of 2008. This data from 2008 was previously shown and described in the 2008 Operations Report (Figures 11–14 in ICF International 2010). These data are shown again here to emphasize the similarity of the variations in the DWSC DO concentrations at the five monitoring stations during the summer of 2008 in comparison to the natural DO variations in 2007. The Aeration Facility was operated for about half of the days in the summer of 2008, as shown by the red boxes at the bottom of Figure 8b. A value of 1 indicates full operation of about 7,500 lb/day and a value of 0.5 indicates that the Aeration Facility was operated for half of the day or one pump was operated for the entire day. The NA 48 DO data declined from about 6 mg/l to 4 mg/l during June. The DO concentrations at the other DWSC stations were above 5 mg/l in June. Testing of the Aeration Facility during the second half of June raised the DO at NA 42 (most representative of the DO increment from the Aeration Facility) by about 1 mg/l. The natural DO concentrations (identified during the periods when the Aeration Facility was turned off) apparently increased from 5 mg/l to 6 mg/l in July, and remained at about 6 mg/l in August and September.

Figure 8c shows the daily average DO concentrations at the five DWSC monitoring stations for the summer of 2009. The Aeration Facility was only tested during 2 weeks in September 2009. These tests were half capacity operations (during flood-tides, or during the night). The natural DO at each of the DWSC stations was above 5 mg/l for the entire summer period. The NA 48 DO data was often the lowest, and the NA 40 DO data was the highest for most of the summer, indicating a downstream gradient of increasing DO from just above 5 mg/l to just above 6 mg/l. The natural DO in September 2009 was less than 6 mg/l so the Aeration Facility would likely have been operated to increase the DO to above the 6 mg/l DO objective.

Figure 8d shows the daily average DO concentrations at the five DWSC monitoring stations for summer 2010. The Aeration Facility was tested during a 10-day period in August and a 7-day period in September, both with one pump operation (half capacity). The natural DO at each of the DWSC stations was above 5 mg/l for most of the summer period. The natural DO at NA 48 and RRI was less than 5 mg/l during the second half of July. The DO data from all of the stations were usually within a range of 1 mg/l on most days. Sometimes the NA 48 DO data was the highest with a decreasing downstream DO gradient, and sometimes the NA 48 data was the lowest with an increasing downstream DO gradient. The natural DO in the first half of September 2009 was less than 6 mg/l so the Aeration Facility would likely have been operated to increase the DO to above the 6 mg/l DO objective (as tested in the second week of September 2010).

Summary of June–September 2008 Dissolved Oxygen Measurements

June 2008 was the first month of operational testing to determine the ability of the Aeration Facility to maintain DO concentrations above the water quality objective in the DWSC between NAs 40 and 48. The Aeration Facility was turned on around 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 on Monday, June 22, allowing the DO concentrations at the monitoring stations to return to natural conditions during the 3 days of non-operation. The maximum increased DO concentration at the RRI monitoring station 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 concentrations were caused by tidal variations of the DO increments.

The measured DO at NA 40 showed very small increases during periods of Aeration Facility operation. A delay in the DO increments at NA 40 was expected, but very few of the DO increments observed at RRI and NA 42 were measured at NA 40. Because each monitoring station is located at a different distance from the Aeration Facility diffuser, it is difficult to distinguish, when viewing the graphed DO concentration data, the effects of the added DO from natural DO fluctuations. Generally the DO concentration was observed to have increased at each station while the Aeration Facility was operating.

Each Monday the Aeration Facility was turned on around noon and operated for 4 days until noon on each Friday, with five operation periods and four non-operation periods measured in July 2008. 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 NA 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 NA 42. The measured DO at NA 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 NA 40 was expected during these low-flow conditions, but very few of the DO increments observed at RRI and NA 42 were measured at NA 40.

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. It was expected that the longer operation periods would provide more time for the added DO from the Aeration Facility to register at the downstream DO monitoring stations and hopefully show a clearer separation between observed natural DO conditions and any changes created by the Aeration Facility. 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 NA 42 DO increased less than at RRI because the NA 42 measurements are taken 10–15 feet below the surface, and most of the DO moving past NA 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 NA 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 NA 40 station.

The Aeration Facility was operated for just two periods during September 2008—a 10-day period of September 1–5 (beginning on August 26), and a 10-day period from September 16–26 to see if these longer operation periods would provide a greater increase in DO concentrations downstream from the diffuser. The measured DO at RRI was above DO saturation during ebb tides 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 NA 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 NA 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 NA 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).

Dissolved Oxygen Measurements in September 2009

Testing of the Aeration Facility was delayed in 2009 because of California State Bond funding issues that prevented any contractor work. The operational testing of the Aeration Facility resumed in September 2009. Figure 9 shows the monthly DO measurement at the five DWSC monitoring stations in June, July, and August 2009. The DO concentrations during these 3 summer months were remarkably constant between about 5 and 6 mg/l. DO concentrations were increased to between 6 and 7 mg/l from June 15 to 25, and the NA 48 DO was reduced to about 4 mg/l for the last 5 days in June. The DO concentrations were 5 to 6 mg/l throughout July and August. The DO concentrations in these summer months were consistent compared to previous years when the minimum daily DO at RRI would decline to 3 or 4 mg/l for several weeks. If the Aeration Facility would have been operated as part of the TMDL implementation plan to maintain the 5 mg/l objective during 2009, it likely would not have been operated for most of the summer. It could have been operated at half capacity (one pump) to increase the DO by 0.5 to 1 mg/l in the DWSC downstream of the RRI station, but DO concentrations generally remained above the 5 mg/l objective, especially if considered as a daily average value.

Figure 10a shows the measured DO at the five DWSC monitoring stations. The DO concentrations were generally between 5 and 6 mg/l at the beginning of the month, increased slowly to about 6 to 7 mg/l by September 10, and then slowly decreased to about 5 to 6 mg/l by September 15. The inflow DO measured at NA 48 increased from about 5 mg/l on September 15 to about 7 mg/l on September 17, and remained at about 7 mg/l to the end of the month. The RRI DO concentrations were generally lower than at the other stations, following the typical pattern of the minimum DWSC DO being located near this station during relatively low flows. The RRI mid-depth sensor is shown in the graph; the surface sensor shows larger daily variations associated with stratification and algae photosynthesis.

The Aeration Facility was operated during each flood-tide (upstream flow) from September 8 to September 11 in an attempt to distribute more of the DO increments upstream of the diffuser. It is difficult to detect the effects of the Aeration Facility in the measured DO data because DO concentrations at all five station were generally increasing in the first 10 days of September. Because the DO concentrations generally decreased over the next 5 days when the Aeration Facility was not operating, an average DO increment of about 1 mg/l from the Aeration Facility is perhaps indicated. Figure 8a shows monitoring data from September 11, 2009, at the end of the flood-tide operations period. The UOP boat survey at high tide indicted increased DO concentrations upstream of the diffuser. Figure 8b shows the results from the DO Increment Model for September 11 at high tide, suggesting the Aeration Facility increased the DO by about 1 mg/l upstream of the diffuser.

Figure 10b shows the tidal averaged (net) flow measured at various locations in the SJR. The SJR flow at Vernalis was between 500 cfs and 750 cfs from September 1 to 10, and then increased to over 1,000 cfs from September 15 to the end of the month. The measured flows in the DWSC at RRI and upstream at Garwood and Lathrop increased from about 0 cfs to 250 cfs for the first 10 days to about 500 cfs to 750 cfs from September 15 to the end of the month. Perhaps in response to the increased flow, the measured DO at NA 48 increased from about 5 mg/l on September 15 to about 7 mg/l on September 18. However, the DO probe was switched on September 16 and the previous probe was measuring 5 mg/l and the new probe measured 6.5 mg/l. The DO at NA 48 continued to increase and was above 7 mg/l on September 18 to the end of the month. The spring-neap tidal cycle (of about 14 days) is another environmental factor that is always changing and may have some effect on the DO concentrations in the DWSC. All of these shifting factors (tides, temperatures, flows, and DO probes) make it difficult to determine the effects of the Aeration Facility from the monitoring records alone. The DO Increment Model and the tidal profile display (Figure 8) assist in the data analysis.

Figure 11a shows the measured DO and the calculated DO increments at NA 43 with actual Aeration Facility operations during September 2009. Previous data analysis has indicated that NA 48 does not see any effects from the Aeration Facility because the tidal excursion is not quite large enough to move much water from the diffuser to NA 48. Although NA 43 is across the channel from the diffuser, the estimated DO increments are about 1 mg/l during high tides. The Aeration Facility was operated during flood tides of September 8– 11, and was then operated at night September 21–25. The nighttime operation was intended to add oxygen when the DWSC was vertically mixed, to reduce the amount of added DO that was lost to the surface layer. Similar DO increments of about 1 mg/l were estimated at NA 43 for the nighttime operation at high tide. The natural DO pattern at NA 43 was estimated by subtracting the calculated remaining DO increments from the measured DO. The measured DO (red line) can be compared to the estimated natural DO (green line) for NA 43. The periods of peak DO at NA 43 do not always correspond to the modeled increments at high tide, but the general effects of the Aeration Facility at NA 43 appear to have a reasonable magnitude.

Figure 11b shows the measured DO and the calculated DO increments at the RRI station (0.2 mile downstream) with actual Aeration Facility operations during September 2009. Because this station is located downstream of the diffuser, the estimated DO increments are about 1 mg/l for a longer portion of the tidal cycle at RRI. Only at the lowest tides during flood operations were there no estimated DO increments at RRI. For nighttime operations from September 21 to 25, there were always some estimated DO increments at the RRI station until a day after the Aeration Facility operations ceased. The natural DO estimated for the RRI station was about 5 mg/l during the first period of flood-tide operation and was about 5.5 mg/l during the second period of nighttime operation. The Aeration Facility produced estimated DO increments at the RRI station of about 1 mg/l for both the flood-tide operations and the nighttime operations.

Figure 11c shows the measured DO and the calculated DO increments at NA 42 (0.7 mile downstream) with Aeration Facility operations during September 2009. The calculated DO increments at NA 42 were similar to those calculated for the RRI station. However, the tidal variations in the DO increments were reduced because some added DO from the diffuser was in the vicinity of NA 43 most of the day. The calculated DO increments were greatest after 4 days of operation and were about 1 mg/l for both the flood-tide operation and the nighttime operation. Both of these operational strategies used two pumps for about half of the day, resulting in an oxygen output of about 3,750 lb/day. The natural DO estimated for NA 43 was about 5.5 mg/l for the flood tide operations of September 8–11, with some DO increments remaining until September 15. The natural DO was about 6 mg/l for the nighttime operations of September 21–25, with some DO increments remaining until September 27.

Figure 11d shows the measured DO and the calculated DO increments for NA 40 (1.6 miles downstream) with Aeration Facility operations during September 2009. The measured DO at NA 40 showed small increases after 4 days of flood-tide operation (with an estimated flow of 250 cfs) and after 3 days of nighttime operations (with an estimated flow of 500 cfs). The greatest DO increments were estimated at low tide when water from the diffuser was transported farthest downstream. The maximum calculated DO increments at NA 40 were about 1 mg/l for both operations periods, with slightly greater increments in the later period because of the higher flows moving the DO increments to NA 40 more quickly. The effects from the Aeration Facility were calculated for about 4 days after the operations ceased. The estimated natural DO at NA 40 was about 5.5 mg/l for the first period and about 6 mg/l for the second period. The Aeration Facility would likely have been operated for more of the month had it been fully operational, to increase the DO in the DWSC to the September objective of 6 mg/l.

Dissolved Oxygen Measurements in October 2009

The operational testing of the Aeration Facility continued in October 2009. Figure 12a shows the measured DO at the five DWSC monitoring stations. The DO concentrations were generally between 6 and 7 mg/l at the beginning of the month and increased to between 7 and 9 mg/l by October 10. The Aeration Facility was scheduled to be operated for a week beginning October 12, but a power failure on October 13 and again on October 15 interrupted this testing period. The Aeration Facility was operated for a week beginning October 19 to October 26. Meanwhile, the DO concentrations in the DWSC were reduced from 8 to 9 mg/l on October 14 to about 6 to 7 mg/l on October 19, for unknown reasons. This drop of about 2 mg/l in just a week was quite an unexpected change in the DO concentrations that were measured at all five stations in the DWSC. The DO then increased to about 8 to 9 mg/l during the week of Aeration Facility operation and remained at 8 to 9 mg/l from October 26 to the end of the month. The DO at NA 48 was often the highest concentration and the DO at RRI was often the lowest concentration, but variations in the five monitoring stations during the month make it difficult to determine the effects from the Aeration Facility.

Figure 12b shows the tidal averaged (net) flow measured at various locations in the SJR. The SJR flow at Vernalis was about 1,000 cfs from October 1 to 10, increased to about 2,500 cfs from October 20 to 27, and then declined to about 2,000 cfs by the end of the month. This increased flow was a pulse release to attract adult Chinook salmon to the upstream tributaries. The tidal flow measurements at Mossdale were 500 cfs higher than the Vernalis flows from October 15 to the end of the month. This is a relatively new tidal flow measurements station, and the rating curve at these increased flows may need adjustment. The three tidal flow measurements below the head of Old River diversion were generally consistent. The head of Old River fall barrier was not installed in 2009. The DWSC flows were about 500 cfs from October 1 to 12, about 1,000 cfs from October 15 to 20, and about 1,500 cfs from October 22 to 28, declining to less than 1,000 cfs by October 31. The changes in the inflow DO at NA 48 did not appear to follow any simple relationship with flow. The difficulty of predicting the inflow DO and the RRI DO from the SJR and DWSC flows alone emphasizes the need for using the on-off strategy to measure the effects of the Aeration Facility in the DWSC.

A series of daily UOP boat surveys at low tide were made from October 19 (before operations began) to October 25 (after 6 days of operation). These surveys were helpful in demonstrating the downstream DO increments from the Aeration Facility (see next section). However, the generally increased levels of DO at all stations during this period of increasing flow in the DWSC make the analysis of the DO increments from the Aeration Facility difficult. The results from the DO Increment Model were used to help identify the Aeration Facility effects during October 2009. Figure 13a shows the measured DO and the calculated DO increments at NA 43 with actual Aeration Facility operations during October 2009. Previous data analysis has indicated that NA 48 does not measure any effects from the Aeration Facility because the tidal excursion is not quite large enough to move much water from the diffuser to NA 48. Although NA 43 is across the channel from the diffuser, the estimated DO increments are about 1 mg/l during high tides. The Aeration Facility was operated between October 12 and 14 when the measured DO was above 8 mg/l. Actual measured DO at NA 43 was 9 mg/l on October 13 and the estimated DO increments were about 1 mg/l. Maximum DO increments of about 1.5 mg/l were estimated at NA 43 for the continuous operation from October 19 to 26 at high tide. The natural DO pattern at NA 43 was estimated by subtracting the calculated DO increments from the measured DO. The measured DO (red line) can be compared to the estimated natural DO (green line) for NA 43. The periods of peak DO at NA 43 corresponded well to the modeled DO increments at high tide, but the general increase in DO from 6 mg/l to 8 mg/l dominated the measured DO pattern and swamped the effects from the Aeration Facility. Actual long-term TMDL operations would likely have started the Aeration Facility when the measured DO declined to about 6 mg/l on October 18, but would have likely turned off the Aeration Facility when the measured DO increased above 7 mg/l on October 23.

Figure 13b shows the measured DO and the calculated DO increments at the RRI station (0.2 mile downstream) with actual Aeration Facility operations during October 2009. Because this station is located downstream of the diffuser, the estimated DO increments were more than 1 mg/l for a longer portion of the tidal cycle at RRI, and the maximum DO increments were about 2 mg/l at high tides. There were always some estimated DO increments at the RRI station until a day after the Aeration Facility operations ceased. The average DO increment was less than 1 mg/l because the DWSC flows were greater than 1,000 cfs during the week of operations. The natural DO estimated for the RRI station was about 7 mg/l during the first period of operation (October 12–15), was about 6 mg/l during the first 3 days of the week-long operations, and then increased to about 8 mg/l at the end of the week-long operations on October 26. The Aeration Facility produced estimated DO increments at the RRI station of between 0.25 mg/l and 2 mg/l during the week of operation. The variability in the DO increments at RRI was higher because the DWSC flows were over 1,000 cfs, and most of the DO was transported downstream past RRI within a day.

Figure 13c shows the measured DO and the calculated DO increments at NA 42 (0.7 mile downstream) with Aeration Facility operations during October 2009. The calculated DO increments at NA 42 were similar but with less tidal variation than those calculated for the RRI station. The calculated DO increments were greatest after 1 day of operation and were about 1 mg/l during the continuous operations from October 20 to 26 (delayed by 1 day). The natural DO estimated for NA 43 was about 6 mg/l for October 20–22 and then increased to about 9 mg/l on October 28. This rapid increase in the natural DO makes it difficult to identify the effects of the Aeration Facility without the DO Increments Model. Figure 13d shows the measured DO and the calculated DO increments for NA 40 (1.6 miles downstream) with Aeration Facility operations during October 2009. The measured DO at NA 40 showed small increases on October 15 and 16, delayed about 2 days after the Aeration Facility was operated with a DWSC flow of about 500 cfs. The DO increments at NA 40 during the week of continuous operation were about 1 mg/l, delayed about 2 days for the DWSC flow of about 1,000 cfs from October 21 to 28. The effects from the Aeration Facility were calculated for about 2 days after operation ceased. The estimated natural DO at NA 40 was decreasing from 8 to 7 mg/l on October 15 and 16, and was increasing from 6 to 9 mg/l during the week-long operations from October 21 to 28. The Aeration Facility would likely have been operated for only a few days at the beginning of the month and for a few days between October 16 and October 24, when the natural DO was less than 6 mg/l, if it had been used to increase the DO in the DWSC to the objective of 6 mg/l as part of the TMDL implementation plan.

Dissolved Oxygen Measurements in August 2010

Operational testing of the Aeration Facility in 2010 began in late July with a 4-day operation from July 26 to July 30 with one-pump at about a 3% gas/water ratio for an oxygen delivery of about 3,000 lb/day. Figure 14a shows the measured DO concentrations at the five DWSC monitoring stations in June and July of 2010, prior to operational testing. The DO concentrations at all five stations were very similar during June, with DO at NA 48 showing the most variation. DO concentrations in the DWSC were about 8 mg/l at the beginning of the month and declined to about 7 mg/l between June 7 and June 14, and then increased to about 8 mg/l from June 16 to June 20, and then slowly decreased to about 6 mg/l by the end of the month. The DWSC DO concentrations have often exhibited this slowly varying “wavy” pattern, which may be related to the 14-day spring-neap period with variation in tidal energy and associated vertical mixing. The daily variations in the measured DO at these stations were about 1 mg/l, although the variability at NA 48 (upstream station) was sometimes greater. The measured DO was about 1 to 2 mg/l below the saturated DO concentration that was 9 mg/l for most of the month and declined to 8.5 mg/l at the end of the month (because of warmer water temperature). Because the DO concentrations in the DWSC remained above 6 mg/l, there would have been no need to operate the Aeration Facility in June 2010 as part of the TMDL implementation plan.

Figure 14b shows the measured DO concentrations at the five DWSC monitoring stations in July of 2010. The DO concentrations at the five stations showed greater differences in July 2010. The DO concentrations were about 6 mg/l at the beginning of the month but increased to 7 mg/l from July 5 to July 8, and declined to about 6 mg/l between July 10 and July 20, and then decreased to about 5 mg/l on July 22. The NA 48 DO decreased to about 4 mg/l on July 24–27, and increased slightly to 5 mg/l by the end of the month. The DO at the other DWSC stations generally remained between 5 and 6 mg/l from July 20 to the end of the month. The Aeration Facility was turned on with one pump on July 26 for operational testing. If the Aeration Facility was being operated as part of the TMDL implementation plan, it might have been turned on about July 20 when the daily average DO concentrations were decreasing to less than 6 mg/l. The DWSC DO concentrations in July exhibited a “wavy” pattern, but the inflow DO (NA 48) was very low from July 22 to July 30. The changing inflow

DO created longitudinal DO gradients of about 2 mg/l in the DWSC, but they were increasing downstream.

Figure 15a shows the measured DO concentrations at the five DWSC monitoring stations in August of 2010. The DO concentrations at the five stations ranged from about 4 mg/l to 6 mg/l for the first 5 days in August, which was a greater daily range than observed in June and July. This might have been the result of the previous week of operational testing or might have been the result of the unusually low inflow DO from the previous two weeks. The DO concentrations were about 5 mg/l to 6 mg/l from August 6 to August 10. One pump of the Aeration Facility was started on August 9 to determine the effects on the DWSC DO with a 3% gas/water ratio for a delivery of about 3,000 lb/day. The goal of this operation, from August 9 to August 19, was to produce a more uniform distribution of DO increments in the DWSC, and avoid DO increments that were greater than DO saturation. The NA 48 DO concentrations fluctuated between 4 mg/l and 6 mg/l. The downstream DO concentrations generally increased to between 6 mg/l and 7 mg/l, suggesting an increase of about 1 mg/l from the Aeration Facility. The DO concentrations at all stations were between 5 mg/l and 6 mg/l from August 23 to the end of the month. The highest DO concentrations were often measured in the late afternoon, suggesting effects of algae photosynthesis even at these sensors that were at a depth of about 10 feet. Figure 15b shows the estimated DWSC flow compared to the SJR flow at Vernalis. The Vernalis flow was about 1,250 cfs while the DWSC net tidal flow was generally less than 250 cfs. Most of the SJR flow was diverted into Old River, so most of the SJR algae and associated BOD load was not transported to the DWSC.

Figure 16a shows the measured DO and the calculated DO increments at NA 43 with actual Aeration Facility operations during August 2010. The estimated DO increments were a maximum of about 1 mg/l during high tides. Measured DO at NA 43 ranged from about 5 mg/ to 6.5 mg/l during the period of Aeration Facility operation. The periods of peak DO at NA 43 correspond with the modeled DO increments at high tide. The natural DO (green line) was estimated to remain at 5 mg/l during the operational period. Figure 16b shows the measured DO and the calculated DO increments at the RRI station (0.2 mile downstream) with actual Aeration Facility operations during August 2010. The maximum estimated DO increments were about 1 mg/l for most of the tidal cycle at RRI. Some DO increments remained at the RRI station for about 2 days after the Aeration Facility was turned off, because of the relatively low flow of 250 cfs. The natural DO estimated for the RRI station increased from about 5 mg/l to about 6 mg/l during the operational period.

Figure 16c shows the measured DO and the calculated DO increments at NA 42 (0.7 mile downstream) with Aeration Facility operations during August 2010. The calculated DO increments at NA 42 were similar but with less tidal variation than those calculated for the RRI station. The calculated DO increments were about 1 mg/l during the one pump operations and persisted for about 3 days after the Aeration Facility was turned off on August 19. Figure 16d shows the measured DO and the calculated DO increments for NA 40 (1.6 miles downstream) with Aeration Facility operations during August 2010. The measured DO at NA 40 was about 5.5 mg/l at the beginning of August and was about 6 mg/l from August 7 to August 13. The calculated DO increments at NA 40 were delayed about 3–4 days with the low flow conditions, and increased to a maximum of 0.75 mg/l after a week of operations. The DO increments decreased to about 0.1 mg/l after a week. The calculated natural DO concentrations (green line) were about 6 mg/l throughout the testing period. Because the natural DO concentrations were less than 6 mg/l during August 2010, the Aeration Facility would likely have been operated with one pump for a delivery of about 4,000 lb/day for most of August 2010.

Dissolved Oxygen Measurements in September 2010

Figure 17a shows the measured DO concentrations at the five DWSC monitoring stations in September 2010. The DO concentrations at the five stations ranged from about 5 to 6 mg/l on September 1 and increased slightly during the first week to between 5.5 and 6.5 mg/l. There were some high DO concentrations at NA 48 in the afternoons of the first 5 days in September, suggesting algae photosynthesis in the DWSC rather than the upstream river, because the tides were increasing (upstream movement) during each day. The DO concentrations were about 5.5 to 6.5 mg/l on September 7 when the Aeration Facility was turned on with one pump at a 5% gas/water ratio for a delivery of about 4,000 lb/day. The DO concentration at all of the DWSC stations increased during the week of operation, but this was not likely the result of the Aeration Facility, because DO concentrations continued to increase after the operations ended on September 14 and were greater than 6.5 mg/l on September 17. Because the DO objective increases from 5 mg/l in August to 6 mg/l in September, the Aeration Facility would likely have been operated towards the end of August to increase the DO slightly had it been operating as part of the TMDL implementation plan. Although the DO concentrations were greater than 6 mg/l on September 14, it would have been difficult to turn off the Aeration Facility without a confident estimate of the DO increments from the Aeration Facility. This illustrates the value of using the DO Increment Model as a method for estimating the natural DO concentrations while the Aeration Facility is operating.

Figure 17b shows the estimated DWSC flow compared to the SJR flow at Vernalis in September 2010. The Vernalis flow was about 1,250 cfs for the first 10 days, but then increased to a maximum of 2,500 cfs on September 13–15 as part of the pulse flow to attract SJR Chinook salmon to the tributaries for spawning. The majority of the pulse flow in 2010 was released from the Merced River. The Vernalis flow slowly decreased to about 1,500 cfs from September 23 to the end of the month. The DWSC net tidal flows were about 250 cfs until the pulse flow. The DWSC flows increased to about 1,000 cfs on September 15–17, delayed about 3 days from the peak at Vernalis. The DSCS flows were about 500–750 cfs from September 18 to the end of the month. The head of Old River temporary rock barrier was not installed in fall 2010 because the DWSC flows were judged to be high enough to maintain the DO concentrations above the DO objective of 6 mg/l. Comparison of Figure 17a indicates that DO concentrations in the DWSC during September 2010 were generally above 6 mg/l.

Figure 18a shows the measured DO and the calculated DO increments at NA 43 with actual Aeration Facility operations during September 2010. The DO data was missing for a week at NA 43. The DO at NA 43 was about 6 mg/l when the Aeration Facility was started on September 7, and the natural DO (green line) was estimated to remain at about 6 mg/l until the flow pulse increased the DO on September 15–17 to about 7 mg/l. The estimated DO increments at NA 43 were a maximum of about 1.25 mg/l during high tides. The measured DO was above 6 mg/l for the remainder of the month.

Figure 18b shows the measured surface sensor DO and the calculated DO increments at the RRI station (0.2 mile downstream) with actual Aeration Facility operations during September 2010. The maximum estimated DO increments varied from 1 mg/l to 1.5 mg/l for most of the tidal cycle at RRI. The calculated DO increments remained at the RRI station for only a day after the Aeration Facility was turned off on September 14, because the DWSC flows were 750–1,000 cfs during the pulse flow period. The natural DO estimated for the RRI station increased from about 5.5 mg/l on September 7 to about 6 mg/l on September 14, and the measured DO remained above 6 mg/l for the remainder of the month. The afternoon peak in DO at RRI indicates some algae photosynthesis, making the surface DO sensor more difficult to interpret. A mid-depth sensor at RRI might be a better long-term monitoring strategy for operating the Aeration Facility as part of the TMDL implementation plan.

Figure 18c shows the measured DO and the calculated DO increments at NA 42 (0.7 mile downstream) with Aeration Facility operations during September 2010. The calculated DO increments at NA 42 were similar but with less tidal variation than those calculated for the RRI station. The maximum calculated DO increments were about 1.25 mg/l during the one pump operations but persisted for only 1 day after the Aeration Facility was turned off on September 14 because the DWSC flows were about 750 to 1,000 cfs. The measured DO at NA 42 was 7 mg/l during the pulse flow period and slowly decreased to about 6 mg/l at the end of the month.

Figure 18d shows the measured DO and the calculated DO increments for NA 40 (1.6 miles downstream) with Aeration Facility operations during September 2010. A week of data was missing at NA 40. The measured DO at NA 40 was about 6 mg/l at the beginning of September and increased to 7 mg/l from September 12 to September 22 and then decreased slowly to about 6.5 mg/l by the end of the month. The calculated DO increments at NA 40 were delayed about 3–4 days with the 250 cfs flow conditions until September 12, and increased to a maximum of 1 mg/l after a week of operations. The DO increments persisted for only about 2 days at NA 40 because the increased flow of 750 to 1,000 cfs more quickly transported the added DO downstream.

The results from August and September 2010 testing of the one-pump operation of the Aeration Facility (with daily delivery of about 4,000 lb/day) suggest that the added DO increments in the DWSC were generally about 1 mg/l to 1.5 mg/l and were more uniformly distributed between NA 43 and NA 40. This appears to be a very effective operational strategy during periods of relatively low DWSC flows (less than 500 cfs) when the natural DO concentrations were within 1 mg/l of the DO objective (i.e., 4 mg/l or greater in June–August, 5 mg/l or greater in September). The Aeration Facility would be able to increase the DO in the DWSC by about 1 mg/l over the 3-mile segment from the diffuser at Mile 38 downstream past NA 40 to Mile 35 (measured at low tide).

University of the Pacific Longitudinal Dissolved Oxygen Profiles in the Deep Water Ship Channel

The basic method for evaluating the UOP boat survey longitudinal DO profiles measured in the DWSC between Turner Cut and Channel Point was to compare the DO measurements taken before the Aeration Facility was operating with the DO profiles measured after several days of operation. Assuming that the flow and inflow BOD concentration did not change during the period of operation, the natural DO profile should not have changed during the period of operation. Therefore, the differences between the two longitudinal DO surveys would represent the added DO increments from the Aeration Facility. The DO increments were expected to move slowly downstream with the net DWSC flow. Some of the UOP DO surveys were collected at high tide and others were collected at low tide to directly measure the movement of the DO profile and the distribution of the added DO from the Aeration Facility in the DWSC between high tide and low tide.

Summary of August and September 2008 UOP Longitudinal Surveys

All of the UOP boat surveys of DO in the DWSC conducted in 2008 are fully described in the 2008 Operations Report (ICF International 2010). The first series of longitudinal surveys were collected from August 12 to 16, 2008, to measure the effects of the Aeration Facility on the DWSC DO concentrations during a 4-day operation period. Figure 19a shows the DO profiles at the three depths on August 12, 2008 that reveal the natural DO conditions in the DWSC. Surveys on the next 4 days measured the buildup of DO increments from the Aeration Facility. Figure 19b shows the DO profiles on August 16, 2008, after 4 days of operation, and it shows the mid-depth DO from August 12 for reference as the natural DO concentration profile. 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. There was not much of a downstream “sag” in the DO concentrations, 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, suggesting algal growth (i.e., photosynthesis). The DO profile after 4 days of aeration showed that the surface and mid-depth DO concentrations 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 to 2.5 miles downstream of the diffuser (to 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 was not fully mixed and not distributed uniformly in the channel. Identifying the DO increments from the Aeration Facility will be difficult because of these variations in the natural DO concentration and variations in the longitudinal and vertical distribution of the added DO increments.

The second series of UOP boat surveys from August 26 to September 5, 2008, measured the increase in DO concentration 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 20a shows the measured DO profiles at the three depths on August 26, 2008. The surface, mid-depth, and bottom DO concentrations were all about 6 mg/l in the DWSC, so the natural DO deficit (below saturation) was very uniform at about 2 mg/l. There was no measured DO sag, indicating that the BOD concentration entering the DWSC was low. After 4 days of operation, 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. After 8 days of operation, 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 20b shows the measured DO profiles on September 5, 2008, after 10 days of operations, with the mid-depth DO profile from August 26 shown for reference. The measured 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.

The third series of longitudinal DO profiles was measured with the UOP boat surveys from September 15 to September 26, 2008, and measured the increase in DO concentrations upstream of the diffuser at high tide during a 10-day operation period. These longitudinal surveys were collected at high tide to document the upstream tidal movement and distribution of the added DO increments. 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 measured every 2 days. Figure 21a shows the DO measurements at the surface, mid-depth (15 feet), and near bottom (25 feet) on September 15, 2008, at low tide. 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. Figure 21b shows the DO profiles on September 26, 2008, after 10 days of aeration, surveyed at high tide. The mid-depth DO profile from September 15 is shown for reference. The DO profiles from the three depths 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 measured 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 1 mile 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 distribution of DO increments from the Aeration Facility 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.

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 couple of 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 a 3–4 mile portion of the DWSC downstream of the diffuser at Mile 38. The amount of added DO in the measured downstream wedge of DO increments can be estimated from the DO increase measured by the UOP boat surveys at low tide. The mass of DO added by the diffuser in each DWSC channel segment can be estimated as:

DO Increment Mass (lb) = 2.72 x Volume (af) x DO concentration change (mg/l)   [Equation 5]

Because each 0.1-mile segment of the DWSC has a volume of about 175 af, about 500 lb of oxygen is required to increase the DO concentration by 1 mg/l in a 0.1 mile segment. Therefore, about 5,000 pounds of added oxygen could raise the DO in a mile of the DWSC by 1 mg/l. The volume of water in the DWSC between Mile 38 (diffuser) and Mile 35 is about 5,250 af at low tide, so this 3-mile segment would require about 15,000 pounds of added oxygen to raise the DO concentrations by 1 mg/l.

Using the UOP survey data, the added wedge of DO can be estimated as the pounds of DO added by the Aeration Facility that still remain in the DWSC. For each survey, the pounds of DO added to each 0.1-mile segment is estimated by subtracting the DO from the initial survey (before operation) from the measured mid-depth DO. For example, on August 28, 2008, the added DO from the Aeration Facility had increased the DO content between Mile 38 and 35 by about 7,000 pounds after 2 days of aeration (15,000 pounds added). On August 30, 2008, the DO content was increased by about 15,000 pounds between Mile 38 and 35 after 4 days of aeration (30,000 pounds added). On September 1, 2008, the DO content was increased by about 25,000 pounds after 6 days of aeration (45,000 pounds added). On September 3 the DO content was increased by about 23,000 pounds after 8 days of aeration (60,000 pounds added), and on September 5, 2008, the DO content was increased by about 28,000 pounds between Mile 38 and 35 after 10 days of aeration (75,000 pounds added). The maximum wedge of DO increments observed during these 10 days of operation therefore was about 25,000 pounds 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. There may be some DO increments downstream of Mile 35, but they are difficult to determine because the differences from the baseline DO concentrations remain small.

2009 UOP Longitudinal DO Profiles

Three series of longitudinal DO profiles were collected by UOP boat surveys in 2009. The first series of longitudinal DO surveys in 2009 were collected from September 8 to 12 to measure the effects of the Aeration Facility on the DWSC DO concentrations during a 4-day flood-tide operation period. Figure 22a shows the DO profiles at high tide at three depths on September 8, 2009. The flood-tide operations may have increased the DO upstream of the diffuser (Mile 38), but this profile was at 6:00 p.m., so some of the surface DO may have been natural algae photosynthesis. The inflow DO was about 6.5 mg/l and the bottom DO was about 6 mg/l from Mile 39.5 downstream to Mile 36. Figure 22b shows the DO profiles measured on September 12, 2009, after 4 days of flood-tide operation. The mid-depth probe was lost in a previous survey, but the surface and bottom DO profiles indicated that the Aeration Facility had increased the DO from Mile 38.5 (upstream of the diffuser) to Mile 35.5 (downstream of the diffuser), with a maximum DO increment of about 1 mg/l at Mile 37. The flood-tide operation put out about half as much DO as full-time operation. Because DWSC DO conditions were stable during this testing period, the effects of the Aeration Facility were easily detected from the UOP surveys.

The second series of UOP boat surveys were conducted from September 21 to 25 at low tide to measure the effects of 4 days of nighttime operations. Nighttime operations were evaluated to determine if increased vertical mixing of the added DO from the diffuser would be achieved. Figure 23a shows the UOP DO profiles measured at low tide on September 21, 2009. Because this survey was at 6:00 a.m., there was no difference between the surface and bottom DO profiles in the DWSC. There was an unusual increase in the inflow DO entering the DWSC from about 6 mg/l on September 15 to about 9 mg/l (1 mg/l above saturation DO) on September 21. The DWR *San Carlos* survey on September 19 confirmed that the inflow DO was very high compared to the DWSC DO of about 6 mg/l downstream of Mile 36. Figure 23b shows the measured DO profiles at low tide on September 25, 2009, after 4 days of nighttime operation. Because this was an early morning survey there were no differences between surface and bottom DO profiles. The comparison with the September 21 mid-depth DO profile indicates that the inflow DO was reduced from 9.5 to 8.5 mg/l. The DWSC DO upstream of the diffuser (Mile 38) was about 7 mg/l. This was similar to the upstream DO on September 21. These changes in the inflow DO and the corresponding DO profile in the upstream portion of the DWSC make it difficult to detect the Aeration Facility effects. The effects of the Aeration Facility can perhaps be detected between the diffuser at Mile 38 downstream to Mile 34. This downstream effect was longer than observed on September 12, perhaps because the DWSC flow had increased from 250 cfs during the September 8–11 flood-tide operations to about 500 cfs during the September 21–25 nighttime operations.

The third series of UOP boat surveys were conducted from October 19 to 25 at low tide to determine the daily buildup of the downstream effects from the Aeration Facility during a one-week operational period. However, as can be seen in Figure 12a (DO monitoring in October 2009), there was a dramatic decline in the DWSC DO during the week preceding this operational period. The DO in the DWSC declined from 8–9 mg/l on October 14 to 6–7 mg/l on October 19 when the baseline DO profile was measured in the first UOP survey and the Aeration Facility was turned on. DWR survey results from October 16 indicated that the DWSC DO was about 7.5–8 mg/l, about 1 mg/l higher than measured by the UOP boat survey on October 19. UOP boat surveys were conducted every day during the week.

Figure 24a shows the measured UOP boat survey DO profiles at low tide on October 19. The inflow DO was about 7 mg/l and the DO downstream of NA 40 at Mile 36.5 was also about 7 mg/l. The UOP survey at low tide measured a slight DO depression of about 1 mg/l between Mile 40 and Mile 36.5 with a minimum DO of about 6 mg/l at Mile 38.5. Temperatures were cooler than in September, and the saturated DO concentration was above 9 mg/l. The DWSC DO was therefore about 2 mg/l below saturated DO on October 19, 2009. Figure 24b shows the UOP measured DO profile at low tide on October 24, 2009 after 5 days of continuous operation. The measured DO at Turner Cut (Mile 32.5) remained at 7 mg/l, but DO concentrations had increased to about 8 mg/l from Mile 35 upstream to the SJR inflow to the DWSC at Mile 40. The surface and mid-depth profiles show direct effects from the Aeration Facility at Mile 38 downstream to about Mile 36. Because this DO profile was measured at low tide, there are no expected effects from the diffuser upstream of Mile 38, and the increased DO in this upstream portion of the DWSC was the result of increased inflow DO between October 19 and 24. Because the inflow DO changed during the Aeration Facility operations, the baseline measured on October 19 is no longer applicable, and it is more difficult to determine the effects from the Aeration Facility. It is likely that the DO increase between Mile 34 and 35 represents the downstream extent of the Aeration Facility DO effect, with a DWSC flow of more than 1,000 cfs.

Identifying the DO increments from the Aeration Facility is always uncertain because of variations in the DWSC flows and the inflow DO and inflow BOD concentrations. Because the natural DO concentration profiles shift with these changes in DWSC conditions, it is difficult to determine how much of the measured downstream DO was caused by natural DO changes and how much was caused by the added DO from the Aeration Facility. Variations in the longitudinal and vertical distribution of the added DO increments prevent an exact accounting of the added DO. However, the general effects of the Aeration Facility during these two operational periods in September 2009 were generally confirmed with these UOP boat surveys. The DO effects were observed further downstream when the flow was higher (500 cfs) during the September 21–25 period. The DO effects of the Aeration Facility were observed downstream about 2 miles and a DO "front" was observed 4 miles downstream on October 24 after 5 days of continuous operation with a high DWSC flow of more than 1,000 cfs.

Lateral DWSC DO Surveys in October 2009

Lateral DO measurements were made during the UOP boat surveys in October 2009 to evaluate the lateral and vertical distribution and mixing of oxygen from the Aeration Facility. Most of the lateral surveys were made at NAs 40 and 42, downstream of the diffuser, with some made further downstream and upstream of the diffuser to represent natural conditions. DO measurements were recorded at approximately 50-foot lateral intervals across the 500-foot-wide channel with 8-foot vertical intervals from the surface to the DWSC bottom at about 35 feet.

Figure 25 shows the lateral DO measurement at NAs 40 and 42 at low tide at about 8:00 a.m. on October 15, 2009. The surface DO was about 9 mg/l. The lateral variation was relatively small, with minimum DO of about 8.5 mg/l below the surface at the sides of the channel. The bottom DO was also about 8.5 mg/l. Therefore, an overall DO variation of 0.5 mg/l was observed laterally and with depth. Figure 26 shows the lateral DO measurement at NAs 40 and 42 at low tide at about 10:00 a.m. on October 20, 2009. The surface DO was about 7 mg/l. This was a dramatic decrease of 2 mg/l from just 5 days previously. The lateral variation was less than 0.2 mg/l, and the vertical variation was also small. The minimum DO at the bottom was about 6.9 mg/l. The DWSC appears to be very well mixed on these 2 days without much influence of the Aeration Facility. Lateral measurements on October 22 at NAs 40 and 42 were very similar with surface DO measurements of 7.5 mg/l and lateral or vertical variations of just 0.2 mg/l.

Lateral measurements on October 23 at NA 42 at 7:00 a.m. at low tide showed some lateral variations that were likely caused by the Aeration Facility. The maximum DO concentration was about 7.9 mg/l on the west side of the channel (downstream of the diffuser) and the east side DO was about 7.7 mg/l. There were no vertical differences in this early morning profile. The DO in the DWSC was changing rapidly during the operational period, but the entire channel remained fairly uniform. The west side of the channel has a slightly greater influence from the Aeration Facility, but most of the added DO is well mixed across the channel at the downstream monitoring stations at NAs 42 and 40.

Figure 27 shows the lateral DO measurement at NAs 42 and 43 (upstream of diffuser) at low tide at about 8:00 a.m. on October 24, 2009, after 5 days of continuous operation. The surface DO at NA 42 was about 8.5 mg/l. The lateral variation at a depth of 10 feet was about 0.5 mg/l, with 8.5 mg/l on the west side and 8.0 mg/l on the east side. The bottom DO was about 7.9 mg/l. Therefore, an overall DO variation of 0.5 mg/l was observed laterally and with depth. The lateral variation at NA 43 (0.2 mile upstream of the diffuser) was about 2 mg/l on October 24. The maximum DO was about 10.3 mg/l on the west side and about 8.2 mg/l on the east side near the monitoring station. The bottom DO was about 8.2 mg/l. Presumably the higher DO concentrations are from the Aeration Facility diffuser, and these lateral differences observed in this cross-section will be mixed across the channel with additional tidal movement.

Figure 28 shows the lateral DO measurement at NAs 42 and 43 at low tide at about noon on October 25, 2009, after 6 days of continuous operation. The surface DO at NA 42 was about 9.5 mg/l and the bottom DO was about 8.5 mg/l, suggesting stratification and algae photosynthesis for these mid-day measurements. The lateral variation at NA 42 was less than 0.1 mg/l. The lateral variation at NA 43 (0.2 mile upstream of the diffuser) was about 1.5 mg/l on October 25. The maximum DO was about 10.8 mg/l on the west side and about 9.3 mg/l on the east side near the monitoring station. The surface DO was about 10 mg/l and the bottom DO was about 8.5 mg/l. The vertical differences were observed at most stations when the lateral survey was conducted during the afternoon, while the largest lateral differences were measured at NA 43 and at NA 42 for low tide surveys.

In summary, the DWSC appeared to be reasonably well mixed laterally and vertically during the conditions surveyed in October 2009. The average DO in the DWSC changed considerably from about 9 mg/l to about 7 mg/l and then increased to 10 mg/l during the 2-week series of lateral profiles measured from October 15 to 26. The vertical differences were generally less than 1 mg/l, and the lateral variations were usually less than 0.5 mg/l, except at NA 43 where the effects from the diffuser were observed with a maximum lateral variation of about 2 mg/l.

DWR *San Carlos* Boat Surveys for September and October 2009

DWR collected DWSC surveys of DO (and other water quality parameters) in September and October of 2009. These data confirm the DO conditions that were measured by the DO monitoring stations and by the UOP boat surveys (compare to Figure 10a). The DWSC DO Model was used to match these DO measurements with estimated inflow DO and inflow BOD concentrations. The observed DO "sag" in the DWSC was relatively small during these surveys. Figure 29 shows the *San Carlos* surface and bottom DO data for September 2 and 19, 2009. The September 2 profile indicated an inflow DO of about 6 mg/l and a minimum DO of about 5 mg/l near Mile 37 with an estimated flow of about 500 cfs and an estimated BOD of about 10 mg/l. The September 19 profile indicated a very high inflow DO concentration of about 10 mg/l (above saturation). The most likely explanation for this would be high algae concentrations in the river. The minimum DO was still about 5 mg/l between Mile 34 and Mile 36, and the flow was still about 500 cfs. The best match of the measured DO profile with the DWSC DO Model was an estimated BOD of about 12 mg/l. However, this upstream DO "sag" might be the result of increasing river DO concentrations and not an indication of increased BOD concentrations.

Figure 30 shows the *San Carlos* surface and bottom DO data for October 2 and 16, 2009. The October 2 profile indicated a high inflow DO of about 9 mg/l and a minimum DO of about 6 mg/l near Mile 34 with an estimated flow of about 750 cfs and an estimated BOD of about 10 mg/l. The high inflow DO was needed to match the bottom DO of 8.3 mg/l measured at Mile 39.4 (NA 48). The October 16 profile indicated that the inflow DO was about 8 mg/l and the BOD was only about 6 mg/l to maintain the minimum DO at about 7 mg/l near Mile 34 with a flow of about 1,000 cfs. These relatively high DO concentrations in the DWSC were confirmed by the continuous DO monitoring and by the UOP boat surveys on October 15 and 19, 2009 (compare Figure 24a).

2010 UOP Longitudinal Profiles

A series of longitudinal DO profiles were collected by UOP boat surveys in August and September of 2010. Figure 31a shows the first longitudinal DO survey measured on July 30, after 5 days of one-pump operations with a gas/water ratio of about 3% and a daily oxygen delivery of about 3,000 lb/day. This was a very unusual DO profile because the inflow DO was only about 4 mg/l and the DWSC DO increased from less than 5 mg/l at Mile 38 to about 7 mg/l at Mile 33. The continuous monitoring data (see Figure 14b) indicates that the minimum DO at NA 48 was observed on July 26 and the inflow may have been increasing during the 5 days of operations. The baseline DO profile (from July 26)—needed for estimating the DO effects from the Aeration Facility from the DO profile measured on July 30, 2010—is uncertain. An estimated DO profile of 4.5 mg/l from Mile 40 to Mile 37, with a steady increase to 6 mg/l at Mile 34, was used to estimate the DO wedge (shown in Figure 31a). The total wedge of added oxygen between Miles 38 and 35 was about 12,500 pounds, with an average DO increment of 0.9 mg/l in this 3-mile segment of the DWSC (5,250 af). Based on the assumed loss of the added DO increments (20% per day), the maximum expected DO wedge would be about 12,000 pounds (i.e., 4 x 3,000 lb/day= 12,000 pounds). The UOP survey at the end of this operational period was consistent with this maximum downstream wedge estimate of 4 days of daily oxygen delivery in the 3-mile downstream segment.

The second operational period in 2010 began on August 9. The Aeration Facility was operated with one-pump with a gas/water ratio of about 3% and a daily oxygen delivery of 3,000 lb/day. Figure 31b shows the measured DO profiles on August 16 after 7 days of one-pump operations. The baseline DO profile measured on August 9 is shown, with an inflow DO of just 5 mg/l, and the DWSC DO slowly increased from 5 mg/l at Mile 38 to 6 mg/l at Mile 34 and 7 mg/l at Mile 33. The measured DO profiles on August 16 indicated an increased DO between Miles 39 and 34. The effects of the Aeration Facility on the DWSC DO profile was a maximum of about 1.5 mg/l at Mile 37, with smaller DO increments downstream. The wedge of DO increments between Miles 38 and 35 was estimated to be about 16,000 pounds with an average DO increment of 1.1 mg/l. This is greater than the expected 4 days of DO delivery (12,000 pounds). However, some of the increase in DO between August 9 and 16 may have been caused by increasing inflow DO concentrations. If 0.25 mg/l was subtracted from the DO increments measured on August 16, the average DO increment between Miles 38 and 35 would be about 0.85 mg/l, and the wedge of DO increments would contain about 13,000 pounds.

Figure 31c shows the measured DO profiles on August 19 after 10 days of one-pump operations. The measured DO profiles on August 19 indicated an increased DO between Miles 39 and 34. The maximum DO increments were about 2 mg/l at Mile 37, with smaller DO increments downstream. The wedge of DO increments between Miles 38 and 35 was estimated to be about 17,000 pounds with an average DO increment of 1.2 mg/l. However, some of the increase in DO between August 9 and 19 may have been caused by increasing inflow DO concentrations. If 0.4 mg/l was subtracted from the DO increments measured on August 19, the average DO increment between Miles 38 and 35 would be about 0.8 mg/l, and the wedge of DO increments would contain about 12,000 pounds. This is closer to the estimated maximum DO wedge of 12,000 pounds (4 days oxygen delivery).

Figure 31d shows the last DWSC DO profile measured with the UOP boat surveys on September 14, 2010. The Aeration Facility was operated with one-pump with a gas/water ratio of about 5% and a daily oxygen delivery of 4,000 lb/day. The baseline DO profile measured on September 7 is shown, with an inflow DO of 6 mg/l, and the DWSC DO also at 6 mg/l from Miles 40 to 35. This uniform DO profile provided a good baseline DO profile. The measured DO profiles on September 14 indicated an increased DO between Miles 38 and 34. However, some of the increased DO was caused by the increasing inflow DO concentrations. The maximum effects of the Aeration Facility on the DWSC DO profile was a maximum of about 1.25 mg/l at Mile 36.5, with smaller DO increments downstream. The wedge of DO increments between Miles 38 and 35 was calculated to be about 14,000 pounds with an average DO increment of 1 mg/l. If 0.5 mg/l was subtracted from the DO increments measured on September 14, the average DO increment between Miles 38 and 35 would be about 0.5 mg/l and the wedge would contain about 7,000 pounds.

These 2010 UOP boat survey profiles of DO in the DWSC show the difficulties of directly measuring the longitudinal distribution of the DO increments from the Aeration Facility. The DWSC flow control shows far downstream the DO increments will move within the 10-day period when DO increments will be reduced to less than 10%, because of the assumed loss of 20% per day from the effects of surface reaeration. In 2009 and 2010 the UOP profiles measured the DWSC DO profiles during periods with shifting DO inflow concentrations, making the baseline DO profile difficult to estimate. The basic on-off sequence for testing Aeration Facility effectiveness was only partially successful in eliminating the shifting natural (i.e., baseline) DO conditions. Nevertheless these UOP profiles provide the best method for directly measuring the wedge of DO increments downstream of the diffuser at low tide. Most of the measured DO profiles were consistent with the expected maximum of about 4 days of oxygen delivery. This again was the consequence of the added DO reducing the natural surface reaeration and causing the DO increments to be reduced by about 20% per day.

Downstream Wedge of Increased DO in the DWSC

The Aeration Facility will produce a downstream wedge of DO increments that will increase the DO in the DWSC. Comparing data from the DO monitoring stations with the UOP boat survey profiles demonstrates that the tidal movement in the DWSC shifts the longitudinal distribution of the wedge of DO increments about 2 miles between the high tide and low tide each day. This section of the final report will summarize the results from the DO monitoring station data and the UOP boat surveys of longitudinal DO profiles and provide a consistent description of the overall effectiveness of the Aeration Facility for increasing the DO concentrations in the DWSC. Because of the effects of natural surface reaeration, not all of the added DO from the Aeration Facility will be measured at the DO monitoring stations or in the longitudinal DO profiles in the DWSC. As described previously (see Table 2), the downstream wedge of DO increments is decreasing from the effects of surface reaeration at about 20% per day.

Figure 32a shows the 15-minute DO measurements from the three downstream monitoring stations from August 25–September 5. 2008, that included a 10-day operational period from August 26 to September 5. The largest DO effects were measured at low tide, because the wedge of DO increments from the Aeration Facility was moved farther downstream. The DO increments were largest (about 2 mg/l) at the RRI station, and were almost as large (1.5 mg/l) at NA 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 NA 40 because this station is about 1.6 miles downstream from the diffuser. The DO increments at NA 40 at low tides were 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. This is because the wedge of added DO increments is decreasing at a rate of about 20% per day because the DO increments reduce the DO deficit from saturation and thereby reduce the surface reaeration.

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 a 3-4 mile portion of the DWSC downstream of the diffuser at Mile 38.

Figure 32b shows that the downstream DO monitors measured the greatest DO effects from the Aeration Facility operations (from September 15 to 26, 2008) at low tide because the wedge of DO increments from the Aeration Facility was moved farther downstream. The measured DO increments were largest (about 1.5–2 mg/l) at the RRI station, and were almost as large (1–1.5 mg/l) at NA 42 but for shorter periods during each tidal period. The DO increments at NA 40 during low tides were about 0.5 to 1 mg/l for just a few hours each day during low tides. 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 than about 3–4 miles downstream of the diffuser (at Mile 38) with a longer operation period.

The zone of influence for the added DO from the Aeration Facility appeared to represent a maximum of about 4 days of DO discharge capacity (about 25,000 pounds of oxygen) distributed in a volume of about 5,000 af (3 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 3–4 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 confirms the maximum downstream movement of the added DO increments and the reduction of the DO increments caused by the effects of the added DO on the natural surface reaeration.

Figure 32c shows the DO data from the downstream monitoring station for September 19–30, 2009. The aeration facility was operated each night from September 21 to 25 (4 nights). This operation was testing the effectiveness of adding most of the DO during the night when vertical mixing would allow most of the added DO to be mixed into the DWSC, rather than "lost" in the warmer surface layer that often develops during the day. The wedge of increased DO moved downstream about 2 miles with each ebb tide and with the net downstream flow that was about 500 cfs (0.5 mile per day downstream movement) during this testing period. The downstream DO monitoring stations measured the greatest DO effects from the Aeration Facility at low tide, which usually occurs in the early morning hours. The nighttime aeration included the major ebb tide period each day. The measured DO increments were largest (about 1.5–2 mg/l) at the RRI station, and were almost as large (1–1.5 mg/l) at NA 42 but for shorter periods during each tidal period. The DO increments at NA 40 were about 0.5 to 1 mg/l for just a few hours each day during low tides. The DO increments were observed at the downstream stations at low tide on the first day of operation. This was apparently because the tide elevation dropped by more than 3 feet (i.e., spring tide) and moved the water from the diffuser more than 1.6 miles downstream to NA 40. 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 3–4 miles downstream of the diffuser by the second day, but did not move much farther downstream with a longer operation period. The calculations of the DO increments from the UOP boat survey DO profiles were difficult because the inflow DO was high (above saturation) and may have been increasing the DWSC DO during this testing period. Using the mid-depth DO concentrations, and adjusting the baseline DO from September 21 slightly, the added DO on the September 23–25 surveys appears to be about 10,000 pounds, which represents about 3 days of nighttime operations (3,750 lb/night). This estimate may be slightly high since there were only 4 days of nighttime operations.

Figure 32d shows the DO data from the downstream monitoring station for October 18–29, 2009. The Aeration Facility was operated for 7 days from October 19 to 26 with both U-tubes at a 3% gas/water ratio, for a capacity of about 7,500 lb/day. The measured DO increments were largest (about 1.5–2 mg/l) at the RRI station and were observed on the first day of operations during ebb tide, but were not observed after October 26 when the Aeration Facility was turned off. The estimated flow in the DWSC was about 1,000 cfs during the testing period, and this high flow moved the DO increments downstream about 1 mile each day. The DO increments at NA 42 were about 1–1.5 mg/l each day during ebb tide and were not observed after October 26. There were no DO increments observed at NA 40 for the first 3 days of operation. DO increments of about 0.5 mg/l were observed at low tide on October 23–26. The DO increments observed in the UOP boat surveys (Figure 24) indicated a more uniform downstream DO pattern, perhaps caused by increased lateral and vertical mixing from the higher flow. The DO increments were higher at the surface and mid-depth sensor only for a mile downstream. The DO concentrations were the same at each depth further downstream. Because the DO was increasing dramatically during the testing period, calculating the wedge of DO increments from the Aeration Facility was difficult (uncertain).

The combination of the DWR *San Carlos* DO surveys in the DWSC, the downstream DO monitoring stations, and the UOP boat surveys of DO profiles upstream of Turner Cut provide a consistent picture of the effects of the Aeration Facility in the DWSC. The Aeration Facility diffuser adds oxygen to the tidal mixing zone of about 2 miles beginning with an increment of about 1 mg/l in a volume of about 3,000 af during the first day. This DO increment increases with each day of operation and moves downstream with the net flow. But about 20% of the added DO is lost each day from effects of reduced surface reaeration. Therefore, the downstream wedge of added DO is decreasing (as shown in Table 2) with distance, and the maximum DO wedge will be about four times the daily capacity. The combination of monitoring methods indicates that a downstream wedge of DO increments of about 1 mg/l that extends about 3–5 miles downstream (depending on the DWSC flow) can be produced by the Aeration Facility operating with a capacity of about 7,500 lb/day. A maximum of about 25,000 pounds of added DO will be observed after five days of operation, and this maximum wedge of added DO cannot be increased because of the effects of the DO increments on the surface reaeration. The Aeration Facility can therefore be used to increase the DWSC DO by about 1 mg/l, and this added DO will likely be enough to maintain the DO objectives most of the time, because the major source of inflow BOD has been eliminated since 2007 with the completion of the City of Stockton's RWCF nitrification facility.

Fish Effects Monitoring and Laboratory Studies

At the request of NMFS, a study was conducted by the UC Davis Bodega Marine Laboratory (BML) to determine whether the Aeration Facility would cause oxidative or other damage to outward migrating juvenile salmon. Two separate studies were conducted by BML staff—a laboratory study to define specific effects of hyperoxia on juvenile salmon in the absence of other stressors, and a second field study that used the knowledge gained from the laboratory study to determine whether the U-tube oxygenation system adversely affected juvenile salmon.

The December 2010 *Oxidative Stress in Juvenile Salmon in Response to Elevated Oxygen Levels in the Stockton Deep Water Ship Channel created by the Discharge of Hyperoxic Waters from a Demonstration Aeration Facility* report presents data that show hyperoxia up to 400% DO (≈40 mg/l) for 5 days did not cause juvenile Chinook salmon mortality nor did it hinder ability of fish to withstand transfer to full-strength seawater (Cherr et al 2010). The report also shows that fish responded to hyperoxia by activating protective antioxidant mechanisms but that there was no oxidative damage to tissues or organs. Finally, results of an *in situ* hyperoxic exposure in the Stockton DWSC confirmed these results and suggested that fish are no less able to tolerate multiple stressors under hyperoxic conditions in the DWSC than they are in ambient DO water.

Cost Estimates for Long-Term Aeration Facility Operation

Based on operational testing that has been conducted for the study, costs to operate the Aeration Facility have been estimated based on current (2010) rates for electricity and LOX. Because annual operating costs are contingent on how many days per year the facility operates (based on DO conditions in the Stockton DWSC), a range of annual costs are estimated.

Figure 33a shows the amount of oxygen gas that must be supplied to operate at a range of gas/water ratios for either one-pump or two-pump operation of the Aeration Facility. The average gas-transfer efficiencies that were measured during the performance testing are also shown (these gas supply rates and gas-transfer efficiency values are also shown in Table 5). Figure 33b shows the daily amount of DO (in pounds of oxygen per day) that can be effectively delivered from the Aeration Facility diffuser to the DWSC using either one or two pumps. The daily oxygen delivery increases with higher gas supply rates (gas/water ratio), although the gas transfer efficiency decreases. Operation of the Aeration Facility would be based on the expected demand for additional oxygen in the DWSC to meet the DO objectives.

Figure 33c shows that for the current (2010) electrical cost of $0.16/kWh and LOX cost of $0.10/lb, a single pump operation cost would range from about $800 to $1,700 per day, depending on the selected gas/water ratio (oxygen delivery). A two-pump operation cost would range from $1,600 to $3,200 per day. Based on the pounds of DO that are delivered to the DWSC, operating costs per pound of oxygen delivered are shown in Figure 33d. The cost per pound delivered to the DWSC is relatively flat, because the cost of operating the pumps is fixed, so the pumping cost per pound delivered decreases with the gas supply rate. The cost per pound for the oxygen gas increases with the gas supply rate, because the efficiency decreases with the gas supply rate. Therefore, the amount of DO needed to meet the DO objective can be used to select the operating parameters each day (i.e., one or two pumps, and gas/water ratio).

As mentioned above, the annual cost of operating the facility depends on the number of operational days and the amount of oxygen delivered to the DWSC. During wet water years with relatively high summer flows, it is unlikely the facility would need to be operated for many days, so costs would be minimal. During dry years with relatively low summer flows (as observed in 2007 to 2010), it is anticipated that the facility may need to be operated for up to 100 days annually, but only about half of these days would likely require two-pump operations. This would result in annual operational costs ranging between $150,000 and $250,000. The range of cost is dependent on the oxygen demand and the oxygen gas/water supply ratio at which the facility is operated. In addition to the operational costs discussed, maintenance costs would exist for upkeep of the facility. Even when the facility does not operate, routine maintenance is required to keep the components of the facility in working condition. These costs are estimated to be in the range of $10,000–$60,000 depending on how many days per year the facility is operated (Table 8).

Table 8. Estimated Annual Maintenance Costs

		Annual Days of Operation				
	$/day	**0**	**25**	**50**	**75**	**100**
Maintenance	$ 500	10,000*	22,500	35,000	47,500	60,000

*$10,000 is the estimated minimum cost for system upkeep, assuming zero days of operation. All other estimated costs listed include this $10,000 baseline cost.

Conclusions and Recommendations

The goals for the Aeration Facility were to test the physical operation of the facility (performance) and to evaluate its ability to increase the DO concentrations in the DWSC (effectiveness). The Aeration Facility was completed in 2007, testing began in 2008, and testing was completed in September 2010. Aeration Facility performance was evaluated by measuring the facility's water flow and DO concentrations under a range of operating parameters, and Aeration Facility effectiveness was evaluated by carefully considering all available measurements of DWSC DO conditions and identifying the tidal distribution of the added oxygen from the Aeration Facility diffuser. This final report describes the Aeration Facility measurements and the DWSC monitoring data collected from 2007 to 2010, and it presents the analysis methods and the results that were used to evaluate the demonstration objectives.

A previous report described the methods and results from the first year of testing in 2008. The 2008 Operations Report (ICF International 2010) included two technical appendices that more fully describe the data analysis and modeling methods used to evaluate Aeration Facility performance and effectiveness. Appendix A describes the DWR *San Carlos* boat surveys of DO in the DWSC and describes the DWSC DO Model, which was used to evaluate these measured DWSC DO conditions. Appendix B describes the DO monitoring in the DWSC used to identify the added DO increments from the Aeration Facility. Also described is second model, the DO Increments Model, which was used to estimate the DO increments from the Aeration Facility at each of the DO monitoring stations.

Testing in 2009 and 2010 confirmed each of the analysis methods used for the 2008 testing program and provided additional evidence that the Aeration Facility performance was similar to the design parameters for efficiency and capacity and was sufficient to add a considerable amount of oxygen to the DWSC. The focus of the testing in 2009 and 2010 was the effectiveness of the Aeration Facility for increasing DWSC DO concentrations with a downstream wedge of added DO from the diffuser. The demonstration testing of the Aeration Facility has now been completed by DWR, and the future long-term operations of the Aeration Facility as part of the SJR DO TMDL implementation plan can begin in 2011.

Aeration Facility Performance Conclusions

Several performance and effectiveness objectives were established for the Aeration Facility. The Aeration Facility performance objectives and findings are summarized below and in Table 5. The major operational parameters are the choice between one-pump or two-pump operations and the selected gas/water ratio.

- Determine the Aeration Facility water flow with one-pump and two-pump operations.

  Because the two U-tubes share a common 30-inch discharge pipeline between the U-tube discharge and the diffuser (located about 1,000 feet upstream of the U-tubes), the energy loss in the discharge line is higher when both pumps are operating. Therefore, the water flow with one pump operating is about 25 cfs, but the water flow with two pumps operating is about 45 cfs (10% less than the design flow of 50 cfs).

- Determine the gas flow capacity for a range of operating pressures.

  The two gas supply lines are 1-inch diameter stainless steel pipes, and there is a considerable gas pressure loss of about 20–25 psi. Therefore, with the initial gas pressure of 45 psi that was used during 2008, a maximum approximate 4% gas/water ratio could be supplied to each U-tube. However, it was found in 2010 that the gas supply pressure could be increased to 80 psi without causing any trouble with the gas flow meters (calibrated at 45 psi) or the safety pressure valves. At this increased gas pressure, each U-tube can be supplied with more than a 6% gas/water ratio.

- Determine the gas-transfer efficiency for a range of gas/water ratios with a variety of sparger (gas injection device) designs.

  Changing sparger designs (smaller holes, more holes, open pipe, aeration hose) did not change the basic performance diagram (efficiency curve) for the Aeration Facility. The gas-transfer efficiency is reduced at higher gas/water ratios (Table 5). At a gas/water ratio of 2%, the gas-transfer efficiency is about 75%. At a gas/water ratio of 4%, the gas-transfer efficiency is about 60%, and at a gas/water ratio of 6%, the gas-transfer efficiency is about 50%.

- Determine the oxygen delivery capacity of the Aeration Facility with one-pump and two-pump operations for a range of gas/water ratios.

  The oxygen delivery capacity of the Aeration Facility for one-pump and two-pump operations depends on the gas/water ratio and the corresponding gas-transfer efficiency (Table 5). At a gas/water ratio of 2%, the capacity is about 2,500 lb/day for one-pump operations and about 4,750 for two-pump operations. At a gas/water ratio of 4%, the capacity is about 4,000 lb/day for one-pump operations and about 7,250 lb/day for two-pump operations. At a gas/water ratio of 6%, the capacity is about 5,250 lb/day for one-pump operations and about 9,500 lb/day for two-pump operations.

- Determine the possible loss of DO concentration in the discharge line when the outlet DO is greater than the oxygen saturation (about 40 mg/l).

  The possible loss of DO in the discharge line to the diffuser was evaluated at 2%, 3%, 4%, and 6% gas/water ratios with both pumps operating. The exit DO was 27 mg/l and the diffuser DO was 27 mg/l for the 2% gas/water ratio, indicating that no DO was lost along the discharge line. The exit DO was 37 mg/l and the diffuser DO was 35 mg/l with a gas ratio of 3%, suggesting that about 2 mg/l was lost along the discharge line. The exit DO was 42 mg/l and the diffuser DO was 38 mg/l with a gas/water ratio of 4%, suggesting that 4 mg/l was lost. The exit DO was 50.5 mg/l and the diffuser DO was 44 mg/l with a 6% gas/water ratio, suggesting that about 6.5 mg/l was lost along the discharge line. These discharge pipe DO measurements indicate that increasing the gas/water ratio above 4% would not be effective in increasing the delivered DO to the DWSC, because about half of the discharge DO concentration above 40 mg/l will be lost in the discharge line.

- Determine the most cost-effective operating regime for a range of required DO delivery rates (lb/day).

  The results of the facility testing demonstrated that the gas-transfer efficiency was reduced at higher gas/water ratios. However, the capacity of the Aeration Facility to deliver increased DO to the DWSC will be increased with higher water flow and with a higher gas/water ratio. The estimated operating costs for the full range of operating parameters (Table 5) indicates that

2,500 lb/day can be delivered with one pump at 2% gas/water ratio for about $1,000 per day. About 5,000 lb/day can be delivered with one-pump at about 5% gas/water ratio, except that the discharge DO would be higher than 40 mg/l and some of the added DO would likely be lost in the discharge line. Therefore, the best operations for delivering 5,000 lb/day would likely be two pumps at 2% gas/water ratio for about $2,000 per day. About 7,500 lb/day can be delivered with two pumps at 4.5% gas/water ratio for about $2,750 per day. The design capacity of 10,000 lb/day could likely be delivered with two-pumps at 7% gas/water ratio, to compensate for some of DO concentration above 40 mg/l that would be lost in the discharge line. The cost would therefore be about $3,500 per day. The most cost-effective operating regime would be a 3–5% gas/water ratio, and the combined cost for electrical power and liquid oxygen would be about $0.35/lb of DO added to the DWSC.

Aeration Facility Effectiveness Conclusions

The effectiveness objectives were tested and evaluated in the 2008–2010 demonstration period. Each of the DWSC monitoring methods (DO monitoring, UOP longitudinal DO profiles, City of Stockton water quality sampling, and DWR *San Carlos* DO surveys) contributed to testing and evaluating the Aeration Facility effectiveness objectives. The effectiveness objectives and findings are summarized below. The overall effectiveness was summarized for a range of DWSC flows in Table 6.

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

  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 operating 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.

  Because the RRI station is located near the minimum natural DO concentrations in the DWSC, the construction of the 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 NAs 43 and 48. The majority of the added DO was observed from slightly downstream of the diffuser to NA 42. Some added DO from the Aeration Facility was observed downstream at NA 40.

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

  The DWSC DO Model was calibrated with DWR *San Carlos* surveys and used to demonstrate the downstream effects of the Aeration Facility for a range of flows between 250 cfs and 1,500 cfs (Table 6). 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.

  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.

  Results from DO longitudinal profiles measured by the UOP boat surveys suggest that a maximum of about 30,000 pounds 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 objective of 5 mg/l from December 1 through August 31 and 6 mg/l from September 1 through November 30.

  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, the added DO from the Aeration Facility may not be sufficient to meet the Basin Plan DO objectives in all future situations.

  Table 6 shows the incremental DO effects of the Aeration Facility in the DWSC as a function of the daily delivery of oxygen (lb/day) and the net flow in the DWSC. However, the resulting DO profile in the DWSC with the Aeration Facility operating will depend on the natural DO profile that is a function of the DWSC flow and the inflow DO and BOD concentrations. A higher inflow BOD concentration will cause a lower-than-minimum DO in the DWSC. The DWSC DO model, with a surface reaeration rate of 20%, suggests that an increase of 4 mg/l of BOD will lower the minimum DO in the DWSC by about 1 mg/l. Figure 6 shows results from the DWSC DO model and indicates that a higher flow will move the location of the minimum DO downstream, but will not change the minimum DO concentration, which is controlled by the inflow BOD concentration. The effects of the Aeration Facility on DO in the DWSC can be generally summarized with the combination of the natural DO profiles (Figure 6) and the incremental DO effects (Table 6).

The Aeration Facility has an oxygen delivery capacity of about 7,500 lb/day, and the maximum added DO in the DWSC is limited by the effects from natural reaeration to about 4 days of oxygen delivery, or about 30,000 pounds. Table 6 shows the downstream distribution of the added DO from the Aeration Facility for flows of 250 cfs to 1,500 cfs. Comparison with Figure 6 shows that this added DO will generally be sufficient to increase the natural DO profile to meet the DO objective of 5 mg/l for inflow BOD concentrations of less than 16 mg/l with an inflow DO concentration of about 6 mg/l. It is likely that with the Stockton RWCF nitrification facility operating, the inflow BOD will be less than 16 mg/l, so the Aeration Facility will likely be able to raise the minimum DWSC DO to maintain the DO objective of 5 mg/l. It may be more difficult to meet the September DO objective of 6 mg/l because water temperature is still relatively warm and the saturated DO concentration is still about 8 mg/l. An inflow BOD concentration of more than 12 mg/l will cause a minimum DO concentration of about 5 mg/l, and the Aeration Facility will be needed to raise the DO to 6 mg/l. Review of the DO monitoring data indicates that the Aeration Facility capacity of 7,500 lb/day would have been adequate to meet the DO objectives for the past 4 years, 2007–2010.

The net flow in the DWSC has been less than 250 cfs for many periods in the summer months of 2007–2010. During these low flow conditions, tidal mixing will distribute the added DO from the Aeration Facility into about 3 miles of the DWSC surrounding the diffuser (1.5 miles upstream and 1.5 miles downstream). Under low flow conditions (less than 250 cfs), all of the Stockton RWCF effluent will be transported into the DWSC, but very little of the upstream river algae from Mossdale will enter the DWSC. Therefore, the inflow BOD concentration will be relatively low and the observed minimum DO will not likely be much less than 5 mg/l (as observed in 2007–2010). Although the DWSC DO model will not accurately calculate the DO profile for a net flow of 0 cfs, the natural DO profile will likely be uniform or slowly increasing downstream. If the Aeration Facility is operated, the added DO will be tidally distributed in a triangle, about 1.5 miles upstream and 1.5 miles downstream of the diffuser. If operated with a delivery of 7,500 lb/day, about 30,000 pounds of oxygen will be distributed in these 3 miles (with a volume of 5,000 af) of the DWSC. The average DO increment would be about 2 mg/l and the maximum DO increment would be about 4 mg/l near the diffuser.

For a reverse flow condition, the water entering the DWSC from downstream will be Sacramento River water with very little BOD, and the effluent form the Stockton RWCF will be tidally transported upstream. Therefore, the minimum DO in the DWSC will likely be greater than 6 mg/l during the summer (with a saturated DO of 8 mg/l), and there will be no need to operate the Aeration Facility. However, unless this reverse flow can be maintained all of the time, to dilute the RWCF effluent and transport it upstream to Old River and the export pumping plants, a minimum flow of about 250 cfs should be maintained in the DWSC.

Recommendations for Future Operations

Based on the successful operational testing of the Aeration Facility from 2008 to 2010, there are three general recommendations for the future long-term operations of the Aeration Facility. These three recommendations are listed and briefly discussed below.

(1) The Aeration Facility could be a major component of the TMDL implementation plan for achieving the Basin Plan DO objective in the DWSC when the river flow and inflow DO and BOD concentrations would have resulted in low-DO conditions. TMDL "accounting procedures" for

identifying the likely causes for low-DO conditions in the DWSC could be developed but would have to be accepted by the CVRWQCB as well as affected stakeholders.

(2) A long-term monitoring strategy should be developed as part of the TMDL implementation plan to identify periods when the Aeration Facility should be operated and to confirm that the added DO was sufficient to achieve the DWSC DO objective. The monitoring strategy should include all data needed for the TMDL accounting procedures.

(3) Several modifications to the Aeration Facility should be further evaluated to increase the capacity to deliver added DO to the DWSC or to improve the distribution of added DO upstream of the diffuser. For example, the discharge from the two U-tubes could be separated, with a second discharge line and diffuser extended upstream 0.5 miles to distribute more of the added DO upstream of the existing diffuser.

Aeration Facility Operating Strategy

The Aeration Facility will likely be operated when the natural DO concentrations in the DWSC decrease to approach the DO objective of 5 mg/l (6 mg/l from September through November). The Aeration Facility likely will not be operated when DWSC flows are greater than about 1,000 cfs because the observed DO concentrations are generally above 5 mg/l when the flows are this high. An operational strategy that uses a combination of DWSC DO monitoring and upstream water quality monitoring to forecast periods of reduced DO in the DWSC would be helpful for operating the Aeration Facility as part of the SJR DO TMDL implementation plan. Operating the Aeration Facility during periods of reduced DO concentrations will likely be the most cost-effective approach for long-term TMDL implementation. The possible integration of the Port of Stockton aerators 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.

A review of the 2007–2010 daily average DO from the five DWSC DO monitoring stations (Figures 8a to 8d) indicates that the natural DO conditions were often slightly above the DO objective of 5 mg/l during the summer months of June-August. The DO was not usually above the 6 mg/l DO objective in September. The period of time when the Aeration Facility would have been operated as part of the SJR DO TMDL implementation can be identified from the daily average DO at each station. If the assumed trigger for operations was 0.5 mg/l above the DO objective, then the number of days the Aeration Facility would have been operated can be estimated from the daily average DO concentrations.

Table 9 gives a summary of these calculations for each of the five monitoring stations during the June-September period for 2007 to 2010. The monthly average DO at each monitoring station is given on the left hand side of the table, and the number of days that the DO was below the objective (plus a 0.5 mg/l buffer) is given on the right hand side of the table. The number of days of Aeration Facility testing operations each month is given in the far right hand column. Because the DO concentrations are different at each station, the number of days of Aeration Facility operations would depend on which station(s) are used to control the operation. For example in 2007, the total number of days of likely operations ranged from 56 days (for NA 48) to 109 days (for RRI).

Table 9. Summary of Potential Aeration Facility Operations for Historical Conditions in June-September of 2007-2010

		Average Monthly DO Concentration (mg/l)					Potential Days of Aeration Facility Operation (days with DO less than the objective plus 0.5 mg/l)					Days of Aeration Testing
Year	**Month**	**NA 40**	**NA 42**	**RRI**	**NA 43**	**NA 48**	**NA 40**	**NA 42**	**RRI**	**NA 43**	**NA 48**	
2007	June	4.8	4.8	4.1	5.4	6.6	21	20	26	14	6	0
	July	4.9	4.8	4.4	4.8	5.0	31	31	31	31	25	0
	August	5.4	5.6	5.2	5.3	5.8	20	14	24	21	10	0
	September	5.8	5.7	5.7	5.2	6.3	28	30	28	12	15	0
							100	**95**	**109**	**78**	**56**	**0**
2008	June	5.8	5.7	5.8	5.5	4.6	6	7	12	13	28	11
	July	6.2	6.1	6.6	6.3	5.5	0	0	0	1	16	22
	August	6.2	6.6	6.7	6.7	5.8	0	0	0	0	2	20
	September	6.8	7.1	7.0	6.9	6.7	9	8	10	8	12	16
							15	**15**	**22**	**22**	**58**	**69**
2009	June	6.2	5.8	5.6	5.7	5.5	0	0	13	12	16	0
	July	6.1	5.8	5.6	5.7	5.4	0	0	9	5	23	0
	August	6.0	6.0	5.7	5.7	5.5	0	0	5	4	15	0
	September	6.0	6.1	6.3	6.2	6.4	25	25	21	18	15	9
							25	**25**	**48**	**39**	**69**	**9**
2010	June	7.1	7.2	7.3	7.3	7.4	0	0	0	0	0	0
	July	6.1	6.1	6.0	5.8	6.0	1	3	8	11	10	0
	August	6.2	6.1	5.9	5.5	5.5	0	0	7	15	12	11
	September	6.7	6.8	6.5	6.5	6.8	9	10	15	12	6	8
							10	**13**	**30**	**38**	**28**	**19**

Figure 8a indicates that the daily average DO concentration were generally less than 5.5 mg/l during the second half of June, all of July, half of August, and were less than 6.5 mg/l all of September 2007 at most monitoring stations. The period of operation would have therefore been about 90 days in 2007. Because the Aeration Facility can increase the DWSC DO concentrations by about 1 mg/l, the DO objectives could likely have been fully met in 2007 with Aeration Facility operations. The lowest DO was measured in the second half of June, with a minimum of 4 mg/l at most stations (3 mg/l at RRI). If the September objective were reduced to 5 mg/l, the Aeration Facility would not likely have been operated for the second half of September 2007.

The period of time when the Aeration Facility would likely have been operated in 2008 as part of the SJR DO TMDL implementation can be identified from Figure 8b (and Table 9). When the Aeration Facility was operated for testing in 2008, the DO concentrations at most of the monitoring stations was increased by at least 1 mg/l, and this must be considered (subtracted) when estimating the natural DO concentrations without the Aeration Facility DO increments. The Aeration Facility would likely have been operated for most of June and July, and the first half of August, but not the second half of August (because the natural DO was above 5.5 mg/l). The Aeration Facility would likely have been operated in September, unless the DO objective was reduced to 5 mg/l. Table 9 shows that the DO objectives were generally satisfied in June, July and August of 2008, but this was influenced by the Aeration Facility testing operations for many days in these months. It appears that the Aeration Facility would have operated for 75 to 90 days during 2008. The DO objective would likely have been satisfied during all of 2008 if the Aeration Facility had been operated as part of the TMDL implementation.

The period of time when the Aeration Facility would have been operated in 2009 as part of the SJR DO TMDL implementation can be identified from Figure 8c (and Table 9). The natural DO concentrations were above 5 mg/l for all of June, July, and August, but not always above 5.5 mg/l. The Aeration Facility would likely have been operated with at least one pump (half capacity) for portions of these 3 months. One pump operation would likely have also been needed during September 2009 (as was tested for 2 weeks), unless the DO objective was reduced to 5 mg/l. Table 9 indicates that the Aeration Facility would have been operated for 45 to 75 days during 2009. The DO objective would likely have been satisfied during all of 2009 if the Aeration Facility had been operated as part of the TMDL implementation.

The period of time when the Aeration Facility would have been operated in 2010 as part of the SJR DO TMDL implementation can be identified from Figure 8d (and Table 9). The natural DO concentrations were above 5.5 mg/l for all of June and most of July, when the DWSC flows were greater than 500 cfs. The Aeration Facility would likely have been operated with at least one pump (half capacity) for the second half of July, most of August, and the first half of September 2010. Table 9 indicates that the Aeration Facility would have been operated for about 50 days during 2010. No Aeration Facility operation would have been needed in September if the DO objective was reduced to 5 mg/l. The DO objective would have been satisfied during all of 2010 if the Aeration Facility had been operated as part of the TMDL implementation.

Procedures for identifying the relative contributions from the possible causes of low DO in the DWSC (i.e., reduced flows, upstream algae, RWCF effluent, and DWSC geometry) could be developed but would need to be accepted by CVRWQCB as part of the TMDL implementation plan. Appendix A of this report provides additional information about a possible TMDL "accounting procedures" that could be used to identify the likely causes for periods with DWSC below the DO, as well as the likely benefits achieved with the Aeration Facility and other TMDL implementation measures (i.e., the nitrification facility). The TDML accounting procedures would require daily monitoring of various flows, water quality parameters, and effluent concentrations, in addition to DO concentrations in the DWSC at several locations.

Long-term Monitoring Strategy

A long-term TMDL monitoring strategy should be developed for the DWSC based on the 2007–2010 DO monitoring at NA 48, NA 43, RRI, NA 42, and NA 40 stations. The operational strategy for the Aeration Facility will also likely require upstream SJR flow and water quality monitoring at Mossdale or Vernalis to forecast the DWSC DO profile and the need to operate the Aeration Facility with a specified oxygen delivery capacity (lb/day).

The monitoring strategy should also provide confirmation that the Aeration Facility operations, or other TMDL implementation measures, were sufficient to raise the minimum DWSC DO to above the DO objective. 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. The historic RRI data therefore may be representative of minimum DO conditions in the DWSC upstream of Turner Cut. Because the RRI station is just 0.2 mile downstream of the diffuser, it also measures the greatest response to added DO from the Aeration Facility. The mid-depth sensor (10 feet deep at low tide) at the RRI station might provide a better estimate of the average DWSC DO conditions, because it would be less influenced by stratification and algae photosynthesis. It should be possible to evaluate the natural DO conditions while the Aeration Facility is operating by estimating and subtracting the incremental DO effects from the RRI monitoring station DO records, using the DO Increments Model.

The TMDL monitoring strategy should integrate the City of Stockton's river samplings stations. This would consolidate the monitoring requirements from two CVRWQCB programs and provide an improved understanding of the water quality conditions in the DWSC.

Aeration Facility Improvements

Several improvements to the Aeration Facility should be considered. For example, the diffuser performance might be improved if about half the ports were closed to produce a higher jet velocity and better lateral mixing. Because there are more gas bubbles in the discharge line than anticipated (lower gas-transfer efficiency), the diffuser mixing might be improved if bubble "escape tubes" were added to the top of the diffuser. These vertical tubes would allow bubbles to escape prior to being discharged from the ports, which causes the discharge water to rise towards the surface layer.

Another improvement that should be considered is separating the discharges from the two U-tubes, and extending a second discharge line and diffuser upstream 0.5 miles to distribute more of the added DO upstream of the existing diffuser. This design would maintain the full discharge capacity of the existing diffuser with one pump (25 cfs) and one U-tube. The second U-tube would discharge to a new discharge line and second (upstream) diffuser.

These recommendations for an operational strategy, a monitoring strategy, and possible improvements in the Aeration Facility should be considered as the Aeration Facility transitions to long-term operations as part of the SJR DO TMDL implementation to meet the DWSC DO objective.

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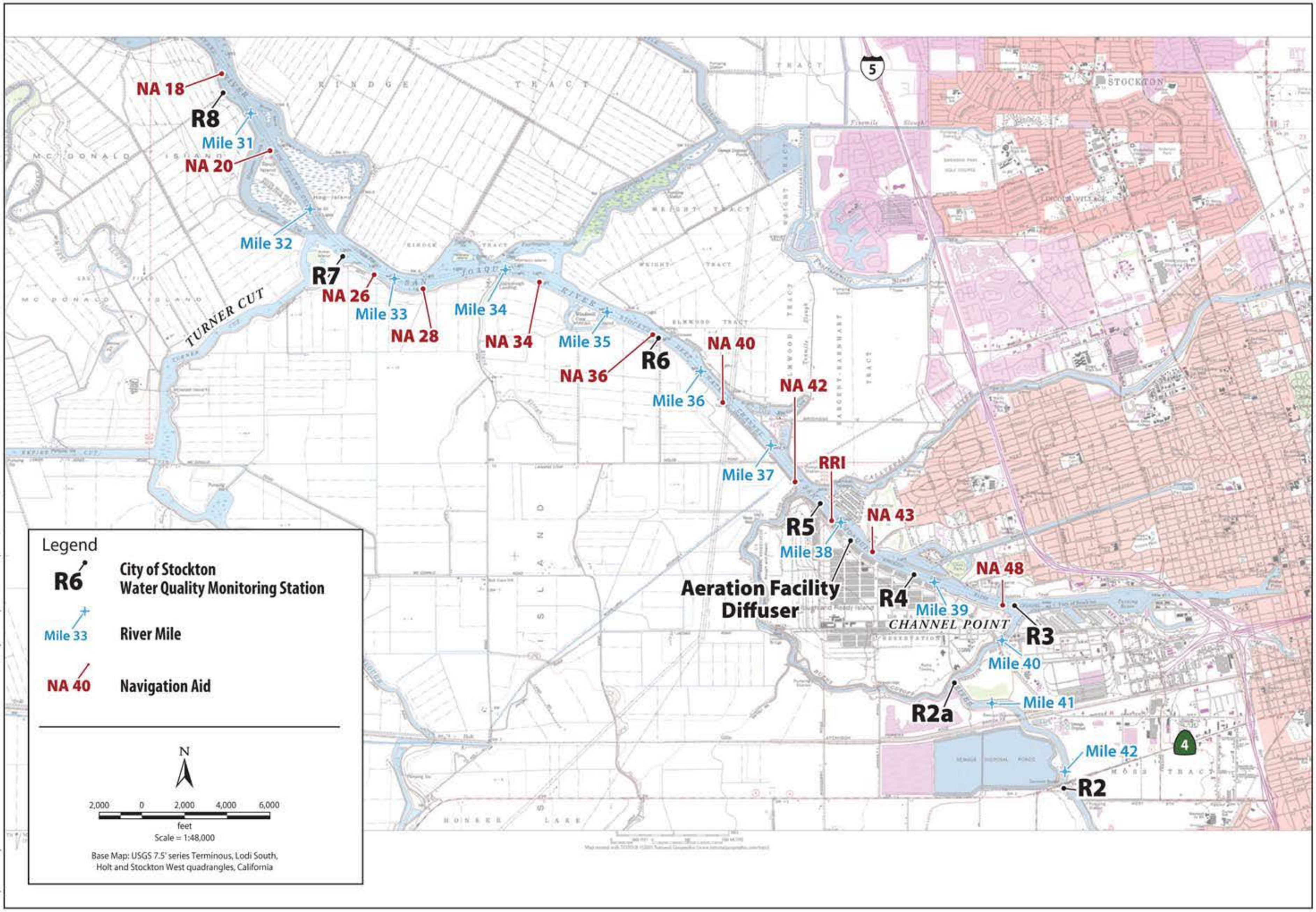

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Figure 1
Stockton DWSC Water Quality Monitoring Stations

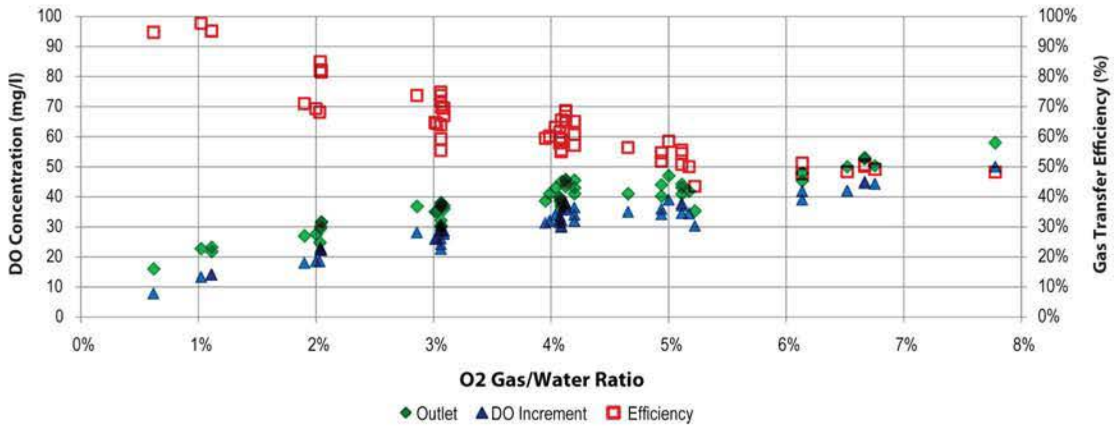

Figure 2a: Testing of Oxygen Gas Transfer Efficiency for Drilled Hole Sparger with Two Pump Operation

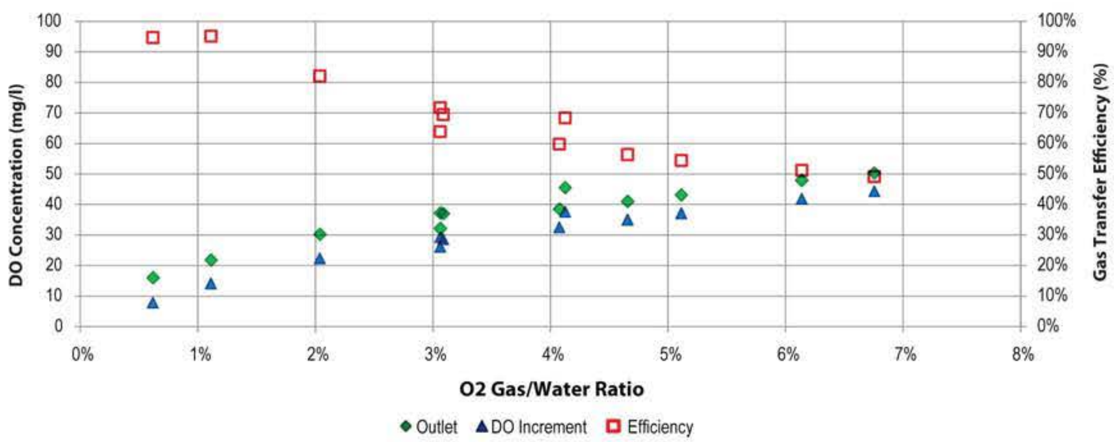

Figure 2b: Testing of Oxygen Gas Transfer Efficiency for Aeration Hose Sparger with Two Pump Operation

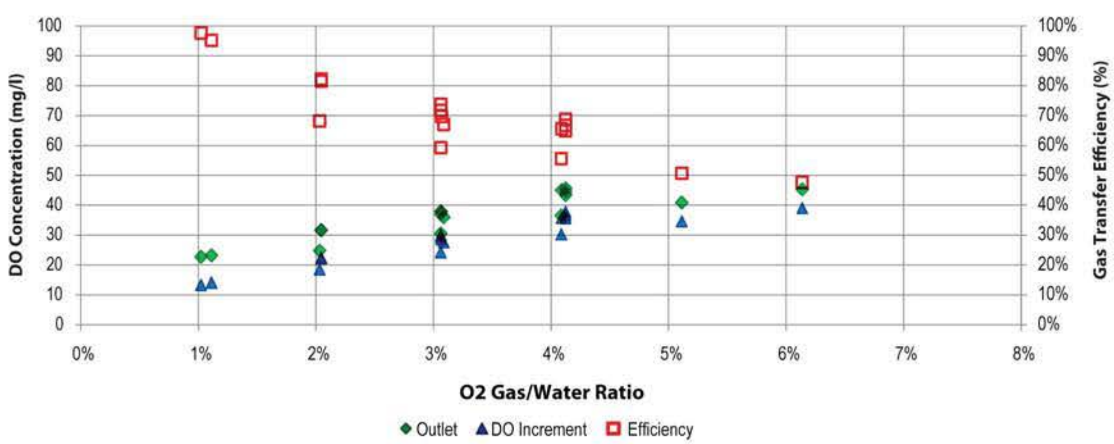

Figure 2c: Testing of Oxygen Gas Transfer Efficiency for Open Pipe Sparger with Two Pump Operation

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Figure 2

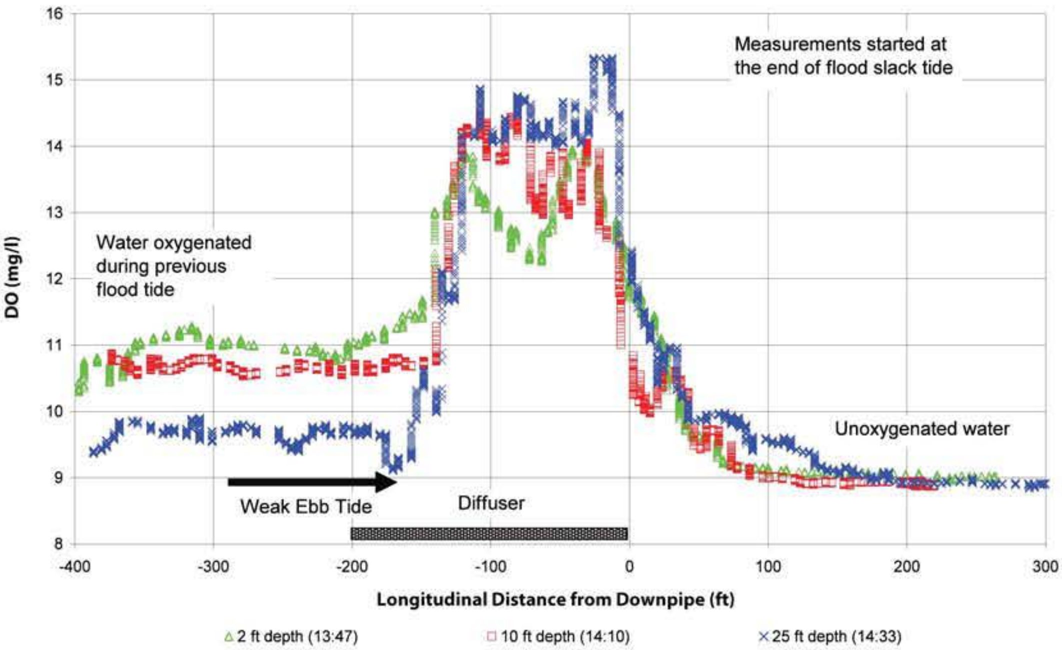

Figure 3a: Longitudinal DO Profiles Measured 15–20 Feet from Diffuser on April 30, 2008

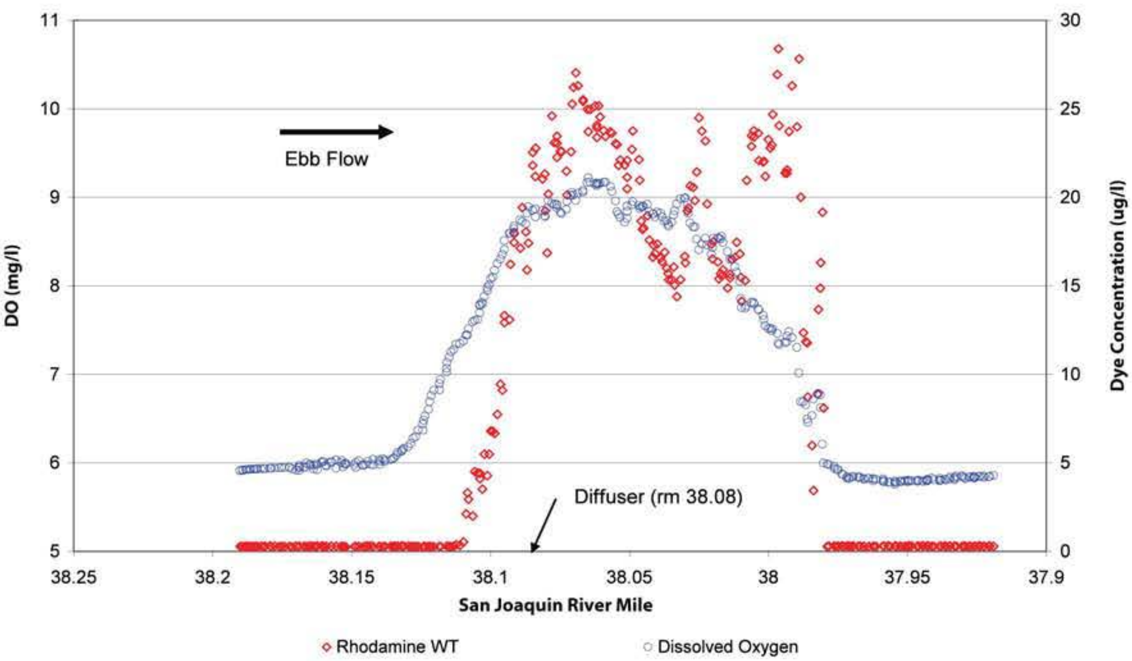

Figure 3b: Longitudinal Dye and DO Concentration Profiles along Mid-channel Measured at 10-foot Depth after First Dye Injection of August 16, 2008

Figure 3

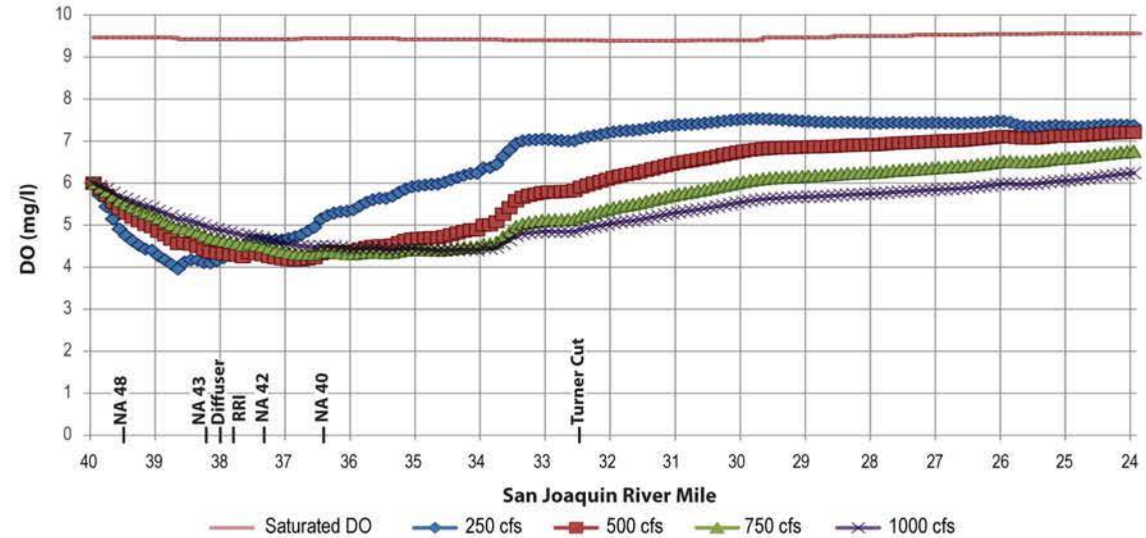

Figure 4a: Sensitivity of DWSC Longitudinal DO Profile to Flow for 250–1,000 cfs with BOD of 12 mg/l and 20% Reaeration Rate

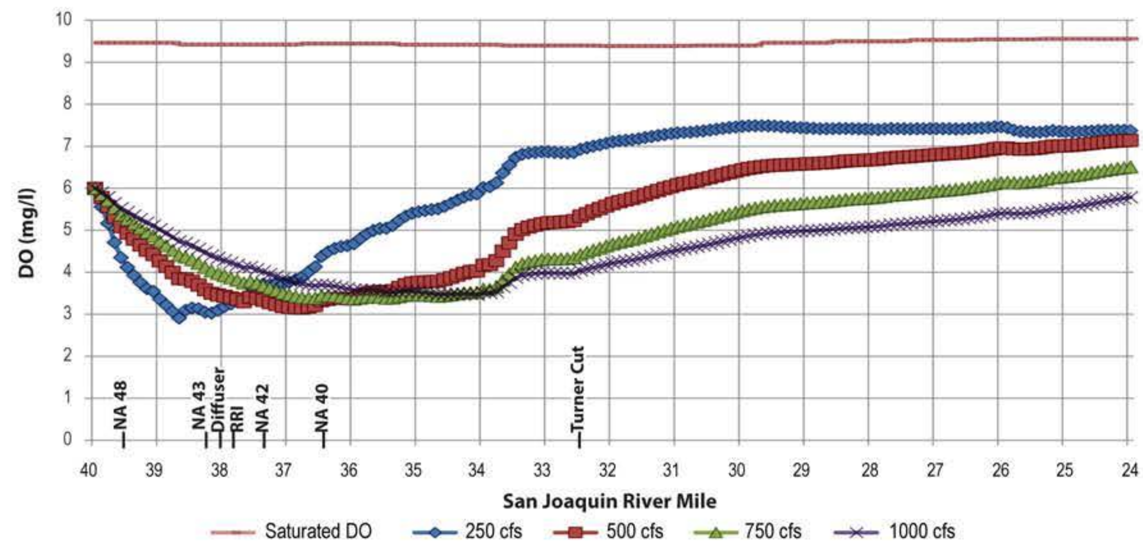

Figure 4b: Sensitivity of DWSC Longitudinal DO Profile to Flow for 250–1,000 cfs with BOD of 16 mg/l and 20% Reaeration Rate

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Figure 4

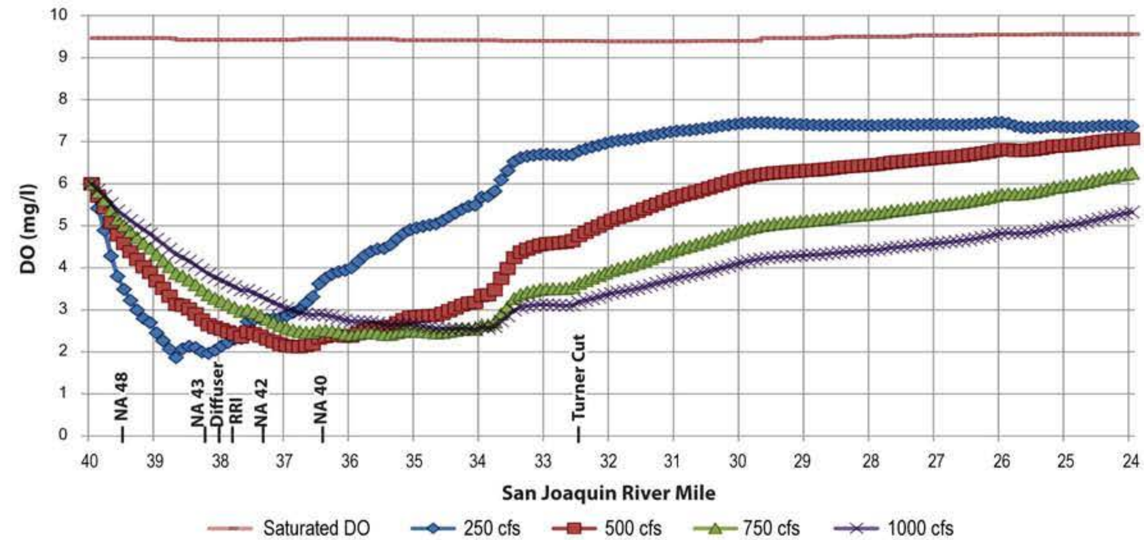

Figure 4c: Sensitivity of DWSC Longitudinal DO Profile to Flow for 250–1,000 cfs with BOD of 20 mg/l and 20% Reaeration Rate

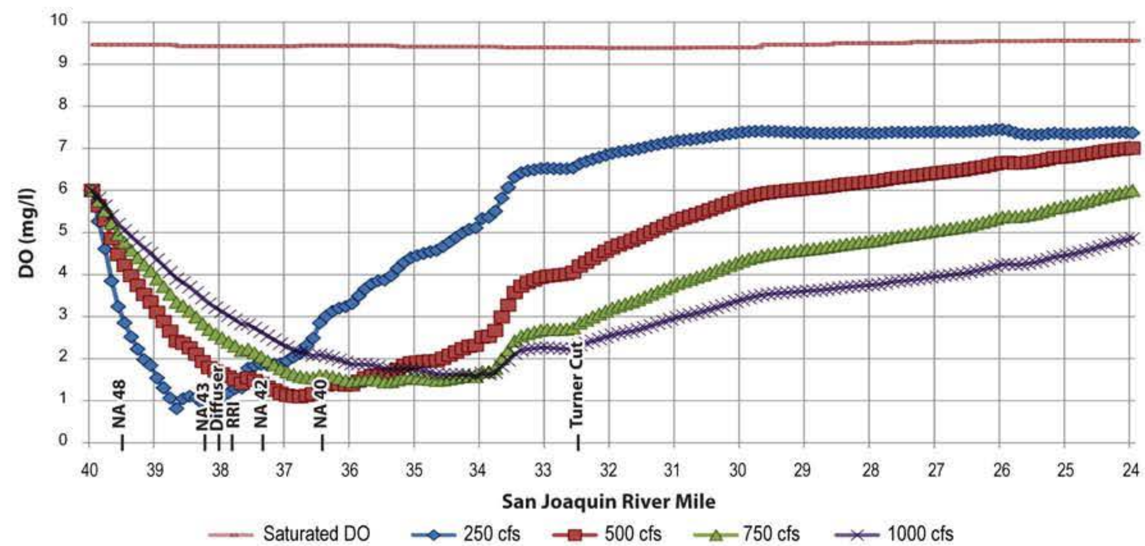

Figure 4d: Sensitivity of DWSC Longitudinal DO Profile to Flow for 250–1,000 cfs with BOD of 24 mg/l and 20% Reaeration Rate

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Figure 4 (continued)

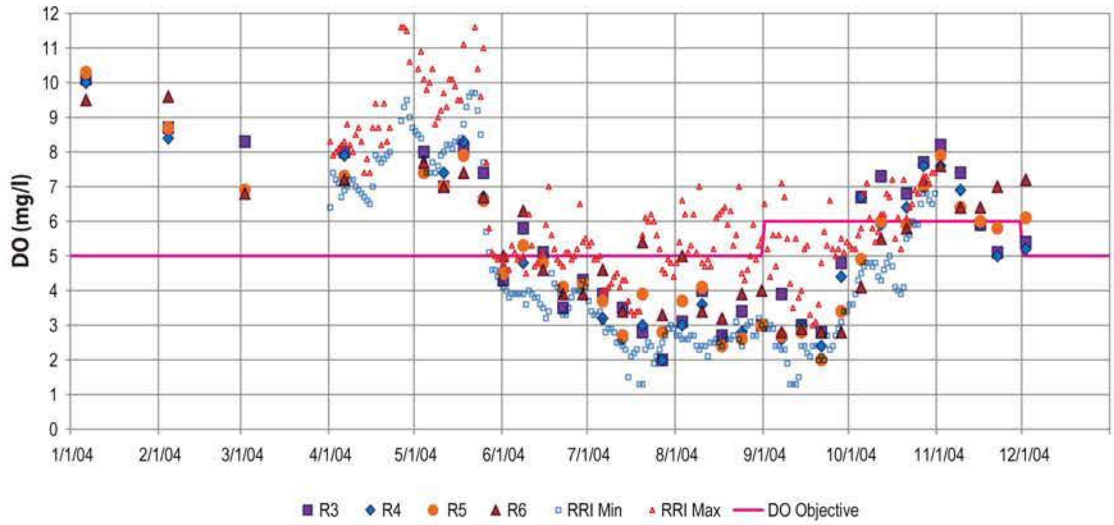

Figure 5a: City of Stockton DO Measurements in the DWSC (R3–R6) Compared to the Daily Minimum and Maximum DO at the RRI Station for 2004

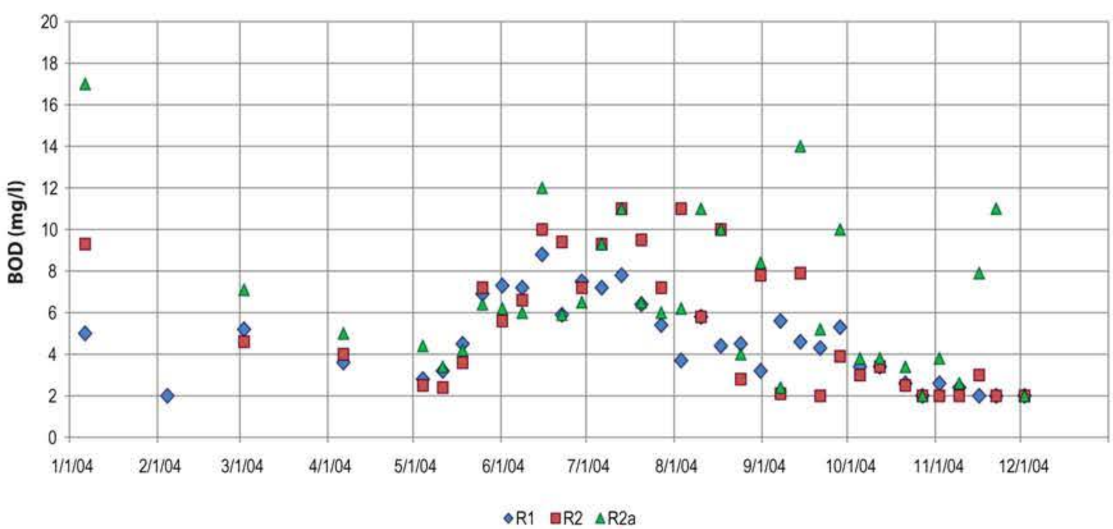

Figure 5b: City of Stockton Measurements of SJR 10-day BOD Concentrations (mg/l) at R1 R2 and R2a in 2004

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Figure 5

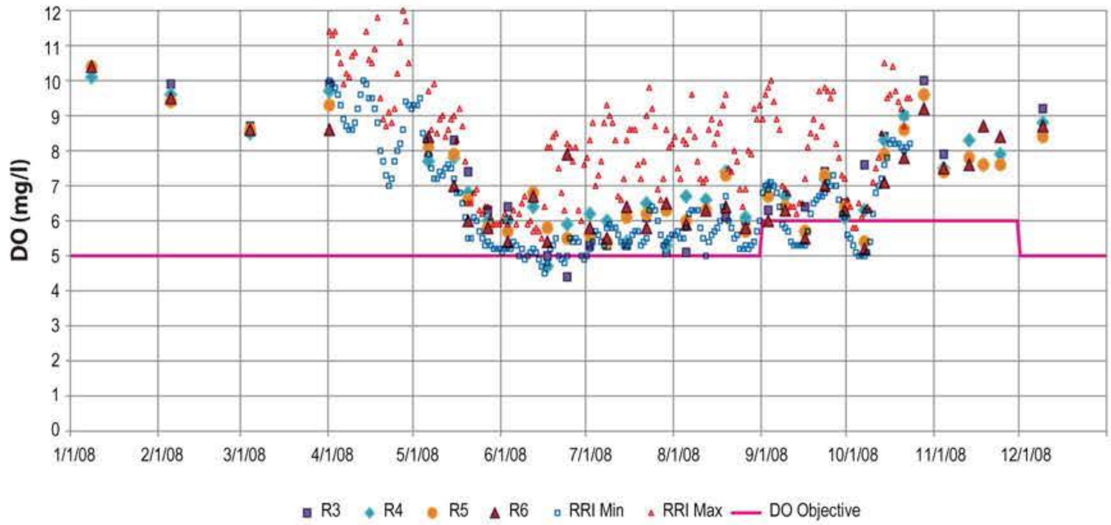

Figure 5c: City of Stockton DO Measurements in the DWSC (R3–R6) Compared to the Daily Minimum and Maximum DO at the RRI Station for 2008

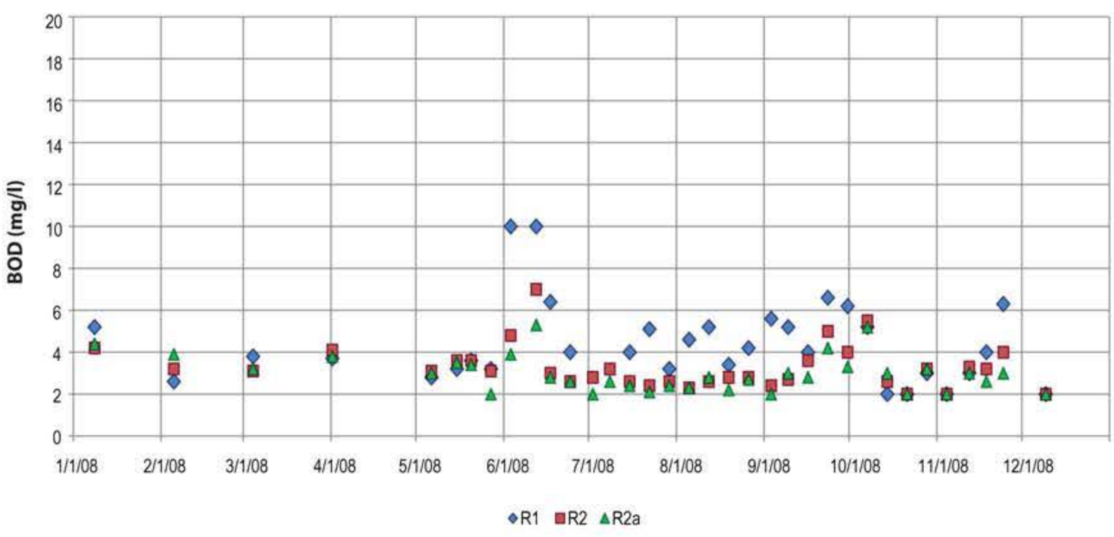

Figure 5d: City of Stockton Measurements of SJR 10-day BOD Concentrations (mg/l) at R1 R2 and R2a in 2008

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Figure 5 (continued)

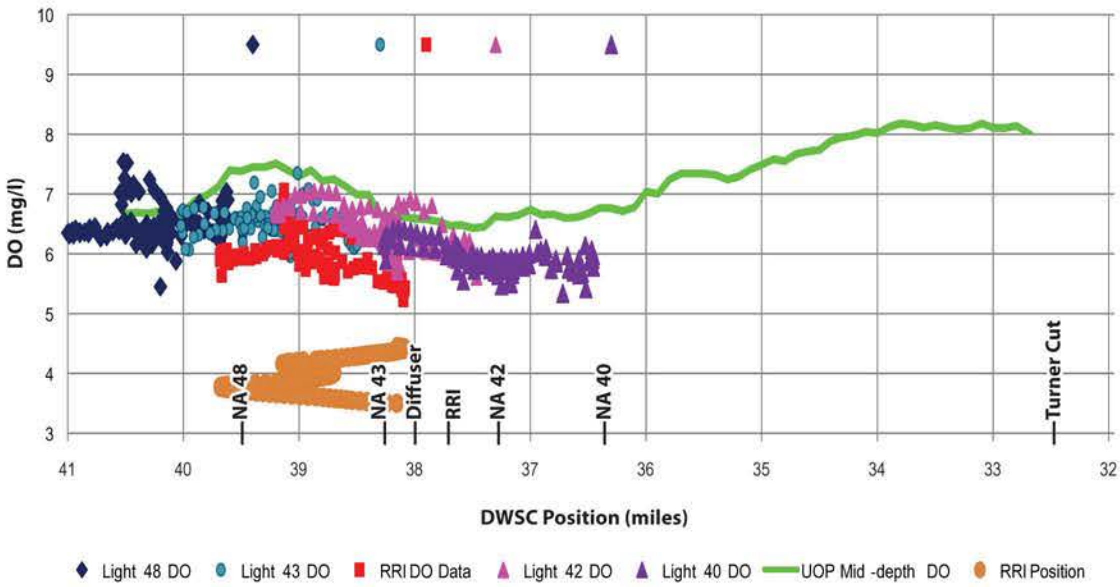

Figure 6a: Example of Estimated Longitudinal DO Profile from DO Monitoring Data Compared to UOP Boat Survey at High Tide on September 11, 2009 (After 4 days of Flood-tide Operations)

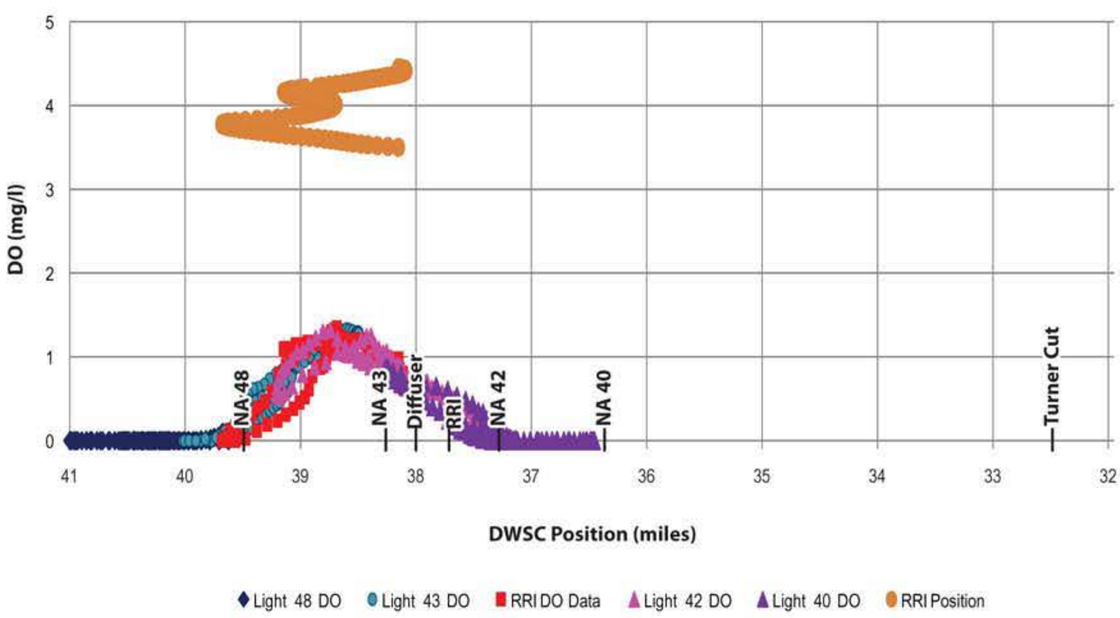

Figure 6b: Example of Calculated Longitudinal Distribution of DO Increments at High Tide on September 11, 2009 (After 4 days of Flood-tide Operations)

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Figure 6

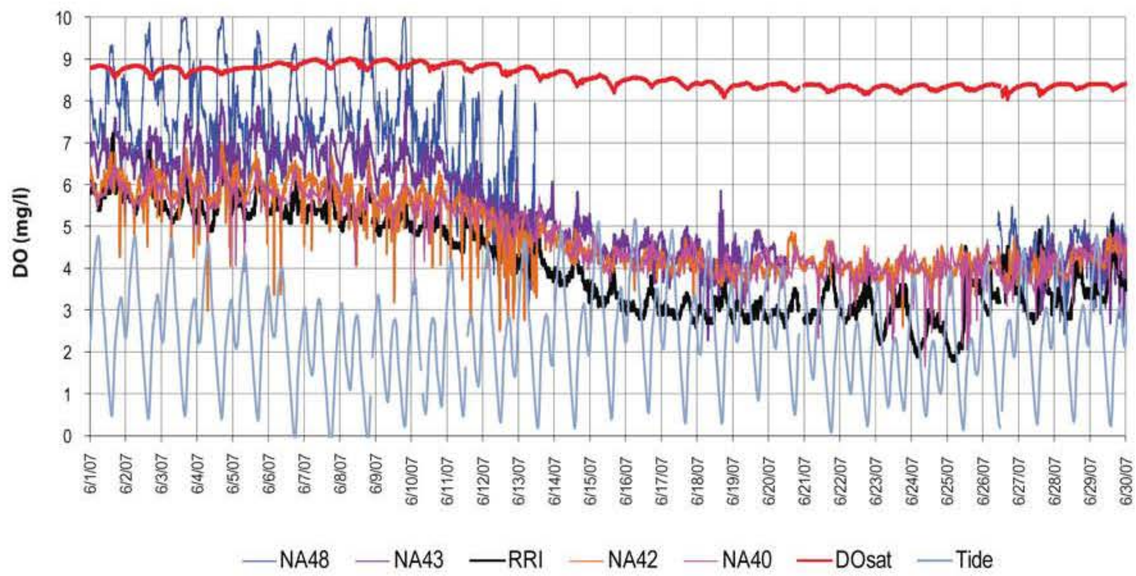

Figure 7a: Measured DO at the DWSC Monitoring Stations in the DWSC during June 2007

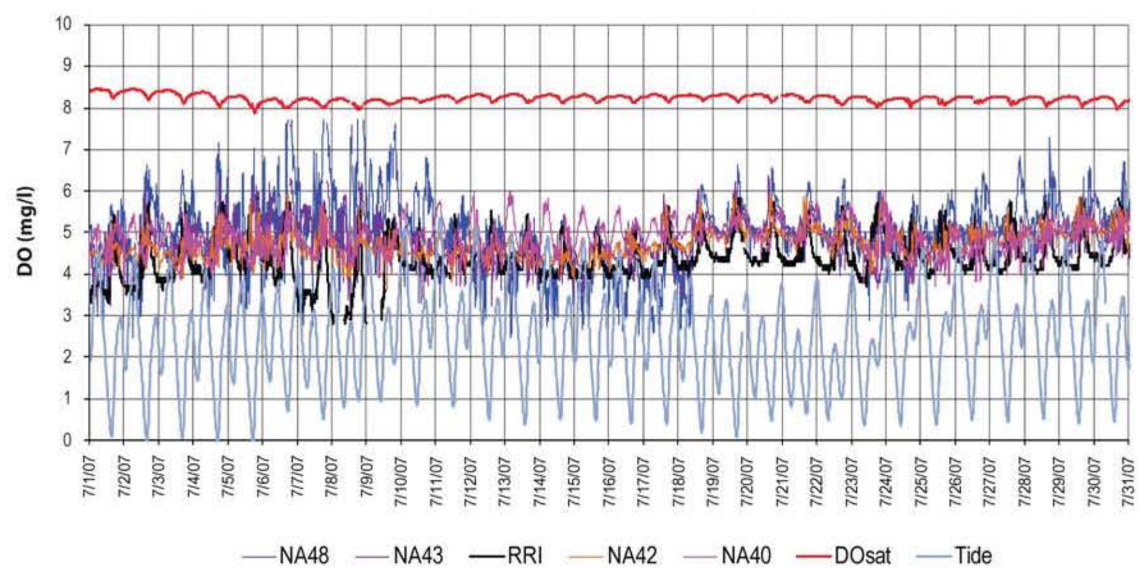

Figure 7b: Measured DO at the DWSC Monitoring Stations in the DWSC during July 2007

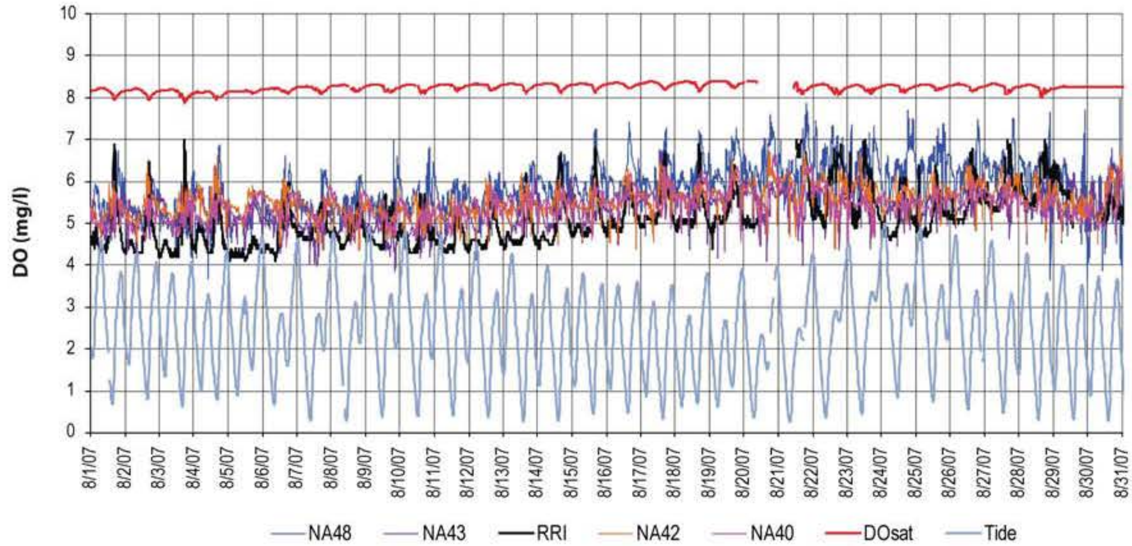

Figure 7c: Measured DO at the DWSC Monitoring Stations in the DWSC during August 2007

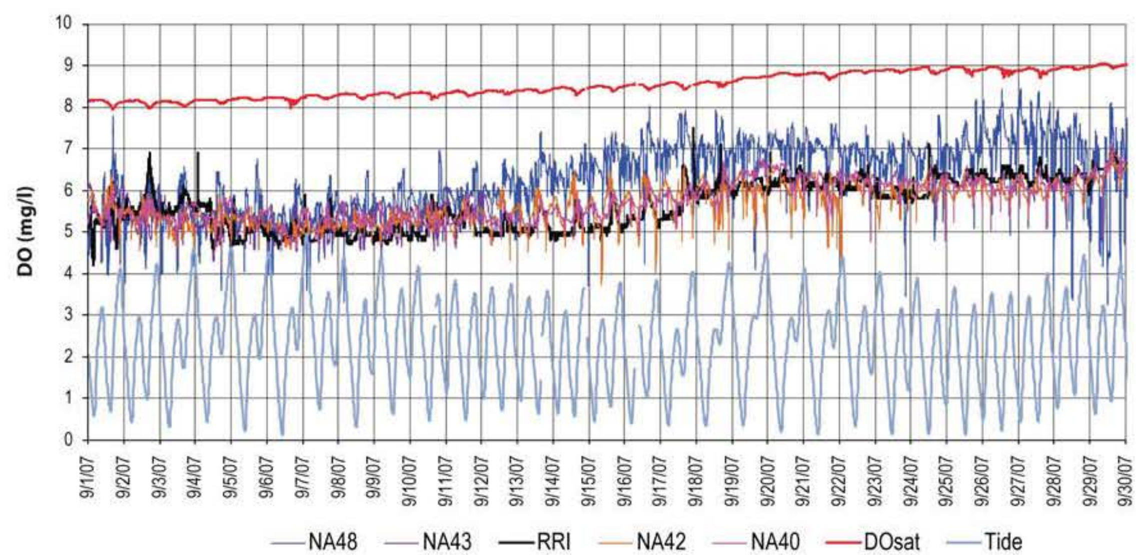

Figure 7d: Measured DO at the DWSC Monitoring Stations in the DWSC during September 2007

Figure 7 (continued)

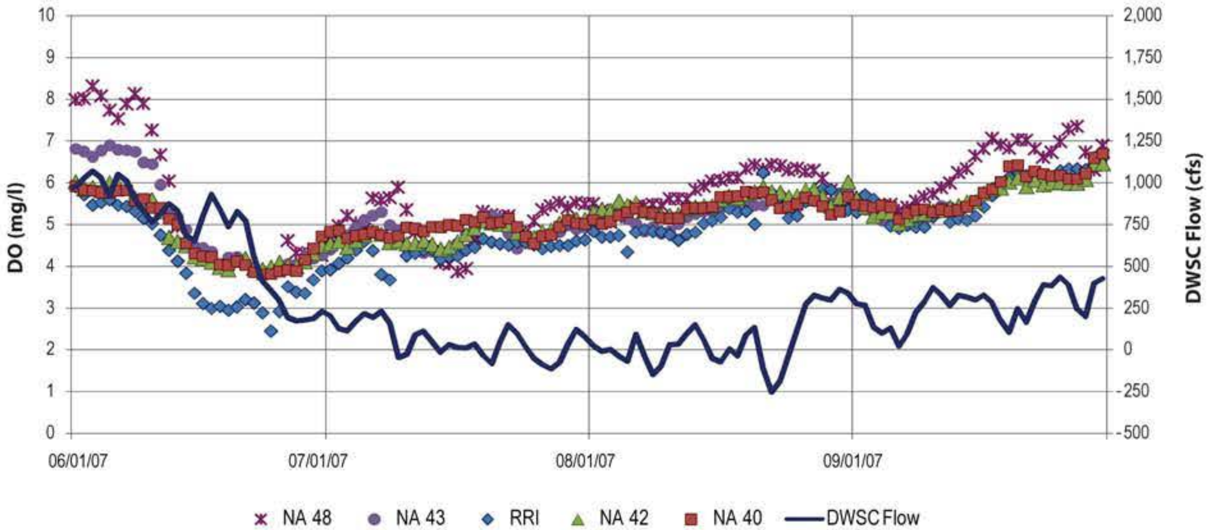

Figure 8a: Daily Average DO at the DWSC Monitoring Stations in June–September 2007

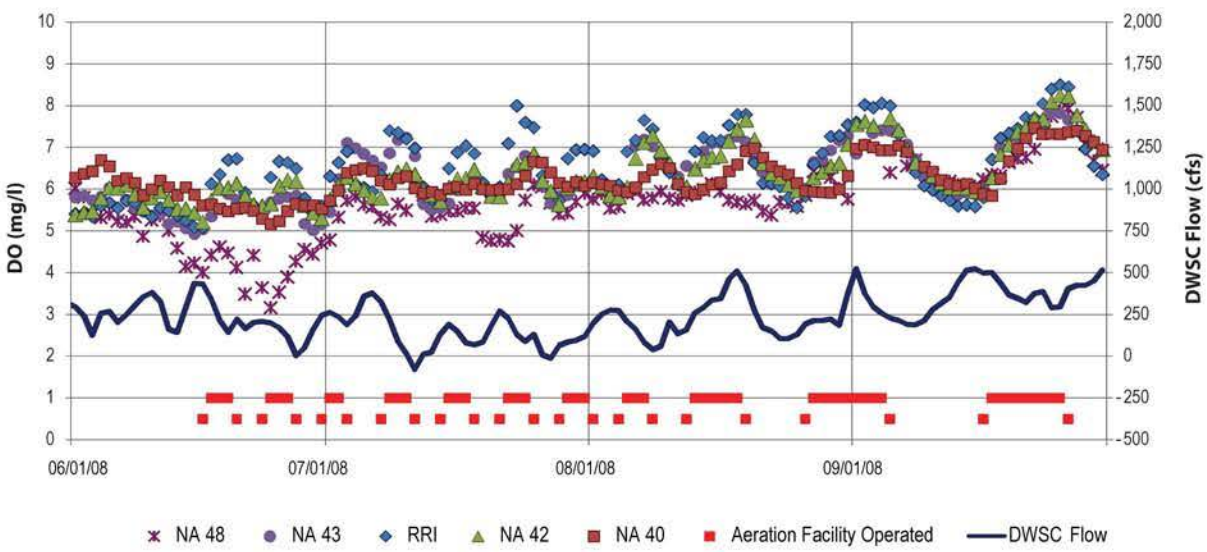

Figure 8b: Daily Average DO at the DWSC Monitoring Stations in June–September 2008

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Figure 8

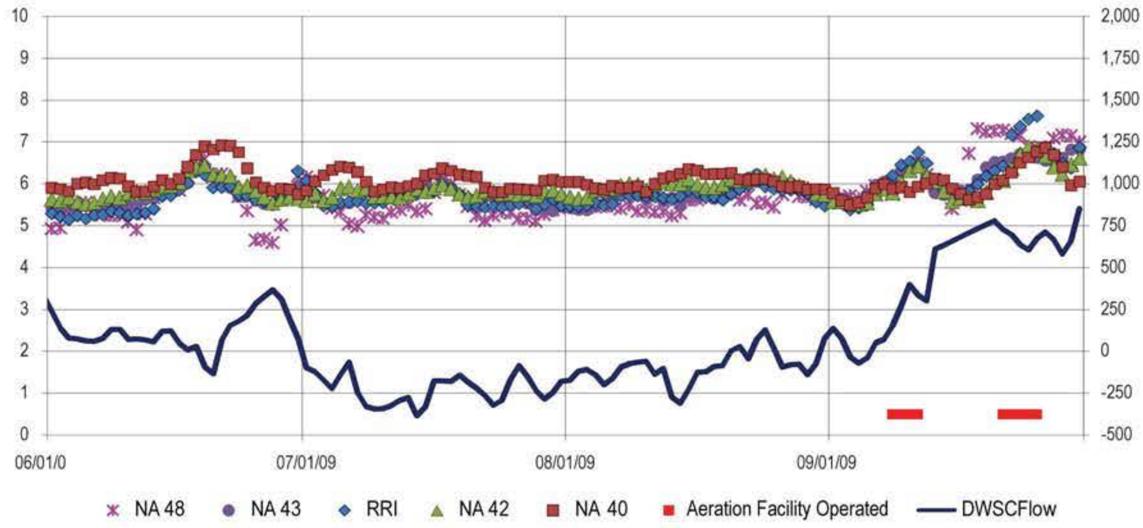

Figure 8c: Daily Average DO at the DWSC Monitoring Stations in June–September 2009

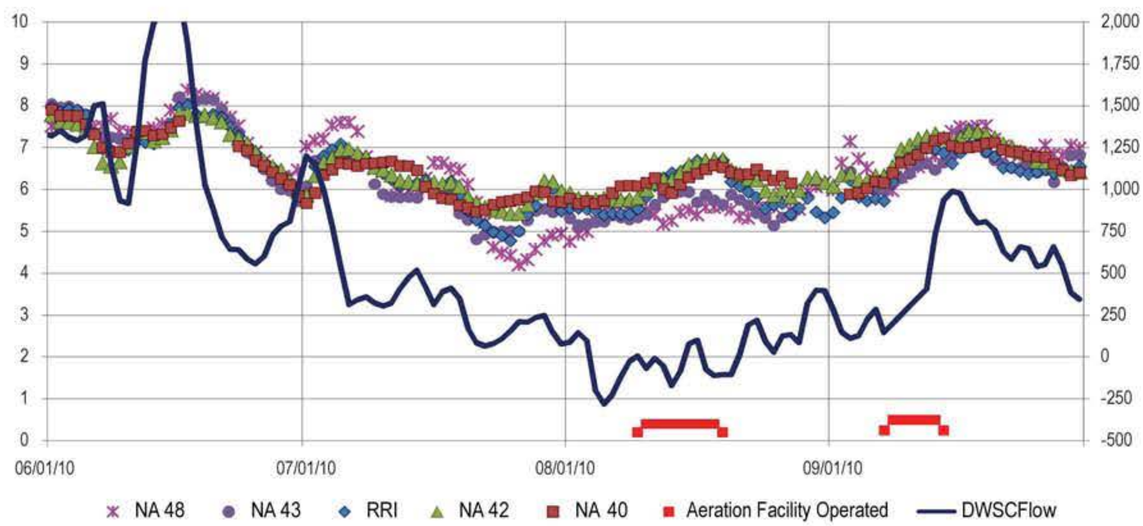

Figure 8d: Daily Average DO at the DWSC Monitoring Stations in June–September 2010

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Figure 8
(continued)

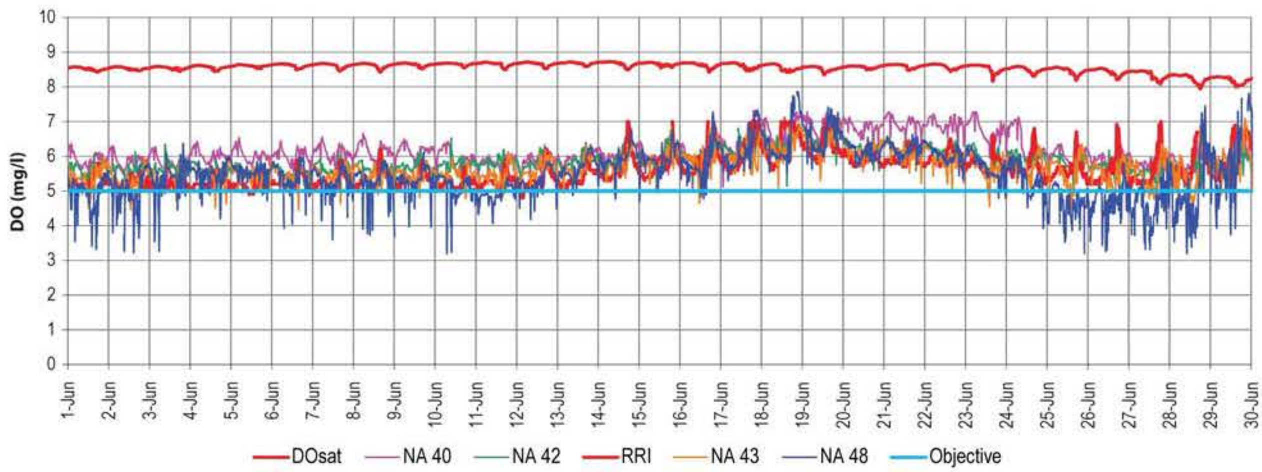

Figure 9a: Measured DO at the DWSC Monitoring Stations in the DWSC during June 2009

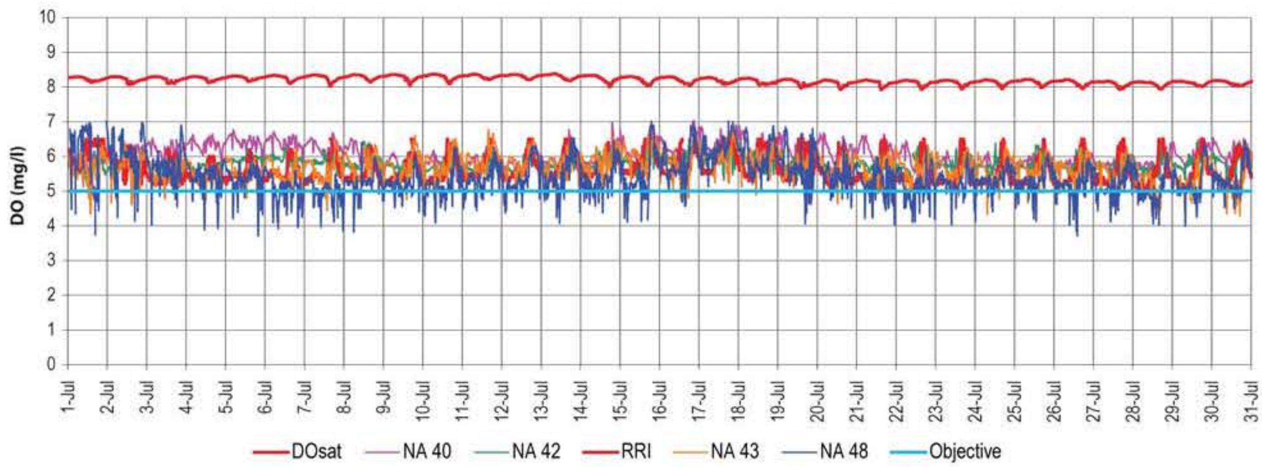

Figure 9b: Measured DO at the DWSC Monitoring Stations in the DWSC during July 2009

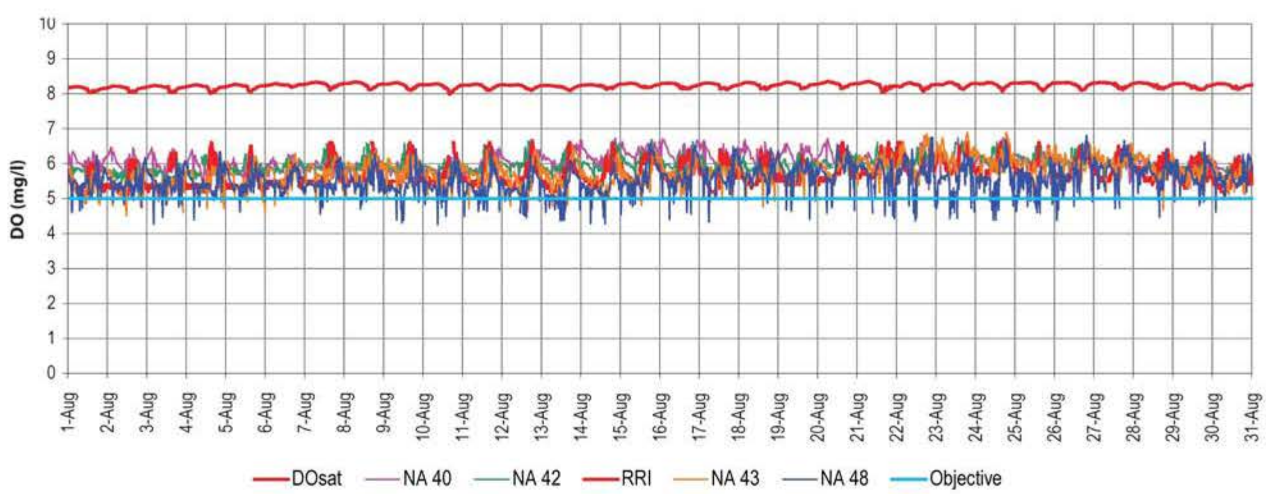

Figure 9c: Measured DO at the DWSC Monitoring Stations in the DWSC during August 2009

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Figure 9

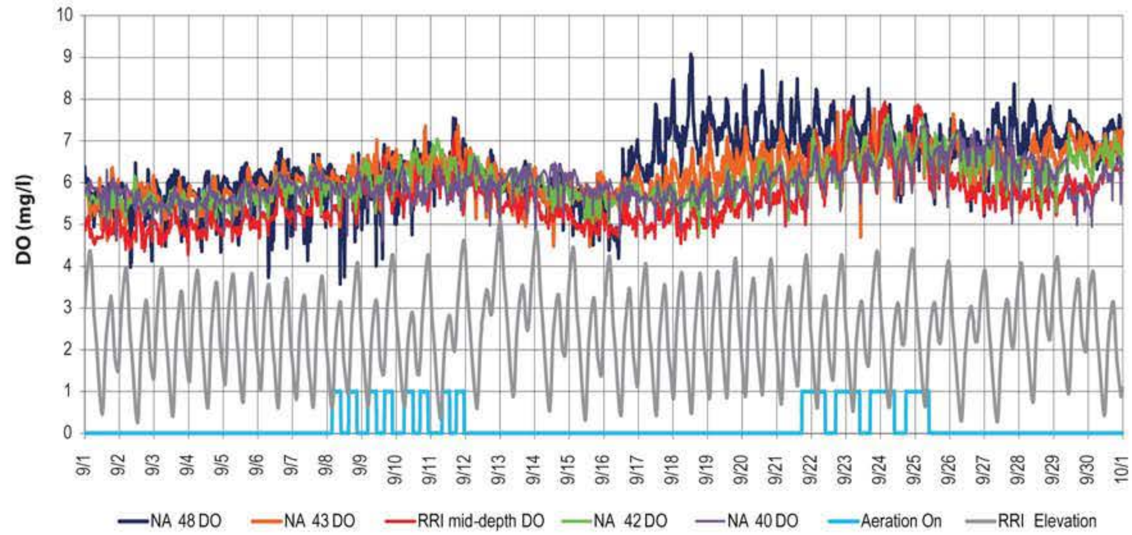

Figure 10a: Measured DO at the DWSC Monitoring Stations in the DWSC during September 2009

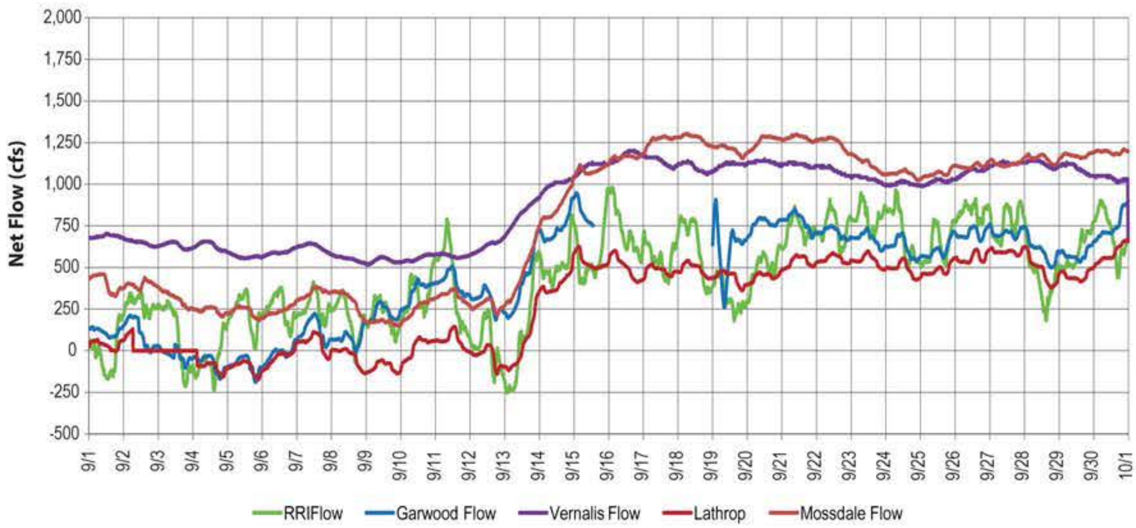

Figure 10b: Comparison of Estimated Daily Flows in the SJR and DWSC during September 2009

Figure 10

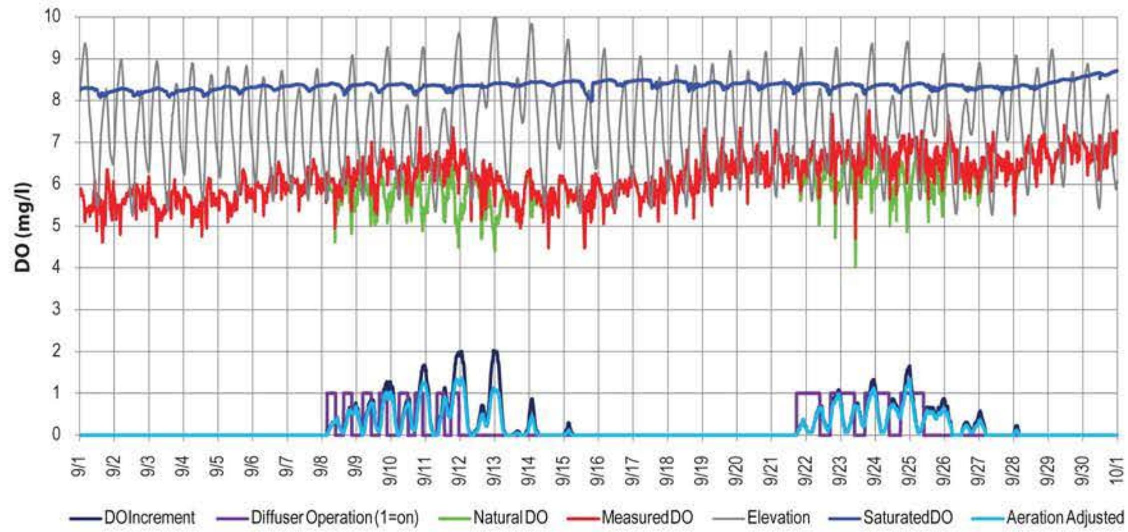

Figure 11a: Estimated DO Increments at NA 43 (0.2 Mile Upstream) from Aeration Facility Operation for September 2009

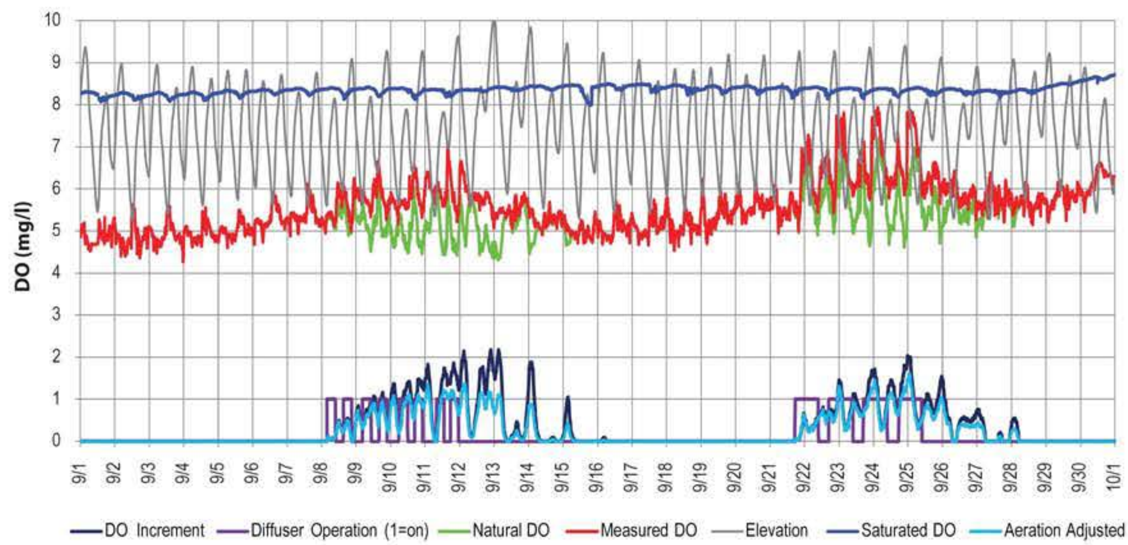

Figure 11b: Estimated DO Increments at RRI (0.2 Mile Downstream) from Aeration Facility Operation for September 2009

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Figure 11

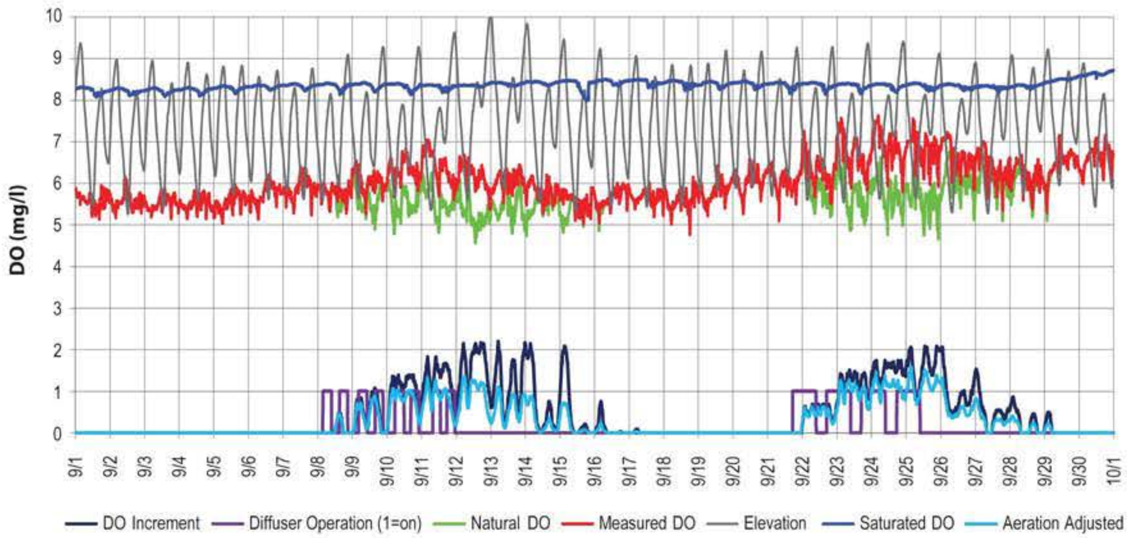

Figure 11c: Estimated DO Increments at NA 42 (0.7 Mile Downstream) from Aeration Facility Operation for September 2009

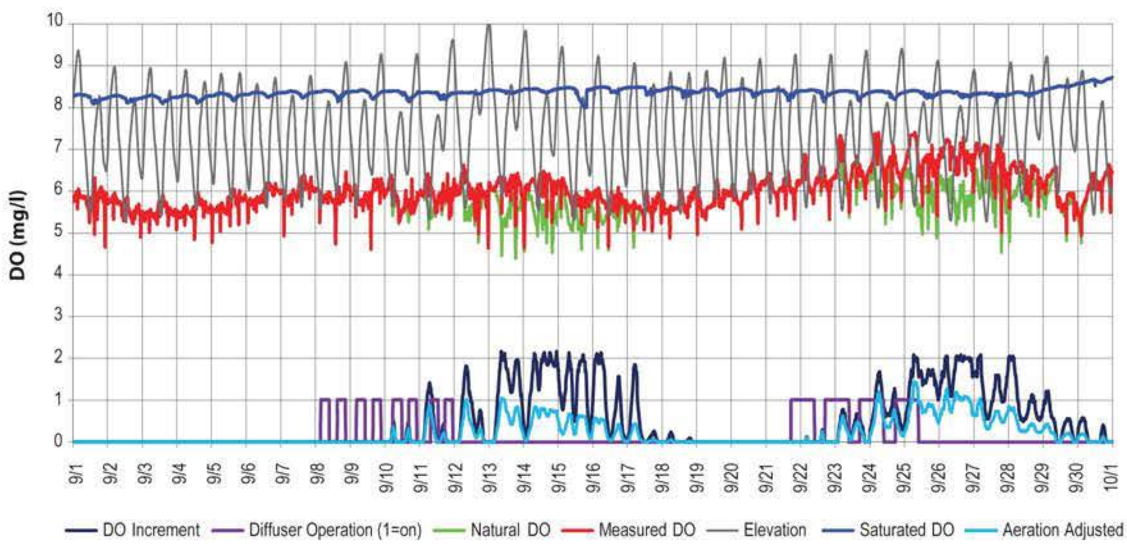

Figure 11d: Estimated DO Increments at NA 40 (1.6 Miles Downstream) from Aeration Facility Operation for September 2009

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Figure 11 (continued)

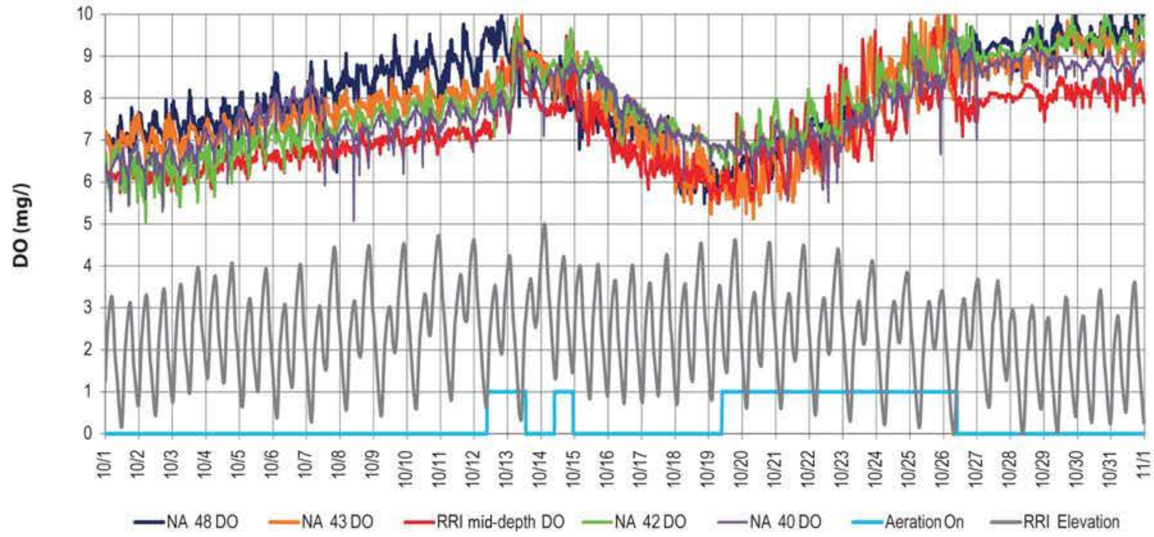

Figure 12a: Measured DO at the DWSC Monitoring Stations in the DWSC during October 2009

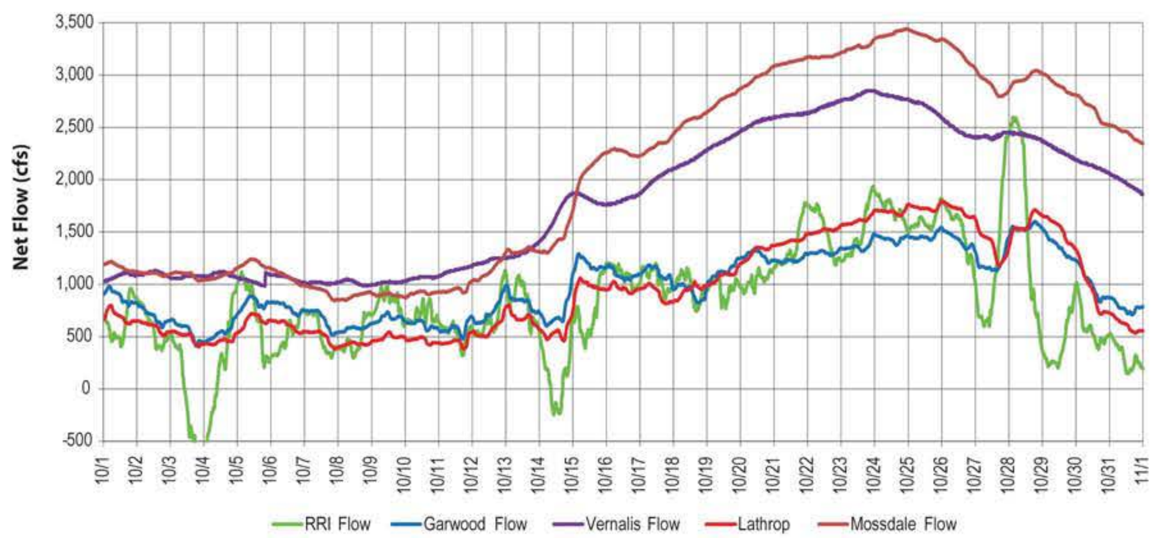

Figure 12b: Comparison of Estimated Daily Flows in the SJR and DWSC during October 2009

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Figure 12

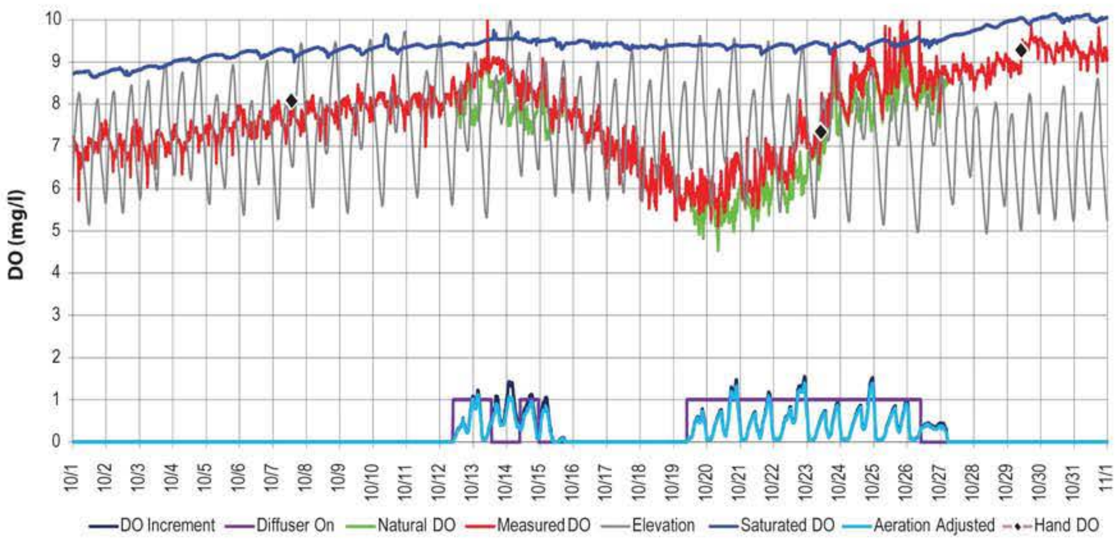

Figure 13a: Estimated DO Increments at NA 43 (0.2 Mile Upstream) from Aeration Facility Operation for October 2009

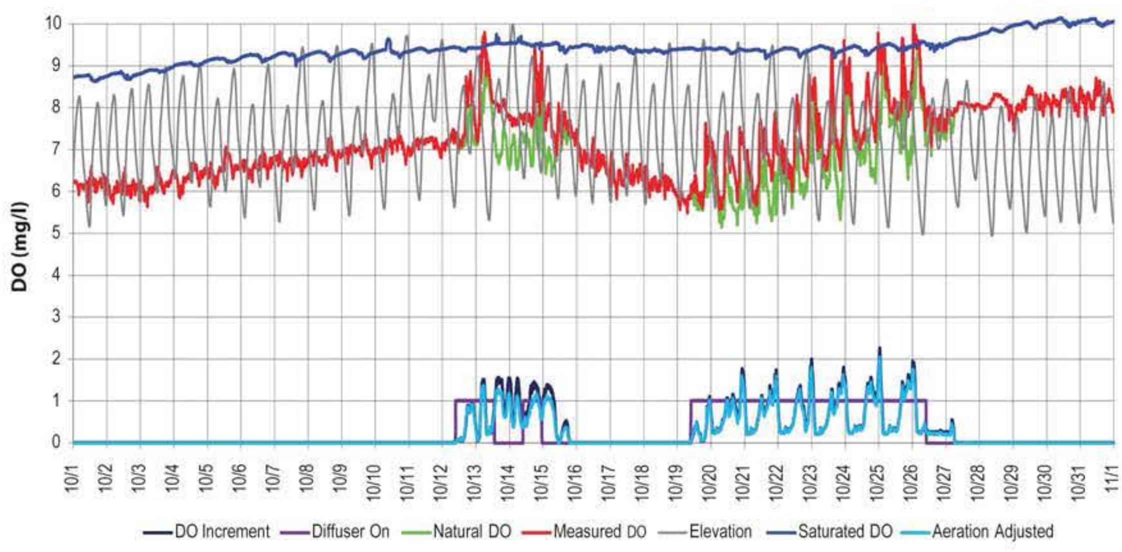

Figure 13b: Estimated DO Increments at RRI (0.2 Mile Downstream) from Aeration Facility Operation for October 2009

Figure 13

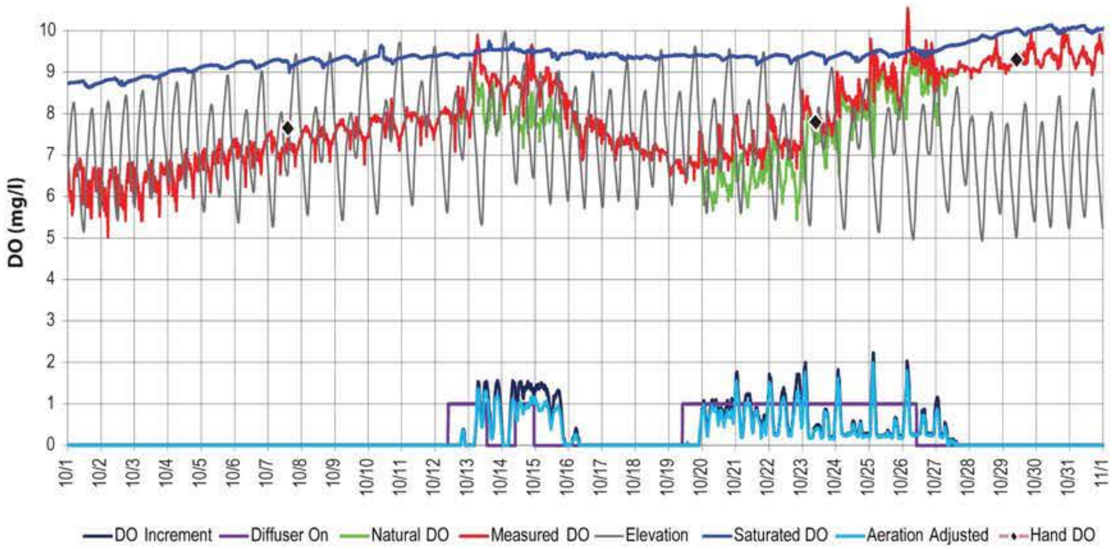

Figure 13c: Estimated DO Increments at NA 42 (0.7 Mile Downstream) from Aeration Facility Operation for October 2009

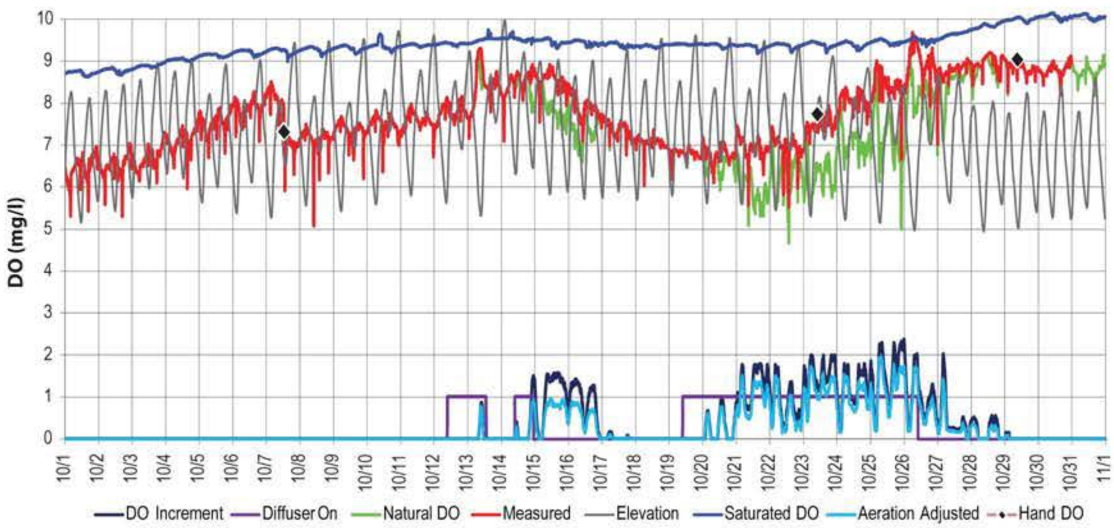

Figure 13d: Estimated DO Increments at NA 40 (1.6 Miles Downstream) from Aeration Facility Operation for October 2009

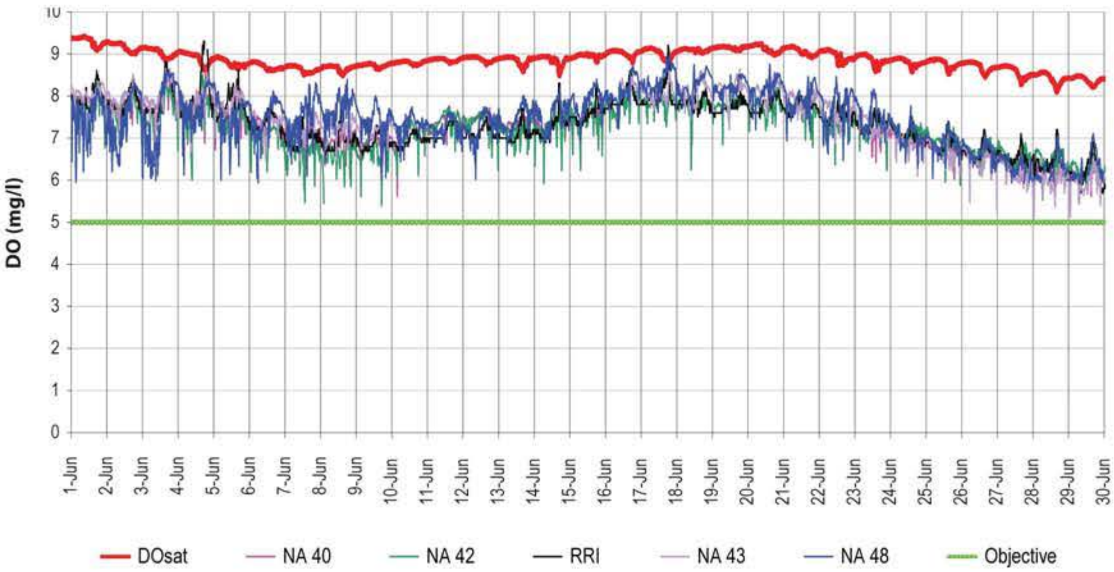

Figure 14a: Measured DO at the DWSC Monitoring Stations in the DWSC during June 2010

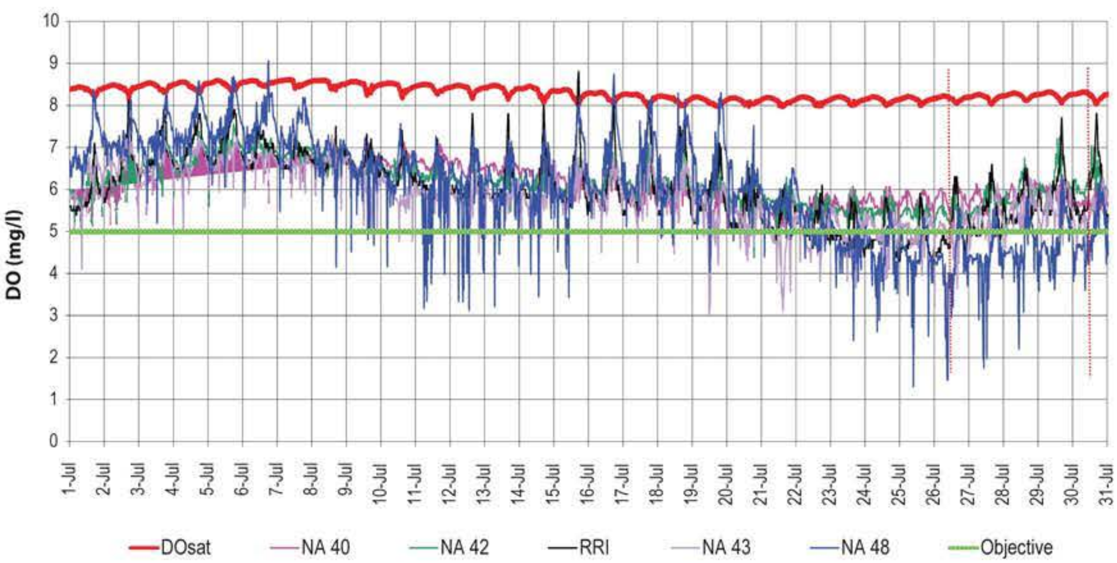

Figure 14b: Measured DO at the DWSC Monitoring Stations in the DWSC during July 2010

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Figure 14

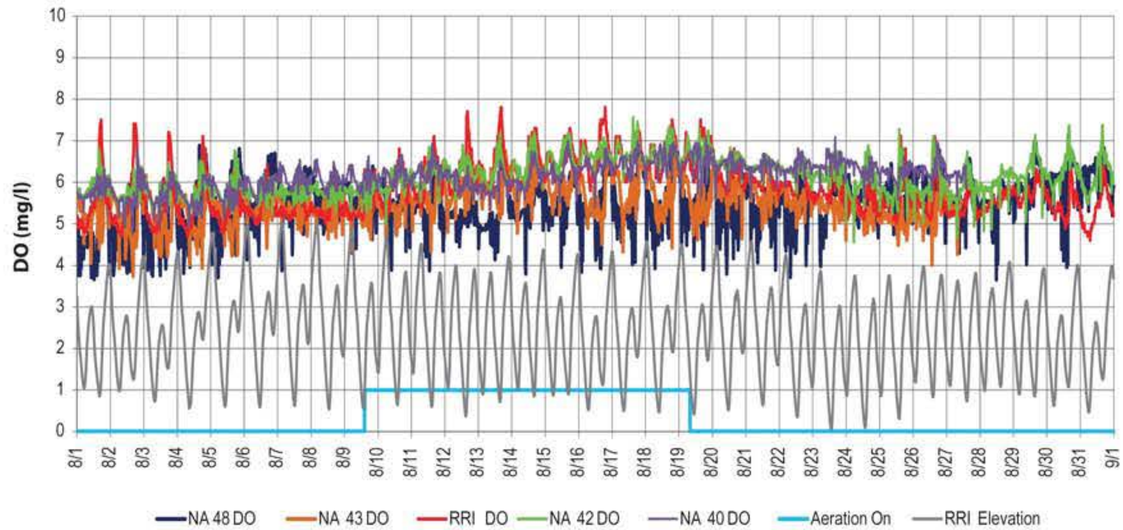

Figure 15a: Measured DO at the DWSC Monitoring Stations in the DWSC during August 2010

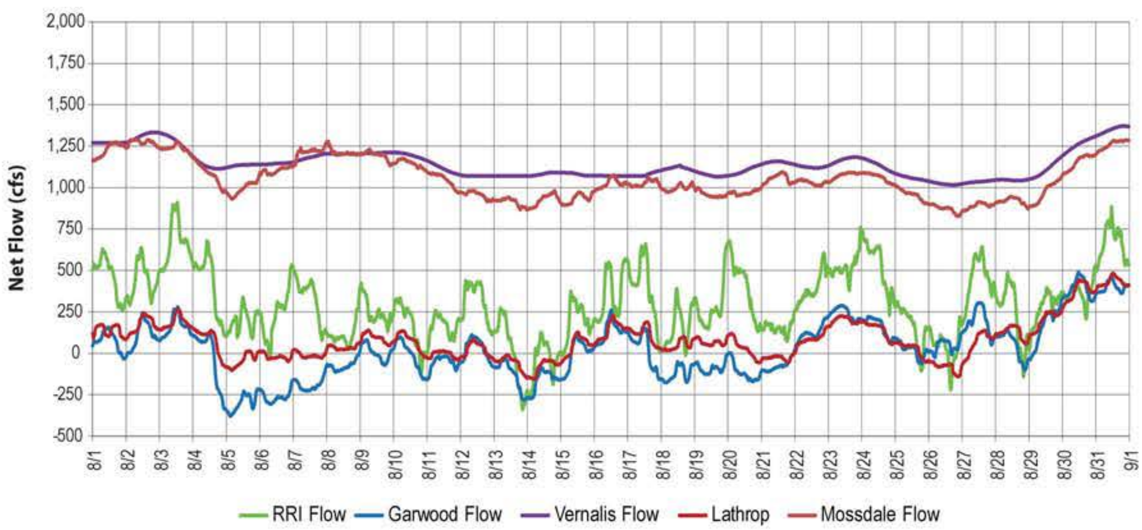

Figure 15b: Comparison of Estimated Daily Flows in the SJR and DWSC during August 2010

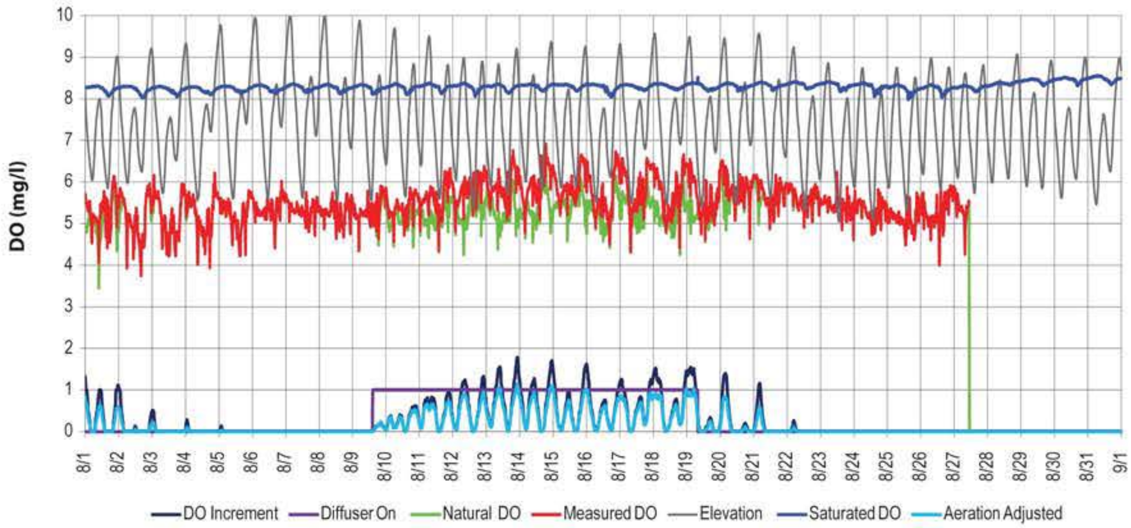

Figure 16a: Estimated DO Increments at NA 43 (0.2 Mile Upstream) from Aeration Facility Operation for August 2010

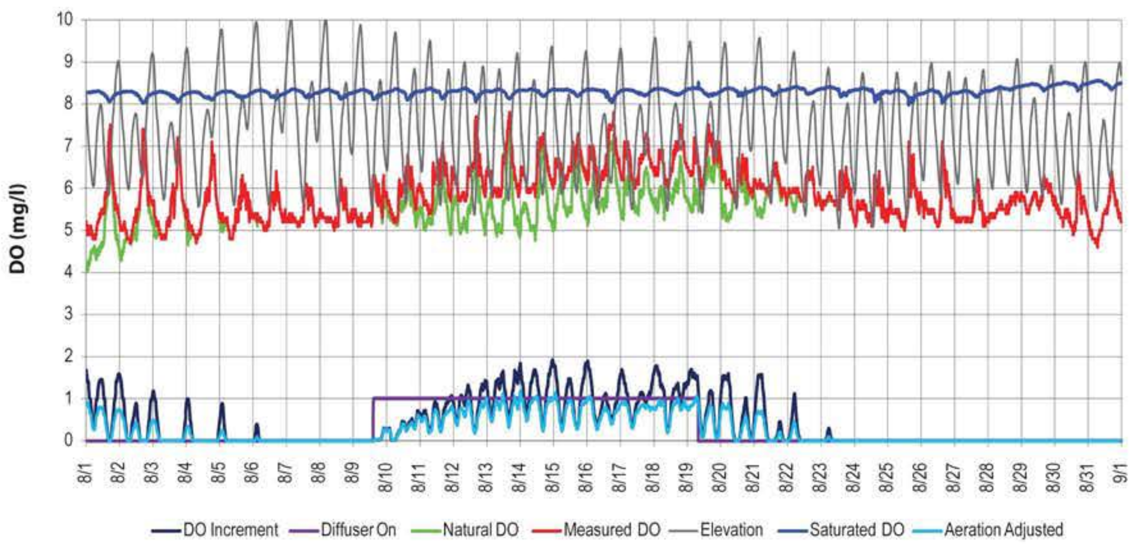

Figure 16b: Estimated DO Increments at RRI (0.2 Mile Downstream) from Aeration Facility Operation for August 2010

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Figure 16

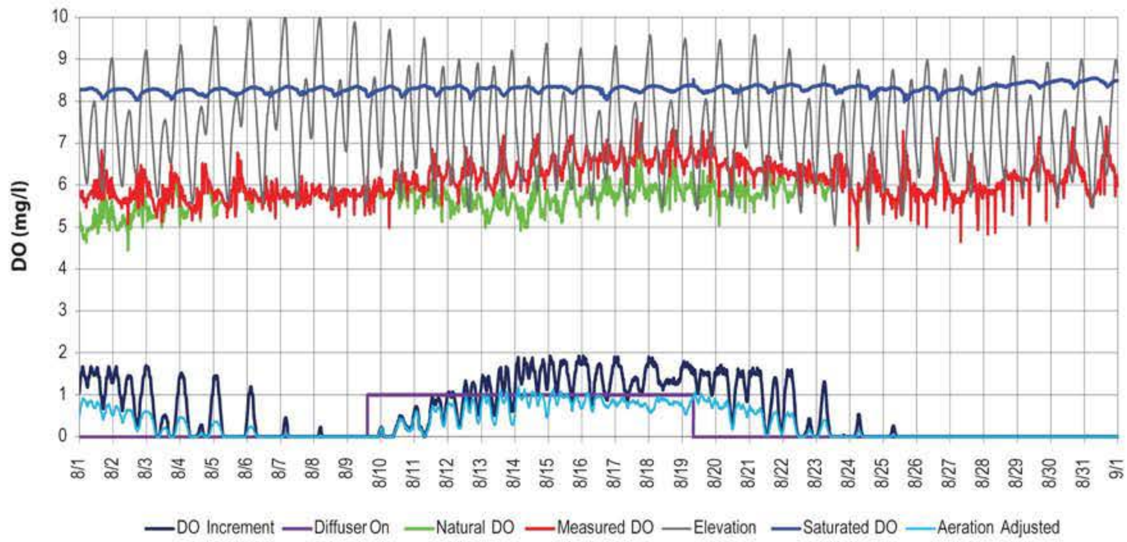

Figure 16c: Estimated DO Increments at NA 42 (0.7 Mile Downstream) from Aeration Facility Operation for August 2010

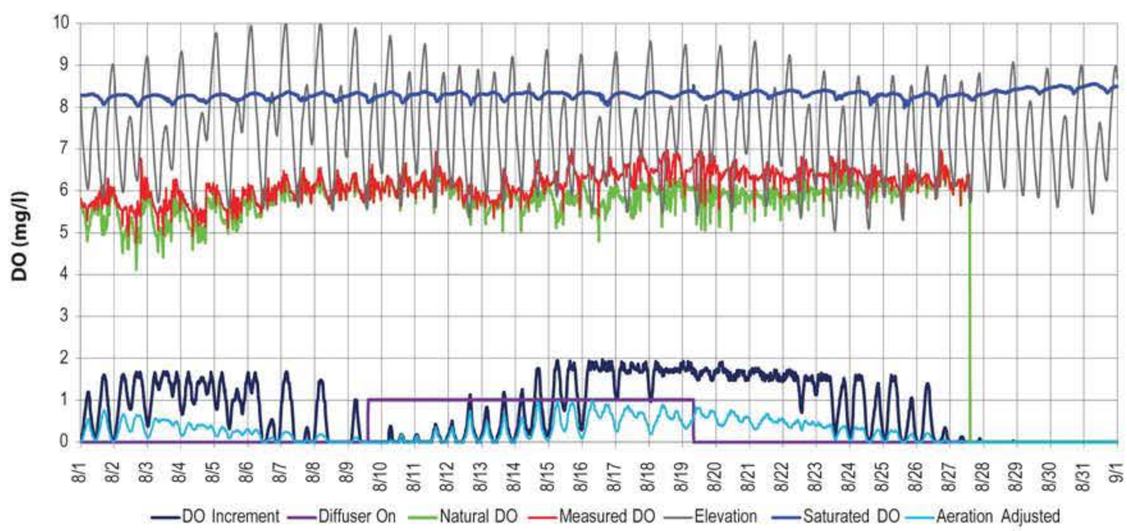

Figure 16d: Estimated DO Increments at NA 40 (1.6 Miles Downstream) from Aeration Facility Operation for August 2010

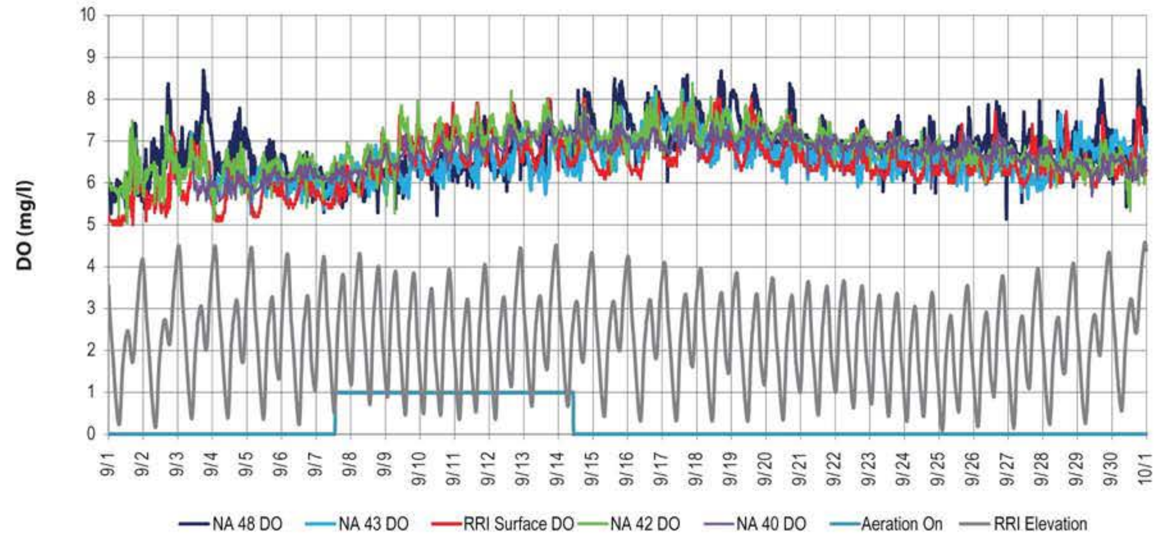

Figure 17a: Measured DO at the DWSC Monitoring Stations in the DWSC during September 2010

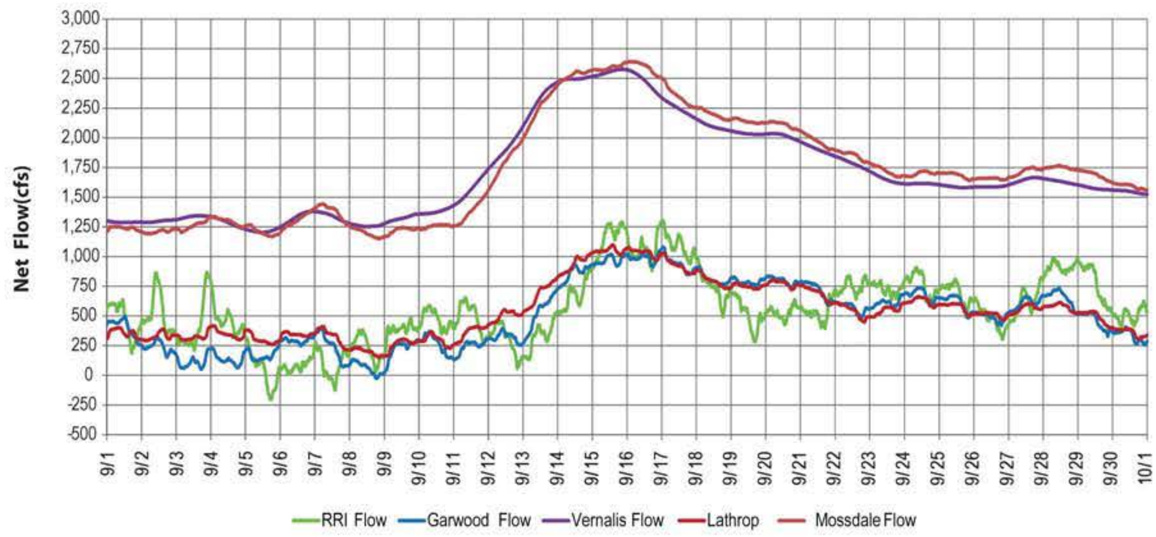

Figure 17b: Comparison of Estimated Daily Flows in the SJR and DWSC during September 2010

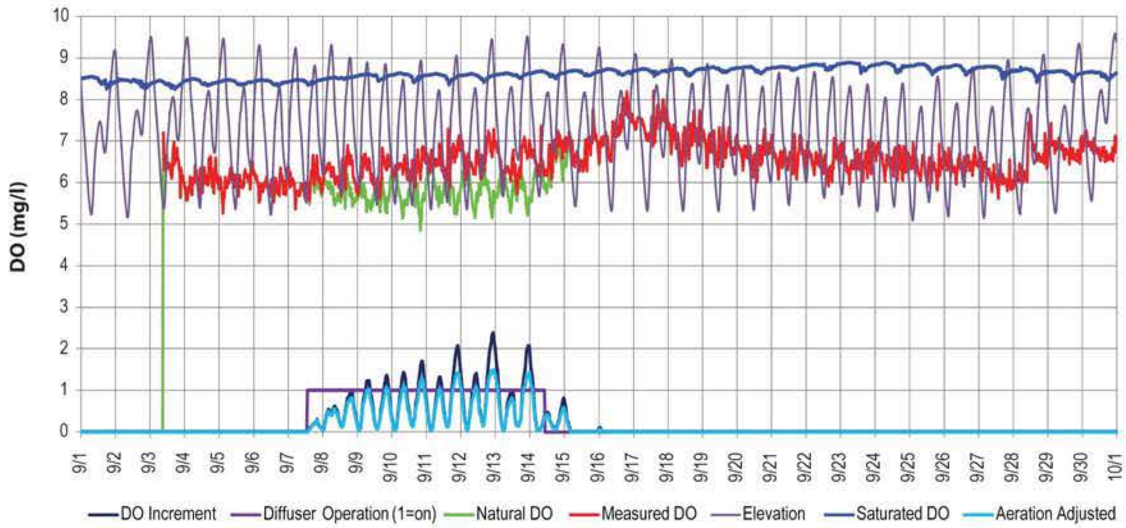

Figure 18a: Estimated DO Increments at NA 43 (0.2 Mile Upstream) from Aeration Facility Operation for September 2010

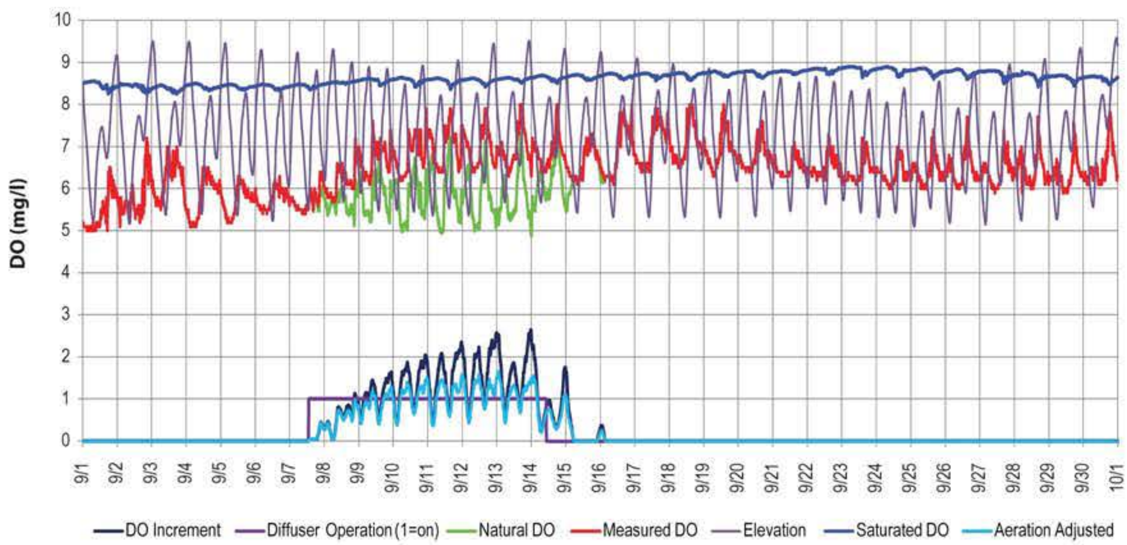

Figure 18b: Estimated DO Increments at RRI (0.2 Mile Downstream) from Aeration Facility Operation for September 2010

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Figure 18

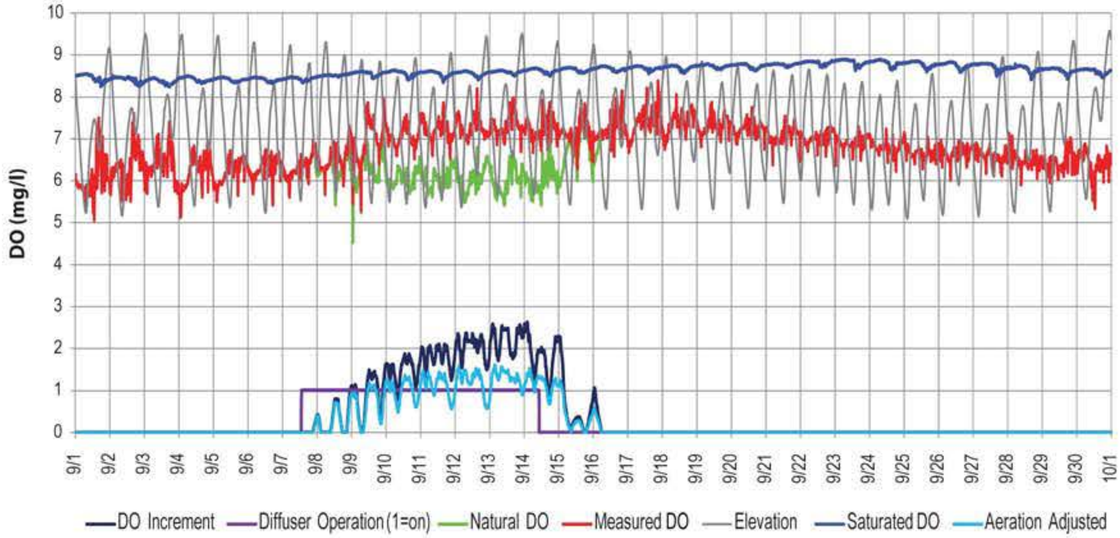

Figure 18c: Estimated DO Increments at NA 42 (0.7 Mile Downstream) from Aeration Facility Operation for September 2010

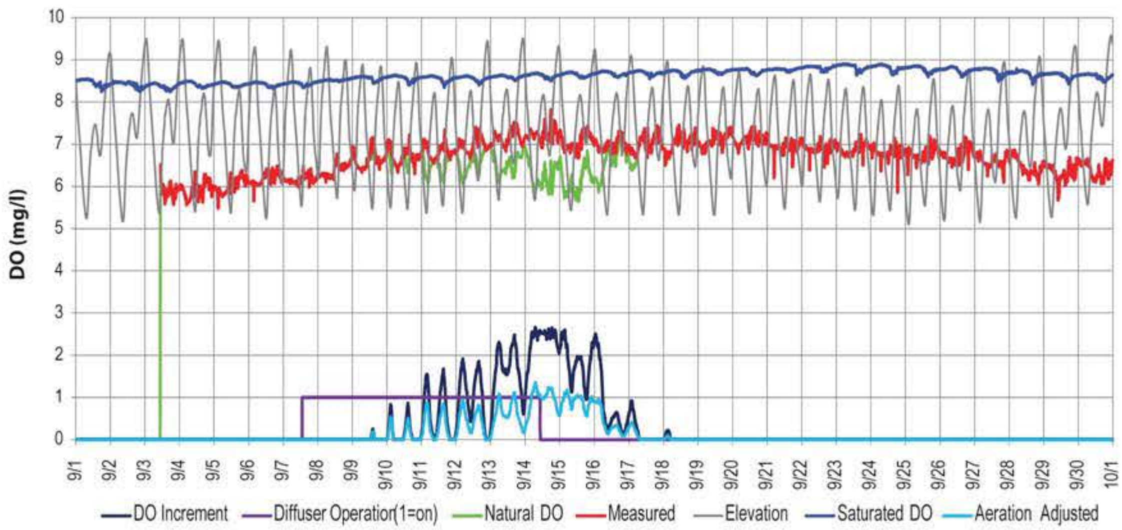

Figure 18d: Estimated DO Increments at NA 40 (1.6 Miles Downstream) from Aeration Facility Operation for September 2010

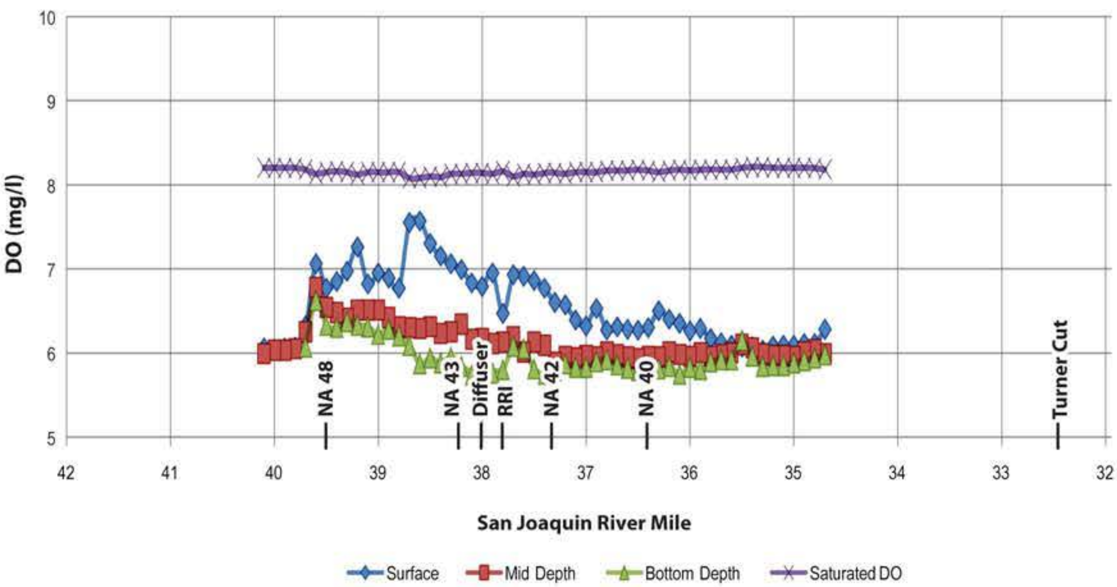

Figure 19a: DWSC DO Profile on August 12, 2008 (Prior to Operation)

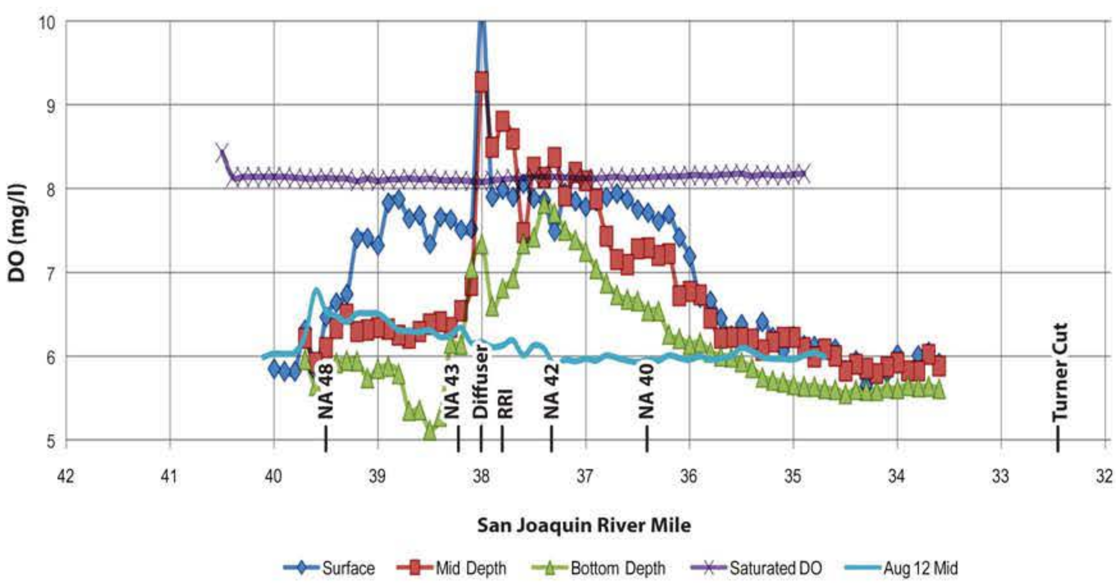

Figure 19b: DWSC DO Profile on August 16, 2008 (After 4 Days of Operation)

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Figure 19

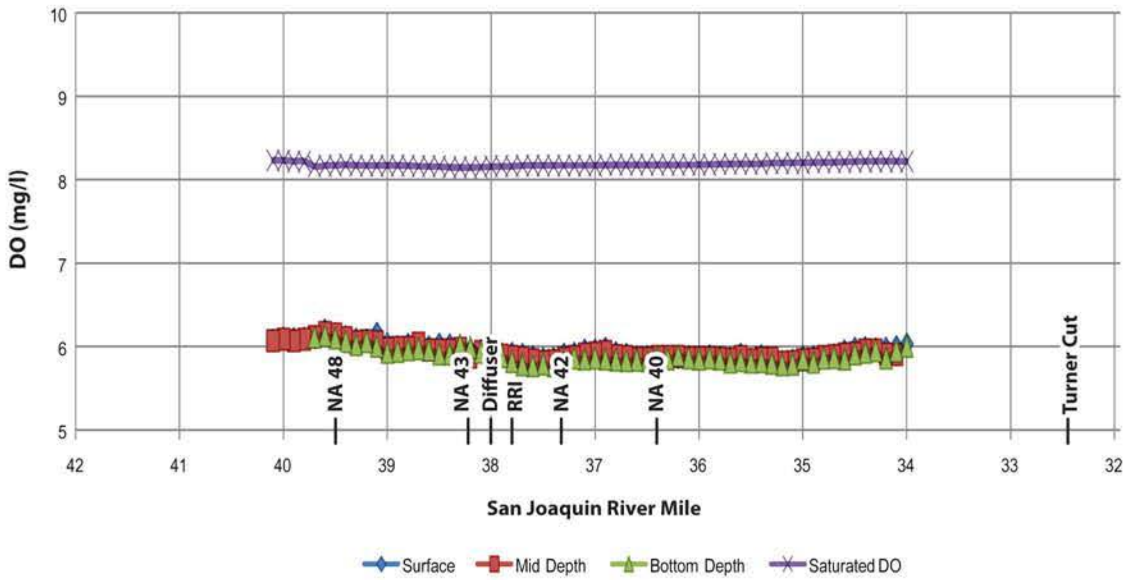

Figure 20a: DWSC DO Profile on August 26, 2008 (Prior to Operation)

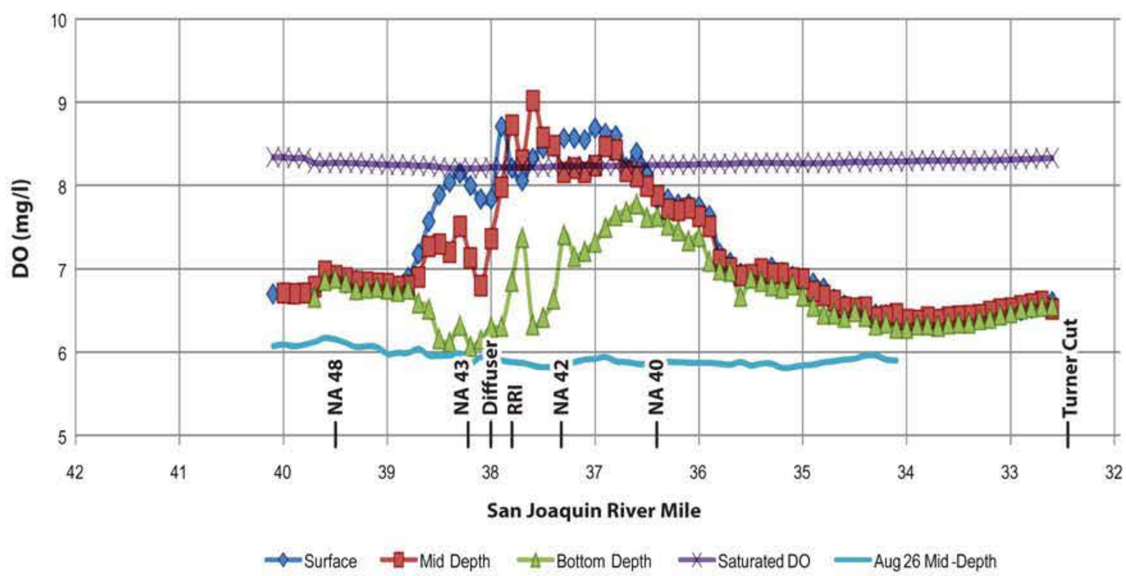

Figure 20b: DWSC DO Profile on September 5, 2008 (After 10 Days of Operation)

Graphics/Projects/SENH5TB:Work:00508.10 TO_K Aeration_FacOp_TS:FinalReportFigs_120210.indd (12/02/10) SS

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Figure 20

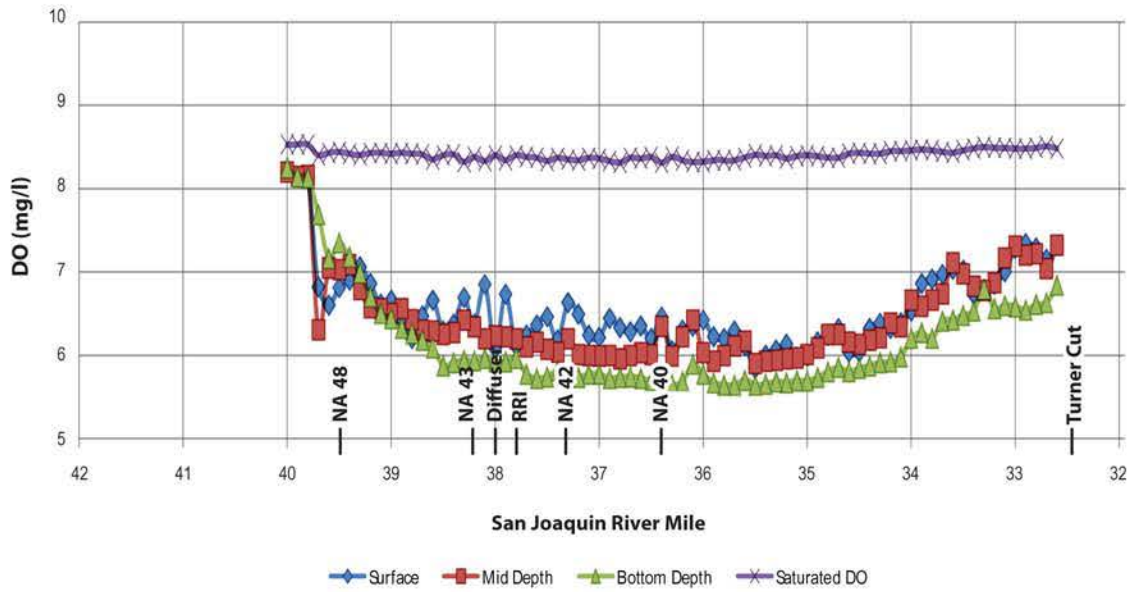

Figure 21a: DWSC DO Profile on September 15, 2008 (Prior to Operation)

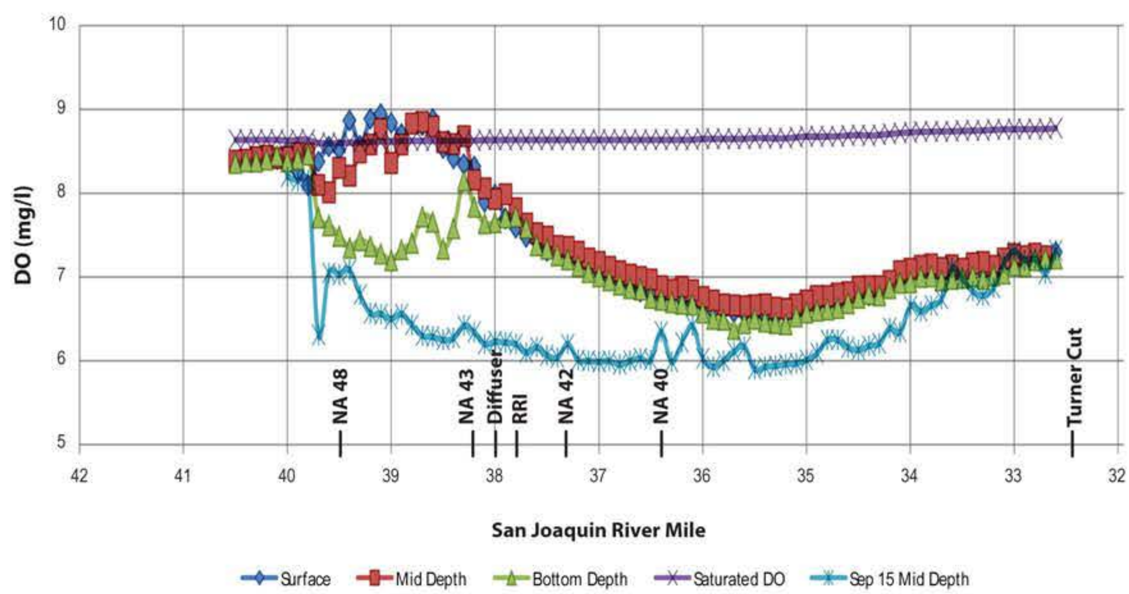

Figure 21b: DWSC DO Profile on September 26, 2008 (After 10 Days of Operation)

Graphics/Projects/SENH5TB:Work:00508.10 TO_K Aeration_FacOp_TS:FinalReportFigs_120210.indd (12/02/10) SS

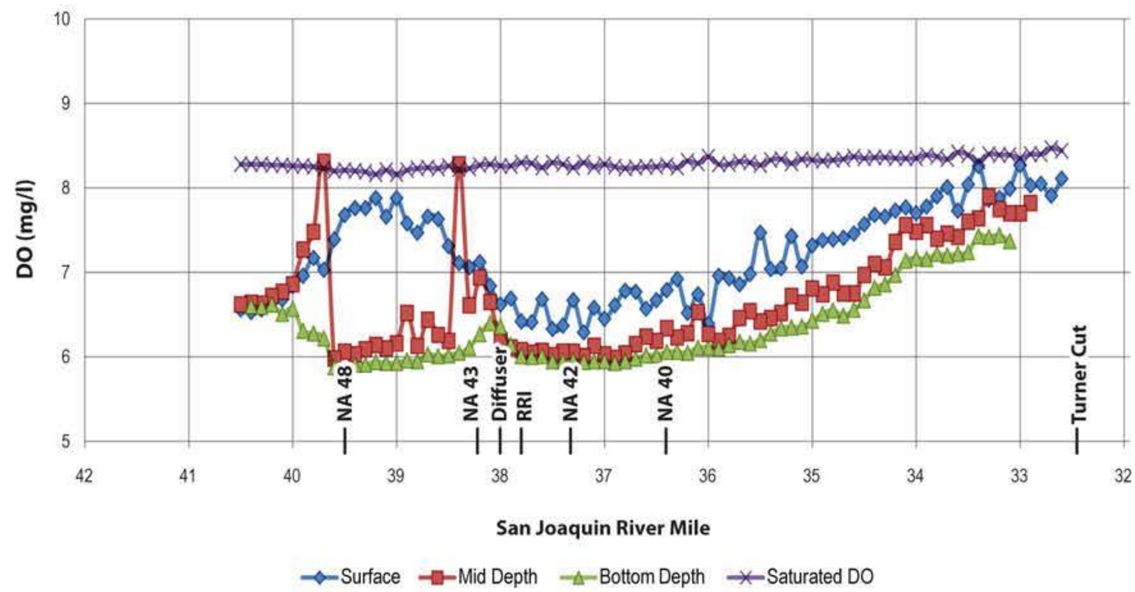

Figure 22a: DWSC DO Profile at High Tide on September 8, 2009 (After 1 Day of Flood-tide Operation)

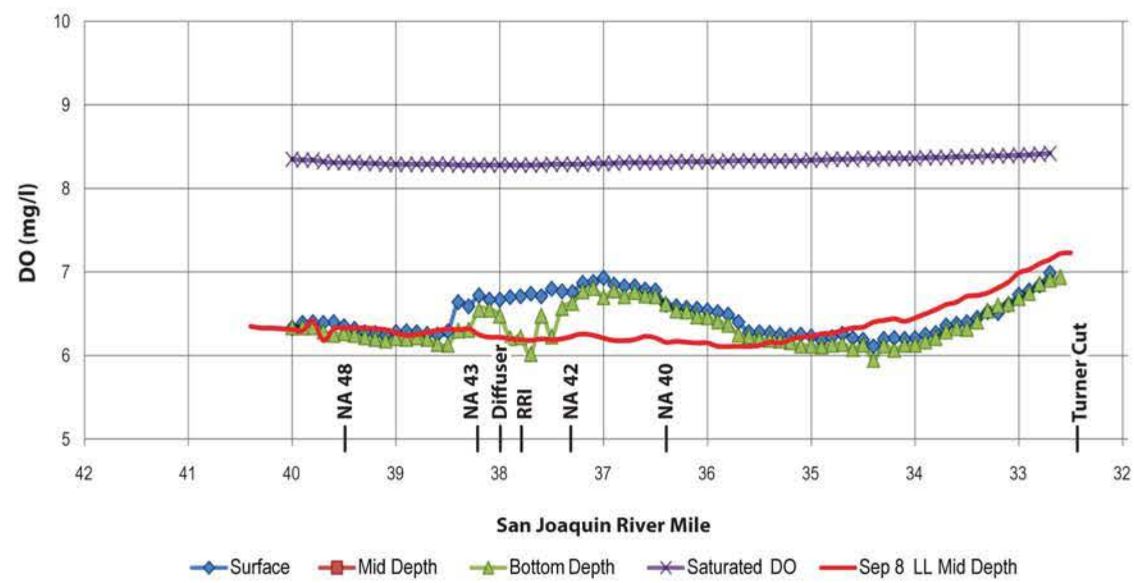

Figure 22b: DWSC DO Profile at High Tide on September 12, 2009 (After 4 Days of Flood-tide Operation)

Graphics/Projects/SENH5TB:Work:00508.10 TO_K Aeration_FacOp_TS:FinalReportFigs_120210.indd (12/02/10) SS

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Figure 22

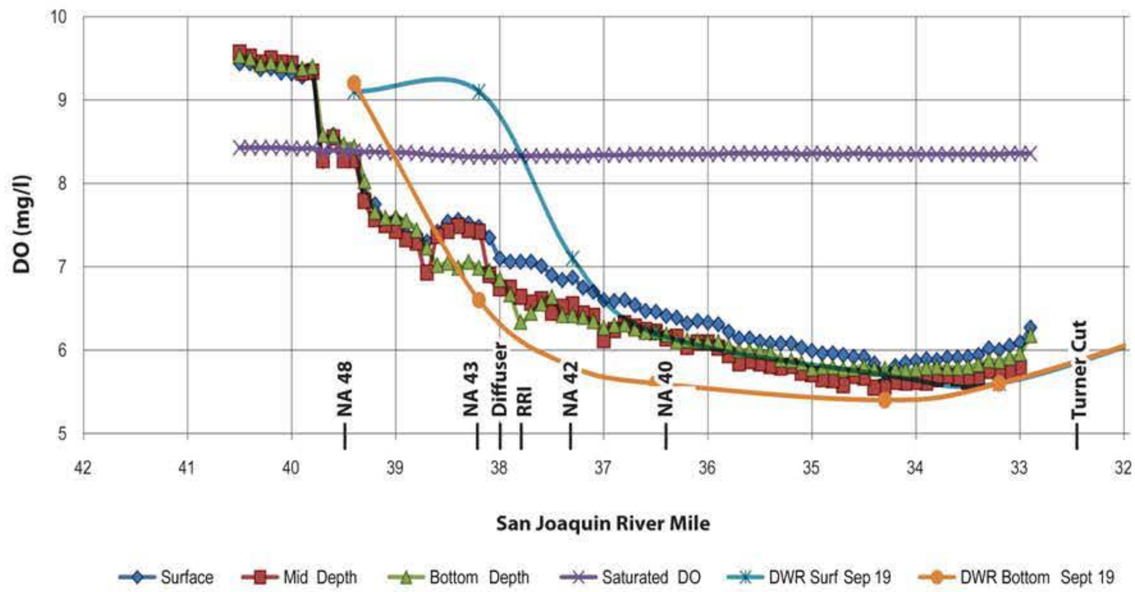

Figure 23a: DWSC DO Profile at Low Tide on September 21, 2009 (Prior to Operation)

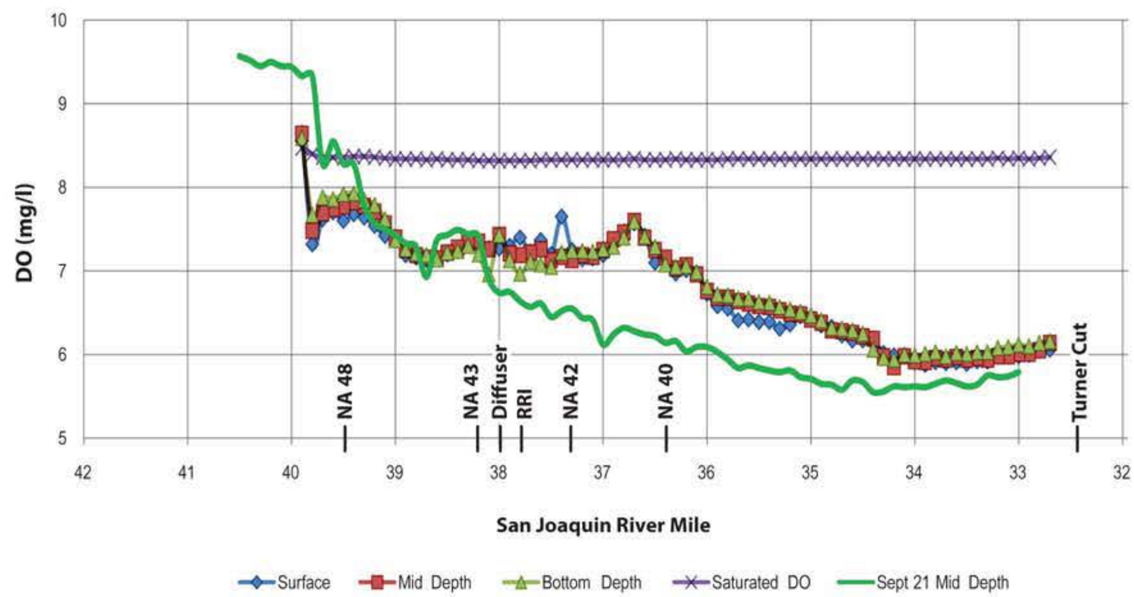

Figure 23b: DWSC DO Profile at Low Tide on September 25, 2009 (After 4 Days of Night-time Operation)

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Figure 23

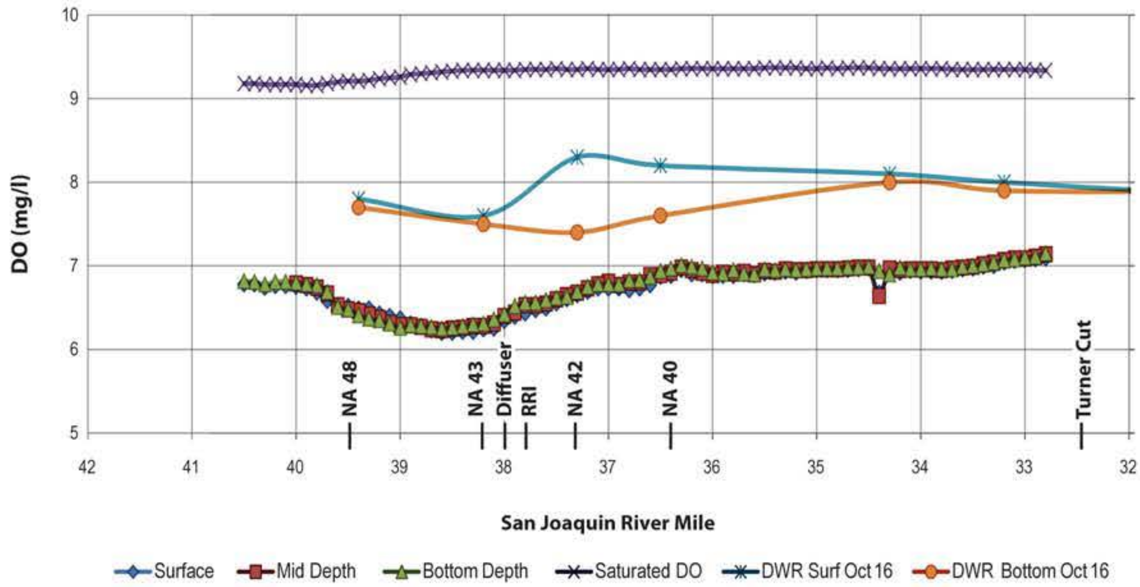

Figure 24a: DWSC DO Profile at Low Tide on October 19, 2009 (Prior to Operation)

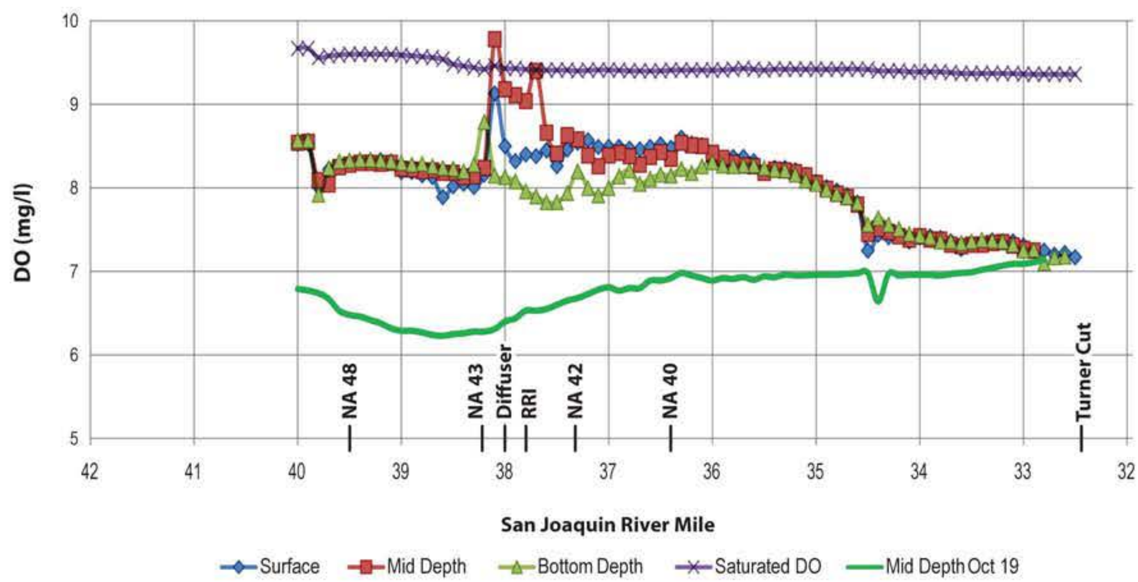

Figure 24b: DWSC DO Profile at Low Tide on October 24, 2009 (After 5 Days of Operation)

Graphics/Projects/SENHSTB:Work:00508.10 TO_K Aeration_FacOp_TS:FinalReportFigs_120210.indd (12/02/10) SS

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Figure 24

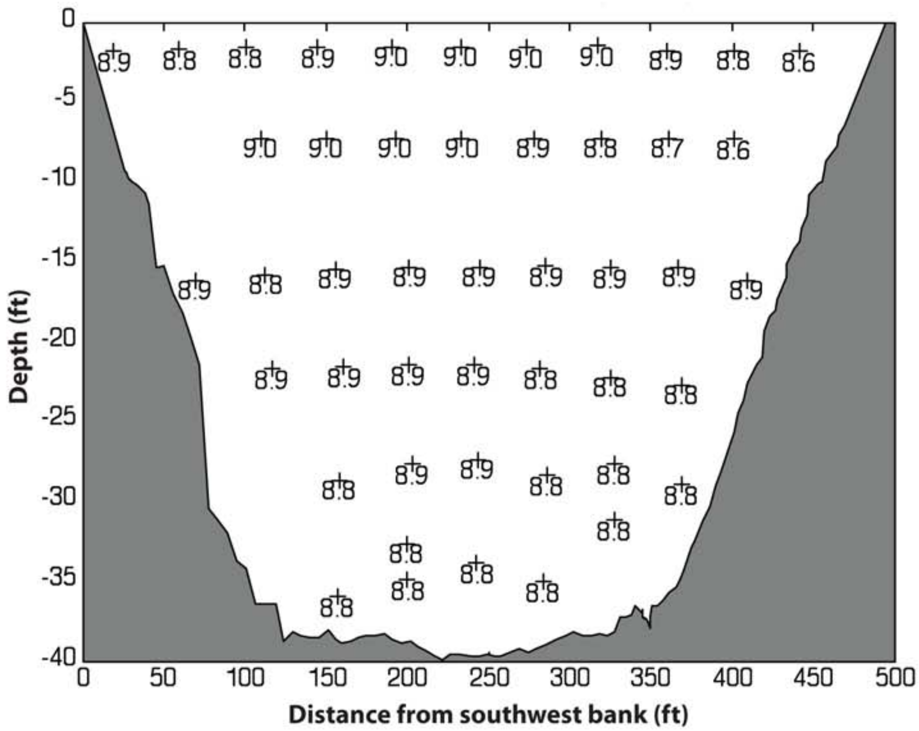

Figure 25a: Lateral DO Concentrations at NA 40 (Mile 36.4) viewed looking downstream at Low Tide on October 15, 2009 (After 2 Days of Operation)

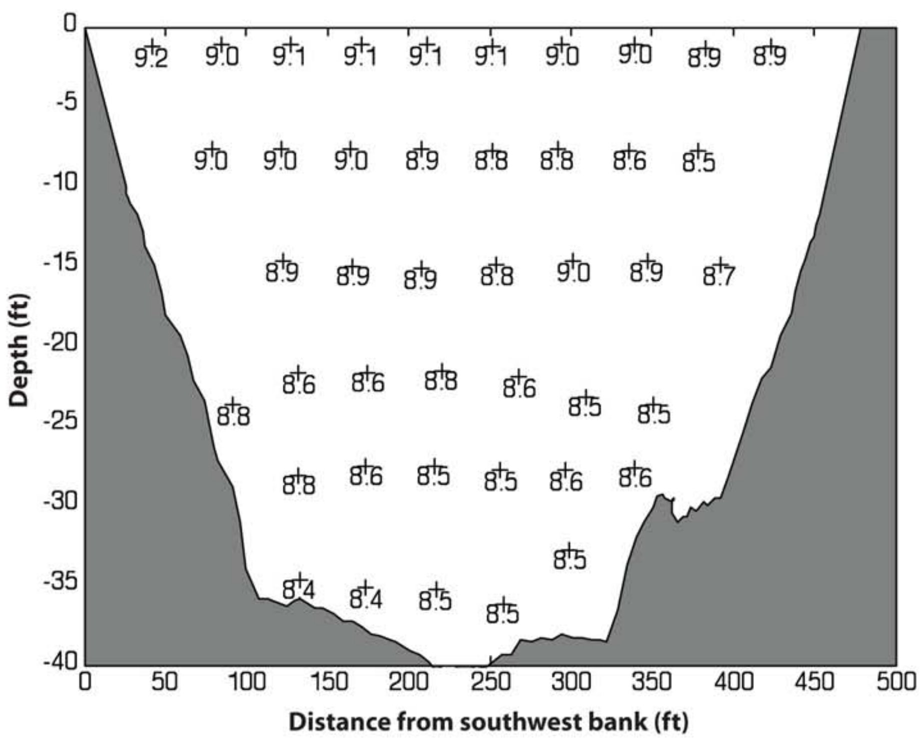

Figure 25b: Lateral DO Concentrations at NA 42 (Mile 37.3) viewed looking downstream at Low Tide on October 15, 2009 (After 2 Days of Operation)

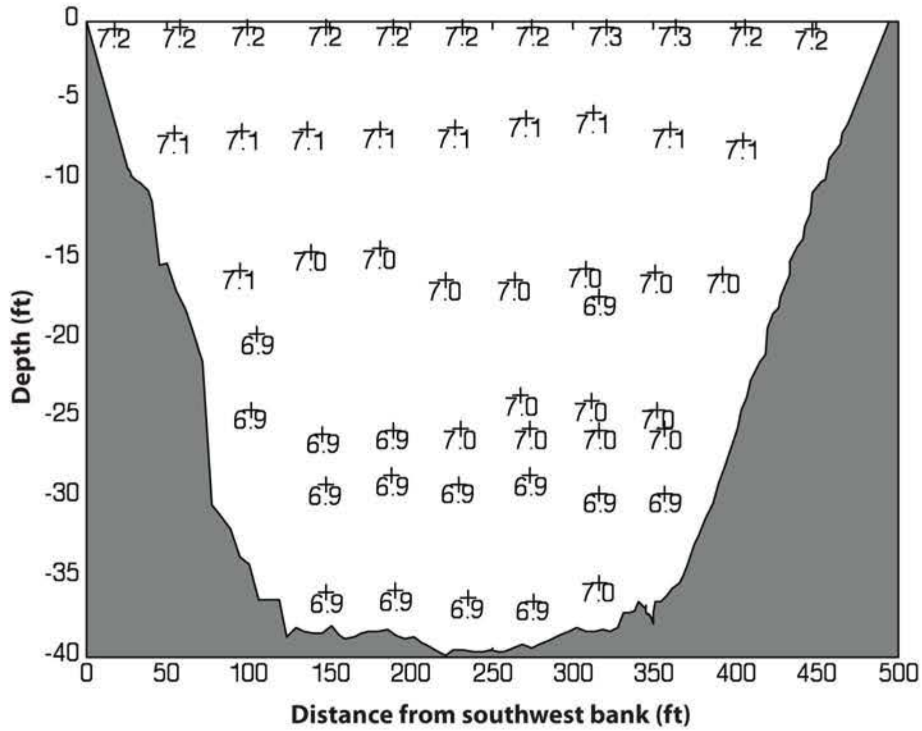

Figure 26a: Lateral DO Concentrations at NA 40 (Mile 36.4) viewed looking downstream at Mid-tide at 10 a.m. on October 20, 2009 (After 1 Day of Operation)

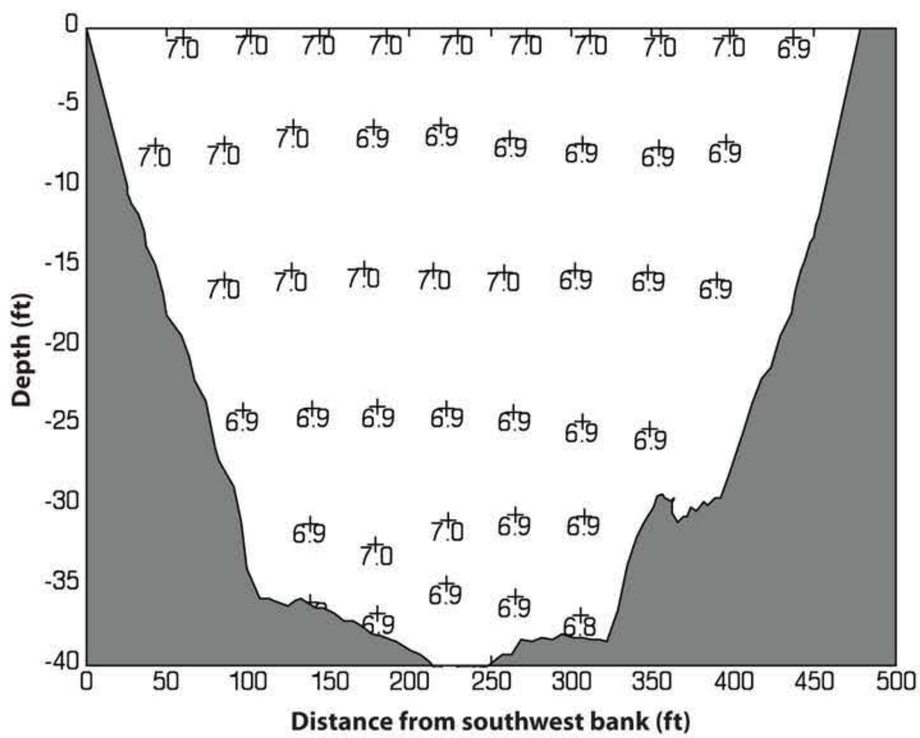

Figure 26b: Lateral DO Concentrations at NA 42 (Mile 37.3) viewed looking downstream at Mid-tide at 10 a.m. on October 20, 2009 (After 1 Day of Operation)

Figure 26

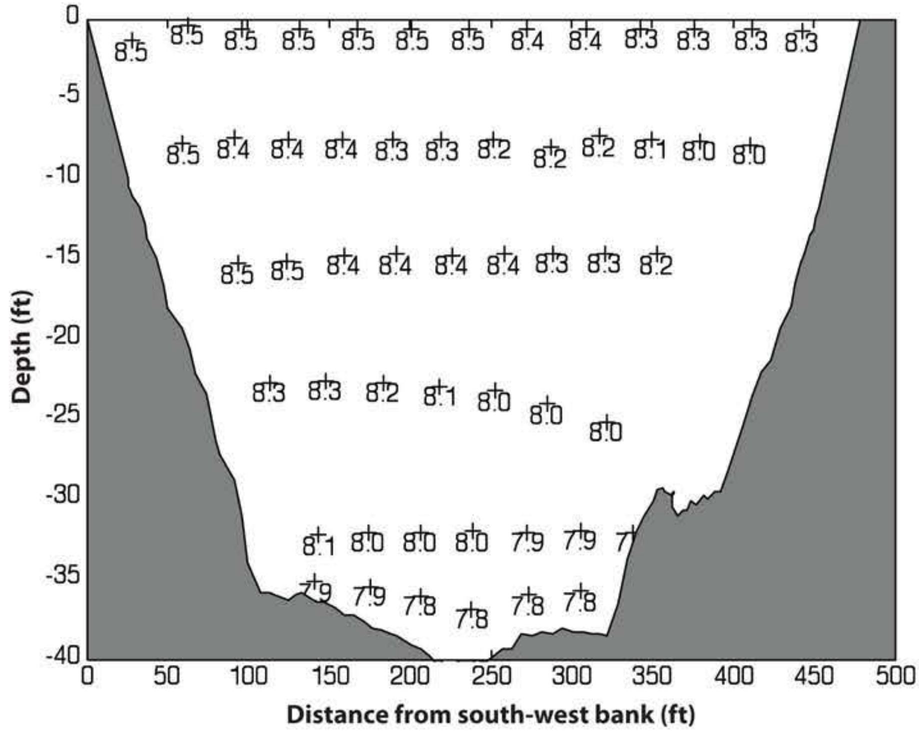

Figure 27a: Lateral DO Concentrations at NA 42 (Mile 37.3) viewed looking downstream at Low Tide at 8 a.m. on October 24, 2009 (After 5 Days of Operation)

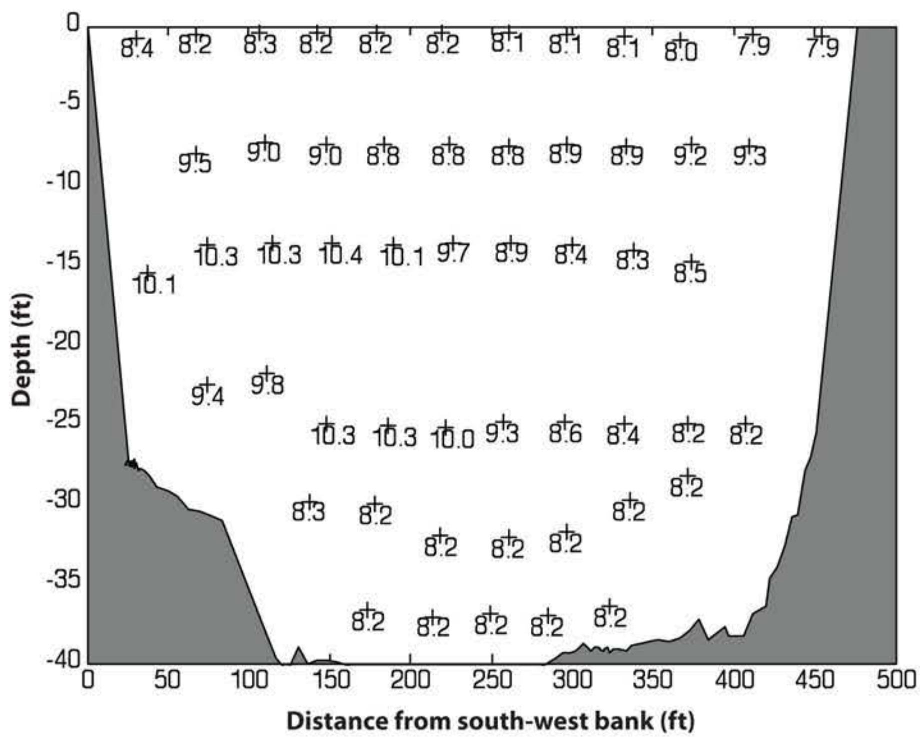

Figure 27b: Lateral DO Concentrations at NA 43 (0.2 Mile Upstream of the Diffuser) viewed looking downstream at Low Tide at 8 a.m. on October 24, 2009 (After 5 Days of Operation)

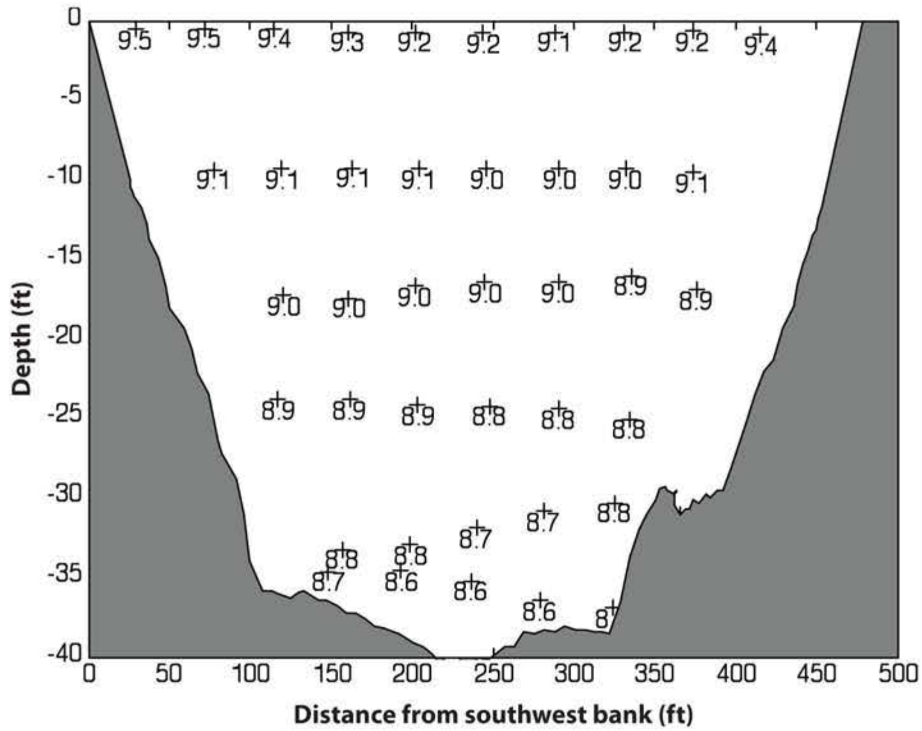

Figure 28a: Lateral DO Concentrations at NA 42 (Mile 37.3) viewed looking downstream at Mid-tide at Noon on October 25, 2009 (After 6 Days of Operation)

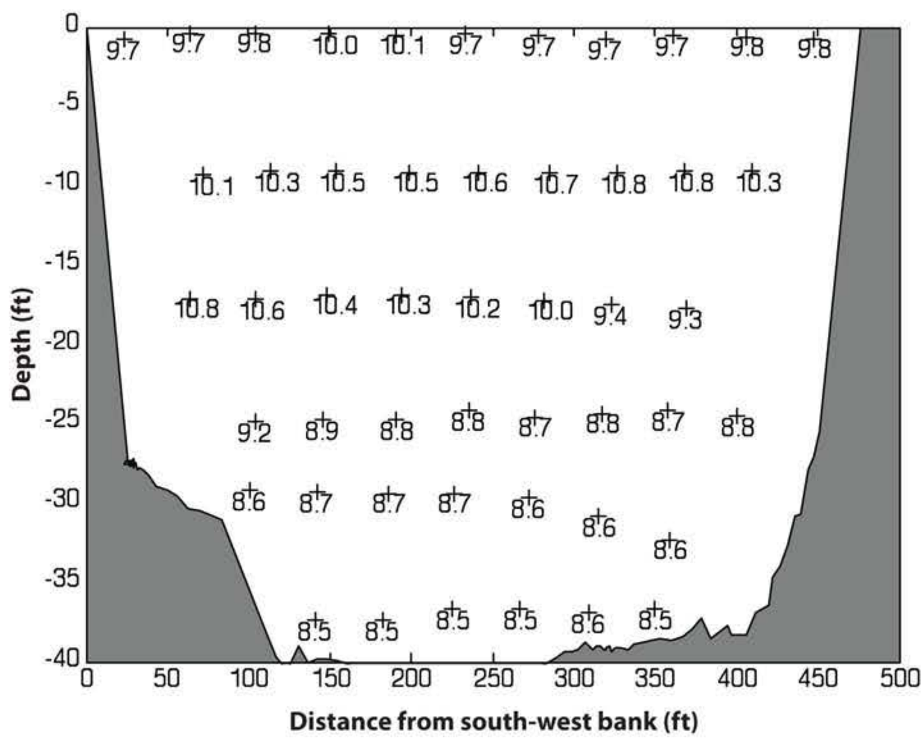

Figure 28b: Lateral DO Concentrations at NA 43 (0.2 Mile Upstream of the Diffuser) viewed looking downstream at Mid-tide at Noon on October 25, 2009 (After 6 Days of Operation)

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Figure 28

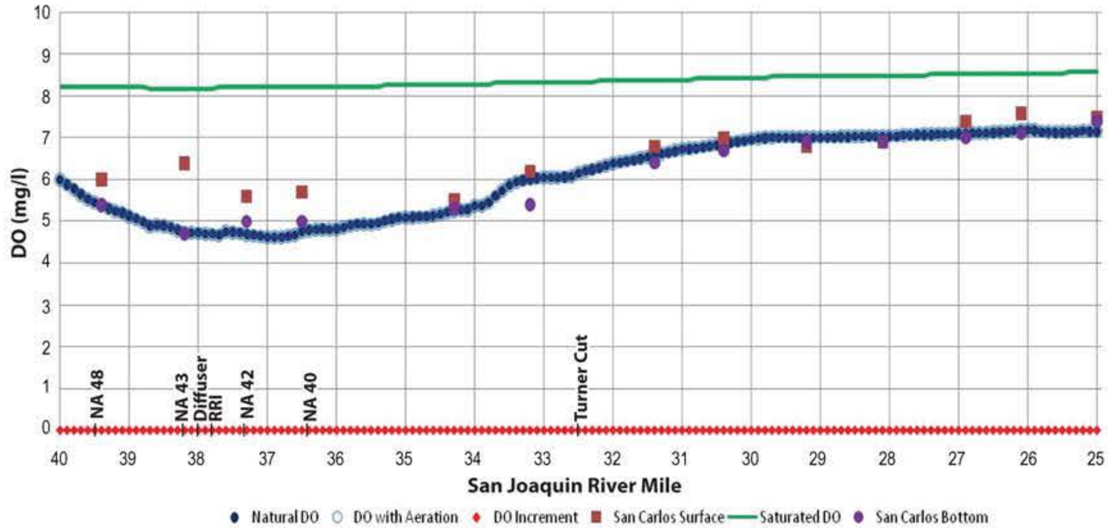

Figure 29a: Comparison of *San Carlos* Boat Survey Measured DO and Calculated DO in the DWSC for September 2, 2009 (flow of 500 cfs, inflow BOD of 10 mg/l)

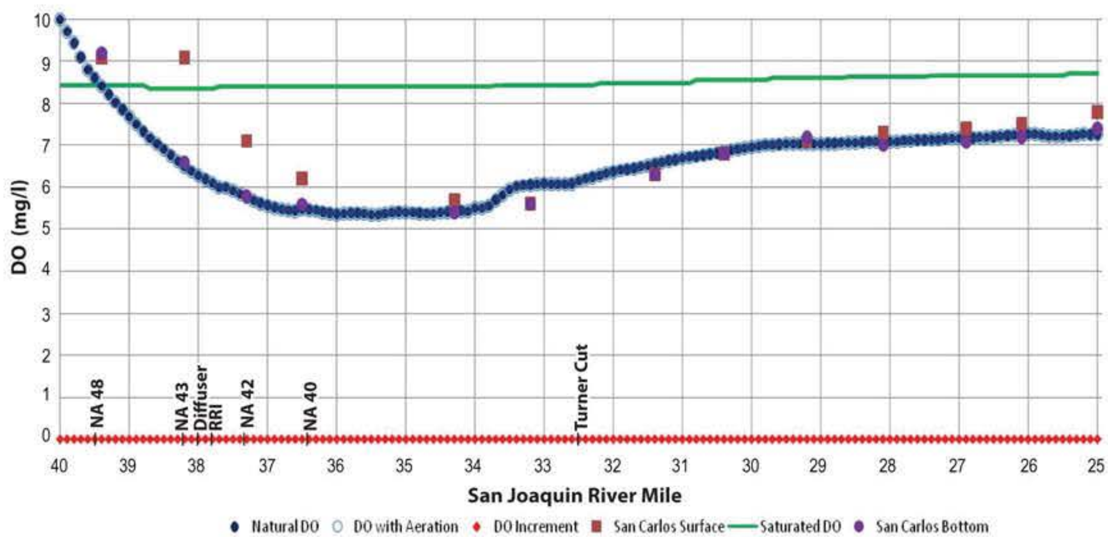

Figure 29b: Comparison of *San Carlos* Boat Survey Measured DO and Calculated DO in the DWSC for September 19, 2009 (flow of 500 cfs, inflow BOD of 12 mg/l)

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Figure 29

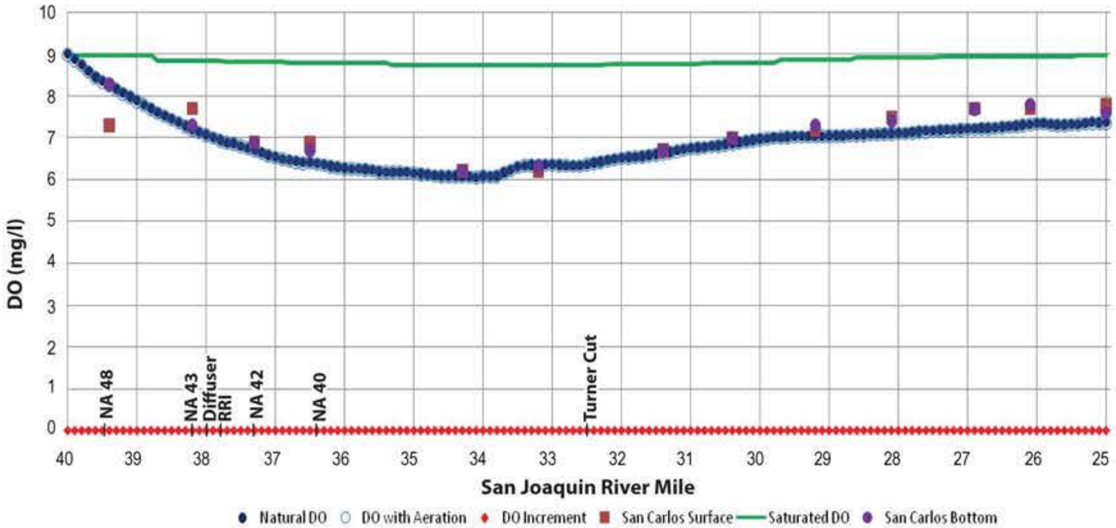

Figure 30a: Comparison of *San Carlos* Boat Survey Measured DO and Calculated DO in the DWSC for October 2, 2009 (flow of 750 cfs, inflow BOD of 10 mg/l)

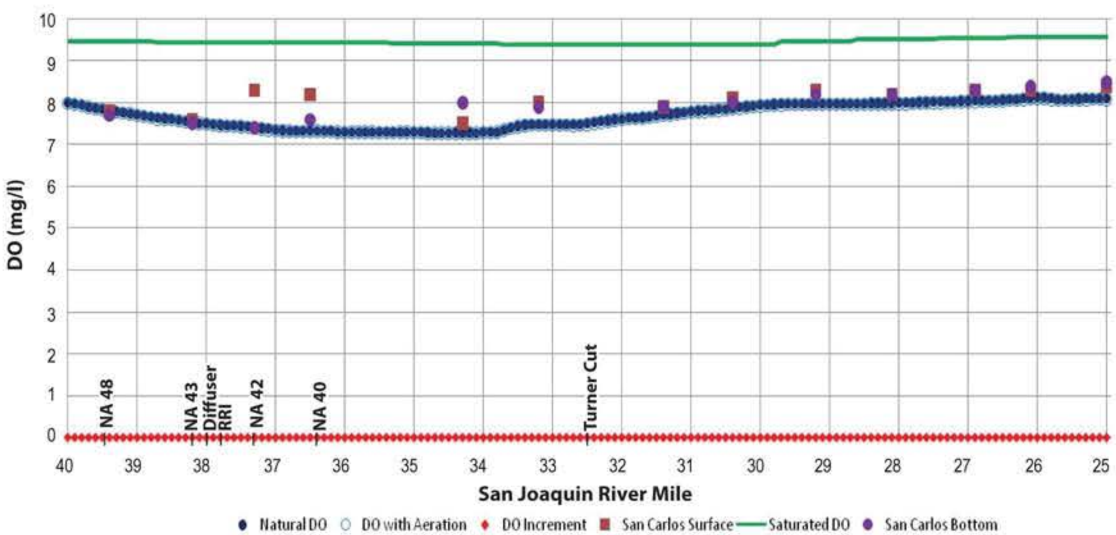

Figure 30b: Comparison of *San Carlos* Boat Survey Measured DO and Calculated DO in the DWSC for October 16, 2009 (flow of 1,000 cfs, inflow BOD of 6 mg/l)

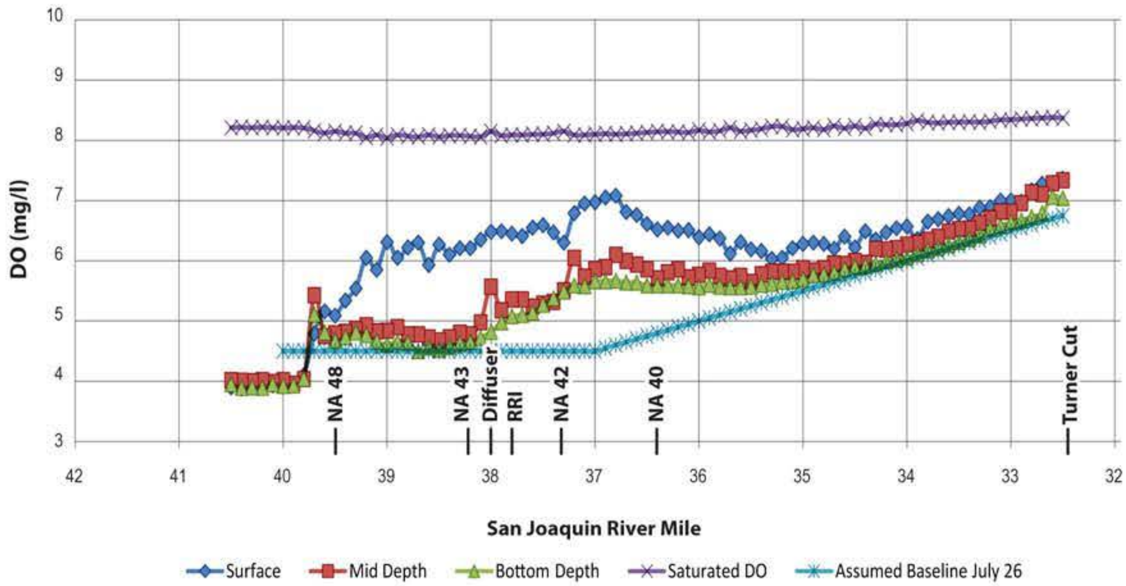

Figure 31a: DWSC DO Profile at Low Tide on July 30, 2010 (After 5 Days of One-pump Operation). (Baseline DO profile for July 26 was estimated)

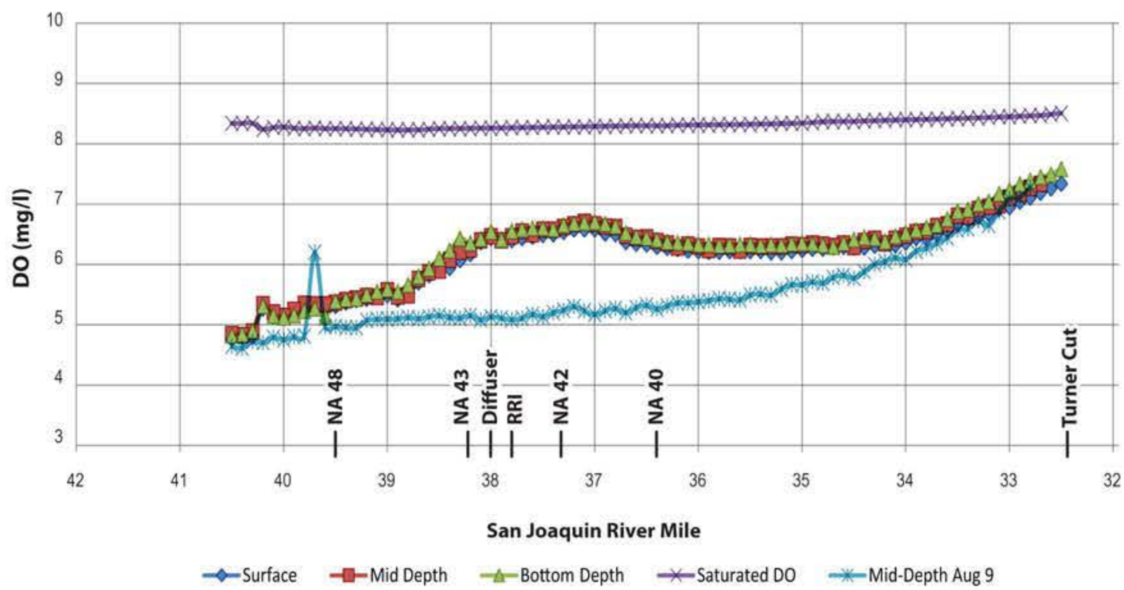

Figure 31b: DWSC DO Profile at Low Tide on August 16, 2010 (After 7 Days of One-pump Operation). (Baseline DO profile was measured on August 9)

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Figure 31

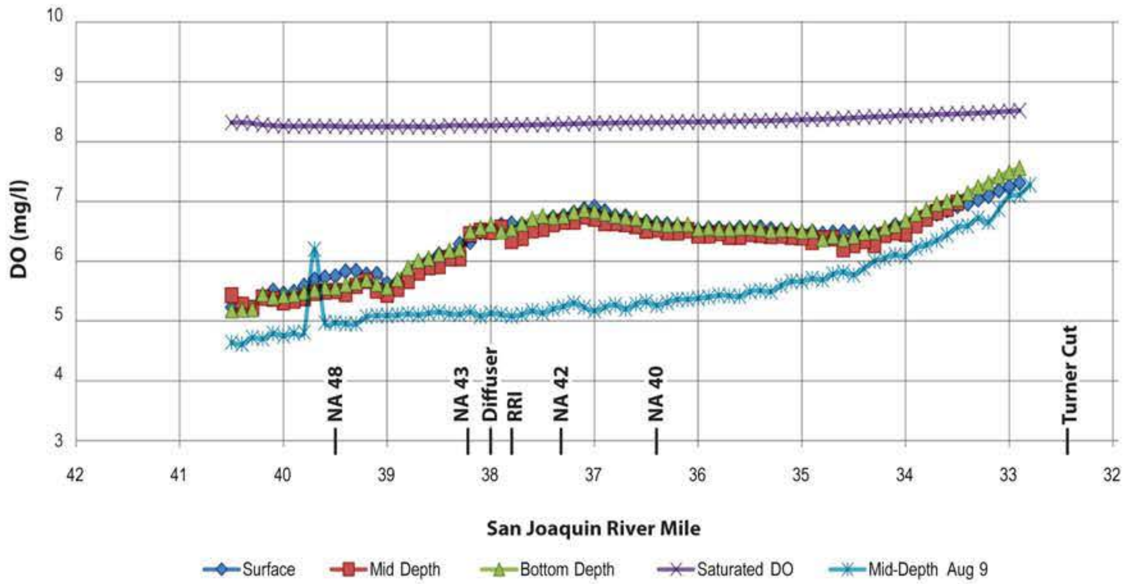

Figure 31c: DWSC DO Profile at Low Tide on August 19, 2010 (After 10 Days of One-pump Operation). (Baseline DO profile was measured on August 9)

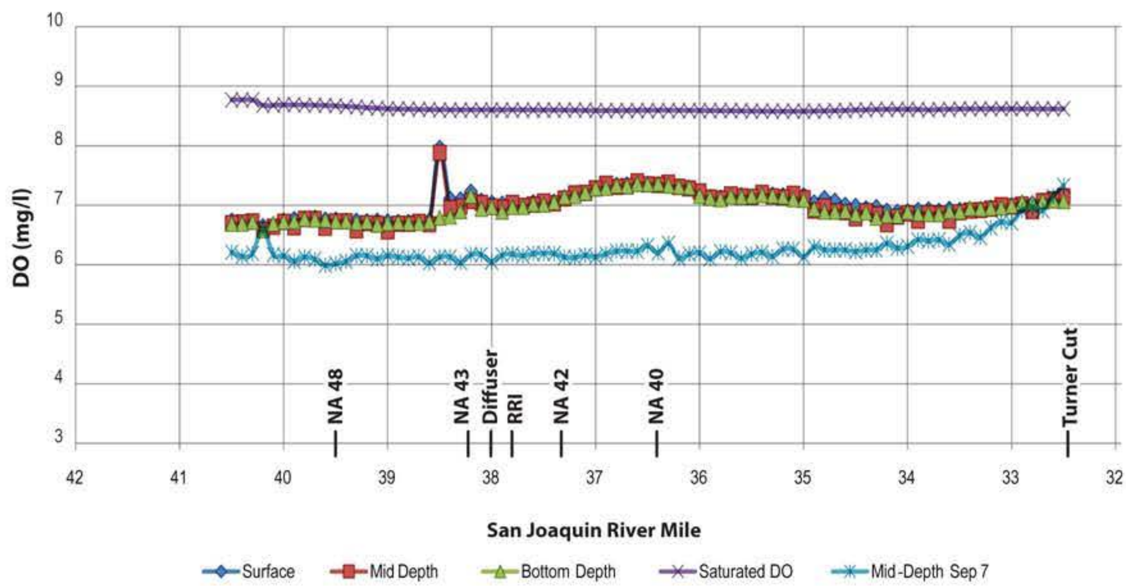

Figure 31d: DWSC DO Profile at Low Tide on September 14, 2010 (After 7 Days of One-pump Operation). (Baseline DO profile was measured on September 7)

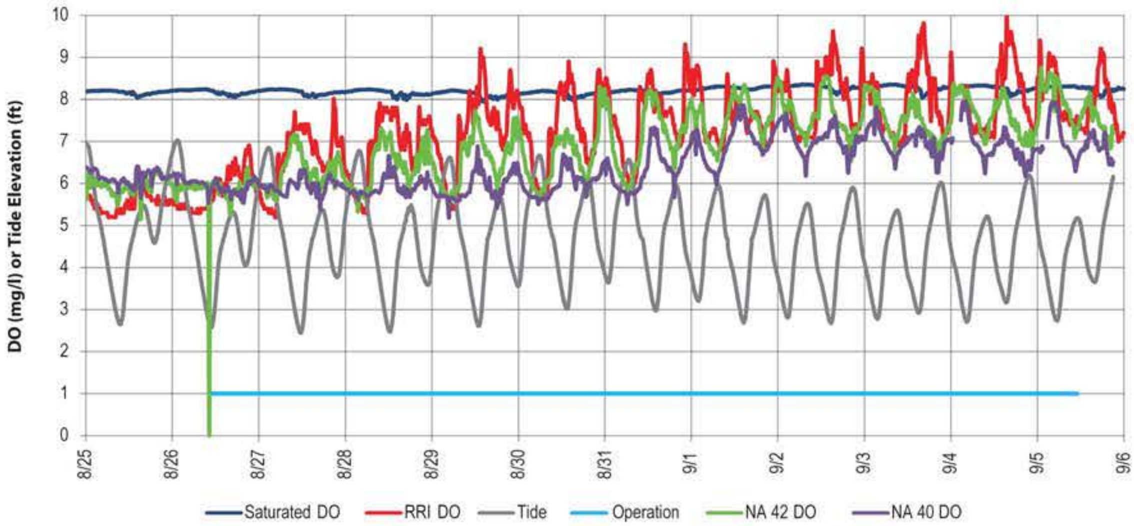

Figure 32a: DO Concentrations at Downstream Monitoring Stations for August 25 to September 5, 2008

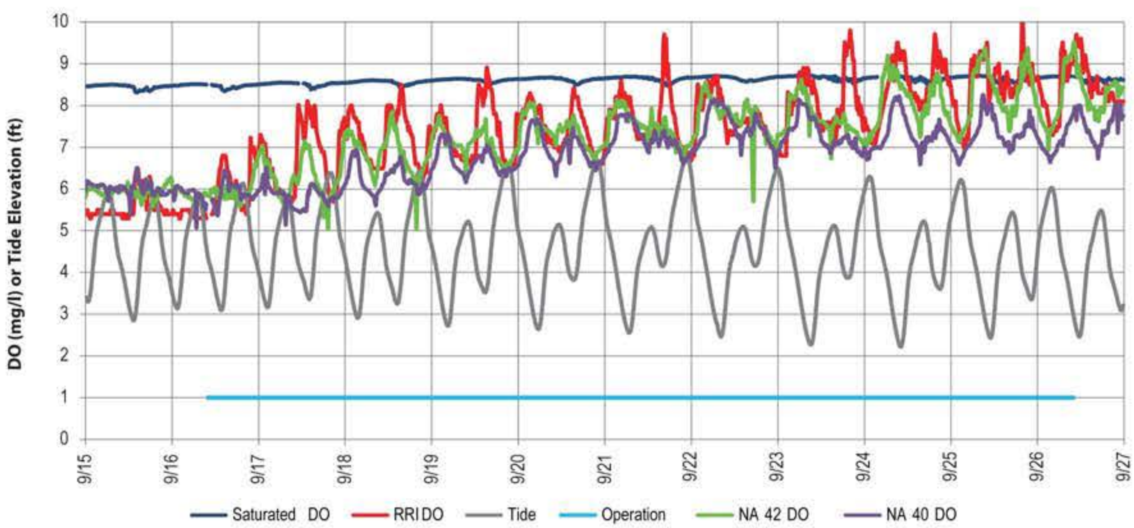

Figure 32b: DO Concentrations at Downstream Monitoring Stations for September 15–26, 2008

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Figure 32

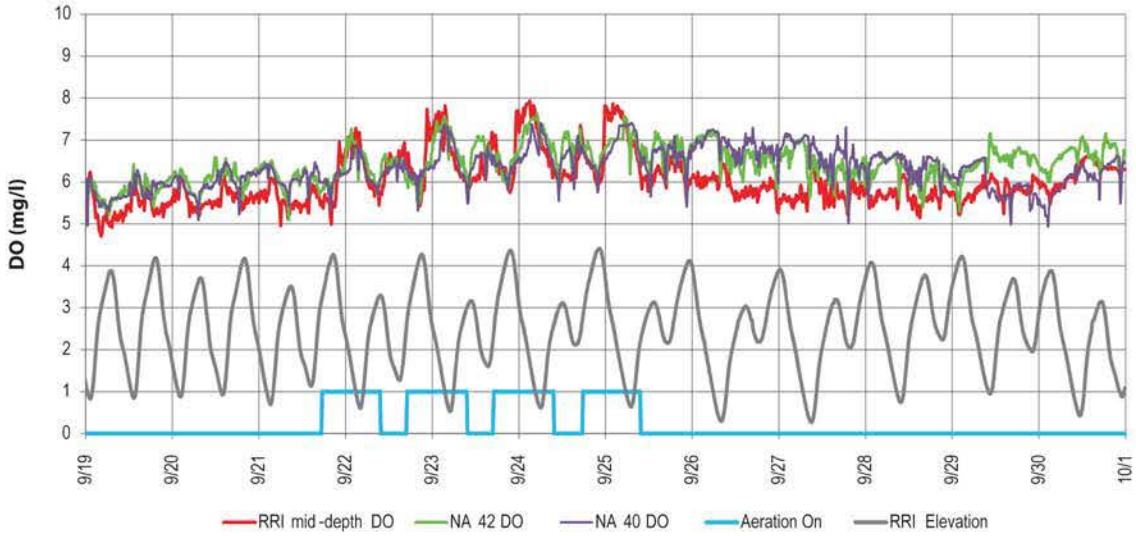

Figure 32c: DO Concentrations at Downstream Monitoring Stations for September 19–30, 2009

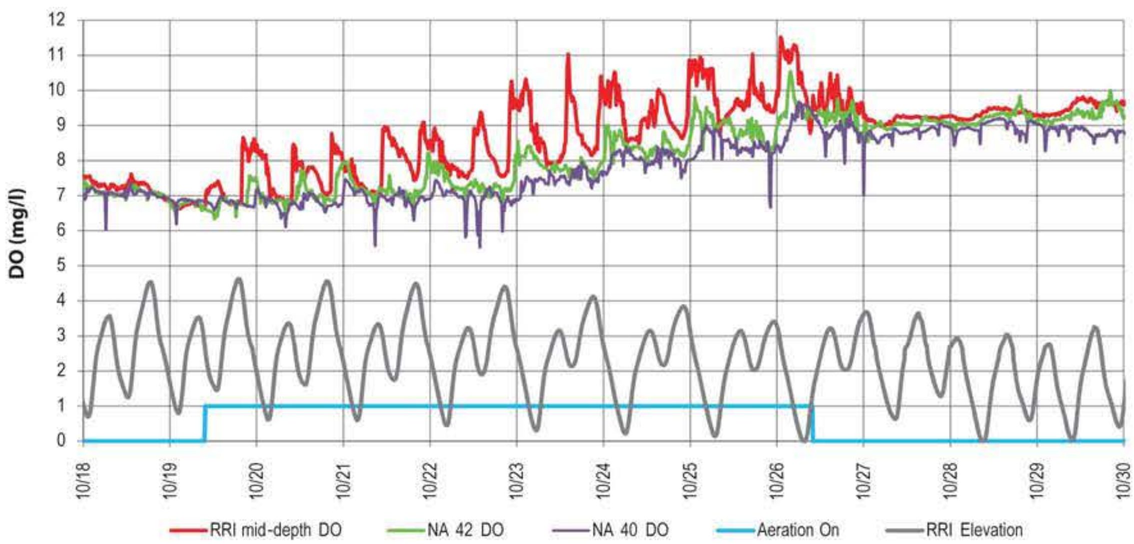

Figure 32d: DO Concentrations at Downstream Monitoring Stations for October 18–29, 2009

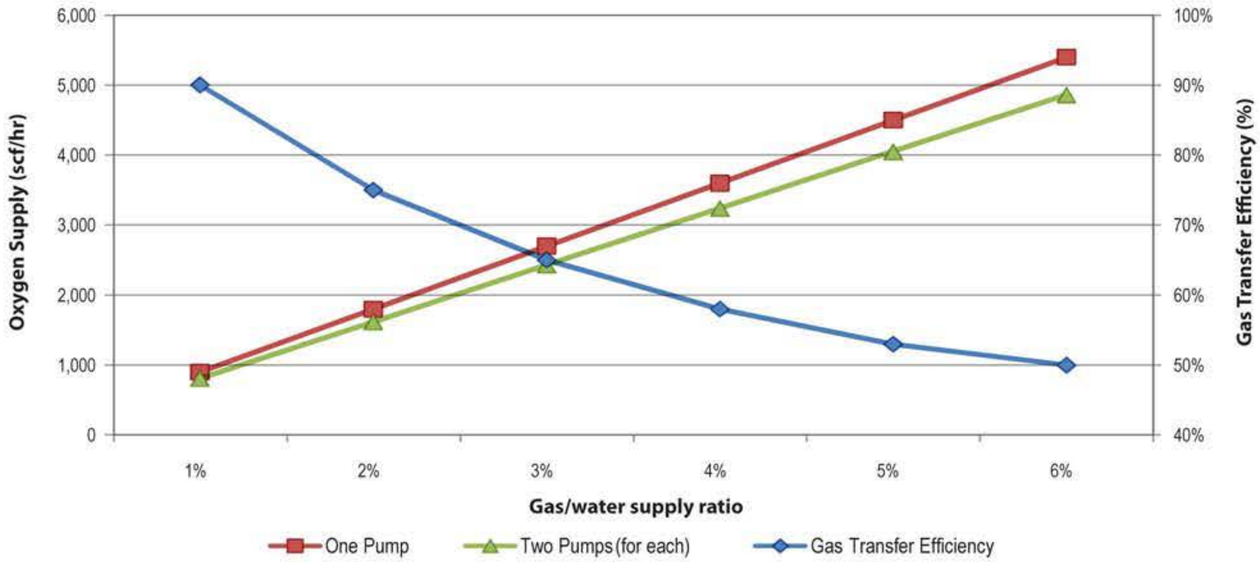

Figure 33a: Oxygen Gas Supply Rates and Gas Transfer Efficiencies for the Aeration Facility

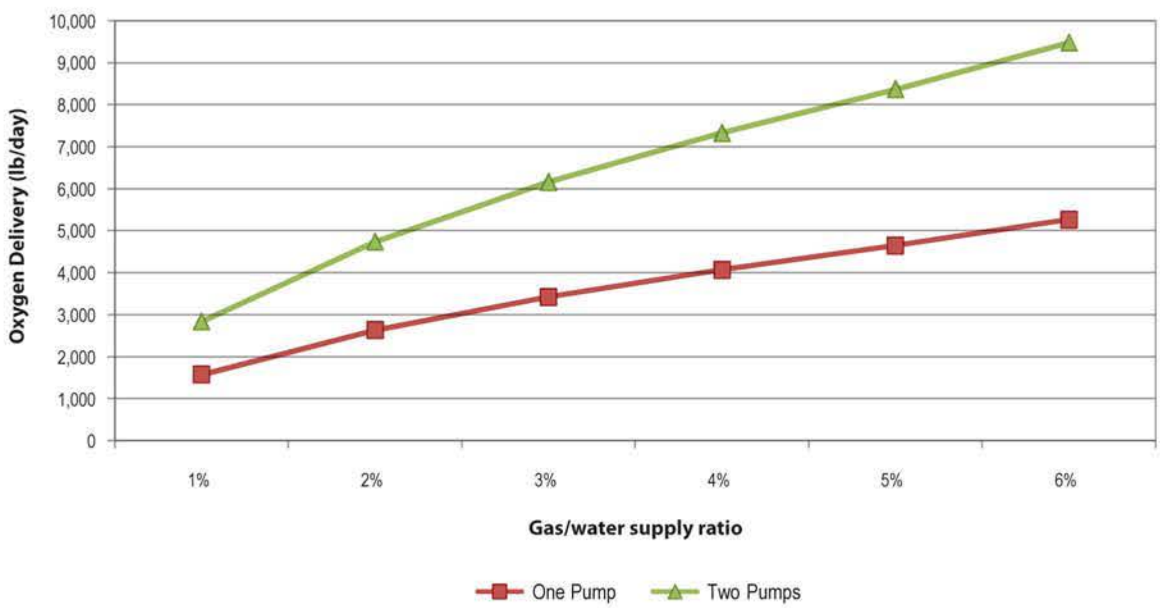

Figure 33b: Daily Dissolved Oxygen Delivery (lb/day) for the Aeration Facility

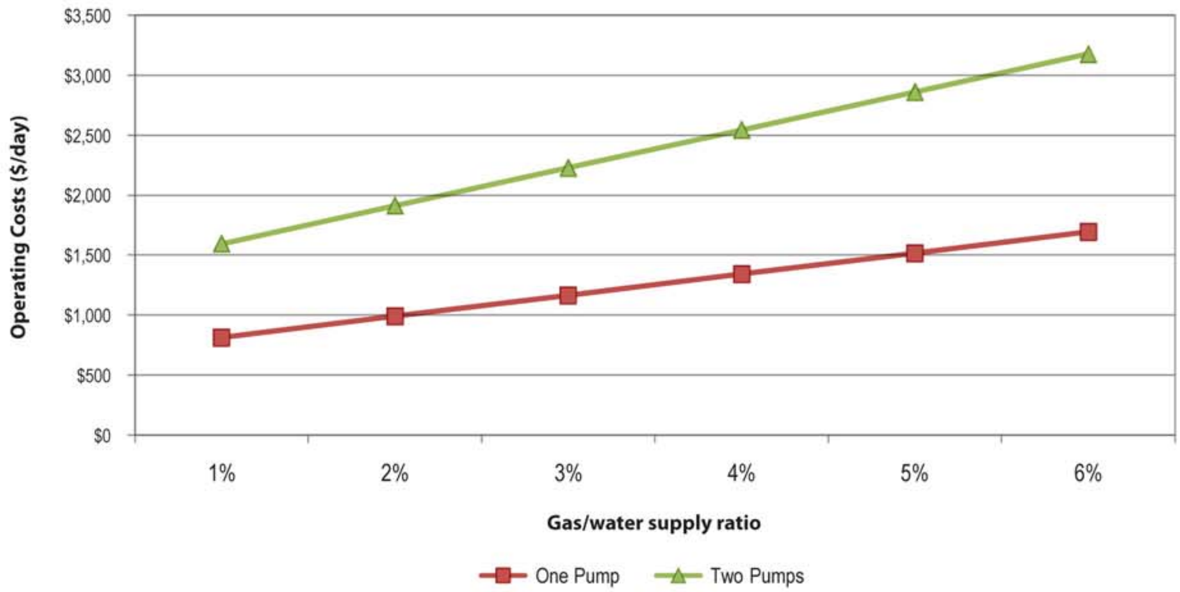

Figure 33c: Daily Estimated Operating Costs for the Aeration Facilty

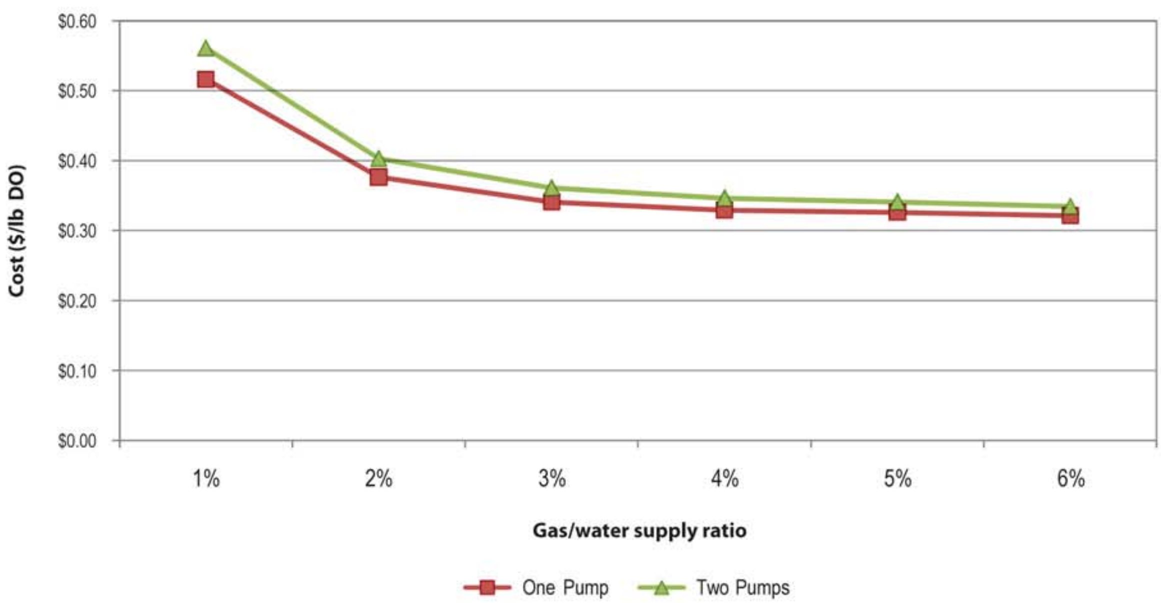

Figure 33d: Cost per Pound of Dissolved Oxygen Delivered to the DWSC

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Figure 33 (continued)