Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel

CALFED Project No. 01-N61-05

Principal Investigator: Dr. Russ T. Brown

Jones & Stokes
2600 V street
Sacramento CA 95818
Phone: (916) 739-3032
Fax: (916) 737-3030
e-mail: rbrown@jsanet.com

Report to CALFED Bay-Delta Program
Sacramento CA

January 2003

Jones & Stokes. 2003. Evaluation of Aeration Technology for the Stockton Deep Water Ship Channel. January. (J&S 01-418.) Prepared for CALFED Bay-Delta Program. Sacramento, CA.

Table of Contents

List of Tables and Figures

Tables

Figure

Executive Summary

This report describes the scientific background for quantitatively understanding aeration processes that transfer oxygen between the atmosphere (gas) and a water volume (dissolved gas). Although water (H_2O) is composed of 89% oxygen, fish and aquatic organisms require dissolved oxygen gas (O_2) for respiration and cannot use the oxygen in the water molecules. The natural reaeration that occurs at the surface of the San Joaquin River and the Stockton Deep Water Ship Channel (DWSC) is described to introduce the equations and coefficients that are used to quantify this oxygen gas transfer process.

This report describes the basic methods that have been used to increase this oxygen gas transfer process in rivers and lakes (or reservoirs). It summarizes the performance of the existing U.S. Army Corps of Engineers (USACE) jet-diffuser device and compares, in terms of general feasibility, alternative methods to increase dissolved oxygen (DO) concentrations in the DWSC with aeration technology. Each alternative method is described for possible application to the DWSC worst-case summer design condition where the DO recorded at the Rough & Ready DO monitoring station is lowest and the maximum amount of oxygen is needed to raise the DO concentration to the DO objective for the DWSC.

Figure 1 shows the location of the City of Stockton river water quality stations within the DWSC. The Department of Water Resources' (DWR's) continuous DO monitoring station is located at the downstream end of Rough & Ready Island, near the R5 sampling station. Data from these stations are used to estimate the DO deficit below applicable water quality objectives for the DWSC (5 milligram/liter [mg/l] from December through August, and 6 mg/l from September through November). This DO deficit represents the amount of DO augmentation that would be necessary to meet the DO objectives in the DWSC. Based on the daily minimum DO concentrations at the Rough & Ready monitoring station and the daily net flow measured at the U.S. Geological Survey (USGS) tidal flow station, about 1 million pounds of oxygen would have been needed in the summer of 2001. An aeration device that delivered about 10,000 lb/day would have satisfied the measured DO deficit during the summer of 2001. The required amount of DO supplied by aeration in 1999 and 2000 would have been somewhat less, although the 10,000-lb/day capacity would likely have been needed in each year.

The natural surface reaeration process in the DWSC is described and evaluated. No direct measurements of the reaeration rate for the DWSC are available. The likely magnitude of the reaeration in the DWSC is estimated from regression equations from the literature. The likely effects of temperature stratification on reaeration are discussed. The equations used to quantify water surface reaeration are useful in understanding and comparing the artificial aeration/oxygenation techniques.

Artificial Aeration: Theory and Design

There are two main categories of artificial in-stream aeration methods for DO improvement in large water bodies: (1) systems that aerate (and mix) the entire water column; and, (2) systems that selectively aerate (without mixing) thermally stratified layers. Mixing of thermally stratified water helps to homogenize DO conditions throughout the water by mixing higher DO concentration surface water with lower DO concentration bottom water. Destratification in some situations can have adverse impacts through eliminating coldwater habitat for fish and zooplankton, or distributing contaminants or nutrients from bottom areas with high concentration into the entire water column.

The basic features of instream aeration can be illustrated with an air-bubbler system like those commonly used in aquariums. An air-bubble diffuser would add DO to the river segment where it is located. The diffuser would be installed at a specified depth and create a stream of air bubbles that would provide a source of DO as the bubbles rise toward the surface. Very little specific data are available, however, for evaluating the performance efficiency of aeration systems in natural water bodies.

Lake aeration and circulation techniques using bubble columns transfer oxygen from the rising bubbles to the surrounding water. Bubble columns also produce a secondary effect by entraining a large flow of water. This upwelling water plume spreads out in both directions as the plume approaches the surface, causing “a flow-away” current at the surface. In a lake situation, this induced circulation can provide considerable vertical mixing, eventually weakening the temperature stratification and mixing the lake. This might work well in the DWSC.

Hypolimnetic (i.e., cool bottom layer of lakes) oxygenation systems use oxygen bubbles within a pipe or chamber to control the flow of oxygenated water to remain in the deep layer of the lake, below the surface-heated layer. These devices increase the DO in the hypolimnion while minimizing the mixing with the surface layer. All of the oxygenated water is returned to the bottom layer of the lake. This might provide an effective design for the DWSC.

The overall performance of all aeration methods can be compared by their oxygen transfer efficiency and energy requirements. This report has focused on identifying studies and data useful for application to the DWSC and comparing aeration systems in common terms of oxygen transfer efficiency and energy requirements.

Chapters 3 through 7 describe the five basic aeration techniques that might be successfully used in the DWSC. Previous applications of these techniques are reviewed, and the relative performance and costs for these techniques within the DWSC are estimated and described. The five basic options are briefly summarized below.

Waterfall Aeration Performance

This method uses waterfalls or cascades and is sometimes called side-stream aeration. Performance is described in terms of the height of the waterfall and the discharge per unit width of the waterfall. The aeration improves with higher waterfalls. The maximum efficiency (i.e., fraction of DO deficit that can be aerated) for a single waterfall is about 50%. A series of waterfalls (cascades) can increase the aeration efficiency. The main problem with a waterfall or cascade is that a large fraction of the water volume needing aeration must be pumped through the waterfall or cascade. The waterfall or cascade can only increase the DO concentration to the saturation concentration. The high pumping rate for a waterfall aerator has the advantage of affecting a majority of the water in the channel. Consequently, waterfalls may provide a high assurance of meeting water quality objectives throughout the DWSC.

Bubble Column Aeration Performance

This method uses pipes with holes, porous hoses, or porous diffusers to produce bubble columns near the bottom of the water volume. Performance of these devices is described in terms of the depth of the bubble column (controlling the saturated DO concentration), and the size of the bubbles (controlling the area for oxygen transfer). The existing USACE aeration device is a water-jet diffuser that creates bubbles in the special nozzle and then distributes the bubbles out into the water column. The jet is located at the edge of the water column without any diffuser lines on the bottom. One problem with the bubble column devices is that the aerated water ends up on the surface where the DO may already be highest, rather than in the bottom layer where the DO is lowest. The only way to increase the gas transfer efficiency of bubble columns in the DWSC with a diffuser located in only 25 feet of water is to reduce the bubble size. Hollow fiber membranes are an alternative to bubble columns that have a much higher oxygen transfer efficiency. The high pressure maintained across the membrane produces small bubbles with a higher DO saturation concentration that increases the oxygen transfer.

Submerged Bubble Chambers Aeration Devices

This method uses a bubble device placed near the bottom of the water volume within a “horseshoe” pipe so that the buoyancy of the bubbles will produce a flow of water and also transfer oxygen into the flowing water that is discharged back towards the bottom of the water volume. This device is similar to hypolimnetic aeration devices used in lakes that need oxygen added without mixing the lake. A basic design for this type of device was field tested in the DWSC. One advantage of this design is that the devices could be located under the Rough & Ready Island ship dock and completely protected from potential damage caused by passing ships or recreational boats. Another advantage is that the water flow can be discharged horizontally as a water jet to provide lateral mixing of the aerated water in the DWSC.

Pressurized Side-Stream Aeration Systems

These systems pump a portion of the water volume into a high-pressure mixing chamber (at 2 to 5 atmospheres of pressure) so that the saturation DO concentration is increased substantially. Air or oxygen is mixed into this side-stream flow. The high DO concentration water is then mixed back into the water column through a jet diffuser. The volume of water being pumped is reduced compared with a waterfall device, but the pressure head being pumped against is increased. The Speece Cone (e.g., the one installed at Camanche Reservoir) is a chamber placed near the bottom that uses the hydrostatic pressure to increase the DO transfer from oxygen bubbles that are forced to remain in the chamber by a pumped flow of water. The pump energy is greatly reduced compared with a pressure chamber located at the surface. In a similar deep-well device called a U-tube, oxygen gas is injected into water that is forced through a tube that extends down into the ground (i.e., like a well). A Speece Cone or deep-well U-tube device could be used to increase the DO concentration in the DWSC. A fish screen would be needed for the water intake, but the flow rate would be much less than required for the waterfall system. Because of the high transfer efficiency, a Speece Cone or U-tube device could be a very economical and effective alternatives for the DWSC.

Water Fan Aeration Performance

Water fans, often referred to as "Garton pumps," are used to pump surface water deeper into a lake or reservoir to aerate the deeper water with higher DO concentrations from the surface. The flow velocities are relatively low (i.e., 1 to 3 ft/sec), but the volume of water moved can be high (i.e., 500 cubic feet per second [cfs] from a 15-feet diameter pump). This device relies on the vertical DO gradient caused by algae or surface aeration. The aeration efficiency of the device depends on the natural DO gradient that develops between the two layers of water. Because the DWSC can form a stratified surface layer that prevents transfer of higher DO water in the surface layer, a water fan may be an effective device during periods of low DO. Water fans might also be used in combination with bubble devices to redistribute the upwelling high DO water back into the deeper portions of the DWSC. However, surface fans may not increase the DWSC DO concentrations during periods when there is not a strong vertical DO gradient.

Field Testing of Aeration Devices in the DWSC

Four different field measurement efforts were conducted as part of this project. The first involved performance evaluation of the existing USACE jet-bubble aeration device, that is located at the mouth of the San Joaquin River as it enters the DWSC. Two field tests of the USACE jet aerator were performed. One study method measured the upwelling flow and DO concentrations from each jet diffuser with a series of near-surface velocity and DO profiles at various points around each jet diffuser. The south jet had a measured flow-away current estimated to be 215 cfs. Because water is entrained from the entire water column as the bubble plume rises, the average DO increment in the upwelling flow is difficult to estimate. The DO increment was estimated to be 0.8 mg/l and the flow-away current carried about 925 lb/day of oxygen. This is about 75% of the design aeration capacity of 1,250 lb/day.

The north jet was also tested, but the air bubbles appeared to be smaller, and substantially less air was upwelling to the surface. The resulting flow-away current was measured to be only 40 cfs and although the DO increment was 1.4 mg/l, the much smaller flow-away current from the north jet only carried an estimated 225 lb/day of oxygen. This is less than 20% of the design aeration capacity of 1,250 lb/day.

Another method used to measure the performance of the bubble-jet device was to compare the velocity and DO concentrations across the channel at the Port of Stockton railroad bridge, located 600 feet upstream, with the aeration device turned on and then turned off. Velocity and DO profiles were measured during the period of constant upstream flood-tide flow. The overall change in the estimated DO mass flux was about 740 lb/day. If this average change in DO between the two sets of DO profiles was reliable, this would indicate a performance that is 30% of the design capacity of 2,500 lb/day. However, the variability in the DO profiles was much greater than expected and the uncertainty of this mass-balance method of DO differences is considered too high to be reliable.

Some design changes should be considered for the USACE aeration device. It appears that a single 20-hp air blower (260 standard cubic feet per minute [scfm]) could produce an equivalent air bubble column from traditional bubble diffusers (i.e., ceramic, soaker hose, or holes in a pipe). The water jets and the two 15-hp water pumps could be eliminated, and the same oxygen transfer could be achieved with less than 30% of the energy. Another possible design change would replace the air compressor with an oxygen gas supply, to increase the amount of oxygen dissolved by the relatively shallow bubble column. The compressor power costs would be saved but the oxygen costs to satisfy the design capacity (i.e., 2,500 lb/day with an assumed transfer efficiency of 20%) would be about $1,250/day.

The second field study measured the diurnal temperature stratification that may influence the performance of aeration devices operated in the DWSC. A string of temperature recorders were installed at the DWR Rough & Ready Island water quality monitoring station to determine the strength of the vertical temperature stratification in the DWSC during the summer period. These temperature recorders were deployed vertically on a cable, which was attached to a floating buoy to keep the recorders at fixed depths below the surface. These depths were 1.5, 3, 4.5, 6, 9, 12, 15 and 18 feet. The temperatures at these different depths identify periods of thermal stratification (during the day) within the DWSC. There was a very consistent diurnal temperature variation of about 1 ºF at the 12-foot and 18-foot depths. The surface temperatures warm much more than this average diurnal variation during the afternoon, and some stratification was observed on almost every day. The afternoon stratification was often 2 ºF and sometimes as much as 5 ºF. Stratification was weakest during cooling periods, and was strongest when average DWSC temperatures were warming.

Determining how the stratification may influence the DO is more difficult because there are no vertical DO measurements at the DWR Rough & Ready Island station. The DO variations appear to track the vertical temperature stratification, suggesting that days with the strongest stratification will also have a greater near-surface variation in DO concentration. Surface stratification may provide an ideal habitat for sustained algae growth, but it isolates the lower layers of the DWSC from the surface reaeration. More specific studies of the vertical DO gradient throughout the day in the DWSC will be required to resolve these possible effects of stratification on DO concentrations in the DWSC.

These vertical temperature measurements for 2002 are the first period when vertical temperature patterns have been documented in the DWSC. These temperature records should be used to help initially calibrate the vertical mixing coefficients in the 2-D or 3-D models that are planned for the DWSC. Determining how this vertical stratification might effect algae growth, surface reaeration, and the performance of various aeration devices should be resolved during the field testing and evaluation planned for the summer of 2003.

The third field study tested the performance of a prototype design for a mounted oxygen bubble injector (MOBI) device that could be located under the Rough & Ready Island dock in 25 feet of water. The MOBI device is a pilot-scale version of a device that may be considered for installation along the Port of Stockton Rough & Ready Island dock. The device was tested for a range of oxygen gas flow rates. Performance was observed with direct measurement of upwelling water flow, DO increment and oxygen transfer efficiency.

The MOBI pilot-scale oxygenation device gave very promising results with a maximum oxygen transfer efficiency of 20%. The upwelling flow can be directed into the DWSC as a jet to improve the distribution of the oxygenated water into the DWSC. Maintenance requirements of this device are likely to be relatively low. The final design for the MOBI devices will require additional field testing with a full-scale version.

The fourth field measurement effort was a dye study to evaluate the lateral spreading of aerated water from the Rough & Ready Island dock across the DWSC. This lateral spreading and mixing of the dye was used to indicate how well an aeration or oxygen injection system that might be located under the Rough & Ready Island docks would spread water with an increased DO concentration across and throughout the DWSC. This field study verified that dyed water, representing the discharge from an oxygen injection device that might be located under the docks, would be adequately spread across the DWSC due to the tidal movement of water in one day. Aeration or oxygenation technology appears to be appropriate and feasible for improving the DO concentration in the DWSC. Full-scale pilot testing of alternative devices should be conducted to determine the oxygen transfer efficiencies in the relatively shallow DWSC.

Chapter 1

Dissolved Oxygen in the Deep Water Ship Channel

Natural Surface Reaeration in the Deep Water Ship Channel

The general mass balance equation for oxygen gas transfer from the atmosphere to a mixed volume of water exposed to the atmosphere is:

$$V * dC/dt = K_L * A * (C_s - C)$$

Where V = volume of water in contact with the surface (m^3)

A = area of water surface (m^2)

C = concentration of oxygen in water volume (mg/l)

Cs = saturated concentration of oxygen in water (mg/l)

K_L = oxygen transfer velocity (m/day)

This relationship is often written as

$$dC/dt = K_2 * (C_s - C)$$

Where K_2 = reaeration coefficient (1/day). This coefficient originates from the general DO–biochemical oxygen demand (BOD) equation, where K_1 is used to signify the decay coefficient describing the decline in DO in a stream from BOD oxidation (i.e., decay). The oxygen transfer velocity and reaeration coefficient are often given in units of m/day or 1/day because reaeration is a relatively slow process. Much shorter time increments must be used to evaluate gas transfer in aeration devices.

By comparing the two equations, it can be seen that $K_2 = K_L * A/V = K_L/\text{Depth}$. The reaeration coefficient, K_2, expresses the combination of the depth of the surface mixed layer and the oxygen transfer velocity. However, these two aspects of surface reaeration should be considered separately because the mixed depth changes with stratification in the DWSC. The oxygen transfer velocity is related to the surface turbulence conditions that are primarily dependent on water velocity, wind speed and vertical mixing rates. The rate of this surface transfer's ability to change the DO concentration in the water volume is inversely proportional to the mixed depth below the surface.

To understand (and model) surface reaeration in the DWSC, the depth of the surface mixed layer that is exposed to the atmosphere must be considered as a variable that will change as stratification isolates the surface mixed layer from the bottom layers of the DWSC. The change in DO concentration in the surface mixed layer is therefore:

$$dC/dt = K_L \text{ (m/day)} * [C_s - C] / \text{Mixed Depth (m)}$$

The oxygen transfer velocity is dependent on the turbulence near the water surface, which is generally estimated from the water velocity and depth (or other hydraulic parameters), as well as the wind speed. The water depth may influence the turbulence at the surface and is included in most regression equations used for estimating the transfer velocity. The rate of change in DO will always decrease as the mixed depth increases.

Reaeration Rate Estimates

Several empirical regression equations for estimating the transfer velocity, K_L, have been used in water quality models. As an example, the O'Conner-Dobbins equation is used in the Stockton water quality model that has been applied by the Total Maximum Daily Load (TMDL) Technical Advisory Committee to evaluate DO conditions in the DWSC. This equation is:

$$K_L \text{ (m/day)} = 2.0 * \text{Water Velocity (ft/sec)}^{0.5} / \text{Depth (ft)}^{0.5}$$

When the DWSC is fully mixed vertically, the average depth is about 25 feet. The average tidal velocity is about 0.25 ft/sec. The average oxygen transfer velocity is estimated from the 15-minute tidal velocities measured at Rough & Ready Island to be about 0.15 m/day, based on this equation.

The oxygen transfer velocity is expected to be higher in the San Joaquin River near the Regional Wastewater Control Facility (RWCF) discharge. In this vicinity of the San Joaquin River channel, the average depth is about 15 feet, and the average oxygen exchange velocity, calculated from the 15-minute tidal velocity that averages about 0.8 ft/sec as measured at the USGS tidal flow station, is about 0.3 m/day (i.e., twice the oxygen exchange velocity in the DWSC).

Wind may substantially increase the oxygen transfer velocity. One formulation proposed by Yu, Tuffey and Lee (1977) suggests that the K_L value should be increased as:

$$K_L \text{ (m/day)} = K_L \text{ (water)} + 0.05 * \text{wind (m/sec)}^2$$

For a moderate wind speed of 2 m/sec (5 mph), the K_L value would be increased by 0.2 m/day. This would approximately double the oxygen transfer velocity in the DWSC. This formulation is based on experimental results from small pools floating in a lake. The coefficient of 0.05 is uncertain and may be as high as 0.10. In either case, wind effects may substantially increase the reaeration transfer velocity in the DWSC. For September 2001, the wind speed measured by DWR at the Rough & Ready Island water quality station averaged 2 m/sec. Some afternoon winds were much higher, but the average calculated increase in the oxygen transfer velocity, based on the 15-minute wind speed and the coefficient of 0.05, was 0.2 m/day.

Another effect on the DWSC reaeration from wind speed is that the surface mixed depth will be increased during periods of higher winds. This will allow a larger fraction of the DWSC to be exposed to reaeration, and a greater mass of oxygen will be transferred to the DWSC during periods of higher wind speed. Stratification will limit the mixed depth that is exposed to surface reaeration. An hourly simulation of the surface mixed layer may be appropriate to evaluate these effects because the wind is often highly variable during the day.

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 transfer distance (i.e., velocity ∗ time) can be considered as the distance into the water that the reaeration process will saturate the water with DO. If the transfer velocity is 0.5 m/day (i.e., assumed to be higher than the O'Conner-Dobbins equation because of wind), the transfer distance will be 0.5 meter. Although the reaeration rate will decrease as the DO concentration approaches saturation, 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 deficit in the DWSC would be reduced only by about 6% each day. This is a very weak reaeration effect because the water velocity is relatively slow and the water depth is relatively large. Reaeration in the upstream portions of the San Joaquin River is assumed to be much greater (but has not been measured directly) because the oxygen transfer velocity is greater and the average depth is smaller.

Reaeration Mass Transfer

For computing the mass of oxygen added by reaeration, it is convenient to use metric units because 1 mg/l is equivalent to 1 g/m^3. The reaeration transfer distance times the DO deficit will give the grams of DO transferred per square meter of surface area:

$$\text{DO Mass (g/m}^2\text{/day)} = \text{transfer distance (m/day)} \ast \text{DO deficit (mg/l)}$$

There are 4,047 square meters per acre and 453 grams per pound. The DO mass transfer per acre per day can therefore be calculated as:

DO Mass (lb/acre/day) = 8.9 ∗ transfer distance (m/day) ∗ DO deficit (mg/l)

For an assumed DWSC reaeration transfer distance of 0.5 m/day with a DO deficit of 4 mg/l, reaeration will supply about 18 pounds of oxygen per acre per day. There are about 250 acres between R3 (Channel Point) and R5 (Rough & Ready Island station), so the reaeration in this portion of the DWSC would be about 4,500 lbs/day. The DO concentration increase from one day of reaeration would be about 0.25 mg/l (i.e., 0.06 ∗ 4 mg/l). This is only a moderate reaeration term compared with the Stockton RWCF and San Joaquin River loads of BOD. Because the assumed oxygen transfer velocity of 0.5 m/day is uncertain, a relatively simple field experiment to confirm the oxygen transfer velocity (at several different wind speeds) in the DWSC would provide an improvement in the modeling of DO concentrations in the DWSC.

Dissolved Oxygen Concentration Pattern in the Deep Water Ship Channel

The DO concentration patterns in the DWSC are controlled by reaeration and algae production of DO as well as BOD and sediment oxygen demand (SOD) decay processes. The BOD loads originate from the Stockton RWCF effluent and from upstream San Joaquin River sources, as well as from algae biomass growing in the DWSC. The City of Stockton water quality model uses a typical first-order DO-BOD equation coupled to the governing hydrodynamic equations for tidal flow within the DWSC. The current model does not include effects of stratification on algae growth and reaeration (i.e., mixed depth dynamics). The DO modeling simulates the longitudinal DO pattern and identifies the location of the lowest DO concentration (greatest DO deficit). The water quality model is divided into river segments that are about 1 mile long. This corresponds roughly with the tidal movement in the DWSC, which is estimated to be about 1.25 miles for a 3-foot tide change.

Figure 2 shows the measured minimum and maximum DO concentrations at the DWR Rough & Ready monitoring station during 2001. The minimum DO concentrations were generally about 3 mg/l during the lowest DO episodes. The saturated DO concentration is shown for comparison to indicate that the minimum DO concentrations were generally 4–5 mg/l less than saturation during the summer period. The minimum DO concentrations were about 2 mg/l less than the DO objective of 5 mg/l during these worst-case episodes. The maximum DO concentrations measured during the afternoon are influenced by algae photosynthesis and are usually about 2–3 mg/l higher than the minimum DO values and may approach the saturation concentration on some days. The reaeration rate, which is controlled by the DO deficit in the surface water, is therefore less during these afternoon periods of relatively higher DO concentrations.

Evaluation of Dissolved Oxygen Deficits in the Deep Water Ship Channel

The hourly DO measurements at the Rough & Ready water quality station operated by DWR can be used to estimate the daily DO source needed to increase the DO in the DWSC to satisfy the DO objective. The minimum daily DO measured at the Rough & Ready surface (2 m depth) monitor station is assumed to be a good estimate of the mixed DO concentration in the DWSC. A target DO concentration is assumed to be 0.5 mg/l higher than the water quality objective. The required mass of DO needed to satisfy the DO objective is calculated from the daily net river flow and the difference between the DO target and the minimum DO concentration:

DO deficit (lbs/day) = 5.4 ∗ Net Flow (cfs) ∗
[Target DO (mg/l) - Minimum DO (mg/l)]

Figure 3 shows the minimum DO pattern measured in 1999 along with the ultrasonic velocity meter (UVM) net flow estimates during the year. The daily calculated DO required to satisfy the DO target concentration (DO objective + 0.5 mg/l) is also shown. The DO concentration was below the DO target concentration from about July through September of 1999 (the DO in October was not recorded). The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would likely have maintained the DO concentration in the DWSC at the DO target during 1999. The total DO deficit in 1999 was at least 650,000 pounds, although a DO deficit might have also occurred in October and not been recorded. The total cost for oxygen (at $0.10/lb) in 1999 (including 100,000 pounds in October) would have been about $75,000. The efficiency of oxygenation devices to dissolve the required oxygen will control the amount of oxygen that must be purchased. For example, if a device with a 20% bubble transfer efficiency was used, the purchase of oxygen in 1999 would have been $375,000 because only 20% of the purchased oxygen could be transferred to the DWSC water.

Figure 4 shows the minimum DO pattern measured in 2000 along with the UVM net flow estimates during the year. The DO concentration was below the DO target concentration from about mid-June through September of 2000 (the DO in October again was not recorded). The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would have maintained the DO concentration in the DWSC at the DO target during 2000. The total DO deficit in 2000 was at least 475,000 pounds, although a DO deficit also might have occurred in October. The total cost for oxygen in 2000 would have been about $55,000 (with 75,000 pounds in October). Assuming a 20% bubble transfer efficiency, the purchase of oxygen in 2000 would have been about $275,000.

Figure 5 shows the daily calculated DO source required to satisfy the DO target concentration in 2001. The DO concentration was below the DO target concentration from early June through early October of 2001. The daily DO deficit was often 10,000 lb/day with a few peaks of 15,000 lb/day. An aeration device with a daily DO delivery of 10,000 lb/day would have maintained the DO concentration in the DWSC at the DO target during 2001. The total DO deficit in 2001 was about 1,000,000 pounds. The total cost for this oxygen would have been about $100,000 in 2001. Assuming a 20% bubble transfer efficiency, the purchase of oxygen in 2001 would have been about $500,000.

The worst-case summer DO conditions have been previously characterized with the results from DWR Rough & Ready Island DO monitor as well as City of Stockton water quality monitoring results (Jones & Stokes 1997, Jones & Stokes 2001). Net San Joaquin River flows through the DWSC during the low-flow summer period of about 500 cfs can be expected to occur on a routine basis. The travel time for water between R3 and R6 with a flow of 500 cfs (1,000 acre-feet per day) is about 10 days because the DWSC volume from the turning basin to R6 is about 10,000 acre-feet. Monitoring data indicate that similar low DO concentrations can occur with a flow of up to about 2,000 cfs. Generally, the minimum DO concentration is located further downstream in the DWSC as flows increase. When flows exceed 2,000 cfs, the magnitude of the DO sag within the DWSC is reduced because of shorter residence times or lower BOD concentrations entering the DWSC. As hydraulic residence time decreases with increasing flow, the time available for BOD decay is reduced. At higher streamflow rates, a greater portion of the BOD load passes through the DWSC into other channels of the Sacramento-San Joaquin Delta. Higher flows may also reduce the San Joaquin River concentrations of BOD and dilute the RWCF effluent BOD loads.

At a flow of 1,000 cfs, a 2 mg/l DO decline below the 5 mg/l objective is equivalent to a daily DO deficit of 10,800 lb/day (i.e., $5.4 * 1{,}000 * 2 = 10{,}800$). This is the quantity of oxygen that needs to be added into the DWSC on a daily basis to result in average DO concentrations near the minimum DO concentration location that meet the Basin Plan DO objective of 5 mg/l. This is taken as the worst-case design capacity for the alternative DWSC aeration devices. Several days with a lower measured DO concentration at the Rough & Ready Island station may still be effectively increased to above the DO objective with an aeration system that can supply 10,000 lbs/day. The aeration device would likely increase the average DO concentration in the DWSC to slightly more than the target level prior to the low-DO episode. The tidal mixing within the DWSC is expected to distribute the added DO throughout a considerable portion of the DWSC.

Figure 6 indicates how a combination of stakeholder responsibilities for the DWSC DO deficit could be managed to provide the necessary source of DO using an aeration system. For 2001, a DO deficit at the Rough & Ready Island monitoring station was measured from early June through mid-October. The USACE has previously agreed to provide an increment of 0.2 mg/l during the chinook salmon migration period of September 1 through November 30, whenever the DO at any location in the DWSC is less than 5.5 mg/l. Because the required source of DO (lb/day) depends on the river flow moving through the DWSC, the daily DO requirement is just about equal to the river flow [lb/day = $5.4 * 0.2$ mg/l $*$ flow (cfs)]. The required USACE mitigation is shown as the dark blue area from September through mid-October. The daily magnitude of this 0.2 mg/l mitigation varied from about 750 lb/day to about 1,500 lb/day. If the existing jet-aerator device produces 2,500 lb/day, there is additional DO that is contributing to the remaining TMDL responsibility to bring the DO concentration to above the 6.0-mg/l objective during this period. If the same magnitude of DO effect from the channel deepening is applied to the summer period of June through August, an extended mitigation responsibility for the Port of Stockton deepening might be assigned.

If the existing jet-aerator device was operated at a capacity of 2,500 lb/day from June through October, additional DO would be added to the DWSC that would improve the DO concentration slightly and reduce the remaining TMDL responsibility. Additional aeration devices will be required to satisfy the average summer DO deficit of 10,000 lb/day. Supplemental aeration units might be needed to supply a maximum of 15,000 lb/day during the minimum DO periods if aeration at 10,000 lb/day throughout the period does not maintain the DO concentration above the objective. TMDL allocations for DO might be translated into an appropriate aeration responsibility.

Chapter 2

Artificial Aeration: Theory and Design

There are two main categories of artificial in-stream aeration methods for DO improvement in large water bodies: (1) systems that serve to aerate (and mix) the entire water column; and, (2) systems that selectively aerate (without mixing) thermally stratified layers. Simple aeration devices that aerate the entire water column generally are used to induce mixing as well as aeration. Mixing of thermally stratified water helps to homogenize DO conditions throughout the water by mixing higher DO concentration surface water with lower DO concentration bottom water.

In contrast, hypolimnetic (i.e., lower layer of a stratified lake) aeration of stratified water bodies is sometimes preferred when vertical mixing is undesirable (Beutel and Horne 1999). Destratification in some situations can have adverse impacts through eliminating coldwater habitat for fish and zooplankton, or distributing contaminants or nutrients from bottom areas with high concentration into the entire water column.

Numerous standard aeration techniques are available, including mechanical mixing (i.e., propeller, paddle, pump, or jet systems) and submerged bubble column systems using air or pure oxygen. Mechanical paddle-type surface aerators are typically limited to situations where the water is only 10 to 15 feet deep and will not be evaluated for the DWSC. Other more innovative methods have been developed, including pressurized side-stream oxygenation and hollow fiber membrane diffusion techniques. Describing the physical and molecular processes that govern the performance of various aeration methods was beyond the scope of this report. The overall performance of all aeration methods can be compared by their oxygen transfer efficiency and energy requirements. The governing equations for calculating oxygen transfer efficiency have been roughly developed for most aeration methods. This report has focused on identifying studies and data useful for application to the DWSC and comparing aeration systems in common terms of oxygen transfer efficiency and energy requirements.

The basic features of instream aeration can be illustrated with an air-bubbler system. An air-bubble diffuser would add DO to the river segment where it is located. The diffuser would be installed at a specified depth and create a stream of air bubbles that would provide a source of DO as the bubbles rise toward the surface. The effective pressure governing DO transfer between the air bubbles and the water can be estimated as about half the water depth. A deeper bubble diffuser may have a greater oxygen transfer efficiency, but will require slightly more power to provide the same air-flow rate. The DO transfer rate is calculated just like surface aeration, but the DO saturation concentration depends on the partial pressure of oxygen at the bubble depth:

$$\text{DO Transfer (g/sec)} = 10^{-6} * \text{Transfer velocity (mm/sec)} * \text{Area (m}^2\text{)} * [\text{DO saturation (mg/l)} - \text{DO water (mg/l)}]$$

The DO transfer rate from a bubble plume to the water is difficult to estimate from physical properties alone. It is difficult to estimate the bubble area, transfer velocity, and DO saturation values for most field applications. The oxygen transfer efficiency is usually determined empirically by measuring the DO transfer into a tank of water that has been de-oxygenated, so that the DO concentration in the tank is initially 0.0 mg/l. This is the general procedure used for testing aeration equipment in activated sludge tanks and other wastewater treatment processes requiring aeration. Most of these so-called clean water tests are performed in chambers with 10 to 15 feet of water. Therefore, the efficiency ratings may be slightly greater when applied to open-water situations such as the DWSC where diffusers could be placed in slightly deeper water. It is generally difficult to separate and identify the DO changes produced by the aeration system in a natural water body because other oxygen-producing (i.e., algae) and oxygen-consuming (i.e., BOD) processes are also occurring.

The DO source from an air-bubble diffuser can be generally estimated as a function of the air flow rate, an assumed DO transfer rate, and the difference between the DO saturation and the DO concentration in the river segment (DO deficit). Differences in oxygen transfer rates of aeration systems depend on several factors. Depth of diffusers (i.e., partial pressure), air or oxygen flow rate, diffuser density, bubble contact time with the water, bubble size, and turbulence around the bubble-liquid interface are all important factors for estimating oxygen transfer efficiency (Wagner and Popel 1998). Very little specific data are available for evaluating the performance efficiency of aeration systems in natural water bodies.

The use of pure oxygen can improve transfer efficiencies because air bubbles contain only about 21% oxygen. Therefore the saturated concentration of water exposed to oxygen gas is about 5 times greater than for water exposed to air. Nitrogen gas supersaturation at increased hydrostatic pressures, which can adversely impact metabolic processes in sensitive fish, is also avoided with the use of pure oxygen gas.

Table 1 shows typical oxygen transfer efficiency values for a variety of mechanical and air diffuser technologies on the basis of pounds oxygen dissolved in the water per unit of energy consumption (pound per kilowat hour [lb/kWh]). An intermediate measure of transfer efficiency compares the amount of oxygen transferred into the water to the amount of oxygen supplied (%).

The transfer efficiency for shallow treatment systems is typically in the relatively low range of about 5–10%. With aeration, a general rule is that the transfer efficiency will increase by 0.75% for each foot of depth. A depth of 10 feet will provide an efficiency of 7.5%. A depth of 20 feet might provide an efficiency of 15%. A review of hypolimnetic oxygenation systems (Beutel and Horne 1999) indicated that some hypolimnetic oxygenation devices may have an oxygen transfer efficiency of more than 80%. Many of these hypolimnetic devices are operated at depths of more than 100 feet, so the partial pressure of oxygen is higher than possible in the DWSC. Supporting data for these reported performance values, however, are not provided.

Oxygen Transfer Rate

The maximum oxygen transfer rate for aeration systems is often tested empirically for a range of air flow rates and depths with an initial DO concentration of 0 mg/l to provide the maximum possible DO deficit (9.2 mg/l at a temperature of 20 ºC). The oxygen transfer at DO concentrations greater than 0 mg/l will be less and can be estimated as:

> DO Source (lb/day) = Power (kWh/day) ∗ Maximum DO transfer rate (lb/kWh ∗ [Saturated DO - Water DO] (mg/l) / 9.2 (mg/l)

For example, aeration equipment systems in activated sludge tanks have maximum DO transfer rates of about 5 lb/kWh for a tank depth of 20 feet. If this same transfer efficiency could be achieved with an in-stream aeration bubble diffuser in the DWSC when the DO deficit was 3 mg/l, only about 1.6 lb/kWh of oxygen transfer would be achieved. (5 ∗ 3/9.2). This can then be compared with the DO source required to increase the river DO concentration to satisfy the measured DO deficits, of about 10,000 lb/day. A total power input of about 6,250 kWh would be needed (10,000/1.6) to provide the necessary DO source. This aeration could be supplied by a total of 260 kW (6250 kWh/24 hr) of compressors that might be distributed along the DWSC as five diffuser installations of about 52 kW each. The power costs for these compressors (6,250 kWh) would be about $625 per day, assuming a power cost of $0.10/kWh. The total power requirement for 2001 (100 days with a deficit of 10,000 lb/day) would have been $52,500.

General Comparison of Aeration and Oxygenation Methods

Two relatively old U.S. Environmental Protection Agency (EPA) documents provide a thorough review of lake aeration and circulation techniques using bubble columns. Bubble columns will transfer oxygen from the rising bubbles to the surrounding water. Bubble columns also produce a secondary effect by entraining a large flow of water. This upwelling water plume spreads out in both directions as the plume approaches the surface, causing “a flow-away” current at the surface. In a lake situation, this induced circulation can provide considerable vertical mixing, eventually weakening the temperature stratification and mixing the lake.

One EPA report (Lorenzen and Fast 1977) describes methods that can be used to destratify lakes and reservoirs to eliminate problems caused by seasonal depletion of DO and increased concentrations of anoxic chemical (i.e., iron and manganese, hydrogen sulfide) in the bottom layers (i.e., hypolimnion) of lakes and reservoirs.

Another EPA report (Pastorok and Ginn 1981) provides a similar review of aeration applications in lakes with an emphasis on the water quality changes that have been observed. The overall improvement in water quality associated with the elimination of anoxic conditions has been the general goal of these aeration and oxygenation systems in lakes. The oxygen transfer efficiency was not measured in any of these field applications of aeration devices. Success was measured by the improved DO conditions without regard for the energy or oxygen costs of the devices.

A review of hypolimnetic (i.e., cool bottom layer of lakes) oxygenation systems is provided in Beutel and Horne (1999). These devices use oxygen bubbles within a pipe or chamber to control the flow of oxygenated water to remain in the deep layer of the lake, below the surface heated layer. These devices increase the DO in the hypolimnion while minimizing the mixing with the surface layer. All of the oxygenated water is returned to the bottom layer of the lake. This might provide an effective design for the DWSC.

Aeration/Oxygenation Options for the DWSC

The basic options for aeration/oxygenation techniques that might be successfully used in the DWSC are briefly described below:

1. Waterfalls or cascades – sometimes called side-stream aeration. Performance is described in terms of the height of the waterfall and the discharge per unit width of the waterfall. Waterfalls are generally designed for a flow of 1 cfs per foot of waterfall width. The aeration improves with higher waterfalls. A typical design height is 5 feet. The maximum efficiency (i.e., fraction of DO deficit that can be aerated) for a single waterfall is about 50%. A series of waterfalls (cascades) can increase the aeration efficiency. The design equation for the waterfall(s) can be formulated as the required flow from the river times the height of the falls. The main problem with a waterfall or cascade is that a large fraction of the water volume needing aeration must be pumped through the waterfall or cascade. The waterfall or cascade can only increase the DO concentration to the saturation concentration. For example if the saturated DO is 8 mg/l (80 ºF) and the water DO is 4 mg/l, one 5-foot high waterfall will increase the concentration to 6 mg/l (50% of [8 - 4] mg/l). To raise the entire river volume by 2 mg/l the entire river flow must be pumped over the waterfall. The high pumping rate for a waterfall aerator has the advantage of affecting a majority of the water in the channel. Consequently, waterfalls may provide the highest assurance of meeting water quality objectives throughout the DWSC.
2. Air or oxygen bubble columns – pipes with holes, porous hoses, or porous diffusers to produce bubble columns near the bottom of the water volume. Performance of these devices is described in terms of the depth of the bubble column (controlling the saturated DO concentration), and the size of the

bubbles (controlling the area for oxygen transfer). These are generally designed to deliver some constant gas flow (depends on the length or area of the diffusers) with an efficiency of oxygen transfer that increases with depth, and decreases with bubble size. Porous (ceramic) heads or porous hoses (i.e., garden "soaker" hoses) are often used as the diffuser device. Oxygen diffusers are identical to air diffusers, except that they use oxygen gas delivered to the diffuser. The efficiency of oxygen transfer for oxygen gas is about five times that for air, because air is only 20% oxygen so the partial pressure of oxygen in air is only 20% of the partial pressure of pure oxygen. The additional cost for the oxygen is usually compensated for by this increased oxygen transfer efficiency. The existing USACE aeration device is a water-jet diffuser that uses a combination of a strong water jet and a venturi nozzle device (i.e., low-pressure zone) to create an air-water mixture. The water jet takes the place of the hose or porous diffusers to create and distribute the bubbles. The jet can be located at the edge of the water column without any diffuser lines on the bottom. One problem with the bubble column devices is that the aerated water ends up on the surface where the DO may already be highest, rather than in the bottom layer where the DO is lowest.

3. Submerged bubble chambers – a bubble device placed near the bottom of the water volume within a "horseshoe" pipe so that the buoyancy of the bubbles will produce a flow of water and also transfer oxygen into the flowing water that is discharged back towards the bottom of the water volume. This device is similar to hypolimnetic aeration devices used in lakes that need oxygen added without mixing the lake. A basic design for this type of device was field tested in the DWSC. One advantage of this design is that the devices could be located under the Port of Stockton Rough & Ready Island dock and completely protected from potential damage caused by passing ships or recreational boats. Another advantage is that the water flow can be discharged horizontally as a water jet to provide lateral mixing of the aerated water in the DWSC.

4. Pressurized side-stream aeration systems – pump a portion of the water volume into a high-pressure mixing chamber (at 2 to 5 atmospheres of pressure) so that the saturation DO concentration is increased substantially. Air or oxygen is mixed into this side-stream flow. The high DO concentration water is then mixed back into the water column through a jet diffuser. The volume of water being pumped is reduced compared with a waterfall device, but the pressure head being pumped against is increased. Environmental effects that might occur from pumping a large fraction of the river flow are thereby reduced. The Speece Cone is a chamber placed near the bottom that uses the hydrostatic pressure to increase the DO transfer from oxygen bubbles that are forced to remain in the chamber by a pumped flow of water. The high DO concentration water is discharged through a jet diffuser. One of these devices is installed in Camanche Reservoir. The pump energy is greatly reduced compared with a pressure chamber located at the surface. The same principle has been applied in a deep-well device called a U-tube. Oxygen gas is injected into water that is forced through a tube that extends down into the ground (i.e., like a well). At depth, the greater hydrostatic pressure increases the rate of oxygen transfer and the bubble contact time is increased as the bubbles are carried down into the

well. This device has been used at a pulp paper mill along the Tombigbee River in Alabama to provide 12,000 lb/day of oxygen in a treated wastewater flow of only 50 cfs.

5. Water fans – these are used to pump surface water deeper into the lake or reservoir to aerate the deeper water with higher DO concentrations from the surface. The original design by Prof. James Garton from Oklahoma State University used an airplane propeller as the fan blade, so the device is often referred to as a Garton pump. The flow velocities are relatively low (i.e., 1 to 3 ft/sec), but the volume of water moved can be high (i.e., 500 cfs from a 15-feet diameter pump). This device relies on the vertical DO gradient caused by algae or surface aeration, and the majority of the energy is used to pump water between the surface and bottom layers. The aeration efficiency of the device depends on the natural DO gradient that develops between the two layers of water. Because the DWSC can form a stratified surface layer that prevents transfer of higher DO water in the surface layer, a water fan may be an effective device during periods of low DO. Water fans might also be used in combination with bubble devices to redistribute the upwelling high DO water back into the deeper portions of the DWSC.

Each of these five basic aeration techniques will be described in greater detail. Previous applications of these techniques will be reviewed, and the relative performance and costs for these techniques within the DWSC will be estimated and described. The two major operational costs will be electricity to run water pumps or air blowers (i.e., compressors), and the cost of liquid (i.e., industrial 98%) oxygen. The cost of electricity is assumed to be about $0.10/kWh. The cost of oxygen is estimated to be about $200 per ton of oxygen (i.e., $0.10 per pound). These estimates will be used to compare the operational costs for different aeration devices in the DWSC. Feasibility studies for potential devices to be located in the DWSC should include more accurate estimates for these major operational parameters.

Oxygen Gas Supply Options

If an oxygenation system is selected, the oxygen gas must be purchased or produced on site. Commercial liquid oxygen can be produced with various processes. The most widely used of these is cryogenic air separation. Large refrigeration units are used to cool air to oxygen's condensation temperature (-275 ºF). It can then be separated from the nitrogen and shipped in liquid form. However, because of the massive refrigeration units required, cryogenic methods require a large facility that may cost tens of millions of dollars. The potential need for oxygen at the DWSC is not large enough to justify a separate facility, and purchase from a commercial supplier and renting the liquid oxygen storage tanks is probably the most economical option.

A non-cryogenic method for oxygen gas production is membrane gas separation. This process requires dense ceramic materials known as "ion transport membranes." When heated to high temperatures, these membranes ionize oxygen molecules in the air using electrons that have migrated to the outer side of the membrane. The oxygen ions then pass through the wall of the ceramic membrane. Once inside, the oxygen ions release the electrons forming a stream of pure oxygen and the ions migrate back to the outer edge allowing the process to continue. This method is also expensive to install initially, and it consumes large quantities of electricity, just like the refrigeration process.

An unusual oxygen separation process uses zeolite molecular sieve (ZMS) canisters. Under ambient temperature nitrogen and oxygen have different absorptive abilities on ZMS. This system adsorbs nitrogen at high pressure (100 pounds per square inch [psi]) and releases nitrogen at low pressure (15 psi). Compressed air is fed into two Zeolite canisters, alternatively. The high pressure from the compressed air causes absorption of the nitrogen within the canister, and high oxygen content gas is discharged from the pressurized canister. Meanwhile, the other canister pressure is reduced by opening a valve and releasing high nitrogen content gas to the atmosphere. The two canisters switch automatically every 20 seconds to allow a constant flow of oxygen from the pressurized canister. Because there are very few moving parts the system needs few repairs and has a long life. While this is a very novel process, the cost of producing the 10,000 lb/day needed for the DWSC is likely to be greater than the cost of the commercial oxygen supply.

Chapter 3

Waterfall Aeration Performance

Increased aeration at waterfalls is caused by the increased surface area and increased turbulence (i.e., transfer velocity) as the water flows over the waterfall. A series of field and laboratory studies have provided a reasonable estimate of the aeration efficiency as a function of the waterfall height and unit flow rate. The shape of the waterfall and the plunge pool depth may also influence the aeration efficiency. The aeration efficiency is defined as the fraction of the DO deficit that is reduced by the waterfall:

> Efficiency (%) = 100 ∗ (DO saturation - DO downstream) / (DO saturation - DO upstream)

The DO downstream will be closer to the DO saturation value than the DO upstream. The effects of unit discharge and waterfall height on efficiency was investigated by Avery and Novack (1978) and by Nakasone (1987) who each determined that the efficiency increased with height and decreased with higher unit discharge.

The aeration increment is bounded by the saturation deficit, and the effects of height are less effective as the height increases beyond 5 feet. The efficiency increases approximately as height $^{0.5}$. A waterfall height of 3 feet or 5 feet was selected for the Chicago SEPA stations (see below). They used three or four waterfalls (cascade) with a combined height of 12–15 feet at the five stations.

The laboratory and field measurements suggest that a relatively small discharge value of 1 cfs per foot of waterfall width should be used. For a pumping rate of 1,000 cfs, a waterfall width of 1,000 feet should be designed. This can be accomplished with a labyrinth (back and forth turret design) to increase the waterfall width with a minimum of waterfall facility frontage along the river.

Review of Chicago SEPA Stations Performance

The most well known waterfall facility for aeration of a river is the Chicago Metropolitan Water Reclamation District's side-stream elevated pool aeration (SEPA) stations along the Calumet Waterway Cal-Sag channel. This 17-mile-long navigation channel connecting the Des Plaines River with Lake Michigan is 225 feet wide, about 10 feet deep, and is relatively slow moving. The low-flow condition in the channel is estimated to be about 1,200 cfs. The DO objective established by the Illinois Pollution Control Board is 3 mg/l. Each of the five SEPA stations are designed to lift about 400 cfs with 2–5 rotary or screw pumps about 12 to 15 feet and discharge over a series of 3–4 waterfalls (i.e., cascade). The number of pumps operated can be adjusted to match the ambient DO conditions to minimize electrical costs. The design assumption was that the waterfalls would increase DO to 95% of saturation. The five SEPA stations were completed in 1993 at a cost of about $40 million.

The Illinois State Water Survey (ISWS) conducted a 2-year measurement program following the construction and operation of the SEPA stations to determine the actual performance of the five stations for a range of ambient DO conditions and temperatures. They report that the cascades produced water that was more than 90% saturated with DO. A majority of the aeration activity occurred in the large screw pumps (Butts et al 1998).

The effects of the waterfall stations on the river DO were more difficult to detect (Butts et al 2000). Mixing of the waterfall water back into the channel occurred near the surface and the downstream hourly channel measurements could not easily detect an increase in DO compared with the upstream river measurements. Algae and macrophyte (i.e., aquatic plants) productivity and natural surface aeration caused the surface DO concentrations to fluctuate and made it difficult to isolate the effects of the waterfall aeration. Although the waterfall cascades will provide saturated water, more attention should be given to mixing the aerated waterfall effluent back into the river.

Potential Application to the Deep Water Ship Channel

If the assumed waterfall aeration efficiency is 75% for a cascade of two 5-foot waterfalls, the increment of DO concentration that will be achieved by the waterfall is a function of the intake (i.e., upstream) DO concentration. The DO increment will be largest for the lowest intake DO. For protecting a given DO objective (i.e., 5 mg/l), the intake should be located near where the lowest DO is expected. The lowest possible intake DO will be equal to the DO objective of 5 mg/l. For summer conditions, the water temperature will be warmer than 21 ºC (70 ºF) and the saturated DO will be less than 9 mg/l. A cascade of two waterfalls would increase the DO from 5 mg/l to 8 mg/l, increasing the DO concentration by about 3 mg/l. To provide the assumed supply of about 10,000 lb/day, the waterfall flow would be about 625 cfs.

This 625-cfs waterfall cascade would require a pumping head of at least 15 feet because there is a 4-foot tidal range in the DWSC, and the waterfall needs to be located slightly above high-tide elevation. The power requirement can be estimated from the following equation:

$$\text{Power (kWh)} = 2 / \text{Pump efficiency} * \text{flow (cfs)} * \text{head (feet)}$$

The energy requirement for a 625 cfs waterfall with a pumping head of 15 feet with a pump efficiency of 0.8 would be about 25,000 kWh per day. At an assumed price of $0.10/kWh, the electricity cost for the waterfall would be about $2,500 per day. The cost per pound of oxygen added would therefore be about $0.25 per pound. This is more than twice the current price for industrial oxygen in a tank, but the oxygen from the waterfall would be already dissolved in the water and it may be difficult to achieve a 50% oxygen transfer efficiency with other aeration devices.

The cost of operating the waterfall per pound of oxygen added will be greater if the intake DO is higher. The waterfalls would therefore be operated at capacity only during periods when the DO is approaching the DO objective. At other times a smaller flow can be pumped to provide the necessary oxygen and keeping the waterfall facility visually and aesthetically functional as a water park.

The design for the waterfall facility would include an intake (with fish screen) located near the bottom of the DWSC so that the water pumped to the waterfall has the lowest possible DO concentration to improve the waterfall performance. The waterfall facility should also have a return pipe for the aerated water. If the discharge from the waterfall is allowed to return to the surface of the ship channel, the higher DO water will simply replace the water near the surface that already has a relatively high DO concentration. A drain pipe should return the aerated water to near the bottom of the DWSC. This can be easily accomplished with gravity assuming a small head difference (1–2 feet) at high tide. Locating the waterfall pond at elevation 5 feet mean sea level (msl), there will always be sufficient head to return the aerated water to the bottom of the channel through a large discharge pipe.

Chapter 4

Bubble Column Aeration Performance

Figure 7 shows the principal features of an upwelling bubble column plume in calm water from the two primary types of diffusers, line diffusers and point source diffusers. Several numerical formulations have been developed for describing the upwelling water flow rate that results from bubble diffusers. The performance of a typical bubble diffuser that is operated at a sufficient airflow rate to induce mixing of the water column depends on site-specific conditions such as the water depth and strength of thermal stratification. (Schadlow 1993) The oxygen transfer efficiency from the bubbles to the water and the upwelling water flow rate must be estimated to calculate the amount of aeration that a bubble column will deliver to the DWSC.

Bubble diffusers produce bubble columns near the bottom of the water column that rise to the surface with a nearly constant speed of about 0.75 ft/sec. This rising bubble plume creates an upwelling flow of water that generally rises to the surface and then may return to the matched density (i.e., temperature) layer in a stratified lake. Some of the oxygen from the bubbles will dissolve into the water that is upwelling with the bubbles, but most bubble mixing systems provide additional aeration from circulation of surface water into the deeper layers of the lake or reservoir. The mixing performance of these bubble column devices can be described in terms of the air (or oxygen) flow rate, the depth of the bubble column (controlling the DO partial pressure), and the size of the bubbles (controlling the area for oxygen transfer). Porous (i.e., ceramic) diffuser heads, pipes with holes, or porous hoses (i.e., garden soaker hoses) are often used as the diffuser device.

Oxygen diffusers are identical to air diffusers, except that they use oxygen gas rather than air. The efficiency of oxygen transfer from oxygen gas is about five times that for air, because air is only about 21% oxygen so the partial pressure of oxygen gas is five times the partial pressure of oxygen in air. The additional cost for the oxygen gas, relative to the energy cost for compressed air, is usually compensated for by this increased oxygen transfer efficiency. An oxygen bubble system should be designed for a sufficiently low rate and at a great enough depth so that the rising bubbles produce minimal upwelling of the water and so that most of the oxygen is dissolved (Mobley and Brock 1995). However, this is not possible in the DWSC where the maximum depth is 35 feet and the operating depth along the sides of the channel (i.e., under the Rough & Ready dock) where aeration equipment can be safely placed is only 25 feet.

Two equations for estimating the upwelling water flow from a line source air diffuser were field verified in a reservoir and found to provide relatively good estimates of upwelling flow characteristics (Brown et al. 1989). The 12-m long line diffusers were located in about 20 m of water. The upwelling current was measured in the surface flow-away zone. The first equation indicates that the upwelling flow is proportional to the depth and increases with the square root of the air flow rate. For the 20 m depth and 0.012 m^3/sec (0.4 cfs) airflow rate, the estimated upwelling flow was about 6.2 m^3/sec (220 cfs). This represents a water to air flow ratio of about 515. The same diffuser at 10 m depth (i.e., DWSC depth) would have produced an upwelling of 2.0 m^3/sec (70 cfs), with a water to air flow ratio of about 165. This example illustrates that a large volume of water is entrained in the bubble column because of the very large buoyancy force. The actual measurements suggested an upwelling flow of about 10 m^3/sec, at least 50% more than this first equation would suggest.

The second formulation for a line diffuser was found to give similar predictions of upwelling flow and consists of two equations for upwelling velocity and the thickness of the flow-away current produced at the water surface:

$$\text{Upwelling velocity (m/s)} = \left(g \cdot G_o / K_1 \right)^{1/3}$$

$$\text{Plume width (m)} = K_1 * D$$

Where G_o = air flow (per meter of diffuser) at the diffuser depth (m^2/s); K_1 = entrainment factor, 0.16; and g = gravitational acceleration, 9.8 m/s^2.

For the Bear Creek 12-m long diffuser, the estimated upwelling velocity would be 0.3 m/sec with a plume width of 3.2 m. The predicted upwelling flow would be about 10 m^3/sec (350 cfs) from an air flow of just 0.012 m^3/sec (0.4 cfs). This was quite close to the upwelling that was actually measured. The estimated upwelling for a depth of 10 m would have been about 6 m^3/sec. The water flow to air flow ratio would be about 500.

This high upwelling water flow to air flow ratio suggests that it will be very difficult to measure the change in DO concentration in the upwelling flow because such a large flow will dilute the mass of DO dissolved from the air or oxygen bubbles. No direct measurements of oxygen transfer from upwelling bubble column plumes have been reported in the literature.

Several studies of aeration for wastewater treatment plants (i.e., activated sludge) suggest that the oxygen transfer velocity for bubble greater than 5-mm diameter will be less than 0.25 mm/sec (Bischof et al 1994). The transfer velocity is measured in laboratory experiments to be as high as 0.5 mm/sec at a bubble diameter of about 2.5 mm, and reduces to less than 0.1 mm/sec as the bubble size decreases to 0.5 mm. The bubble transfer velocity of 0.25 mm/sec (0.9 m/hr) for a relatively large bubble diameter is very fast compared with surface reaeration rates because the bubbles create high turbulence as they rise in the water column. The transfer efficiency will increase with depth because the travel time of the rising bubbles is increased. A general estimate of the gas transfer efficiency is about 0.75% per foot of water depth. A 10-foot tank would provide about 7.5%

gas transfer and a 20-foot tank would provide about 15% gas transfer. A deeper tank requires more energy to compress the air, and the overall aeration efficiency (lb/kWh) has been found to be almost independent of water depth.

Oxygen Bubble Diffuser in Los Vaqueros Reservoir

An oxygen bubble diffuser system has been installed in the Contra Costa Water District's Los Vaqueros Reservoir. The DO diffuser will be operated as needed to maintain aerobic conditions in the hypolimnion of the reservoir. Oxygen was selected to prevent turbulent mixing of the temperature stratification. Each of the two parallel diffuser lines are constructed with a supply line and a soaker hose diffuser line that are each approximately 4,000 feet long, and are designed to deliver a maximum of about 28,000 lb/day at a water depth of about 100-120 feet. The system was designed and constructed for less than $2.5 million. The efficiency of the oxygen transfer is expected to be about 80% because of the relatively deep diffuser depth. The diffuser line was operated for several weeks during the summer of 2002. A 9,000-gallon liquid-oxygen storage tank hold about 40 tons of oxygen, sufficient for about 3 days of peak operation. At maximum capacity an oxygen gas flow of 240 scfm is fed to the two parallel diffuser sections. The oxygen bubble line at 120 feet is designed to deliver about 3.5 lb/day per foot of diffuser line. A similar oxygen bubble diffuser system was installed by the East Bay Municipal Utility District in Upper San Leandro Reservoir in 2001. The 4,800 feet of diffuser line was designed to deliver a maximum of 18,000 lb/day (3.75 lb/day per foot of diffuser) for about $2 million. Neither system has been field-tested to determine the actual oxygen transfer efficiency, however.

Potential Application to the Deep Water Ship Channel

A bubble diffuser could be located along the Rough & Ready Dock at a depth of about 25 feet. A gas transfer efficiency of 40% might be achieved (DeMoyer et al 2001). With oxygen gas, about 2.5 times the daily average DO deficit of 10,000 lb/day would be supplied to the diffuser line that might be 5,000 feet long. The bubbles would produce a large upwelling flow that would circulate water across the DWSC. The cost for the daily supply of 25,000 pounds of oxygen would be about $2,500. No compressors or water pumps would be needed if oxygen gas were used because the liquid oxygen tank evaporator pressure is sufficient to supply the oxygen gas to the diffuser. The design and construction costs would likely be less than 2.5 million, based on the recent installations at Los Vaqueros Reservoir and Upper San Leandro Reservoir.

If air were used, then an air flow of about 125,000 pounds per day (1,160 scfm) would be required if the transfer efficiency is assumed to be 40%. The energy necessary to supply this air flow is roughly estimated to be 1,675 kWh (assuming a 60-kW compressor will supply 1,000 scfm of air at 15 psi). The electricity cost would be approximately $167 per day. The only way to increase the gas transfer efficiency of bubble columns in the DWSC with a diffuser located in only 25 feet of water is to reduce the bubble size to increase the surface area of the bubbles.

Hollow Fiber Oxygen Transfer Technique

Hollow fiber membranes are an alternative to bubble columns that have a much higher oxygen transfer efficiency that may approach 90% (Weiss et al. 1994, Ahmed and Semmens 1996). Hollow fiber technology uses bundles of micro-porous fibers with outside diameters of a few millimeters that provide a large surface area for gas transfer. Air or oxygen is fed to the fibers at elevated pressures (up to 100 psi) which effectively increases the partial pressure exerted at the water interface and thereby increases the gas transfer rate. This technique creates a large partial pressure of oxygen from the gas side (rather than from hydrostatic pressure of the water). A series of hollow fiber bundles located under the Rough & Ready Island dock may be more efficient than a bubble column device. The number of hollow fiber bundles that would be required to supply the necessary oxygen will depend on the oxygen transfer capacity of the hollow fiber devices. Results from laboratory experiments suggest that the fibers will operate at about 4 atmospheres and that 50,000 square feet of fibers would transfer 10,000 lb/day. The fibers cost less than $2 per square foot of surface area, so the necessary fibers themselves would cost less than $100,000. The remainder of the oxygen supply lines should be less than $1 million. The daily oxygen cost would then be about $1,250 if the transfer efficiency is assumed to be 80%. The oxygen supply pressure from the liquid oxygen evaporator should be sufficient to operate the hollow fiber bundles. The tidal flows in the DWSC are probably adequate to maintain the oxygen transfer rate from the hollow fibers to the water under the dock. However, the lateral distribution of the high DO water might be limited since there is no upwelling water flow to circulate the high DO water across the DWSC. (See results from DWSC dye study.)

Chapter 5

Submerged Bubble Chamber Aeration Devices

Submerged bubble chamber devices use air or oxygen bubbles that are confined in a tube or chamber so the oxygenated water can be returned to the deeper portion of the lake or reservoir (i.e., hypolimnetic aerators). A submerged (i.e., pressurized) chamber can increase the DO concentration to the saturation concentration corresponding to the partial pressure at the depth of the chamber (i.e., Henry's law). The saturation concentration will increase with pressure (or equivalent water depth) as:

$$\text{DO saturation at depth (mg/l)} = \text{Atmospheric saturation (mg/l)} * [1 + \text{Depth (feet)}/34]$$

Atmospheric pressure (14.7 psi) is equivalent to about 34 feet of water. The DO saturation at the bottom of the DWSC (i.e., 35 feet) is therefore about twice the DO saturation at atmospheric pressure. If oxygen gas is used in the chamber, the saturated DO concentration will be about 5 times greater because the partial pressure of oxygen becomes 100% of the total pressure, rather than 21% of the pressure in air. The DO saturation for oxygen gas at atmospheric pressure is about 40 mg/l at 25 ºC. The saturated DO concentration for oxygen gas at the bottom of the DWSC would be about 80 mg/l. Saturated DO concentration at the surface will remain 8 mg/l at 25 ºC, so the high DO water exiting from the bubble chamber must be mixed with other DWSC water before it reaches the water surface or some of the higher DO concentration will be lost to the atmosphere.

The simplest possible device that might work in the DWSC is an inverted U-tube. An oxygen bubble device is placed at the opening of the tube and bottom water is drawn into the tube by the buoyancy of the bubbles. The bubbles partially dissolve in the tube as the bubbles rise, and the oxygenated water is returned to near the bottom of the DWSC in the other section of the inverted U-tube. This design is called a MOBI device. A prototype device was constructed and tested in the DWSC. The field test results indicated that a 20% oxygen transfer efficiency was achieved with a water flow to gas flow ratio of about 50. The test results are described in the field study chapter of this report.

Little (1995) has developed a simple model for oxygen transfer in hypolimnetic aerators. The first step is to estimate the water velocity in the aerator tube that depends on the length of the bubble column in the aerator:

$$\text{Water velocity (m/sec)} = 0.7 * \text{Gas velocity (m/sec)}^{0.5} * \text{Length (m)}^{0.5}$$

The gas velocity is the gas flow rate divided by the area of the aerator tube. For example, a one meter diameter tube that is 10 m long with an oxygen flow rate of 1 cfs (0.028 m^3/sec) will produce a water velocity of 0.3 m/sec with a water flow of about 0.25 m^3/sec (8.7 cfs). This suggests that a tube device will produce a much smaller water to gas flow ratio (i.e., about 10 for a 10 m length tube) than an unconfined bubble column. Results from a range of operating hypolimnetic aerators (using air bubbles) indicated water flows of 10–30 times the air flow. A 90-foot-deep aerator had a water flow of 20–30 times the air flow with a transfer efficiency of about 60%. A 35-foot-deep aerator had an upwelling flow of 10–15 times the air flow with a transfer efficiency of 15–20%.

The equation would suggest that the 20-inch diameter prototype MOBI device would have a gas velocity of 0.0125 m/sec at a gas flow of 5 scfm, and should have a water velocity of about 0.2 m/sec (0.6 ft/sec) with a water-to-gas ratio of about 15. The actual measured velocity was 1.5 ft/sec, with a water-to-gas ratio of about 35. This high water velocity limits the oxygen transfer by reducing the travel time of bubbles rising in the tube, and should be reduced if possible for maximum transfer efficiency.

The oxygen transfer efficiency is more difficult to estimate. A gas-bubble transfer model has been developed and calibrated with field measurements from hypolimnetic aerator tubes located in two of the City of Norfolk, Virginia water supply reservoirs (Burris and Little 1998). The aerator tubes are 1 m (3.3 feet) in diameter and 10 m (30 feet) long. The upwelling flow was about 10–15 times the air flow and the measured transfer efficiency was 20% at the lowest air flow of 40 scfm, but decreased to about 10% as the air flow was increased to 120 scfm. Apparently the bubble tube becomes saturated with bubbles and the air flow should not be increased beyond this bubble capacity or the transfer efficiency will drop. The device was measured to transfer about 200 lb/day with an air flow of 40 scfm and about 350 lb/day with an air flow of 120 scfm. Three times the energy (air flow) produced only about two times the oxygen transfer.

Potential Application to the Deep Water Ship Channel

Results from field testing of the MOBI device in the DWSC, as well as results from the hypolimnetic aerators in the Norfolk, Virginia, reservoirs (Burris and Little 1998) suggest that the maximum transfer efficiency in 25 feet of water will be about 20%. The likely DO capacity of a full-scale 3-foot diameter tube device would be about 200 lb/day if compressed air is used, based on the measured performance for the Norfolk devices. The optimum capacity of each tube device can be better determined with additional field measurements using a full-size device in the DWSC. If the oxygen transfer capacity is assumed to be 500 lb/day for each device, for example, then 20 devices would be located along the Rough & Ready Island dock. There is sufficient overhang of the dock to allow the devices to be placed underneath the dock, without any danger of damage from ship collisions or anchor line dragging. The dock is about a mile long, so the 20 devices could be located every 250 feet. More of the devices could be installed if necessary. More of the devices would be turned on to supply the necessary oxygen to maintain the DO concentration above the DO objective. More oxygen can be supplied by increasing the gas flow to the devices, although the transfer efficiency may decrease at the higher oxygen flow.

There is no other energy costs for water pumping or air compressors. If the tube devices can be operated with 20% transfer efficiency, then the needed amount of liquid oxygen will be five times the estimated DO deficit of 10,000 lb/day. The cost is therefore estimated to be $5,000 per day. The annual supply is estimated to be 5 million pounds, with an estimated cost of $500,000. The tube devices might be modified to increase the transfer efficiency to 40% by recycling a portion of the exhaust gas, or by introducing additional diffusers in the down-flow tube where the bubbles would have an extended residence time (i.e., counter-flow of water and bubbles). This would reduce the oxygen supply costs and might give the cost advantage to liquid oxygen compared with compressed air. Either option looks promising and would not involve any pumping of water. The upwelling water flow through the tube devices is similar to tidal river flows (i.e., 1 ft/sec) and is not expected to harm small fish that might be entrained in the upwelling flow. The upwelling flow will allow the aerated water to be discharged into the DWSC with an initial jet velocity that will enhance the lateral mixing from the tidal flows in the DWSC.

Chapter 6

Pressurized Side-Stream Aeration Performance

Pressurized side-stream aeration serves to increase the oxygen transfer efficiency by infusing oxygen or air into the water at elevated hydrostatic pressures, thereby increasing the peak saturation DO concentration and associated DO transfer in the water. A number of systems can be designed to take advantage of this principle. True side-stream pressurized aeration refers to withdrawing a portion of the source water into a pressurized chamber and injecting oxygen. The highly oxygenated water is then mixed back into the source water to increase the net source water DO concentration. A U-tube device uses hydrostatic pressure to increase the DO transfer of bubbles moving through the U-tube.

One actual application of U-tubes on the Tombigbee River involves directing water flow through a 175-foot-deep “double-well” with an inside pipe for the down-flow and the return flow coming back to the surface in the outer pipe (Speece 1996). U-tubes must provide for downward flow velocities that exceed the approximate 1 ft/sec velocity at which bubbles will rise. Bubbles are releases from the top of the U-tube and are carried by the water down to the bottom of the U-tube “well” where the hydrostatic pressure and the DO saturation concentration are much greater than at the surface.

The installation on the Tombigbee River in Alabama adds 12,000 lbs/day to pulp paper mill effluent after passing through a 175-feet-deep U-tube. This has been constructed and operated and the performance is documented (Speece 1996). This addition of DO to the river was achieved with a water flow of 45 cfs (using the paper mill effluent) through the U-tube that produced a DO concentration increment of 50 mg/l (i.e., $5.4 * 50 * 45 = 12{,}000$ lb/day). The amount of oxygen added to the U-tube flow should be balanced with the saturated DO concentration at the discharge depth. The high DO water was discharged through a jet diffuser into the Tombigbee River at a depth of about 30 feet. Rapid mixing assures that the DO increment is spread throughout the river and that very little oxygen is lost to surface de-aeration (i.e., DO greater than surface saturation).

A side-stream chamber has been used for some river applications, but requires considerably more power to maintain sufficient pressure to increase the DO transfer. The pressurized flow rate could be as low as 40 cfs. For this water flow rate, an additional 50 mg/l of DO would need to be added to deliver 10,000 lbs/day of DO to the DWSC. The working pressure to allow oxygen saturation to be about 55 mg/l under pure oxygen atmosphere is therefore 55/40 = 1.4 atmospheres or an additional 21 psi (i.e., water head equivalent to about 50 feet). Oxygen could be imparted through fine bubble diffusers or hollow fiber membranes, either of which should be able to provide high transfer efficiencies; the efficiency of the bubble transfer would primarily be a function of the bubble contact time. The head losses through the water piping and pressurization system are assumed to be about 10 feet, and the chamber would be about 15 feet above the low tide water surface, so the total pumping head would be about 75 feet. A 40 cfs flow rate would require about 7,500 kWh of energy per day (pump efficiency of 80%). This would require a pump with 315 kW (235 hp) of power. The total electrical costs for aerating the river with this system at $0.10/kWh would be about $750 per day for power and $1,250 per day for liquid oxygen, assuming an 80% transfer efficiency to supply 10,000 lb/day.

Camanche Reservoir Speece Cone

A submerged chamber called a Speece Cone (downflow bubble contact oxygenator) was installed in Camanche Reservoir in the summer of 1993 (Jung et al 1998). The 23-foot-tall cone-shaped chamber with a 12-foot diameter bottom is located at elevation 100 feet msl in about 100–135 feet of water at normal summer pool elevations. The Camanche device uses a 127-kW submerged pump to provide a water flow of 35 cfs through the cone and the jet diffuser. Oxygen gas is supplied at the top of the cone (without any diffuser) and the down-flowing water velocity in the cone is sufficient to produce a stream of bubbles, and the flow counteracts the bubble rise velocity, so that most of the bubble are dissolved within the cone. The volume of water in the cone is about 1,150 cubic feet, so the water residence time is about 33 seconds. The Camanche device was designed to supply between 70 scfm and 200 scfm of oxygen depending on the depth of the water. This represents a supply of between 8,000 lb/day and 23,000 lb/day. If the transfer efficiency were 80%, this would dissolve between 6,400 lb/day and 18,400 lb/day into the hypolimnion of Camanche Reservoir. The Camanche device cost about $1.25 million and was constructed on a small barge that was then submerged.

The Camanche device is operated as needed each summer and fall to maintain acceptable discharge DO concentrations for the downstream hatchery and the Mokelumne River. DO monitoring within the reservoir during the first two years of operation indicated that a considerable improvement in DO concentrations was achieved. However, because the BOD within the reservoir is not known accurately, the supply of DO from the Camanche Speece Cone cannot be identified. There was no specific performance testing of the device. Neither the flow of water, oxygen gas flow, nor the resulting DO in the jet diffusers are measured. Although the Camanche device definitely works well to improve DO concentrations in the hypolimnion, the transfer efficiency has not been determined.

Field measurements of a slightly smaller Speece Cone have been made at the Logan Martin Dam (Speece 1990). This cone operated with a hydrostatic pressure of about 50 feet. It had a volume of 620 cubic feet with a water flow of about 22 cfs. With an oxygen gas supply of about 50 scfm (4% oxygen/water ratio), the device dissolved more than 90% of the oxygen to produce a DO supply of 5,650 lb/day. The efficiency was reduced to 80% at a higher gas supply rate of 65 scfm (5% oxygen/water). This device was operated at about twice the hydrostatic pressure that would be available in the DWSC. A prototype cone device in the DWSC should be field tested to determine the transfer efficiency at a depth of 25 feet.

Application to the Deep Water Ship Channel

A deep well U-tube device could be used to increase the DO concentration in the DWSC. The oxygenated water can be discharged at a depth of 35 feet where the DO saturation is 80 mg/l (with oxygen gas). The 50 mg/l increment achieved in the Alabama application could also be used as the design goal for the DWSC. The oxygenated water would be discharged with a jet diffuser located under the Rough & Ready dock to achieve a dilution of about 5 that would provide a DO concentration of about 10 mg/l at the edge of the diffuser. This oxygenated water would continue to mix in the DWSC and provide the needed increment of DO. (See Lateral Dye Study results.)

The head loss through the U-tube well device is only about 5 feet, and because of the tidal variation the total pumping head would probably need to be 20 feet (to supply a U-tube facility located at an elevation of 15 feet msl to be higher than flood stage). A fish screen would be needed for the water intake, but the flow rate would be much less than required for the waterfall system.

Because less than 50 cfs would need to be pumped through the U-tube device, the power requirements would be less than 2,500 kWh/day (i.e., 2 /0.8 * 50 cfs * 20 feet = 2,500) with a power cost of about $250/day. The oxygen costs for 10,000 lb/day maximum delivery would be about $1,250/day assuming a transfer efficiency of 80%. This would be a very economical and effective alternative.

A Speece Cone device could also be designed for the DWSC to operate effectively at a depth of only 25 feet. Several of these could be placed under the Rough & Ready Island dock. Although the Camanche device has not been tested to directly determine its ability to add DO to the water, the depth in the DWSC is considerably less, and the performance of a cone would probably need a different combination of cone volume, water flow, and oxygen feed rate. Nevertheless, it would appear that the 10,000 lb/day might be achieved with less than five devices, each designed to produce 2,000 lb/day. Assuming a transfer efficiency of 80% would cost $1,250 per day for oxygen. The electricity costs for the Camanche device are about $300 per day for the 127-kW pump. The smaller pumps that will be needed for the DWSC devices will require slightly more total power because more water will be pumped to supply the DO for the DWSC (lower saturation DO concentration in shallow depth). If electricity costs of $500/day are assumed, the total cost will still be less than $2,000 per day. Construction costs for the assumed five DWSC cones would likely be less than $5 million, based on the $1.2 million cost for the larger Camanche device in 1993.

Chapter 7

Water Fan Aeration Performance

Water fans are used to pump surface water deeper into the lake or impoundment to aerate the deeper water with higher DO concentrations from the surface. The original design used an airplane propeller and is referred to as a Garton pump (Garton 1978). The flow velocities are relatively low (i.e., 1 to 3 ft/sec), but the volume of water moved can be high (i.e., 500 cfs from a 15-foot diameter pump with a 55-kW motor). The propeller is suspended at a depth of 3–5 feet and pumps surface water down into the lake. These low-speed surface water fans are different from high-speed surface aerators that rely on propellers to create surface turbulence and mixing.

No oxygen is added directly by a submerged surface water fan. This device relies on the vertical DO gradient caused by algae or surface aeration, and the majority of the energy is used to pump water between the surface and bottom layers. The aeration efficiency of the device depends on the natural DO gradient that develops between the two layers of water. Because the DWSC can form a stratified surface layer that prevents transfer of higher DO water from the surface layer, a surface water fan may be an effective device during periods of low DO to increase the average DO in the DWSC. Water fans might be used in combination with bubble devices to redistribute the upwelling high DO water back into the deeper portions of the DWSC.

The Tennessee Valley Authority (TVA) has surface water fans installed at two large hydropower dams (i.e., Douglas and Cherokee). The surface water fans have a diameter of 16 feet and each pump more than 500 cfs with a 55-kW electric motor. The velocity of water is 3.5 ft/sec and the TVA pumps move water 100 feet deep against a vertical temperature gradient of 10–20 ºF. A slightly lower velocity with more water flow (i.e., different fan blade) might be used for the DWSC because the water does not need to travel as deep as at the TVA hydropower dams.

Application to the Deep Water Ship Channel

Figure 2 indicates that the afternoon maximum DO concentrations at the Rough & Ready DO monitoring station are usually at least 2 mg/l higher than the minimum DO concentrations. It is assumed that the maximum DO represents the surface concentrations in the afternoon following algae photosynthesis in a slightly stratified surface layer. Surface fans might be used to transfer this aerated water down into the DWSC. The surface area of the Turning Basin and DWSC down to the R6 monitoring station is about 250 acres. If the surface layer with substantially increased afternoon DO concentrations is about 3 feet deep, then there is about 750 acre-feet of water in the DWSC with higher DO concentrations that could be transferred to the underlying portion of the DWSC. If four Garton pumps with the general characteristics of the TVA design were used in the DWSC during the 6 hours with the greatest DO gradient, about 1,000 acre-feet of water would be pumped from the surface layer into the deeper portion of the DWSC.

The energy requirement for these surface pumps would be 1,350 kWh per day, with a power cost of about $135 per day. There would be no additional oxygen or air compressor costs. If the average DO gradient between the surface water and the bottom water was 1 mg/l during these 6 hours of pumping, the surface pumps would transfer about 2,700 lbs of oxygen into the DWSC. If the DO difference were 2 mg/l, these same pumps would transfer 5,400 mg/l into the DWSC. This is an option for improving DO conditions in the DWSC during periods when there is sufficient DO production at the surface from algae photosynthesis (which appears to be June–September). However, it is uncertain how much of this afternoon surface DO is already mixed into the DWSC during mixing that occurs as the surface water cools at might. The surface water fans might increase the amount of photosynthesis produced in the surface layer by moving more algae biomass through the surface layer where light would allow more algae growth. The surface water fans might also increase the natural aeration from the atmosphere by slightly reducing the surface DO concentration in the DWSC during the day. These water fan performance uncertainties can only be addressed with a pilot demonstration and DO measurement effort. Comparison of vertical temperature and diurnal DO measurements in the vicinity of a surface fan and at another location could be taken to demonstrate the performance of this aeration device in the DWSC. The performance of water fans might be evaluated with a layered water quality model.

Chapter 8

Field Testing of Aeration Devices in the DWSC

Four different field measurement efforts were conducted as part of this project. The first involved performance evaluation of the existing USACE jet-bubble aeration device, that is located at the mouth of the San Joaquin River as it enters the DWSC. The second field study measured the diurnal temperature stratification that may influence the performance of aeration devices operated in the DWSC. The third field study tested the performance of a prototype design for a MOBI device that could be located under the Rough & Ready Island dock in 25 feet of water. The fourth field measurement effort was a dye study to evaluate the lateral spreading of aerated water from the Rough & Ready Island dock across the DWSC.

USACE Water-Bubble Jet Device

The USACE aeration device, located just where the San Joaquin River enters the DWSC, is a water-jet diffuser that uses a combination of a strong water jet and a venturi nozzle device (i.e., low-pressure zone) to create a water jet with air bubbles (Nichol and Slinkard 1999). The water jet is used to “shear” the air flow into small bubbles in the specially-designed nozzle and then to distribute the bubbles out into the water column. The water jet takes the place of the hose or porous diffusers to create and distribute the bubbles. The jet device is located at the edge of the water column at a depth of 25 feet. The ability to remove the jet-diffusers from the water during the winter and spring is a very nice design feature of the USACE aeration device. Its location along the side of the San Joaquin River channel without anything on the bottom of the DWSC is another very important design feature.

The USACE aeration device uses two identical 16-foot-wide platforms holding a 15-hp (11-kW) water pump and eight water jet nozzles, with 2-foot spacing. A 20-hp (15-kW) air blower provides the air flow of about 260 scfm (4.3 cfs) to create the air supply for the eight jets. Because the size of the air bubbles is sensitive to the air flow rate, a relief valve is provided to reduce the air flow rate to the jets. However, the resulting air flow rate to the jets is not measured. A considerable (but unknown) flow of compressed air is allowed to vent to the atmosphere. Although the design documents suggest that an air-water mixture would be transported across the channel, observations suggest that the bubbles rise towards the surface near the jet device, without any horizontal spreading across the channel.

Upwelling Flow Measurements

A field test of the two water-air jets was made on September 26, 2001. The study method measured the upwelling flow and DO concentrations from each jet diffuser operating separately (i.e., the other air blower turned off) with a series of near-surface velocity and DO profiles at various points around a 10- to 15-foot radius circumference of each jet. The velocity and DO profile was assumed to represent the upwelling flow for the perimeter arc that extended mid-way to the next profile location. The profiles were measured from the USACE deck that holds the two air compressors and electrical switch boxes and from the Port of Stockton dock located in front of the USACE aeration platform. The upwelling flow and DO data are given in Table 2.

Figure 8 shows the layout of the ship dock and air compressor deck where the velocity and DO profiles were measured. The south jet had the most turbulent bubble column “boil” that was surfacing just 10 feet in front of the jet. This indicates that the bubble column was immediately breaking away from the water jet and rising to the surface. The measured flow-away current was estimated to be 215 cfs. This suggests a water flow-to-air flow–ratio of about 50, assuming all the air was being supplied to the jets. Most of the flow was measured in the upper 2–3 feet, and the maximum velocity was about 2 ft/sec at a radius of 15 feet from the center of the upwelling bubbles. The DO concentration in this flow-away current was about 7.3 mg/l. The assumed background DO was 6.6 mg/l, as estimated from the deeper water in the vicinity of the jets. The jet entrains water from the entire water column as the bubble plume rises, so the average DO of the entrained water is difficult to estimate. The actual increment of DO that the bubbles are producing in the upwelling flow is therefore difficult to estimate. If the DO increment was 0.7 mg/l, and the flow away current was 198 cfs, then the flow-away current carried about 780 lb/day of oxygen (i.e., $5.4 * 198 * 0.7$). This is about 62% of the design aeration capacity of 1,250 lb/day for each set of water jets.

The north jet was also tested on September 26, 2001. Although the pressure of the air supply line for the north jet was about the same as the south jet (i.e., 7 psi), the air bubbles appeared to be smaller, and substantially less air was upwelling to the surface. The resulting flow-away current was measured to be only 40 cfs. The maximum water velocity at a radius of 15 feet was only 0.5 ft/sec and the depth of the flow-away current was less than 1 feet. The DO concentration in this smaller upwelling flow averaged about 8.1 mg/l (increment of 1.5 mg/l), suggesting that the smaller bubbles were more effective in saturating the DO concentration in the upwelling flow. But the much smaller flow-away current from the north jet only carried an estimated 340 lb/day of oxygen. This is less than 30% of the design aeration capacity 1,250 lb/day.

On-Off Mass Balance Measurements

Another method used to measure the performance of the bubble-jet device was to compare the velocity and DO concentrations across the channel at the Port of

Stockton railroad bridge, located 600 feet upstream, with the aeration device turned on and then turned off. Velocity and DO profiles were measured during the period of constant upstream flood-tide flow between the low tide (1 p.m.) and the high tide (6 p.m.) on the afternoon of October 3, 2001. The flood flow becomes fully established about 2 hours after low tide. The estimated flow from the velocity profiles was 1,750 cfs. This is a reasonable flood tide flow compared with the USGS tidal flow meter (UVM) station 1 mile upstream. A series of velocity and DO profiles were measured at 5 m-lateral spacing with 1-m depth increments on October 3, 2001. The velocity and DO measurements across the channel are given in Table 3.

Unfortunately, the DO variation across the river channel during the survey with the aeration device operating was much higher than expected. At the deepest section (left side of the center bridge column looking downstream), the vertical DO gradient was more than 1 mg/l. At the 15-m location, the DO concentration was 7.5 mg/l at the surface and 5.5 mg/l at the bottom (5 m depth). The expected DO increment from the bubble-jet aeration device would only be an average of 0.25 mg/l at this tidal flow if the device was delivering the full amount of DO (i.e., design DO supply of 2,500 lbs/day).

Both air-compressors were turned off and a float was released from mid-channel opposite the aeration device to mark the tidal flow that would not have any aeration DO increment. A second series of DO profiles were measured, starting at 6 p.m. using a 10-m spacing (because the period of flood-tide flow was running out). The velocity measurements confirmed that the flood tide flow continued for about an hour after high tide.

The measured DO variations across the channel and vertical DO differences were still greater than the expected DO decrease from turning off the aeration device. The DO change from the “on” survey to the “off” survey was positive in some surface locations, possibly caused by high surface DO patches from earlier algae photosynthesis in the DWSC. The DO decreased in several of the measurement locations, as expected. The overall change in the estimated DO mass flux was about 740 lb/day. If this average change in DO between the two sets of DO profiles was reliable, this would indicate a performance that is 30% of the design capacity (i.e., 740/2,500 = 30%). However, the variability in the DO profiles was much greater than expected and the uncertainty of this mass-balance method of DO differences is considered too high to be reliable. Measuring the on–off differences during a night-time flood–tide period might reduce the variability from algae photosynthesis.

Suggested Aerator Modifications

Some design changes should be considered for the USACE aeration device. It appears that a single 20-hp air blower (260 scfm) could produce an equivalent air bubble column from traditional bubble diffusers (i.e., ceramic, soaker hose, or holes in a pipe). The water jets and the two 15-hp water pumps could be eliminated, and the same oxygen transfer could be achieved with less than 30%

of the energy (i.e., 20 hp for one compressor compared to 70 hp for current device with two water pumps and two compressors).

Another possible design change would replace the air compressor with an oxygen gas supply, to increase the amount of oxygen dissolved by the relatively shallow bubble column. The compressor power costs would be saved but the oxygen costs to satisfy the design capacity (i.e., 2,500 lb/day with an assumed transfer efficiency of 20%) would be about $1,250/day.

The transfer efficiency of the bubble aeration device should be directly verified. One method for accomplishing this test would be to use propane as a tracer gas. Propane has a gas transfer rate that is comparable to oxygen and has been used to measure reaeration in laboratory and tidal estuary systems (Bales and Holley 1986). A small amount of propane would be added to the gas flow (air or oxygen) going to the aerator. Representative water samples from the upwelling flow or the river flow at the railroad bridge would be used to determine the fraction of the propane gas that was dissolved in the aerated water. The transfer efficiency for oxygen could be calculated from the measured propane transfer efficiency.

DWSC Temperature Stratification Measurements

A string of temperature recorders were installed at the DWR Rough & Ready Island water quality monitoring station to determine the strength of the vertical temperature stratification in the DWSC during the summer period. The 15-minute measurements were collected from May 10 to the end of August of 2002. These temperature recorders were deployed vertically on a cable, which was attached to a floating buoy to keep the recorders at fixed depths below the surface. These depths were 1.5, 3, 4.5, 6, 9, 12, 15 and 18 feet. The temperatures at these different depths identify periods of thermal stratification (during the day) within the DWSC. This information will be important for estimating the likely near-surface DO patterns and evaluating aeration and oxygen diffuser performance results. The vertical DO gradients should be confirmed with periodic afternoon vertical DO profiles.

Figure 9 shows the measured water temperatures in the DWSC for most of the month of July 2002. Temperatures from depths of 3, 6, 9, and 18 feet are shown. Average DWSC temperatures in July of 2002 were warmer than 78 ºF and increased to 80 ºF during the middle of the month. There was a very consistent diurnal temperature variation of about 1 ºF at the 9-foot and 18-foot depths. The surface temperatures warm much more than this average diurnal variation during the afternoon, and stratification was observed on almost every day of July. The difference between the 3-foot temperature and the 18-foot temperature is calculated to show the stratification pattern in the bottom of Figure 9. The afternoon stratification was often 2 ºF and sometimes as much as 5 ºF. Results for the other months that were measured were similar. Table 4 gives the average temperature, the divernal temperature variation, and the maximum vertical temperature difference recorded each day of measurement in 2002. Stratification is weakest during cooling periods, and is strongest when average DWSC temperatures are warming.

Determining how the stratification may influence the DO is more difficult because there are no vertical DO measurements at the DWR Rough & Ready Island station. However, the DWR station samples from a floating pump intake located at a depth of 6 feet. The effective depth of the sampling intake was verified by comparison of the DWR temperatures to the vertical temperature string (table 4). The DWR temperatures track the 6-foot temperature probe very closely. This suggests that the DWR DO concentrations are representative of the 6-foot depth in the DWSC. Days with a large diurnal variation in the DWR DO record indicates that there was a substantial source of DO near the surface from algae photosynthesis or surface reaeration.

Figure 9 shows the DWR DO measurements for July of 2002. The DO variations appear to track the vertical temperature stratification, suggesting that days with the strongest stratification will also have a greater near-surface variation in DO concentration. The measured light extinction in the DWSC is quite rapid, and the 6-foot depth is near the lower limit of the euphotic zone, where enough light (i.e., 1% of surface light) is available for algae photosynthesis to produce more DO than algae respiration consumes. Surface stratification may provide an ideal habitat for sustained algae growth, but it isolates the lower layers of the DWSC from the surface reaeration. More specific studies of the vertical DO gradient throughout the day in the DWSC will be required to resolve these possible effects of stratification on DO concentrations in the DWSC.

These vertical temperature measurements for 2002 are the first period when vertical temperature patterns have been documented in the DWSC. The DWSC did exhibit diurnal stratification of about 2 ºF on most days during the summer of 2002. These temperature records should be used to help initially calibrate the vertical mixing coefficients in the 2-D or 3-D models that are planned for the DWSC. Determining how this vertical stratification might effect algae growth, surface reaeration, and the performance of various aeration devices should be resolved during the field testing and evaluation planned for the summer 2003.

MOBI Performance Testing

Scientists at Jones & Stokes constructed a submerged-chamber oxygen bubble device and tested its performance in the DWSC. The device has been named MOBI. The MOBI device is a pilot-scale version of a device that may be considered for installation along the Port of Stockton Rough & Ready Island dock. The device was tested for a range of oxygen gas flow rates with seven trials on four days of experiments. Performance was observed at each trial with direct measurement of upwelling flow, oxygen transfer efficiency, and nitrogen gas stripping. The summary data for the experiments are given in Table 5.

The oxygenation device is an inverted U-tube constructed of 20-inch diameter PVC pipe (Figure 10). The U-tube structure was supported with a wood frame that also served as the lifting platform and anchor point for control ropes. The legs of the tube are each 20 feet long and about 6 feet apart. The 180-degree turn adds another 4 feet to the overall length. Doors were cut into the tube in order to provide access for various measurement instruments (velocity probe and DO meters).

The oxygen delivery system is located at the base of one of the tubes. Two diffuser types were compared. Eight ceramic small-bubble diffusers, each approximately three feet long and four inches wide, were mounted to the interior wall of the tube near its base. (Figure 11). The second method used 3/4-inch diameter garden soaker hose to deliver the oxygen within the tube. Ten parallel sections of 5-foot-long hose were attached to a PVC rack. The ceramic diffusers had a combined surface area of approximately 7.2 square feet and the soaker-hose diffuser had a combined surface area of approximately 9.5 square feet.

The buoyancy of the oxygen bubbles creates an upwelling flow of water in the riser tube. The rising bubbles dissolve into this flow of water. A majority of the bubbles remaining at the top of the U-tube will escape from the exhaust hole in the top of the tube. A faster upwelling will reduce the travel time for the bubbles to dissolve into the water, and reduce the transfer efficiency. The oxygen transfer efficiency was measured with the combination of the upwelling flow and the change in DO between the intake and the outlet from the U-tube. The flow of exhaust gas was measured by the time required to fill a 13-gallon (1.75 cubic feet) plastic bag.

Trials 1 & 2 were conducted on June 20, 2002, to determine if the device would work and measure the upwelling flow and DO increment using the ceramic diffuser plates. The device worked well, with a large upwelling flow and a substantial increase in DO concentration that increased with the oxygen supply rate. The major purpose of trials 3 and 4, conducted on July 11, 2002, was to replicate the initial results and observe differences between ceramic plates and soaker hose diffusers. The exhaust gas flow rate was measured because the flow-meter on the oxygen supply tank was suspected of inaccurate readings at higher oxygen supply rates, as a result of higher back pressure from the diffusers. Two trials on August 7, 2002, were conducted with the ceramic and soaker hose diffusers to make visual observations of the bubbles (size, speed, etc.) and to sample the exhaust gas to determine the nitrogen gas content that would indicate the amount of nitrogen gas stripping as the oxygen gas bubbles rise in the tube.

One more set of tests (trial 7) was conducted in conjunction with the dye study on November 26, 2002. The soaker hose diffuser was used to create the upwelling flow and provide the main supply of oxygen gas. An elbow and "reducer" pipe section was added to provide a jet flow for initial dye mixing into the DWSC. The jet nozzle had a 12-inch diameter so the measured velocities in the 20-inch tube would be increased by a factor of 2.75 in the discharge nozzle. It was anticipated that the energy required to produce this higher momentum discharge would slow down the water flow in the tube and thereby increase the bubble transfer efficiency. A secondary diffuser (four ceramic plates) was installed near the top of the down-tube to create a counter-flow bubble contact area and allow a high transfer efficiency for the gas supplied to this secondary diffuser.

A DO probe was placed near the intake portion of the tube to quantify the initial DO concentration during each test. DO probes were also mounted at the midpoint of the down tube for all trials, and a third DO probe was mounted at the base of the down tube for trials 3 through 6. A variety of DO probes were used. An electromagnetic velocity meter was installed at the midpoint of the down tube to measure the upwelling water flow. Prior to each trial, all instruments were calibrated and compared.

MOBI Test Results

The test procedure was to set an oxygen flow rate with the gas flow meter on the oxygen tank and wait until the readings of the velocity and DO concentration meter became steady. Once the readings became relatively stable, all measurements were recorded manually in a field notebook. During the first trial, the oxygen gas supply rate was increased by 0.5 scfm between each reading.

Investigations into the mechanics of the gas flow meter after the first trials revealed that the gas flow meter does not automatically compensate for the back pressure on the delivery line. The flow meter reading in scfm units may not be accurate as the back pressure from the diffusers located in 25 feet of water increases at higher gas flow rates. Therefore, the oxygen gas supply rate was calculated from the measured exhaust gas flow and the incremental mass of DO discharged from the tube. The exhaust gas flow was decreased by 12% to compensate for the measured nitrogen gas content. Table 5 indicates that the flow meter value was only about 50% of the calculated oxygen supply rate. This relationship between measured gas flow and calculated gas flow is shown in Figure 12.

During trial 2, a dye dilution method was used to verify the flow rate measured with the velocity meter. Dr. Gary Litton (University of the Pacific, Dep. of Civil Engineering) performed these dye measurements. A known flow and concentration of Rhodamine WT dye was continually injected at a steady rate into the tube approximately 3 feet above the diffusers. A ¼-inch-diameter polyethylene tube was used to pump a continuous sample of the water from near the end of the tube. The dilution of the dye was used to calculate the flow of water in the tube. Table 5 indicates that the dye estimates of flow were very close to the velocity measurements of flow.

Water flow velocity was measured in the down tube approximately halfway down its length. The 20-inch-diameter tube has a cross-section of approximately 2.2 square feet. Therefore, the flow (cfs) is about twice the measured velocity (ft/sec). Table 5 indicates that the upwelling flow increased with the oxygen gas supply rate. Figure 13 shows that the upwelling flow increased with higher oxygen gas supply. At the highest oxygen supply rate of 8 scfm, the upwelling flow was between 3 cfs and 4 cfs for both diffuser types.

The effects of the secondary diffuser gas supply on the upwelling flow were quite strong. The maximum secondary gas supply was only 0.4 scfm measured with the gas flow-meter, and less than 1 scfm estimated from the DO increment and exhaust gas measurements. However, the additional gas produced a large decrease in the upwelling velocity because the secondary diffuser bubbles were rising in the down-tube against the flow of water and slowed the water flow by as much as 50%. The secondary bubbles were apparently dissolving in the reduced water flow and the primary diffuser bubble may have increased their transfer efficiency from the increased travel time in the tube.

Figure 14 shows that the DO increment also increased as the oxygen supply rate increased. At the maximum supply rate of 8 scfm, the DO increment was between 5 mg/l and 9 mg/l. The ceramic diffuser appears to provide less upwelling flow with more of a DO increase. This is consistent with smaller bubbles. The soaker hose diffuser appears to provide slightly more upwelling flow and less of a DO increase.

The effects of the jet nozzle and secondary diffuser gas supply on the measured DO increment in the MOBI device were dramatic. The DO increment measured in trial 7 (without any secondary gas) were higher than the previous trials, apparently because the jet nozzle was slowing the upwelling velocity and giving more time for the bubbles to dissolve. The DO increment was 5 mg/l for the lowest gas supply of about 2 scfm, and increased to more than 10 mg/l at a gas supply of 8 scfm (these gas supply rate correspond to water flows of between 1 cfs and 3 cfs). The effects of the secondary gas supply was to increase the already high DO increment to more than 10 mg/l at the lowest primary gas supply of about 2 scfm, and the DO increment was more than 15 mg/l for several of the measurement conditions with the primary gas supply of 4 scfm, 6 scfm, and 8 scfm.

The DO concentration increase was combined with the measured water flow to calculate the amount of oxygen dissolved in the MOBI device. A standard cubic foot of oxygen contains about 0.08 pounds of oxygen. Table 5 gives the measured DO delivery rates. Figure 15 shows that the DO delivery increased with the oxygen supply rate for all diffusers. A maximum of between 100 lb/day and 150 lb/day was measured at the oxygen supply rate of 8 scfm. With the discharge jet nozzle and the secondary diffusers, the DO delivery increased substantially, with about 200 lb/day measured with the highest gas supply of 8 scfm.

The ratio of the DO delivery rate to the oxygen gas supply rate is the efficiency. Table 5 indicates that the efficiency was generally between 15% and 20%, with only about 10% obtained at the higher gas flow rates. It is expected to decline with increasing oxygen gas supply rate, as indicated in Figure 16. The ceramic diffuser may be more efficient because it produces smaller bubbles. An initial estimate of the likely efficiency for a full-scale device would be 20%. The necessary improvements to obtain a 20% efficiency might be achieved with more diffuser area per oxygen gas supply rate to produce smaller bubbles, and with reduced upwelling flow to allow slightly longer bubble rise time for the oxygen transfer.

The discharge nozzle and secondary diffusers increased the efficiency to over 20% for all of the measured gas supply rates between 2 scfm and 8 scfm. There appears to have been an optimum balance between the primary gas supply and the secondary gas supply. Additional field testing on a full-scale device with a wider range of possible gas flows (limited by the diffuser area) should be tested during the summer of 2003.

Figure 17 shows the measured nitrogen content of the exhaust gas from trials 5 and 6. Nitrogen stripping occurs because the partial pressure of nitrogen gas in the oxygen bubbles is initially 0 and so dissolved nitrogen from the water transfers to the gas bubble as it rises. The nitrogen content of the exhaust gas was greater than 10% at each of the oxygen supply rates and for both diffuser types. This indicates a very high transfer velocity since the bubble rise time is less than 10 seconds. The nitrogen stripping rate may be used as a method to estimate the oxygen transfer efficiency, using a bubble transfer model (McGinnis and Little 2002). The nitrogen content of rising bubbles should be included in the performance testing of pilot-scale aeration systems in the summer of 2003.

Application to the Deep Water Ship Channel

This MOBI pilot-scale oxygenation device gave very promising results. The MOBI device (as well as other types of oxygen diffusers) has no moving parts and requires no electricity for operation. Maintenance requirements of this MOBI device are likely to be relatively low because it would be mounted under the Rough & Ready Island dock and could be lifted onto the dock for periodic inspection and repair. This device will be out of the way of ship traffic. The upwelling flow can be directed into the DWSC as a jet to improve the distribution of the oxygenated water into the DWSC.

A full-size version of the MOBI device is anticipated to be the same length, but constructed with 36-inch-diameter tubes. Each will be designed with sufficient diffuser area to deliver 500 lb/day into the DWSC. To deliver the total needed supply of 10,000 lb/day, would require just 20 of the MOBI devices. The MOBI devices would be mounted permanently under the dock at the Port of Stockton West Complex (Rough & Ready Island) as shown in Figure 18. The dock is more than 5,000 feet long, so the devices can be placed at a spacing of 250 feet (Figure 19). Each device would be connected to an oxygen storage tank installed on top of the dock. Assuming that the oxygen transfer efficiency would be 20%, each device would be supplied with 22 scfm of oxygen gas. A total of 50,000 lb/day of oxygen would be supplied to deliver 10,000 lb/day of DO into the DWSC.

The only costs to operate the MOBI oxygen supply system are the liquid oxygen storage tanks and evaporators that must be leased, and the cost of the oxygen. The 6,000-gallon storage tanks will cost approximately $750 per month for each tank. Because there are 115 standard cubic feet of oxygen per gallon of liquid oxygen and 0.08 pounds of oxygen per cubic foot, each tank will hold about 55,000 pounds of oxygen (one-day supply at 20% transfer efficiency). A tanker truck of liquid oxygen contains about 4,000 gallons. For this installation, at least four storage tanks would be used to avoid weekend delivery operations ($3,000 per month). The oxygen cost would be about $5,000 per day with the assured 20% transfer efficiency.

Consideration should be given to improving the performance of the tubes by recycling some of the exhaust gas in addition to the possible use of a discharge nozzle and secondary diffusers in the down-flow tube to provide a counter flow to increase the residence time for the bubbles to dissolve. An overall transfer efficiency of 40% would make the MOBI devices competitive with open bubble diffusers.

The measured nitrogen stripping was substantial, producing exhaust gas with a nitrogen content of 10–15%. This exhaust gas could be compressed to the diffuser supply pressure (100 psi) and recycled at least once. The final selection of the recycle fraction may require field testing, but the overall effect on transfer efficiency should justify the expense for the gas compressors. Another design modification might be to supply the primary diffusers with air to create the upwelling flow, and use oxygen gas for the secondary diffusers. The final design for the MOBI devices will require additional field testing. The performance of each of the alternative aeration methods should be field-verified for the limited depth of the DWSC.

Dye Study of Lateral Mixing in the Deep Water Ship Channel

A dye study was performed on November 26, 2002, to evaluate how rapidly dye would spread from the MOBI 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 that might be located under the Rough & Ready Island docks 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 16,000 square feet.

The hypothesis being tested with this field study was that dyed water, representing the discharge from an oxygen injection device that might be located under the docks, would be adequately spread across the DWSC due to the tidal movement of water within the DWSC. Adequately spread is assumed to mean evenly mixed (to within 20% of the mean value) throughout the DWSC cross-section within 24 hours (i.e., one complete tidal cycle). For example, assuming a mean dye concentration of 10 μg/l, the dye measurements should all be between 8 μg/l and 12 μg/l at the end of a day.

Methods

The MOBI device was used as the dye injection device to provide initial jet mixing of the dye and create a hotdog-shaped dye cloud along the Rough & Ready Island dock within the DWSC. The MOBI device was operated for a 45-minute period near the end of the flood tide to produce a dye cloud that was about 1,500 feet long. The MOBI device was operated to produce a water flow of about 3 cfs (20-inch diameter tube velocity of 1.4 ft/sec). The background DO concentration was about 4.0 mg/l and the water temperature was 14 °C (57 °F). The MOBI device was modified to add a 90-degree bend and jet nozzle onto the down-tube (Figure 20). The jet nozzle had a diameter of 12 inches, so the jet velocity was about 4 ft/sec. The dye was injected at a rate of 50 g/min that would have resulted in an initial dye concentration of 100 µg/l in the water after the jet mixed with 100 times the 3-cfs jet discharge. The measured dye concentrations along the Rough & Ready dock ranged from 10 µg/l to 20 µg/l at the end of the injection period indicating an initial jet mixing of 500 to 1,000.

The lateral and longitudinal dispersion was measured with a boat-towed dye fluorometer and water quality monitoring array operated by Dr. Gary Litton from the University of the Pacific Civil Engineering Department (Litton 2002). One-second interval measurements were recorded along with depth and GPS position. Longitudinal concentrations along the dye injection side of the DWSC at a depth of 10 feet were used to characterize the longitudinal spreading of the dye cloud. Vertical and lateral contours of dye concentration at 5-foot depth intervals were used to characterize the vertical and lateral spreading across the DWSC. These lateral profiles were made near the center of the longitudinal dye cloud.

Lateral Mixing Results

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 ft/sec. The dye injection ended about 30 minutes before the low-high slack tide for the day. The following ebb tide was quite short in duration, due to the neap tide condition, lasting only about 4 hours. Therefore, tidal flows during the first 6 hours after the dye injection were quite low. The tidal records suggest the dye plume moved downstream about 1 mile on the morning of November 27, but then moved back upstream to near the injection point when measurements were performed 24 hours after the initial dye injection.

Figure 21 shows the longitudinal dye concentrations 1 hour after the end of the dye injection. These measurements were performed shortly after the low-high slack tide. The dye cloud begins at about 750 feet upstream and is relatively uniform with a dye concentration of 10–20 µg/l and with a dye cloud length of about 1,250 feet. After 6 hours, the dye cloud has moved downstream with the ebb tide, and the peak concentration of 10 µg/l is observed 500 feet downstream of the injection location. Some dye has spread further downstream and the total length of the dye cloud has increased to about 3,000 feet. After 24 hours, the peak dye concentration of less than 1 µg/l was an order of magnitude lower when compared to the 5-hour plot and approximately 6,000 feet in length. The reduction in dye concentrations from 6 to 24 hours appears to be largely due to lateral mixing because the length of the dye plume increased only about twofold, although the concentrations were about 10 times lower.

Figure 22 shows the lateral dye contours 1 hour after the dye injection stopped. From this survey, the dye plume does not appear to have spread laterally since the initial injection. The initial jet mixing during the dye injection was observed to spread the dye to about 100 feet from the dock with a maximum dye concentration of about 50 µg/l. The maximum dye concentration for this cross-section data collected about 1 hour after the dye injection ended was approximately 25 µg/l. This reduction in the initial dye concentration appears to be associated with longitudinal dispersion, since lateral dispersion appears limited. Some dye concentrations of 5 µg/l were observed about 200 feet from the dock, but the majority of the dye was still within 100 feet of the dock.

Figure 23 shows the dye concentration contours 6 hours after the dye injection ended. Lateral dispersion is not much greater than observed after 1 hour. The lack of lateral dispersion is probably due to the short ebb tide and the low slack tide occurring before these measurements. The tidal flow moved the dye cloud a total distance of only about 4,000 feet. The peak concentration has decreased to 8 µg/l. Some dye is observed at 200 feet from the dock, but the majority is still within 100 feet of the dock.

Figure 24 presents the dye concentration contours 24 hours after the dye injection ceased. These cross-section measurements were performed at the highest concentration measured by a longitudinal traverse (1,000 feet downstream from the injection point). The measured lateral mixing from tidal flow dispersion is nearly complete. Most of the measured concentrations ranged from 0.6 to 0.8 µg/l with an average of about 0.7 µg/l. Lateral mixing is not as effective on the shallow shelf on the opposite side of the DWSC.

Lateral Mixing Estimates

The traditional method for evaluating the downstream spreading of a shore discharge in a river involves estimates of the lateral dispersion coefficient. The lateral dispersion coefficient describes the rate of spreading of a dye cloud, and is estimated as a function of the river depth and the shear velocity that is characteristic of the turbulent movements within the river. The shear velocity is generally about 5–10% of the average river velocity. A series of laboratory dye experiments and a handful of actual field measurements suggest that the lateral dispersion can be estimated as:

$$\text{Lateral Dispersion (ft}^2\text{/sec)} = 0.15 * \text{Depth (ft)} * \text{Shear Velocity (ft/sec)}$$

The shear velocity in a river is usually calculated as:

$$\text{Shear velocity (ft/sec)} = (g * \text{depth (ft)} * \text{slope})^{0.5}$$

For the DWSC, with a tidal flow of about 5,000 cfs and a cross section of 16,000 square feet, the effective slope during tidal flow can be estimated from the manning equation as:

$$\text{Tidal slope} = [\ \text{velocity (ft/sec)} * \text{friction factor (n)} / (1.5 * R^{2/3})]^{2}$$

The tidal velocity is about 0.3 ft/sec and the hydraulic radius (R) is about 30 feet. The friction factor (n) is assumed to be 0.03. The tidal slope is only about $0.45 * 10^{-6}$ (0.002 ft/mile). The shear velocity is therefore about 0.02 ft/sec (7% of the average velocity).

The lateral dispersion is estimated to be about 0.1 ft^2/sec. The analytical solution to the longitudinal-lateral (two-dimensional) advection-dispersion differential equation can be used to approximate the downstream spreading. The spreading from the oscillating tidal flow is assumed to be the same as the spreading from river flow in the downstream direction. The distance required to spread across the river channel with less than a 20% variation from the mean value is about (Fischer at al 1979, figure 5.5):

$$\text{Distance} = 0.2 * \text{velocity} * \text{width}^2 / \text{dispersion}$$

For the DWSC width of 500 feet, this distance will be very large. For the 0.3 ft/sec velocity and the dispersion of 0.1 ft^2/sec, the required distance is about 150,000 feet (28 miles). This represents a travel time of almost 6 days. If the dye spreading in the DWSC follows this theoretical dispersion relationship, it will fail the hypothesis of complete lateral mixing within 25 hours (5 miles). There are several assumptions in this analysis that may not be correct and the actual mixing might be faster. The assumed relationship involving the width squared is generally there only because of dimensional arguments. The relationship might actually be width ∗ depth. This would reduce the mixing distance to 9,000 feet (2 miles). Because there is a large uncertainty in the lateral mixing rate, the dye study was a useful experiment to more accurately describe lateral mixing in the DWSC.

Lateral Mixing Model

The analytical solution to the dispersion equation may be a little hard to grasp. A simple analogy was used to model the lateral spreading with a range of possible lateral mixing rates. A spreadsheet calculation was made to approximate lateral spreading. The analogy is to spreading of cars within a 10-lane highway. The spreading of red cars that all start in the right-side lane is simulated. Viewed from above, it is observed that cars switch lanes (exchange) at a rate that is proportional to the number of cars passing a fixed location (speed). All lanes travel at the same velocity. The initial spreading rate is specified as 10% of the downstream movement of cars. As twenty red cars pass, one red car switches with a white car to its left. Each of the interior lanes switch one car with each of the two adjacent lanes (2/20 = 10% exchange rate). If we track twenty cars from each lane (200 cars) we can watch until the red cars are evenly distributed across the ten lanes of traffic.

The model was actually implemented with ten segments of the DWSC with each segment 50 feet wide by 50 feet long by 32 feet deep (80,000 cubic feet). The tidal velocity is 0.3 feet/sec and the exchange rate is assumed to be 10%. Each segment has a flow of 480 cfs and therefore has a lateral exchange flow of 48 cfs. The two side segments exchange at only 24 cfs (5%) because there is no exchange at the shore. Each of the segments is fully mixed, and calculations were made every 5 minutes for a day. The initial dye concentration is 100 in the segment along the dock and 0 in the other nine segments.

The results are summarized in Figure 25. At the end of the first hour, the dye concentration is 50 in segment 1, 32 in segment 2, 14 in segment 3, and 4 in segment 4, and 1 in segment 5. At the end of 6 hours, the dye is 22 in segment 1, 10 in segment 5, and 1 in segment 10. After 24 hours the dye concentration is 11.5 in segment 1, 10 in segments 5 and 6 and 8.5 in segment 10. This simulated 10% exchange rate is sufficient to produce complete lateral mixing within 24 hours.

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 extremely calm wind conditions. It is expected that lateral mixing will be greater from the effects of high winds that are common in the Delta. 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.

Chapter 9
References

Ahmed, T. and M. J. Semmens. 1996. Use of Transverse Flow Hollow Fibers for Bubbleless Membrane Aeration. *Water Resources* 30(2): 440–446.

Avery, S. and P. Novack. 1978. Oxygen Transfer at Hydraulic Structures Journal of Hydraulics Division ASCE 104(11)1521–1540.

Bales, J. D. and E. R. Holley. 1986. Flume Tests on Hydrocarbon Reaeration Tracer Gases. *ASCE Journal of Environmental Engineering* 112(4) 695–700

Beutel, M. W. and A. J. Horne. 1999. A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality. *Lake and Reservoir Management* 15(4): 285-297.

Bischof, F., F. Durst, M. Hofken, and M. Sommerfeld. 1994. Theoretical Considerations about the Development of Efficient Aeration Systems for Activated Sludge Treatment. In *Aeration Technology*, R. E. A. Arndt and A. Prosperetti (eds). ASME, New York.

Boon, A. G. and B. Chambers. 1986. Design Protocol for Aeration Systems – United Kingdon Experience. Pages, in *Aeration Systems – Design Testing, Operation, and Control,* pp. 102–141. *Pollution Control Technology Review* No. 127, W. C. Boyle (eds.). Noyes Publications, Park Ridge, N.J.

Boyd, C. E. 1990. Water Quality in Ponds for Agriculture. Alabama Agricultural Experiment Station. Birmingham Publishing Company. Birmingham, Ala.

Brown, R. T., J. A. Gordon, and C. E. Bohac. 1989. Measurement of Upwelling Flow from Air Diffuser. *Journal of Environmental Engineering* 115(6):1269–1275.

Burris, V. L. and J. C. Little. 1998. Bubble Dynamics and Oxygen Transfer in a Hypolimnetic Aerator. Water Science Technology 37(2) 293–300.

Butts, T. A., D. B. Shackelford, T. R. Beugerhouse. 2000. Sidestream Elevated Pool Aeration (SEPA) Stations: Effects on In-Stream Dissolved Oxygen. Illinois State Water Survey. Champaign, Ill.

Butts, T. A., D. B. Shackelford, T. R. Beugerhouse. 1998. Evaluation of Reaerator Efficiencies of Sidestream Elevated Pool Aeration (SEPA) Stations. Illinois State Water Survey. Champaign, Ill.

DeMoyer, C. D., J. S. Gulliver, and S. C. Wilhelms. 2001. Companion of Submerged Aerator Effectiveness. *Lake and Reservoir Management* 17(2) 139–152.

Fisher, H. B., J. E. List, R. C. Y. Koh, J. Imberger, N. H. Brooks. 1979. Mixing in Inland and Coastal Waters. Academic Press.

Garton, J. E. 1978. Improved Lake Quality through Lake Destratification. *Water Wastes Engineering* 15:42-44.

Jones & Stokes Associates. 1997. Potential Solutions for Achieving the San Joaquin River Dissolved Oxygen Objectives. (JSA 97-180.) December. Sacramento, CA. Prepared for DeCuir & Somach, Sacramento, CA, and City of Stockton Department of Municipal Utilities, Stockton, CA.

Jones & Stokes. 2001. Data Summary Report for San Joaquin River Dissolved Oxygen TMDL City of Stockton Year 2000 Field Sampling Program. October. (J&S 99-044). Sacramento, CA. Prepared for City of Stockton Department of Municipal Utilities, Stockton, CA.

Jung, R., J. O. Sanders, and H. H. Lai. 1998. Improving Water Quality through Lake Oxygenation at Camanche Reservoir. AWWA Water Quality Technology Conference. November.

Kortmann, R. W., G. W. Knoecklein, and C. H. Bonnell. 1994. Aeration of Stratified Lakes: Theory and Practice. *Lake and Reservoir Management* 8(2): 99–120.

Lindenschmidt, K. E. and P. F. Hamblin. 1997. Hypolimnetic Aeration in Lake Tegel, Berlin. *Water Ressources* 31(7): 1619–1628.

Little, G. C. 1995. Hypolimnetic Aerators: Predicting Oxygen Transfer and Hydrodynamics. *Water Research* 29(1): 2475-2482.

Litton, G. M. 2002. Dye Tracer Dispersion Associated with MOBI Aeration in the Stockton Ship Channel. Department of Civil Engineering, University of the Pacific. Stockton, CA.

Lorenzen, M. and A. Fast. 1977. A Guide to Aeration/Circulation Techniques for Lake Management. Corvallis Environmental Research Laboratory. Corvallis, OR.

McGinnis, D. F. and J. C. Little. 2002. Predicting Diffused-Bubble Oxygen Transfer Rate Using the Discrete-Bubble Model. *Water Research* (accepted for publication).

Mobley, M. H. and W. G. Brock. 1995. Widespread Oxygen Bubbles to Improve Reservoir Releases. *Lake and Reservoir Management* 11(3): 231-234.

Nakasone, H. 1987. Study of Aeration at Weirs and Cascades Journal of Environmental Engineering ASCE 113(1):64–81.

Nichol, G. and S. Slinkard. 1999. Jet Aeration of a Ship Channel. Corps of Engineers Sacramento District, Sacramento, CA.

Pastorok, R. A. and T. C. Ginn. 1981. Evaluation of Aeration/Circulation as a Lake Restoration Technique. Tetra Tech, Inc. Lafayette, CA.

Prepas, E. E., K. M. Field, T. P. Murphy, W. L. Johnson, J. M. Burke, and W. M. Tonn. 1997. Introduction to the Amisk Lake Project: Oxygenation of a Deep, Eutrophic Lake. *Canadian Journal of Fisheries Aquatic Sciences* 54: 2105–2110.

Schadlow, S. G. 1993. Lake Destratification by Bubble-Plume Systems: Design Methodology Journal of Hydraulic Engineering. ASCE Vol 119 No. 3 Pg 350–368.

Speece, R. E. 1996. Oxygen Supplementation by U-Tube to the Tombigbee River. *Water Science Technology* 34(12): 83–90.

Speece, R. E. 1990. Summary Test Results on Pilot Oxygenation Cone at Logan Martin Dam for Alabama Power Company. Vanderbilt University. Nashville TN.

Wagner, M. R. and H. J. Popel. 1998. Oxygen-Transfer and Aeration Efficiency: Influence of Diffuser Submergence, Diffuser Density, and Blower Type. *Water Science Technology* 38(3): 1–6.

Weiss, P. T., B. T. Oakley, J. S. Gulliver, and M. J. Semmens. 1994. The Performance of a Vertical Fiber Membrane Aerator. In *Aeration Technology* R.E.A. Arndt and A. Prosperetti (eds), pp. 59–66. A compendium of presentations at the 1994 ASME Fluids Engineering Division Summer Meeting, Lake Tahoe, Nevada, June19–23, 1994. American Society of Mechanical Engineers, New York, N.Y.

Yu, S. L., T. J. Tuffey, D. S. Lee. 1977. Atmospheric Reaeration in a Lake. Rutgers University, NTIS Pg 273–849.

Table 1. Summary of Literature Values for Aerator Efficiency Ratings

Source	Aerator Type	Energy Efficiency (lb/kWh) [1]	Transfer Efficiency (%)
Boon and Chambers 1986	Diffused air: fine bubble (< 5 mm)	3.3 – 7.9	-
Boon and Chambers 1986	Diffused air: course bubble (> 5 mm)	2.0 – 2.6	-
Boon and Chambers 1986	Mechanical surface aerators	2.6 – 5.3	-
Boyd 1990	Shallow pond air diffusers	0.7 – 1.2 (0.9)	
Lindenschmidt and Hamblin 1997	Hypolimnetic aeration – air diffusers	1.2 [2]	16%
Kortmann, et al. 1994	Hypolimnetic aeration – air diffusers	3.2 / 4.8 [3]	-
Mobley and Brock 1995	Reservoir aeration – pure oxygen	Unknown [4]	90% [5]
Beutel and Horne 1999	Hypolimnetic aeration – air diffusers	-	12% -50%
Beutel and Horne 1999	Hypolimnetic aeration - pure oxygen	-	60% - 80%
Prepas et al. 1997	Hypolimnetic aeration - pure oxygen	Unknown [4]	90%
Weiss et al. 1994	Hollow fiber membranes	Unknown	90%-100%
Speece 1996	U-tube – pure oxygenation	-	75% - 90%

Notes:

- Data not available to calculate efficiency, or not applicable.

[1] Values given as range (mean) unless otherwise noted. Single values are reported mean values unless otherwise noted.

[2] Calculated based on reported airflow rate, oxygen transfer rate, and diffuser depth from standard compressor power consumption equation.

[3] Reported as calculated average efficiencies of tests on hypolimnetic aeration / layer aeration.

[4] Information not available. However, expansion of liquid oxygen generates pressure and gas flow to the diffusers resulting in minimal power consumption.

[5] Efficiency reported in Beutel and Horne 1999.

Table 2A. Upwelling Field Test of USACE Aeration Device South Jet

Preliminary Field Test of Corps of Engineers Jet Aeration Equipment Near-Field Testing of Aeration Upwelling and Flow-away Currents

	Background DO in Front of Dock			
Measurement Location was X-distance along dock (north positive) and Y-distance indirection of jet (towards channel positive)	X- Distance (feet)	Y-Distance (feet)	Depth (ft)	DO (mg/l)
Testing of South Jet. North Jet air blower temporarily turned off	0	5	10	6.7
Air Pressure of 6.9 psi			20	6.8
Time 12:30 to 1:30 pm			23	6.7
			26	6.7
			29	6.6
			31	6.5
Vertical velocity profiles were made at a radial distance of about 10-15 feet.	10	5	10	7.5
Each profile represents an arc of 30-45 degrees.				
Flow was estimated as velocity profile times the circumference arc.	-15	5	10	6.7
	15	-5	10	7.3
	Behind but North of Jet towards DWSC		20	6.6

Assumed Background DO (mg/l)	Total Flow-away Flow (cfs)	Average Flow-away DO (mg/l)	Pounds per day
6.6	198	7.33	781

X- Distance (feet)	Y-Distance (feet)	Radius (feet)	Depth (feet)	Velocity (ft/sec)	Average Velocity (ft/sec)	Angle (degree)	Arc (degree)	Arc Length (feet)	Arc Flow (cfs)	DO (mg/l)	Flow Weighted DO (mg/l)
0	5	5	0.1	2	1.02	0	45	3.9	24	7.3	7.2
			1.5	1.5						7.2	
			3	1.2						7.1	
			4.5	0.8						7.1	
			6	0.2						7.1	
5	5	7	0.1	2.5	0.84	45	30	3.7	18.5	7.4	7.4
			1.5	1.5						7.3	
			3	0.6						7.3	
			4.5	0.3						7.3	
			6	0.1						7.4	
10	5	11.2	0.1	3	0.69	60	32.5	6.3	26.4	7.4	7.4
			1.5	1						7.3	
			3	0.3						7.3	
			4.5	0.1						7.3	
			6	0						7.4	
15	-5	15.8	0.1	2	0.27	110	37.5	10.3	16.7	7.5	7.5
			1.5	0.1						7.4	
			3	0.1						7.4	
			4.5	0.1						7.4	
			6	0.1						7.5	
10	-10	14.1	0.1	1.1	0.2	135	35	8.6	10.5	7.4	7.4
			1.5	0.1						7.4	
			3	0.1						7.4	
			4.5	0.1						7.4	
			6	0						7.4	

Table 2A. Continued.

X- Distance (feet)	Y-Distance (feet)	Radius (feet)	Depth (feet)	Velocity (ft/sec)	Average Velocity (ft/sec)	Angle (degree)	Arc (degree)	Arc Length (feet)	Arc Flow (cfs)	DO (mg/l)	Flow Weighted DO (mg/l)
0	-15	15	0.1	2	0.5	180	45	11.8	35.3	7.5	7.4
			1.5	1						7.3	
			3	0.1						7.2	
			4.5	0						7.1	
			6	0						7	
-10	-10	14.1	0.1	1.6	0.38	225	35	8.6	19.7	7.4	7.4
			1.5	0.7						7.3	
			3	0.1						7.2	
			4.5	0						7.2	
			6	0						7.2	
-15	-5	15.8	0.1	1.6	0.24	250	32.5	9	12.6	7.3	7.3
			1.5	0.2						7.1	
			3	0						7	
			4.5	0						7	
			6	0						7	
-15	5	15.8	0.1	1.2	0.33	290	32.5	9	18	7.3	7.2
			1.5	0.7						7	
			3	0.1						6.8	
			4.5	0						6.7	
			6	0						6.6	
-5	5	7	0.1	2.8	0.64	315	35	4.3	16.4	7.3	7.2
			1.5	1.3						7	
			3	0						6.8	
			4.5	0						6.7	
			6	0						6.6	

Table 2B. Upwelling Field Test of USACE Aeration Device North Jet

Preliminary Field Test of Corps of Engineers Jet Aeration Equipment Near-Field Testing of Aeration Upwelling and Flow-away Currents

	Background DO in Front of Dock			
Measurement Location was X-distance along dock (north positive) and Y-distance indirection of jet (towards channel positive)	X- Distance (feet)	Y-Distance (feet)	Depth (ft)	DO (mg/l)
Testing of North Jet. South Jet air blower temporarily turned off	0	5	10	8.5
Air Pressure of 7.0 psi			20	6.9
Time 3:00 to 4:00 pm			26	6.7
			29	6.6
			31	6.5
Vertical velocity profiles were made at a radial distance of about 10-15 feet	10	5	10	8.3
Each profile represents an arc of 30-45 degrees	-5	5	10	7.7
Flow was estimated as velocity profile times the circumference arc			12	7.4
	-15	5	10	6.6

Assumed Background DO (mg/l)	Total Flow-away Flow (cfs)	Average Flow-away DO (mg/l)	Pounds per day
6.6	42	8.1	340

Table 2B. Continued

X- Distance (feet)	Y-Distance (feet)	Radius (feet)	Depth (feet)	Velocity (ft/sec)	Average Velocity (ft/sec)	Angle (degree)	Arc (degree)	Arc Length (feet)	Arc Flow (cfs)	DO (mg/l)	Flow Weighted DO (mg/l)
0	5	5	0	0.4	0.07	0	45	3.9	1.6	8.8	8.8
			0.75	0.2						8.8	
			1.5	0.1						8.8	
			3	0						8.8	
			4.5	0						8.9	
			6	0						8.9	
5	5	7	0	0.4	0.06	45	30	3.7	1.4	8.6	8.6
DO estimated from 10,5 data			0.75	0.3						8.7	
			1.5	0						8.7	
			3	0						8.8	
			4.5	0						8.6	
			6	0						8.5	
10	5	11.2	0	0.4	0.06	60	32.5	6.3	2.4	8.6	8.6
Velocity estimated from 5,5 data			0.75	0.3						8.7	
			1.5	0						8.7	
			3	0						8.8	
			4.5	0						8.6	
			6	0						8.5	
15	-5	15.8	0	0.3	0.03	110	37.5	10.3	1.9	8.6	8.6
DO estimated from 10,5 data			0.75	0.1						8.7	
			1.5	0						8.7	
			3	0						8.8	
			4.5	0						8.6	
			6	0						8.5	
10	-10	14.1	0	0.5	0.04	135	35	8.6	2.3	8.9	8.9

Table 2B. Continued

X- Distance (feet)	Y-Distance (feet)	Radius (feet)	Depth (feet)	Velocity (ft/sec)	Average Velocity (ft/sec)	Angle (degree)	Arc (degree)	Arc Length (feet)	Arc Flow (cfs)	DO (mg/l)	Flow Weighted DO (mg/l)
DO estimated from 0,-15 data			0.75	0.1						8.9	
			1.5	0						8.8	
			3	0						8.8	
			4.5	0						8.8	
			6	0						8.8	
0	-15	15	0	0.5	0.06	180	45	11.8	4	8.9	8.9
			0.75	0.2						8.9	
			1.5	0						8.8	
			3	0						8.8	
			4.5	0						8.8	
			6	0						8.8	
-10	-10	14.1	0	0.5	0.04	225	35	8.6	2.3	8.9	8.9
DO estimated from 0,-15 data			0.75	0.1						8.9	
Velocity estimated from 10,-10 data			1.5	0						8.8	
			3	0						8.8	
			4.5	0						8.8	
			6	0						8.8	
-15	-5	15.8	0	0.5	0.04	250	32.5	9	2.4	8.9	8.9
DO estimated from 0,-15 data			0.75	0.1						8.9	
Velocity estimated from 10,-10 data			1.5	0						8.8	
			3	0						8.8	
			4.5	0						8.8	
			6	0						8.8	
-15	5	15.8	0	0.5	0.38	290	32.5	9	20.5	7.7	7.5
			0.75	0.7						7.6	
			1.5	0.4						7.5	
			3	0.4						7.4	

Table 2B. Continued

X- Distance (feet)	Y-Distance (feet)	Radius (feet)	Depth (feet)	Velocity (ft/sec)	Average Velocity (ft/sec)	Angle (degree)	Arc (degree)	Arc Length (feet)	Arc Flow (cfs)	DO (mg/l)	Flow Weighted DO (mg/l)
			4.5	0.3						7.4	
			6	0.1						7.3	
-5	5	7	0	0.7	0.11	315	35	4.3	2.9	8	7.9
			0.75	0.2						7.8	
			1.5	0.1						7.6	
			3	0.1						7.5	
			4.5	0						8	
			6	0						8.5	
										8	

Table 3. USACE Aeration Device Performance Survey at Upstream Railroad Bridge

Difference in Mass of DO passing under Bridge was 740 lb/day more with Aerator Jets than when they were turned off

	Lateral Location (meters from left bank)												
	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	60m	65m
A. Aerator On													
Water Temperature (Deg. F)													
Surf	72.3	73	73.2	73.2	73.2	72.7		72.7	72.7	73.6	73.9	74.3	72.1
1.0m	72.3	72.7	72	72.3	72.3	73		72.1	72.1	72.7	72.6	72	71.8
2.0m	72.1	72.1	71.8	71.8	72.1	72.1		72	72.3	72.1	72.1	71.8	71.8
3.0m	72	71.8	71.6	71.8	72	72.1		72.1	72.1	71.8	72	71.6	71.6
4.0m		71.8	71.6	71.6	71.8	72		72.1					
5.0m			71.6	71.6	71.8	72							
6.0m				71.6	71.8	72							
7.0m					71.8	71.8							
8.0m													
9.0m													
Dissolved Oxygen (mg/L)													
Surf	7.07	6.78	7.56	7.54	7.5	6.93		7.25	6.97	7.72	8.37	9.06	5.87
1.0m	6.8	7.22	6.4	6.29	7.33	6.26		6.38	6.68	7.17	6.75	6.43	5.9
2.0m	6.71	6.68	5.99	6.31	6.78	6.32		6.39	6.7	6.9	6.52	5.93	5.65
3.0m	6.54	5.98	5.57	5.67	6.66	6.11		6.42	6.46	6.44	6.05	5.78	5.53
4.0m		5.71	5.53	5.71	6.5	6.07		6.35					
5.0m			5.47	5.62	6.46	6							
6.0m				5.64	6.31	6							
7.0m					6.24	5.93							
8.0m													
9.0m													

Table 3. Continued

	Lateral Location (meters from left bank)												
	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	60m	65m
Velocity (ft/sec)													
Surf	0.8	0.8	0.8	0.7	0.6	0.4		0.3	0.3	0.4	0.5	0.7	0.8
1.0m	0.7	0.8	0.8	0.6	0.6	0.2		0.3	0.3	0.4	0.4	0.5	0.5
2.0m	0.8	0.8	0.6	0.6	0.6	0.3		0.3	0.3	0.3	0.3	0.5	0.4
3.0m	0.8	0.7	0.6	0.5	0.6	0.3		0.3	0.3	0.3	0.3	0.5	0.2
4.0m		0.6	0.4	0.5	0.6	0.3		0.3					
5.0m		0	0.4	0.4	0.6	0.2							
6.0m				0.3	no data	no data							
7.0m					no data	no data							
8.0m													
9.0m													
B. Aerator Off													
Water Temperature (Deg. F)													
Surf	72.1		73.4		73.4				73.2		73.6		73.2
1.0m	71.8		71.6		73.6				73.2		72		72
2.0m	71.6		71.6		72.3				73		71.6		71.8
3.0m	71.4		71.4		72.3						71.6		71.6
4.0m	71.4		71.4		72.1								
5.0m					71.6								
6.0m					71.6								
7.0m													
8.0m													
9.0m													

Table 3. Continued

	Lateral Location (meters from left bank)												
	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	60m	65m
Dissolved Oxygen (mg/L)													
Surf	8.3		7.7		8.2				7.8		8.2		8.3
1.0m	5.8		5.9		7.3				7.8		5.5		6.2
2.0m	5.4		5.8		6.9				7.5		5.5		5.5
3.0m	5.3		5.2		6.7						5.3		5.3
4.0m	5.2		5.1		6.2								
5.0m					5.6								
6.0m					5.6								
7.0m													
8.0m													
9.0m													
Velocity (ft/sec)													
Surf	0.8		0.8		0.6				0.4		0.7		0.7
1.0m	0.7		0.8		0.7				0.4		0.5		0.5
2.0m	0.7		0.8		0.7				0.4		0.6		0.4
3.0m	0.8		0.8		0.7						0.5		0.3
4.0m	0.6		0.6		0.7								
5.0m					0.8								
6.0m					0.7								
7.0m													
8.0m													
9.0m													

	Lateral Location (meters from left bank)												
	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	60m	65m
C. Comparison (Aerator ON - Aerator OFF)													
Water Temperature (Deg. F)													
Surf	0.2		-0.2		-0.2				-0.52		0.3		-1.1
1.0m	0.5		0.4		-1.3				-1.1		0.6		-0.2
2.0m	0.5		0.2		-0.2				-0.7		0.5		0
3.0m	0.6		0.2		-0.3						0.4		0
4.0m			0.2		-0.3								
5.0m					0.2								
6.0m					0.2								
7.0m													
8.0m													
9.0m													
Dissolved Oxygen (mg/L)													
Surf	-1.23		-0.14		-0.7				-0.83		0.17		-2.43
1.0m	1		0.5		0.03				-1.12		1.25		-0.3
2.0m	1.31		0.19		-0.12				-0.8		1.02		0.15
3.0m	1.24		0.37		-0.04						0.75		0.23
4.0m			0.43		0.3								
5.0m					0.86								
6.0m					0.71								
7.0m													
8.0m													
9.0m													

Table 3. Continued

	Lateral Location (meters from left bank)												
	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	60m	65m
Velocity (ft/sec)													
Surf	0		0		0				-0.1		-0.2		0.1
1.0m	0		0		-0.1				-0.1		-0.1		0
2.0m	0.1		-0.2		-0.1				-0.1		-0.3		0
3.0m	0		-0.2		-0.1						-0.2		-0.1
4.0m			-0.2		-0.1								
5.0m					-0.2								
6.0m													
7.0m													
8.0m													
9.0m													
Dissolved Oxygen Mass (lb/day)													
Surf	-286	-286	-33	-28	-122	-81		-72	-72	20	25	-494	-565
1.0m	203	232	116	87	5	2		-98	-98	145	145	-44	-44
2.0m	304	304	33	33	-21	-10		-70	-70	89	89	22	17
3.0m	288	252	64	54	-7	-3				65	65	33	13
4.0m			50	62	52	26							
5.0m					150	50							
6.0m					103	41							
7.0m													
8.0m													
9.0m													

Table 4. Measured Temperature Stratification During the Summer of 2002 at the Rough & Ready Island Water Quality Monitoring Station in the DWSC

Date	3-ft depth Avg T	6-ft depth Avg T	R&R Is. Avg T	18-ft depth Avg T	3-ft depth Max T - Min T	6-ft depth Max T - Min T	R&R Is. Max T - Min T	18-ft depth Max T - Min T	Daily Maximum Stratification 3 ft – 18 ft
1-May			59.7				1.7		
2-May			60.1				1.3		
3-May			61.2				2.4		
4-May			62.9				2.3		
5-May			64.6				2.0		
6-May			65.5				1.1		
7-May			66.3				1.4		
8-May			66.6				1.5		
9-May			66.3				0.7		
10-May			65.9				1.2		
11-May	65.7	66.0	65.7	65.3	2.3	2.0	1.8	1.2	2.4
12-May	66.1	66.3	65.9	65.6	2.4	2.2	1.9	0.8	1.8
13-May	66.5	66.8	66.5	66.3	2.4	2.1	1.9	0.7	2.4
14-May	66.8	67.1	66.8	66.6	2.2	1.7	1.6	1.0	2.4
15-May	67.4	67.5	67.2	67.1	2.3	2.3	2.0	1.3	1.8
16-May	67.8	68.1	67.8	67.8	1.9	1.5	1.6	1.4	1.5
17-May	68.6	68.6	68.3	68.2	2.3	1.8	1.6	1.1	2.1
18-May	68.4	68.7	68.5	68.4	1.3	1.3	1.1	0.9	1.0
19-May	68.0	68.4	68.2	68.2	0.9	0.7	0.8	0.9	0.4
20-May	67.0	67.4	67.1	67.1	1.2	1.5	1.3	1.8	0.4
21-May	66.3	66.5	66.1	65.9	2.0	1.0	1.0	1.2	2.1
22-May	66.2	66.3	65.8	65.4	2.8	2.7	1.5	1.8	3.0
23-May	66.0	66.0	66.1	65.7	1.9	0.9	1.2	1.0	1.5
24-May	67.2		66.5	66.1	4.0		2.5	0.9	3.9
25-May	67.7		67.5	67.0	3.1		2.5	1.8	3.0
26-May	68.0		67.9	67.8	2.9		2.4	1.7	2.4
27-May	68.8		68.6	68.5	3.4		2.8	2.2	3.0
28-May	69.3		69.5	69.4	3.0		3.2	1.8	1.0
29-May	70.0		70.7	70.1	2.4		4.3	1.9	0.7
30-May	71.7		72.5	71.5	1.1		4.4	0.9	1.3
31-May	73.6		73.5	73.0	3.1		2.9	2.4	2.8

Table 4. Continued.

Date	3-ft depth Avg T	6-ft depth Avg T	R&R Is. Avg T	18-ft depth Avg T	3-ft depth Max T - Min T	6-ft depth Max T - Min T	R&R Is. Max T - Min T	18-ft depth Max T - Min T	Daily Maximum Stratification 3 ft – 18 ft
1-Jun	73.2		73.2	73.3	1.2		1.2	1.0	1.0
2-Jun	73.5		73.4	73.6	0.3		2.1		0.1
3-Jun	73.7		73.4	73.2	2.6		1.6	1.5	2.5
4-Jun	74.2		74.0	73.7	2.9		2.0	1.4	2.2
5-Jun	75.0		74.8	74.2	2.8		2.4	1.9	2.5
6-Jun	75.5		75.4	75.1	2.3		1.7	1.3	1.6
7-Jun	75.4		75.5	75.5	1.9		1.4	0.9	1.3
8-Jun	74.7		74.9	75.0	1.1		1.0	0.9	-0.3
9-Jun	73.2		73.5	73.6	1.2		1.4	1.2	0.1
10-Jun	73.3		73.3	73.1	3.4		3.0	1.4	2.5
11-Jun	73.6		73.5	73.4	4.2		3.2	1.4	3.2
12-Jun	73.6		73.6	73.6	2.2		1.9	1.5	1.6
13-Jun	74.1		73.9	73.8	3.5		2.8	1.8	2.9
14-Jun	74.4		74.3	74.2	2.9		2.4	1.6	2.2
15-Jun	74.8		74.6	74.6	2.9		2.0	1.6	1.9
16-Jun	74.8		74.7	74.7	1.8		1.5	0.9	1.6
17-Jun	74.7		74.8	74.8	1.3		1.1	1.1	1.3
18-Jun	75.0		75.0	74.9	1.6		1.4	0.9	1.6
19-Jun	74.7		75.2	75.0	0.5		1.0	0.3	0.1
20-Jun			75.3				1.1		
21-Jun	74.4	74.8	74.6	74.6	1.0	0.9	1.0	0.9	0.7
22-Jun	74.4	74.6	74.3	74.1	2.2	1.7	1.5	0.7	1.9
23-Jun	74.3	74.6	74.3	74.2	2.8	2.3	1.7	0.9	2.5
24-Jun	75.0	74.9	74.5	74.2	3.7	2.7	2.0	0.6	3.8
25-Jun	74.4	74.9	75.2	74.8	1.4	1.2	3.1	0.9	0.4
26-Jun	75.8	76.1	75.8	75.6	3.3	2.8	2.8	1.6	2.6
27-Jun	75.6	76.0	75.9	75.9	2.1	2.2	2.1	1.7	0.1
28-Jun	76.1	76.3	76.1	76.1	2.6	2.0	1.8	1.1	1.9
29-Jun	76.6	76.8	76.6	76.4	2.2	2.2	2.0	1.6	1.6
30-Jun	77.6	77.7	77.4	77.1	3.1	3.1	2.6	1.8	2.9

Table 4. Continued.

Date	3-ft depth Avg T	6-ft depth Avg T	R&R Is. Avg T	18-ft depth Avg T	3-ft depth Max T - Min T	6-ft depth Max T - Min T	R&R Is. Max T - Min T	18-ft depth Max T - Min T	Daily Maximum Stratification 3 ft – 18 ft
1-Jul	78.8	78.5	78.1	77.7	4.6	3.3	3.5	1.3	5.1
2-Jul	78.7	78.9	78.5	78.3	2.6	2.3	1.9	1.4	2.6
3-Jul	78.8	79.0	78.5	78.4	3.1	2.4	1.5	1.2	2.9
4-Jul	78.7	79.0	78.6	78.5	1.9	1.4	1.4	0.8	2.0
5-Jul	78.7	78.9	78.5	78.4	2.1	1.7	1.3	0.9	1.6
6-Jul	78.7	78.9	78.5	78.4	2.1	1.9	1.4	0.9	2.0
7-Jul	78.3	78.6	78.3	78.3	2.1	1.7	1.0	0.4	2.0
8-Jul	78.2	78.5	78.2	78.2	1.7	1.8	1.3	1.0	1.0
9-Jul	79.6	79.3	78.5	78.2	5.6	3.9	1.9	0.5	5.5
10-Jul	80.4	80.1	79.1	78.7	6.9	5.2	2.3	0.8	6.5
11-Jul	80.0	80.0	79.6	79.3	3.7	2.7	2.0	0.9	3.9
12-Jul	80.1	80.2	79.8	79.6	4.3	3.5	3.0	0.8	3.6
13-Jul	80.1	80.4	80.0	79.9	2.9	2.8	2.5	1.6	2.3
14-Jul	80.4	80.6	80.3	80.2	3.0	2.7	2.5	1.4	2.3
15-Jul	80.4	80.5	80.3	80.2	2.9	2.2	2.0	1.2	2.3
16-Jul	80.2	80.4	80.2	80.1	2.3	1.8	1.7	1.3	2.0
17-Jul	80.1	80.4	80.1	80.0	1.9	1.6	1.5	1.0	1.7
18-Jul	80.2	80.4	80.0	79.8	2.2	2.3	1.9	0.7	2.3
19-Jul	80.3	80.5	80.0	79.7	2.6	2.0	1.7	0.7	2.3
20-Jul	80.2	80.4	80.1	80.0	2.6	1.8	1.4	0.6	2.0
21-Jul	79.5	79.9	79.7	79.8	1.6	1.2	1.1	0.6	1.0
22-Jul	79.2	79.5	79.3	79.2	2.3	1.9	1.4	0.6	2.0
23-Jul	79.1	79.4	79.2	79.0	2.8	2.4	1.8	0.9	2.3
24-Jul	79.0	79.2	79.0	78.8	3.2	2.5	2.2	0.9	2.6
25-Jul	79.0	79.2	78.9	78.8	2.9	2.5	2.2	0.9	2.3
26-Jul	78.8	79.1	78.8	78.7	3.0	2.0	2.0	1.3	2.3
27-Jul	79.0	79.2	78.9	78.9	3.2	2.5	2.3	1.5	2.0
28-Jul	78.7	79.0	78.8	78.8	2.1	1.7	1.7	1.2	1.3
29-Jul	78.7	79.0	78.7	78.7	2.2	2.0	1.7	1.1	1.3
30-Jul	78.9	79.0	78.8	78.6	3.3	2.5	2.1	0.6	2.9
31-Jul	78.8	78.9	78.6	78.6	2.8	1.8	1.7	0.9	2.3

Table 4. Continued.

Date	3-ft depth Avg T	6-ft depth Avg T	R&R Is. Avg T	18-ft depth Avg T	3-ft depth Max T - Min T	6-ft depth Max T - Min T	R&R Is. Max T - Min T	18-ft depth Max T - Min T	Daily Maximum Stratification 3 ft – 18 ft
1-Aug	78.7	79.0	78.6	78.4	2.4	1.9	1.9	0.9	2.0
2-Aug	78.8	78.9	78.6	78.5	2.6	1.6	1.4	1.1	2.3
3-Aug	78.3	78.7	78.4	78.3	2.0	1.5	1.2	0.6	2.0
4-Aug	78.3	78.5	78.1	77.9	2.8	2.0	1.1	0.6	2.6
5-Aug	77.9	78.2	78.0	78.0	1.8	1.5	1.3	0.6	1.3
6-Aug	77.5	77.8	77.6	77.4	1.9	1.9	1.5	0.7	1.6
7-Aug	77.1	77.5	77.3	77.4	1.4	1.2	1.2	0.9	0.7
8-Aug	77.5	77.7	77.3	77.2	2.9	2.2	1.6	0.7	2.9
9-Aug	77.9	78.0	77.6	77.4	3.3	2.4	2.1	0.8	2.3
10-Aug	78.3	78.4	78.1	77.8	3.3	2.8	2.5	0.9	2.6
11-Aug	78.3	78.6	78.3	78.2	2.9	2.4	2.3	1.5	2.0
12-Aug	78.7	78.8	78.5	78.3	3.5	2.9	2.3	1.0	2.9
13-Aug	79.1	79.1	78.8	78.6	3.7	2.6	2.4	0.6	3.3
14-Aug	78.9	79.1	78.8	78.8	2.2	1.8	1.5	1.2	1.6
15-Aug	79.2	79.3	78.9	78.7	2.8	2.1	2.0	1.1	2.6
16-Aug	78.7	79.0	78.7	78.7	1.4	1.0	0.9	0.9	1.3
17-Aug	78.6	78.8	78.5	78.5	1.9	1.3	0.8	0.6	1.6
18-Aug	78.5	78.7	78.4	78.3	1.7	1.5	1.0	0.6	1.6
19-Aug	78.1	78.4	78.2	78.1	1.9	1.9	1.2	0.7	1.6
20-Aug	77.7	78.0	77.7	77.7	2.0	1.4	1.3	0.6	2.3
21-Aug	77.4	77.6	77.3	77.2	1.9	1.5	1.2	0.6	1.6
22-Aug	76.9	77.2	76.9	76.9	2.7	1.7	1.4	0.7	3.2
23-Aug	76.6	76.8	76.7	76.6	2.7	1.8	1.8	0.8	2.6
24-Aug	76.5	76.7	76.5	76.3	2.3	1.7	1.5	0.9	2.2
25-Aug	76.0	76.3	76.1	76.0	1.9	1.3	1.4	1.1	1.9
26-Aug	75.9	76.1	75.9	75.8	1.7	1.5	1.2	1.3	1.9
27-Aug	75.9	76.1	75.8	75.5	3.4	2.7	2.4	0.9	3.2
28-Aug	75.7	76.0	75.7	75.6	2.3	1.7	1.4	1.3	2.2
29-Aug	75.5	75.9	75.6	75.6	2.4	1.9	1.7	0.9	1.6
30-Aug	75.8	75.9	75.6	75.5	3.1	2.3	1.5	0.9	
31-Aug	76.0	76.2	75.8	75.6	2.5	2.0	1.7	0.8	2.2

Table 5. Measurements of MOBI Device Upwelling Flow and Oxygen Bubble Transfer Efficiency

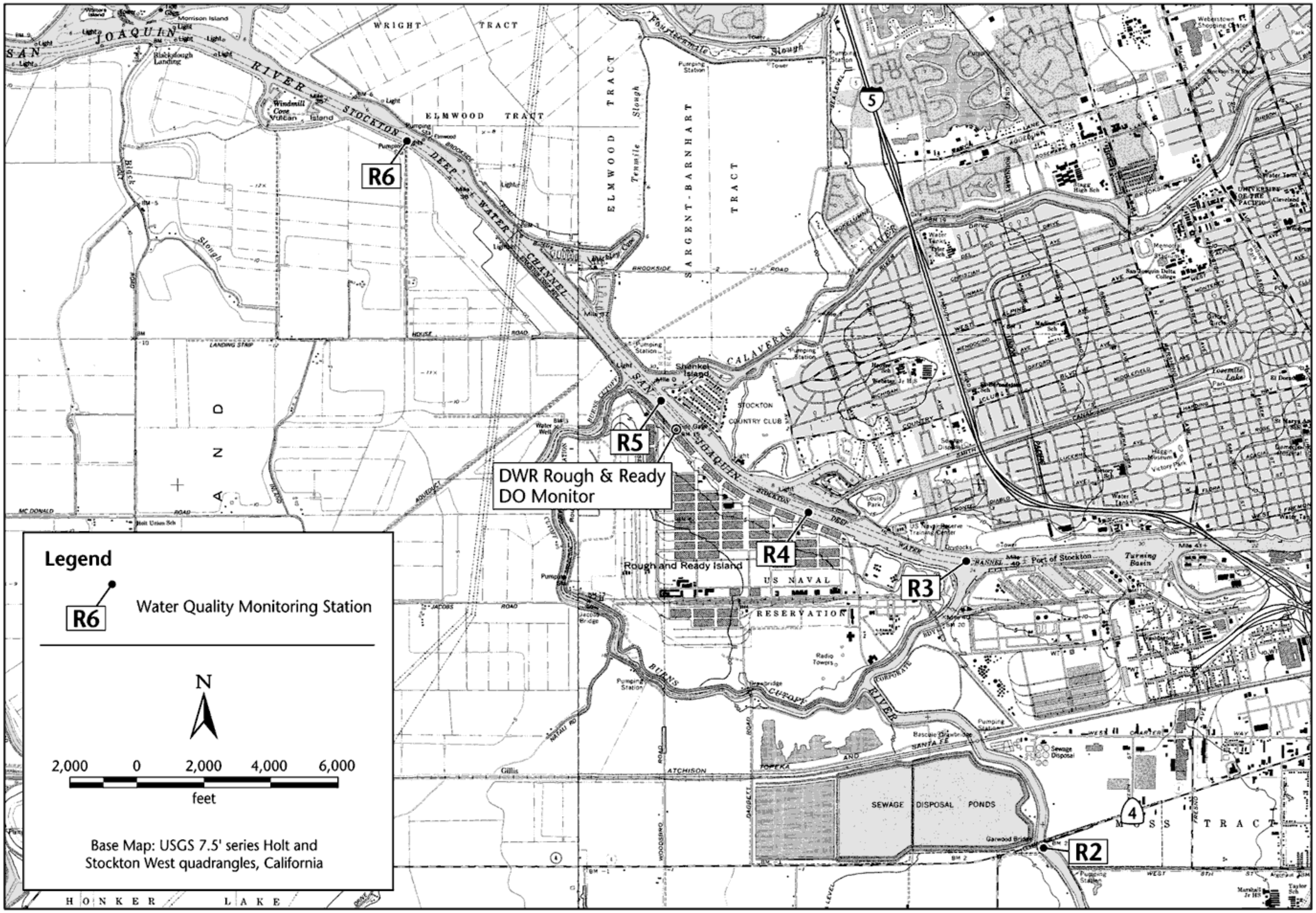
	Total Calculated Oxygen Flow Rate scfm	Primary Metered Oxygen Flow Rate scfm	Primary Regulator Pressure psi	Secondary Metered Oxygen Flow Rate scfm	Secondary Regulator Pressure psi	DO at Intake mg/L	DO at Midpoint mg/L	DO at Outflow mg/L	DO Increment mg/L	Velocity in Tube ft/sec	Flow in Tube cfs	Flow in Tube Dye Dilution cfs	Exhaust time to fill 13 gal bag sec	Exhaust Gas Flow scfm	DO Delivery lbs/day	DO Delivery Efficiency %	Nitrogen Content %
Run #1																	
		0.5	18			4.4	6		1.6	0	0				0		
20-Jun		0.8	30			4.4	6.4		2	0.1	0.3				3.2		
		1	38			4.8	7.6		2.8	0.5	1				15.1		
Ceramic		1.3	41			4.4	7.9		3.5	0.7	1.3				24.6		
Diffuser		1.5	47			5.1	8.4		3.3	0.9	1.8				32.1		
		2				5.3	9		3.7	1	2				40		
		2.5	75			4.8	9.5		4.7	1.3	2.6				66		
		2.8	82			5.1	9.6		4.5	1.5	3				72.9		
Run #2		0.8	30			4.5	5.8		1.3	0.1	0.3	0			2.1		
		1	35			4.5	7.8		3.3	0.4	0.7	0.7			12.5		
20-Jun		1.3	40			4.5	8.2		3.7	0.5	0.9	1.4			18		
		1.5	45			4.5	8.4		3.9	0.8	1.5	1.5			31.6		
Ceramic		1.8	51			4.5	8.7		4.2	0.8	1.6	1.7			36.3		
Diffuser		2	59			4.5	8.8		4.3	0.9	1.8	2			41.8		
		2.3	65			4.5	8.9		4.4	1	1.9	2.4			45.1		
		2.5	77			4.4	9		4.6	1.2	2.3	2.7			57.1		
Run #3	0.3	0.3	100			3.2	4.2	4.9	1.7	0.3	0.6		500	0.2	5.5	18.5	
	0.7	0.5	100			2.9	5.1	5.8	2.9	0.4	0.8		170	0.6	12.5	15	
11-Jul	1.2	0.8	100			3	5.6	6.3	3.3	0.5	1		105	1	17.8	13.4	
	1.6	1	100			3	6.2	6.6	3.6	0.8	1.6		79	1.3	31.1	16.9	
Ceramic	2.1	1.3	100			3.1	6.2	6.9	3.8	1	2		60	1.8	41	16.9	
Diffuser	2.8	1.5	100			3.1	6.7	7.3	4.2	1.1	2.2		45	2.3	49.9	15.7	
	3.2	1.8	100			3	7	7.6	4.6	1.3	2.5		40	2.6	62.1	17	
	4	2	100			3.1	7.1	7.7	4.6	1.4	2.7		31	3.4	67.1	14.7	
	4.3	2.3	100			3	7.2	7.9	4.9	1.4	2.8		29	3.6	74.1	15.1	

Table 5. Continued. Page 2 of 3

	Total Calculated Oxygen Flow Rate scfm	Primary Metered Oxygen Flow Rate scfm	Primary Regulator Pressure psi	Secondary Metered Oxygen Flow Rate scfm	Secondary Regulator Pressure psi	DO at Intake mg/L	DO at Midpoint mg/L	DO at Outflow mg/L	DO Increment mg/L	Velocity in Tube ft/sec	Flow in Tube cfs	Flow in Tube Dye Dilution cfs	Exhaust time to fill 13 gal bag sec	Exhaust Gas Flow scfm	DO Delivery lbs/day	DO Delivery Efficiency %	Nitrogen Content %
	4.8	2.5	100			3	8.2	8.7	5.7	1.5	3		26	4	92.3	16.6	
	5.7	2.8	100			3.1	11.2	11.7	8.6	1.5	2.9		23	4.6	134.7	20.4	
	6.1	3	100			3	11	11.3	8.3	1.4	2.8		21	5	125.5	17.9	
	8.4	3.3	100			3	11.8	12.3	9.3	1.6	3.2		15	7	160.7	16.6	
Run #4	0.5	0.5	100			2.7	4.5	5	2.3	0.5	1		300	0.4	12.4	23.5	
	0.9	1	100			3.3	5.4	6	2.7	0.7	1.4		145	0.7	20.4	19.7	
11-Jul	1.6	1.5	100			3.2	5.7	6.3	3.1	0.9	1.8		80	1.3	30.1	16.6	
	2.1	2	100			3	6.1	6.6	3.6	1.1	2.2		60	1.8	42.8	17.5	
Soaker	2.9	2.5	100			3	6.4	7	4	1.1	2.2		42	2.5	47.5	14.2	
Hose	4	3	100			3.2	6.9	7.5	4.3	1.3	2.6		30	3.5	60.4	13	
	4.7	3.5	100			3.3	7.4	8.1	4.8	1.4	2.8		26	4	72.6	13.5	
	5.6	4	100			3.2	8	8.9	5.7	1.6	3.2		22	4.8	98.5	15.2	
	6.5	4.5	100			2.9	7.8	8.7	5.8	1.8	3.6		19	5.5	112.8	15	
	8.2	5	100			2.9	8.4	9.4	6.5	1.9	3.8		15	7	133.4	14.2	
Run #5	1.7	1	100			7.4	10.1	10	2.6	1	2		73	1.4	28.1	14.5	16
	3.5	2	100			8	10.9	11.8	3.8	1.5	3		35	3	61.6	15.1	12
7-Aug	7.6	3	100			8.1	11.4	12	3.9	1.6	3.2		15	7	67.4	7.7	12
	7.9	3.5	100			8.1	12.5	13	4.9	2	4		15	7	105.8	11.6	10
Ceramic																	
Diffuser																	
Run #6	1.7	1	160			7.1	9.6	11.6	4.5	0.8	1.6		77	1.4	38.9	19.8	12
	4.9	2	160			7.3	11.2	11.6	4.3	1.4	2.8		24	4.4	65	11.4	21
7-Aug	8.4	3	160			7.4	12.2	13	5.6	1.8	3.6		14	7.5	108.9	11.2	11
	11.6	4	160			7.4	13.5	13.5	6.1	2	4		10	10.5	131.8	9.8	10
Soaker																	
Hose																Air sample	79

Table 5. Continued.

	Total Calculated Oxygen Flow Rate scfm	Primary Metered Oxygen Flow Rate scfm	Primary Regulator Pressure psi	Secondary Metered Oxygen Flow Rate scfm	Secondary Regulator Pressure psi	DO at Intake mg/L	DO at Midpoint mg/L	DO at Outflow mg/L	DO Increment mg/L	Velocity in Tube ft/sec	Flow in Tube cfs	Flow in Tube Dye Dilution cfs	Exhaust time to fill 13 gal bag sec	Exhaust Gas Flow scfm	DO Delivery lbs/day	DO Delivery Efficiency %	Nitrogen Content %
Run # 7	5.5	4	100	0	50	3.9	13.9	12.86	8.96	1.16	2.32		23	4.6	112.3	17.6	
	5.9	4	100	0.1	50	3.8		17.5	13.7	1	2		23	4.6	148	21.9	
26-Nov	6.2	4	100	0.2	50	3.9		18.8	14.9	1	2		22	4.8	160.9	22.6	
	5.8	4	100	0.4	50	3.8		19.8	16	0.7	1.4		22	4.8	121	18	
Soaker	7.6	5	100	0	50	3.9		15	11.1	1.4	2.8		17	6.2	167.8	19.1	
Hose	7.5	5	100	0.1	50	3.9		16.4	12.5	1.4	2.8		18	5.8	189	21.9	
Primary	7.6	5	100	0.2	50	3.9		19.75	15.85	1.2	2.4		18	5.8	205.4	23.4	
	7.5	5	100	0.4	50	3.9		20	16.1	1	2		17.5	6	173.9	20.1	
Ceramic	3.9	3	100	0	50	3.9	13	12	8.1	1.1	2.2		34	3.1	96.2	21.3	
Diffuser	4.1	3	100	0.1	50	3.9		14.9	11	0.9	1.8		33	3.2	106.9	22.6	
Secondary	4.2	3	100	0.2	50	3.8		16.5	12.7	0.8	1.6		32	3.3	109.7	22.5	
	4.4	3	100	0.4	50	3.8		18.5	14.7	0.6	1.2		29	3.6	95.3	18.6	
	4.8	3	100	0.6	50	3.8		20	16.2	0.6	1.2		27	3.9	105	19	
	2.5	2	100	0	50	3.85	11.5	10.8	6.95	0.85	1.7		55	1.9	63.8	22.5	
	2.8	2	100	0.1	50	3.85		14.4	10.55	0.65	1.3		49	2.1	74.1	23.1	
	3.1	2	100	0.2	50	3.85		15.2	11.35	0.55	1.1		41	2.6	67.4	18.6	
	4	2	100	0.4	50	3.85		17	13.15	0.55	1.1		32	3.3	78.1	17.1	
	4.1	2	100	0.6	50	3.85		18.5	14.65	0.55	1.1		31	3.4	87	18.2	
	1.3	1	100	0	50	3.8	9.8	8.9	5.1	0.63	1.26		102	1	34.7	22.6	
	1.6	1	100	0.1	50	3.8	12.5	11.2	7.4	0.51	1.02		85	1.2	40.8	22.3	
	1.6	1	100	0.2	50	3.75	12.5	11.5	7.75	0.46	0.92		85	1.2	38.5	21.3	
	1.9	1	100	0.4	50	3.7	14.2	12.7	9	0.43	0.86		68	1.5	41.8	19	
	2.3	1	100	0.6	50	3.7		15.6	11.9	0.31	0.62		53	2	39.8	14.9	



Jones & Stokes

Figure 1
Stockton Deep Water Ship Channel Water Quality Stations

Figure 2. DO Minimum and Maximum Measured at Rough & Ready DO Monitor During 2001

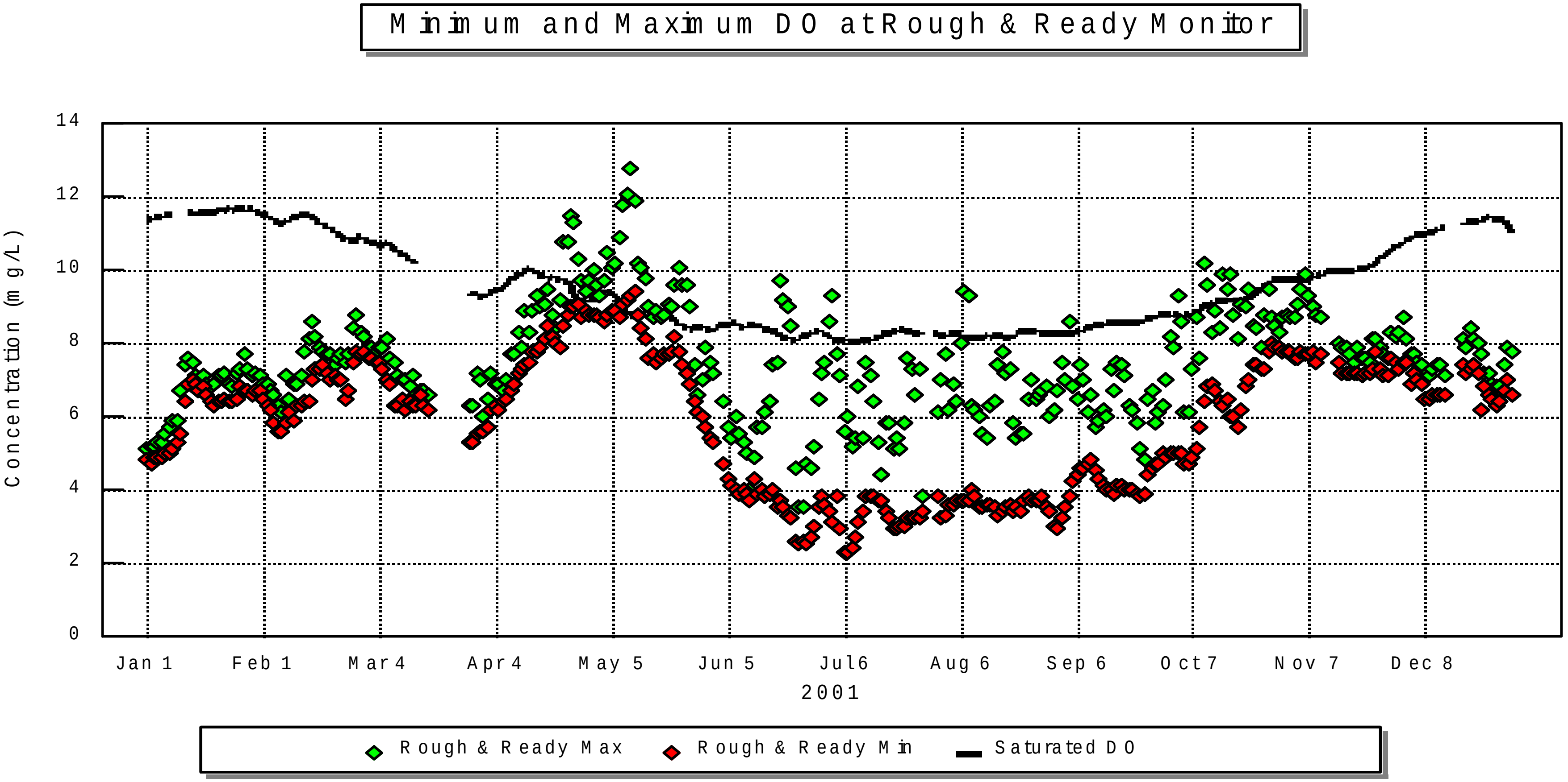


Figure 3. Calculated DWSC Dissolved Oxygen Deficit During 1999

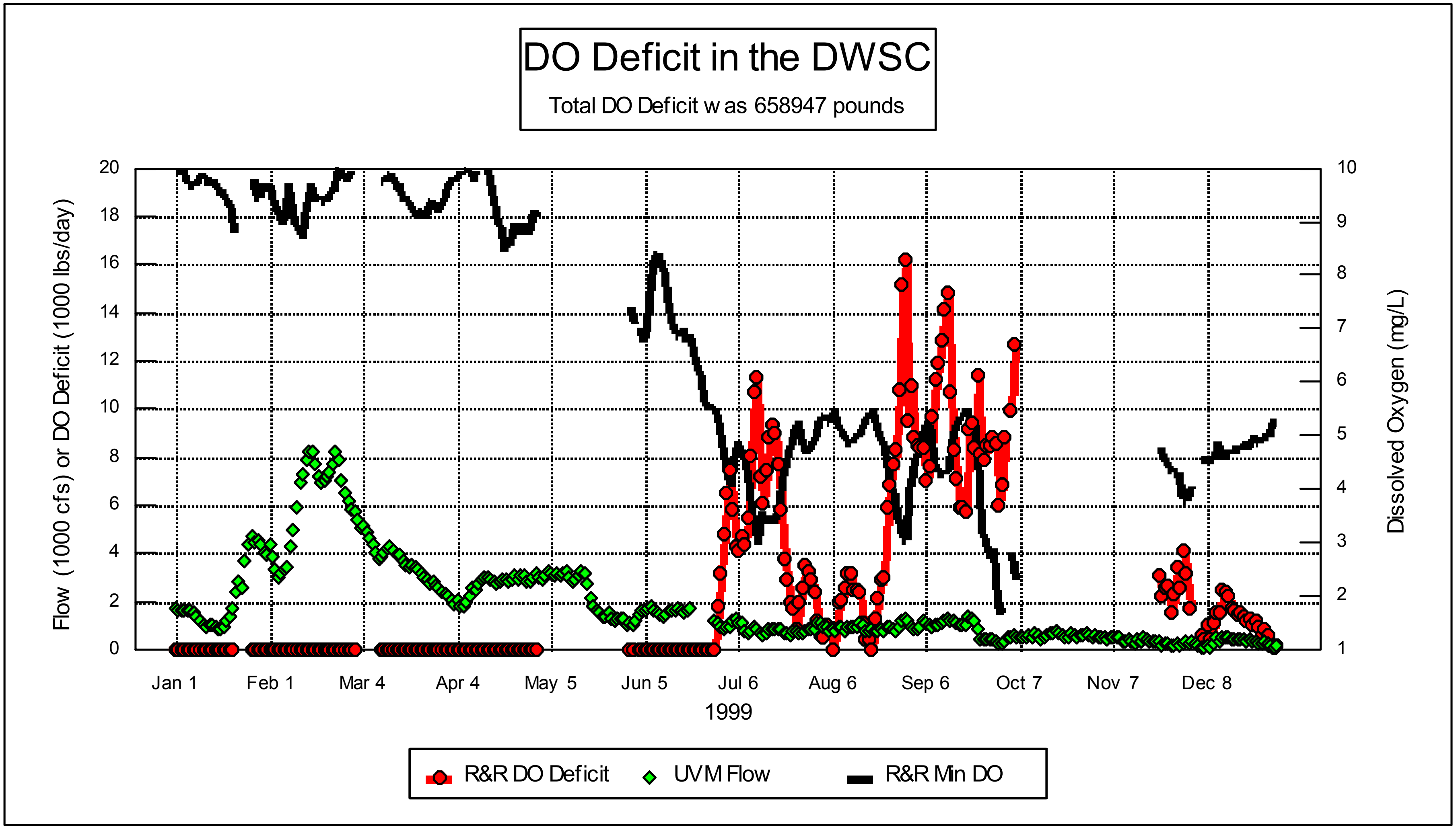


Figure 4. Calculated DWSC Dissolved Oxygen Deficit During 2000

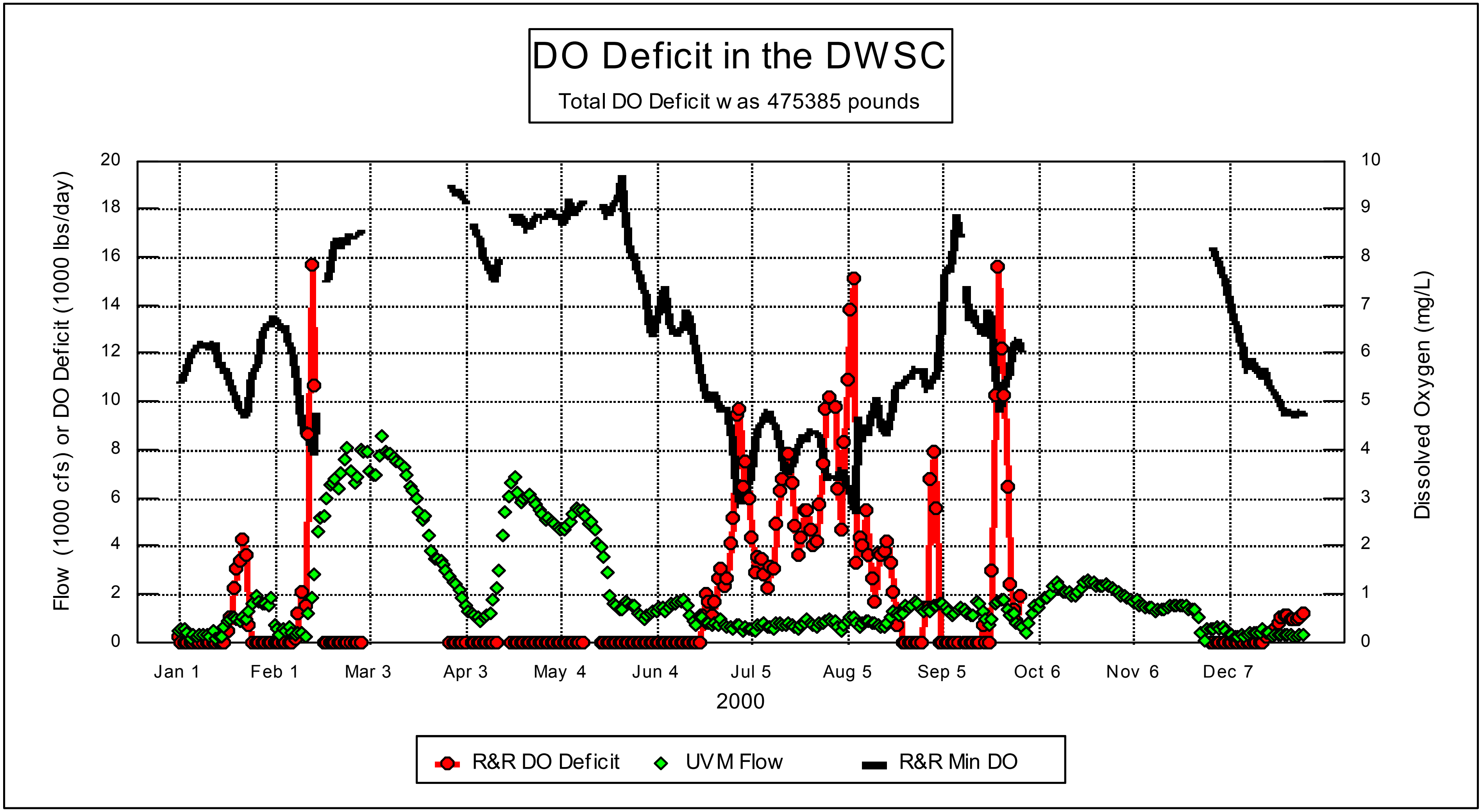


Figure 5. Calculated DWSC Dissolved Oxygen Deficit During 2001

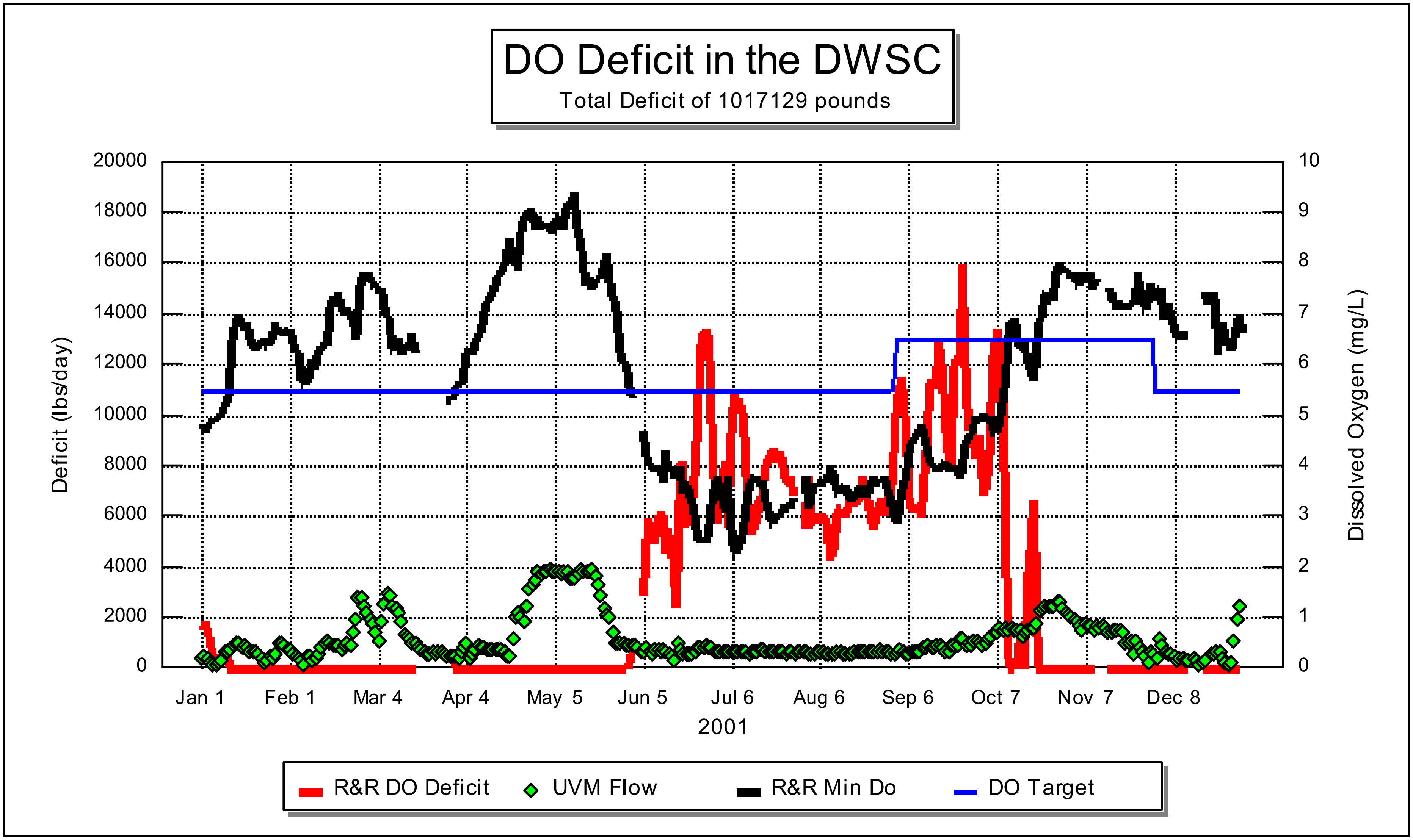


Figure 6. SJR DO TMDL Aeration Responsibilities and Credits in the DWSC During 2001

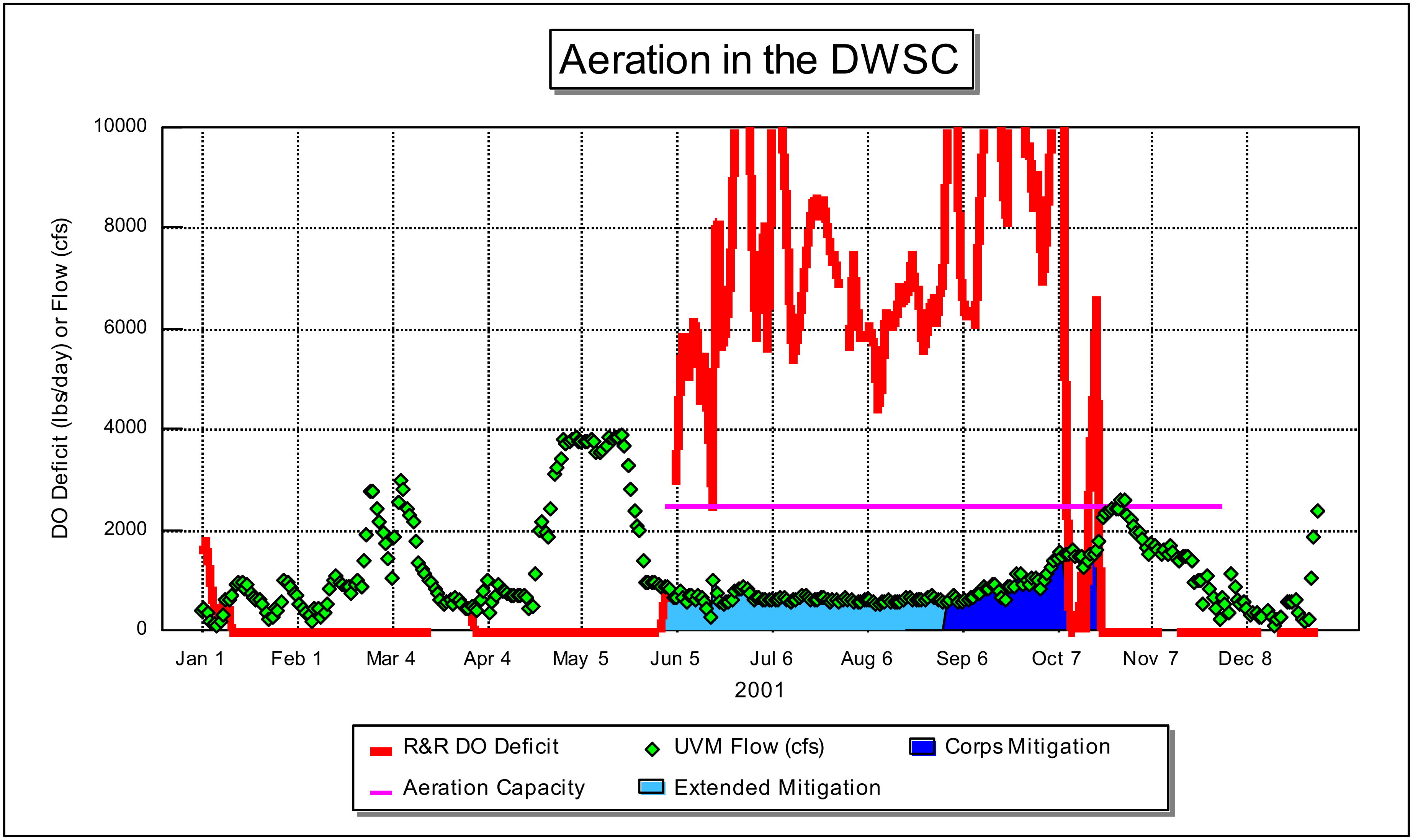
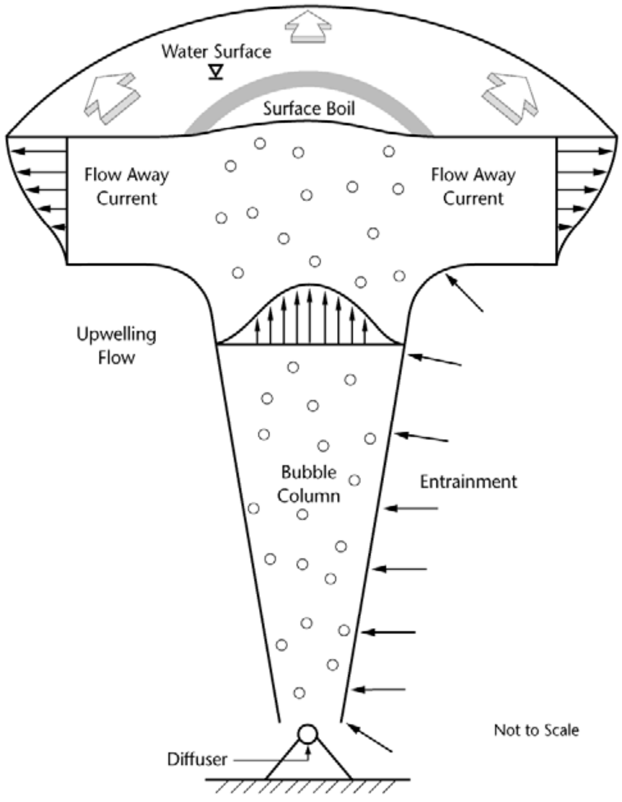
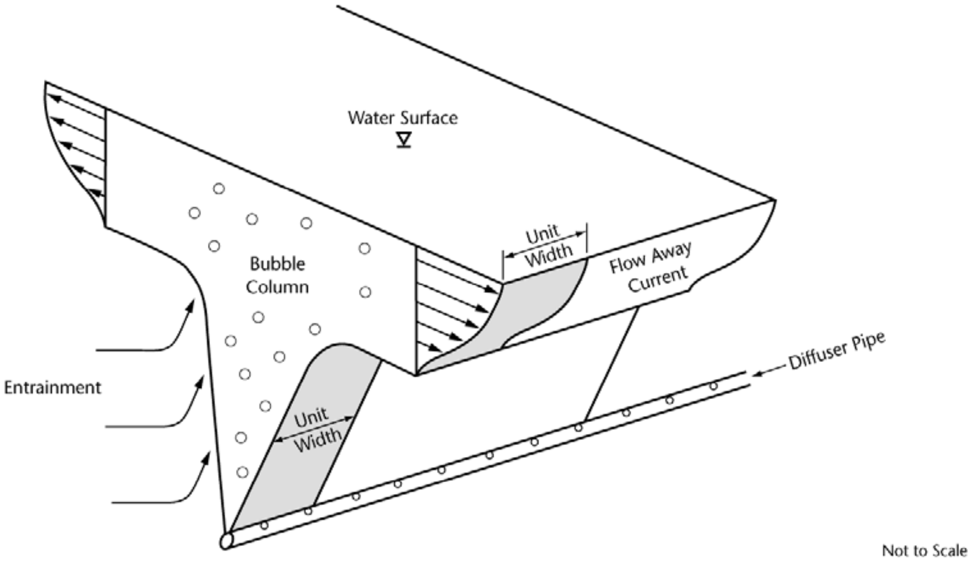


Figure 7. Diagram of Bubble Column Aeration Device



Point-Source Diffuser



Line Diffuser

Figure 8. Layout of Near-Field Upwelling Flow-Away Current Measurements for North and South Bubble-Jets of Corps of Engineers Stockton Aerator

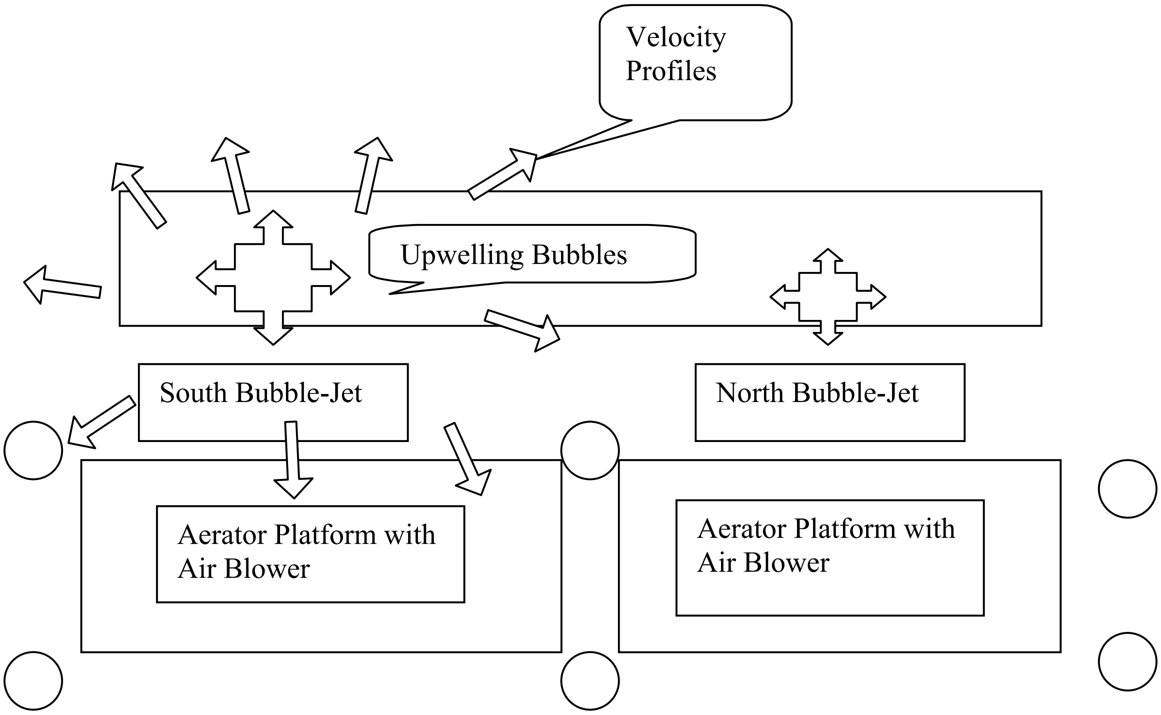


Figure 9. Vertical Temperature Measurements in the DWSC During July 2002

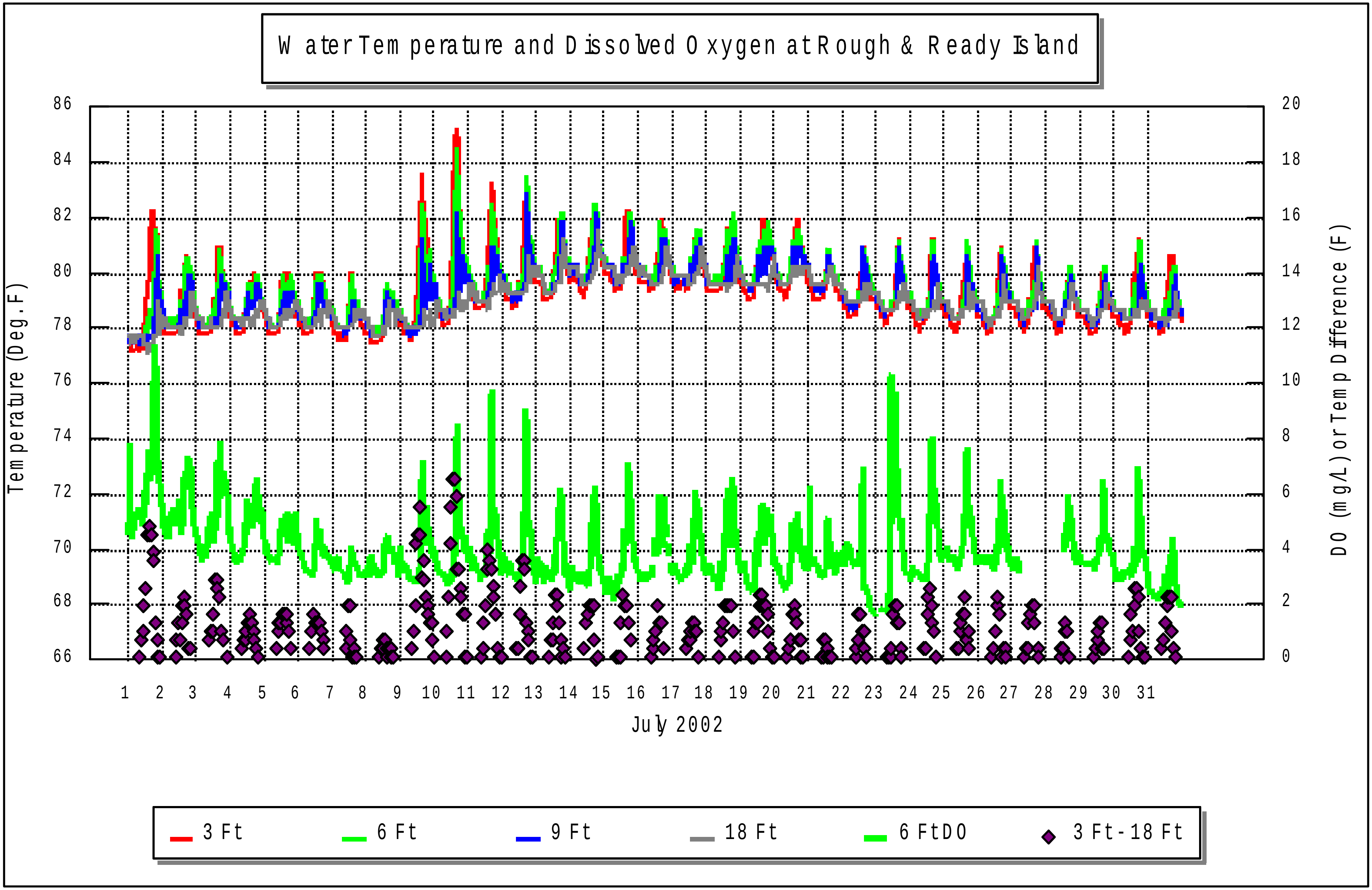


Figure 10. Construction of the MOBI Device

Figure 11. Ceramic Diffusers installed at Bottom of MOBI Device and Ready to be Lowered into DWSC

Figure 12. Calculated Oxygen Gas Flow and Meter Gas Flow in MOBI Experiments

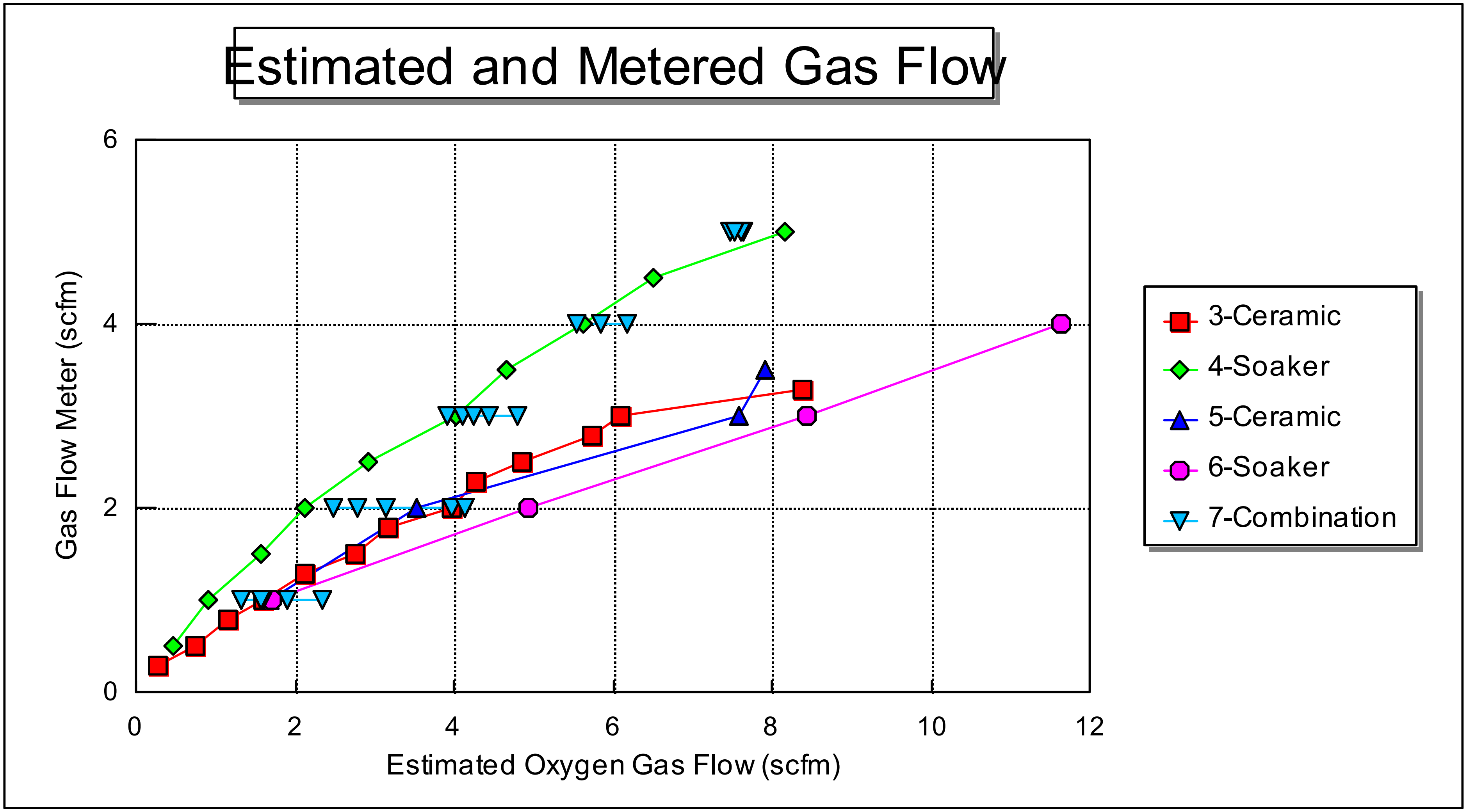


Figure 13. Upwelling Water Flow in MOBI Device As Function of Oxygen Gas Flow

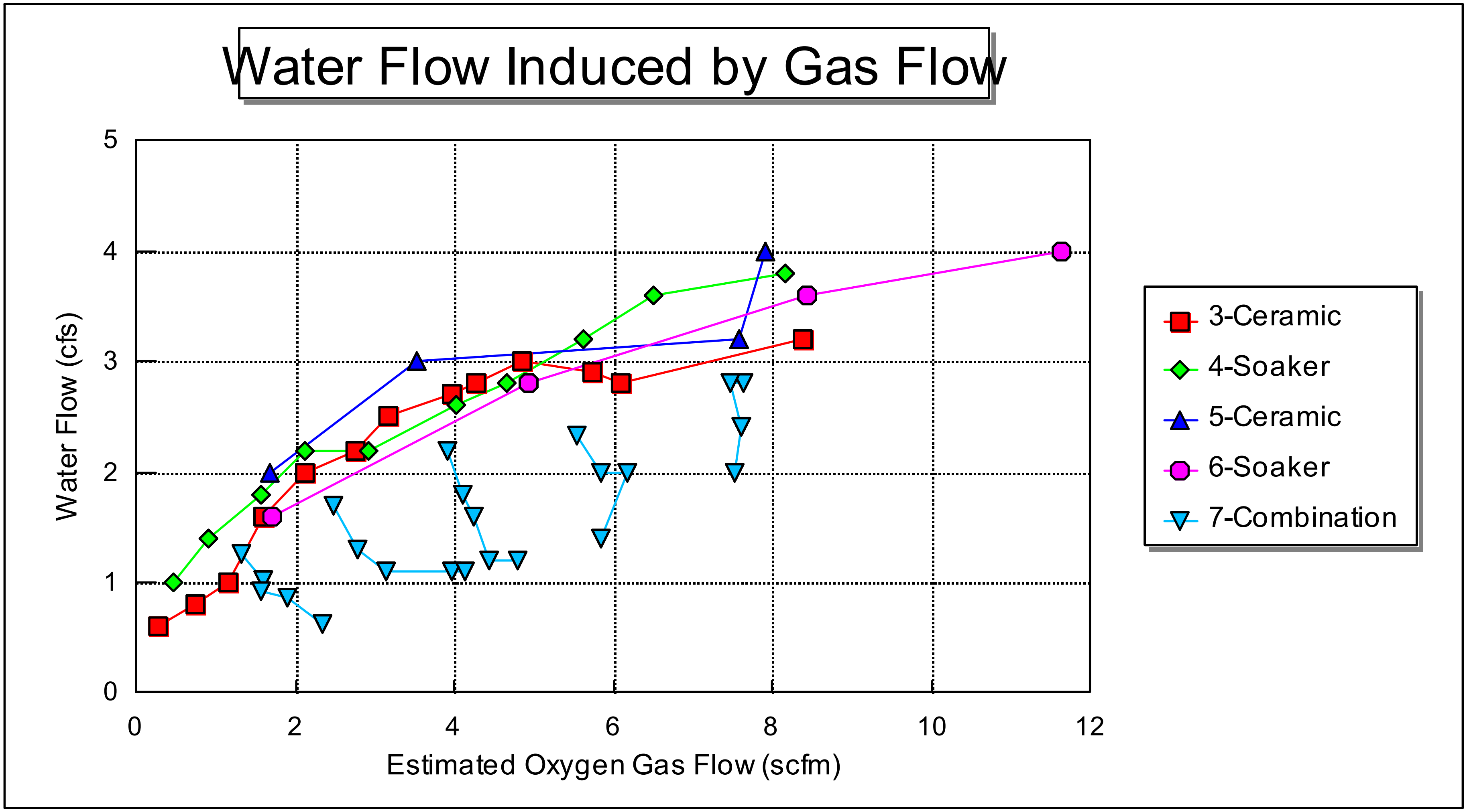


Figure 14. Measured DO Increment in MOBI Device as Function of Oxygen Gas Flow

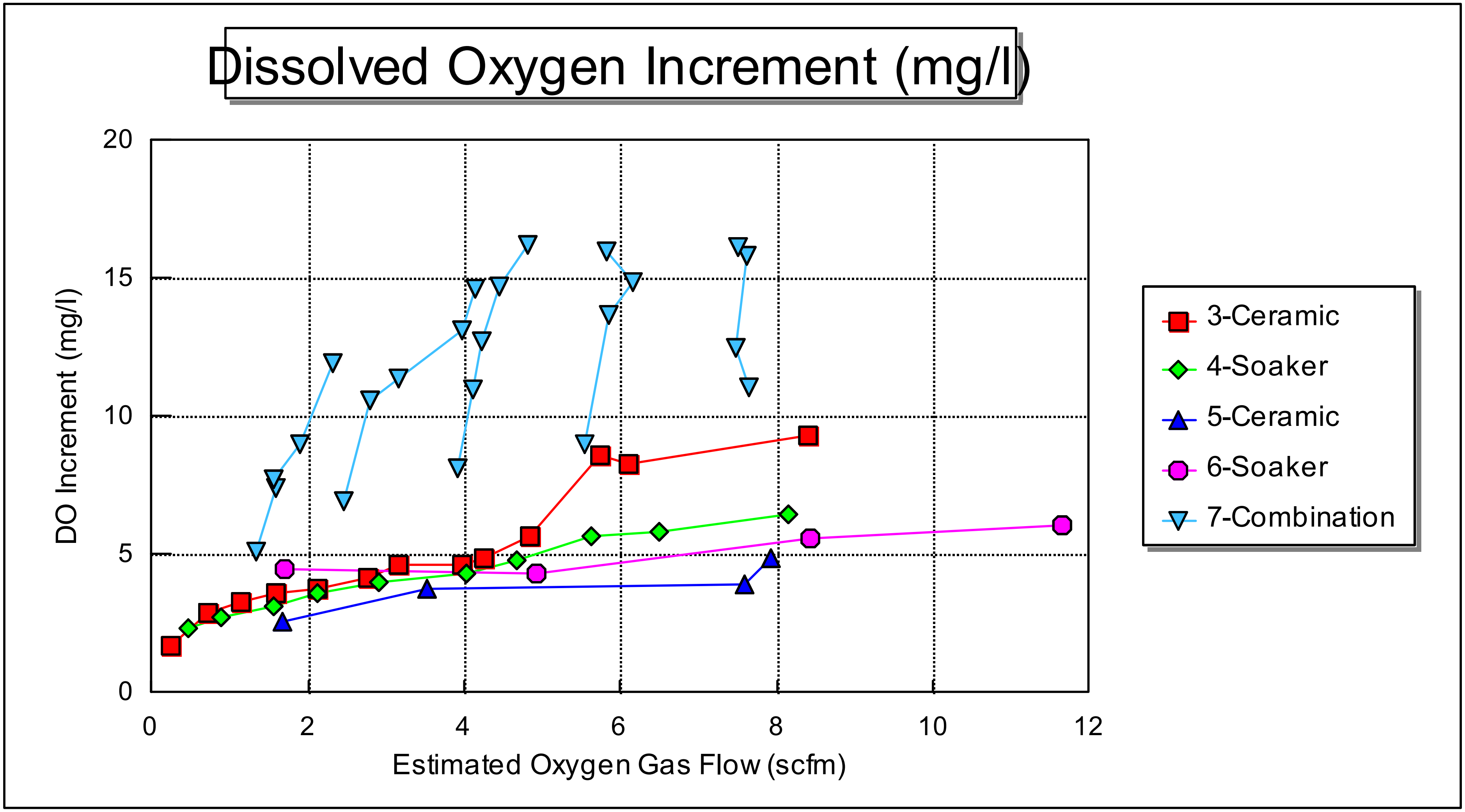


Figure 15. Measured DO Delivery Rate as Function of Oxygen Gas Flow

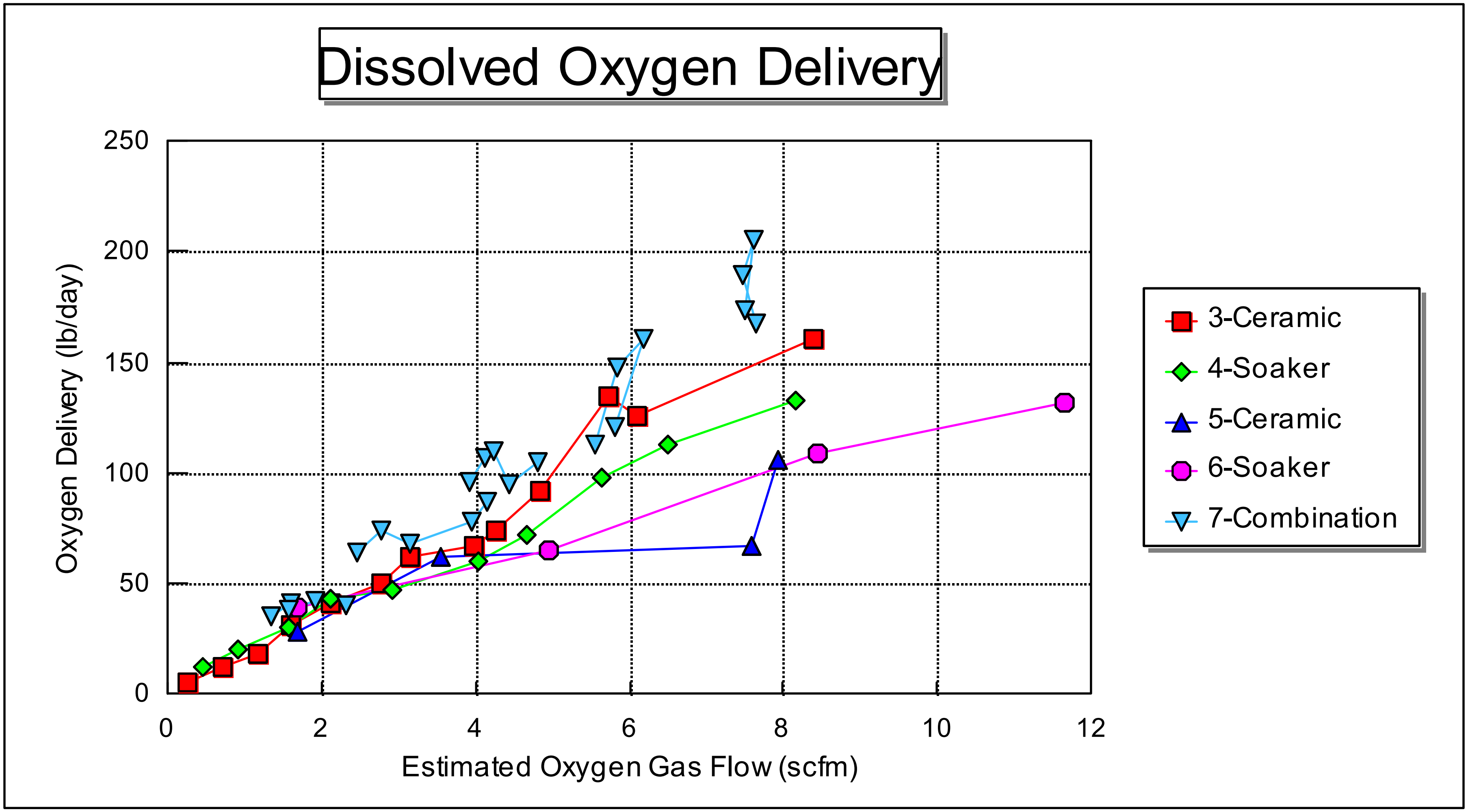


Figure 16. Oxygen Bubble Transfer Efficiency as Function of Oxygen Gas Flow

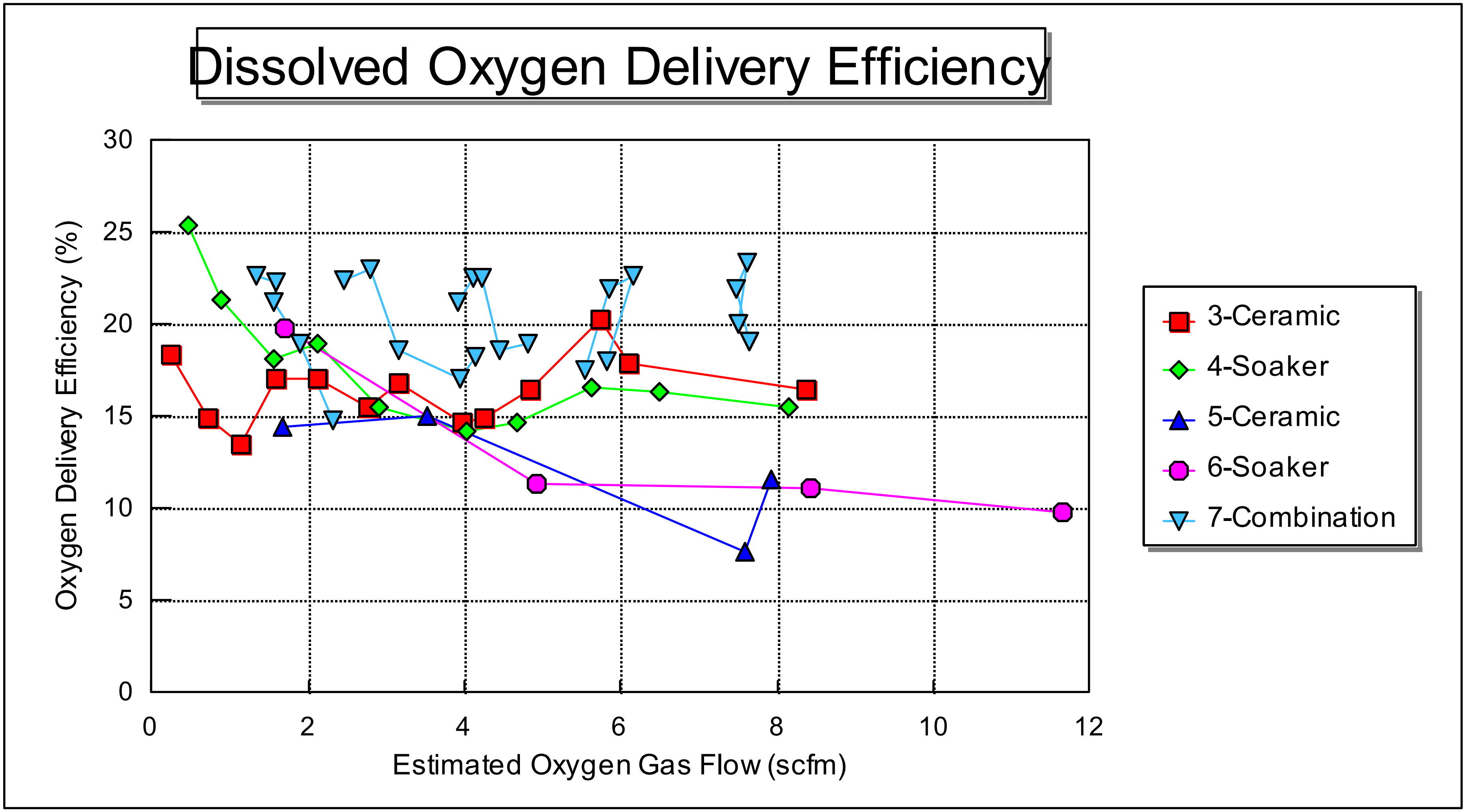


Figure 17. Measured Nitrogen Content of Exhaust Gas from the MOBI Device

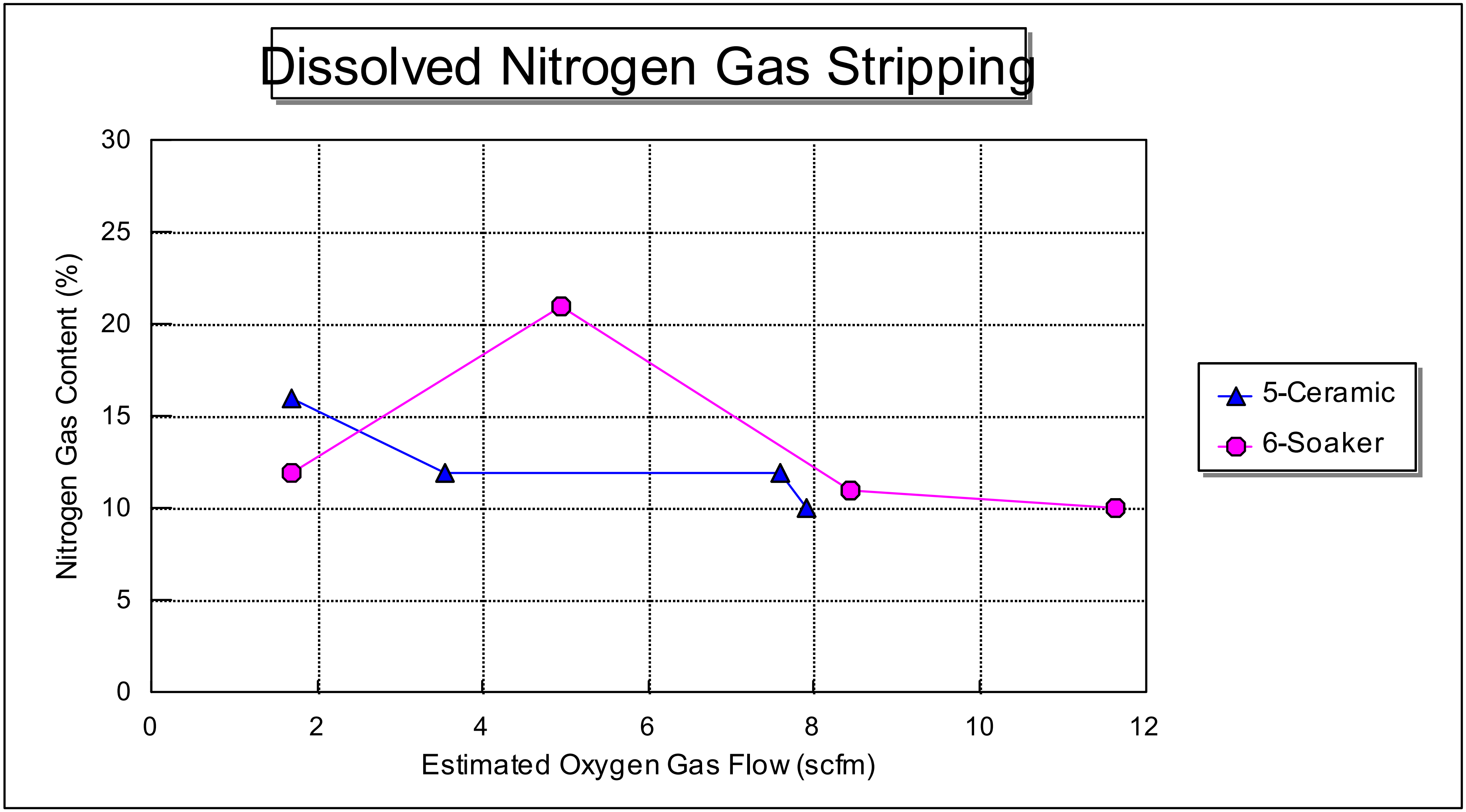


Figure 18. Potential Placement of MOBI Devices along the Port of Stockton Rough & Ready Island Dock

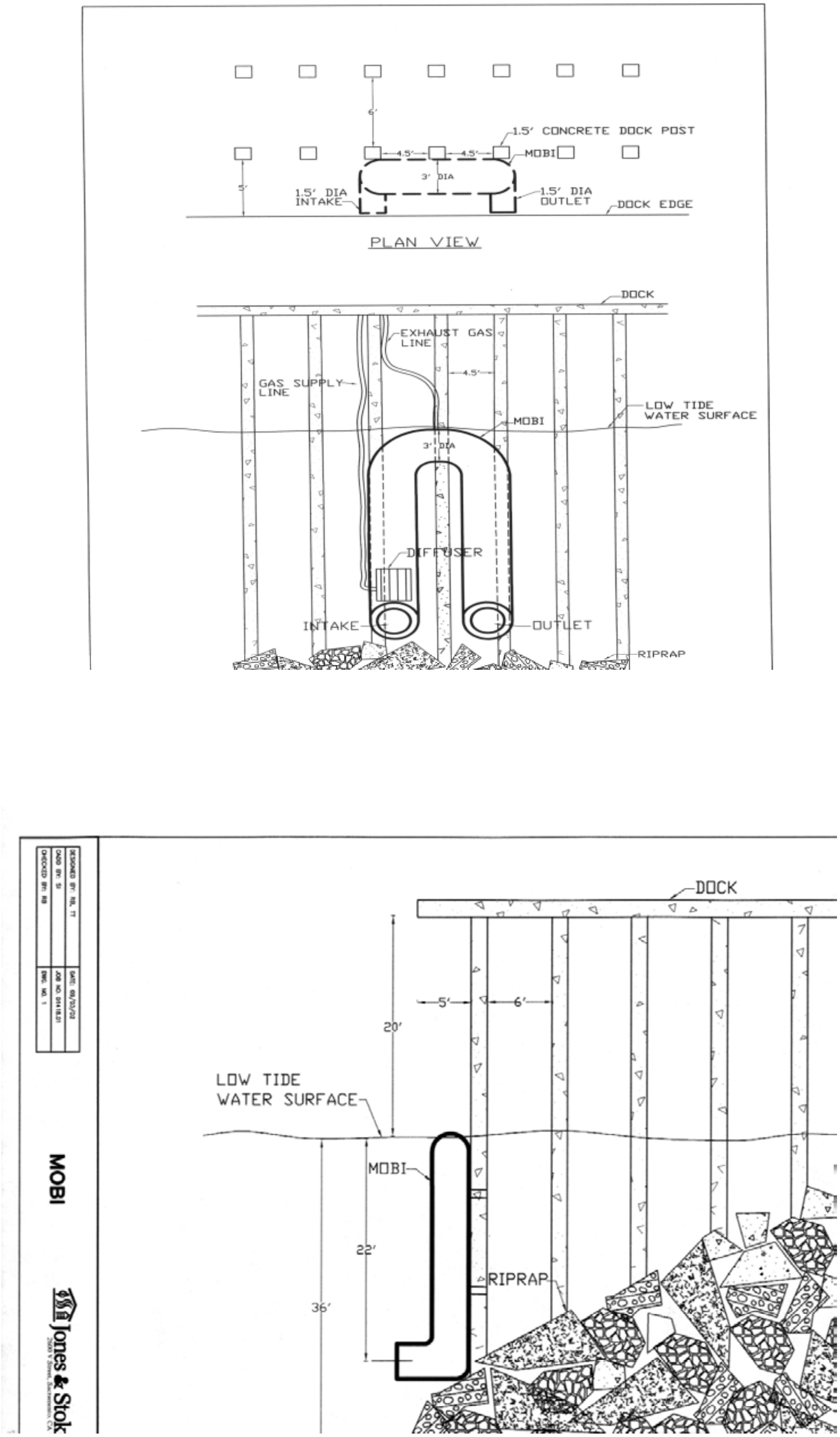


Figure 19. Upstream View of the Port of Stockton Rough & Ready Island Dock

Figure 20. MOBI Device Modified for Dye Study with Elbow and Nozzle

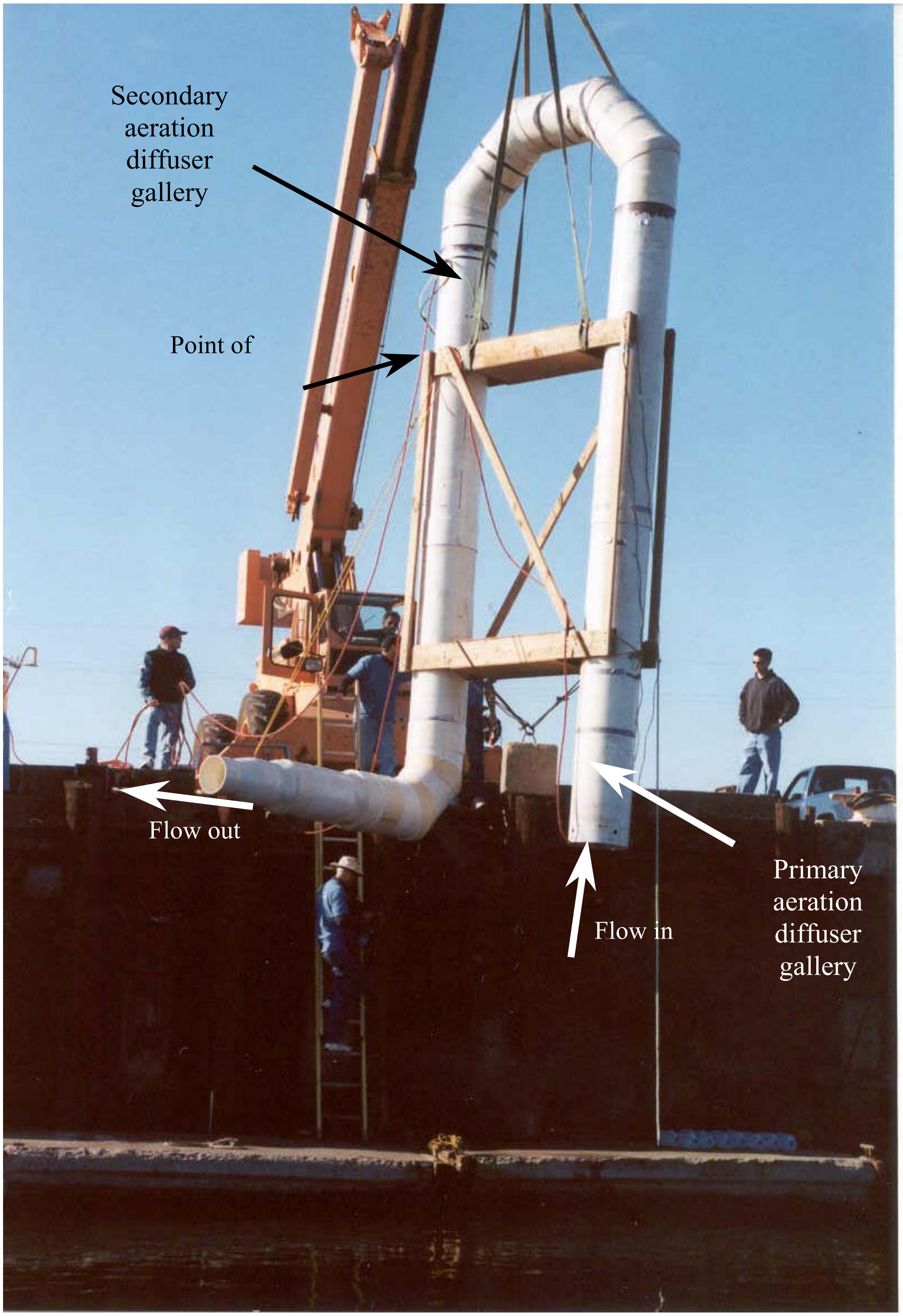
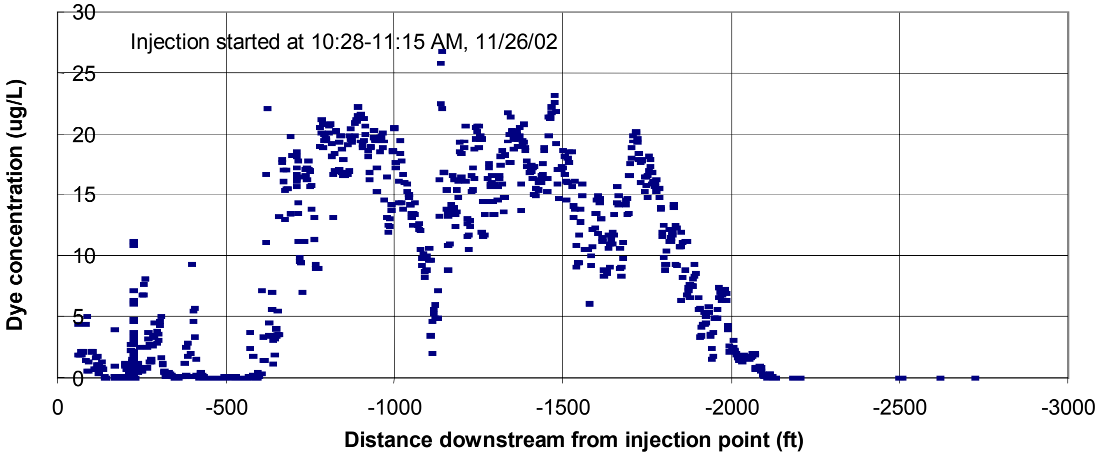
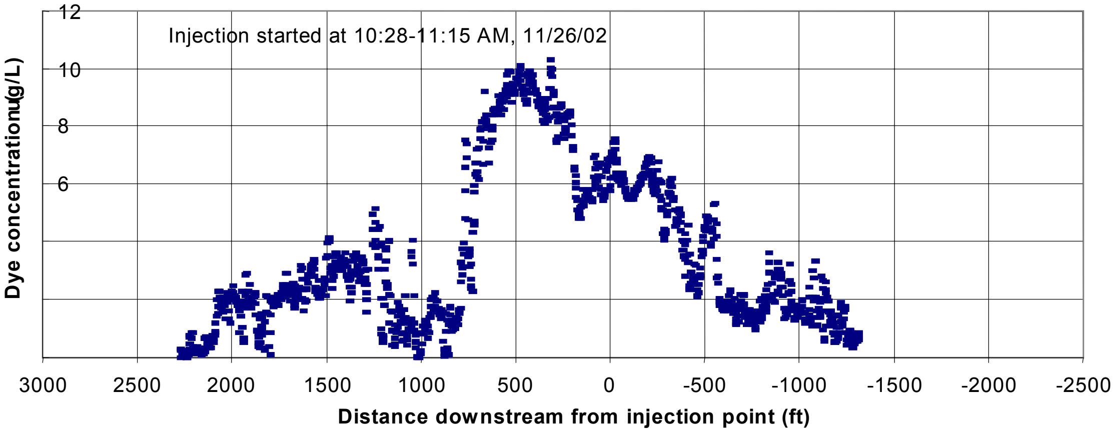


Figure 21. Longitudinal Spreading of Dye Plume by Tidal movement in the DWSC

A. One hour after dye injection ended.



B. Six hours after dye injection ended



C. 24 hours after Dye injection ended

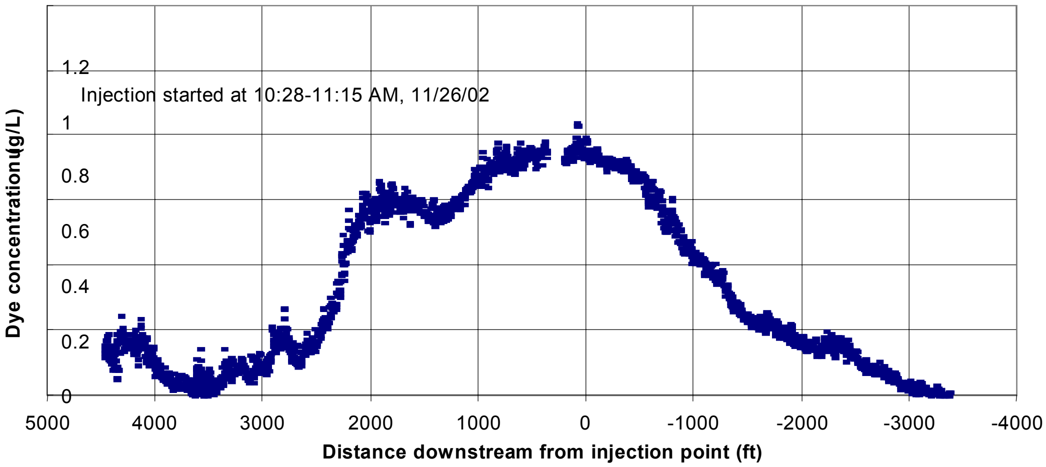


Figure 22. Vertical and Lateral Distribution of Dye at 1-hour after Injection (upstream 1,000 feet)

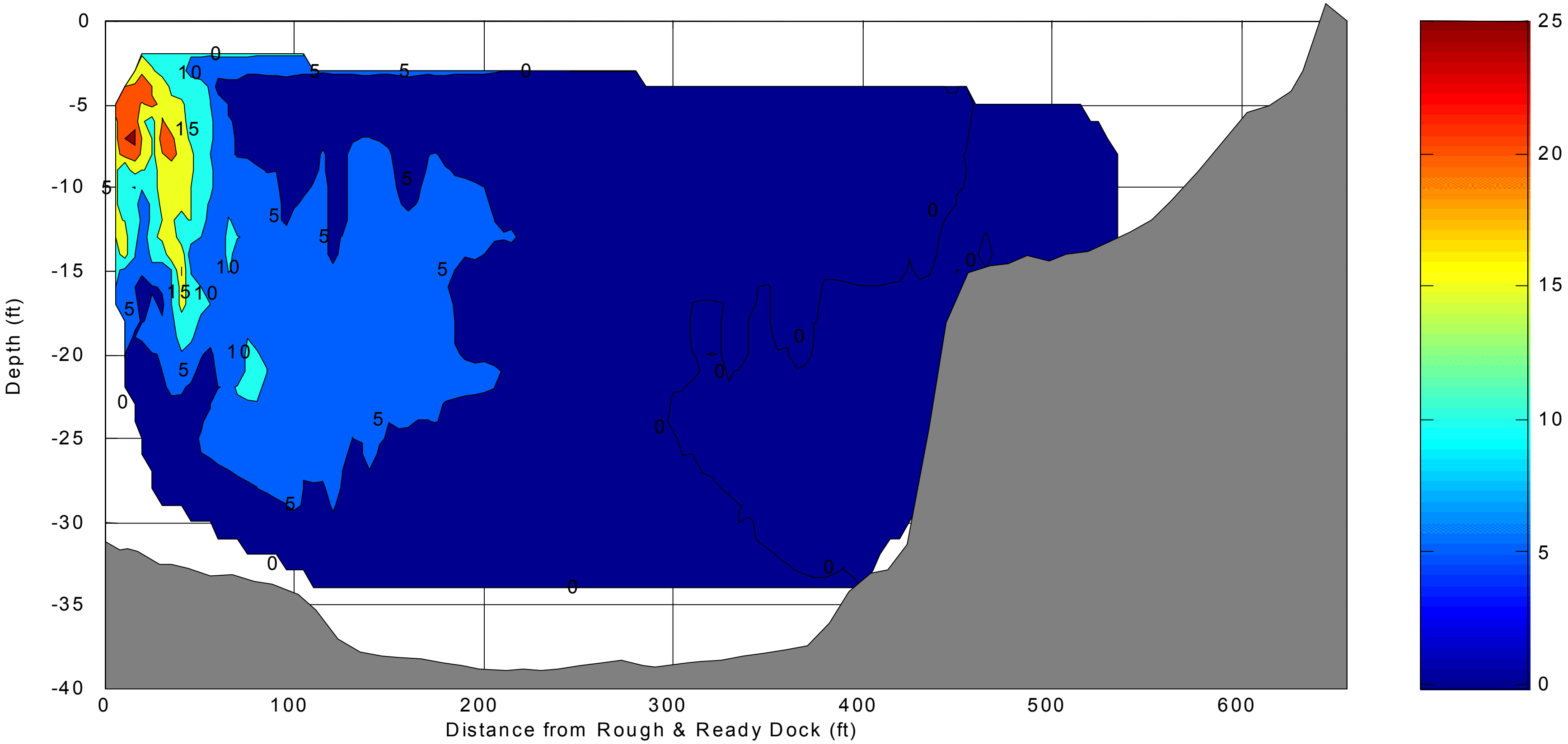


Figure 23. Vertical and Lateral Distribution of Dye after 6 hours (downstream 500 feet)

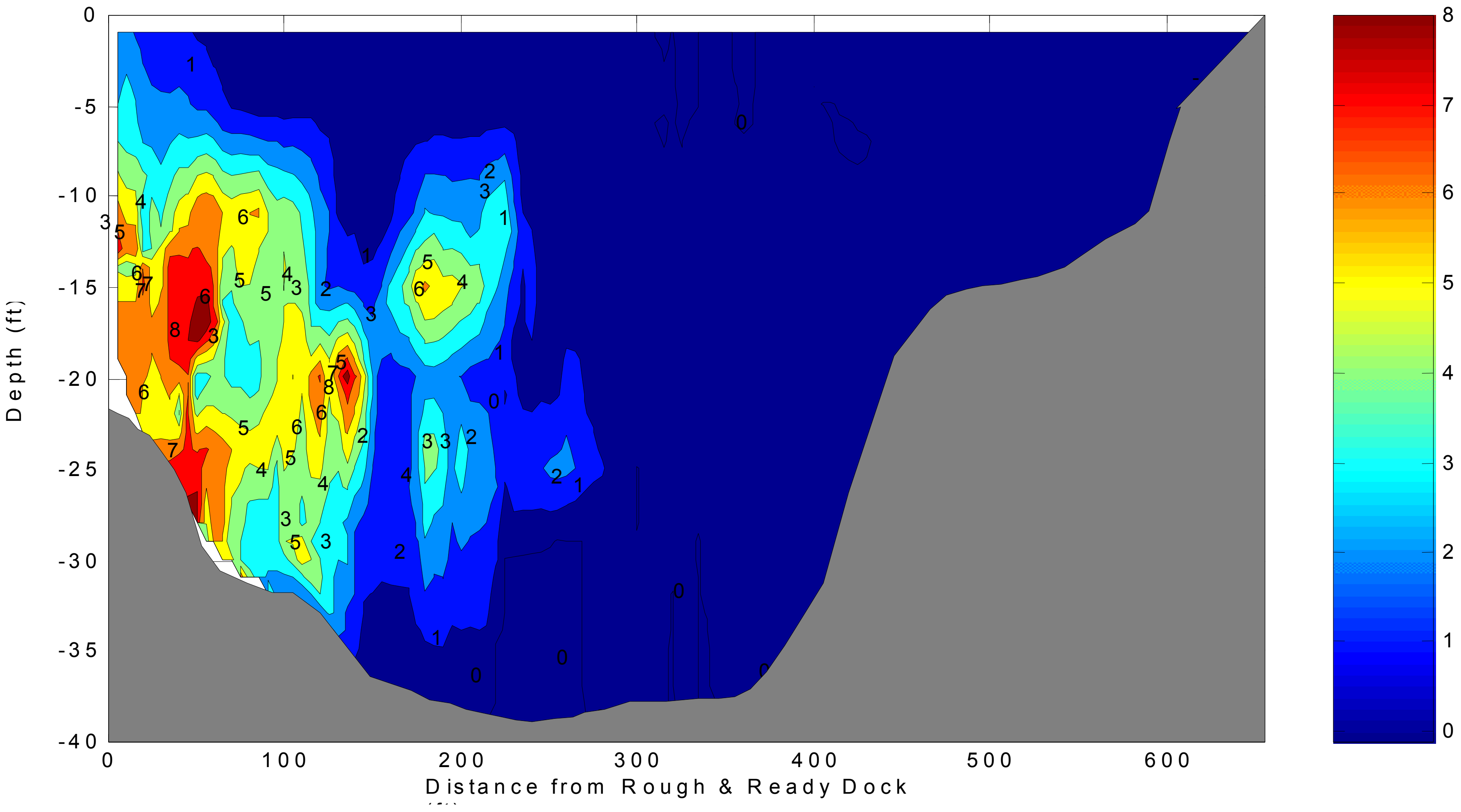


Figure 24. Vertical and Lateral Distribution of Dye after 24 hours (downstream 1,000 feet)

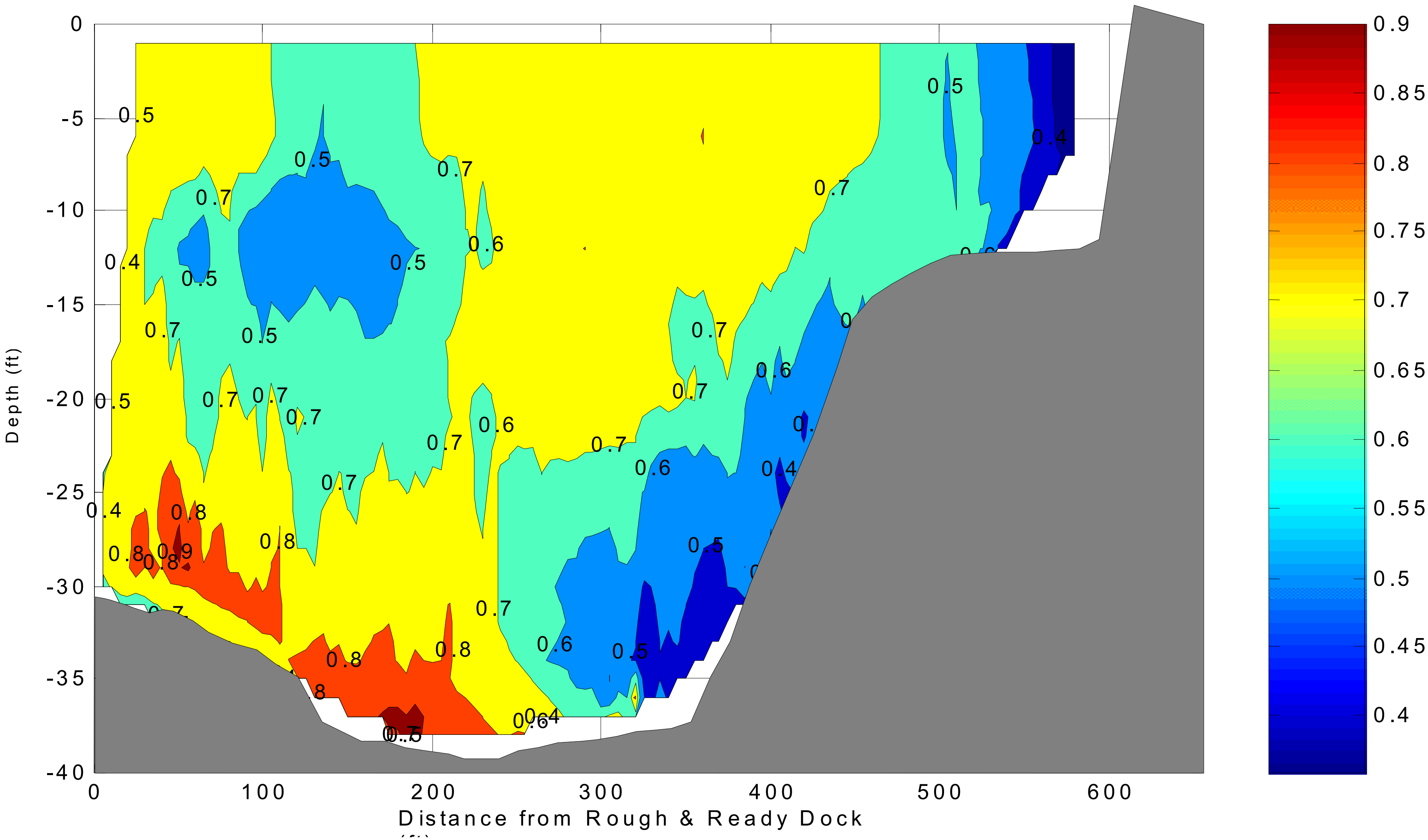


Figure 25. Results of Simple Lateral Spreading Model of the DWSC with 10% exchange rate