Appendix A

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

Appendix A

Table of Contents

List of Tables and Figures

Table **Page**

Figure **at end of Appendix**

List of Abbreviated Terms

Aeration Facility	Water Ship Channel Dissolved Oxygen Aeration Demonstration Facility
af	acre-feet
BOD	biochemical oxygen demand
CBOD	carbonaceous BOD
cfs	cubic feet per second
CO2	carbon dioxide
CVP	Central Valley Project
DO	dissolved oxygen
DWR	California Department of Water Resources
DWSC	Stockton Deep Water Ship Channel
EC	electrical conductivity
ft	feet
ft2	square feet
K2	reaeration rate
KL	reaeration velocity
lbs/day	pounds per day
Lights	Navigation Aid Lights
M	meters
m/day	meters per day
mg/l	milligrams/liter
NBOD	nitrogenous BOD
RRI	Rough and Ready Island
RWCF	Regional Wastewater Control Facility
RWQCB	Regional Water Quality Control Board
SJR	San Joaquin River
SWP	State Water Project
TMDL	total maximum daily load
TSS	total suspended solids
UOP	University of the Pacific
VAMP	Vernalis Adaptive Management Plan
VSS	volatile suspended solid

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

This appendix describes the dissolved oxygen (DO) measurements made in the Stockton Deep Water Ship Channel (DWSC) by the California Department of Water Resources (DWR) Delta water quality monitoring boat, San Carlos. These measured DO data are used to describe and evaluate the natural DO conditions in the DWSC as a function of river flow, inflow concentration of biochemical oxygen demand (BOD) material (ammonia and algae), and the natural surface reaeration rate.

This appendix also describes the DWSC dissolved oxygen model (DWSC DO Model), which was developed to calculate the DO along the 15-mile stretch of the San Joaquin River (SJR) between river miles 25 and 40. The DWSC DO Model was developed as a tool to help quantify the amount of oxygen dissolved into the impaired reach of the DWSC through operation of the Aeration Facility at Dock 20 at the Port of Stockton.

San Carlos boat survey data from 2004 and 2008 are used to test the DWSC DO Model calculations. The model was used to evaluate the likely effects of the Aeration Facility for the measured flow and DO conditions in 2004 and 2008. City of Stockton river water quality sampling data for 2004 and 2008 are shown to demonstrate the changes in BOD likely caused by the Regional Wastewater Control Facility (RWCF) nitrification facility that began operation in 2007. Some previous measurements of the DO demands and sources that were used to develop the DWSC DO Model are also reviewed at the end of this appendix.

Measured Deep Water Ship Channel Dissolved Oxygen from the *San Carlos* Boat Surveys

DWR has conducted longitudinal boat surveys of the DWSC in the late summer and fall period to document the performance of the head of Old River barrier that has been installed to increase flows and increase DO concentrations in the DWSC, thereby improving conditions for adult Chinook salmon (upstream) migration to tributary spawning areas.

DWR's biweekly *San Carlos* boat survey is just one of many sampling surveys conducted by DWR as part of the Interagency Ecological Program for water quality and biological monitoring of the Delta channels. The *San Carlos* boat surveys extend from Prisoners Point near the Mokelumne River mouth to the DWSC Turning Basin. Surface and bottom measurements are collected for DO, temperature, and salinity (electrical conductivity [EC]), and surface measurements of turbidity and chlorophyll (fluorescence estimate) are collected from about 12 stations.

Figure A-1 shows the DWSC and identifies the SJR miles and the Navigation Aid Lights (Lights) that are used as sampling stations for the *San Carlos* boat surveys. The *San Carlos* boat surveys usually start in the early morning at Prisoners Point, near the mouth of the Mokelumne River, and move upstream to the Turning Basin before noon. There are 14 stations in this 15-mile reach of the SJR. The downstream station is at SJR mile 24.7, and the upstream station is at SJR mile 41.5. Seven stations are downstream of Turner Cut, and seven are upstream. Most of the low-DO conditions are observed upstream of Turner Cut. *San Carlos* boat surveys upstream of Turner Cut include the four DO monitoring stations installed by DWR for the Aeration Facility testing, at Light 40 (SJR mile 36.5), Light 42 (SJR mile 37.3), Light 43 (SJR mile 38.2), and Light 48 (SJR mile 39.4).

A spreadsheet with the most recent 5 years of San Carlos boat survey DWSC data (2004–2008) was prepared. The spreadsheet shows graphs of the San Carlos boat survey DO, turbidity, EC, and chlorophyll data for any selected longitudinal survey date (listed in the spreadsheet). The measured surface and bottom DO concentrations are shown plotted by SJR mile. These 5 years provide a good range of conditions from before and after the City of Stockton added nitrification to the RWCF tertiary treatment, reducing the effluent ammonia to much lower concentrations starting in 2007. This substantially reduced the total BOD concentrations entering the DWSC and increased the observed DO concentrations in the DWSC. The measured DO, temperature, and EC data for a selected survey date can be displayed by river mile from the downstream station at Prisoners Point (SJR mile 25) to the upstream station at Light 48 (SJR mile 39.5).

DWSC DO Model Calculations

The DWSC DO Model includes calculations of the expected DWSC DO profile for the specified conditions of net (i.e., daily average) flow, inflow DO and BOD concentrations, and reaeration rate being used to match the measured DO data from a selected survey date. The calculations include the major sources of DO (reaeration and the Aeration Facility) and losses of DO from decay processes, including sediment oxygen demand (SOD), decay of BOD entering the DWSC, and new BOD produced in the DWSC (from algae or other organic detritus). The calculations are “steady-state” (i.e., a snapshot with constant flow, inflow BOD and DO, and reaeration). The flow, inflowing DO, and total BOD concentrations; BOD decay rate and daily source of BOD within the DWSC; and SOD along the channel are specified. The model is used to calculate the downstream DO profile based on these specified conditions. The DO data from the selected survey are displayed to help adjust the specified conditions to match the measured DO data.

The DWSC DO Model calculates the DO in each 0.1-mile volume segment, with the channel depth, cross section, and surface area along this 15-mile section of the DWSC (SJR miles 25 to 40) at low tide specified as input. The DWSC DO Model is similar to the well-known river profile equations for DO and BOD originally developed for the Ohio River (Streeter and Phelps 1925). A series of comparative model results for a range of river flows, reaeration rates, and initial BOD concentrations will be shown to demonstrate the sensitivity (importance) of the major factors for determining (matching) the downstream DO profile. Several examples of measured DO profiles from *San Carlos* boat surveys are shown along with the calculated DO profiles, using the measured flows prior to the profile date and calibrating the initial DO and BOD concentrations and the reaeration rate to provide the best match with the measured DO data.

The BOD decay rate is assumed to be about 10% per day, based on many long-term BOD decay rate measurements (at 20° C) by the City of Stockton and University of the Pacific (UOP). The SOD rate is assumed to be about 0.25 grams of oxygen per square meter per day (g-O_2/m^2/day), as measured in several sediment cores by UOP. Because the daily effect of SOD on the DO concentration is the SOD rate divided by the mean depth (about 7.5 meters [m]), the daily effect of SOD on DO in the DWSC is small (about 0.035 milligrams/liter [mg/l]).

A reaeration rate of about 20% per day was assumed in the DWSC DO Model, based on the DO monitoring station data analysis during periods of Aeration Facility operation in 2008 (described in Appendix B). The daily change in DO (mg/l) in each segment is calculated as the reaeration rate multiplied by the DO deficit (mg/l) and the segment travel time (days). At the downstream end of the DWSC profile, this reaeration rate is in equilibrium with the daily DO demand from BOD decay. The downstream measured DO deficit is often about 1.0 mg/l, so the daily BOD source was specified as 0.2 mg/l per day to match the reaeration source of 0.2 mg/l for a 1.0 mg/l DO deficit.

The DWCS DO Model calculations do not always match the DO downstream of Turner Cut because the DWSC flow is reduced by the net diversion flow into Turner Cut. The Turner Cut diversion flow is controlled by the Central Valley Project (CVP) and State Water Project (SWP) pumping plant exports (about 10% of combined exports), and it can be greater than the DWSC flow. In this case, the DO in the downstream portion of the DWSC is controlled by the Sacramento River water that is flowing across the SJR channel from Little Connection and Disappointment Sloughs and the Mokelumne River and tidally mixing with the SJR water as it flows toward the export pumps. The DO is generally highest at the downstream portion of the DWSC and approaches a minimum DO deficit of about 1.0 mg/l.

The DWSC DO Model can be used to evaluate the measured DO changes following installation of the head of Old River barrier. Installation of the Old River barrier increases the DWSC flows and reduces the travel time from Vernalis to the DWSC, allowing more of the river BOD concentration and perhaps a higher DO concentration (from algal photosynthesis or river reaeration) to enter the DWSC. The DWSC DO Model also can be used to describe the effects of the Aeration Facility on the downstream DO concentrations.

Examples from 2004 and 2008 demonstrate the ability of the DWSC model to match the measured DO profiles for a variety of flows and BOD conditions, with an assumed reaeration rate of 20% per day. These examples also show the effects of the Aeration Facility (i.e., ability to increase the DO in the DWSC) for a range of DWSC flows. At a capacity of 7,500 pounds per day (lbs/day), the Aeration Facility can increase the DWSC DO concentrations by at least 1 mg/l for a distance of about 2–3 miles for flows of 250–1,000 cubic feet per second (cfs). At higher flows, a greater portion of the initial DO increment will remain at Turner Cut, about 5 miles downstream from the diffuser.

Example Deep Water Ship Channel Dissolved Oxygen Profiles in 2004

Figure A-2a shows the measured DO concentrations in the DWSC on August 30, 2004. The measured surface DO is labeled as “San Carlos Surface” (brown square), and the measured bottom DO is labeled as “San Carlos Bottom” (purple circle). The calculated DO profile depends on the selected flow and other model coefficients. The calculated natural DO is labeled as “Natural DO” (small dark blue circles), and the calculated DO with aeration is labeled “DO with Aeration” (open light blue circles). The saturated DO (based on measured temperature) is shown as the pink line near the top of the graph, and the calculated DO increment from the Aeration Facility is shown at the bottom of the graph (small red diamonds). A flow of 250 cfs was specified based on the measured tidal flows at Garwood to demonstrate the effects of the Aeration Facility with a flow of about 250 cfs. To match the measured DO profile with a flow of 250 cfs, the inflowing DO was specified as 6 mg/l, and the initial BOD concentration was specified as 18 mg/l. This was a relatively high BOD concentration typical of the SJR inflow to the DWSC prior to the RWCF nitrification facility that began operation in 2007.

Once the natural DO profile was matched, the estimated effects of the Aeration Facility on the DO profile were calculated. The estimated fully mixed initial DO increment with a flow of 250 cfs would be about 5.6 mg/l. However, the initial DO increment will decrease with travel time because of the reduced surface reaeration. The calculated DO increment at Light 42 (mile 37.3), located downstream of the diffuser tidal mixing zone, was 2.9 mg/l, and the calculated DO increment at Light 40 (mile 36.3) was about 1.3 mg/l. The DO increment at Turner Cut (mile 32.5) was less than 0.1 mg/l because of the long travel time (20 days) with a flow of 250 cfs. The model results for August 30, 2004, illustrate the large effects from the Aeration Facility when the DWSC flow is 250 cfs.

Figure A-2b shows the measured DO concentrations in the DWSC on September 15, 2004. A flow of about 500 cfs provided a good match with the minimum DO location and the zone of increasing DO that extended downstream past Turner Cut (although a flow of 250 cfs was measured at Garwood). The inflowing DO was specified as 5 mg/l, and the initial BOD was specified as 18 mg/l. For the assumed flow of 500 cfs, the fully mixed DO increment would be 2.8 mg/l. The calculated DO increment at Light 42 (mile 37.3) was 2.0 mg/l at a flow of 500 cfs. The calculated DO increment at Light 40 (mile 36.3) was 1.4 mg/l with a flow of 500 cfs. The DO increment at Turner Cut (5.5 miles downstream of the diffuser) was 0.23 mg/l with a flow of 500 cfs. Most of the initial DO increment was eliminated by the reduced surface reaeration during the 10-day travel time to Turner Cut.

Figure A-2c shows the measured DO concentrations in the DWSC on September 29, 2004 with a flow of about 750 cfs. The position of the minimum DO and zone of DO recovery were farther downstream than with a flow of 500 cfs. The inflowing DO was specified as 7 mg/l, and the initial BOD was specified as 22 mg/l. The minimum DO of about 3 mg/l extended from mile 37 to 34. For the estimated flow of 750 cfs, the fully mixed DO increment would be 1.9 mg/l. The calculated DO increment at Light 42 (mile 37.3) was 1.5 mg/l at a flow of 750 cfs. The calculated DO increment at Light 40 (mile 36.3) was 1.2 mg/l with a flow of 750 cfs. The DO increment at Turner Cut (5.5 miles downstream of the diffuser) was 0.35 mg/l with a flow of 750 cfs. Most of the initial DO increment was eliminated by the reduced surface reaeration during the 7-day travel time to Turner Cut.

Figure A-2d shows the measured DO concentrations in the DWSC on October 15, 2004, with a flow of about 1,000 cfs. The minimum DO location and the zone of DO recovery extended farther downstream than with a flow of 750 cfs. The inflowing DO was specified as 8.0 mg/l, and the initial BOD was specified as 16 mg/l. The minimum DO of about 5.0 mg/l extended from mile 36 to 33. For the estimated flow of 1,000 cfs, the fully mixed DO increment would be 1.4 mg/l. The calculated DO increment at Light 42 (mile 37.3) was 1.2 mg/l at a flow of 1,000 cfs. The calculated DO increment at Light 40 (mile 36.3) was 1.0 mg/l with a flow of 1,000 cfs. The DO increment at Turner Cut (5.5 miles downstream of the diffuser) was 0.4 mg/l with a flow of 1,000 cfs. About one-third of the initial DO increment remained at Turner Cut because the travel time was about 5 days (Table A-1).

These four examples of the DWSC DO profiles demonstrate the ability of the DWSC DO Model to generally match the measured DO for a variety of flows and BOD conditions, with an assumed reaeration rate of 0.2 day^{-1}. These examples also show the effects of the Aeration Facility (i.e., performance) for a range of DWSC flows. At full capacity of 7,500 lbs/day, the Aeration Facility can increase the DWSC DO concentrations by at least 1.0 mg/l for a distance of about 2–3 miles for flows of 250–1,000 cfs. At higher flows, a greater portion of the initial DO increment will persist to Turner Cut, about 5 miles downstream from the diffuser.

Example Deep Water Ship Channel Dissolved Oxygen Profiles in 2008

Four examples of DWSC DO profiles measured by *San Carlos* boat surveys in 2008, after the RWCF added nitrification to reduce the ammonia discharge concentrations, demonstrate the reduced BOD concentrations, and illustrate the general effects of the Aeration Facility.

Figure A-3a shows the measured and calculated DO concentrations in the DWSC on July 16, 2008, with a flow of about 500 cfs. As described above, the actual flows in summer 2008 were about 250 cfs, but 500 cfs gives a better match to the longitudinal DO profile. The estimated inflow BOD concentration was 10 mg/l, about half of the BOD concentrations used to match the 2004 survey data (before nitrification). The minimum DO was about 5.0 mg/l from mile 38 to 35, and DO was about 6.0 mg/l at Turner Cut (mile 32.5). The Aeration Facility was operated with an on/off schedule during July and August, was adding about 7,500 lbs/day, and had operated for 2 days. The surface and bottom DO at mile 38.2 (Light 43) were about 0.5 mg/l higher than the calculated natural DO profile. The DO at mile 37.3 (Light 42) was about 1.5 mg/l higher than the calculated natural DO profile, and the DO at mile 36.5 (Light 40) was about 1 mg/l higher than the natural DO profile. The calculated downstream effects of the Aeration Facility matched the measured DO reasonably well, although the facility had operated for only 2 days (15,000 pounds of oxygen added). Some of the elevated DO in this region might have been from algal photosynthesis.

Figure A-3b shows the measured and calculated DO concentrations in the DWSC on July 30, 2008, with a flow of about 500 cfs. The estimated inflow BOD concentration was 10 mg/l. This is about half of the BOD concentrations used to match the 2004 survey data (before nitrification). The minimum DO was about 5.0 mg/l from mile 38 to 35, and DO was about 6.0 mg/l at Turner Cut (mile 32.5). The surface and bottom DO at mile 38.2 (Light 43) were about 1.0 mg/l higher than the calculated natural DO profile. The DO at mile 37.3 (Light 42) was about 1.5 mg/l higher than the calculated natural DO profile, the surface DO at mile 36.5 (Light 40) was about 2.0 mg/l higher, and the bottom DO was about 1.5 mg/l higher than the natural DO profile. The calculated downstream effects of the Aeration Facility matched the measured DO reasonably well, although the facility had operated for only 2 days.

Figure A-3c shows the measured and calculated DO concentrations in the DWSC on August 14, 2008, with a flow of about 500 cfs. The estimated inflow BOD concentration was again 10 mg/l. Flow and BOD conditions were very steady during July and August 2008. The minimum DO was about 5.0 mg/l from mile 38 to 35, and DO was about 6.0 mg/l at Turner Cut (mile 32.5). The bottom DO at mile 38.2 (Light 43) matched the natural DO profile, but the surface DO was about 2.5 mg/l higher than the calculated natural DO profile. The bottom DO at mile 37.3 (Light 42) was about 1.0 mg/l higher, and the surface DO was 2.0 mg/l higher than the natural DO profile. The surface DO at mile 36.5 (Light 40) was also about 1.5 mg/l higher, and the bottom DO was about 1 mg/l higher than the natural DO profile.

Figure A-3d shows the measured and calculated DO concentrations in the DWSC on August 28, 2008, again with a flow of about 500 cfs. The estimated inflow BOD concentration was 10.0 mg/l. The minimum DO was about 5.0 mg/l from mile 38 to 35, and DO was about 6.0 mg/l at Turner Cut (mile 32.5). The bottom DO at mile 38.2 (Light 43) was 0.5 mg/l higher than the natural DO profile, and the surface DO was almost 2 mg/l higher than the calculated natural DO profile. The surface and bottom DO at mile 37.3 (Light 42) was about 1.5 mg/l higher than the natural DO profile. The surface and bottom DO at mile 36.5 (Light 40) was also about 1.5 mg/l higher than the natural DO profile. The calculated DO profile with aeration was about 0.5 mg/l higher than the natural DO at mile 34, and was just 0.1 mg/l at Turner Cut. At a flow of 500 cfs, the travel time to Turner Cut would be about 10 days, so very little of the initial added DO increment would remain at Turner Cut.

Table A-1 gives the Aeration Facility performance calculations for a range of flows between 250 and 1,500 cfs for a capacity of 7,500 lbs/day. The percentage of the added DO that is retained in the DWSC between the diffuser and Turner Cut is given as a general performance indicator. Higher flows reduce the travel time and allow more of the added DO to be retained in the DWSC. However, the initial DO increments are smaller at higher flows. Operating strategies for the DWSC can be developed for the range of observed flows, as a function of the inflowing DO and BOD concentrations. When the BOD is high enough to create a low DO concentration in the DWSC (approaching the DO objectives), the Aeration Facility can be operated and the effects of the added DO can be estimated from the performance results given in Table A-1.

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

	Flow (cfs)	250	500	750	1,000	1,250	1,500
DO Increment without Reaeration (mg/l)		5.6	2.8	1.9	1.4	1.1	0.9
Location	San Joaquin River Mile						
	40.0	0.00	0.00	0.00	0.00	0.00	0.00
Light 48	39.5	0.00	0.00	0.00	0.00	0.00	0.00
	39.0	0.00	0.00	0.00	0.00	0.00	0.00
Light 43	38.5	0.51	0.27	0.18	0.14	0.11	0.09
DO Diffuser	38.0	2.55	1.46	1.02	0.78	0.63	0.53
Light 42	37.5	3.24	2.12	1.55	1.22	1.00	0.85
	37.0	2.37	1.82	1.40	1.13	0.94	0.81
Light 40	36.5	1.56	1.48	1.22	1.02	0.87	0.75
	36.0	1.10	1.25	1.09	0.93	0.81	0.71
	35.5	0.77	1.05	0.97	0.86	0.75	0.67
	35.0	0.52	0.87	0.85	0.78	0.70	0.63
	34.5	0.36	0.73	0.76	0.71	0.65	0.60
	34.0	0.22	0.57	0.65	0.63	0.59	0.55
	33.5	0.10	0.39	0.50	0.52	0.51	0.48
	33.0	0.05	0.29	0.42	0.46	0.46	0.44
Turner Cut	32.5	0.03	0.23	0.35	0.40	0.41	0.41
	DO Retention to Turner Cut	23%	40%	49%	54%	57%	59%
	Travel Time to Turner Cut (days)	19.1	10.1	7.0	5.5	4.6	4.0

Modeled Deep Water Ship Channel Geometry

The DWSC at the Rough and Ready Island (RRI) tidal measurement station is about 670 feet (ft) wide with a cross section area of about 16,000 square feet (ft^2) at low tide (mean depth of 24 ft). Therefore, the DWSC volume is about 2,000 acre-feet (af) per mile (i.e., 5,280 ft x 16,000 ft^2 / 43,560 ft^2 per acre = 1,940 af) at low tide. A net flow of 1,000 cfs is equivalent to a daily volume of about 2,000 af, which would cause a net downstream movement through the DWSC of about 1.0 mile per day. A flow of 500 cfs would cause a net downstream movement of about 0.5 mile per day, and a flow of 250 cfs would cause a net downstream movement of about 0.25 mile per day.

Table A-2 gives the estimated DWSC channel geometry in 0.1-mile increments, based on measured cross sections available from the U.S. Army Corps of Engineers or used in the Delta Simulation Model II Cross Section Development Program tidal flow model geometry. The DWSC geometry is given from Webber Point at Stockton (SJR mile 42) downstream to Turner Cut, which is located at SJR mile 32.5. The diffuser is located at mile 38.1, and the RRI station is located at mile 37.9.

The tidal flows and geometry of the DWSC were described previously in a report on the tidal mixing at the downstream end near Turner Cut (Jones & Stokes 2002). Water moving from the Sacramento River toward the CVP and SWP pumps flows upstream in the SJR, enters Turner Cut, and flows upstream in Middle River and Victoria Cut to West Canal and the export pumps. The Sacramento River water has high DO concentrations relative to the SJR, so this portion of the DWSC generally is above the 5 mg/l objective (December 1 through August 31, and 6 mg/l for the rest of the year) and does not require any supplemental DO from the Aeration Facility.

The distance from the inflow of SJR water to the DWSC at mile 40 (Channel Point) to Turner Cut at mile 32.5 is about 7.5 miles. The low-tide volume in this section of the DWSC is about 14,000 af (Table A-2), so the travel time for a river flow of 1,000 cfs would be 7 days. The travel time for a flow of 750 cfs would be about 10 days, the travel time for a flow of 500 cfs would be about 14 days, and the travel time for a flow of 250 cfs would be about 28 days. The distance from Channel Point to the downstream DO monitoring station at Light 40 (mile 36.3) is about 3.7 miles, and the volume is 7,000 af. Therefore, the travel times from Channel Point to the Light 40 DO monitoring station are about half of the travel times to Turner Cut.

The tidal flows in the DWSC may not be uniformly distributed within the cross section as assumed in this evaluation. Because a substantial tidal flow moves upstream into the SJR channel with a maximum depth of about 15 ft, most of this flood-tide flow may come from the surface of the DWSC. This increased surface flow may be especially strong during stratified temperature conditions. In this case, the upstream tidal movement (i.e., tidal velocity) may be greater at the surface than for the average DWSC tidal velocity described in this section. During ebb tides, as the SJR flows into the DWSC, temperature differences (especially at night) cause the flow to move toward the bottom of the DWSC. This “layered tidal flow” likely would increase the estimated upstream movement, longitudinal spreading, and vertical mixing of the added DO from the Aeration Facility diffuser.

Table A-2. Stockton Deep Water Ship Channel Geometry for 0.1-Mile Segments to Turner Cut

River Mile	River Location	Average Segment Width at 2 Feet (feet)	Segment Cross Section at 2 Feet (sq ft)	Segment Area (acres)	Cumulative Area (acres)	Segment Average Depth (feet)	Segment Volume at 2 Feet (af)	Cumulative Volume at 2 Feet (af)	Estimated Volume at 7 feet (110% area) (af)	Upstream Tidal Prism Volume (af)
42.0	Stockton Downtown	0	0	0.0	0.0	0.0	0	0	0	0
41.9	Weber Point	200	3,000	2.4	2.4	7.5	18	18	32	12
41.8		225	3,000	2.7	5.2	13.3	36	55	83	26
41.7		250	3,500	3.0	8.2	13.0	39	94	139	41
41.6		300	4,000	3.6	11.8	12.5	45	139	204	59
41.5		395	4,000	4.8	16.6	10.1	48	188	279	83
41.4		470	4,500	5.7	22.3	9.0	52	239	362	112
41.3		435	4,500	5.3	27.6	10.3	55	294	446	138
41.2		435	4,500	5.3	32.8	10.3	55	348	529	164
41.1		395	4,500	4.8	37.6	11.4	55	403	610	188
41.0		315	4,500	3.8	41.5	14.3	55	458	686	207
40.9		395	4,223	4.8	46.2	11.0	53	510	765	231
40.8	Turning Basin	1,220	27,832	14.8	61.0	13.1	194	705	1,040	305
40.7	Turning Basin	1,165	30,000	14.1	75.2	24.8	350	1,055	1,469	376
40.6	Turning Basin	1,160	36,910	14.1	89.2	28.8	406	1,461	1,951	446
40.5		670	15,865	8.1	97.3	39.4	320	1,781	2,316	487
40.4		435	12,000	5.3	102.6	32.0	169	1,949	2,514	513
40.3		435	12,000	5.3	107.9	27.6	145	2,095	2,688	539
40.2		435	12,000	5.3	113.2	27.6	145	2,240	2,863	566
40.1		670	12,000	8.1	121.3	17.9	145	2,386	3,053	606
40.0		435	15,000	5.3	126.5	31.0	164	2,549	3,245	633
39.9		575	15,000	7.0	133.5	26.1	182	2,731	3,466	668
39.8	Dock 13 Aerators	585	15,240	7.1	140.6	25.8	183	2,915	3,688	703
39.7	San Joaquin River Inflow	800	25,000	9.7	150.3	25.2	244	3,158	3,985	752
39.6	Channel Point	720	12,318	8.7	159.0	25.9	226	3,385	4,259	3,002

River Mile	River Location	Average Segment Width at 2 Feet (feet)	Segment Cross Section at 2 Feet (sq ft)	Segment Area (acres)	Cumulative Area (acres)	Segment Average Depth (feet)	Segment Volume at 2 Feet (af)	Cumulative Volume at 2 Feet (af)	Estimated Volume at 7 feet (110% area) (af)	Upstream Tidal Prism Volume (af)
39.5		470	14,000	5.7	164.7	28.0	160	3,544	4,450	3,030
39.4	R3/Light 48/DO Monitor	550	14,000	6.7	171.4	25.5	170	3,714	4,656	3,063
39.3		550	14,000	6.7	178.1	25.5	170	3,883	4,863	3,097
39.2		550	14,000	6.7	184.7	25.5	170	4,053	5,069	3,130
39.1		670	14,431	8.1	192.8	21.2	172	4,225	5,286	3,171
39.0		440	15,000	5.3	198.2	33.4	178	4,404	5,494	3,197
38.9		495	15,000	6.0	204.2	30.3	182	4,586	5,709	3,227
38.8		460	15,796	5.6	209.8	33.5	187	4,772	5,926	3,255
38.7		435	16,000	5.3	215.0	36.5	193	4,965	6,148	3,282
38.6	Smith Canal	945	16,000	11.5	226.5	16.9	194	5,159	6,405	3,339
38.5	R4/Light 45	755	16,157	9.2	235.6	21.3	195	5,354	6,650	3,385
38.4		620	16,000	7.5	243.2	25.9	195	5,549	6,886	3,422
38.3	Light 43/DO Monitor	490	16,000	5.9	249.1	32.7	194	5,743	7,113	3,452
38.2		560	16,000	6.8	255.9	28.6	194	5,937	7,344	3,486
38.1	DO Diffuser	680	16,000	8.2	264.1	23.5	194	6,131	7,583	3,527
38.0		710	16,000	8.6	272.7	22.5	194	6,325	7,825	3,570
37.9	R&R Island DO Monitor	670	16,000	8.1	280.8	23.9	194	6,518	8,063	3,611
37.8		670	16,157	8.1	289.0	24.0	195	6,713	8,303	3,651
37.7		550	15,000	6.7	295.6	28.3	189	6,902	8,528	3,685
37.6	Calaveras River	1,065	15,000	12.9	308.5	14.1	182	7,084	8,781	3,749
37.5	Burns Cutoff	585	15,000	7.1	315.6	25.6	182	7,266	9,002	3,785
37.4		545	15,000	6.6	322.2	27.5	182	7,448	9,220	3,818
37.3	R5/Lights 41–42/DO Monitor	470	15,000	5.7	327.9	31.9	182	7,629	9,433	3,846
37.2		505	15,000	6.1	334.1	29.7	182	7,811	9,649	3,877
37.1		475	15,000	5.8	339.8	31.6	182	7,993	9,862	3,905

River Mile	River Location	Average Segment Width at 2 Feet (feet)	Segment Cross Section at 2 Feet (sq ft)	Segment Area (acres)	Cumulative Area (acres)	Segment Average Depth (feet)	Segment Volume at 2 Feet (af)	Cumulative Volume at 2 Feet (af)	Estimated Volume at 7 feet (110% area) (af)	Upstream Tidal Prism Volume (af)
37.0		535	15,000	6.5	346.3	28.0	182	8,175	10,080	3,938
36.9		550	14,072	6.7	353.0	26.4	176	8,351	10,292	3,971
36.8		550	14,000	6.7	359.6	25.5	170	8,521	10,499	4,005
36.7		640	14,000	7.8	367.4	21.9	170	8,691	10,712	4,043
36.6		655	14,000	7.9	375.3	21.4	170	8,861	10,925	4,083
36.5	P8 Buckley Cove	940	20,000	11.4	386.7	18.1	206	9,067	11,194	4,140
36.4		680	14,000	8.2	395.0	25.0	206	9,273	11,445	4,181
36.3	Lights 39/40/DO Monitor	615	14,000	7.5	402.4	22.8	170	9,442	11,656	4,218
36.2		545	14,000	6.6	409.0	25.7	170	9,612	11,862	4,252
36.1		470	12,760	5.7	414.7	28.5	162	9,774	12,055	4,280
36.0		495	12,500	6.0	420.7	25.5	153	9,927	12,241	4,310
35.9		680	12,500	8.2	429.0	18.4	152	10,079	12,438	4,351
35.8	Lights 37/38	670	12,500	8.1	437.1	18.7	152	10,230	12,634	4,392
35.7		600	12,500	7.3	444.4	20.8	152	10,382	12,826	4,428
35.6		520	12,500	6.3	450.7	24.0	152	10,533	13,012	4,460
35.5	R6/Lights 35–36	410	12,230	5.0	455.6	30.2	150	10,683	13,189	4,485
35.4		570	12,500	6.9	462.5	21.7	150	10,833	13,377	4,519
35.3		725	12,500	8.8	471.3	17.2	152	10,985	13,577	4,563
35.2		680	12,500	8.2	479.6	18.4	152	11,136	13,774	4,604
35.1		620	12,500	7.5	487.1	20.2	152	11,288	13,967	4,642
35.0		510	12,500	6.2	493.3	24.5	152	11,439	14,152	4,673
34.9		505	13,040	6.1	499.4	25.3	155	11,594	14,341	4,703
34.8		505	13,500	6.1	505.5	26.3	161	11,755	14,535	4,734
34.7		495	14,000	6.0	511.5	27.8	167	11,922	14,735	4,764
34.6		645	14,500	7.8	519.3	22.1	173	12,094	14,951	4,803
34.5		710	15,000	8.6	527.9	20.8	179	12,273	15,177	4,846

River Mile	River Location	Average Segment Width at 2 Feet (feet)	Segment Cross Section at 2 Feet (sq ft)	Segment Area (acres)	Cumulative Area (acres)	Segment Average Depth (feet)	Segment Volume at 2 Feet (af)	Cumulative Volume at 2 Feet (af)	Estimated Volume at 7 feet (110% area) (af)	Upstream Tidal Prism Volume (af)
34.4		740	15,500	9.0	536.9	20.6	185	12,458	15,411	4,891
34.3	Lights 33/34	755	16,000	9.2	546.1	20.9	191	12,649	15,652	4,937
34.2		740	17,312	9.0	555.0	22.5	202	12,851	15,903	4,982
34.1		620	16,000	7.5	562.5	26.9	202	13,053	16,147	5,019
34.0	Lights 31/32	1,100	16,000	13.3	575.9	14.5	194	13,247	16,414	5,086
33.9		615	16,000	7.5	583.3	26.0	194	13,441	16,649	5,123
33.8		945	16,000	11.5	594.8	16.9	194	13,634	16,906	5,180
33.7		1,530	16,000	18.5	613.3	10.5	194	13,828	17,202	5,273
33.6	Lights 29/30	1,460	16,187	17.7	631.0	11.0	195	14,023	17,494	5,362
33.5		1,605	16,000	19.5	650.5	10.0	195	14,219	17,796	5,459
33.4		1,180	16,000	14.3	664.8	13.6	194	14,412	18,069	5,530
33.3		940	16,000	11.4	676.2	17.0	194	14,606	18,325	5,587
33.2	Lights 27/28	860	16,000	10.4	686.6	18.6	194	14,800	18,577	5,639
33.1		865	16,000	10.5	697.1	18.5	194	14,994	18,828	5,692
33.0		750	15,591	9.1	706.2	21.1	191	15,186	19,070	5,737
32.9		670	16,000	8.1	714.3	23.6	191	15,377	19,306	5,778
32.8	Lights 25/26	685	16,000	8.3	722.6	23.4	194	15,571	19,545	5,819
32.7		685	16,000	8.3	730.9	23.4	194	15,765	19,785	5,861
32.6	Turner Cut	780	16,000	9.5	740.4	20.5	194	15,959	20,031	5,908
32.5	R7/Lights 23/24	1,180	16,000	14.3	754.7	13.6	194	16,153	20,304	5,980

Modeled Effects of Aeration and Reaeration

Measurements of reaeration generally involve a small experimental enclosure (tank or pool) that is chemically de-oxygenated, and the reaeration rate is calculated from the rate of increasing DO. Direct measurements of reaeration in tidal waters are not possible because the tidal mixing and surface transfer would be interrupted by any experimental enclosure. Measurements in surface pools within lakes demonstrate that reaeration increases rapidly with wind speed.

The natural surface reaeration DO source can be estimated for the DWSC as:

Reaeration DO Source (lb/acre/day) = 67 * Reaeration Rate (% per day) * DO Deficit (mg/l)

The coefficient of 67 is the combined conversion from mg/l [or g/m^3] of DO times the mean depth [7.5 m] times 4,047 m^2 per acre, and 454 grams per pound. For an assumed DWSC reaeration rate of 20% per day (based on modeling results described below) with a DO deficit of 3.0 mg/l (5.0 mg/l DO in summer), reaeration would supply about 40 lbs of oxygen per acre per day. Because there are about 250 acres between Channel Point and RRI, reaeration in this portion of the DWSC would supply about 10,000 lbs/day. The reaeration will decrease with a reduced DO deficit, which would result from adding DO with the Aeration Facility. This interaction between the added DO increment from the Aeration Facility and the natural surface reaeration will be explored in more detail in the next section.

The DWSC DO Model was used to investigate the effects of the added DO from the Aeration Facility on the reduced surface reaeration and the resulting downstream DO profile when operating the Aeration Facility. The daily oxygen added by the Aeration Facility is specified as one of the model parameters (lbs/day). The initial DO increment from the Aeration Facility in the upstream portion of the DWSC will depend on the daily flow. The initial fully mixed DO increment can be estimated as:

Added DO Increment (mg/l) = 0.185 x DO Source (lbs/day) / Flow (cfs)

The coefficient of 0.185 is the combined conversion factor. The DWSC DO Model distributes the DO increment into a 1.0-mile section of the DWSC to represent the tidal spreading from the diffuser at low tide. A source of 7,500 lbs/day was used to represent the maximum possible DO increment from the Aeration Facility. The initial DO increment would be 5.6 mg/l for a flow of 250 cfs, 2.8 mg/l for a flow of 500 cfs, 1.9 mg/l for a flow of 750 cfs, and about 1.4 mg/l for a flow of 1,000 cfs. The added DO increment will reduce the downstream DO deficit and reduce the surface reaeration. The model calculates the downstream DO profile with the Aeration Facility increment compared with the DO profile without the Aeration Facility increment.

The Aeration Facility will affect a longer section of the DWSC when the flow is higher, but with a smaller DO increment. The effects of the Aeration Facility generally will be upstream of Turner Cut because the travel time from the diffuser to Turner Cut is greater than 5 days when the flow is less than 1,000 cfs. However, this is also the section of the DWSC where the lowest DO concentrations have been observed in the *San Carlos* boat surveys.

The Aeration Facility normally would be operated only if DO concentrations in the DWSC were less than 5.0 or 6.0 mg/l (i.e., DO objective). When the DO concentrations are relatively low and flows are moderate (less than 1,000 cfs), the Aeration Facility increments will be greater than 1.0 mg/l and will persist downstream several miles (i.e., several days). The performance of the Aeration Facility can be characterized by the initial DO increment (as a function of flow) and the distance downstream that some portion of the initial DO increment will persist (farther downstream with higher flow). The fraction of the added DO remaining upstream of Turner Cut also could be used to indicate the general performance. The Aeration Facility performance (i.e., increase in DO concentration downstream in the DWSCD) depends on the DWSC flow, but does not depend on the BOD or the natural DO profile in the DWSC.

Modeled Effects of Flow, Biochemical Oxygen Demand, and Reaeration

The DWSC natural DO profiles (i.e., the DO "sag" measured downstream in the DWSC) are most sensitive to the flow, the inflowing BOD concentration, and the reaeration rate. This can be demonstrated with comparative results for a range of flows, BOD concentrations, and reaeration values. The range of flows will be 250 cfs, 500 cfs, 750 cfs, and 1,000 cfs. Higher flows will move rapidly through the DWSC, and BOD decay will not produce a substantial DO deficit. Lower flows will have a slow downstream movement, so most of the BOD will decay in the upstream portion of the DWSC. The minimum DO location will move upstream with a lower flow, but will not become substantially lower. The range of reaeration velocities compared was 10% to 30% per day. The range of BOD concentrations compared was 8.0 to 24.0 mg/l. These ultimate (30-day) BOD values correspond to 5-day BOD concentrations of 3.0 to 10.0 mg/l.

Effects of Biochemical Oxygen Demand Concentration

Figure A-4 shows the sensitivity (changes) of the DWSC DO profile to BOD concentrations of 8.0 to 24.0 mg/l for flows of 250 cfs, 500 cfs, 750 cfs, and 1,000 cfs. The inflow DO concentration was assumed to be 6 mg/l, about 2.5 mg/l below the summer DO saturation concentration of 8.5 mg/l. The assumed reaeration rate was 20% per day for these BOD sensitivity comparisons.

Figure A-4a shows the calculated effects of inflow BOD from 8.0 to 24.0 mg/l with a flow of 250 cfs. The DO concentration decreased from 6.0 mg/l to about 5.0 mg/l with an inflow BOD of 8.0 mg/l. Most of the DO decay from the BOD was balanced by reaeration. The minimum DO was near mile 38 (at the RRI station); the DO increased to 6.0 mg/l at mile 36 and was 7.5 mg/l at the downstream end of the DWSC (mile 25). The increase in DO near mile 33.5 was caused by reaeration with relatively shallow average depths. An inflow BOD of 12.0 mg/l reduced the minimum DO to about 4.0 mg/l, an inflow BOD of 16.0 mg/l reduced the minimum DO to about 3.0 mg/l, an inflow BOD of 20.0 mg/l reduced the minimum DO to about 2.0 mg/l, and an inflow BOD of 24.0 mg/l reduced the minimum DO to about 1.0 mg/l.

For BOD concentrations of more than 12.0 mg/l, the minimum DO was below the DO objective of 5.0 mg/l. A BOD of 12.0 mg/l reduced the DO below 5.0 mg/l for about 3.0 miles, from mile 39.5 to 36.5. A BOD of 16.0 mg/l reduced the DO below 5.0 mg/l for about 4.0 miles, a BOD of 20.0 reduced the DO below 5.0 mg/l for about 5.0 miles, and a BOD of 24.0 mg/l reduced the DO below 5.0 mg/l for about 6.0 miles. The DO was about 7.5 mg/l at the downstream end of the DWSC (mile 24) for any of the inflow BOD cases.

Figure A-4b shows the effects of inflow BOD from 8.0 to 24.0 mg/l with a flow of 500 cfs. The minimum DO concentrations were about the same as with a flow of 250 cfs, but the minimum DO would occur farther downstream, and the portion of the DWSC with a DO below 5.0 mg/l was longer with a flow of 500 cfs. The daily reaeration balanced the daily BOD decay to give about the same DO concentration at the end of each day, but because the downstream movement was twice as fast, the DO profile was stretched out in the DWSC.

Figure A-4c shows the effects of inflow BOD from 8.0 to 24.0 mg/l with a flow of 750 cfs. The minimum DO was calculated between miles 37 and 34 for each of the inflow BOD cases. The minimum DO with an inflow BOD of 24.0 mg/l was about 1.5 mg/l, which was about 0.5 mg/l higher than for a flow of 250 cfs. The portion of the DWSC having DO below 5.0 mg/l was longer with a flow of 750 cfs. An inflow BOD of 16.0 mg/l reduced the DO to less than 5.0 mg/l from mile 39 to 31. An inflow BOD of 24.0 mg/l reduced the DO to less than 5.0 mg/l from mile 39.5 to 27. With a flow of 750 cfs, the DO concentrations at mile 24 were reduced with higher BOD concentrations. The DO at mile 24 was 7.0 mg/l for a BOD of 8.0 mg/l, but was reduced to 6.0 mg/l for a BOD of 24.0 mg/l.

Figure A-4d shows the effects of inflow BOD from 8.0 to 24.0 mg/l with a flow of 1,000 cfs. The minimum DO was calculated between miles 35 and 34. The minimum DO with an inflow BOD of 24.0 mg/l was about 1.5 mg/l, which was about the same as with a flow of 750 cfs. The portion of the DWSC channel having DO below 5.0 mg/l was slightly longer with a flow of 1,000 cfs than with a flow of 750 cfs. An inflow BOD of 16.0 mg/l reduced the DO to less than 5.0 mg/l from mile 39 to 30. An inflow BOD of 24.0 mg/l reduced the DO to less than 5.0 mg/l from mile 39.5 to 24.

Higher flows will move the location of the minimum DO farther downstream and slightly increase the minimum DO concentrations. The assumed reaeration velocity of 20% per day was not quite high enough to allow the DO concentrations at the downstream end of this section of the DWSC (mile 24) to increase to the inflow DO of 6 mg/l. A flow of 1,000 cfs will move the minimum DO locations downstream almost to Turner Cut at mile 32.5, although the relatively shallow depth upstream of Turner Cut allows increased reaeration.

Effects of Reaeration

The natural reaeration rate in the DWSC is unknown and cannot be directly measured. The measured DWSC DO profiles were used to calibrate the aeration rate, by matching the calculated natural DO profile to the measured DO. The DWSC DO Model sensitivity to a range of possible reaeration rates is shown in this section. Figure A-5 shows the sensitivity of the DWSC DO profile to reaeration velocities from 10% to 30% per day for flows of 250 cfs, 500 cfs, 750 cfs, and 1,000 cfs. The inflow DO concentration was assumed to be 6.0 mg/l, about 2.5 mg/l below the summer DO saturation concentration of 8.5 mg/l. The inflow BOD concentration of 12.0 mg/l was assumed for these reaeration comparisons.

Figure A-5a shows the effects of reaeration velocity from 10% to 30% per day with a flow of 250 cfs. The DO concentration decreased from 6.0 mg/l to about 1.0 mg/l with an inflow BOD of 12.0 mg/l for the lowest reaeration velocity of 10% per day. The minimum DO was calculated between mile 38 and 35. The DO increased to 5.0 mg/l at mile 30 even with this low reaeration velocity. The minimum DO was about 3.0 mg/l located between miles 39 and 37 for a reaeration velocity of 15% per day. The DO recovered to 6.0 mg/l at mile 33. With a reaeration velocity of 20% per day, the minimum DO was about 4.0 mg/l at mile 38, and the DO recovered to 6.0 mg/l at mile 35. With a reaeration velocity of 25% per day, the minimum DO was 4.5 mg/l at about mile 38.5, and the DO recovered to 6.0 mg/l at mile 36.5. The minimum DO was 5.0 mg/l with a reaeration velocity of 30% per day. The higher reaeration velocities increased the minimum DO concentrations and moved the location of the minimum DO upstream.

Figure A-5b shows the effects of reaeration velocity from 10% to 30% per day with a flow of 500 cfs. The minimum DO concentrations were about the same, but were farther downstream than with a flow of 250 cfs. The recovery of the DO to 6.0 mg/l was farther downstream with a flow of 500 cfs than with a flow of 250 cfs because the same number of days of reaeration was required to balance the BOD.

Figure A-5c shows the effects of reaeration velocity from 10% to 30% per day with a flow of 750 cfs. The locations of the minimum DO concentrations were farther downstream than with a flow of 500 cfs. The locations of the DO recovery to 6.0 mg/l were also farther downstream than for a flow of 250 or 500 cfs. Because the DO profiles measured in the *San Carlos* boat surveys seldom show DO sags that extend downstream of Turner Cut when the flows are 500–1,000 cfs, the reaeration velocities of 0.5 and 1.0 m/day appear to be too low.

Figure A-5d shows the effects of reaeration velocity from 10% to 30% per day with a flow of 1,000 cfs. The location of the minimum DO concentration and the zone of recovery to 6.0 mg/l for each reaeration velocity for a flow of 1,000 cfs were stretched downstream about twice as far as for the 500 cfs flow. Reaeration velocities of more than 20% per day appear to give DO profiles that are similar to many of the *San Carlos* boat survey DO profiles, with minimum DO concentrations upstream of Turner Cut. Reaeration velocities of less than 20% per day produced more extended sections of DWSC with lower DO concentrations than usually are measured in the *San Carlos* boat surveys. The reaeration velocity of 20% per day has been selected for matching the *San Carlos* boat survey DO data in the DWSC. The reaeration rate of 20% per day also corresponds to the reaeration rate that was selected for the DO increment calculations and natural DO estimates for the downstream monitoring stations at Lights 42 and 40 (described in Appendix B).

Previous Studies of Dissolved Oxygen Demands and Sources in the Deep Water Ship Channel

The longitudinal (i.e., downstream) DO concentration profile in the DWSC is a balance between the decay of materials in the water (decreasing the DO) and the sources of DO from algal photosynthesis and surface reaeration. The DO decline that often is observed in the DWSC is generally the result of BOD and ammonia loads from the RWCF, and river loads of algae and other organic materials (detritus) that enter the DWSC with the SJR inflow. Some of the BOD and detritus may settle onto the sediment and produce a DO demand from the bottom (SOD). Therefore, the BOD (detritus) and the SOD are linked, but the downstream effects on DO are difficult to distinguish. Settling of detritus and re-suspension of detritus from the bottom provide a constant exchange between the suspended BOD and the SOD.

Because the decay of these BOD or SOD materials and oxidation of the ammonia to nitrate (requiring almost 5.0 mg/l of DO for 1.0 mg/l of ammonia-N) are both temperature-dependent processes, the observed DO decline (or oxygen sag) is often greatest in the summer months. The river and RWCF discharge sources of BOD and ammonia entering the DWSC change seasonally and with river flows. The combined BOD concentration (from river algae and RWCF discharges) can be approximated from the observed DO profiles in the DWSC.

River Biochemical Oxygen Demand

River concentrations of BOD and algae, as well as the RWCF discharge concentrations, were measured and described for the 2001 intensive monitoring and modeling conducted for the CALFED study of DO in the DWSC (Jones & Stokes 2003). The 2001 measurements identified the typical seasonal pattern for BOD associated with river algae and RWCF discharges. The maximum concentrations of river algae and the lowest dilution flows (highest river concentrations of RWCF effluent) were observed in the summer months.

The measured volatile suspended solids (VSS) concentrations, consisting of organic particles (including algae and detritus), had a pronounced maximum concentration during summer. The VSS measurements at Mossdale and Vernalis were similar, declining rapidly in September at both stations. The maximum river VSS concentrations were 10.0–12.0 mg/l in June and July. Most of this material was determined to be algae biomass (alive or dead). Because the 30-day BOD equivalent of 1.0 mg/l of VSS is about 1.6 (from average carbon content of biomass and carbon dioxide [CO_2]), the maximum summer river BOD concentration was about 15.0 to 18.0 mg/l.

Sediment Oxygen Demand

Dr. Gary Litton at UOP collected many VSS, algae, and BOD measurements in the DWSC during 1999, 2000, and 2001 (Litton 2003). These measurements were collected during periods when the RWCF was discharging high ammonia concentrations of about 10.0–15.0 mg/l, and the nitrogenous BOD was about 40% of the total long-term BOD in the DWSC. The 30-day BOD for the inflow to the DWSC ranged from about 5.0 to 10.0 mg/l. The carbonaceous BOD (CBOD) ranged from 3.0 to 6.0 mg/l. Some of these samples had considerable algae and detritus. They confirmed that the long-term BOD was about 1.5 times the measured VSS. Measurements of 5-day, 10-day, and 30-day BOD (standard BOD tests at 20°C) indicated that ultimate (30-day) BOD was about 2.5 times the 5-day BOD and about 1.5 times the 10-day BOD. These ratios suggest that the BOD decay rate is about 0.10 day^{-1}. Therefore, about 40% of the ultimate BOD will decay in the first 5 days, and about 65% will decay in the first 10 days.

Dr. Litton deployed sediment traps that measured the settling rate of particulates in the DWSC. The measured settling rates were much faster than the longitudinal decrease in total suspended solids (TSS), VSS, and algae concentrations would indicate, suggesting that there is considerable re-suspension of these particulates in the upstream portion of the DWSC. This emphasizes that the effects of BOD and SOD are difficult to separate in the DWSC. They measured SOD rates with sediment cores in laboratory chambers and found the average summer SOD near Light 48 (upstream end of DWSC) to be about 0.5 g-O_2/m^2/day. The SOD decreased to about 0.25 g-O_2/m^2/day at Light 38, about 3.5 miles downstream. The SOD presumably decreased farther downstream because an equilibrium concentration of organic particulates (VSS) and settled material (SOD) is maintained by the tidal velocities (which are increasing downstream).

Based on these previous measurements, the daily effect of the specified SOD rate (g-O_2/m^2/day) used in the DWSC DO Model is the SOD rate divided by the mean depth (m). The mean depth of the DWSC from Light 48 to Turner Cut is about 7.0 m, so the daily DO decrease from SOD would be about 0.07 mg/l at the upstream end and less than 0.04 mg/l at the downstream end. The daily effect of BOD will be about 10% of the BOD concentration. The effect of SOD and BOD on DWSC DO concentration will be similar and difficult to separate. The effects from BOD and SOD will be reduced at higher flows because the DWSC travel times will be shorter.

Stockton Regional Wastewater Control Facility Discharge

The RWCF collects daily measurements of 5-day CBOD, VSS, and ammonia-N. The estimates of 30-day (ultimate) CBOD from 5-day CBOD and VSS are similar throughout summer and fall. Because the oxidation ponds and tertiary treatment (dissolved air flotation and sand filters) are most effective in summer, the CBOD concentrations are lowest in spring and summer. The RWCF effluent 30-day CBOD estimates varied from about 5.0 to 25.0 mg/l during the summer and fall months of 2001.

The maximum RWCF effluent ammonia-N concentrations were 25.0 mg/l during winter 2001. The nitrogenous BOD (NBOD) equivalent for the ammonia can be estimated assuming about 5.0 mg/l of oxygen are required to oxidize (i.e., nitrify) each 1.0 mg/l of ammonia-N. Therefore, the maximum NBOD was about 125.0 mg/l when the ammonia-N concentration was 25.0 mg/l. The RWCF discharge of about 50.0 cfs is diluted by the SJR flow before entering the DWSC. The RWCF discharge is located about 2.0 miles upstream from the DWSC, and tidal flows are effective in mixing the RWCF discharge within the tidal mixing volume, so the concentrations entering the DWSC are well mixed (Jones & Stokes 2005). Because the RWCF added nitrification (i.e., bio-towers, or trickling filters) to the tertiary treatment facilities in winter 2007, the ammonia concentrations have been reduced substantially.

Effects of River Flow on Biochemical Oxygen Demand Concentrations

The SJR concentrations of algae at Mossdale usually decline as the water flows to the DWSC because the channel depth increases and light limitation reduces algae growth. The travel time from Mossdale to the DWSC is about 5 days at a flow of 250 cfs, about 2.5 days at a flow of 500 cfs, and about 1.25 days at a flow of 1,000 cfs. Field measurements of VSS and chlorophyll in 2001 indicated that there was considerable reduction between Mossdale and the DWSC, although the travel time was generally only 1–2 days during summer 2001.

A higher river flow will provide less reduction in the river BOD, but greater dilution of the RWCF discharge. Assuming a 10% daily decay rate, the BOD concentrations that entered the DWSC were estimated to be about 60% of the Mossdale BOD for a flow of 250 cfs, 75% of the Mossdale BOD for a flow of 500 cfs, and 90% of the Mossdale BOD for a flow of 1,000 cfs. A river flow of 250 cfs would dilute the RWCF BOD to about 17% (i.e., 50 cfs/300 cfs) as it enters the DWSC. A river flow of 500 cfs would dilute the RWCF BOD to about 9% (i.e., 50 cfs/550 cfs) as it enters the DWSC. A river flow of 1,000 cfs would dilute the RWCF BOD to about 5% (i.e., 50 cfs/1050 cfs) as it enters the DWSC. The maximum NBOD (from ammonia) of about 125.0 mg/l would be diluted to about 20.0 mg/l for a flow of 250 cfs, about 10.0 mg/l for a flow of 500 cfs, and about 5.0 mg/l for a flow of 1,000 cfs. The nitrification process that was added to the RWCF tertiary treatment in 2007 reduced the ammonia effluent to less than 2.0 mg/l, so the NBOD is now less than 10.0 mg/l. The diluted NBOD for a flow of 250 cfs is about 2.0 mg/l, the diluted NBOD for a flow of 500 cfs is about 1.0 mg/l, and the diluted NBOD for a flow of 1,000 cfs is about 0.5 mg/l. The RWCF nitrification facility has therefore lowered the NBOD reaching the DWSC since 2007.

Stratification and Algal Photosynthesis

The 15-minute DO measurements at RRI show substantial stratification and algal growth. Generally, a daily DO variation (i.e., maximum DO – minimum DO) of more than 1.0 mg/l suggests stratification and algal growth at the RRI station. The effects of algal photosynthesis on DO in the DWSC are difficult to account for. Algae growth generally is light-dependent in the moderately turbid SJR and very light-limited in the deeper DWSC. However, surface temperature stratification may reduce vertical mixing and allow algal growth (i.e., 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 reaeration during stratification. This algae growth will produce additional biomass that will increase the BOD and SOD from subsequent settling and decay of the algal biomass.

Port of Stockton Aeration

The Port of Stockton operates two aeration facilities on Dock 13 near Channel Point. One device was installed by the U.S. Army Corps of Engineers in 1992 and uses a water jet to entrain air bubbles (jet aerator). This device was designed with an aeration capacity of 2,500 lbs/day and was tested in 2002 as part of the total maximum daily load (TMDL) studies (Jones & Stokes 2003). The jet aerator was found to have an aeration capacity of about 1,850 lbs/day when the DO concentration was about 3.0 mg/l (DO deficit of 5.0 mg/l). The capacity would be reduced at higher DO concentrations. A second device using oxygen bubbles discharged from perforated hose suspended about 20 feet below the water surface under Dock 13 was installed by the Port of Stockton in 2007 as required for mitigation of dredging impacts. The transfer efficiency was measured to be 50%, and the aeration capacity is about 2,000 lb/day (4,000 lb/day oxygen supply). Both facilities were operated for most of summer 2008 (June 7 through October 13) because DO at Light 48 was often approaching or less than the established operational trigger of 5.2 mg/l for June–August or 6.2 mg/l daily average in September–November.

City of Stockton River Water Quality Data

The City of Stockton conducts weekly sampling at nine river stations as part of its discharge permit from the Regional Water Quality Control Board (RWQCB). River station R1 is located upstream about 6.0 miles from the RWCF discharge at SJR mile 47.5 (Brandt Bridge). River station R2 is located just upstream of the RWCF discharge at Garwood Bridge. River station R2a is located downstream of the RWCF discharge at Burns Cutoff. River stations R3 to R8 are located in the DWSC (Figure A-1): R3 is located at Light 48, R4 is located at Light 45, R5 is located downstream of RRI at Light 42, R6 is located at Light 36, R7 is located near Turner Cut at Light 24, and R8 is located at Light 18. DO concentrations at stations R7 and R8 are usually high because they are strongly influenced by Sacramento River water. City of Stockton data from stations R1 to R6 are compared for 2004 and 2008 to demonstrate the reduction in DWSC BOD as the result of the City of Stockton nitrification facility completed in 2007. This is likely to increase the minimum DO measured in the DWSC and reduce the need for Aeration Facility operation.

2004 River and Deep Water Ship Channel Data

Figure A-6a shows the mid-depth DO concentrations measured at stations R3, R4, R5, and R6 for 2004, compared to the daily minimum and maximum DO concentrations from the RRI station. The

City of Stockton summer DO data were generally confirmed by the DO concentrations measured at the RRI station. The major decline in the DWSC DO concentrations in 2004 was measured in June as flow decreased after the Vernalis Adaptive Management Plan (VAMP) period. The RRI DO was less than 5.0 mg/l from early June through early October, and was 2.0–3.0 mg/l in July, August, and September. The minimum DO often was measured at stations R4 and R5, located in the vicinity of RRI. This indicates that the minimum DO in the DWSC is often observed in the vicinity of the RRI station.

Figure A-6b shows the weekly measurements of river algae pigment (chlorophyll) concentrations (micrograms per liter [µg/l]) measured by the City of Stockton in 2004. River algae pigment concentrations were greater than 100.0 µg/l in June and July, and greater than 50.0 µg/l in August and September at station R1. River algae concentrations were highest in the summer months, and much lower in spring and fall, when light, temperature, and travel time (high flows) limit river algae growth. The algae pigment concentrations generally decreased from station R1 to R3. This may be the result of zooplankton grazing or settling of the diatoms in the deeper, tidally influenced portion of the river.

Figure A-6c shows the VSS measurements at the three river stations upstream of the DWSC. The maximum June and July VSS concentrations were 10.0–15.0 mg/l.

Figure A-6d shows the 10-day BOD measurements from the three river stations. The 10-day BOD concentrations were similar to the VSS concentrations. The maximum 10-day BOD concentrations in June, July, and August were about 10.0–12.0 mg/l. Because the 30-day BOD concentration is generally about 50% more than the 10-day BOD concentration, the 30-day BOD concentration entering the DWSC in June–August 2004 was about 15.0–18.0 mg/l. This was somewhat lower than the BOD concentrations of 18.0–20.0 mg/l estimated to match the *San Carlos* boat survey DO measurements from summer 2004.

2008 River and Deep Water Ship Channel Data

Figure A-7a shows the City of Stockton weekly DO measurements at the DWSC stations (R3 to R6) for 2008. The DO concentrations in 2008 were higher than DO concentrations in 2004, with daily minimum DO concentrations of about 5.0–6.0 mg/l during summer. The minimum RRI DO data matched the City of Stockton measurements, confirming that the minimum DO was generally above the DO objectives of 5.0 mg/l for June–August and 6.0 mg/l for September–November. The Aeration Facility was operated about half of the time (with a pulsed on/off schedule) from mid-June through September. The effects of the aeration on the much higher daily maximum DO at RRI and the fluctuating minimum DO at RRI are apparent.

Figure A-7b shows the City of Stockton measurements of river algae pigment concentrations for 2008. The SJR summer flows in 2008 were slightly less than summer flows in 2004. The river algae pigment concentrations in 2008 and 2004 were similar, with average summer algae pigment concentrations of 25.0 µg/l at stations R2 and R2a.

Figure A-7c shows the City of Stockton measurements of river VSS concentrations for 2008. The summer VSS concentrations at stations R2 and R2a ranged from about 5.0 to 10.0 mg/l, which were similar to the VSS concentrations in 2004. Generally, the amount of upstream algal biomass (VSS) entering the DWSC appeared to be similar in 2004 and 2008.

Figure A-7d shows the City of Stockton measurements of river inflow 10-day BOD concentrations for 2008. The summer 10-day BOD concentrations in 2008 at stations R2 and R2a of about 2.0–3.0 mg/l were much lower than those in 2004, which were about 6.0–12.0 mg/l. The reduced ammonia-N effluent concentration from the RWCF was apparently very effective in reducing the 10-day BOD concentrations entering the DWSC.

Figure A-8 shows the ammonia-N and nitrate-N concentrations in the RWCF effluent (i.e., discharge) for 2004–2008. The City of Stockton added constructed wetlands and nitrifying bio-towers to the tertiary treatment facilities in fall 2006, and the nitrification towers were operating as designed in summer 2007. The seasonal pattern of RWCF effluent ammonia-N concentration (about 25.0 mg/l in winter and 10.0–15.0 mg/l in summer) previously discharged to the SJR was substantially reduced. The nitrifying bio-towers convert almost all of the ammonia-N coming from the oxidation ponds and wetlands to nitrate-N. The ammonia-N concentration coming from the wetlands (light blue squares) represents the concentration that would have been discharged without the nitrifying bio-towers. Beginning in summer 2007, the ammonia-N concentrations in the RWCF effluent were less than 2.0 mg/l.

The wetlands and bio-towers greatly reduced the total BOD from the RWCF because 1.0 mg/l of ammonia-N is equivalent to about 5.0 mg/l of 30-day BOD. Because the river flows entering the DWSC were about 250 cfs in summer 2004 and 2008, the concentration of ammonia-N would have been 2.0–3.0 mg/l (50 cfs of effluent with 10–15 mg/l diluted with 200 cfs of river flow with less than 0.5 mg/l). Because the City of Stockton has operated the nitrifying bio-towers successfully since 2007, it appears that the usual low-DO conditions in the DWSC during low-flow periods (summer or winter) effectively have been eliminated. The required amount of added DO from the Aeration Facility (i.e., capacity) to maintain the DO objectives in the DWSC has likely been reduced because most of the BOD caused by the nitrification (i.e., biological oxidation) of ammonia-N to nitrate-N in the DWSC has been eliminated.

Conclusions

The DWSC DO Model was used to interpret the *San Carlos* boat survey results for 2004 through 2008 to provide a more general understanding of the effects of flow and BOD concentrations on the observed DWSC DO profiles.

Because the daily source of DO from surface reaeration is the reaeration rate times the DO deficit, the effects of the added Aeration Facility increments on the reaeration source of DO can be calculated. The added DO increment reduces the DO deficit and reduces the surface reaeration downstream of the diffuser. Therefore, the measured increment from the Aeration Facility will decrease with time (and distance downstream). This was confirmed with *San Carlos* boat surveys during summer 2008.

Because there are no independent aeration rate measurements for the DWSC, a range of values reported from other relatively deep water conditions was tested with the DWSC DO Model. The *San Carlos* boat survey data from 2004 and 2008 indicate that the best estimate for the reaeration rate was about 0.2 day^{-1}, suggesting that the initial DO increment will decrease by about 20% each day.

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Streeter, H. W., and E. B. Phelps. 1925. *A study of the pollution and natural purification of the Ohio River III. Factors concerned in the phenomena of oxidation and reaeration*. U.S. Public Health Service Bulletin No. 146.

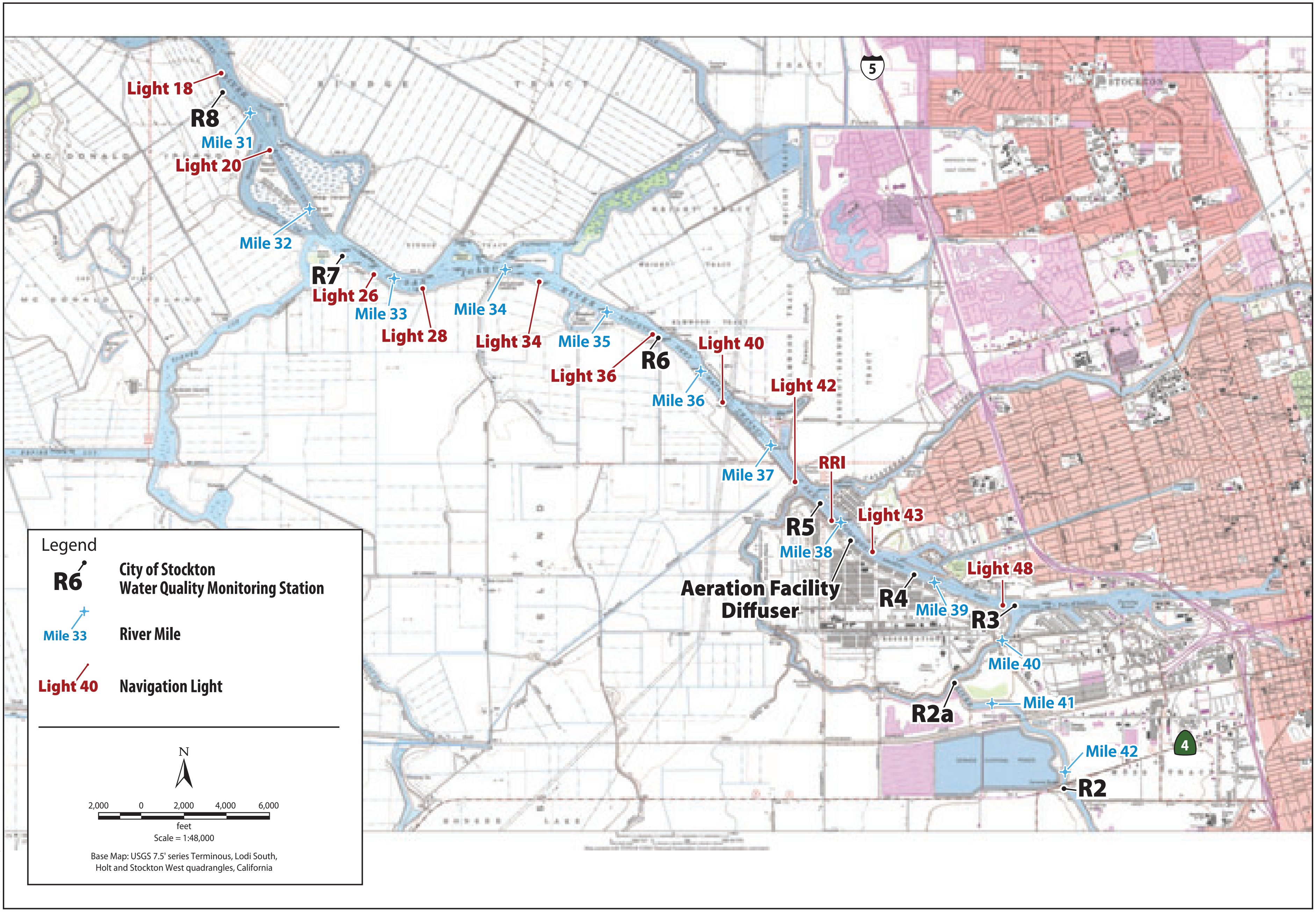

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Figure A-1
Stockton Deep Water Ship Channel Water Quality Stations

DO in the DWSC for August 30, 2004, with flow of 250 cfs and BOD of 18 mg/l

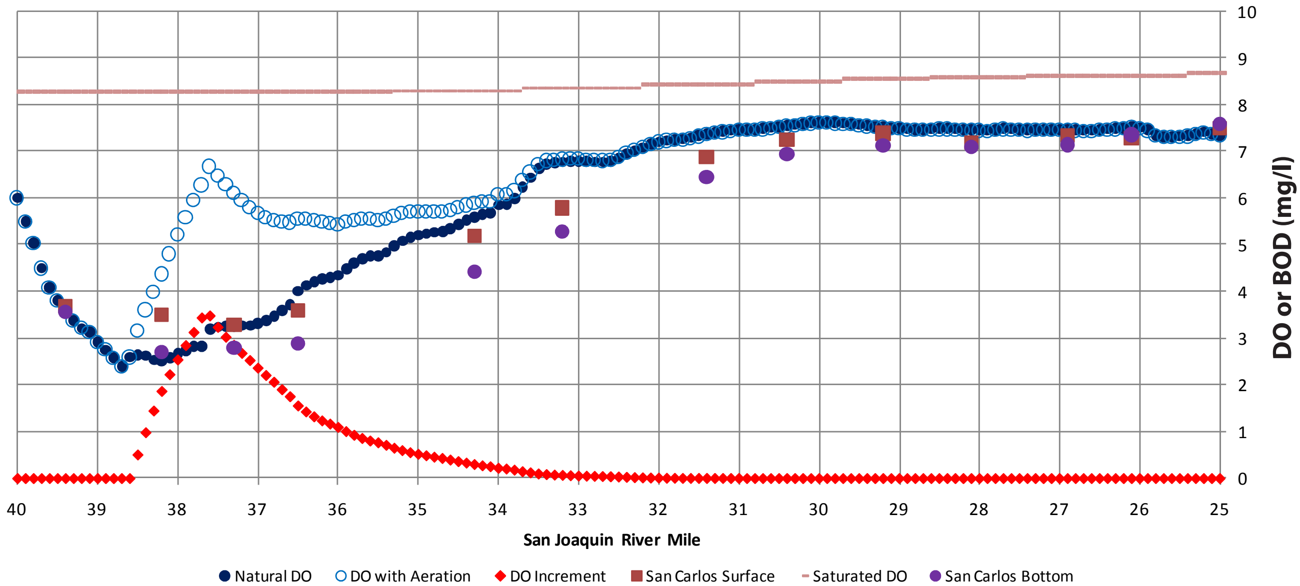

Figure A-2a: Measured and Calculated DWSC DO Profile for August 30, 2004, for Flow of 250 cfs, Initial DO of 6 mg/l, and BOD of 18 mg/l.

Note: The estimated DO with aeration of 7,500 lb/day is shown for comparison.

DO in the DWSC for September 15, 2004, with flow of 500 cfs and BOD of 18 mg/l

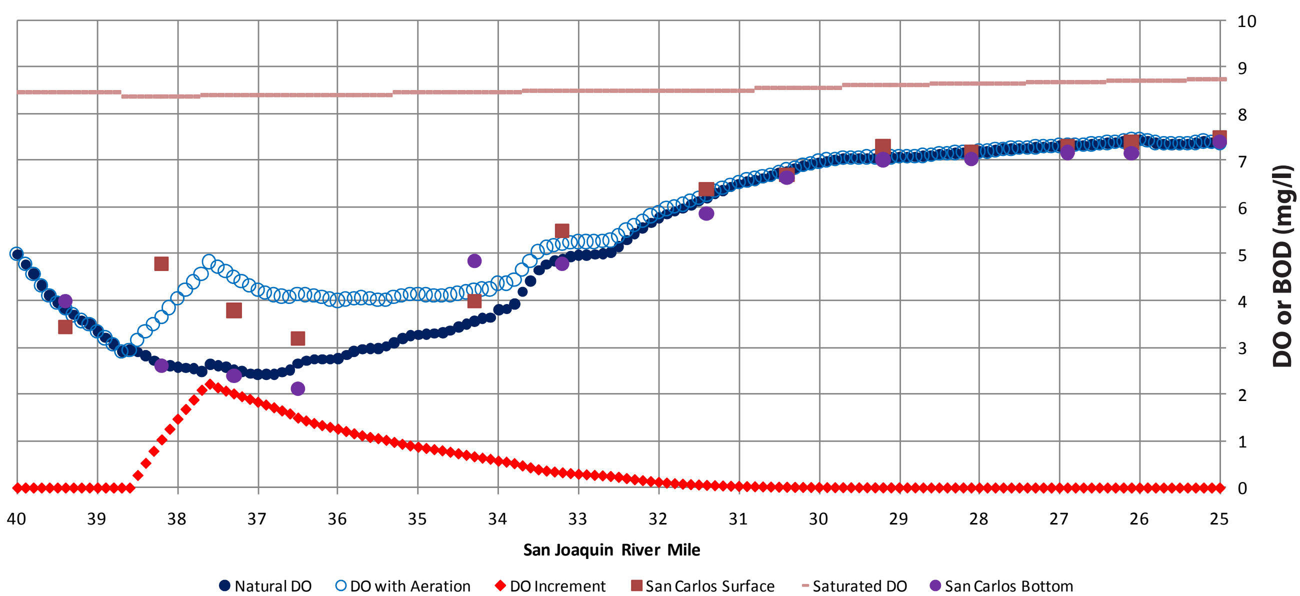

Figure A-2b: Measured and Calculated DWSC DO Profile for September 15, 2004, for Flow of 500 cfs, Initial DO of 5 mg/l, and BOD of 18 mg/l.

Note: The estimated DO with aeration of 7,500 lb/day is shown for comparison.

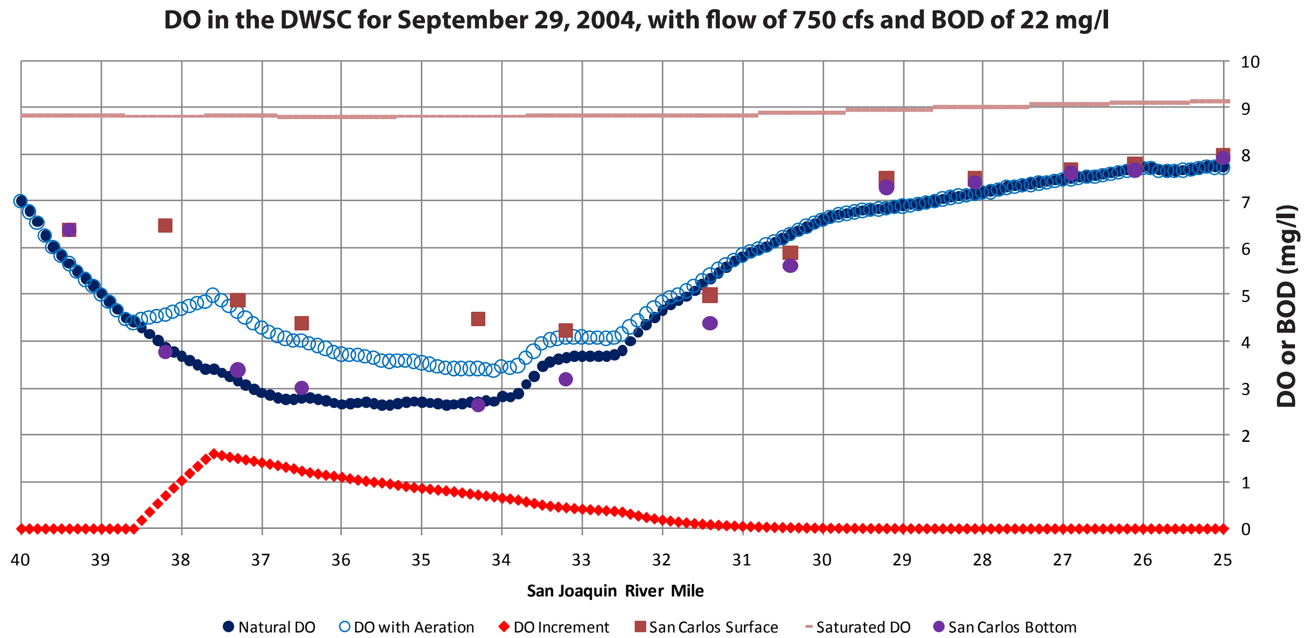

Figure A-2c: Measured and Calculated DWSC DO Profile for September 29, 2004 for Flow of 750 cfs, Initial DO of 7 mg/l, and BOD of 22 mg/l.

Note: The estimated DO with aeration of 7,500 lb/day is shown for comparison.

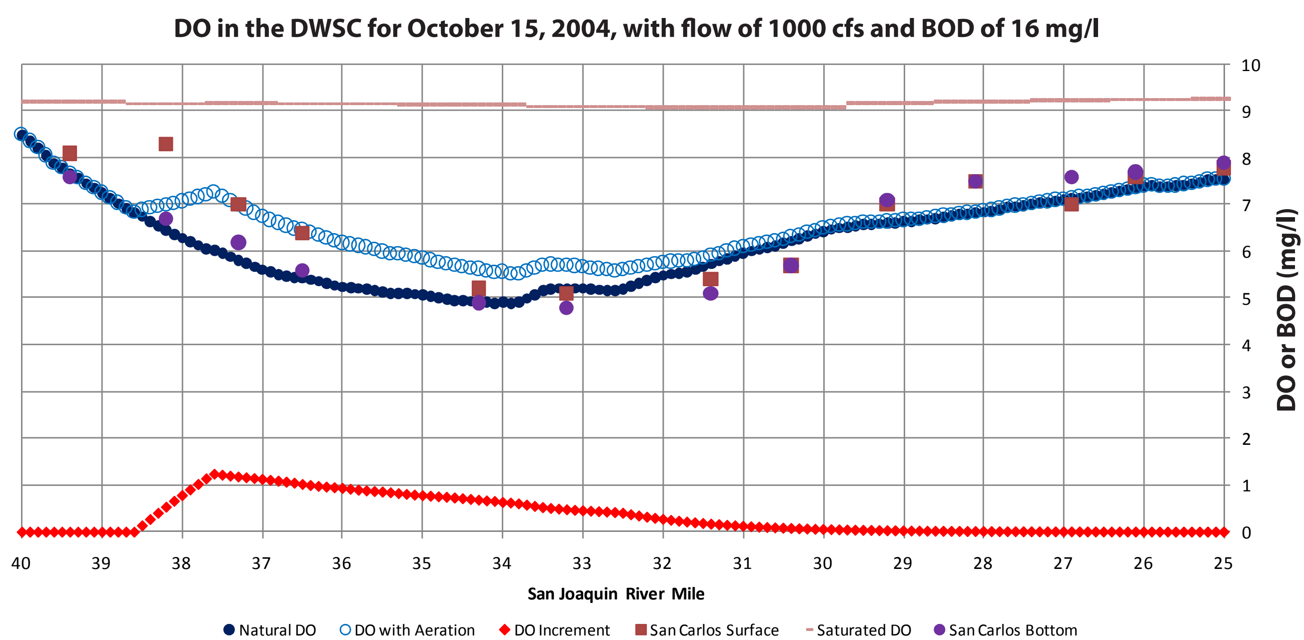

Figure A-2d: Measured and Calculated DWSC DO Profile for October 15, 2004, for Flow of 1,000 cfs, Initial DO of 8 mg/l, and BOD of 16 mg/l.

Note: The estimated DO with aeration of 7,500 lb/day is shown for comparison.

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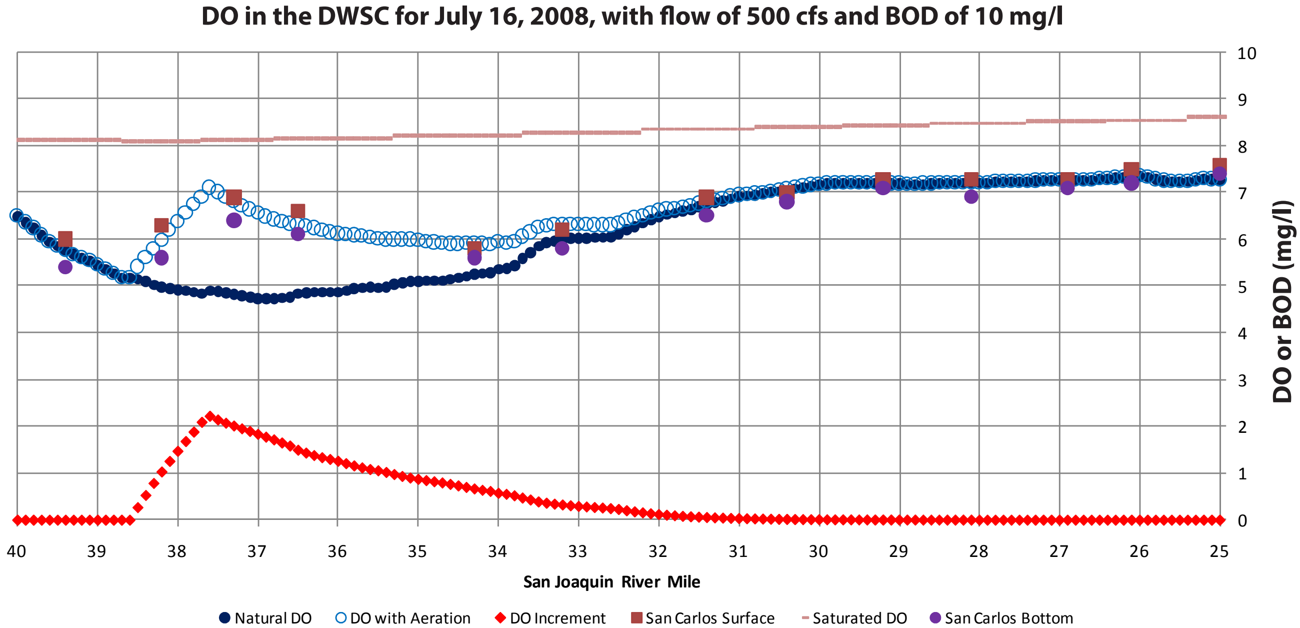

Figure A-3a: Measured and Calculated DWSC DO Profile for July 16, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l and BOD of 10 mg/l.
Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

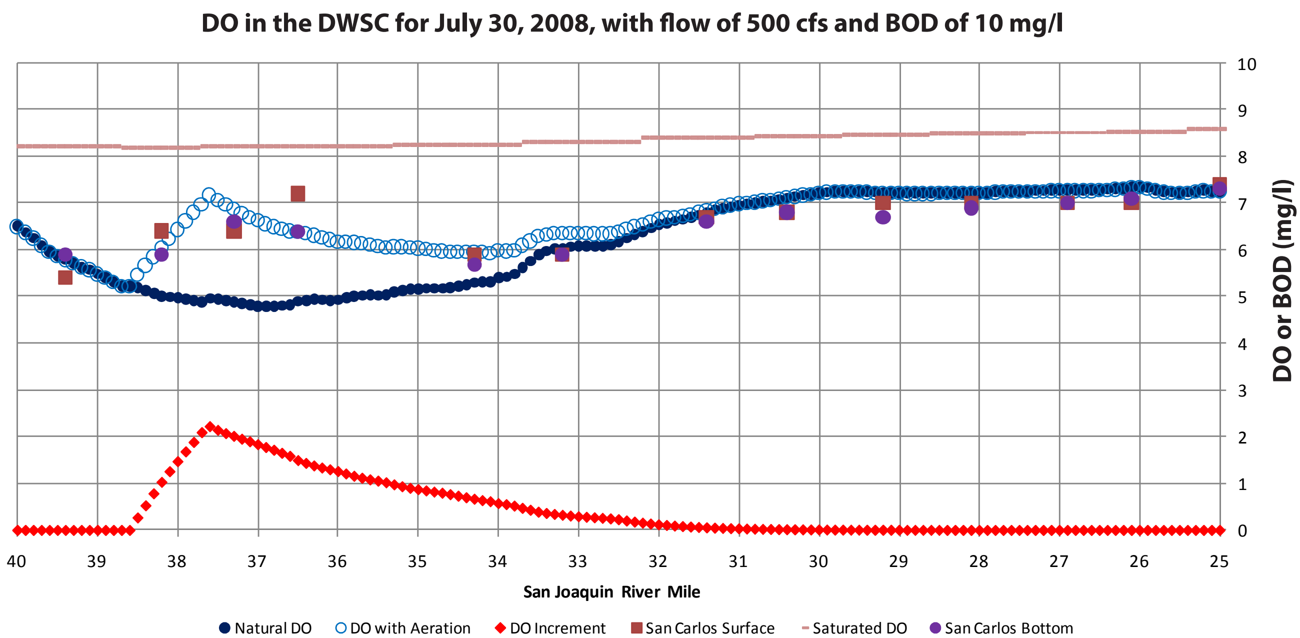

Figure A-3b: Measured and Calculated DWSC DO Profile for July 30, 2008, for Flow of 500 cfs, Initial DO of 6.5 mg/l and BOD of 10 mg/l.
Note: The estimated DO with aeration of 7,500 lbs/day is shown for comparison (diffuser had operated for 2 days prior to survey).

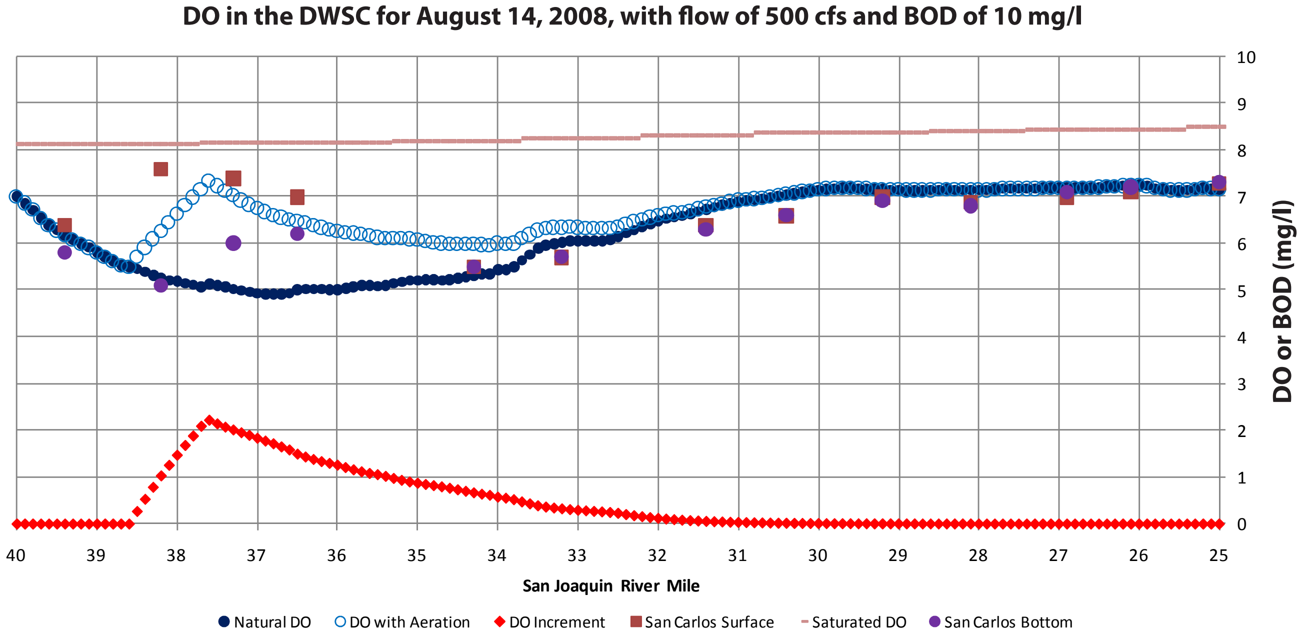

Figure A-3c: Measured and Calculated DWSC DO Profile for August 14, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l and BOD of 10 mg/l.

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

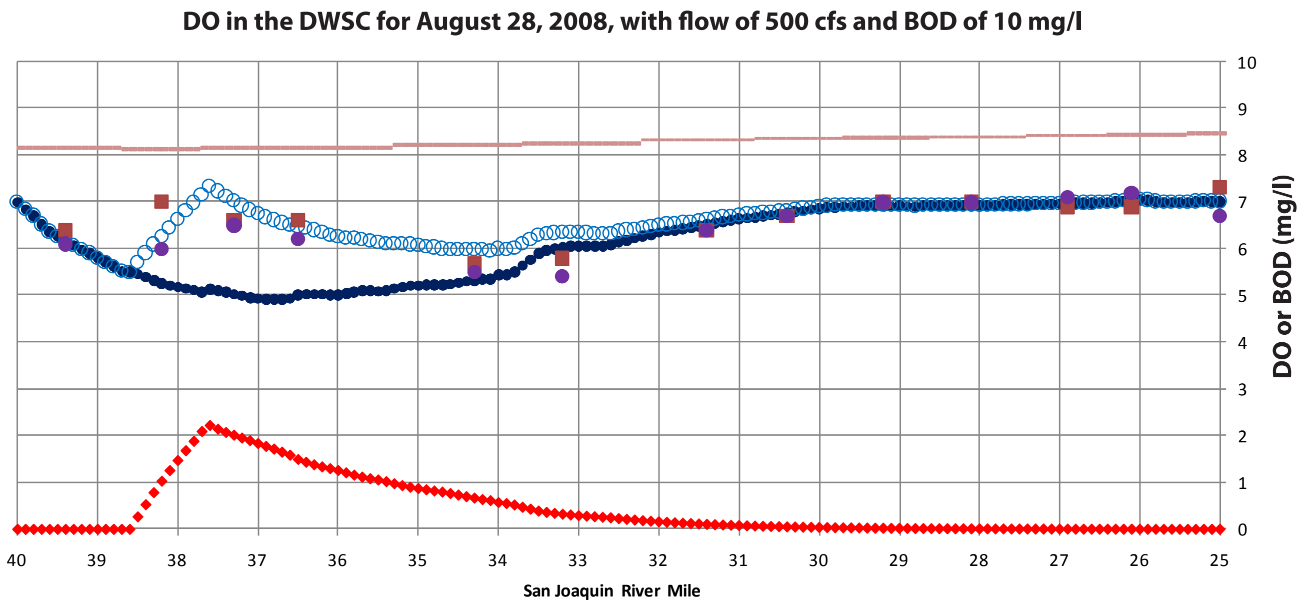

Figure A-3d: Measured and Calculated DWSC DO Profile for August 28, 2008, for Flow of 500 cfs, Initial DO of 7 mg/l and BOD of 10 mg/l

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

Figure A-3 (continued)

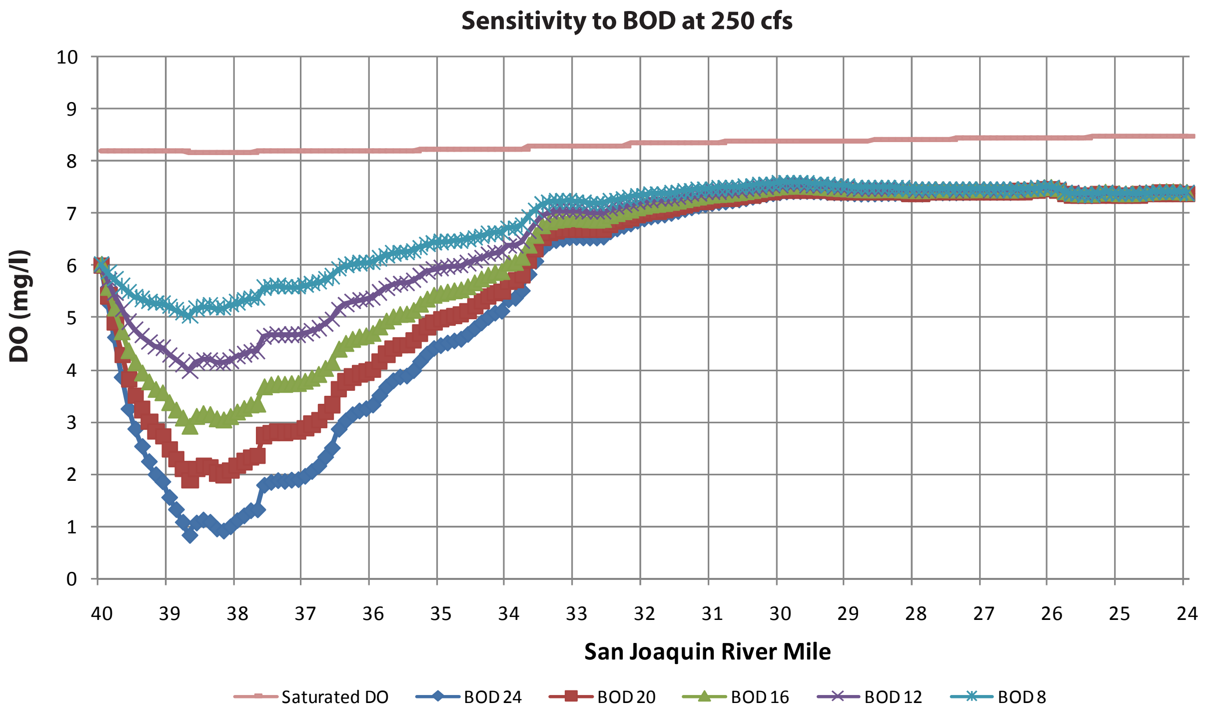

Figure A-4a: Sensitivity of DWSC Longitudinal DO Profile to BOD Concentrations of 8 to 24 mg/l with Daily Reaeration Rate of 20 Percent and Flow of 250 cfs.

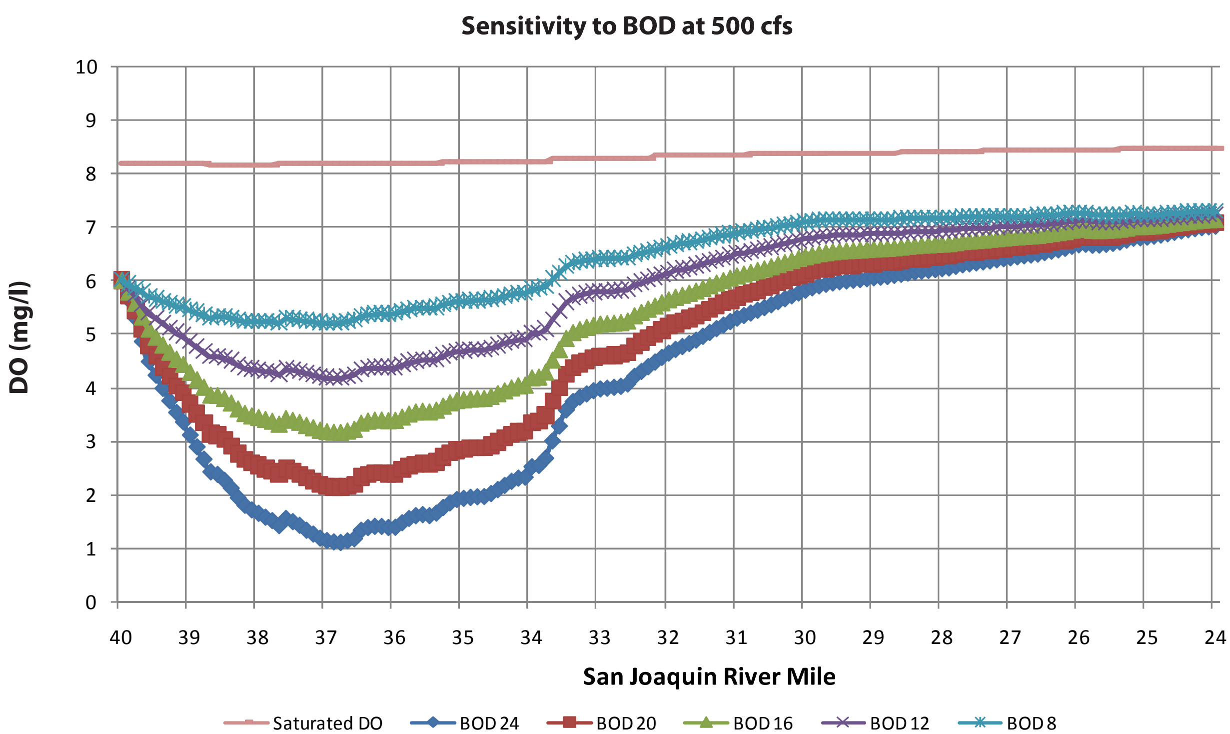

Figure A-4b: Sensitivity of DWSC Longitudinal DO Profile to BOD Concentrations of 8 to 24 mg/l with Daily Reaeration Rate of 20 Percent and Flow of 500 cfs.

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Figure A-4

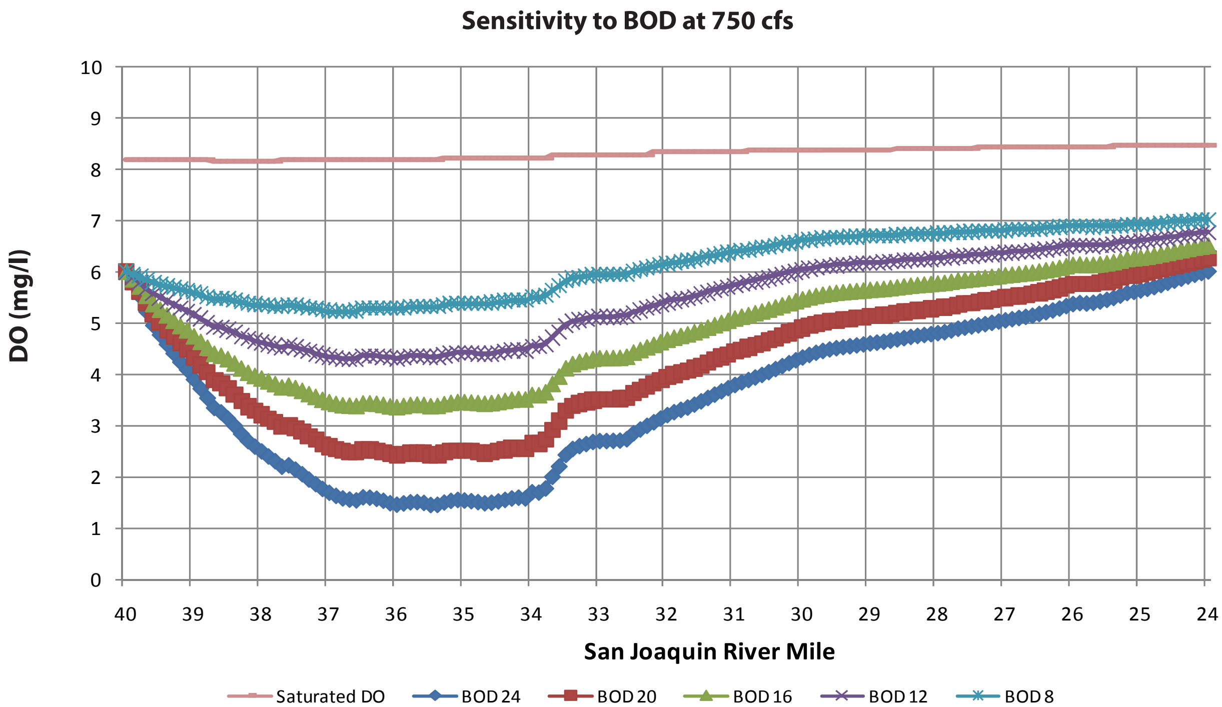

Figure A-4c: Sensitivity of DWSC Longitudinal DO Profile to BOD Concentrations of 8 to 24 mg/l with Daily Reaeration Rate of 20 Percent and Flow of 750 cfs.

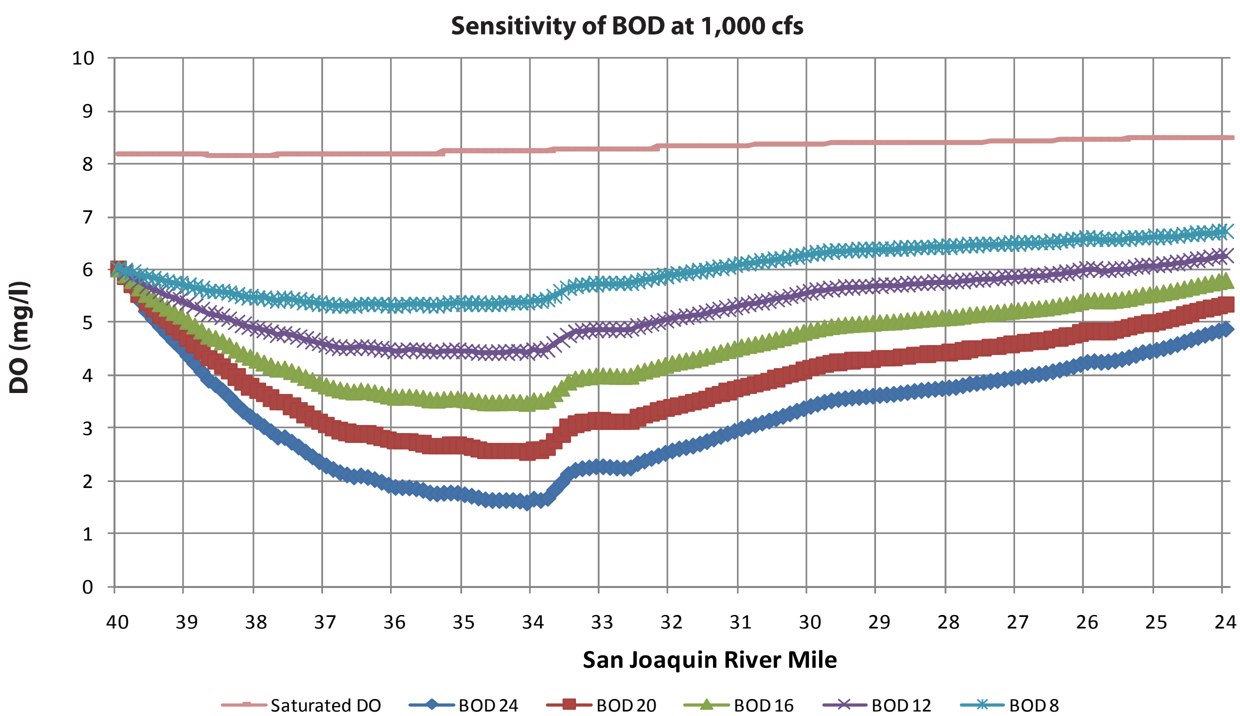

Figure A-4d: Sensitivity of DWSC Longitudinal DO Profile to BOD Concentrations of 8 to 24 mg/l with Daily Reaeration Rate of 20 Percent and Flow of 1,000 cfs.

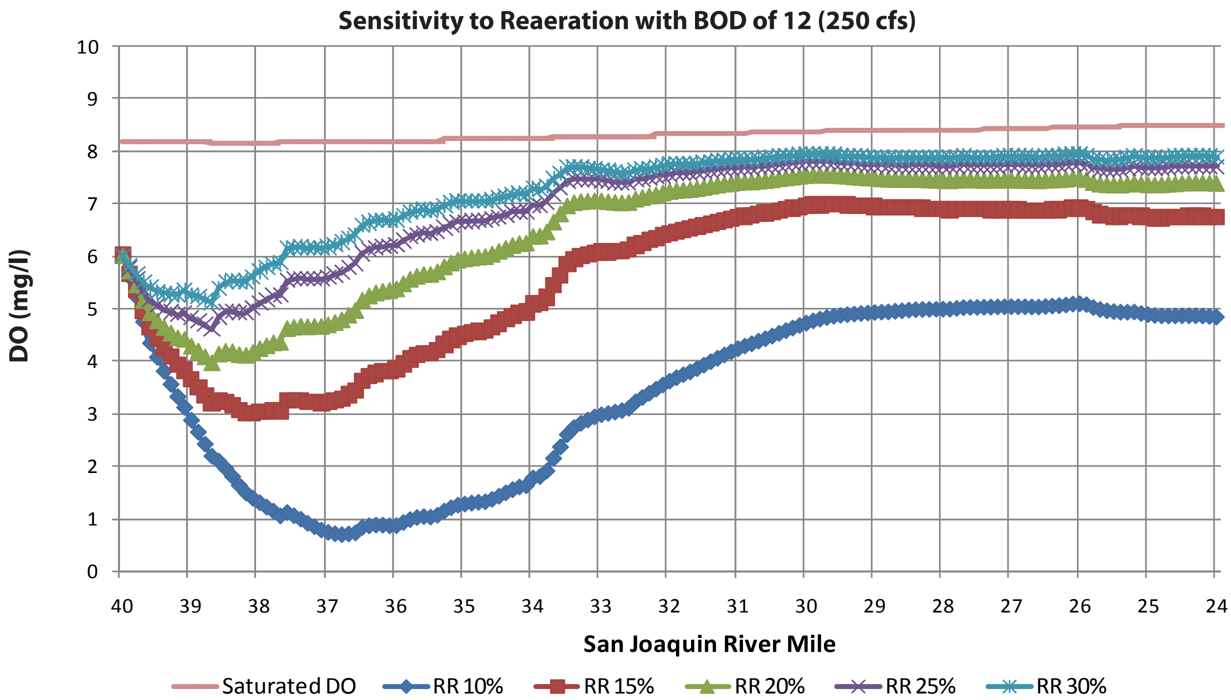

Figure A-5a: Sensitivity of DWSC Longitudinal DO Profile to Daily Reaeration Rates (RR) of 10 to 30 Percent with BOD of 12 mg/l and Flow of 250 cfs

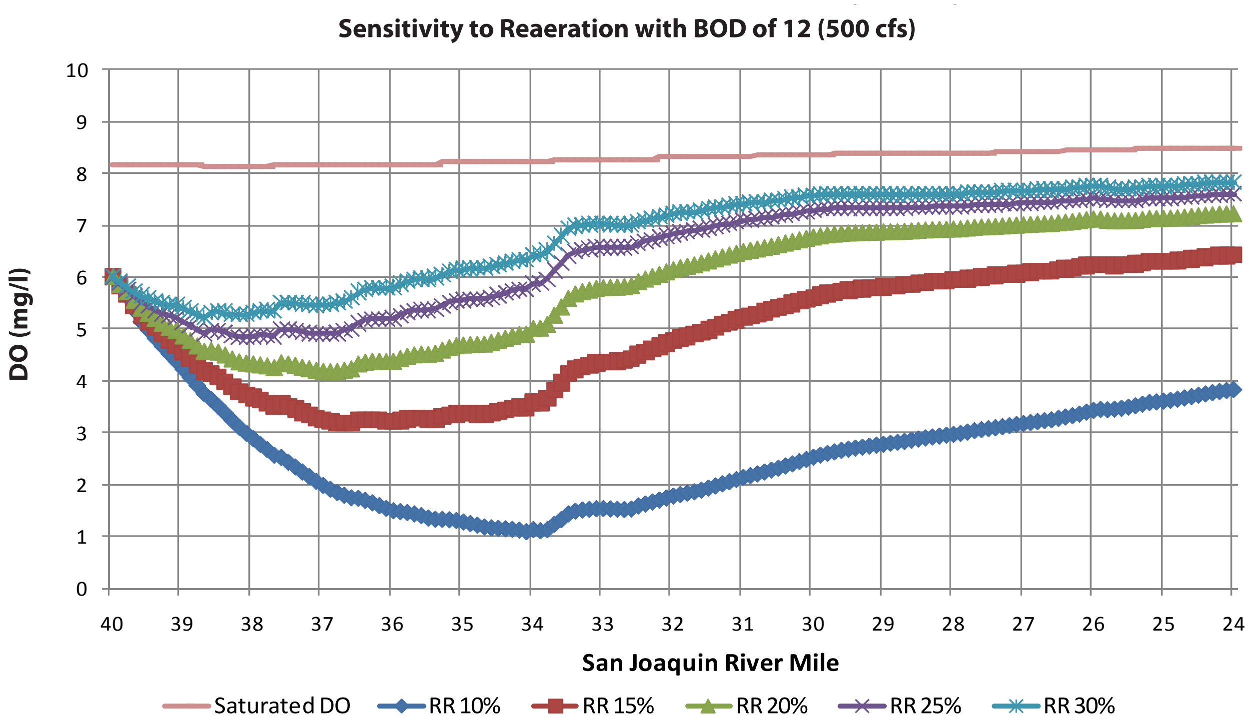

Figure A-5b: Sensitivity of DWSC Longitudinal DO Profile to Daily Reaeration Rates (RR) of 10 to 30 Percent with BOD of 12 mg/l and Flow of 500 cfs.

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Figure A-5

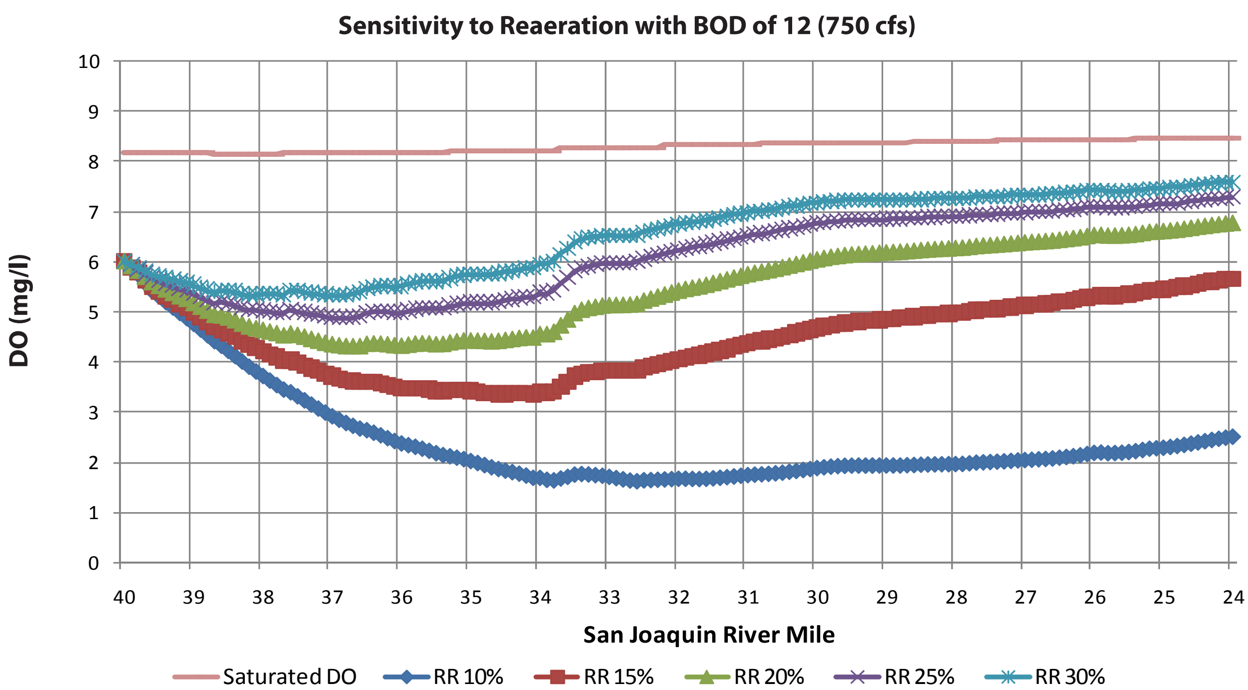

Figure A-5c: Sensitivity of DWSC Longitudinal DO Profile to Daily Reaeration Rates (RR) of 10 to 30 Percent with BOD of 12 mg/l and Flow of 750 cfs.

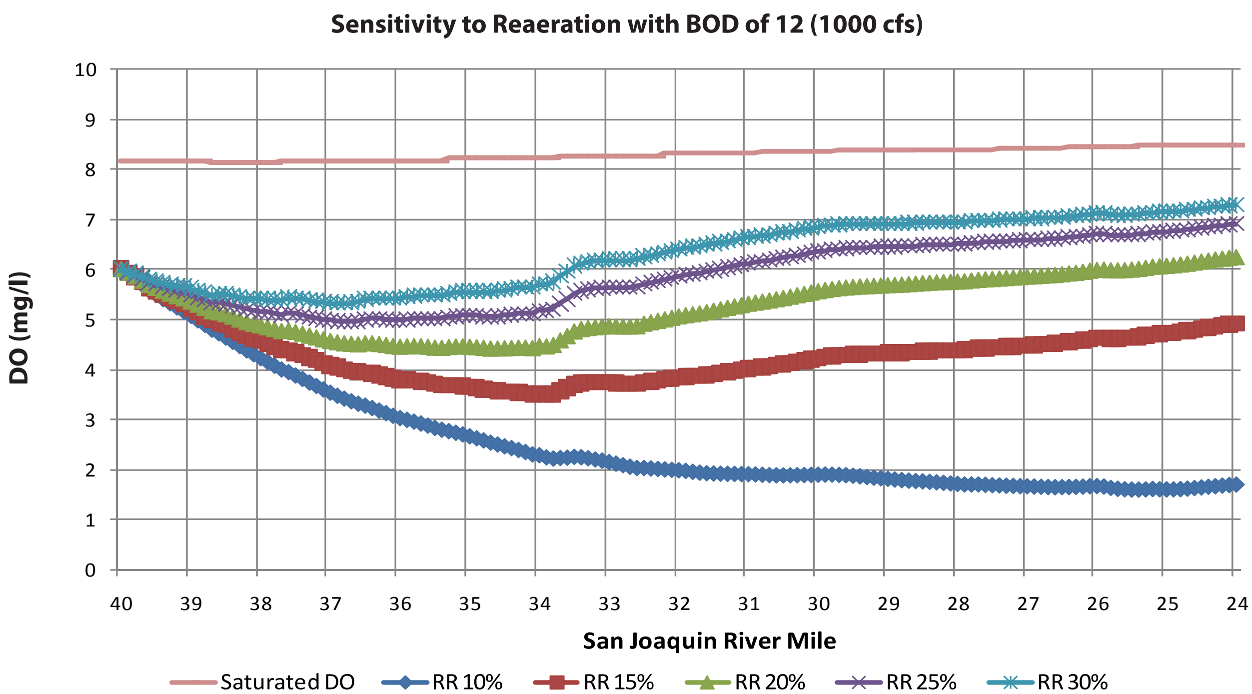

Figure A-5d: Sensitivity of DWSC Longitudinal DO Profile to Daily Reaeration Rates (RR) of 10 to 30 Percent with BOD of 12 mg/l and Flow of 1,000 cfs

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Figure A-5 (continued)

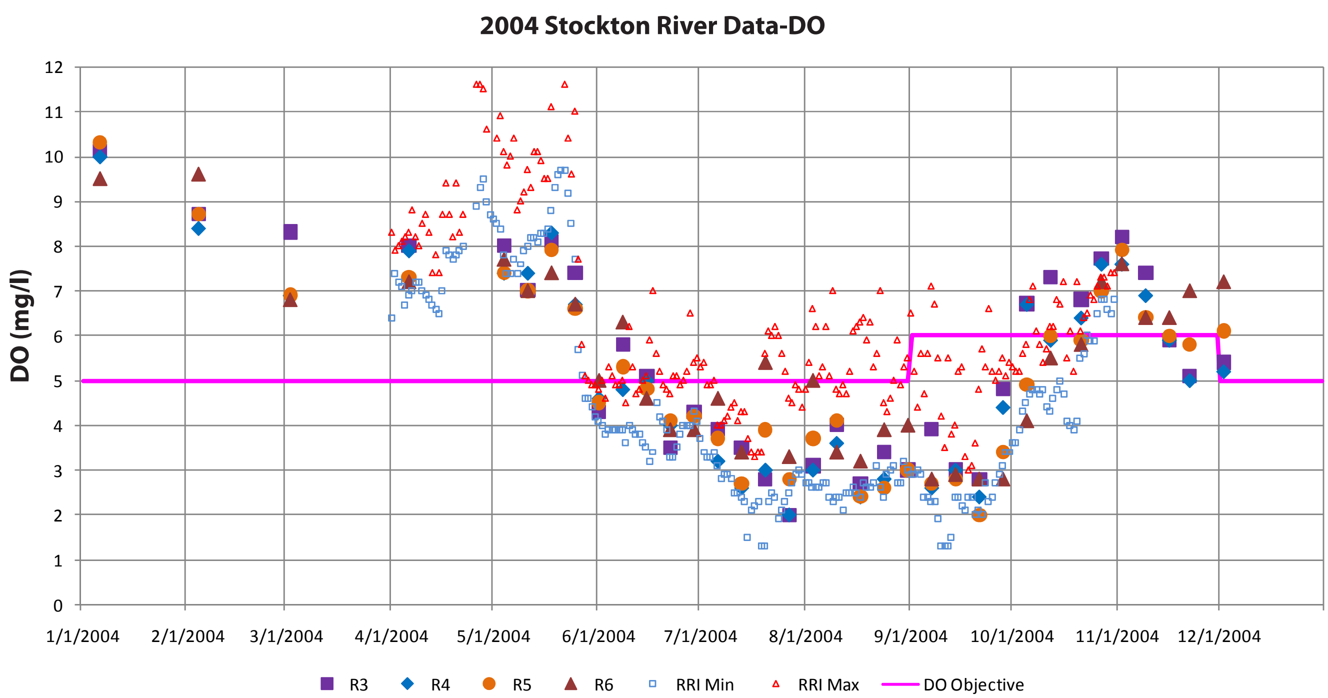

Figure A-6a: City of Stockton DO Measurements in the DWSC (R3, R4, R5, and R6) Compared to the Saturated, Minimum and Maximum DO Concentrations at the DWR RRI Monitoring Station for 2004.

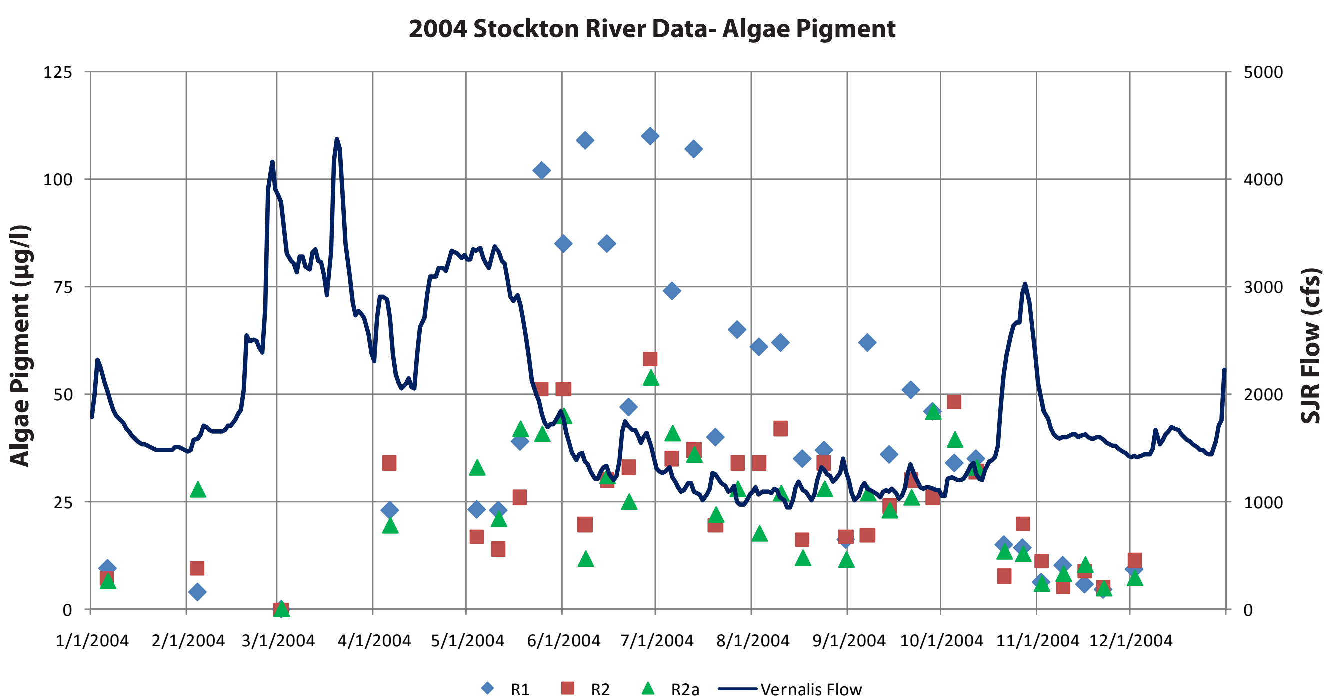

Figure A-6b: Weekly River Algal Pigment Concentrations (µg/l) Measured by City of Stockton in 2004.

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Figure A-6

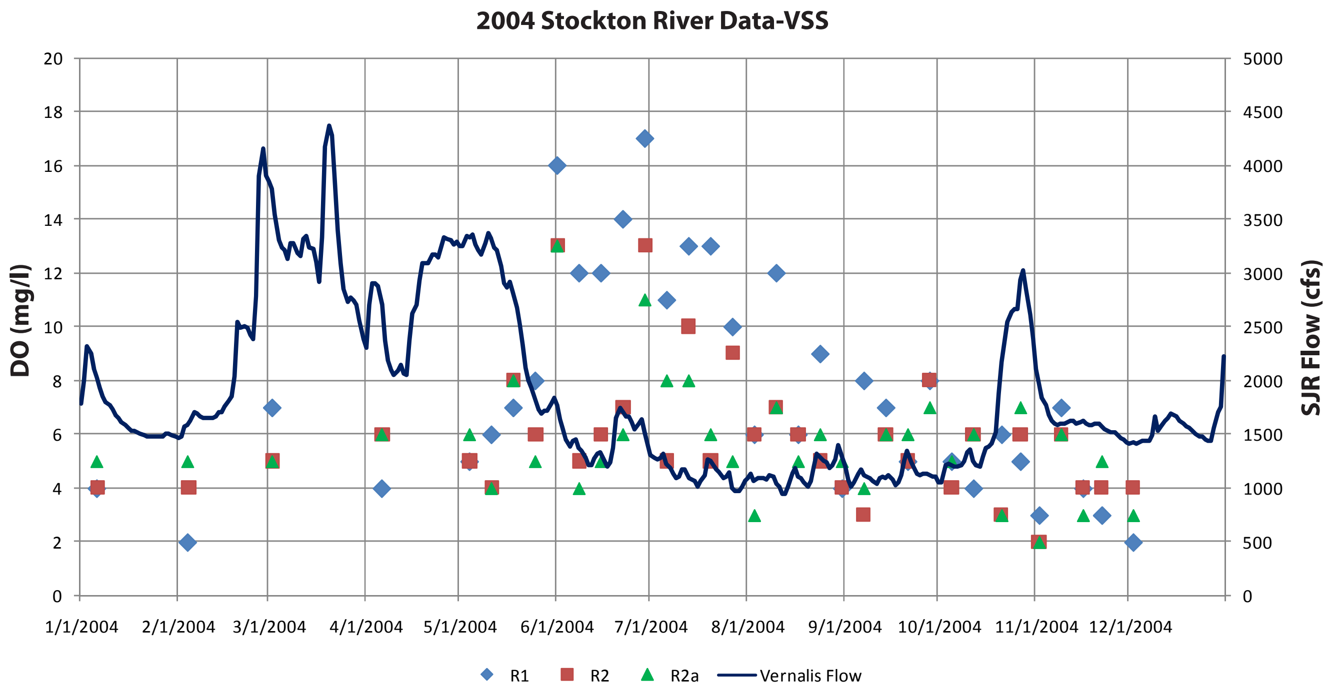

Figure A-6c: San Joaquin River Volatile Suspended Solids Concentration (mg/l) Measured by City of Stockton in 2004
Note: Each 10 µg/l of algal pigment is about 1 mg/l of VSS or BOD.

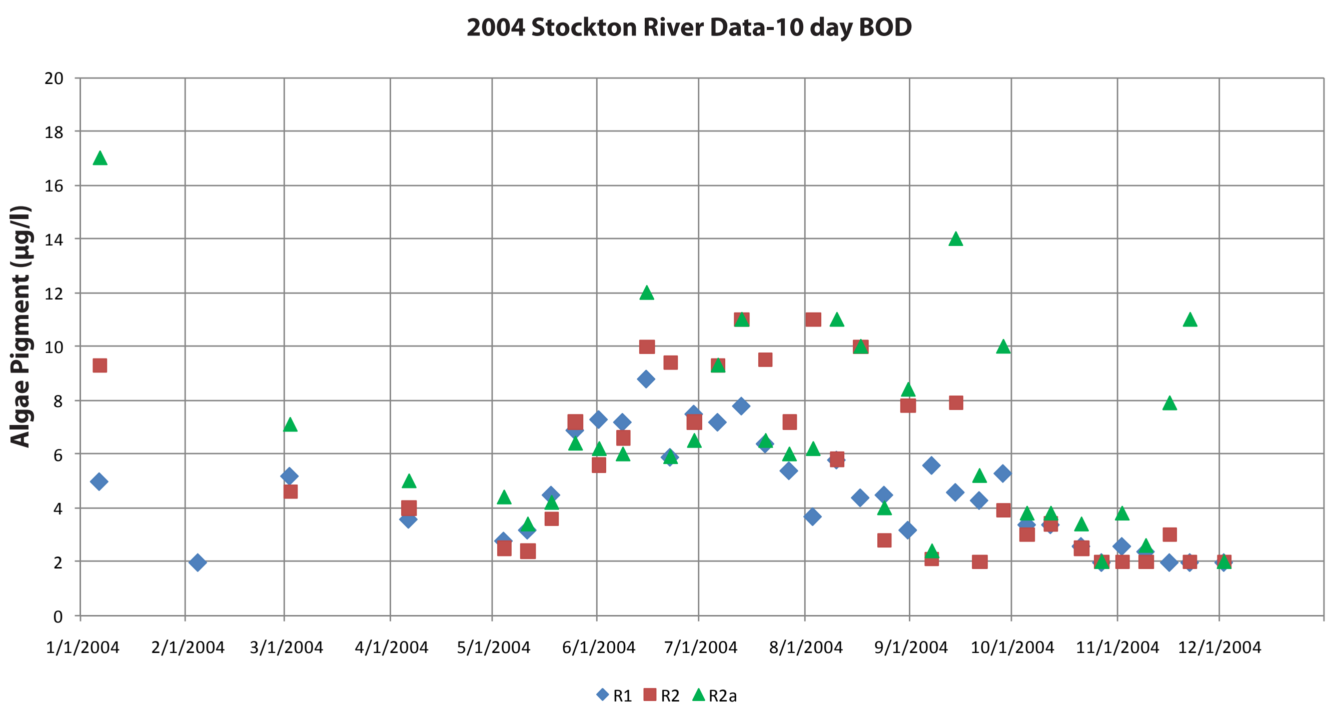

Figure A-6d: San Joaquin River Inflow BOD Concentration (mg/l) Measured by City of Stockton in 2004.

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Figure A-6 (continued)

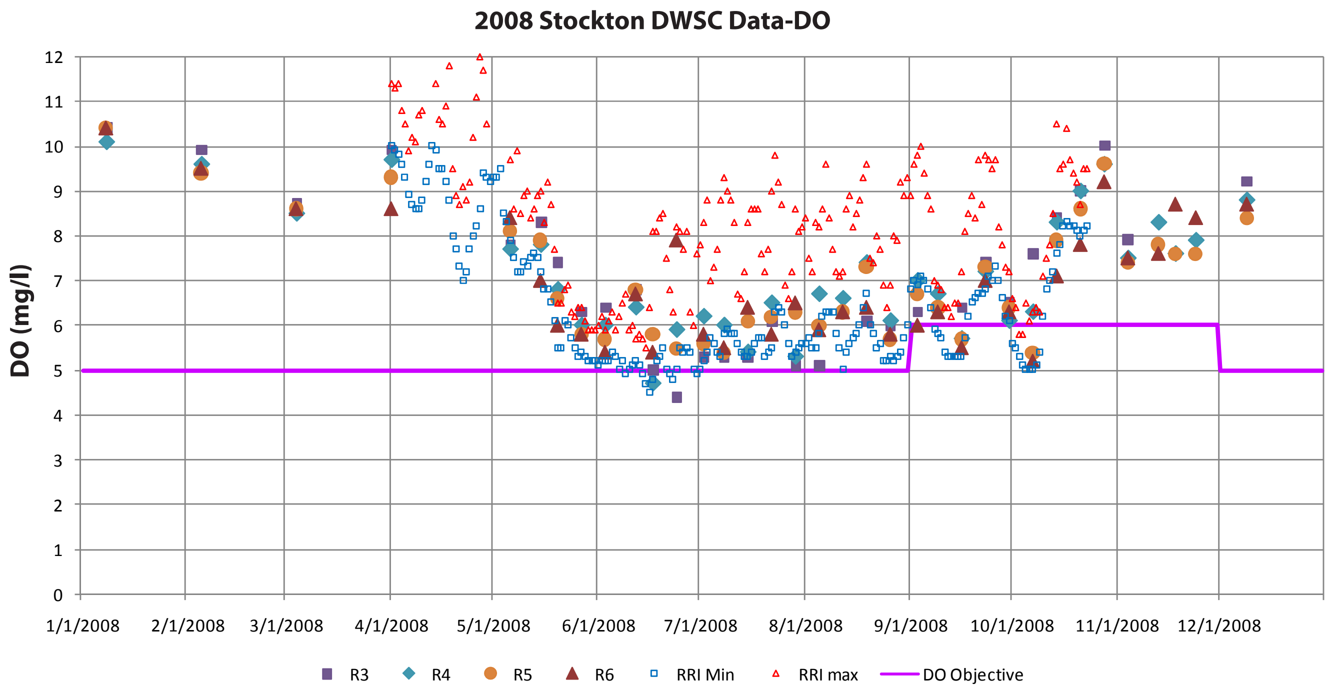

Figure A-7a: Weekly DO Concentrations (mg/l) Measured in the DWSC by City of Stockton in 2008.

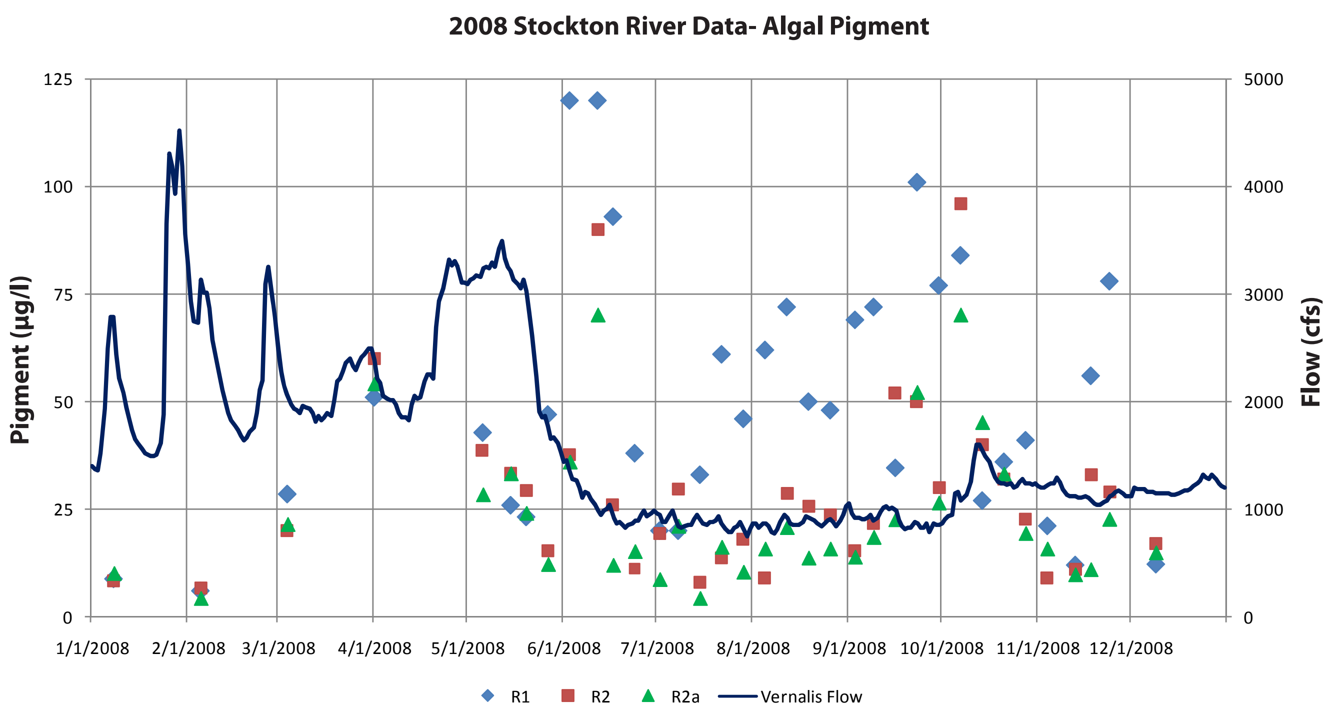

Figure A-7b: Weekly River Algal Pigment Concentrations (µg/l) Measured by City of Stockton in 2008.

Graphics/Projects/00902.08 TO-I Operation and Technical Support/2008 Operation Report/Appendix A (03-09) SS

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Figure A-7

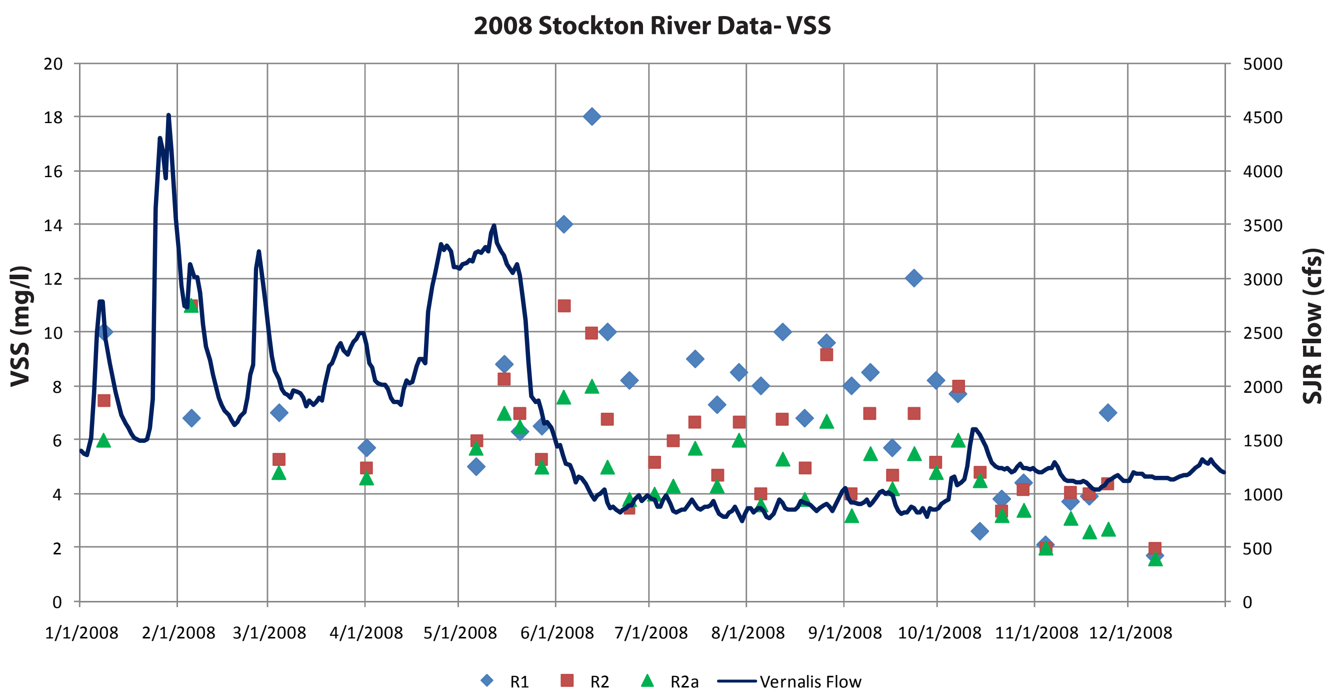

Figure A-7c: Weekly River Inflow VSS Concentrations (mg/l) Measured by City of Stockton in 2008.

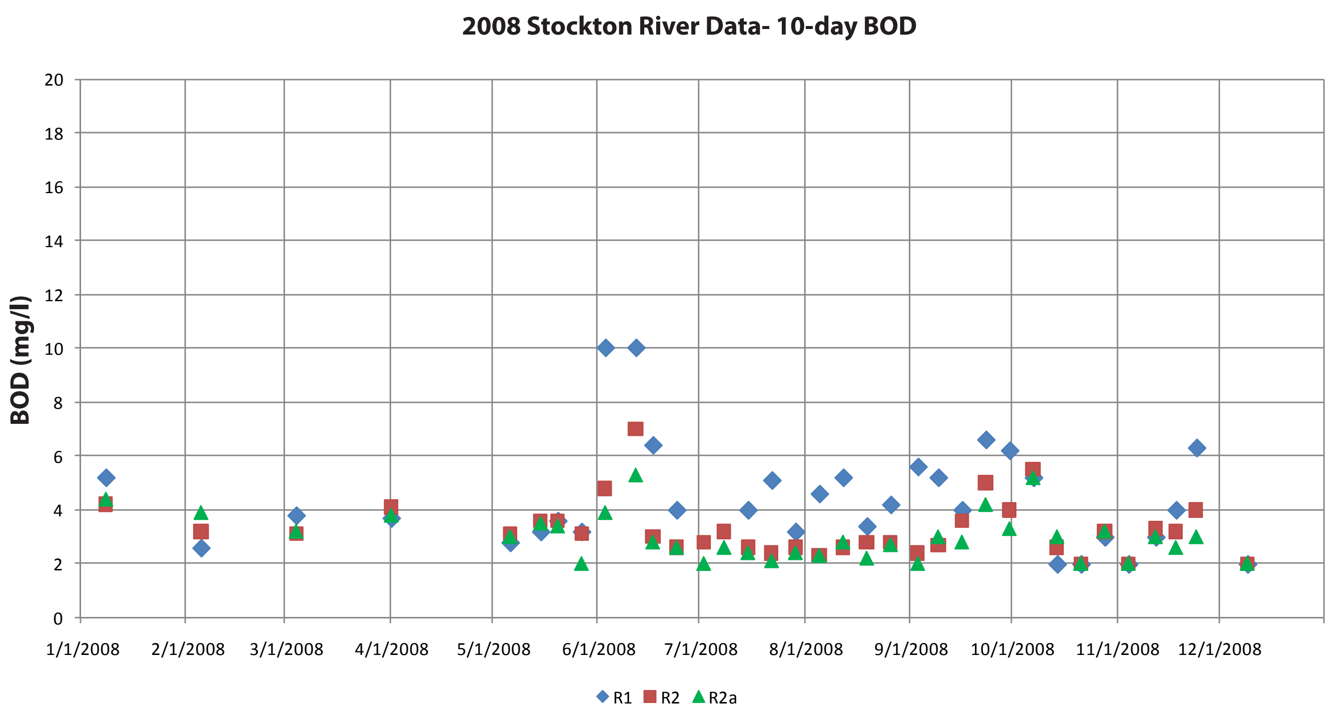

Figure A-7d: Weekly River Inflow 10-day BOD Concentrations (mg/l) Measured by City of Stockton in 2008.

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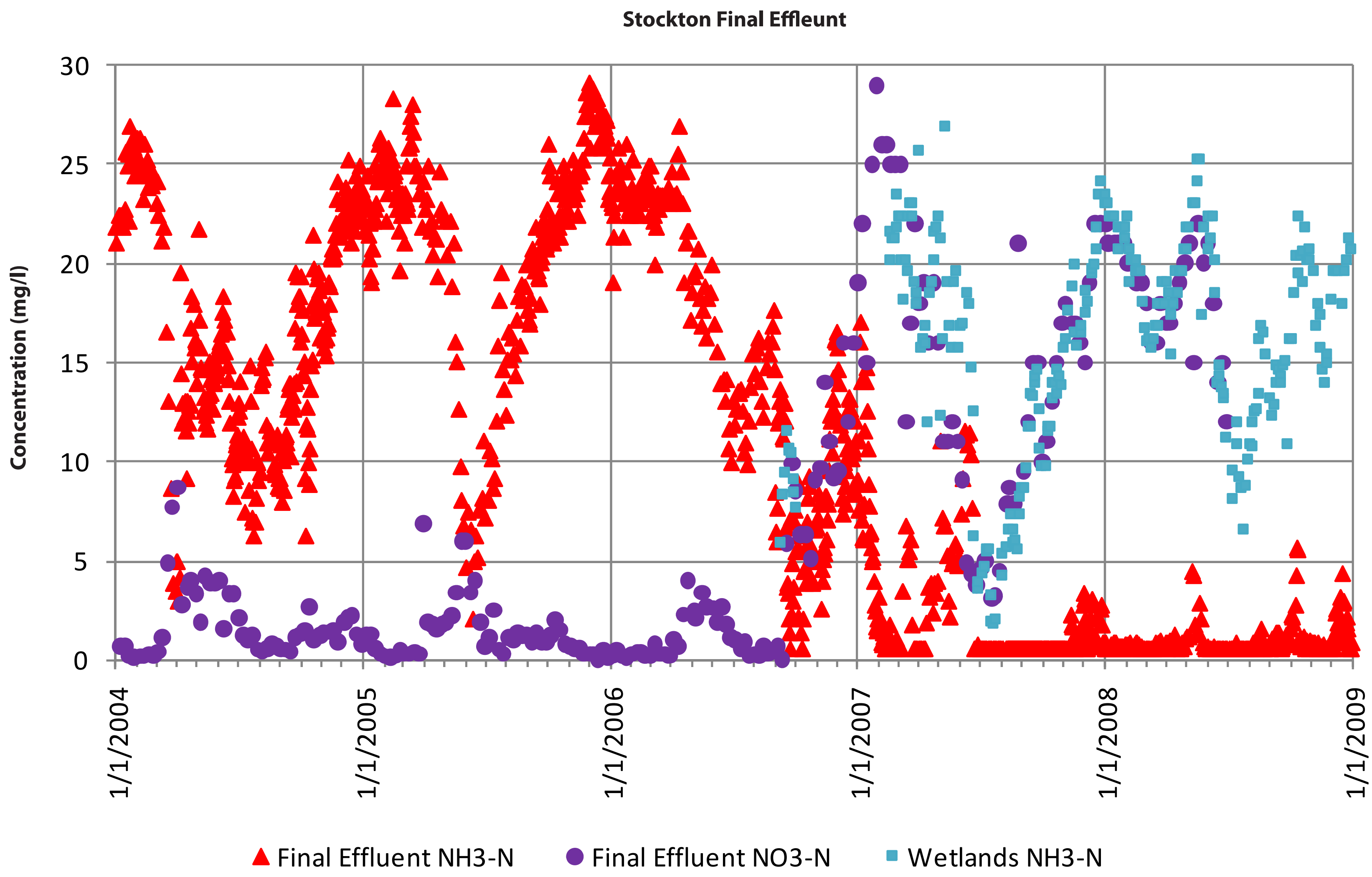
Figure A-7 (continued)



Note: Stockton RWCF added wetlands and nitrification bio-towers early in 2007 to reduce ammonia concentration to less than 2 mg/l.

Figure A-8
Stockton Regional Wastewater Control Facility
Final Effluent Concentrations of Ammonia and Nitrate for 2004–2008