

Aeration Technology Feasibility Report for the San Joaquin River Deep Water Ship Channel



DRAFT



Jones & Stokes

AUGUST 2004

Draft
Aeration Technology Feasibility
Report for the
San Joaquin River Deep Water
Ship Channel

Prepared for:

California Bay-Delta Authority
650 Capitol Mall, Fifth Floor
Sacramento, CA 95814
Contact: Barbara Marcotte

Prepared by:

Jones & Stokes
2600 V Street
Sacramento, CA 95818-1914
Contact: Russell Grimes
916/737-3000

August 2004

Jones & Stokes. 2004. *Aeration technology feasibility report for the San Joaquin River deep water ship channel*. Draft. August. (J&S 03-405.) Sacramento, CA. Prepared for the California Bay-Delta Authority, Sacramento, CA.

Contents

	Page
Aeration Technology Feasibility Report for the San Joaquin River	
Deep Water Ship Channel	1
Executive Summary	1
Characteristics of the DWSC	1
The DO Deficit	2
Natural Mixing Characteristics	2
Selected Technologies for delivering oxygen	3
Introduction	3
Dissolved Oxygen in the Stockton Deep Water Ship Channel	4
Dissolved Oxygen Deficit	4
Characteristics of the DWSC	5
Factors Affecting Dissolved Oxygen Concentrations in Water	9
Aeration/Oxygenation in the DWSC	11
Specific Design Considerations for Suitable Aeration/Oxygenation Technologies	13
Recommendations	16
References	20
Printed References	20
Personal Communication	20

Tables

	Page
1. Geometry of the DWSC and Location of Monitoring Stations.....	8

Figures

Follows Page

1.	Dissolved Oxygen Deficit in the Stockton Deep Water Ship Channel Calculated for 2001	6
2.	Stockton Deep Water Ship Channel Water Quality Stations	6
3.	Dissolved Oxygen Concentrations in the Stockton Deep Water Ship Channel and in the San Joaquin River in 2001	6
4a.	Vertical Profiles of Dissolved Oxygen and Temperature in the Stockton Deep Water Ship Channel, June 12th, 2001	6
4b.	Vertical Profiles of Dissolved Oxygen and Temperature in the Stockton Deep Water Ship Channel, June 19th, 2001	6
5.	Temperature and Dissolved Oxygen Measurements in the DWSC at the Rough & Ready Island Monitoring Station in 2002.	10
6.	Solubility of Oxygen and Nitrogen as a Function of Temperature	10
7.	Longitudinal Spreading of Dye in the DWSC after 25 Hours	18

Photos

	Page
1. Upstream View of the Port of Stockton's Rough & Ready Island Dock.....	6
2. Looking downstream from the Rough & Ready Island Dissolved Oxygen Monitoring Station. Ship moving upstream towards the Port of Stockton.	6

Aeration Technology Feasibility Report for the San Joaquin River Deep Water Ship Channel

Executive Summary

This report examines three technologies for delivering oxygen to the Deep Water Ship Channel (DWSC) in order to increase the amount of dissolved oxygen. These three technologies were recommended for further study in the “Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel,” prepared for CALFED in January 2003. The three technologies investigated here are: Bubble Plume aeration, U-Tube aeration, and the use of a Speece Cone. Of these technologies, it is recommended that demonstration of the Bubble Plume aeration system and U-tube aeration system be performed over two seasons in the DWSC. Included as appendices to this report are an engineering feasibility study and a monitoring plan. These technical appendices provide a great deal of information regarding the reason for recommending demonstration of two devices, and the monitoring that must take place during demonstration.

Characteristics of the DWSC

The DWSC is a maintained (i.e., dredged) portion of the San Joaquin River that begins at the mouth of the San Joaquin River near Antioch and terminates in Stockton, California. It is used as a shipping channel allowing large hauling vessels access to the interior of the Central Valley from the open sea. The terminus of the shipping channel is at the Port of Stockton East Complex. A sizable turning basin allows the vessels to reverse their orientation before departing. The DWSC is dredged to a depth of at least 35 feet measured at the lowest low diurnal tidal cycle (mean lower low water [MLLW]). That is approximately 0 feet mean sea level (msl).

The concentration of DO in the DWSC is a function of three primary factors: variations in flow conditions in the river, the geometry, particularly the depth, of the DWSC, and upstream contributions of algae and oxygen-depleting constituents (e.g. biochemical oxygen demand (BOD) and ammonia). High San Joaquin River flows, greater than 2,000 cubic feet per second (cfs), can prevent low DO levels by diluting oxygen-depleting substances in the DWSC and by transporting the BOD substances through the DWSC faster than at lower river

flows. The DWSC's depth causes San Joaquin River flows to slow through the channel, thereby increasing the residence time of water within the DWSC. Although algae can grow near the surface of the DWSC, the depth of the DWSC limits the net algae growth, and most of the inflowing algae will settle and decay in the DWSC. The growing algae at the surface can provide DO to the DWSC through photosynthesis, but the net effect of algae in the water is to reduce DO levels as the algae respire and as bacteria decompose dead algae. Most ammonia in the DWSC is from the Stockton Regional Wastewater Control Facility (RWCF) discharge.

The DO Deficit

Water quality objectives are established by the Regional Water Quality Control Boards (RWQCBs) to protect the beneficial uses of water bodies in California. The dissolved oxygen (DO) water quality objective (the minimum DO concentration) for the San Joaquin River, from Turner Cut to Stockton, is 6 milligrams per liter (mg/l) from September 1 to November 30, to protect migrating adult Chinook salmon, and 5 mg/l throughout the rest of the year. However, water quality monitoring data have indicated that the Stockton Deep Water Ship Channel (DWSC) frequently has DO levels that are lower than the water quality objectives.

A DO deficit, defined here as the quantity of oxygen that must be added to the DWSC to meet the water quality objectives, was calculated using DO and flow data from 2001, as an example. Based on the daily minimum DO concentrations at the DWR Rough & Ready Island station and the daily net flow measured at the Stockton UVM flow station, about 1 million pounds (lbs) of oxygen would have been needed in the summer of 2001. This calculation includes a 0.5-mg/l DO buffer added to the water quality objective as a margin of safety to allow for small variations within the DWSC compared to the DO monitoring data. An aeration or oxygenation device that delivered about 10,000 lbs/day would have satisfied the measured DO deficit during the summer of 2001. It should be noted that water year 2001 was a slightly below-normal year and that during a dry or critical year with lower river flows the oxygen deficit could at times be greater than 10,000 lbs/day. The annual deficit may also vary from year to year.

Natural Mixing Characteristics

A dye study was performed on November 26, 2002, to evaluate how rapidly dye would spread from an oxygenation device at the Rough & Ready Island dock across the DWSC to the opposite shore. It was reasoned that lateral spreading and mixing of the dye would indicate how well an aeration or oxygen injection system would spread water with an increased DO concentration across and throughout the DWSC. The DWSC is approximately 500 feet wide with a mean depth of 30 feet, so the cross-section area is about 15,000 square feet. Tides fluctuate twice each day, with an average tidal stage change of 2-3 feet. Water

moves upstream or downstream about 1 mile during a three-foot tidal variation, which may occur twice each day.

The measured lateral mixing from tidal flow dispersion was nearly complete at the end of the day. While lateral mixing was minimal during the first 6 hours after dye injection when tidal flow was low, tidal mixing was sufficient to yield nearly uniform lateral dye concentrations after 24 hours. This field study demonstrated that tidal flows strongly influence lateral dispersion in the DWSC near Rough & Ready Island. It appears that lateral mixing is sufficient to allow the aeration or oxygenation system to be installed under the Rough & Ready Island dock and still maintain improved DO concentrations throughout the DWSC.

Selected Technologies for delivering oxygen

Delivering 10,000 lbs/day of dissolved oxygen to the DWSC can be accomplished using a number of artificial aeration techniques. These techniques range from mechanical mixing to submerged bubble column systems. Jones & Stokes evaluated several of these technologies in 2003, and three systems were chosen for further engineering evaluation: Bubble Plume aeration, U-Tube aeration, and the use of a Speece Cone. Each of these technologies can deliver the 10,000 lbs/day required to alleviate the low oxygen conditions, however, each of these systems has unique characteristics for providing the dissolved oxygen.

The Bubble Plume aeration system works by releasing fine bubbles of air or oxygen gas into the DWSC and relying on basic physical characteristics of gas transfer to raise the oxygen concentration of the water. In this case, the diffuser line would be stretched beneath the docks in the DWSC and rely on the bubbles rising from 25 feet to the surface to allow enough time for a substantial amount of oxygen to dissolve into the water column. Because of the bubble dynamics a large upwelling flow would occur which might substantially help to mix the aerated water into and across the DWSC.

The U-Tube and the Speece Cone work on the same principal of delivering dissolved oxygen to water pumped through a device. By subjecting the oxygen bubbles to increased pressure, more oxygen can be dissolve into the water. This oxygen-rich water is then injected into the DWSC through a submerged diffuser and relies on natural tidal influence to ensure thorough mixing.

Introduction

This report describes the existing low dissolved oxygen (DO) problem in the Stockton Deep Water Ship Channel (DWSC), the physical characteristics of the DWSC, the proposed aeration/oxygenation technologies that could improve the dissolved oxygen concentrations, and future steps that should be taken to select a final aeration/oxygenation device. This report also describes the scientific background for quantitatively understanding aeration processes that transfer

oxygen between the atmosphere (gas) and a water volume (dissolved gas). An aeration device uses atmospheric gas (air), while an oxygenation device uses oxygen gas as the oxygen source.

The July 2002 Peer Review of the CALFED-sponsored San Joaquin River Dissolved Oxygen studies, emphasized the need for further science-based analyses and measurements to evaluate the performance and potential environmental side-effects of an aeration device in the DWSC. The engineering feasibility report (Appendix A) and recommendations for monitoring of demonstration-scale aeration devices in the DWSC (Appendix B) are consistent with these peer-review comments.

Dissolved Oxygen in the Stockton Deep Water Ship Channel

Water quality objectives are established by the Regional Water Quality Control Boards (RWQCBs) to protect the beneficial uses of water bodies in California. Beneficial uses are the desired resources, services, and qualities of the aquatic system that are supported by achieving and protecting high water quality (Central Valley RWQCB's Basin Plan 1998). The DO water quality objective (the minimum DO concentrations) for the San Joaquin River, from Turner Cut to Stockton, are 6 milligrams per liter (mg/l) from September 1 to November 30, to protect migrating adult chinook salmon, and 5 mg/l throughout the rest of the year. However, water quality monitoring data have indicated that the DWSC frequently has DO levels that are lower than the water quality objectives (Jones & Stokes 2003). This failure to meet the DO objectives has led to further monitoring of the water quality and hydrodynamics of the DWSC. One of the first steps used to identify and quantify the DO problem in the DWSC was to calculate the DO deficit.

Dissolved Oxygen Deficit

The DO deficit, defined here as the quantity of oxygen that must be added to the DWSC to maintain DO levels at or above water quality objectives, was estimated using DO and flow data from 2001, as an example. Data from the California Department of Water Resources (DWR) Rough & Ready Island DO monitoring station and from the Stockton United States Geological Survey (USGS) ultrasonic velocity meter (UVM) tidal flow station were used to estimate the DO deficit below applicable water quality objectives for the DWSC. The DO deficit in the DWSC was calculated using the following equation:

$$\text{DO deficit (lbs/day)} = 5.4 (\text{Net Flow (cfs)}) ([\text{Target DO (mg/l)} - \text{Minimum DO (mg/l)}])$$

Where lbs/day = pounds per day.

A 0.5–mg/l DO buffer was added to the water quality objective (i.e., target DO) used to calculate the deficits, as a margin of safety to allow for small variations in DO within the DWSC compared with the DO monitoring data. Based on the daily minimum DO concentrations at the DWR Rough & Ready Island station and the daily net flow measured at the Stockton UVM flow station, about 1 million pounds (lbs) of oxygen would have been needed in the summer of 2001. Estimated DO deficits in the DWSC during 2001 are shown in Figure 1. An aeration or oxygenation device that delivered about 10,000 lbs/day would have satisfied the measured DO deficit during the summer of 2001. It should be noted that water year 2001 was a slightly below-normal year and that during a dry or critical year with lower river flows the oxygen deficit could be greater than 10,000 lbs/day. However, the maximum daily DO deficit of about 10,000 lbs was generally the same during several recent years (Jones and Stokes 2003). The period when a DO deficit develops in the DWSC, and the total annual deficit, will vary from year to year.

Characteristics of the DWSC

The DWSC is a maintained (i.e., dredged) portion of the San Joaquin River that begins at the mouth of the San Joaquin River near Antioch and terminates in Stockton, California. It is used as a shipping channel allowing large hauling vessels access to the interior of the Central Valley from the open sea. The terminus of the shipping channel is at the Port of Stockton East Complex. A sizable turning basin allows the vessels to reverse their orientation before departing. The DWSC is dredged to a depth of at least 35 feet measured at the lowest low diurnal tidal cycle (mean lower low water [MLLW]). The MLLW at Stockton is approximately 0 feet mean sea level (msl). Photographs 1 and 2 show images of the DWSC looking downstream from the north end of Rough & Ready Island and looking upstream along the East Complex dock towards the turning basin and the inflow of the San Joaquin River at Channel Point.

Causes of Low Dissolved Oxygen

The concentration of DO in the DWSC is a function of three primary factors: flow conditions in the river; the geometry, particularly the depth, of the DWSC; and upstream contributions of algae and oxygen-depleting constituents (e.g., biochemical oxygen demand [BOD] and ammonia). High San Joaquin River flows, greater than 2,000 cubic feet per second (cfs), can prevent low DO levels by diluting oxygen-depleting substances in the DWSC and by transporting the BOD substances through the DWSC faster than at lower river flows. The DWSC's depth causes San Joaquin River flows to slow through the channel, thereby increasing the residence time of water within the DWSC. Although algae can grow near the surface of the DWSC, the depth of the DWSC limits net algae growth, and a significant number of inflowing algae will settle and decay in the DWSC. The growing algae at the surface can provide DO to the DWSC through photosynthesis, but the net effect of algae in the water is to reduce DO levels as the algae respire and as bacteria decompose dead algae. Most ammonia

in the DWSC is from the Stockton Regional Wastewater Control Facility (RWCF) discharge, with ammonia concentrations of 25 mg/l in the winter months and generally less than 10 mg/l in the summer months. A nitrification facility is being constructed that will reduce the discharge ammonia concentration to about 2 mg/l. This is expected to have a substantial effect on the DO concentrations in the DWSC during periods of low flow.

Dissolved Oxygen and Temperature Patterns

Results of a 2001 water quality study are useful as examples of dissolved oxygen and temperature conditions in the DWSC. In 2001, as part of a directed-action grant by the CALFED Bay-Delta Program (CALFED), the City of Stockton (City) conducted special river surveys to support the DO studies funded by CALFED. The study reach included the river monitoring stations established for the City's National Pollutant Discharge Elimination System (NPDES) sampling in the DWSC (stations R2–R8) and another station in the turning basin (Figure 2). The monitoring program provided a framework of weekly samples to characterize the water quality patterns within the DWSC and evaluate the potential relationships between RWCF effluent loads and San Joaquin River loads (Jones & Stokes 2002).

The results of this study provided important information on vertical stratification in the DWSC, the DO levels, longitudinal DO differences, and the effects of San Joaquin River flows on DO in the DWSC. Dissolved oxygen levels in the DWSC for all of 2001 are shown in Figure 3. Study results showed that the DWSC is generally well mixed vertically (Jones & Stokes 2002). The measured surface temperature and DO at DWR's Rough & Ready Island station was sometimes elevated during the day but was apparently almost always well-mixed during the night, as indicated by a slowly decreasing temperature and DO in the early morning hours each day. The vertical profiles of temperature often showed only a near-surface layer with a slightly higher temperature (1–2°F), but the DO gradient was sometimes declining throughout the depth (Figures 4a and 4b). In addition to showing the DO differences between locations, Figures 4a and 4b demonstrate the DO and temperature changes that can occur from week to week. The temperature and DO stratification was more pronounced at the turning basin station (Figure 4b). Tidal mixing is less in the turning basin because most of the tidal flow moves up the San Joaquin River toward Mossdale. This suggests that the vertical mixing was fast relative to surface heating (mixing at least each night) but slow relative to DO decay processes.

The observed decline in the mid-depth DO concentrations (DO sag) between stations R3 and R6 was always less than 2 mg/l in 2001 (Jones & Stokes 2003). The R3 DO concentrations were usually within 2 mg/l of saturation, suggesting that the lowest DO concentrations were about 4 mg/l. The hourly DWR station recorded values were sometimes less than 4 mg/l. The lowest mid-depth DO concentrations of 4 mg/l are slightly less than the DO objectives of 5 mg/l from December through August and 6 mg/l from September through November.

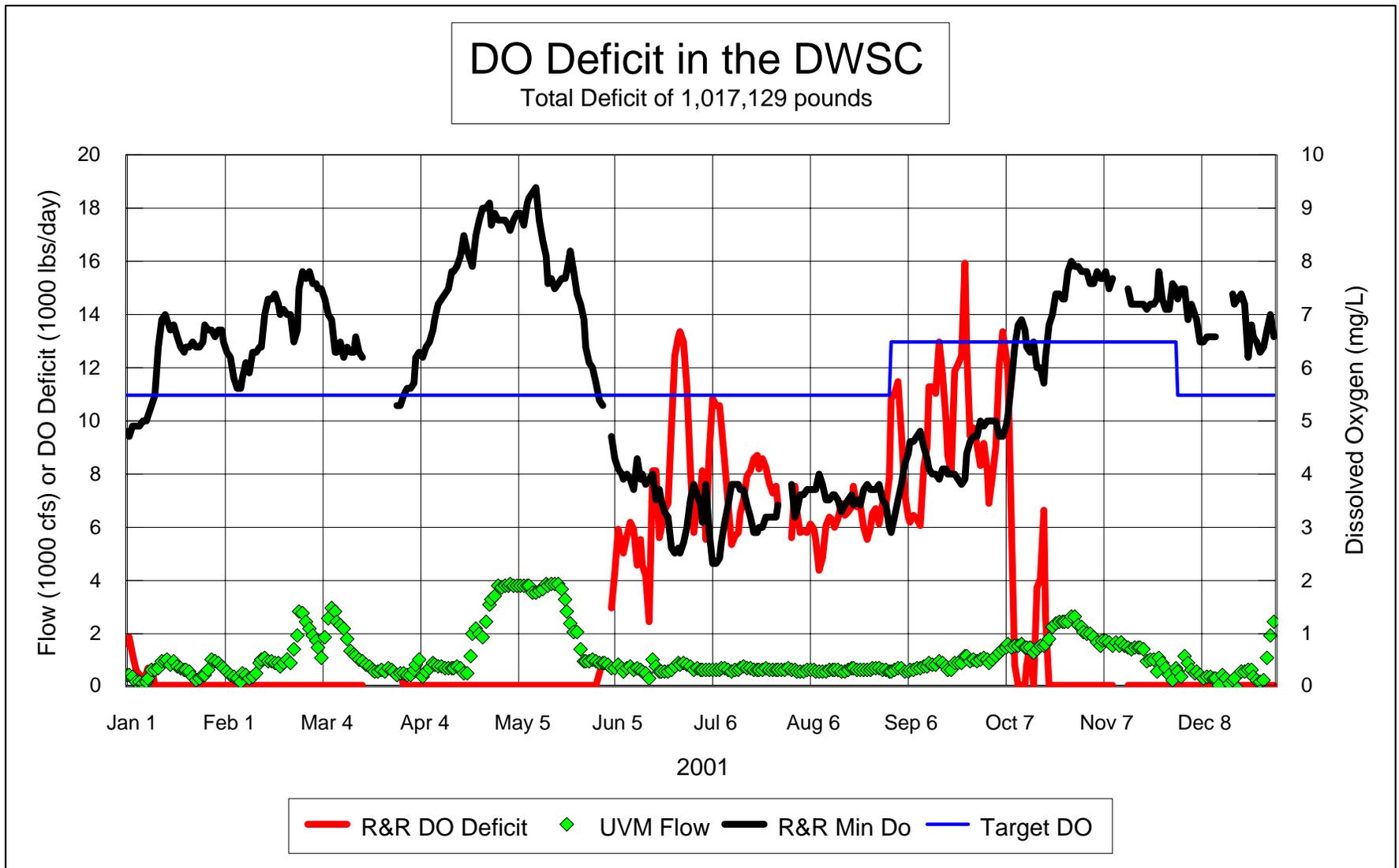
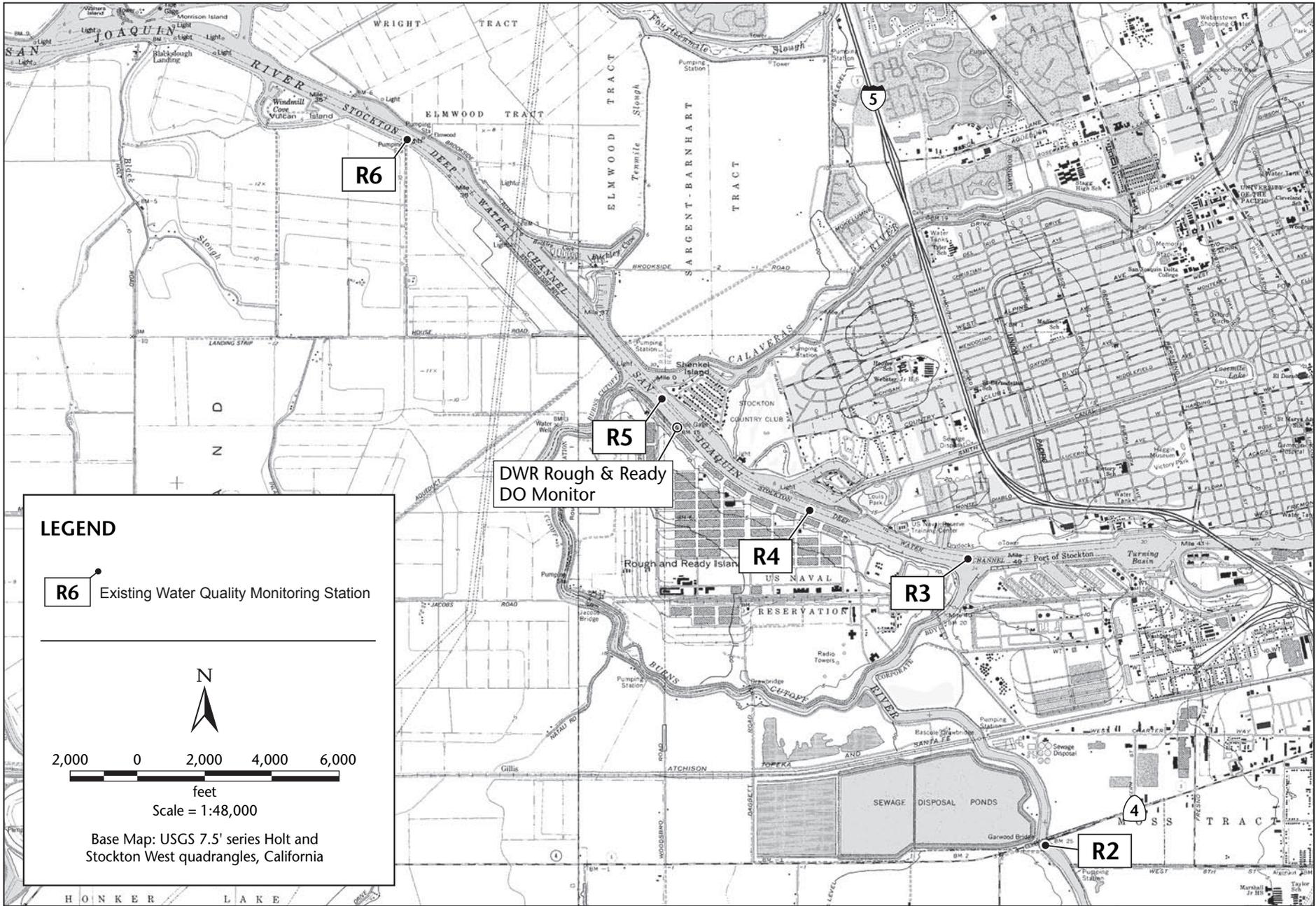


Figure 1. Dissolved Oxygen Deficit in the Stockton Deep Water Ship Channel Calculated for 2001



03405.03

Figure 2
Stockton Deep Water Ship Channel Water Quality Stations

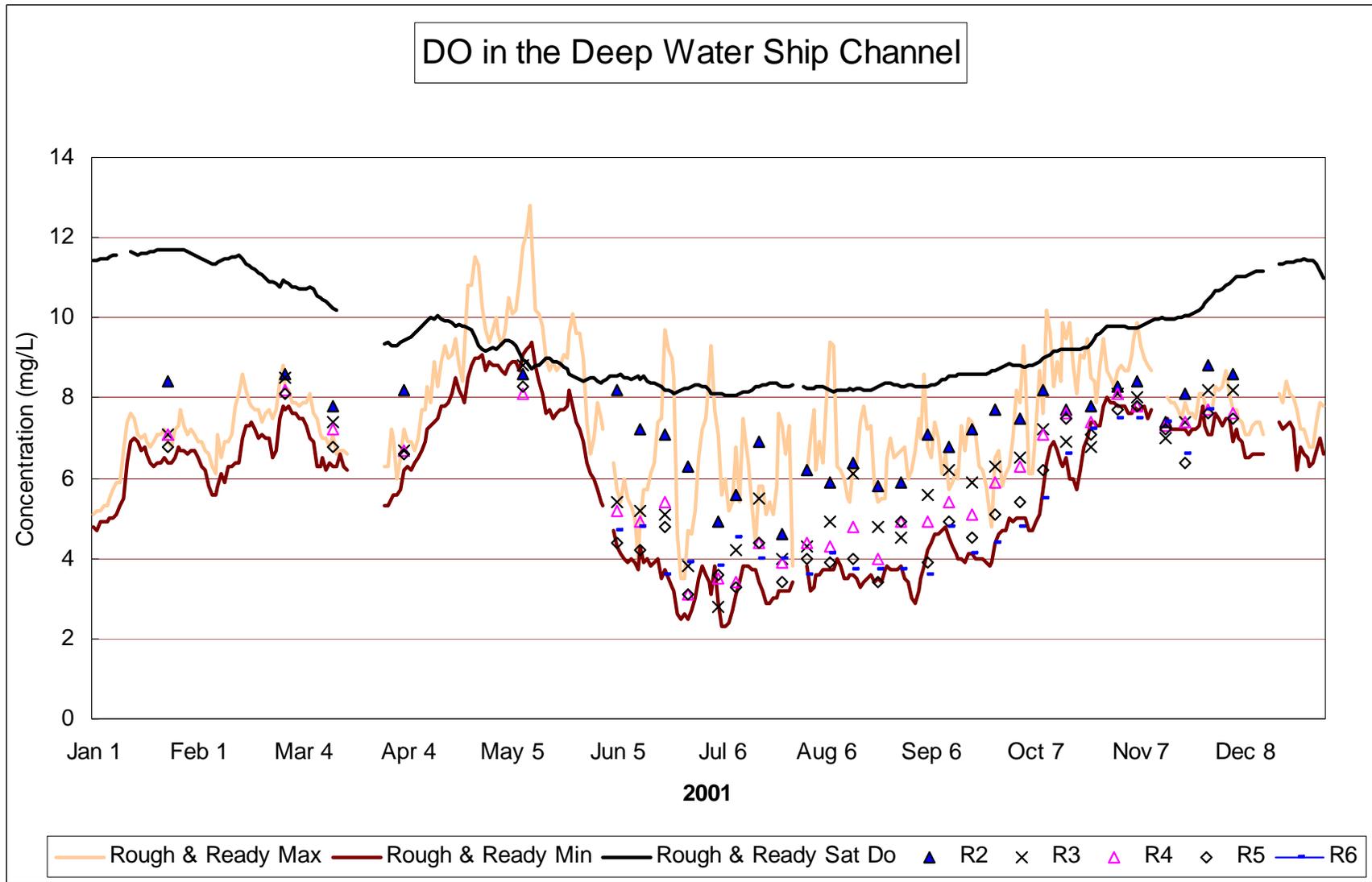


Figure 3. Dissolved Oxygen Concentrations in the Stockton Deep Water Ship Channel and in the San Joaquin River in 2001

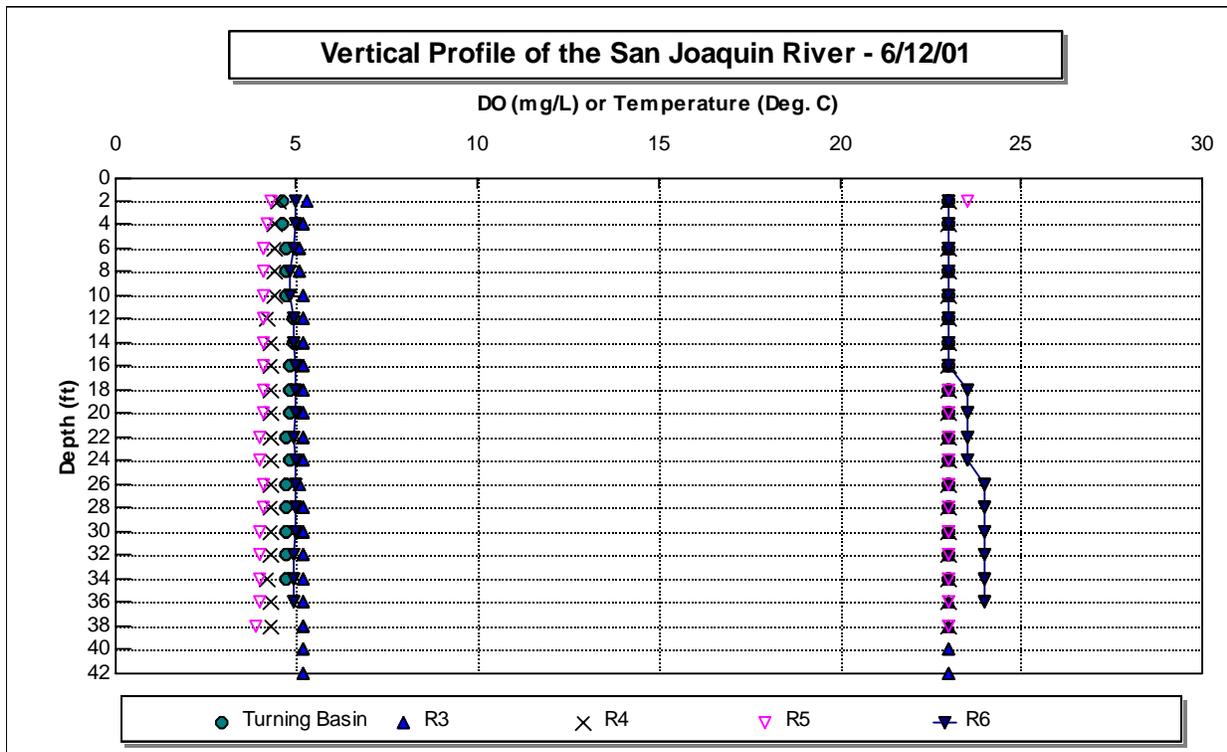


Figure 4a. Vertical Profiles of Dissolved Oxygen and Temperature in the Stockton Deep Water Ship Channel, June 12th, 2001

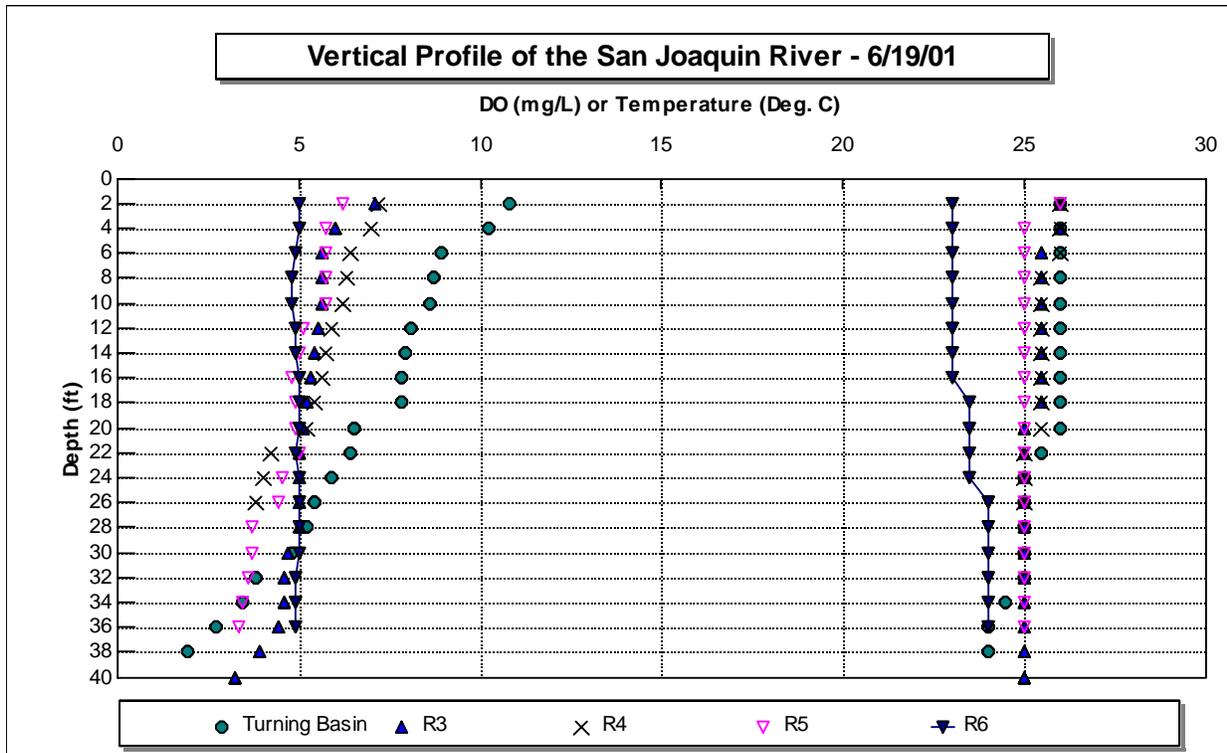


Figure 4b. Vertical Profiles of Dissolved Oxygen and Temperature in the Stockton Deep Water Ship Channel, June 19th, 2001



Photo 1: Upstream View of the Port of Stockton's Rough & Ready Island Dock.



Photo 2: Looking downstream from the Rough & Ready Island Dissolved Oxygen Monitoring Station. Ship moving upstream towards the Port of Stockton.

Flows during the year 2001 survey period ranged from less than 750 cfs in June and July to more than 2,000 cfs in October. The DWSC residence time from Channel Point to the Rough & Ready Island station changed from more than 5 days in June and July to fewer than 5 days in October. The effects of flow changes on DO concentrations in the DWSC are apparently more complex than a simple dilution of RWCF and a reduction in residence time. The river load to the DWSC increases with flow if the flow change is the result of partial closure of the head of Old River barrier. The river concentrations may be reduced if the flow change is from upstream reservoir releases. DWSC water quality may be influenced by changes in San Joaquin River flow, but several factors interact that make it difficult to clearly observe the effects of flow on DO concentrations in the DWSC.

Hydrodynamics of the DWSC

Geometry and Tidal Flows

This section provides a summary of the geometry of the DWSC and the tidal flows in the DWSC (Jones & Stokes 2002). The geometry of the DWSC upstream of Turner Cut is very important because it controls the movement of water through the DWSC and the tidal flows within the DWSC. Table 1 provides a summary of the geometry of the DWSC and the distance between each NPDES water quality monitoring station. The DO sag, previously described, typically occurs within a distance of 4 miles, i.e., between stations R3 and R6. The DWSC's width and depth, on average approximately 600 feet wide and 35 feet deep between R3 and R6, cause water velocities to decrease from the faster velocities upstream in the San Joaquin River (SJR).

Water flow in the DWSC and some of the SJR is affected by the tides, which transport the water upstream at high tides and farther downstream at low tides. The tidal flows are controlled by the tidal stage variations, the surface area of the DWSC, and the tidal portion of the SJR upstream of the DWSC (i.e., between the DWSC and Mossdale). The tidal excursion for a particular monitoring station can be estimated by comparing the tidal volume between low tide and high tide (i.e., upstream surface area X tidal stage change) to the channel cross-section of the station. The tidal excursion can therefore be estimated by the following equation:

$$\text{Tidal excursion (miles)} = \text{Upstream Area (acres)} \times \text{Stage Change (feet)} / \text{Cross-section (square feet)} \times 43,560/5,280$$

$$\text{Excursion (miles)} = 8.25 \times \text{Surface Area} \times \text{Stage Change} / \text{Cross-section Area}$$

At DWR's Rough & Ready monitoring station, the channel is about 700 feet wide and 35 feet deep, and has a surface area of about 17,000 square feet at an elevation of 0 feet. Tidal flows at the Rough & Ready station are relatively symmetrical. The tidal excursion between low and high tides (i.e., 3 feet stage change) is about 2.8 miles at the USGS Stockton UVM station and about 1.25

miles at the Rough & Ready station (Jones & Stokes 2002). The tidal excursion is larger at the UVM station because of the smaller cross-sectional area (i.e., narrower channel and shallower depths). If an oxygenation/aeration device were placed at the Rough & Ready station, the oxygen injected would move upstream and downstream 1.25 miles, and could therefore be available throughout two-thirds of the DO sag area (between the R3 and R6 stations) within 1 day.

Table 1. Geometry of the DWSC and Location of Monitoring Stations

Downstream River Mile	River Location	Cumulative Volume at 0 feet (acre-feet)
40.5	Turning Basin	1,880
39.5	San Joaquin River/ R3	3,500
38.5	R4	5,300
38.0	Rough & Ready	6,260
37.5	R5	7,280
35.5	R6	10,460
32.5	Turner Cut	16,000

Mixing in the DWSC

A dye study was performed on November 26, 2002, to evaluate how rapidly dye would spread from an oxygenation device at the Rough & Ready Island dock across the DWSC to the opposite shore. This lateral spreading and mixing of the dye will indicate how well an aeration or oxygen injection system would spread water with an increased DO concentration across and throughout the DWSC. Methods and results of the dye study are described in detail in Jones & Stokes 2003. The results are summarized below.

The dye injection was conducted during a flood tide (upstream flow) of approximately 3,500 cfs, as estimated by changes in tidal stage. This represents a tidal velocity of about 0.2 feet per second (ft/sec). Tidal flows during the first 6 hours after the dye injection were relatively low. Longitudinal dye concentrations 1 hour after the end of the dye injection were measured shortly after the low-high slack tide. The dye cloud began about 750 feet upstream and was relatively uniform, with a dye concentration of 10–20 $\mu\text{g/l}$ and a dye cloud length of about 1,250 feet. After 6 hours, the dye cloud had moved downstream with the ebb tide, and the peak concentration of 10 $\mu\text{g/l}$ was observed 500 feet downstream of the injection location. Some dye had spread farther downstream, and the total length of the dye cloud had increased to about 3,000 feet. After 24 hours, the peak dye concentration of less than 1 $\mu\text{g/l}$ was an order of magnitude lower compared to the 5-hour plot and approximately 6,000 feet long. The reduction in dye concentrations from 6 to 24 hours appears to be largely attributable to lateral mixing because the length of the dye plume increased only about twofold, although the concentrations were about 10 times lower. Most measured dye concentrations 24 hours after the dye injection ceased ranged from 0.6 to 0.8 $\mu\text{g/l}$, with an average of about 0.7 $\mu\text{g/l}$.

Tidal flows strongly influence lateral dispersion in the DWSC near Rough & Ready Island. Lateral mixing was minimal during the first 6 hours after dye injection when tidal flow was low. This field study demonstrated that tidal mixing was sufficient to yield nearly uniform lateral dye concentrations after 24 hours. These measurements were performed under relatively calm wind conditions. It is expected that lateral mixing will be greater from the effects of high winds, which are common in the DWSC. The wind produces a strong surface current and induces a lateral circulation that will enhance lateral and vertical mixing. It appears that lateral mixing is sufficient to allow the aeration or oxygenation system to be installed under the Rough & Ready Island dock and still maintain improved DO concentrations throughout the DWSC.

Factors Affecting Dissolved Oxygen Concentrations in Water

Although water (H₂O) is composed of 89% oxygen, fish and aquatic organisms require dissolved oxygen gas (O₂) for respiration and cannot use the oxygen in the water molecules. The quantity of oxygen gas that can be dissolved into a water body and the rate of diffusion are affected by temperature and pressure.

Relationship of Temperature and Pressure to Dissolved Oxygen Concentrations

The maximum quantity of DO in water is called the DO saturation concentration. Temperature and pressure are the primary factors that determine the potential DO saturation level for a water body (Horne and Goldman 1994). As water temperatures increase, the DO saturation level will decrease because warmer waters cannot store as much DO as colder waters. Therefore, DO concentrations typically will be lowest during the summer months when river temperatures are warmer. Figure 5 shows the relationship between DO concentrations and water temperatures in the DWSC during 2002. Freshwater DO saturation concentrations range from about 14.6 mg/l at 0°C to 7.6 mg/l at 30°C (Chapra 1997). In January, the average water temperature is 9°C (48°F) and the saturation concentration of DO is 12 mg/l. In August, the average temperature of the river increases to 25°C (77°F) and causes the saturation DO concentration to be reduced to about 8 mg/l.

Gas exchange between the air and water occurs to maintain equilibrium between the partial pressure of the gas in the atmosphere and the concentration in the water. The equilibrium is defined by Henry's Law, which can be represented as:

$$H_e = p/c$$

Where

H_e = Henry's constant (atm × m³/mole) (which changes with temperature)

p = partial pressure (atm)
 c = water concentration (mole/m³).

Partial pressure is defined as the “pressure of a gas in a liquid, which is in equilibrium with the solution. In a mixture of gases, the partial pressure of any one gas is the total pressure times the fraction of the gas in the mixture” (by volume or number of molecules) (Lenntech 2004). Air contains approximately 21% oxygen by volume (and 23% by weight.) Therefore, at sea level where the air pressure is 1 atm, the partial pressure of oxygen would be 0.21 atm, and the DO concentration (at 0°C) would be 14.6 mg/l.

Dissolved oxygen saturation increases directly with pressure. Pressure increases with the depth of water, (e.g., 33 feet of freshwater corresponds to an additional pressure of 1 atmosphere). The DO saturation is therefore 16 mg/l at a depth of 33 feet in the summer, whereas the DO saturation at the surface is just 8 mg/l.

Similar to oxygen gas, the solubility and saturation concentration of nitrogen gas in water depends on temperature and pressure. Both nitrogen and oxygen gases have a low solubility. However, dissolved nitrogen concentrations are higher than dissolved oxygen concentrations because nitrogen gas has a higher atmospheric partial pressure (0.78 atm vs. 0.209 atm). For example, dissolved nitrogen concentrations at 0°C are about 23 mg/l, and dissolved oxygen concentrations are 14.6 mg/l. Figure 6 shows the solubility (and therefore dissolved concentrations) of nitrogen and oxygen gases as a function of water temperature.

Reaeration in the DWSC

The daily rate of change in the DO concentration, relative to DO saturation, that is caused by reaeration can be approximated as the oxygen transfer velocity divided by the average depth. The oxygen transfer velocity is related to the surface turbulence conditions, which primarily depend on water velocity, wind speed, and vertical mixing rates. The transfer velocity for the DWSC is assumed to be approximately 0.5 meter per day (m/day) (i.e., assumed from typical reaeration rate equation with wind). Because the transfer velocity is relatively slow, the daily reaeration rate can be approximated as the transfer velocity divided by the water depth. For an average DWSC depth of 7.5 meters, the reaeration coefficient for the DWSC would be only 0.06 per day. This means that the DO difference from saturation in the DWSC would be reduced by only about 6% per day.

The DO quantity added to the water column through reaeration can be estimated by using the DO transfer distance and the difference between the DO saturation concentration and the actual DO concentration. Assuming the saturated DO concentration is 8 mg/l and the actual DO concentration is 5 mg/l, the DO concentration difference would be 3 mg/l. For an assumed DWSC reaeration transfer distance of 0.5 m/day and a DO concentration difference of 3 mg/l, reaeration will supply about 13 pounds of oxygen per acre per day. There are about 250 acres between R3 (Channel Point) and the Rough & Ready Island

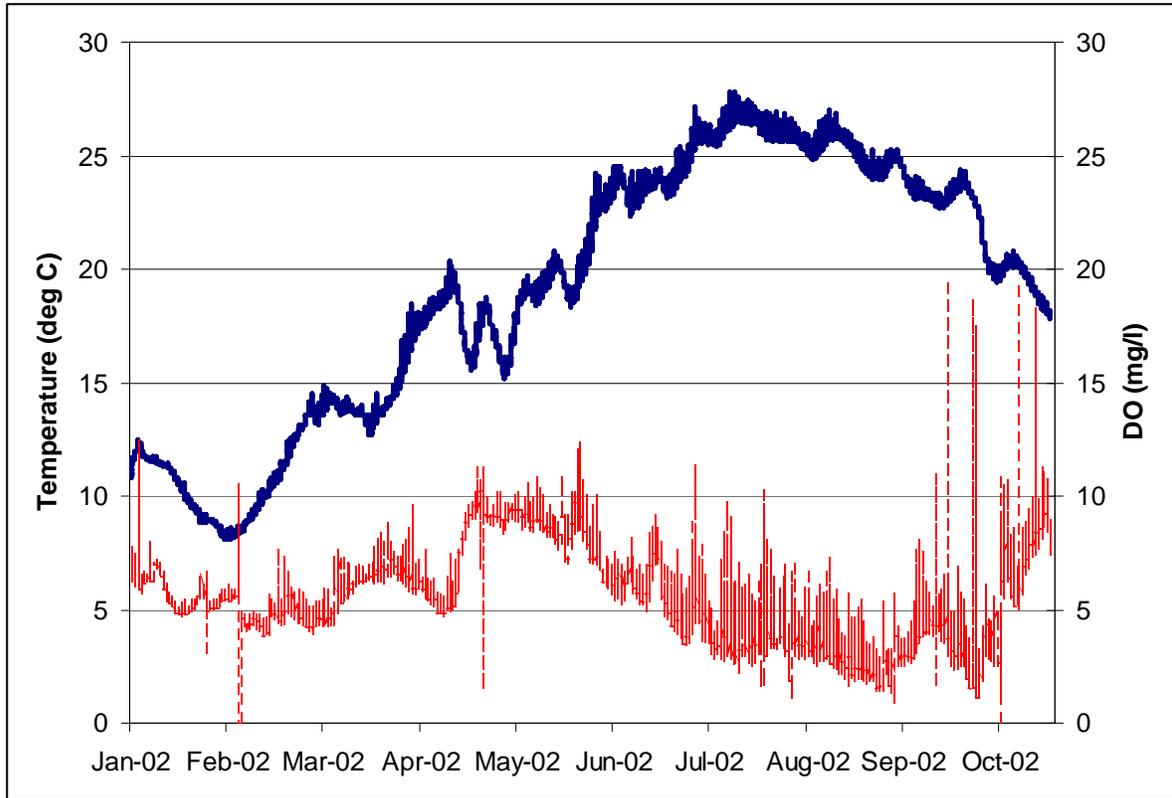
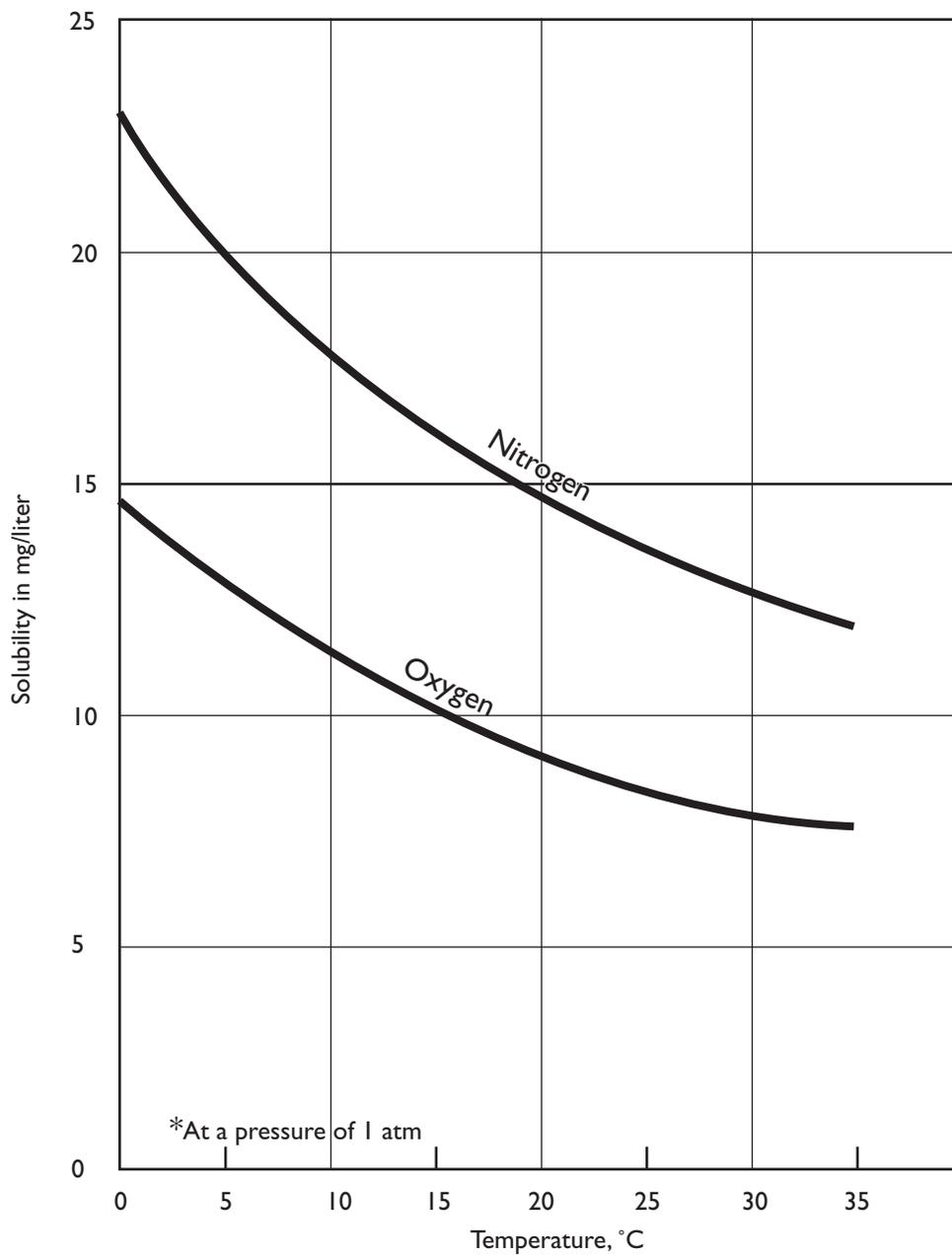


Figure 5. Temperature and Dissolved Oxygen Measurements in the DWSC at the Rough & Ready Island Monitoring Station in 2002.



Source: Sawyer and McCarty 1978.

03405.03.001 (08/04)

monitoring station, so the reaeration in this portion of the DWSC would be about 3,300 lbs/day. The DO concentration increase from one day of reaeration would be about 0.18 mg/l (i.e., 0.06×3 mg/l). This is a very weak reaeration effect because the water velocity is relatively slow and the water depth is relatively large. Natural reaeration would not be sufficient to increase DO concentrations to meet the DO objectives. Thus, an aeration/oxygenation device would be needed to increase the DO concentrations more rapidly and meet the DO objectives.

Aeration/Oxygenation in the DWSC

Reaeration and algae photosynthesis are the primary DO sources to the DWSC and, as described above, because the reaeration rate is very weak and the net effect of algae on DO is small, these sources are at times insufficient to maintain the DO concentrations above the DO objectives. Therefore, other solutions to the low DO levels need to be identified, evaluated, and implemented. One solution that has been discussed in detail previously (Jones & Stokes 2003) is installing and operating an aeration or oxygenation device in the DWSC to supply enough oxygen so that the DO objectives are met throughout the year. An aeration device uses air as the oxygen source, while an oxygenation device uses oxygen gas as the oxygen source. Because oxygenation devices use only oxygen gas, nitrogen super-saturation and possible effects on fish is not an issue.

A variety of aeration and/or oxygenation technologies were examined and discussed in Jones & Stokes (2003) and comparatively evaluated in Jones & Stokes (2004). Three technologies were chosen for further evaluation and are discussed in detail in Appendix A, *San Joaquin River Dissolved Oxygen Aeration Project Draft Engineering Feasibility Study* (HDR 2004). The three technologies are a U-tube oxygenation device, a Speece Cone oxygenation device, and a bubble column oxygenation or aeration device.

U-Tube

The U-tube enhances oxygen transfer efficiencies by subjecting a mixture of water and oxygen gas to increased hydrostatic pressure as the mixture travels deeper into the U-tube system. In general, oxygen gas is released into the U-tube at the top of the U-tube inner casing. As the water travels down through the tube, the oxygen gas bubbles are pushed down and dissolve into the water as the pressure increases with depth. Thus, the DO concentration of the water in the U-tube increases. The oxygenated water then travels up and is discharged by a diffuser into the water body.

One design for a U-tube is as a concentric well, which consists of two concentrically aligned tubes or casings. The smaller, open-ended tube carries water and oxygen gas down through the center of the casing. At the bottom of the tube, the water and oxygen mixture is released into the larger casing and pushed back to the top of the U-tube. The entire U-tube oxygenation system

consists of a U-tube assembly, pumping equipment, oxygen storage tanks, a fish screen, and oxygenated water discharge diffusers. Diagrams of a typical U-tube system are included in Appendix A.

The primary advantage of the U-tube design, compared to the Speece Cone oxygenation device and the bubble column oxygenation or aeration device, is that the U-tube is capable of meeting high levels of performance over a range of operational conditions. If two pumps and U-tubes were constructed, flexibility in meeting the operational objectives would further increase. Half of the designed oxygen transfer capacity could be transferred by only operating one pump and U-tube. Also, the U-tube is expected to be the most efficient of the three devices. The disadvantage of the U-tube is that fish entrainment could potentially be an issue at the pump intake. However, a fish screen would be expected to minimize this potential impact. U-tube applications are currently used in fish farming facilities and industrial processes, and field data is available for a U-tube configuration similar to the one that could be used in the DWSC.

Speece Cone

A Speece Cone assembly generally is placed at the bottom of a lake and consists of an oxygen source pumped from an onshore supply facility, a conical down-flow bubble contact chamber with a skirt, a submersible water pump, and a venting system made up of discharge piping and a gas venting tube. Oxygen gas and water are introduced simultaneously at the top of the Speece Cone. As the water and oxygen mixture travels toward the bottom of the cone, the water velocity decreases as the cone cross-sectional area increases. This decrease in water velocity increases the contact time of the water with oxygen gas. Speece Cones are designed so that there is equilibrium between the downward velocity of water and the upward buoyancy velocity of bubbles (i.e. about 1 ft/sec). This equilibrium creates a layer of oxygen gas bubbles in the cone (gas trap zone). As water is pushed from the top of the cone to the skirt, it passes through this gas trap and becomes saturated with oxygen. This saturated water is then immediately discharged through the diffuser into the surrounding water. Increased pressure within the Speece Cone enhances oxygen transfer efficiency. Pressure can be increased by mechanical means or by positioning the Speece Cone at deeper locations to take advantage of hydrostatic pressures. At the DWSC, a Speece Cone could be installed at depths of only 25 to 30 feet. A diagram of a typical Speece Cone is included in Appendix A.

The Speece Cone performance may be more sensitive to operational changes than the U-tube. Oxygen transfer efficiencies within the Speece Cone could differ when gas or liquid flow rates are altered. Two Speece Cones could be constructed to increase the operational flexibility. As with the U-tube, the Speece Cone has the disadvantage of potential fish entrainment at the water intake source. However, a fish screen would be expected to minimize this potential impact. Another disadvantage of the Speece Cone is that the annualized and capital costs are greater than the costs for a U-tube and bubble cone diffuser application. The Speece Cone has been tested and implemented in several locations, including Camanche Lake.

Bubble Column Diffusers

Bubble diffusers emit air or oxygen gas bubbles into a water body allowing them to travel freely from the discharge point to the water's surface. Generally, a bubble hose diffuser consists of porous hosing laid across the bottom of a water body. The diffuser is filled with compressed air or pressurized oxygen gas from an onshore supply facility. As the gas bubbles rise from the diffuser apparatus, it creates an upwelling of oxygen-rich water in the form of bubble plumes. Oxygen from these plumes is transferred into the surrounding water in the rising bubble plume. While the bubbles travel upward, they also carry volumes of water with them creating an upwelling of water. This additional water circulation provides additional mixing and enhances the oxygen transfer efficiency. Generally, oxygen transfer efficiency increases with water depth. This increased efficiency is a result of the longer contact time between the gas bubble and the water and increased saturation concentration at greater depths. Oxygen transfer efficiency may also increase as the gas flow rate decreases.

The primary disadvantage of the bubble diffuser is the potential for fouling along the entire length of hose due to either biological growth or the scaling of various salts and minerals present in the water. The performance of bubble diffusers has been shown to diminish over time as the system is used and decrease even faster if the system is not used. Bubble diffusers can be used with oxygen gas, but they would be expected to have lower oxygen transfer efficiency than either the Speece Cone or the U-tube. If air were used, the bubble diffuser would have another potential disadvantage of causing nitrogen super-saturation and subsequent effects on fish. However, the bubble diffuser technology has the lowest annualized and capital costs of the three technologies. Further, bubble diffusers have been field-tested with many real applications.

Specific Design Considerations for Suitable Aeration/Oxygenation Technologies

Numerous design considerations must be taken into account when designing the selected aeration/oxygenation technology. When implemented, the selected technology must not interfere with ship traffic and activities at the Port of Stockton, and the device must not adversely affect fish in the DWSC. The selected technology must be capable of transferring oxygen efficiently and diffusing at least 10,000 lbs of DO per day (15,000 lb/day if possible) or up to 1,000,000 lbs of DO per year. Diffusers that will transfer oxygen into the DWSC cannot become clogged with algae or sediment.

Diffusing Oxygen

Diffusing oxygen into the water as efficiently as possible requires that the oxygen gas bubbles entering the water are small (i.e., "fine") because bubble size affects the oxygen transfer efficiency in multiple ways. Fine bubbles have a larger

surface area per volume than coarse (larger) bubbles, which allows for more efficient oxygen transfer. Fine bubbles have a slower vertical velocity than larger bubbles because their increased surface area creates more friction between the water and the bubble surface. Fine bubbles therefore allow a greater fraction of the bubbles to be dissolved.

To maximize oxygen transfer efficiency, the oxygen bubbles should spend as much time in the water column as possible. Therefore, bubbles should be released into the water at the bottom of the water column to maximize the time spent in the water before the oxygen escapes to the atmosphere at the water's surface. Releasing at the bottom of the water column also helps to decrease the bubble size because of the water pressure exerted on the bubble.

Liquid Oxygen Basics

Liquid oxygen is stored in a thermal-insulated tank at temperatures colder than minus (–) 183°C. Though oxygen is primarily used as a gas, it is typically stored as a liquid because the storage for liquid oxygen is less bulky and less costly than the equivalent capacity of high-pressure gaseous storage. A typical storage system for liquid oxygen consists of a temperature-regulated storage tank (placed on a concrete spill pad), one or more vaporizers, a pressure control system, and all piping necessary for the fill, vaporization, and supply functions. Vaporizers convert the liquid oxygen into a gaseous state, and the pressure manifold is used to control the gas pressure that is fed to the device.

The density of liquid oxygen is approximately 9.1 lbs/gallon. The density of oxygen gas is approximately 0.0831 lbs/cubic foot. The relationship between liquid oxygen and gaseous oxygen is 1 gallon of liquid oxygen equals 115.1 cubic feet of oxygen gas at standard conditions of 1 atmospheres of pressure and 20 °C (scf) (Universal Industrial Gases 2003).

If an oxygenation device is implemented in the DWSC, liquid oxygen will be stored onsite in an approximately 9,000-gallon tank and will be transported to the site in tanker trucks that can store about 5,000 gallons (de Koning pers. comm. 2004). The following calculations estimate the minimum quantity of liquid oxygen that would be needed to diffuse 10,000 lbs of oxygen gas into the DWSC.

10,000 lbs of O₂ gas/day x 9.1 lbs/gallon = 1,100 gallons of liquid oxygen/day needed,

which is equivalent to about 84 cubic feet of oxygen gas per minute (scfm).

The quantity of liquid oxygen needed to input 10,000 lbs of DO per day would be higher if the technology were substantially less than 100% efficient. The efficiency of the bubble column device may be as low as 50%, which would require consumption of approximately 2,200 gallons of liquid oxygen per day. If 1,100 gallons of liquid oxygen were being consumed each day in a device with a high transfer efficiency, the 5,000 gallon-tanker trucks would need to visit the site about twice a week to keep the 9,000-gallon tank filled. If the bubble

column device with an efficiency of 50% is used, a tanker truck will be needed about every 2 to 3 days.

Aeration Basics

The bubble column device can be used to diffuse air or oxygen bubbles. If oxygen gas were used in the bubble column, the evaporator pressure from the liquid oxygen tank is sufficient to supply the oxygen gas to the diffuser. If air were diffused into the water through the bubble column, an air compressor or blower would be required.

Air is composed of approximately 79% nitrogen (ignoring other gases) and 21% oxygen by volume (23% by weight). Therefore, if equivalent volumes of air and pure oxygen gas were put into the water, air would input only about 21% of the oxygen that the same volume of oxygen gas could supply. Thus, if air were used, five times the gas volume would need to be supplied (with an air blower) to supply the 10,000 lbs of DO per day.

Air has a density of 0.075 lbs/cubic foot at 20°C and at a pressure of 1 atm (standard cubic feet). The quantity of air necessary to input 10,000 lbs/day is shown below.

$$10,000 \text{ lbs of O}_2/\text{day} \times 1 \text{ lb Air}/0.23 \text{ lbs of O}_2 \times 1 \text{ cubic foot of Air}/0.075 \text{ lbs Air}$$

$$= 5.8 \times 10^5 \text{ cubic feet of Air required per day,}$$

which is equivalent to approximately 410 cubic feet of air per minute (scfm).

An air blower with a flow capacity of 500 scfm at 15 psi could be used to supply the 10,000 lbs of DO per day to the bottom of the DWSC (at a pressure of 11 psi) if the gas transfer efficiency was 100%. However, gas transfer efficiency for air at 25 feet deep may be less than 50%. Therefore, two blowers of 500 scfm at 15 psi would likely be required. The supply pressure may need to be higher than 15 psi to force a sufficient volume of air through the diffuser hose.

Environmental Side-Effects of Aeration/Oxygenation

The chosen oxygenation/aeration device will be designed to minimize any impacts on the environment. The following potential negative environmental impacts could occur if an aeration or oxygenation device were implemented: fish entrainment, nitrogen super-saturation, oxygen toxicity, and sediment resuspension.

Fish entrainment could be minimized by including fish screens as part of the U-tube or Speece Cone designs.

If air were used in the bubble column device, both nitrogen and oxygen would be diffused into the water, which could cause the water to become slightly super-saturated with nitrogen gas. Nitrogen super-saturation can cause gas-bubble disease in fish, which can be fatal. As oxygen gas is diffused into the DWSC from any of the three devices, the water near the diffuser may become super-saturated with oxygen. It is expected that super-saturation may only occur near the diffuser and that, as the oxygen is dissolved and dispersed in the channel, the percentage oxygen saturation would not be high enough to harm fish. Additionally, a number of aquaculture facilities use oxygen gas in combination with a U-tube and have not observed any harmful effects on fish (de Koning, pers. comm. 2004).

The input of bubbles into the DWSC will likely cause an upwelling of water and mixing of the water column and may increase sediment resuspension, which could increase the availability of toxics (such as heavy metals) to the DWSC's biota. Increased sediments could increase turbidity and decrease light penetration, thereby negatively affecting algae growth in the DWSC.

The upwelling and mixing of the DWSC water column might also increase the exposure of algae to sunlight, and may reduce one of the major DO sinks in the DWSC, which is the net respiration and decay of dead algae. This could slightly increase the DO concentrations in the DWSC and maintain slightly higher algae concentrations for food web processes (i.e., zooplankton grazing) within the San Joaquin River. Conversely, resuspension of sediments may provide an opportunity for heavy metals in the bed sediment to become more bioavailable when mixed into a well-oxygenated water column. These are the kinds of environmental impacts that should be addressed when considering which type of aeration system should be deployed for the long-term.

Recommendations

Prior to selecting a single aeration device to construct full scale in the DWSC, there are a number of issues that must be resolved. Of the three technologies summarized above and described in Appendix A, a bubble plume aeration device and a U-tube oxygenation device appear most promising. The Speece Cone oxygenation device could be used but has the least flexibility for changing air and water flow rates to respond to particular aeration conditions, and this device requires deep deployment to realize high efficiencies. It is recommended that both the bubble plume and U-tube devices be tested in situ using oxygen gas to test the efficacy as well as potential impacts of these systems. Based on field results from in-situ experiments at the DWSC, the device evaluation can be further refined and an optimum device can be chosen for construction of a full-scale oxygenation system.

Uncertainties

Some of the uncertainties associated with aeration in the DWSC are as follows: ability of the device to be effective over such a large mass of tidally influenced water, circulation effects from bubble plumes, fish entrainment from the U-tube device, and effects on aquatic life of using pure oxygen gas. In addition, several engineering details still need to be considered when constructing a full-scale aeration device that would benefit from testing the technologies in situ. One of the major engineering concerns is the correct sizing and configuration needed to transfer oxygen most efficiently into the DWSC, for either the bubble plume or U-tube device. Other uncertainties remain regarding the durability of either solution. For instance, the hose used for the bubble plume aeration system might foul more quickly and need replacing much more often under the sporadic operating conditions that might be required in the DWSC. Information on the ability to operate any device over a range of delivery rates and the associated efficiencies would also be helpful.

When designing the demonstration-scale devices, one important question to answer is how large to make the device. The device must be large enough to test several hypotheses while not spending more than necessary on construction and operation of a device that might not be used in the future. To determine the device size, there must be a discussion of the monitoring that is required to test the efficacy of ultimately raising the oxygen levels in the DWSC to meet the RWQCB DO standards. Because each device would rely heavily on tidal mixing to raise the DO level throughout the DWSC, this is one of the parameters that should be used to select the size of any device.

Tidal Mixing Volume in the DWSC

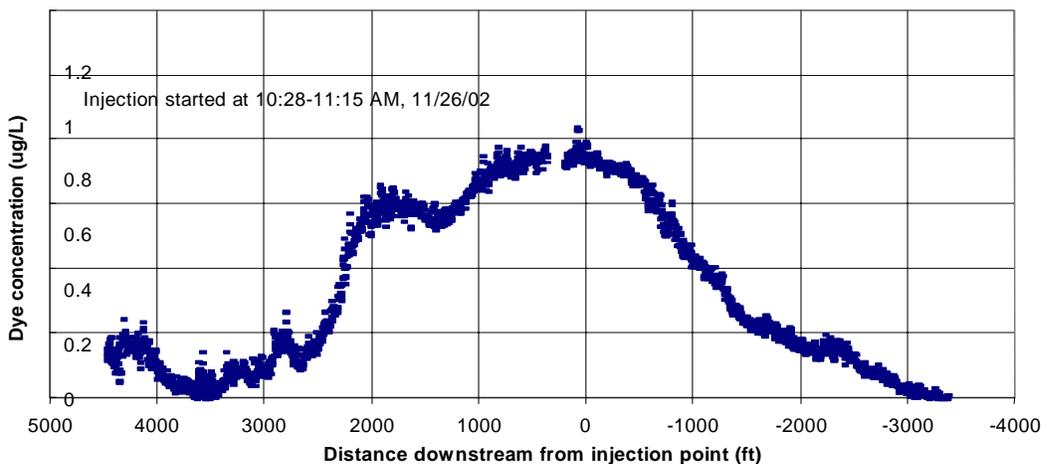
The DO increment expected from an aeration device is related to the tidal mixing volume that moves back and forth past the device each day. At the Rough & Ready Island DO monitoring station, the tidal mixing volume is about 2,500 acre-feet (af). This is based on the idea that the tide change is about 3 feet between high and low tides and the upstream surface area is about 850 acres. A total of about 2,500 af must therefore pass the Rough & Ready station to fill this upstream tidal prism volume. The DO from the aeration device will be mixed and distributed within this volume. The longitudinal distance of this 2,500 af in the DWSC is about 6,800 feet (1.3 miles), which is about the distance from channel point to the Rough & Ready station at the downstream (north) end of the dock. This distance was confirmed by the dye study conducted on November 26, 2002. After 25 hours, the dye was distributed along a 6,000-foot length of channel. The majority of the dye was within a 3,000-foot-long section.

The average DO increment for a day of operation can be calculated from the load equation as: $\text{DO increment (mg/l)} = 0.37 \times \text{Oxygen Added (lb/day)} / \text{Tidal mixing volume (af)}$

Where 0.37 is the DO concentration (mg/l) if 1 lb of oxygen is dissolved in 1 acre-foot of water.

For the full-scale device with a capacity of 10,000 lb/day, the DO increment from one day of operation would be about 1.5 mg/l. It is likely that the middle half of the tidal volume would have a higher increment of DO because the tidal flows move this middle portion of the tidal volume past the diffuser more often. Therefore, to have a detectable DO “signal” (difference) in this tidal mixing volume between channel point and the Rough & Ready monitoring station, a demonstration scale device with a capacity of about 2,500 lb/day should be installed and operated. The average DO increment will be about 0.4 mg/l, with the middle portion of the mixing volume having as much as 0.8 mg/l, which is slightly higher than the assumed 5% DO monitoring accuracy of approximately 0.25 mg/l (when the DO is about 5 mg/l). The diurnal variation in DO within the DWSC as indicated in the Rough & Ready Island monitoring data is often more than 1 mg/l, and the day to day change in the minimum DO is often more than 0.2 mg/l. If the device is operated for 3 days on and 3 days off, a DO variation of about 1.0 mg/l should be detectable with monitoring in the DWSC. Monitoring can be accomplished with longitudinal surveys as well as continuous monitoring records, as described in the monitoring plan in Appendix B.

Figure 7. Longitudinal Spreading of Dye in the DWSC after 25 Hours



Source: Jones & Stokes 2003

Demonstration-Scale Devices

It is recommended that two demonstration-scale devices—a bubble plume device and a U-tube device—be constructed to determine the most applicable technology for the conditions of the DWSC. For reasons mentioned earlier and described more fully in Appendix A, the Speece Cone should be dropped from further consideration because it is not well suited for application in the shallow DWSC. Each device should be constructed at a scale to deliver at least 2,500

lbs/day of oxygen so that operation of the device can be detected in the DWSC. Larger devices might be warranted to determine efficiencies and other operating criteria over a range of delivery scenarios.

The bubble plume aeration device could be constructed and tested in concert with tests being performed by the Port of Stockton at the existing aeration device at channel point, or as a stand-alone device further downstream along the Rough & Ready Island dock. Either way, the device should be operated under several flow and DO conditions to determine efficacy and efficiency. The device should also be deployed for at least 1 year to determine the effects of sporadic use and long-term deployment in the DWSC environment (i.e. fouling).

The U-tube should also be constructed and tested in the DWSC. It is recommended that a single U-tube be constructed capable of delivering at least 2,500 lbs/day of oxygen. This would allow expansion of the device to include multiple tubes in the future if this technology is chosen.

Each of these devices should be constructed to allow testing to begin in summer 2005. At least 1 year and preferably 2 years of testing should be performed. Testing should include monitoring upstream, downstream, and near the device to determine the efficacy of the device as well as any affects of the device on aquatic life. The devices should also be tested over variable flow conditions to determine dispersal characteristics of the DO within the DWSC. An adaptive management approach should be taken when monitoring the characteristics of DO dispersal and efficiency so that unanticipated effects can be added to the operations and monitoring program.

It should be noted that the demonstration of multiple devices would require additional care when monitoring the effects of the particular device. Because of the large area that will be influenced due to the tidal excursion, it may be impractical to have multiple aeration locations and monitoring stations that might be outside of the influence of one another. When designing a particular operational test, it will be necessary to consider whether to operate the devices in tandem or separately to allow for accurate test results. For instance, if the operational test is to ascertain the transfer efficiency of oxygen to the water column it may not matter whether the devices are run in tandem as long as the operational conditions for each device are documented. However, if the effect a particular device will have on sediment resuspension is being conducted, then it may be prudent to run each device during different time periods. Either way, it should be appropriate to use the same monitoring network for the both devices.

Upstream monitoring should include development of flow and loading correlations so that triggers can be developed for turning the aerators on or off. A suggested monitoring plan that was developed for CBDA, titled "Monitoring Plan for the Stockton Deep Water Ship Channel Oxygenation Project," is attached as Appendix B.

References

Printed References

- Central Valley Regional Water Quality Control Board. 1998. *Water quality control plan for the Sacramento and San Joaquin River basins*. Fourth Edition. Sacramento, CA. Adopted September 1, 1998. http://www.epa.gov/ost/standards/wqslibrary/ca/ca_9_central_valley.pdf
- Chapra,S.C. 1997. *Surface Water Quality Modeling*. Boston, Massachusetts: WCB McGraw-Hill.
- HDR Engineering, Inc. 2004. *CALFED Bay Delta Authority San Joaquin River dissolved oxygen aeration project draft engineering feasibility study*. July.
- Horne, A. J. and C. R. Goldman. 1994. *Limnology*. Second Edition. New York: McGraw-Hill, Inc.
- Jones & Stokes. 2002. *Downstream tidal exchange in the deep water ship channel near Turner Cut*. CALFED Project No. 01-N61-06. February.
- Jones & Stokes. 2003. *Evaluation of aeration technology for the Stockton deep water ship channel*. CALFED Project No. 01-N61-05.
- Jones & Stokes. 2004. *Aeration research and implementation analysis study for the Stockton deep water ship channel*. Prepared for California Bay-Delta Authority. January.
- Lenntech. 2004. *Lenntech water glossary*. <http://www.lenntech.com/Water-glossary.htm>. Accessed: July 16, 2004. Last posted or revised: 2004.
- Sawyer, C. N. and P. L. McCarty. 1978. *Chemistry for Environmental Engineering*. Third Edition. New York: McGraw-Hill Book Company.
- Universal Industrial Gases, Inc. (UIG). 2003. *Unit Conversion Data for Oxygen*. http://www.uigi.com/o2_conv.html. Accessed: July 28, 2004. Last posted or revised: 2003.

Personal Communication

- De Koning, J. Territory Manager for Messer MG Industries. 2004. In-person conversation held in May 2004.

