

**EVALUATION OF AERATION TECHNOLOGY  
FOR THE STOCKTON DEEP WATER SHIP CHANNEL**

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## 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). The natural reaeration that occurs at the surface of the San Joaquin River and the Stockton Deep Water Ship Channel (DWSC) is described to provide an introduction of the equations and coefficients that are used to quantify this process. The basic methods that are used to augment or artificially increase this oxygen gas transfer process in rivers and lakes (or reservoirs) are then described. The performance of the existing Corps of Engineers jet-diffuser device is summarized, and the engineering feasibility of alternative methods to increase dissolved oxygen (DO) concentrations in the DWSC with aeration technology are compared. Each alternative 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 assumed to be 3 mg/l while the DO objective for the DWSC is 5 mg/l. Figure 1 shows the location of the City of Stockton River water quality stations within the DWSC. The Department of Water Resources (DWR) continuous DO monitoring station is located at the downstream end of Rough & Ready Island, near the R5 sampling station.

## Natural Surface Reaeration in the DWSC

The natural surface reaeration process in the DWSC is described and quantified in terms of water velocity, water depth, and windspeed, as well as the DO deficit near the water surface. The likely magnitude of the reaeration in the DWSC is estimated from the water surface area, depth, and volume characteristics of the DWSC. The likely effects of stratification on reaeration are also discussed. The equations used to quantify water surface reaeration are useful in understanding and comparing the artificial aeration/oxygenation techniques.

The general mass balance equation for a mixed control 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)

$C_s$  = 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-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).

This is not the best form of the reaeration equation because the reaeration coefficient,  $K_2$ , expresses the combination of the depth of the surface mixed layer ( $V/A$ ) and the oxygen transfer velocity. By comparing the two equations it can be seen that  $K_2 = K_L * A/V = K_L / \text{Depth}$ .

The oxygen transfer velocity is related to the surface turbulence conditions that are primarily dependent on water velocity, windspeed and vertical mixing rates. The rate that this surface transfer will be able to change the DO concentration in the water volume is inversely proportional to the mixed depth below the surface. These two aspects of surface reaeration (i.e., transfer velocity and mixed depth) should be separately considered.

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:

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

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 windspeed (or other wave parameters). The water depth may influence the turbulence at the surface and does appear in most equations used for estimating the transfer velocity.

### Reaeration Rate Estimates

Several empirical equations for estimating values of the transfer velocity,  $K_L$ , have been used. As an example, the O'Conner-Dobbins equation is used in the Stockton water quality model that has been applied by the TMDL TAC 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 maximum tidal velocity is about 0.5 ft/sec, and the average tidal velocity is about 0.25 ft/sec. The maximum oxygen transfer velocity,  $K_L$ , is therefore estimated to be about 0.25 m/day and the average transfer velocity is about 65% of the maximum value (calculated from actual 15-minute tidal velocities measured at Rough & Ready Island), or 0.15 m/day.

The oxygen transfer velocity is expected to be higher in the SJR near the RWCF discharge. In this vicinity of the SJR channel the average depth is about 15 feet, and the maximum tidal velocity is about 1 ft/sec. The maximum exchange velocity near the RWCF is therefore about 0.5 m/day and the average exchange velocity is about 0.3 m/day (i.e., twice the exchange velocity as the DWSC).

Wind may substantially increase the 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 windspeed 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 an estuary. The coefficient of 0.05 may be as high as 0.10. In either case, wind effects may substantially increase the reaeration transfer velocity in the DWSC.

Another effect from windspeed on the DWSC reaeration is that the surface mixed depth will be increased during periods of higher winds. This will allow a greater 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 windspeed. An hourly simulation of the surface

mixed layer may be appropriate to evaluate these effects, since 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 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, the transfer distance will be 0.5 meters. For an average depth of 7.5 meters, the reaeration coefficient for the DWSC would be only 0.06 per day. Although the reaeration will follow an exponential approach to DO saturation, because the transfer velocity is so slow, the reaeration rate can be approximated as the transfer velocity divided by the water depth. This means that the DO deficit would only be reduced 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 deep. Reaeration in the upstream portions of the San Joaquin River is much greater (i.e., 3-4 times greater), because the 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 since 1 mg/l is equivalent to 1 g/m<sup>3</sup>. The reaeration transfer distance times the DO deficit will give the grams of DO transferred per square meter of surface area:

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

There are 4047 square meters per acre and 453 grams per pound. The DO mass transfer per acre per day can be calculated as:

$$\text{DO Mass (lb/day/acre)} = 8.9 * \text{transfer distance (m/day)} * \text{DO deficit (mg/l)}$$

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 and R5, 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 RWCF and SJR river loads of BOD.

### **Dissolved Oxygen Sag in the DWSC**

The DO concentration patterns in the DWSC are controlled by reaeration and algae production of DO as well as BOD (and SOD) decay processes. The BOD loads originate from the Stockton RWCF effluent and from upstream SJR sources, as well as from sediment oxygen demand and algal biomass growing within the DWSC. The City of Stockton water quality model uses a typical first-order DO sag equation coupled to the governing hydrodynamic equations for tidal flow within the DWSC. The current model

does not include effects from stratification on algal 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). Accurate analysis with a DO sag equation in a tidally influenced system requires information about streamflow, tidal flow velocities, and the inflow concentrations of DO, CBOD and ammonia, along with estimates of the SOD and BOD decay rate and reaeration rate.

An aeration system for the DWSC must be designed to reduce the observed DO deficit to satisfy a prescribed DO objective (i.e., 5 mg/l). Dynamic (time-varying) DO modeling is necessary to accurately integrate the major factors that seasonally influence the extent, duration, and location of adverse DO conditions in the DWSC. Dynamic modeling is also necessary to evaluate the potential solutions to DO sag conditions for the range of conditions encountered. However, if DWSC conditions are assumed to remain relatively constant and the general effects of artificial aeration are being evaluated, a simplified approach can be taken. The basic information for sizing an aeration system for the DWSC can be developed based on a simplified analyses of the worst case conditions which typically occur during summer periods. The aeration facility can be designed to increase the DO concentration near the DO sag location by the amount necessary to achieve the DO objective for the typical worst-case DWSC conditions.

Figure 2 shows the measured minimum and maximum DO concentrations at the DWR Rough & Ready monitoring station during 2001. The minimum DO concentrations are generally about 3 mg/l during the worst-case episodes. The saturated DO concentration is shown for comparison to indicate that the minimum DO concentrations are generally 4-5 mg/l less than saturation during the summer period. The minimum DO concentrations are therefore 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 saturation concentrations on some days. The reaeration rate, which is controlled by the DO deficit, is therefore less during these afternoon periods.

These worst-case summer 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, 2001). Net SJR flows through the DWSC are typically less than 500 cfs, and the travel time for water between R3 and R6 is therefore about 10 days because the DWSC volume from the turning basin to R6 is about 10,000 acre-feet.

The DO concentrations in the DWSC can be estimated with a mass-balance equation that includes each major source or sink for DO. This has been incorporated in a simple spreadsheet model of the DWSC, with several 1-mile volume segments. The mass transport of oxygen, BOD, or other constituent in the DWSC can be calculated as:

$$\text{Load (lbs/day)} = 5.4 * \text{Flow (cfs)} * \text{Concentration (mg/l)}$$

At a flow of 500 cfs, a 2 mg/l DO decline below the 5 mg/l objective is equivalent to a daily DO mass deficit of 5,400 lbs/day (i.e.,  $5.4 * 500 * 2 = 5,400$ ). 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 DO sag location that meet the Basin Plan DO objective of 5 mg/l.

Figure 3 illustrates the various processes that add or consume DO within the DWSC. The initial BOD concentration (and the BOD decay rate) and the SOD govern the DO losses along the DWSC. The reaeration is the major source of DO and depends on the DO deficit. The net flow controls the travel time as the water moves through the DWSC from R3 to R6. An estimate of worst-case total BOD concentration is about 10 mg/l (equivalent to a 5-day BOD measurement of about 4 mg/l). At a flow of 500 cfs, this is a total BOD load of 27,000 lb/day. The RWCF and the SJR are the sources for this BOD load. SOD has been estimated to range from 0.5 to 1.0 g/m<sup>2</sup>/day and is assumed to be uniform throughout the DWSC (Litton 2001). This range of SOD exerts a daily oxygen demand of about 1,115 to 2,230 lbs/day based on the channel bottom area (i.e., 250 acres) between stations R3 and R6. The origin of this SOD, however, may be settling of some of the total BOD from the river and RWCF discharge.

Reaeration depends on the estimated transfer velocity (i.e., 0.5 m/day) and the DO deficit. For an average deficit of 4 mg/l, the reaeration between R3 and R6 would add only about 4,500 lbs/day. However, the intermittent development of stratification near the water surface may restrict the reaeration of the DWSC. It is apparent from this comparison that the BOD loading far exceeds the oxygen source from natural reaeration.

### **Artificial Aeration: Process 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 the entire water column; and, (2) systems that selectively aerate 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. Mixing also enhances natural reaeration at the water surface by increasing the transfer velocity and/or the mixed depth.

In contrast, hypolimnetic aeration of stratified water bodies is sometimes preferred when destratification is undesirable. Destratification in some situations can have adverse impacts through eliminating coldwater habitat for fish and zooplankton, or distributing contaminants or mixing nutrients from areas with high concentration into the entire water column.

There are numerous standardized aeration techniques available including mechanical mixing only (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 and will not be described

further in this report. Other innovative methods have been developed, including pressurized side-stream oxygenation techniques and hollow fiber membrane diffusion. Describing the physical and chemical processes that govern the performance in terms of oxygen transfer rate, energy efficiency, and operational advantages of various aeration methods was beyond the scope of this report. In general, the efficiency of all aeration methods can be compared with their oxygen transfer efficiency factors. The governing equations for calculating oxygen transfer efficiency factors have been thoroughly developed for most aeration methods. This report was focused on identifying studies and data useful for application to the DWSC and for comparing aeration systems in common terms of oxygen transfer efficiency and energy requirements.

### **General In-stream Aeration Design**

The basic features of in-stream aeration can be illustrated with an air-bubbler system. An air-bubble diffuser will add DO to the river segment where it is located. The diffuser is installed at a specified depth and creates a stream of air-bubbles that provide a source of DO as the bubbles rise towards the surface. The effective pressure governing DO transfer between the air bubbles and the water can be estimated as about half the depth. A deeper bubble diffuser may have a greater oxygen transfer efficiency, but will require more power to provide the same air-flow rate. The DO transfer processes from a bubble plume to water are difficult to estimate from physical properties alone. 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 15 to 20 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 about 25 feet of water. Oxygen transfer efficiencies of lake, reservoir, and river aeration systems are typically determined with mass balance measurements of DO input and resulting changes in the water body DO concentrations.

The DO source from an air-bubble diffuser can be generally thought of as a function of the air flow rate, the 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 at the bubble-water interface), air or oxygen flow rate, diffuser density, bubble contact time with the water, bubble size, geometry of the water body, and turbulence around the bubble-liquid interface are all important factors for estimating oxygen transfer efficiency (Wagner and Popel 1998, Boyle 1986).

The use of pure oxygen can improve transfer efficiencies because compressed air only contains about 20% oxygen. Therefore the saturated concentration of water exposed to an atmosphere of 100% oxygen is about 5 times greater than exposure to air. Nitrogen gas supersaturation under increasing hydrostatic pressures, which can adversely impact metabolic processes in sensitive fish, is also avoided with the use of pure oxygen.

The oxygen transfer efficiency of aerators can be expressed in a variety of units. 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.

A review of hypolimnetic aerator efficiencies is available based on oxygen transferred as a percentage of the total amount delivered through the diffusers (Beutel and Horne 1999). The reviewed data indicate that hypolimnetic aerators have been shown to be extremely efficient. Hollow fiber membranes have also been shown to have high oxygen transfer efficiencies (Weiss et al. 1994, Ahmed and Semmens 1996) approaching 90% to 100% with relatively low concerns for long-term biological fouling. Hollow fiber technology uses bundles of microporous fibers commonly with outside diameters ranging from 260 to 8500  $\mu\text{m}$  and providing large surface area for gas transfer. Air or oxygen is fed to the fibers in flowing water at elevated pressures (up to 100 psi) which effectively increases the partial pressure exerted at the water interface and increases the potential saturated DO concentration.

The oxygen transfer efficiency is tested empirically for a range of air flow rates and depths (with a measured electrical power input to the air blower) at the maximum possible DO deficit (9.2 mg/l at a temperature of 20 C). The oxygen transfer at other conditions can be estimated as:

$$\text{DO Source (lbs/day)} = \text{Power (kWh/day)} * \text{Maximum DO transfer rate (lbs/kWh)} \\ * [\text{Saturated DO} - \text{Segment DO}] \text{ (mg/l)} / 9.2 \text{ (mg/l)}$$

For example, aeration equipment in activated sludge tanks have maximum DO transfer rates of about 5 lbs/kWh for a tank depth of 20 feet. If this transfer rate could be achieved with an in-stream aeration bubble diffuser when the DO deficit was 3.4 mg/l (i.e. to maintain 5 mg/l with a temperature of 25 C), 925 lbs/day would result from a power input of 500 kWh per day (i.e.  $500 * 5 * 3.4 / 9.2$ ). This can be compared with the DO source required to increase the river DO concentration by 1 mg/l. For a net river flow of 500 cfs, the DO source required to increase the DO concentration by 1 mg/l is about 2,700 lbs/day (i.e.  $5.4 * 500 \text{ cfs} * 1 \text{ mg/l}$ ). Three diffuser installations of about 500 kWh/day each would be sufficient to increase the river DO concentration by 1 mg/l with a river flow of 500 cfs in August.

## 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 (i.e., 1 ft<sup>2</sup>/sec). The aeration improves with higher waterfalls. A typical design height is 5 feet. The maximum efficiency (i.e., DO deficit that can be aerated with a waterfall) is about 50%. The design equation for the waterfall(s) can be formulated as the required flow from the river times the height of the falls. The pumping costs can be easily estimated because a 1 HP pump (0.75 kW) can lift a flow of 1 cfs with a head of about 8 feet. The 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 partially towards saturation at atmospheric pressure (i.e., 8 mg/l at 80 F). For example if the saturated DO is 8 mg/l and the water DO is 4 mg/l, one 5-foot high waterfall will increase the concentration to 6 mg/l. To raise the entire volume by 2 mg/l the entire volume must be pumped over the waterfall. This is a lot of pumping.
- 2) Air or oxygen bubble diffusers- pipes, hoses, or porous diffusers producing bubble columns near the bottom of the water column. Performance of these devices can be described in terms of the depth of the bubble column (controlling the saturated DO vapor pressure), 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" hose) 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 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 Corps of Engineers 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 in a high-velocity jet that transports the bubbles into the water column. The water jet is used to "shear" the air flow into small bubbles in the special 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 can be located at the edge of the water column without any diffuser lines on the bottom. Either air or pure oxygen can be used as the oxygen supply. One problem with the bubble devices is that the aerated water ends up on the surface where the DO may already be high, rather than in the bottom layer where the DO is lowest.

- 3) Pressurized side-stream aeration systems pump a portion of the water into a high-pressure mixing chamber (at 2-5 atmospheres of pressure) so that the saturation concentration of oxygen is increased substantially. This high DO concentration water is then mixed back into the water column. The volume of water being pumped is reduced 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 energy costs may be reduced compared to the waterfall/cascade technique. Porous diffusers or hose diffusers have been used in the high-pressure chamber. The same principle has been applied to in-channel devices called U-tubes. Air or oxygen is injected into water that is forced through a tube that extends down into the water. At depth, the greater hydrostatic pressure on the bubbles increases the volumetric rate of oxygen transfer and bubble contact time is longer since the water is initially going in a reverse direction in the tube and overrides the bubble rise velocity.
- 4) Water fans can be 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. 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). 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 be used in combination with air bubblers to redistribute the upwelling high DO water back into the deeper portions of the DWSC.

Each of these four basic aeration techniques will now 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 described. The two major operational costs will be electricity to run pumps and air blowers (i.e., compressors), and the cost of pure (i.e., industrial 90%) oxygen. The cost of electricity has been 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).

## Literature Review and Evaluation

Two relatively old EPA documents provide a thorough review of lake aeration/circulation techniques and the ecological benefits that have been achieved. Bubble columns will transfer oxygen from the 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.

The first report to be reviewed is titled "A guide to Aeration/Circulation Techniques for Lake Management" (Lorenzen and Fast, 1977). This EPA document 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. One interesting result described in this report is that the seasonal temperature stratification was eliminated with aeration bubble columns without raising DO concentrations in the hypolimnion of several reservoirs. This indicates that DO stratification may persist even after vertical mixing is sufficient to eliminate the vertical temperature gradient. This suggests that DO decay processes are sometimes "faster" than surface heating mechanisms, so that mixing may reduce the temperature gradient without completely mixing the DO profile. This appears to be the general condition observed in the DWSC. There is often a slight DO gradient but rarely much of a temperature gradient in the DWSC. The rate of mixing required to maintain a uniform vertical DO concentration profile is greater than that required to maintain a constant temperature profile.

## 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:

$$\text{Efficiency (\%)} = 100 * (\text{Cs} - \text{DO downstream}) / (\text{Cs} - \text{DO upstream})$$

Where the DO downstream is 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.

Because the aeration is bounded by the saturation deficit, the efficiency is a maximum of 1, and the effects of height are less effective as the height increases beyond 5 or 10 feet. This is referred to as a saturating effect, with the efficiency increasing as height<sup>0.5</sup>. The efficiency of a 2 feet high waterfall is 1.4 times that of a 1 feet high waterfall. The efficiency at 4 feet is 2.0 times that at 1 feet. The efficiency at 9 feet is 3.0 times that at 1 feet. A waterfall height of 3 feet or 5 feet was selected for the Chicago SEPA stations. They used three or four waterfalls (cascade) with a combined height of 12-15 feet at the five stations.

The increased efficiency with reduced discharge per unit width suggests that a relatively small discharge value of 1 cfs per foot of waterfall width should be used. For a pumping rate of 500 cfs, a waterfall width of 500 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 total waterfall frontage.

If the aeration efficiency is 50%, then the increment in DO 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 may be warmer than 21 C (70 F) and the saturated DO will be less than 9 mg/l. The waterfall would increase the DO from 5 mg/l to 7 mg/l, increasing the DO content by 2 mg/l. For a flow of 500 cfs, this additional DO mass will be 5,400 lbs/day.

This 500 cfs waterfall will require a pumping head of at least 10 feet because there is a 4 foot tidal range and the waterfall needs to be at about 5 feet high. 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 500 cfs waterfall with a pumping head of 10 feet with a pump efficiency of 0.8 would be about 12,500 kWh per day. At an assumed price of \$0.10/kWh, the electricity cost for the waterfall would be about \$1,250 per day. The cost per pound of oxygen added would therefore be about \$0.23 per pound. This is twice the current price for industrial oxygen in a tank, but the oxygen from the waterfall is already added to the water.

A cascade of two waterfalls can be compared. The second waterfall would increase the DO from 7 mg/l to 8 mg/l (i.e., reducing the remaining deficit by 50%), adding 2,700 lbs/day. But the increased pumping costs for an additional 5 feet of head will be \$625 per day. Therefore the cost per pound of oxygen will still be \$0.23/lb. The advantage of a cascade will be that a DO increment of 3 mg/l can be achieved in the pumped water for these design conditions. The cost of operating the waterfall per pound of oxygen added will be greater if the intake DO is higher. The waterfalls would 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 keep the waterfall facility visually and aesthetically functional (i.e., prevent stagnation and scum formation) as a water park.

The design for the waterfall facility should include an intake (with fish screen) that is 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 pipe drain should return the aerated water to near the bottom of the DWSC. This can be easily accomplished with gravity assuming a small head difference at high tide. Locating the waterfall pond at elevation 5 feet, there will always be sufficient head to return the aerated water to the bottom of the channel through a large discharge pipe.

### **Review of Chicago SEPA Stations Performance**

The most well known waterfall facility for aeration of a river is the Metropolitan Water Reclamation District's side-stream elevated pool aeration (SEPA) stations along the Calumet Waterway Cal-Sag channel. This navigation channel (connecting the Des Plaines River with Lake Michigan is 225 feet wide, 9 feet deep, and is extremely slow moving with a one-foot drop over the length of the 17-mile long channel. 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 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 (Butts et al 1998) that the cascades (3-4 waterfalls of 3-5 feet each) produced water that was more than 90% saturated with DO. A majority of the aeration occurred in the large screw pumps. The effects of the waterfall stations effluent on the river DO was more difficult to detect (Butts et al 2000). A cascade of 3 waterfalls with a combined drop of 10 feet will likely provide a reaeration efficiency of 90%.

### **Simplified Modeling of Waterfall Method for the DWSC**

A simplified representation of the DWSC DO balance has been formulated in a spreadsheet model so that changes in the design conditions and waterfall size can be quickly compared. For the example shown in Figure 3, the inflow BOD concentration was 10 mg/l, the BOD decay rate was 0.1 per day, the SOD was 1 g/m<sup>2</sup>/day and the reaeration velocity was 1 m/day. The temperature was 25 C (DO saturation of 8.4 mg/l) and the channel flow was 500 cfs. A 250 cfs waterfall is assumed to be located between R4 and R5, with an aeration efficiency of 90% (i.e., 3 waterfall cascade). The base condition DO sag is 4 mg/l at station R6. The waterfall facility is able to increase the DO by about 1.5 mg/l at R5 and maintains the DO objective of 5 mg/l at R6.

## **Bubble Column Aeration Performance**

Bubble diffusers produce bubble columns near the bottom of the water column that rise to the surface with a nearly constant speed of about 1 ft/sec. This rising bubble plume creates an upwelling flow of water that generally rises to the surface and then flow back down to the matched density (i.e., temperature) layer. The bubbles will dissolve some of the oxygen from the bubbles into the water that is upwelling with the bubbles, but most bubble aerators provide most of the aeration performance by circulation of the surface water into the deeper layers of the lake or reservoir. Performance of these bubble columns devices can be described in terms of the air (or oxygen) flow rate, the depth of the bubble column (controlling the saturated DO vapor pressure), and the size of the bubbles (controlling the area for oxygen transfer). Porous (i.e., ceramic) heads, pipe with holes, or porous hoses (i.e., garden "soaker" hose) 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 is about five times that for air, because air is only about 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 gas, relative to energy cost for compressed air, is usually compensated for by this increased oxygen transfer efficiency.

The Corps of Engineers aeration device, located just where the SJR 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 bubbles. The water jet is used to "shear" the air flow into small bubbles in the special 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 without any diffuser lines on the bottom of the DWSC. One problem with bubble column aerators is that the aerated water ends up on the surface where the DO may already be high, rather than in the bottom layer where the DO is lowest.

### **Corps of Engineers Water-Bubble Jet Device**

The existing Corps of Engineers Device is a water-air bubble jet device (Nichol and Slinkard 1999). Several measurements of the water-air jet performance characteristics have been made. The operation of the device is presented and the performance of the device is described.

The Corps 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 to create the air supply for the eight jets. However, the size of the air bubble is sensitive to the air flow rate, so a relief valve is provided to reduce the air flow rate to the jets. Unfortunately, the resulting air flow rate to the jets is not measured. A considerable volume of hot 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 bubble rise directly up towards the surface, without any horizontal spreading across the channel.

### **Upwelling Current Measurements**

An initial field test of the two water-air jets was made on September 26, 2001. The method was to measure the upwelling flow and DO concentrations from each jet diffuser operating separately (i.e., the other air blower turned off) with a series of vertical velocity and DO profiles at various points around a 10-15 feet radius circumference. The profile was assumed to represent the arc of the perimeter that extended mid-way to the next profile location. The profiles were measured from the port dock and the deck of the aeration device that holds the two air compressors and electrical switch boxes.

Figure 4 shows the layout of the ship dock and air-compressor deck. 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 215 cfs. 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 7.4 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 basic idea is that the upwelling water is dissolving some of the oxygen from the air bubbles. The actual increment in DO that the bubbles are producing is difficult to estimate. If the DO increment was 0.8 mg/l, and the flow away current was 215 cfs, then the flow-away current carried about 925 lbs/day of oxygen (i.e.,  $5 * 215 * 0.8$ ). The design of each set of water jets was 1,250 lbs/day.

The flow-away current has a relatively uniform DO concentration that will increase the DWSC DO concentration only if the flow-away DO is higher than the DWSC surface DO. The overall performance of the bubble-jet is therefore dependent on the DO deficit of the entrained water (i.e. DO transfer from the bubbles), as well as the difference between the upwelling water DO and the surface DO in the DWSC. Both of these differences will be greatest at night. During the daytime, the surface of the DWSC DO concentrations will often be increased by algae photosynthesis and wind-enhanced surface aeration. The DO increase from these processes will be greatest when the surface layer of the DWSC stratifies from solar heating during the day. The best transfer from the bubble-jet is therefore likely to be at night.

If all of the measured flow-away current is reaching the DWSC or the SJR flow moving upstream on flood tides and downstream on ebb tides, then this water will be increasing the average DO in the SJR flow and DWSC. But some of the flow-away current moving towards the shore (50 feet away) may be circulated back down towards the jet and be re-entrained in the bubble plume. Perhaps only the portion (50%) of the flow-away current moving out into the river channel will be captured by the SJR flow and increase DO in the DWSC. The benefit of the aerated water will be lost if the surface layer of the DWSC

DO concentration is already similar to the flow-away DO (i.e., 7.5 mg/l on September 26, 2001).

The north jet was also tested on September 26, 2001. Although the air pressure between the compressor and the jet was about the same as the south jet (i.e., 7 psig) the air bubbles appeared to be smaller and substantially less air was upwelling at the surface. The resulting flow-away current was measured to be only 40 cfs. The maximum 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 foot. The DO concentration in this smaller upwelling flow averaged about 8.0 mg/l, suggesting that the smaller DO bubbles were more effective in saturating the DO concentration in the upwelling flow. But the upwelling flow was not strong enough to move much of this saturated water into the DWSC or the SJR flow. The flow-away current from the north jet carried an estimated 225 lbs/day of oxygen.

### **Mass-Balance Measurements**

The planned method for measuring the performance of the bubble-jet device was to compare the DO concentrations across the channel at the Port of Stockton railroad bridge, located 600 feet upstream, with the device turned on and then turned off. A series of DO profiles were measured at 5 m spacing with 1 m depth increments on October 3, 2001. This provided 65 DO measurements across the channel as shown in Table 1.

Velocity profiles were also measured during the period of constant upstream flood tide between the low tide (1 pm) and the high tide (6 pm) on the afternoon of October 3. The estimated flow from the velocity profiles was 1750 cfs. This is a reasonable flood tide flow compared with the UVM station records. The flood flow becomes fully established about 2 hours after low tide.

Unfortunately, the DO variation across the river channel during the survey was much higher than expected. At the deepest section (left side of the center bridge column), the vertical gradient was more than 1 mg/l. At the 15 m location, the DO gradient 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 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 increment of 2,500 lbs/day).

Both air-compressors were turned off and a float (submerged water bottle) was released from mid-channel opposite the bubble-jets to mark the tidal flow that would not have any aeration DO increment (there might be some remaining increment of DO from the previous ebb tide several hours earlier). A second set of DO profiles were obtained, starting at 6 PM using a 10m spacing (because time for flood flow was running out). The velocity measurements confirmed that the flood tide flow continues for about an hour after high tide.

The DO variations across the channel and vertical differences were still much greater than the expected DO decrease from turning off the aeration device. The DO change was

positive in some surface locations, possibly caused by high surface DO "patches" from earlier algae growth. The DO decreased in several of the measurement locations, as expected. The overall change in the DO mass flux was about 740 lbs/day. If this average change in DO between the two sets of DO profiles could really be trusted, this would indicate a performance that is 30% of the design (i.e.,  $740/2500 = 30\%$ ). However, the variability in the DO profiles was much greater than expected and the uncertainty of this mass-balance method of differences is considered too high to be reliable. Additional mass-balance measurements will be attempted if the tracer-gas method cannot be used.

### **Tracer-Gas Method**

The tracer gas method using propane as the tracer gas should provide much more accurate results, because the only source of propane in the DWSC and SJR water will be the bubble-jet device. The Corps of Engineers cooperation to install an air flow meter and a port for injecting propane into the air flow going to the jet is necessary to accomplish this test method. The air flow to the water jets will be augmented with about 1% propane gas. Samples for laboratory analysis of propane concentration will be collected from the railroad bridge, with the same spacing as used for the DO measurements. The average propane concentrations can be evaluated to estimate the likely DO concentrations resulting from the aeration device.

### **Aeration Performance Evaluation**

The manufacture design documents suggested that these two sets of bubble-jets would each transfer 1,250 lbs/day of oxygen. The depth of 25 feet suggested a maximum transfer efficiency of 20% for the oxygen dissolved from the bubbles into the water. The actual performance on September 26, 2001 was about 75% of the design value for the south jet (i.e.,  $925/1250 = 75\%$  of design). This seems quite good considering that the DO deficit was only about 2 mg/l. The oxygen absorption would be greater at a higher deficit. The north bubble-jet was operating at less than 20% of the design value (i.e.,  $225/1250 = 18\%$  of design). It is likely that the performance can be increased considerably by simply turning up the air flow rate to increase the bubble column upwelling and flow-away current. How much of this potential DO increment is transferred to the DSWC depends on the surface DO of the DWSC during the day.

If the average DO increment measured at the railroad bridge is reliable, the overall efficiency of the Corps aeration device was about 30% of the design value (i.e.,  $740/2500 = 30\%$  of design). However, because the air bubbles do not appear to be spread across the river channel, and a considerable amount of the compressed air is allowed to vent to the atmosphere, some design changes should be considered. It appears that a single 20 hp air blower (260 scfm) could produce an equivalent air bubble column from traditional diffuser heads (i.e. ceramic head or holes in pipe). The water jets with the two 15 hp pumps could be eliminated, and an equivalent amount of oxygen transfer from the upwelling currents could be achieved for less than 30% of the energy (i.e., 20 hp compared to 70 hp for current device). Another possible design change would replace the air compressor with pressurized oxygen gas, to increase the amount of oxygen

dissolved by these relatively shallow bubble columns. The ability to remove the diffusers from the water during the winter and spring remains a very nice design feature of the Corps device. Its location along the side of the SJR channel is another very important design feature.

## 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 deficit in the source water. A number of systems can be designed to take advantage of this principal. 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.

Lake applications involve some type of oxygen or air bubble source within a chamber that contains the water at depth. A normal bubble plume that rises to the surface can only increase the DO concentration to saturation at atmospheric pressure. A submerged (i.e., pressurized) chamber can increase the DO concentration to the saturation corresponding to the pressure of the chamber. The saturation concentration will increase with pressure (or equivalent water depth) as:

$$\text{DO saturation (mg/l)} = \text{Atmospheric saturation (mg/l)} * \text{Depth (feet)} / 34$$

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 under with oxygen at atmospheric pressure is about 40 mg/l at 25 C.

River applications have been limited and generally involve directing water flow through flexible conduits known as U-tubes (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 released from the bottom of the U-tube to increase the pressure and the DO saturation concentration. Pressurized side-stream aeration may be an ideal mechanism for installation of hollow fiber membrane technology. Mixing of the supersaturated treated water into the source water must also provide rapid dilution to avoid bubble formation and oxygen escape when treated water exits the diffuser. Consequently, designing a pressurized side-stream aeration system must balance the capital costs of the pressurization and oxygen transfer system with the costs of the return diffuser system to provide for effective rapid mixing in the DWSC.

A simplified set of assumptions will be used to illustrate the potential application of pressurized side-stream or in-stream aeration to the DWSC. The examples are designed to provide an increase of 5,400 lbs/day of DO to satisfy a 2 mg/l DO deficit at the seasonally low river flow rate of 500 cfs and water temperature of 25 C ( $C_s = 8.4$  mg/l)

For a side-stream design, the primary energy costs would be associated with pumping and pressurizing the side-stream water flow to a shoreline pressurized tank aeration facility. The pressurized flow rate could be as low as 20 cfs. For the pressurized water flow rate,

an additional 50 mg/l of DO would need to be added to deliver an additional 5,400 lbs DO (i.e.,  $DO [mg/l] = 5,400 / [5.4 * 20 \text{ cfs}]$  ) 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 bubble diffusers would primarily be a function of the bubble contact time. At 0.09 lbs/ft<sup>3</sup> of oxygen, approximately 60,000 ft<sup>3</sup> (42 scfm) of oxygen would be required each day to deliver 5,400 lbs/day of oxygen, assuming 100% oxygen transfer efficiency can be achieved within the pressure chamber. The head losses through the water piping and pressurization system are assumed to be about 20%, so the total pumping head would be about 60 feet and a 20 cfs flow rate would require about 3,000 kWh of energy per day (pump efficiency of 80%). This would require a pump with 125 kW (165 hp) of power. The total electrical costs for aerating the river with this system at \$0.10/kWh would be about \$300 per day for power and \$540 per day for liquid oxygen (\$0.10/lb).

This super-saturated water must then be mixed into the DWSC. The mixed DO concentration should be less than 90% of atmospheric saturation to avoid loss of oxygen bubbles to the surface. The DWSC water flow (with an assumed DO of 5 mg/l) that must be mixed with the 20 cfs pressurized water with a DO of 50 mg/l to maintain a mixed DO concentration of 7.5 mg/l would be about 340 cfs (i.e.,  $20 \text{ cfs} * 50 \text{ mg/l} + 340 \text{ cfs} * 5 \text{ mg/l} = 360 \text{ cfs} * 7.5 \text{ mg/l}$ ). This required mixing ratio (i.e.,  $360/20 = 18$ ) should be possible to obtain with a well-designed multi-port diffuser. The pressure losses in the diffuser system will increase the pumping costs somewhat.

A U-tube device in the DWSC would operate with a more moderate average pressure head of only about 20 feet (i.e., half the DWSC depth), corresponding to a DO saturation of about 23 mg/l at 25 C. If the DWSC water has a DO of 5 mg/l, the maximum possible DO increase would be 18 mg/l. The flow required to deliver 5,400 lbs/day of oxygen would be about 55 cfs ( $5,400/[5.4*18]$ ). A propeller driven system could be used to convey water through the U-tube pipe suspended in the water column to avoid pumping head losses. An oxygen diffuser would be located at the bottom of the pipe. The water flow velocity needs to be about 1 ft/sec to give the bubbles adequate time to be completely dissolved in the water flow. Literature values suggest that a 5 kW motor could generate the needed 55-cfs flow rate with a 0.6-m diameter water fan system (Fast 1983). Additional pumping flow might be needed to avoid degassing, but total pumping rates should be only about 150 kWh per day. The costs of operation would include only about \$15/day for the power and about \$540 per day for liquid oxygen. Distribution of the oxygenated water would be needed throughout the river to increase overall DO concentrations. Several U-tubes might be designed to allow better distribution of the oxygenated water throughout the DWSC.

## 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. 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 75 hp 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 in the surface layer, a surface water fan may be an effective device during periods of low DO. Water fans might be used in combination with air bubblers to redistribute the upwelling high DO water back into the deeper portions of the DWSC. Water fans can be used to pump the necessary flow into a U-tube as described in the previous section.

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 75 hp (i.e., 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 F. A slightly lower velocity with more flow might be used for the DWSC.

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 Rough & Ready monitoring station is about 330 acres. If the surface layer with substantially increased afternoon DO concentrations is about 3-feet deep, then there is about 1000 AF of water in the DWSC with higher DO concentrations that could be transferred to the underlying portion of the DWSC. If 4 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 1000 AF 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 a very attractive option for

improving DO conditions in the DWSC during periods when there is sufficient DO production at the surface from algae (which appears to be June-September).

The aeration sub-committee is making additional evaluations and may recommend testing of surface water fan in the DWSC this summer. Vertical temperature and diurnal DO measurements would be taken to demonstrate the performance of this simple device in the DWSC.

The Stockton water quality model, and the DSM2 model used by DWR do not currently consider these vertical gradients that may develop during the day from surface heating and algal photosynthesis. These water quality models currently include about one segment for each 1-mile of DWSC. These can be referred to as "1 segment per mile" models. Some effort should be given this summer to produce a simplified layered model, to allow the performance of the surface fans to be simulated. Either the Stockton model or the DSM2 model could be layered (i.e., ten layers with depths of about 3 feet each). The proposed layer model would therefore be a "10 segments per mile" model.

This vertical layering of the existing model should capture most of the near surface temperature and DO dynamics as well as the vertical gradient in VSS and other particulates that have been measured in the DWSC. The Hydroqual model proposal that is being funded by CALFED will be creating a layered 3-D model with about 100 segments per mile. The Stanford/Davis/USGS model that is also being funded by CALFED will produce a 3-D model with about 30,000 segments per mile (i.e., 10-m grid for the DWSC). We only have continuous measurements from the Rough & Ready near-surface DO monitor and weekly measurements from mid-channel depth at about 6 stations within the low-DO section of the DWSC.

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