Final

# Sediment Oxygen Demand, Sediment Deposition Rates and Biochemical Oxygen Demand Kinetics in the San Joaquin River near Stockton, California

Fall, 1999

Prepared for:

City of Stockton, California

and

San Joaquin River Dissolved Oxygen TMDL Technical Committee

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June 25, 2001

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## Executive Summary

Water and sediments in the Stockton Deep Water Ship Channel (DWSC) were studied to elucidate mechanisms that may influence dissolved oxygen (DO) concentrations and provide guidance for future research. Water column profiles for temperature, DO, pH, EC, and turbidity were measured to qualitatively evaluate mixing and stratification. Given favorable hydrodynamic and water quality conditions, the profiles could also provide an estimate of the sediment oxygen demand (SOD). Sediment deposition rates were investigated with a series of traps placed in the DWSC. Laboratory biochemical oxygen demand (BOD) tests were performed with the trapped sediment to estimate the oxygen demand of the trapped matter. In combination these measurements provide an upper limit of the oxygen demand associated with particles settling to the bottom. The trap measurements also indicated whether sediment resuspension is significant, but estimates of resuspension rates can not be determined directly from this information. Sediment cores were collected in the DWSC to evaluate the total abiotic oxygen demand and biochemical oxygen demand of the sediments. Sediment size mass fractions were also determined for input into the DWSC water quality model. Lastly, BOD decay rate studies were performed with final effluent from the City of Stockton, and San Joaquin River water collected at Mossdale Crossing and R-5 (near the confluence of the San Joaquin and Calaveras Rivers). The decay constants are needed for input to the DWSC water quality model input and independent oxygen deficit mass balance calculations.

### *SOD Estimates*

Estimates of the SOD in the DWSC were attempted with DO concentration profiles measured in the Turning Basin and San Joaquin River (near Light 45). Longitudinal variability of DO, tidal flows and mixing within the DWSC masked the influence of SOD on the DO in the water column. Thus, the environmental conditions in the DWSC, on the days when measurements were taken, were not favorable for estimating the SOD from DO profiles. In the San Joaquin River near Lt 45, the water column appears to be well mixed on both September 23 and November 6. This mixing distributes the effect of the SOD throughout water column, yielding differences in DO concentrations that are too small to be quantified. Turning basin profiles measured on August 26 show the profile to be linearly stratified throughout the water column. However, lateral variability of DO within the limits of tidal excursion in the Turning Basin were significant enough to question SOD estimates determined with this data. Two SOD estimates were performed with the August 26 data: 3 g/m$^2$/d (0.3 g/ft$^2$/d) and a negative value. The negative estimate appears to be caused by the lateral variably in DO, and suggests that the 3 g/m$^2$/d is an overestimate. Literature values of SOD for estuarine mud range from 1-2 g/m$^2$/d (Porcella, *et al.,* 1985, Thomann, 1972).

An upper bound for the SOD in the DWSC may also be estimated from sediment deposition rates and the oxygen demand associated with these sediments. Assuming steady-state conditions where the SOD is equal to the rate at which oxygen-utilizing matter settles multiplied by its associated oxygen demand. Calculated steady-state values ranged from 1 to 16 g/m$^2$/d. This estimation is extremely limited. The analysis

fails to consider many important mechanisms such as sediment resuspension and the time lag associated with the actual expression of the DO demand. Review of the sediment trap data indicates that sediment resuspension is significant, but does not enable a direct estimation of its rate. Resuspension is well known to result in an over-trapping of sediments (Kozerski, 1994). Sediment traps capture the primary settling flux, but also material that becomes resuspended. Quiescent water conditions within the traps inhibit escape (resuspension). Thus, SOD values calculated with sediment trap data may be grossly overestimated. Deposited sediment exerts an oxygen demand at a rate much slower than the rates determined with laboratory measurements of the sediment in a suspended state. This is largely due to the slow rate of DO diffusion across the sediment-water interface. Therefore, deposition rates and associated oxygen demands are required over an extended period of time for the steady-state approach to be accurate. The estimates provided here were for data collected in October and November. The sediment trap studies served as a test trial for future research. The data generated thus far has proven to be valuable, but only in a qualitative sense. A methodology needs to be developed to quantify actual sediment and resuspension rates for estimating future SOD values or the oxygen demand of sediments that remain suspended in the water column.

### *Bed Sediment Oxygen Demand and Size Fractions*

Sediments of the DWSC were collected and the abiotic oxygen demand and biochemical oxygen demand (BOD) associated with the sediments were determined on a sediment mass basis. The abiotic oxygen demand results from the oxidation of reduced chemical species when the sediments are exposed to an aerobic environment. The BOD of the sediments is associated with the uptake of oxygen from microbial processes. These data provide an estimate of the oxygen demand in the event the sediment is resuspended into the water column. The average estimated ultimate oxygen demands for the sediments collected from six locations are compared with the trapped sediment results in the following table.

| DO Demand Reporting Convention | DWSC Sediments | | Trapped Sediments |
|---|---|---|---|
| | 1-hr Abiotic Demand | 5-Day Demand | 5-Day Demand |
| | (mg/g) | (mg/g) | (mg/g) |
| Total Dry Mass Basis | 0.30 | 2.0 | 41 |
| Dry Volatile Mass Basis | NA | 35 | 160 |

Comparisons of these data indicate that the total oxygen demand of the DWSC sediments is approximately 7 times greater than the abiotic demand. The abiotic demand will be exerted within several hours, where as the demand associated with microbes may require 30 days or longer. The oxygen demand of the trapped sediments is approximately 5 times greater than the bed sediments on a volatile (approximately organic matter) basis. This difference is probably associated with refractory organic matter of the bed sediments that have already exerted its oxygen demand. The oxygen demands presented above are for different time periods and they exhibit different decay rates, which will influence the ultimate oxygen demand for each measurement. Conversion to ultimate oxygen demand values was not always possible for these measurements, however, comparisons of the oxygen demands of these sediments are nevertheless informative. As with the trapped sediment data, estimating the SOD is not possible without quantification of resuspension rates.

*BOD Decay Constants*

Biochemical oxygen demand tests were conducted with San Joaquin River samples and final effluent from the Stockton Wastewater Treatment Facility. The tests were run for a maximum 28 days to determine the first-order decay constants for BOD, carbonaceous BOD (CBOD), nitrogenous BOD (NBOD), soluble BOD (sBOD), and soluble carbonaceous BOD. Five trials were performed starting late August. The last of the trials was completed in late November. The average decay constant, k, and the $BOD_{ult}/BOD_5$ ratio for 5 trials are presented in the following table.

| | | k ($d^{-1}$) | | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|
| Sample | Species | average | std dev | |
| Final Effluent | BOD | 0.11 | 0.02 | 2.4 |
| | CBOD | 0.11 | 0.04 | 2.4 |
| | SBOD | 0.11 | 0.02 | 2.4 |
| | SCBOD | 0.08 | 0.03 | 2.9 |
| | Particulate BOD | 0.14 | 0.04 | 2.0 |
| | NBOD[2] | 0.10 | na | 2.5 |
| | | | | |
| Mossdale San Joaquin R. | BOD | 0.10 | 0.04 | 2.5 |
| | CBOD | 0.10 | 0.02 | 2.5 |
| | SBOD | 0.09 | 0.01 | 2.9 |
| | SCBOD | 0.09 | 0.02 | 2.8 |
| | Particulate BOD | 0.10 | 0.02 | 2.5 |
| | NBOD[2] | 0.09 | na | 2.7 |
| | | | | |
| R-5 San Joaquin R. | BOD | 0.14 | 0.07 | 2.0 |
| | CBOD | 0.10 | 0.04 | 2.5 |
| | sBOD | 0.08 | 0.04 | 3.1 |
| | sCBOD | 0.09 | 0.02 | 2.7 |
| | Particulate BOD | 0.18 | 0.06 | 1.7 |
| | NBOD[2] | 0.16 | na | 1.8 |

[1] $BOD_{ult} / BOD_t = 1/(1-e^{-kt})$, where t=5 days

[2] Estimates from synthesized results

Many of the rate constants were found to be approximately 0.10 $d^{-1}$. This corresponds to $BOD_{ult}$ / $BOD_5$ ratio of 2.5. This indicates that for the waters tested here, only 40 percent of the oxygen damand had been exerted after 5 days. The decay constant can also be used to estimate the BOD for other periods. For example, if k is 0.10 $d^{-1}$, approximately 95 percent of the oxygen demand has been exerted after 30 days. The particulate and NBOD values appearing in the above table are questionable. Details are provided in the report body.

## Sediment Oxygen Demand Estimates

Water column dissolved oxygen profiles and sediment deposition rates were measured in an attempt to quantify the sediment oxygen demand (SOD) in the DWSC. Water column profiles and sediment deposition rates were also measured for other purposes, including model calibration, mass balance calculations, and qualitatively evaluating mixing and sediment suspension.

### SOD Estimates from Water Column Profiles

Water column profiles were performed to improve knowledge about stratification and mixing of water in the Stockton Ship Channel and also provide estimates of the sediment oxygen demand.

### Methods and Materials

Temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and turbidity were measured as a function of depth for the following dates and locations presented in Table 1 and Figure 1.

Table 1: Locations, dates, and duration of water column profile measurements.

| Location | Date | Duration |
|---|---|---|
| Turning Basin | August 26, 1999 | 12-hr period |
| San Joaquin River near Light 45 | September 23, 1999 | 12-hr period |
| San Joaquin River near Light 45 | November 6, 1999 | 6-hr period |

The two 12-hr sessions were conducted in conjunction with the Department of Water Resources' (DWR) mass loading investigations in an effort to reduce costs. *In situ* measurements of depth, temperature, pH, DO, and electrical conductivity were performed with a YSI multiparameter sonde. Disturbance of sediments by the sonde was reduced by lowering a 2-ft dia plastic disk weighted with a 10-lb steel disk to the sediment-water interface. The mutiparameter sonde was permitted to slide along the anchor rope of the weighted disk. Once in place, the weighted disk remained undisturbed throughout the monitoring for the day. Waters samples (≈0.5 L) were collected at each depth to measure turbidity and verify the *in situ* DO measurement. Samples were collected with a peristaltic pump and 0.25-inch diameter tubing attached to the multiparameter sonde. The sampling flow rate was approximately 0.5 L/min. Prior to the collection of samples the peristaltic pump tubing and sample collection bottles were flushed with water from the depth of measurement. Water quality samples (≈10 L)

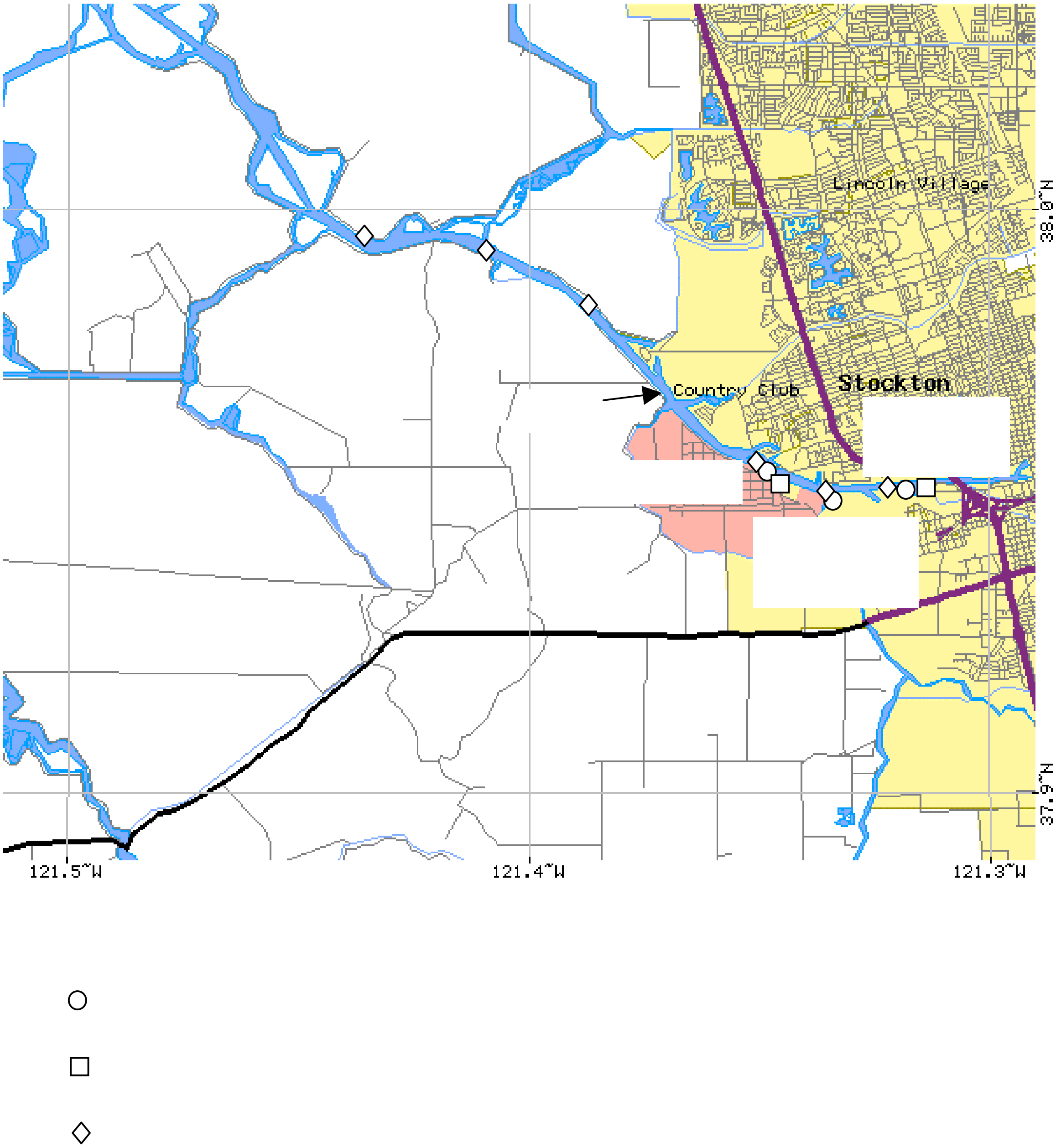


**Figure 1** Monitoring Locations

were also collected for DWR personnel during mid and slack tides at approximately 3 feet above the sediment water interface and 3 feet below the surface. The results of DWR's analysis is presented in a separate report to the San Joaquin River TMDL Technical Committee. The 6-hr monitoring performed on November 6 was conducted around a low slack tide to verify earlier observations in the DWSC. During the November 6 measurements, no water samples were collected to facilitate rapid recording of DO with depth.

Figure 2 presents hypothetical dissolved oxygen profiles to help illustrate how they could be used to estimate the SOD. During flood or ebb tides, the flow of water in the channel may permit mixing of the water column, generating a relatively vertical dissolved oxygen profile. However, during slack tides, flows may be near zero for a long enough period of time that the DO near sediment is reduced due to the uptake from the sediments. The depletion of oxygen associated with the SOD is determined by subtracting the DO measured near the end of the slack tide from the DO measured near the beginning of the slack tide. This is shown visually by the shaded area (units: $g/m^3 \times m$) in Figure 2. The SOD is then calculated by:

$$\mathrm{SOD}\,(\mathrm{g}\cdot\mathrm{m}^{-2}\mathrm{d}^{-1}) = \frac{\text{DO deficit area}\,(\mathrm{g}\cdot\mathrm{m}^{-3}\cdot\mathrm{m})}{\text{time between measurements}\,(\mathrm{d})}.$$

The actual DO profiles measured in the field often did not match the hypothetical case presented in Figure 2 due to mixing and stratification phenomena. However, SOD calculations were still attempted.

## Dissolved Oxygen Profiles

Figures 3, 4, and 5 exhibit the dissolved oxygen profiles measured during August 26, September 23, and November 6, respectively. Inspection of Figure 3 indicates that the DO concentration near the sediment was approximately 4.5 mg/L during the morning ebb tide. The near sediment DO level continued to decrease to about 3.8 mg/L at low-slack tide (1:28 PM). This continuous decrease in DO during the ebb tide appears to be associated with lower DO water flushing out of the Turning Basin, but some portion is attributable to the SOD. Assuming that all of the difference in dissolved oxygen concentrations in the 1 meter overlying the sediments is associated with the SOD, an uptake rate of 3 $g/m^2/d$ was estimated. This value is beyond the range of SOD values commonly reported for estuaries 1 to 2 $g/m^2/d$ (Thomann, 1972) or 0.3 to 0.8 $g/m^2/d$ (Porcella *et al.,* 1985).

The behavior of the DO profiles of August 26 during the flood tide further supports the hypothesis that the near-sediment DO levels are dominated by tidal flows and the difference in DO concentrations in the Turning Basin and San Joaquin River. During the afternoon flood tide, the DO concentrations continue to increase as San Joaquin River water with higher DO levels flows into the Turning Basin. The near-sediment DO concentrations continue to increase from approximately 5:30 PM to the high slack tide at approximately 7:30 PM. Estimates of SOD for the high slack tide period would possess a negative sign, suggesting that the sediments were increasing the oxygen in the water column. Since this cannot be the case, tidal flows and differences in water quality in the Turning Basin and San Joaquin River offer the best explanation for the DO profile behavior. Estimates of SOD for August 26 using these profiles are questionable.

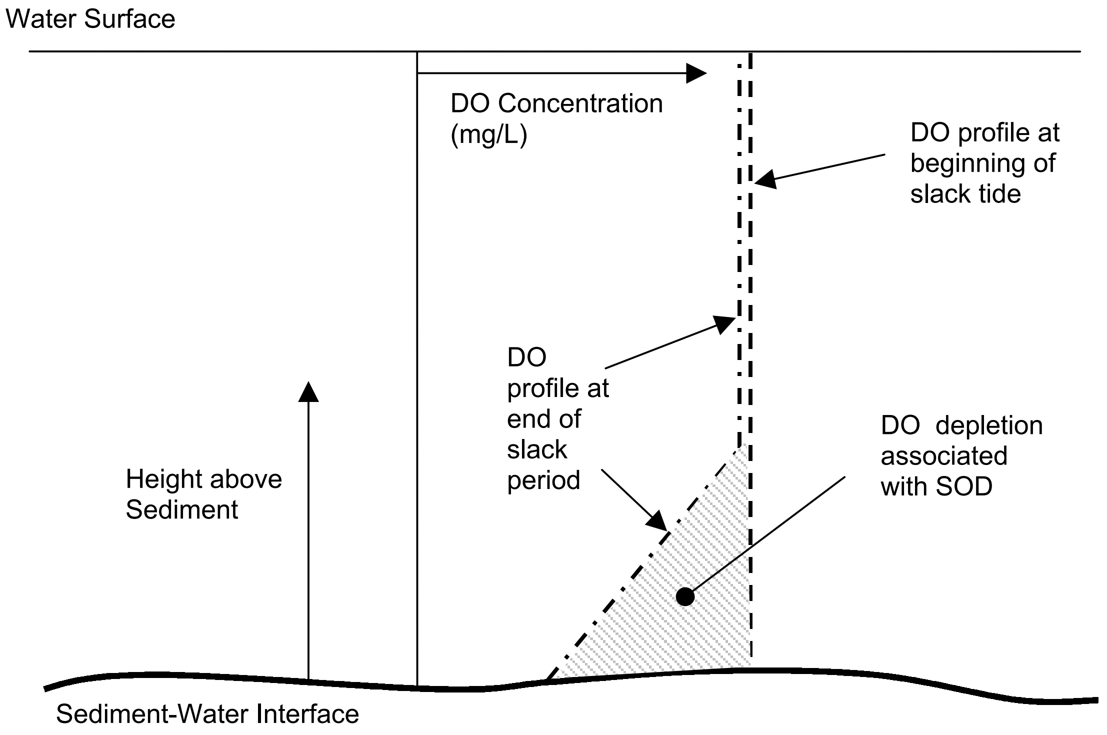


Figure 2 Hypothetical DO Profiles Before and at the End of Slack Tide.

The September 23 DO profiles also appear to be dominated by tidal flows. Inspection of Figure 4 shows that near-sediment DO concentrations were typically higher at periods of slack tide. Evidence of SOD is exhibited by a slight DO gradient of approximately 0.03 mg/L/m. The SOD can also be estimated from the gradient if the vertical mixing and dispersion are well characterized. Unfortunately, these parameters are unknown and probable values could range over two orders of magnitude.

Review of the August and September profiles suggested that SOD estimates might be improved if the profiles could be measured at a greater frequency. During the August and September monitoring water samples were collected at each depth during a profile run with a peristaltic pump. Large volumes of water were also collected for other study

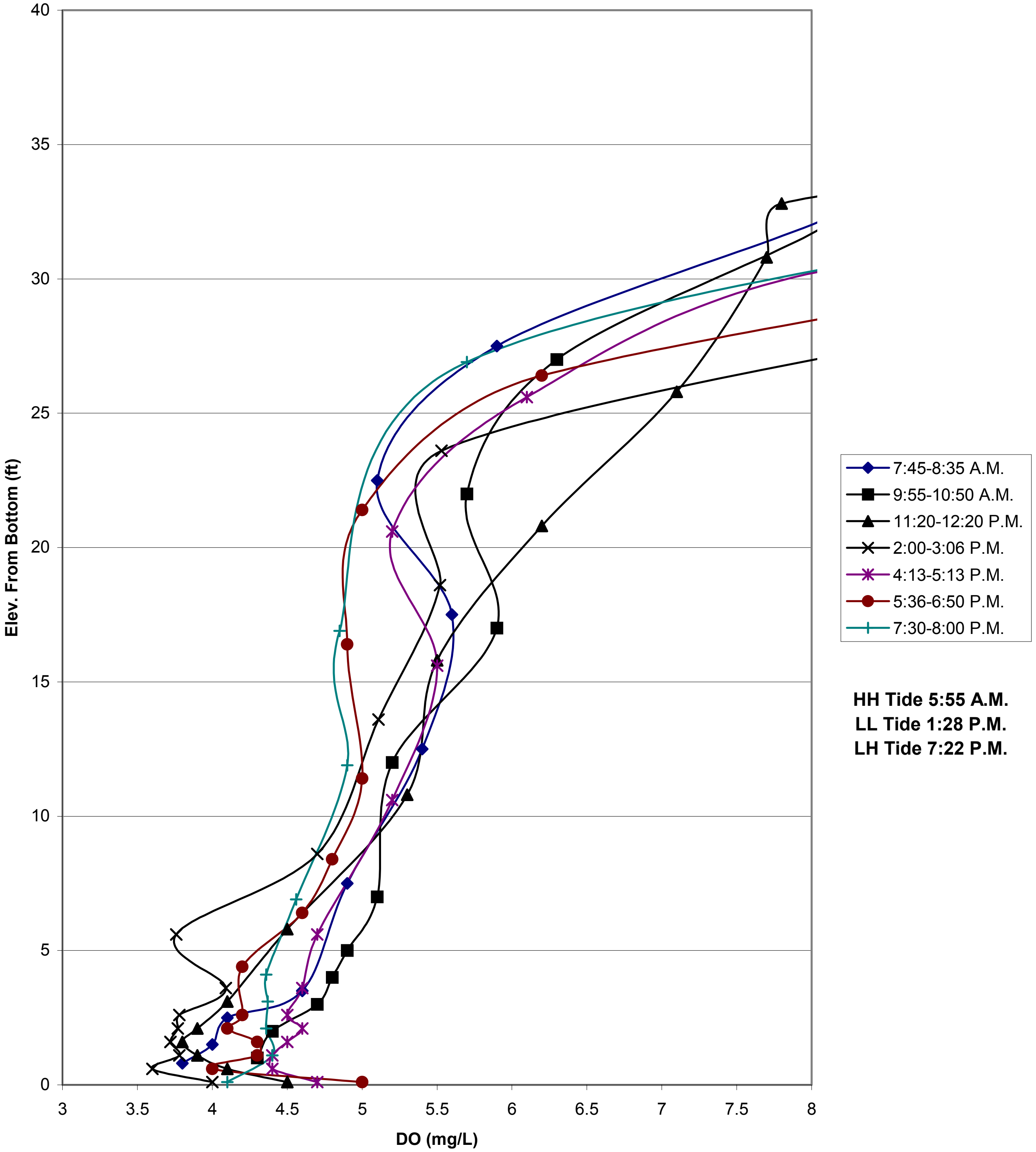


**Figure 3** Dissolved Oxygen Profiles in the Turning Basin on 8/26/1999.

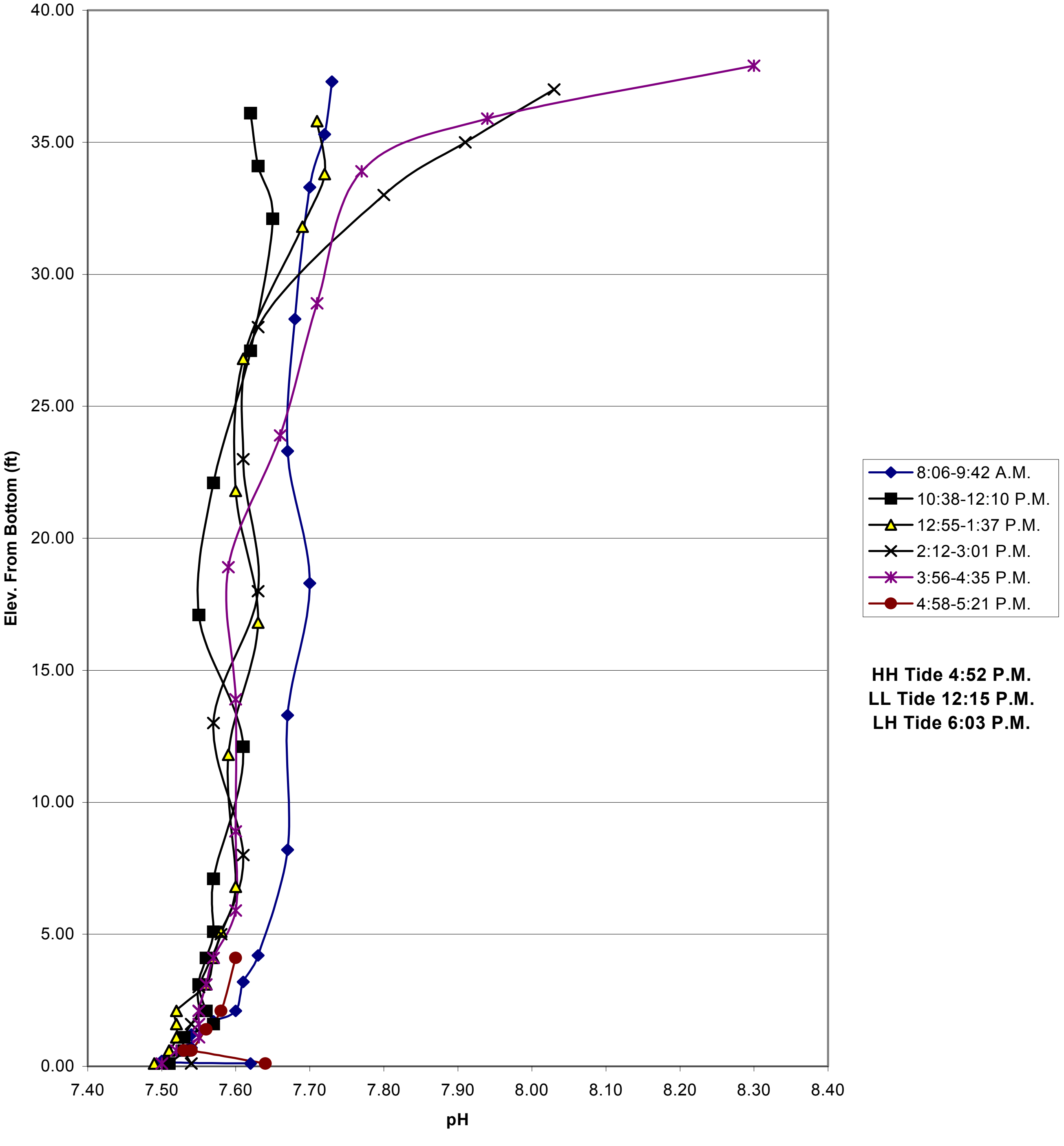
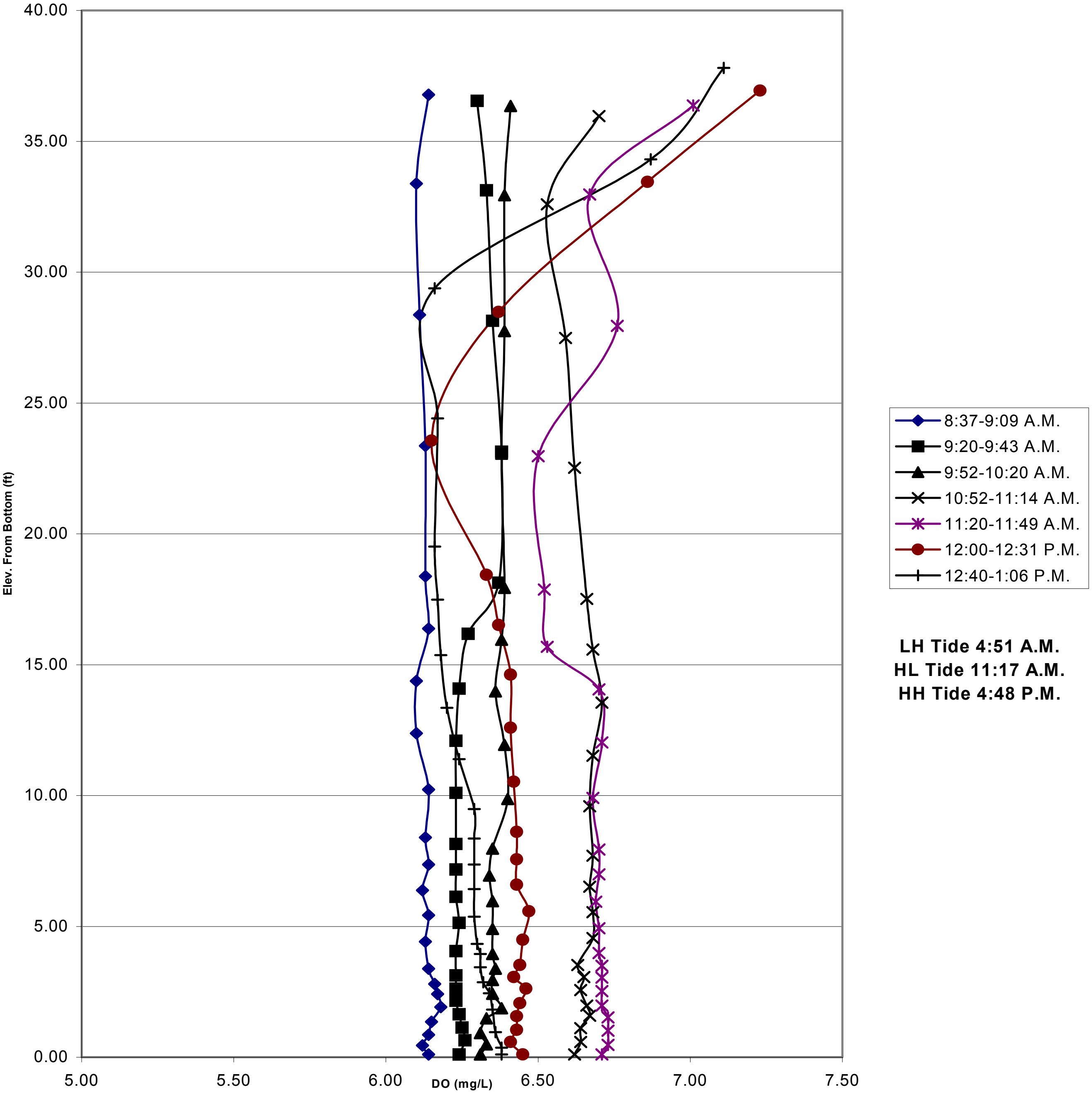


**Figure 4** Dissolved Oxygen Profiles in the DWSC near Lt 45 on 9/23/1999.



**LH Tide 4:51 A.M.**
**HL Tide 11:17 A.M.**
**HH Tide 4:48 P.M.**

**Figure 5** Dissolved Oxygen Profiles in the DWSC near Lt. 45 on 11/6/1999.

elements between profile runs. This sampling reduced the frequency at which the profiles could be measured. On November 6, profiles were again measured near Light 45 without water sampling to slow the process. Seven profiles were conducted around a low tide. As shown in Figure 5, the highest DO concentrations were again measured at low-slack tide. Review of near-sediment DO concentrations in Figure 5 indicates that DO concentrations started at 6.2 mg/L during the mid-morning ebb tide, reached a maximum near the end of the ebb tide, and then decreased during the afternoon flood tide. These observations are consistent with the relatively high DO concentrations measured in the San Joaquin River at Mossdale (Jones and Stokes, 1998) when compared with the DWSC during this period. The profiles also exhibit little DO gradient near the water-sediment interface. While this could be an indication of low SOD, it is probably associated with a well-mixed water column. The vertical temperature and pH profiles measured on November 6 provide further evidence that the waters were well mixed. As with the monitoring performed on September 23, negative SOD values are generated using these DO profiles. In summary, for each of the three days of profile monitoring, hydrodynamics and spatial variability of DO concentrations appeared to mask SOD effects on the water column profiles. Thus, reliable estimates of SOD were not possible with the profile data presented here.

### SOD from Sediment Deposition Rates

Sediment traps were used to estimate sediment deposition rates in the Stockton Ship Channel. From these deposition rates and oxygen demand experiments of the trapped sediments, estimates of SOD may also be possible.

#### Methods and Materials

Three sediment frame systems, each with four traps, were placed in the Turning Basin , Channel Point, and at Light 45 in the San Joaquin River. Trap locations are shown in Figure 1. The traps were left to collect sediment for 24-25 hours. A prototype frame and trap system was tested on October 7. Successful capture of sediments at three stations was performed over a full tidal cycle on October 12-13 and again on November 3-4, 1999. The October 12-13 monitoring was started at high slack tide and retrieved approximately 6 hours later at low slack tide. The traps were again retrieved after another 18 hours. This was performed to evaluate differences in loading rates between ebb and flood tides. During September and October, sediment loads were visually high during ebb tide periods when compared to flood tides.

Figure 6 displays a diagram of the trap apparatus at each station. The sediment traps were constructed of 2-inch diameter PVC pipe, 20 inches long. Traps were located at four depths: 10, 20, and 30 feet below the water surface and 20 inches above the sediment surface. The trap near the sediment water interface was secured to a weighted PVC frame with a 3 by 3-ft footprint. Traps at 10, 20 and 30 feet were attached to nylon line anchored to the sediment trap frame and supported by a buoy.

Sediment samples were transferred from the traps to 1-L polypropylene bottles, immediately iced and transferred to a 4 °C refrigerator within 1-hr of collection. After settling for 24 hours, the supernatant was carefully siphoned until approximately 2 cm of water remained above the sediment. The sediment was then fully suspended and the slurry volume was determined. A 10-mL aliquot of slurry was transferred to a tared crucible, water evaporated at 85-90 °C, and finally dried at 103 °C before weighing. After this weighing, the samples were ignited at 550 °C. In both cases, complete evaporation or combustion was verified by repeated weighing and temperature exposure until the mass remained constant. This solids quantification procedure was also repeated for the supernatant siphoned from each sample. The total weight of settleable matter and organic matter (volatile) was determined by:

$$\text{Total Settled Sediment} = \frac{\left[\left(M^{sed}_{103C} - M_{crusible}\right) - \left(M^{water}_{103C} - M_{crusible}\right) {}^{V_{sed}}\!/\!_{V_{water}}\right] V_T}{V_{sed}},$$

$$\text{Organic Settled Sediment} = \frac{\left[\left(M^{sed}_{550C} - M^{sed}_{103C}\right) - \left(M^{water}_{550C} - M^{water}_{103C}\right) {}^{V_{sed}}\!/\!_{V_{water}}\right] V_T}{V_{sed}},$$

where $M^{sed}$ and $M^{water}$ are the masses of the crucibles after exposing the sediment or water at 103 °C or 550 °C, $M_{crucible}$ is the initial crucible mass, $V_{sed}$ is the volume of sediment slurry dried, $V_{water}$ is the volume of supernatant water evaporated, and $V_T$ is the total volume of sediment slurry collected from each trap.

To estimate an upper bound for the SOD from sediment trap data, both the deposition rate and the oxygen demand associated with the trapped matter is needed. The biochemical oxygen demand was performed with the matter deposited in the bottom and top trap at each location for the samples collected on November 4. Two bottles from each trap were set up with different initial volumes of decanted sediment slurries. The tests were conducted at 20° C. Siphoned supernatant water was used as dilution water. No seed was added The BOD of the supernatant water used as dilution water was also quantified. The sediment was resuspended every 4 to 8 hours. The dissolved oxygen of each bottle was measured for 5 consecutive days. After 5 days, the DO of all of the bottles with sediments was measured below 1 mg/L and the experiment was terminated. The trapped sediment oxygen demand was determined by subtracting the oxygen demand of the river from the oxygen demand measured for each of the experiments with both river water and sediment.

## Sediment Trapping Rates

The sediment trapping rates for the October and November trials are shown in Tables 2 and 3. The October trapping rates were determined for the first 6-hr of an ebb tide to

**Table 2** Sediment Trapping Rates for October 12-13, 1999.

| **Location** | **Depth (ft)** | **Total Load (g)** | | **Volatile Load (g)** | | **6 hr Ebb Tide** | **24 hr Period** |
|---|---|---|---|---|---|---|---|
| | | *6 hr Ebb Tide* | *24 hr Period* | *6 hr Ebb Tide* | *24 hr Period* | % volatile load | % volatile load |
| **Turning Basin:** | | | | | | | |
| Top | 10 | 0.0339 | 0.0670 | 0.0055 | 0.0132 | 16.2242 | 19.7015 |
| Mid | 20 | 0.0604 | 0.1176 | 0.0117 | 0.0230 | 19.3709 | 19.5578 |
| Lower | 30 | 0.0889 | 0.1907 | 0.0152 | 0.0345 | 17.0979 | 18.0912 |
| Bottom | | 0.0969 | 0.2120 | 0.0205 | 0.0432 | 21.1558 | 20.3774 |
| **Confluence San Joaquin River & Stockton Ship Channel:** | | | | | | | |
| Top | 10 | 0.4337 | 1.5484 | 0.0514 | 0.1323 | 11.8515 | 8.5443 |
| Mid | 20 | 0.5710 | 2.1393 | 0.0564 | 0.1700 | 9.8774 | 7.9465 |
| Lower | 30 | 0.9317 | 2.6787 | 0.0996 | 0.2492 | 10.6901 | 9.3030 |
| Bottom | | 0.7405 | 2.7232 | 0.0649 | 0.2083 | 8.7643 | 7.6511 |
| **Light 45,** | **San Joaquin River:** | | | | | | |
| Top | 10 | 0.0671 | 0.1613 | 0.0141 | 0.0289 | 21.0134 | 17.9169 |
| Mid | 20 | 0.1230 | 0.3462 | 0.0113 | 0.0303 | 9.1870 | 8.7522 |
| Lower | 30 | 0.3395 | 0.9076 | 0.0412 | 0.0935 | 12.1355 | 10.3019 |
| Bottom | | 0.7699 | 1.9270 | 0.0785 | 0.1836 | 10.1961 | 9.5278 |
| **Percent Settling between confluence and light 45 (1 mile separation):** | | | | | | | |
| | | **Total Load (g)** | | **Organic Load (g)** | | | |
| Top | 10 | 84.5285 | 89.5828 | 72.5681 | 78.1557 | | |
| Mid | 20 | 78.4588 | 83.8171 | 79.9645 | 82.1765 | | |
| Lower | 30 | 63.5612 | 66.1179 | 58.6345 | 62.4799 | | |
| Bottom | | -3.9703 | 29.2364 | -20.9553 | 11.8790 | | |

**Table 3** Sediment Trapping Rates for November 3-4, 1999

| **Sediment Deposition Measurements** | | | **November 3-4, 1999** | |
|---|---|---|---|---|
| **Location** | **Depth (ft)** | **Total Load (g)** | **Volatile Load (g)** | **24 hr Period** |
| | | *g/24 hr Period* | *24 hr Period* | |
| | | | | |
| **Turning Basin:** | | | | |
| Top | 10 | 0.088 | 0.050 | 57.36 |
| Mid | 20 | 0.146 | 0.057 | 39.37 |
| Lower | 30 | 0.288 | 0.058 | 20.29 |
| Bottom | 36 | 0.333 | 0.063 | 18.80 |
| **Confluence San Joaquin River & Stockton Ship Channel:** | | | | |
| Top | 10 | 0.704 | 0.114 | 16.20 |
| Mid | 20 | 0.963 | 0.130 | 13.51 |
| Lower | 30 | 1.288 | 0.166 | 12.86 |
| Bottom | 44 | 84.490 | 5.256 | 6.22 |
| **Light 45, San Joaquin River:** | | | | |
| Top | 10 | 0.258 | 0.037 | 14.49 |
| Mid | 20 | 0.577 | 0.076 | 13.09 |
| Lower | 30 | 1.438 | 0.139 | 9.70 |
| Bottom | 35 | 1.473 | 0.139 | 9.41 |
| **Percent settling between confluence and Lt 45 (1-mile separation)** | | | | |
| Top | 10 | 87.5 | 55.9 | |
| Mid | 20 | 84.9 | 56.0 | |
| Lower | 30 | 77.6 | 64.7 | |
| Bottom | | 99.6 | 98.8 | |

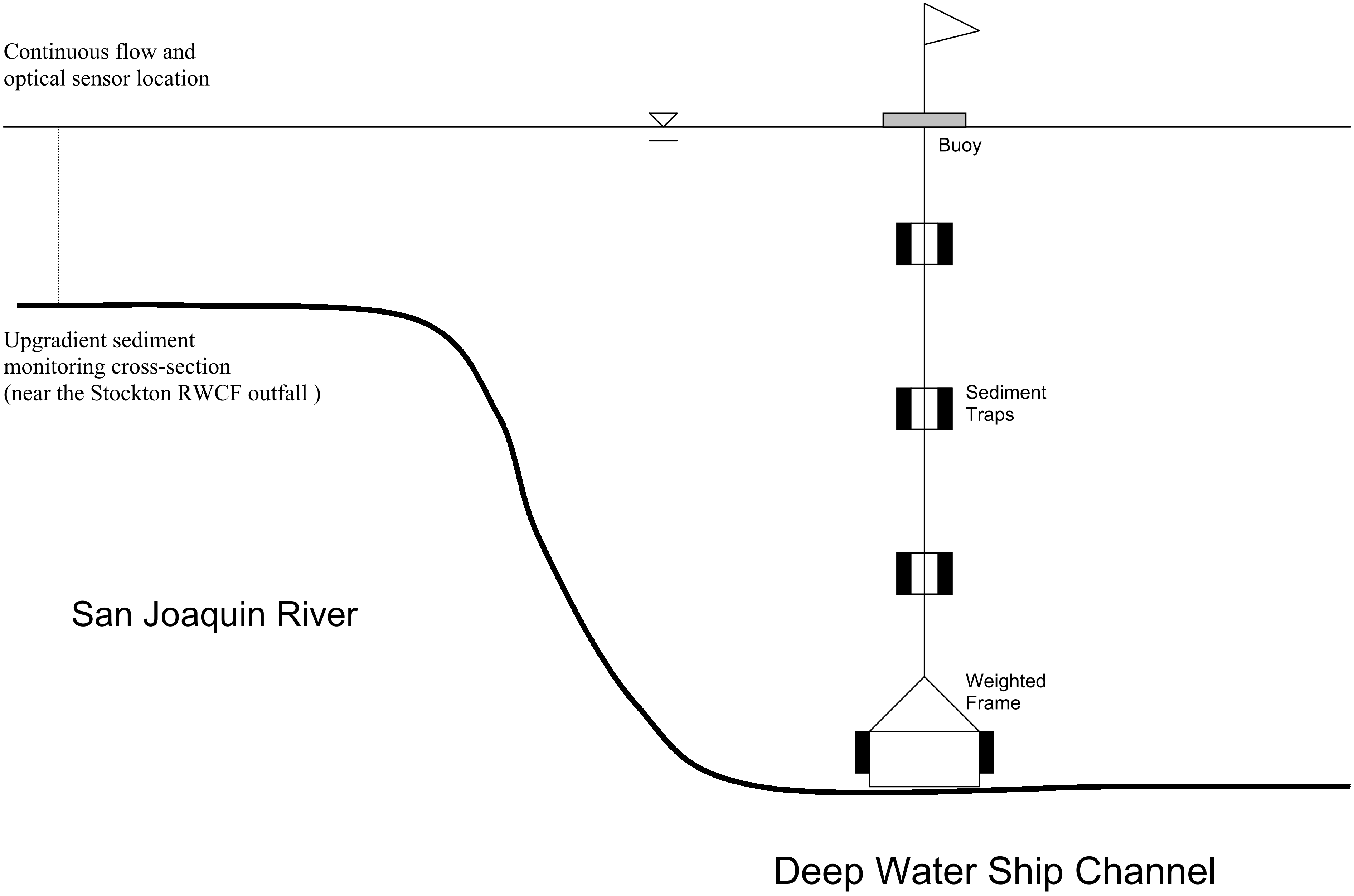


**Figure 6**: Typical Schematic Diagram of a Sediment Trap Station

evaluate differences associated with deposition rates measured during a full 25-hr tidal cycle. As shown in Table 2, deposition rates were greatest during the 6-hr ebb tide of October 12 when compared with the average trapping rate for the full tidal cycle. This is associated with tidal flows in the San Joaquin River during this time. During flood tides the flow of the San Joaquin is reduced or reversed. This reduces the loading of settling particles into the DWSC. The data in Tables 2 and 3 also shows a significant reduction in the trapping rates between Channel Pt and Light 45. Several hundred yards upstream of Channel Point the depth of the San Joaquin River increases from approximately 10 to 40 feet. Water velocites slow and a significant sediment load from the San Joaquin settles in the DWSC. Data presented in Tables 2 and 3 indicate that between Channel Pt and Light 45 sedimentation is significant as the traps at Light 45 captured approximately 60 to 80 percent less sediment compared to Channel Point trap rates.

The data in Table 2 and 3 also suggests that sediment resuspension may be significant. The trapping rates generally increase with trap depth at each location. Sediment resuspension will yield higher sediment trapping rates when compared to the true sediment deposition rate. Quiescent conditions inside the trap prevent the resuspension of particles once settled. However, outside the trap hydrodynamic conditions may resuspend some of the sediment which when settled can increase the trapping rate. Ratios of bottom trap rate to top trap rate are presented in Table 4. The data is presented on a total sediment and volatile sediment mass basis. Although this data suggests that resuspension occurs, the increase in trapping rates with depth can not be explained by resuspension alone. The high ratios at Light 45 compared with Channel Point are also associated with the settling of the more massive particles as the particles are carried from Channel Point. The upper water column will contain lower concentrations of particles that have settled below the elevation of the top trap. The particles that remain above the top trap also possess a lower settling velocity. Since the trapping rate can be calculated by the product of particle concentrations and settling velocity, a reduction in concentration and settling rate will yield lower deposition rates. Although not shown here, water column turbidity profiles also support the conclusion that resuspension is significant, because higher turbidity values were always measured near the sediment water interface when compared to the levels in the upper water column.

**Table 4** Sediment Trapping Rate Ratios.

| Location | Bottom Trap Rate / Top Trap Rate | |
|---|---|---|
| | Total Sediment | Volatile Sediment |
| | October, November | October, November |
| Turning Basin | 3.2, 3.8 | 1.3, 3.3 |
| Channel Point | 1.8, 1.8* | 1.6, 1.5* |
| San Joaquin River at Lt 45 | 6.0, 12 | 3.3, 3.7 |

* The November 4 trap was moved by the San Joaquin County Sheriff. Bottom trap results are questionable, lower (30 ft below surface) suspended trap data was used.

## Trapped Sediment Oxygen Demand

The trapped sediment oxygen demand after 5 days is presented in Table 5. The results are reported on a total mass or volatile mass basis. An attempt was made to fit a first-order curve to the data, using the method described later for the BOD kinetic study. However, many of the data were not consistent with first-order decay behavior. The data suggest that the microbial population was not acclimated to degrade the volatile organic fraction of the sediment. Interestingly, the river water used for the dilution water did exhibit first-order decay behavior. The average oxygen demand of the sediment is 41 mg/g dry trapped matter or 160 mg/g dry volatile trapped matter. The lower coefficient of variation for the volatile basis suggests that the oxygen demand is largely associated with the microbial utilization of organic matter.

**Table 5** Trapped Sediment Oxygen Demand for November 3-4, 1999.

| Trap Location | | 5-Day Oxygen Demand | |
|---|---|---|---|
| | Trap Depth (ft) | total basis (mg/g dry trapped matter) | volatile basis (mg/g dry volatile matter) |
| Turning Basin | 10 | 27 | 176 |
| | Bottom | 7.6 | 92 |
| Channel Point | 10 | 24 | 146 |
| | Bottom | na | na |
| Light 45 | 10 | 93 | 123 |
| | Bottom | 51 | 260 |
| Average | | 41 | 160 |
| Standard Deviation | | 33 | 57 |
| Coefficient of Variation | | 0.80 | 0.36 |

These average 5-day oxygen demands were then used to estimate the oxygen demand flux associated with trapped particles. Table 6 presents the sediment trapping rate and the estimated oxygen demand flux. The flux was calculated from

$$\text{Oxygen Demand Flux } (\text{g} \cdot \text{m}^{-2}\text{d}^{-1}) = \frac{\text{Deposition Rate } (\text{g} \cdot \text{d}^{-1}) \times \text{Oxygen Demand } (\text{g} \cdot \text{g}^{-1})}{\text{Trap Openning Area } (\text{m}^{2})}$$

The 5-day oxygen demand flux calculations are presented as a rough approximate upper bound for SOD in a steady-state system where resuspension is negligible. It also does not take into consideration the additional oxygen demand exerted after 5 days. As presented in Table 6, the calculated steady-state values using the average oxygen demand from all the trapped sediment BOD trials ranged from 1 to 16 g/m$^2$/d. Since average values of the BOD were used here, the variability is associated with differences in trapping rates. If the lower trap deposition rates in the DWSC are influenced by resuspension then the upper estimates of the oxygen demand flux are over estimated.

**Table 6** Estimated Oxygen Demand Flux for Trapped Sediment.

| Trap Location | Trap Depth (ft) | Sediment Trapping Rate | | | | 5-Day Oxygen Demand Flux | |
|---|---|---|---|---|---|---|---|
| | | October 12-13, 1999 | | November 3-4,1999 | | October | November |
| | | Total | volatile | total | Volatile | | |
| | | (g d$^{-1}$) | (g d$^{-1}$) | (g d$^{-1}$) | (g d$^{-1}$) | (g m$^{2}$ d$^{-1}$) | (g m$^{2}$ d$^{-1}$) |
| Turning Basin | 10 | 0.067 | 0.013 | 0.064 | 0.048 | 1.1 | 3.8 |
| | bottom | 0.212 | 0.043 | 0.303 | 0.060 | 3.4 | 4.8 |
| | | | | | | | |
| Channel Point | 10 | 1.548 | 0.132 | 0.671 | 0.110 | 2.9 | 8.8 |
| | low | 2.679 | 0.249 | 1.252 | 0.161 | 16.6 | 12.9 |
| | | | | | | | |
| Light 45 | 10 | 0.161 | 0.029 | 0.224 | 0.035 | 2.3 | 2.8 |
| | bottom | 1.927 | 0.184 | 1.428 | 0.117 | 14.7 | 9.4 |

This approach to estimate the SOD is extremely limited. The analysis fails to consider many important mechanisms such as sediment resuspension and the time lag associated with the actual expression of the DO demand. Review of the sediment trap data indicates that sediment resuspension is significant, but the data does not provide an estimation of its magnitude. Deposited sediment will exert an oxygen demand at a rate much slower than the rates determined with laboratory measurements of the sediment in a suspended state. This is largely due to the slow rate of DO diffusion across the sediment-water interface. Therefore, deposition rates and associated oxygen demands are required over an extended period of time for the steady-state approach to be accurate. The estimates provided here were for data collected only in October and November. The sediment trap studies served as a test trial for future research. The data generated thus far has proved to be valuable, but only in a qualitative sense. A methodology needs to be developed to quantify actual sediment and resuspension rates for estimating future SOD values or the oxygen demand of sediments that remain suspended in the water column.

### *Sediment Resuspension and Oxygen Demand from Ship Traffic*

An incoming cement ship disrupted the last of the water column profile measurements conducted on September 23. The ship was followed to the Turning Basin to evaluate sediment resuspension associated with large ship traffic. Samples were periodically collected within the ship's wake while following approximately 200 to 500 yards behind.

Sediment disturbance was not observed until the ship was turned about by two tugboats in the Turning Basin. Vortices in the wake of the ship or tugs resuspended significant quantities of bottom sediments. The vortices persisted for approximately 2 to 5 minutes after the ship passed. Water samples within and outside of the vortex sediment plumes were collected. Dissolved oxygen concentrations was also measured *in situ* and was found to similar to background levels. Water samples were placed on ice after collection for later oxygen demand tests.

Biochemical oxygen demand tests were performed with the samples collected in the wake of the cement ship. The total and soluble BOD was determined over a 28-d period; no seed was provided. Table 7 presents the results of this monitoring. The highest turbidity was measured at 420 NTU just outside the vortex in the plume center. At the outer perimeter of the sediment plume the turbidity had dropped to 209 NTU and approximately 10 meters outside of the sediment plume turbidity was only 9.6 NTU. Unlike the turbidity measurements, the BOD values were relatively similar. Contrary to expectation, the BOD measurements outside of the plume were slightly greater than values determined within the plume, although there is probably little statistical difference. Total BOD concentrations ranged from 3.5 to 4.6 mg/L. These levels are typical for the Turning Basin.

One water sample was also collected within a tugboat wake after the ship was turned about. The tug was pushing the bow of the ship to dock at the Port of Stockton. Although the wake was quite turbulent, no suspended sediment was observed and the turbidity was only 23 NTU. The $BOD_5$ was 3.0 mg/L, a value similar to the other measurements determined for the Turning Basin.

**Table 7** Biochemical Oxygen Demands of Water Impacted by Sediment Resuspension due to Ship Traffic in the Turning Basin.

| Sample | Turbidity (NTU) | $BOD_5$ (mg/L) | $BOD_{28}$ | $BOD_{28}$ (est) | k (1/d) | $BOD_{ult}$ (mg/L) |
|---|---|---|---|---|---|---|
| Tug wake BOD | 23 | 3.0 | 7.3 | 7.6 | 0.09 | 8.2 |
| Outside plume sBOD | | 1.1 | 3.5 | | | |
| Outside plume BOD | 9.6 | 4.6 | | 10.4 | 0.12 | 10.8 |
| Inner plume sBOD | | 0.9 | 3.4 | | | |
| Inner plume BOD | 420 | 4.1 | | 9.5 | 0.12 | 9.8 |
| Outer plume sBOD | | 0.9 | 3.2 | | | |
| Outer plume BOD | 209 | 3.5 | | 8.6 | 0.10 | 9.1 |

The decay of DO for the total BOD tests was consistent with first-order kinetics, thus the decay constant, k, and the ultimate BOD, $BOD_{ult}$, was determined. Details of the estimation methods are presented on page 30 of this report. The sBOD tests were apparently slow to acclimate, thus estimates of k and $BOD_{ult}$ were not performed. The decay constants ranged from 0.09 to 0.12 $d^{-1}$. This corresponds to an approximate $BOD_{ult}$ /$BOD_5$ ratio of 2.5. These decay constants are also similar to other values determined for the San Joaquin River (see BOD Kinetic Rate Study, page 30). These observations suggest that the SOD associated with the suspended sediments is quite low, perhaps because the sediment is regularly suspended by ship traffic in the Turning Basin.

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## Sediment Oxygen Demand and Size Characterization

Shallow sediment cores were collected to measure the sediment oxygen demand associated with the immediate abiotic oxidation of reduced species (e.g., sulfides and ferrous iron), the biochemical oxygen demand, and the particle size distribution of the sediments. Sediment cores were collected on October 7, 12, and 19. Cores were obtained from the DWSC at Turning Basin, Channel Point, Light 45, Light 37, Light 33, and Light 27. Locations are shown in Figure 1.

### *Methods and Materials*

Samples from the ship channel were collected in 37 to 45 feet of water with a weighted, 2-in dia. core sampler. Sediments were retained in a 2-ft clear plastic insert within the corer. After the sediment and plastic insert were removed from the corer, water overlying the sediment surface was siphoned off, and the insert was packed to stabilize the sediment and capped before placement on ice. A water sample from each site was also collected for the BOD bottle tests.

The abiotic oxygen demand tests were performed with sediment from the upper 2-cm of the core. Approximately 5 -10 g of wet sediment was placed in a 300-mL BOD bottle with water collect at the site and a magnetic stir bar. Dissolved oxygen concentrations were continuously monitored while stirring for approximately one hour. Longer-term oxygen demand evaluations were also performed using the method described earlier for the trapped sediments.

Grain size analyses were also performed for the sediments at core intervals of 0-5, and 5-10 cm below the sediment water interface. Sediments were wet sieved through a No. 200 sieve. The fraction remaining on the sieve was classified as sand. The material passing the 200 sieve was fractionated into silts or clays by the hydrometer method (ASTM D422). The fraction of organic matter for the sediments was estimated by determining the volatile fraction of each sample. The sediment was dried at 103° C followed by ignition at 550° C. This was performed to estimate the organic matter fraction for the sediment. This procedure will volatilize carbonaceous minerals, thus the fractions reported here may significantly overestimate the fraction of organic matter present in the sediment.

### *Sediment Oxygen Demands*

The abiotic sediment oxygen demand tests are presented in Figure 7. A summary of the oxygen demand after 60 minutes is also presented in Table 8. The oxygen demands presented in Figure 7 or Table 8 are expressed on a dry sediment mass basis. The immediate uptake of oxygen shown in Figure 7 is associated with the oxidation of sulfides and reduced iron or other species. Two distinct behavior regions exist for each curve. For the first five minutes, the DO uptake is rapid. After approximately 5 minutes, the consumption rate of oxygen decreases significantly. This has been attributed to the

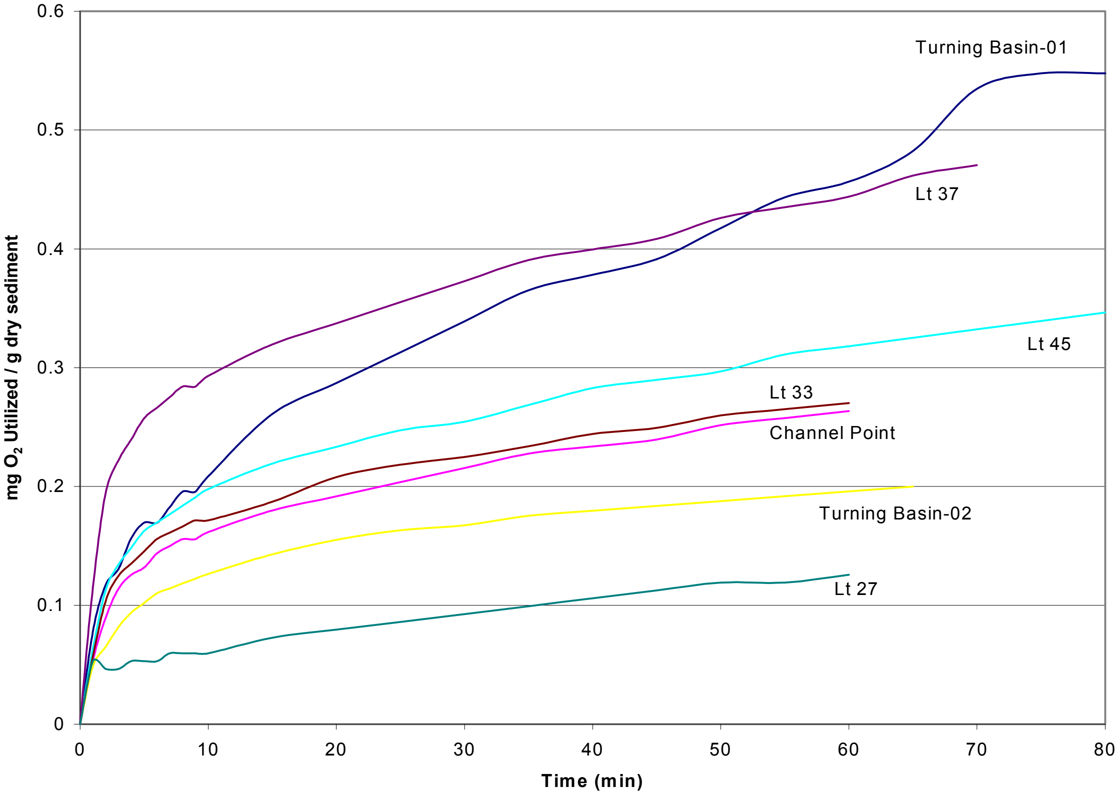

**Figure 7** Abiotic Oxygen Demand Measurements for DWSC Sediments

**Table 8** Abiotic Oxygen Demand of DWSC Sediments (0-2cm depth) after 60 minutes

| Location | Abiotic Oxygen Demand (mg DO/g dry sediment) |
|---|---|
| Turning Basin 1 | 0.46 |
| Turning Basin 2 | 0.20 |
| Channel Point | 0.26 |
| Light 45 | 0.32 |
| Light 37 | 0.44 |
| Light 33 | 0.27 |
| Light 27 | 0.13 |
| Mean<br>Standard Deviation<br>Coefficient of Variation | 0.30<br>0.120376<br>0.405113 |

coating of mineral surfaces with oxidized species (Gardner and Lee, 1965). During this time, oxygen uptake is limited by its diffusion rate through the oxidized coating. As shown in Table 8 these oxygen demands range from 0.13 to 0.46 mg of DO/g dry sediment.

Longer term oxygen demand experiments associated with both abiotic and biochemical processes were also performed. Table 9 presents the results of the 5-day oxygen demands expressed as mg of DO depleted per gram of total or volatile sediment mass. After 5 days, the DO concentration for all the trials was exceeded. As shown in Table 9, the 5-day oxygen demand for the sediments averaged 2.0 and 35 mg/g on a total or volatile mass basis. These estimates of the abiotic and biochemical oxygen demand represent what the oxygen demand may be for sediment resuspended into the water column. The actual oxygen demands exerted *in situ* are expected to much less, however, quantification of mixing and sediment resuspension rates are needed to estimate the actual rate of SOD exertion.

**Table 9** Biochemical oxygen demand of shallow sediments (0-2 cm) of the DWSC.

| Location | 5-Day Oxygen Demand | |
|---|---|---|
| | total basis | volatile basis |
| | (mg/g dry trapped matter) | (mg/g dry volatile matter) |
| Turning Basin 2 | 1.9 | 41 |
| Channel Point | 1.8 | 31 |
| Light 45 | 2.5 | 40 |
| Light 37 | 3.6 | 50 |
| Light 33 | 0.7 | 14 |
| Light 27 | 1.8 | 35 |
| Mean | 2.0 | 35 |
| Standard Deviation | 0.86 | 11 |
| Coefficient of Variation | 0.42 | 0.32 |

A comparison of the oxygen demands for DWSC sediments with the oxygen demand associated with trapped sediments is presented in Table 10. The oxygen demands presented in Table 10 are for different time periods and they exhibit different decay rates, which will influence the ultimate oxygen demand for each measurement. As discussed previously, conversion to ultimate oxygen demand values was not always possible for the trapped and DWSC sediments, however, comparisons of the oxygen demands of these sediments are informative. The average abiotic demand is approximately one order of magnitude less than the 5-d biochemical oxygen demand. Similarly the 5-day demand for the sediments is approximately an order of magnitude less than the oxygen demand of the trapped sediments. These results suggest that much of the demand associated with settleable matter may be exerted in the water column prior to deposition or when resuspended. However, it is also possible that the large difference between the bed sediment and trapped sediment is associated with the testing of sediments within the first 2 cm. The freshest, most reactive material will exist just at the interface while more refractory organic matter will reside below.

**Table 10** Comparison of Oxygen Demands for DWSC Sediments and Trapped Sediments.

| DO Demand Reporting Convention | DWSC Sediments | | Trapped Sediments |
|---|---|---|---|
| | 1-hr Abiotic Demand | 5-Day Demand | 5-Day Demand |
| | (mg/g) | (mg/g) | (mg/g) |
| Total Dry Mass Basis | 0.30 | 2.0 | 41 |
| Dry Volatile Mass Basis | NA | 35 | 160 |

### *Sediment Mass Fractions*

The mass fractions of sediments that exist in the DWSC are reported in Table 11. The mass fractions are categorized according to sand, silt, and clay fractions. As expected, Channel Pt contains a high fraction of sand because flow velocites decrease significantly when the San Joaquin River transitions into the DWSC. High sand fractions were also observed near Light 27 and Light 33. The cause is not known, but may be associated with the fact that tidal flows in the San Joaquin River increase toward the ocean. If the channel geometry remains constant, the increase in flow will result in increased velocities that could be sufficient to transport relatively fine sediments.

As a means of estimating the organic fraction of the sediment in the DWSC, the volatile fraction was determined primarily for reporting BOD results on a dry volatile mass basis. As shown in Table 12 the volatile fractions range from approximately 5 to 7 percent on a dry mass basis. Since the sediments may contain carbonate minerals, exposing the sediment to high temperatures will volatilize these sediments and yield an overestimation of organic matter fraction.

**Table 11** DWSC Sediment Size Mass Fractions.

| | Percent Mass Fraction for Each Size Range 0-5cm /5-10cm Depth | | |
|---|---|---|---|
| Location | Fine Sand 0.075<d<0.425 | Silt 0.002<d<0.075 | Clay d < 0.002 |
| Turning Basin | 14/ -- | 50/ -- | 36/ -- |
| Channel Point | 52/47 | 29/37 | 19/16 |
| Light 45 | 23/23 | 55/52 | 22/25 |
| Light 37 | 34/30 | 30/40 | 36/30 |
| Light 33 | 59/56 | 26/29 | 16/15 |
| Light 27 | 49/ -- | 26/ -- | 25/ -- |

**Table 12** Volatile Fractions for DWSC Sediments.

| Location | Mass Volatile Matter/Total Dry Mass |
|---|---|
| Turning Basin | 0.046 |
| Channel Point | 0.057 |
| Light 45 | 0.062 |
| Light 37 | 0.071 |
| Light 33 | 0.051 |
| Light 27 | 0.050 |

BOD Kinetic Rate Study

Long term BOD tests were performed with treated final effluent from the Stockton Wastewater Treatment Facility and water collected by the City of Stockton at Mossdale Crossing and R-5 in the San Joaquin River. These results were analyzed to determine the kinetic rate constants and ultimate oxygen demands of these waters. These parameters will ultimately be used for model calibration and mass loading calculations.

Bottle trials were set up to evaluate rate constants and ultimate concentrations of:

- total biochemical oxygen demand (BOD)
- soluble BOD (sBOD)
- carbonaceous BOD (CBOD)
- soluble carbonaceous BOD (sCBOD)
- total and soluble BOD spiked with ammonia

From these tests, determining decay rates for particulate and nitrogenous (NBOD) are also theoretically possible:

Particulate BOD = total BOD – sBOD,
NBOD = total BOD – cBOD.

Table 13 lists the day the samples were collected, the day the experiments were set up and started and the last day of each 28-day trial. City of Stockton personnel initiated this experimental plan on August 24, by conducting the first trial. University of the Pacific carried out the remaining four trials. All data was analyzed by UOP and the results are included here.

**Table 13** BOD Kinetic Trials and Relative Starting and Ending Dates.

| Trial | Sample Collection Date | Trial Start Date | Trial End Date |
|---|---|---|---|
| City | 8/24/99 | 8/25/99 | 9/22/99 |
| UOP 1 | 9/7/99 | 9/7/99 | 10/5/99 |
| UOP 2 | 9/21/99 | 9/21/99 | 10/19/99 |
| UOP 3 | 10/5/99 | 10/5/99 | 11/2/99 |
| UOP 4 | 10/26/99 | 10/26/99 | 11/23/99 |

*Materials and Methods*

Approximately 45 bottles are required for each set including seed, glucose-glutamic acid standard, and blank determinations using methods modified from Standard Methods (APHA *et al.*, 1998). River water samples were not diluted for any of the test, while dilution ratios for the final effluent samples varied from 1 to 0.1, the most common being 0.5 and 0.25. Two dilutions and duplicate bottles were prepared for most of the final effluent tests. Prepared bottles were stored in a dark environmental chamber at 20 ±

0.5° C. The major difference between these tests and a standard 5-d BOD determination was the continued DO monitoring of each bottle for 28 days. Dissolved oxygen concentrations were measured at 1, 3, 5, 9 16, and 28 days for the UOP trials. The city trial was monitored at 1, 5, 9, 15, 22, and 28 days. The bottles were not reaerated after each DO measurement.

Unless otherwise specified, the results presented here were seeded with undisinfected secondary effluent provided by the City of Stockton. Each bottle received 0.200 mL of seed. The oxygen demand values used and reported here were adjusted for the oxygen demand of the seed and dilution water. Seeded dilution water results were consistently less than 0.2 mg/L after 5 days, but could exceed 1 mg/L after 28 days. For every trial, the results of the glucose-glutamic acid standard fell within the acceptable range of 168-228 mg/L, suggesting that the samples were adequately seeded with microorganisms utilizing carbon compounds, but not necessary nitrogen. For many of the bottle tests the DO fell below 1 mg/L after 16 or 28 days. These data points were not used in the estimating decay rates and ultimate oxygen demands.

The kinetic rate decay constant and the ultimate BOD was estimated by linearizing the data and fitting a least-squares line. Assuming the decay of organic matter to behave as a first-order reaction,

$$BOD_t = L_0[1 - e^{-kt}]$$

where $BOD_t$ is the biochemical oxygen demand calculated at time, t, in mg/L, k is the first-order decay rate constant, and $L_0$ is the ultimate BOD. Determination of k and $L_0$ is determined graphically by using the following linear approximation of the above equation:

$$\left[\frac{t}{y_t}\right]^{1/3} = (kL_0)^{-1/3} + \left[\frac{k^{2/3}}{6L_0^{1/3}}\right]t\,,$$

where $y_t = BOD_t$.

A plot of $\left[\frac{t}{y_t}\right]^{1/3}$ vs. $t$ is a straight line with slope $m = \frac{1}{6}k^{2/3}L_0^{-1/3}$ and y-intercept of $b = (kL_0)^{-1/3}$. The first-order rate constant and ultimate BOD are calculated from $k=6m/b$ and $L_0=1/(6mb^2)$.

*Estimates of the decay constant*

Examples of the CBOD data and fitted curves are presented Figures 8 and 9 for the August 24 data. As shown in Figure 8, the linearized data will generally exhibit a positive slope. Some of the soluble test results exhibited negative slopes when the data was linearized. This arises when the oxygen demand is increasing exponentially with time. A poorly acclimated microbe population is perhaps the best explanation for this phenomenon. Decay constants are not reported for cases in which the slope of the linearized data was negative.

The goodness of fit was evaluated by squared correlation coefficients ($R^2$) and visual inspection. Anomalous data points were selectively removed so as not to skew the fitted line. However, virtually all the k values were estimated with at least four data points. Each experiment yields a maximum of six points. For tests with multiple dilutions, the dilution that provided the most usable data points was selected for estimating k. When all dilutions or duplicates appeared to be equal quality, the data was averaged.

A summary of the averaged k, $BOD_{ult}$, measured $BOD_5$, and the theoretical ratio of $BOD_{ult}$ to $BOD_5$ is presented in Table 14 for total BOD, sBOD, CBOD, sCBOD, particulate BOD, and NBOD. The $BOD_{ult}/BOD_5$ ratio is determined by,

$$BOD_{ult} / BOD_5 = 1/(1 - e^{-k \times 5}),$$

where k is the decay constant determined by the fitting procedure. Review of Table 14 suggests that many of the decay rates are approximately 0.10, which corresponds to the $BOD_{ult}$ of the sample being approximately 2.5 times greater than the $BOD_5$ value. Tables 15 to 19 present the k values used to determine the averages values shown in Table 14. These tables also show the goodness of fit for each trial.

As mentioned earlier, the particulate BOD constants were determined by fitting a curve to the difference of the individual sBOD and total BOD values. If the decay of sBOD and total BOD is first-order, then the decay constant, k, for the particulate BOD, will theoretically be less than the decay constant for the total BOD. However, as shown in Table 14, decay constants were calculated at levels greater than the total BOD decay constant. Table 19 indicates that the goodness of fit for the particulate BOD line fits were often greater than 0.90, an indication of a reasonably good fit. However, for two of the trials the decay constant for particulate BOD was greater than the total BOD k value. Additional examination of the data is required to resolve this discrepancy.

Determining NBOD results by direct subtraction was also problematic. Poor line fits or negatively sloped data prevented a direct estimation of the decay constant. The values of k appearing in Table 14 originate from using the average values of k and $BOD_{ult}$ for to generate total BOD and CBOD concentrations at discrete times. These synthesized values were then subtracted and a curve was fit for estimating the NBOD decay constants appearing in Table 14. These constants should also be reevaluated.

The effort to generate a first-order decay constant for the NBOD was expended because the water quality model for the San Joaquin River assumes the decay of ammonia and organic nitrogen to be first-order without a lag in oxygen demand associated with microbial acclimation. However, much of the data show that nitrification in the BOD bottles is delayed for 9 to 16 days. This appears to be the cause of the poor curve fits when using the subtraction method. These observations also suggest that the algorithms for nitrification may need to be modified to incorporate a lag in the oxygen demand response.

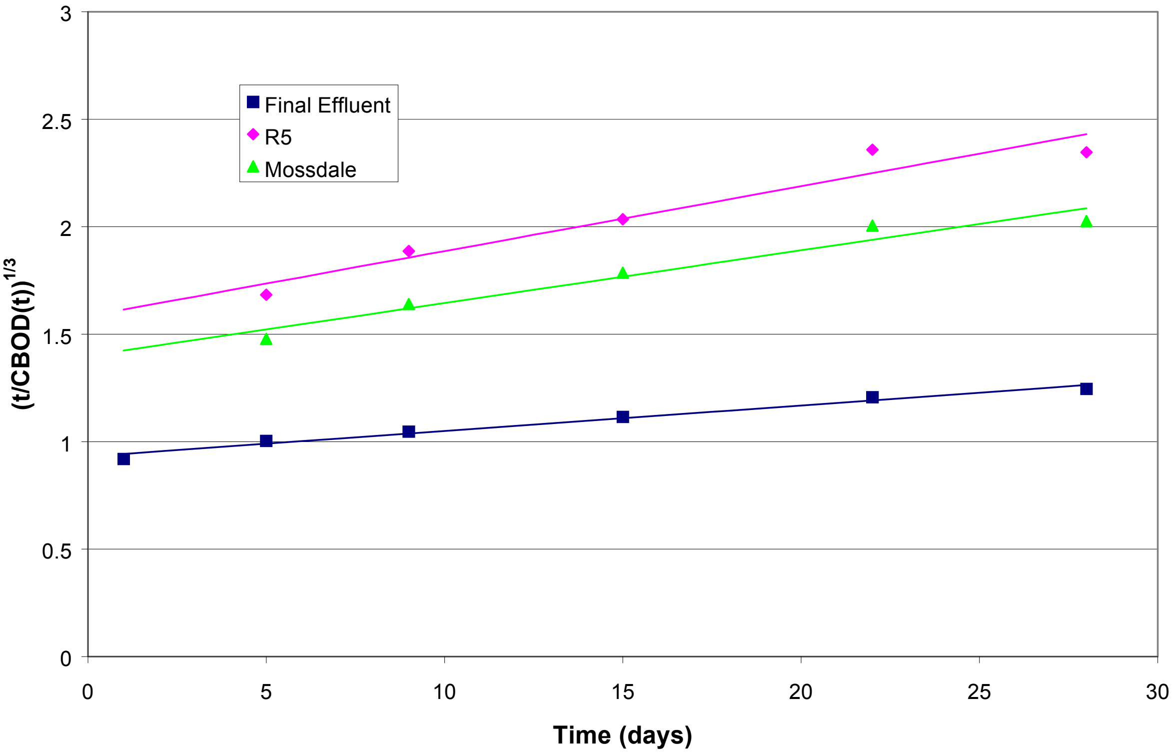

**Figure 8** Linerized Carbonaceous BOD Data from the 8/25/99 Trial with Fitted Line for Estimating k and $BOD_{ult}$.

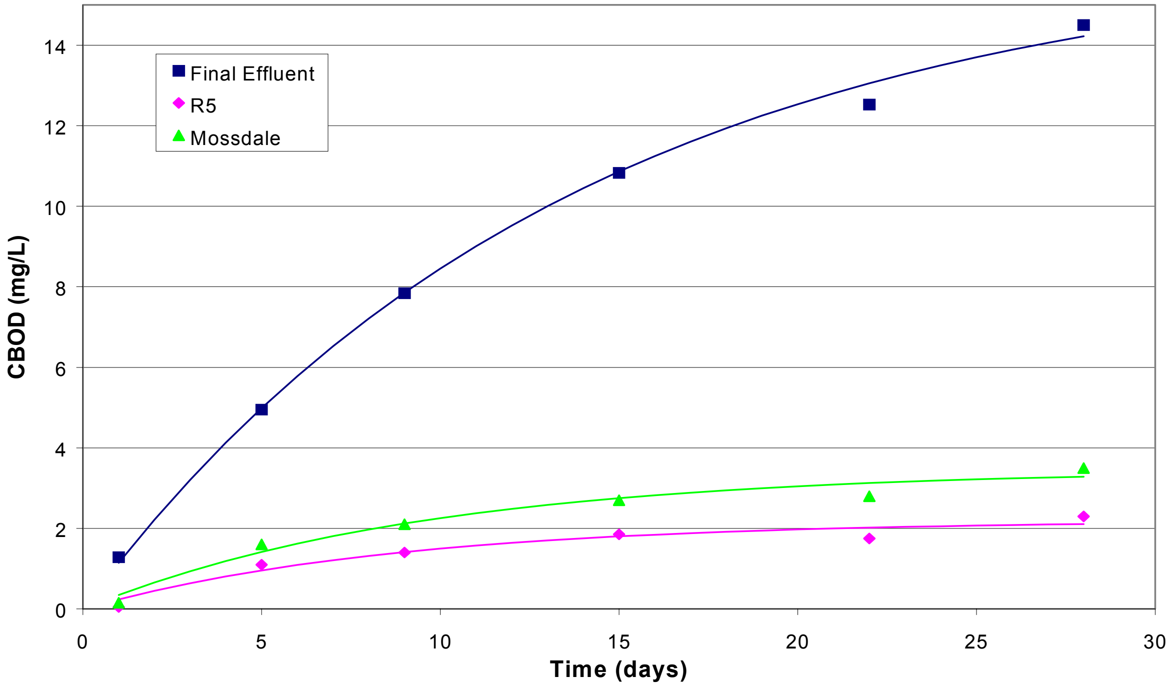

**Figure 9** Carbonaceous BOD Data with Fitted Curve Using the Estimated k and $BOD_{ult}$.

**Table 14** Summary of Average Decay Rates and Ultimate BOD.

| | | K ($d^{-1}$) | | $BOD_{ult}$ (mg/L) | | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Sample | Species | average | std dev | Average | std dev | |
| FE | BOD | 0.11 | 0.02 | 21.0 | 10.2 | 2.4 |
| | CBOD | 0.11 | 0.04 | 14.1 | 1.5 | 2.4 |
| | SBOD | 0.11 | 0.02 | 8.6 | 2.9 | 2.4 |
| | SCBOD | 0.08 | 0.03 | 7.4 | 2.9 | 2.9 |
| | Particulate BOD | 0.14 | 0.04 | 11.5 | 8.0 | 2.0 |
| | NBOD[2] | 0.10 | Na | na | na | 2.5 |
| | | | | | | |
| Mossdale | BOD | 0.10 | 0.04 | 7.4 | 1.7 | 2.5 |
| | CBOD | 0.10 | 0.02 | 4.2 | 0.9 | 2.5 |
| | SBOD | 0.09 | 0.01 | 3.6 | 1.5 | 2.9 |
| | SCBOD | 0.09 | 0.02 | 3.9 | 2.1 | 2.8 |
| | Particulate BOD | 0.10 | 0.02 | 3.8 | 1.5 | 2.5 |
| | NBOD[2] | 0.09 | Na | na | na | 2.7 |
| | | | | | | |
| R-5 | BOD | 0.14 | 0.07 | 5.9 | 2.0 | 2.0 |
| | CBOD | 0.10 | 0.04 | 3.8 | 1.2 | 2.5 |
| | sBOD | 0.08 | 0.04 | 7.6 | 7.9 | 3.1 |
| | sCBOD | 0.09 | 0.02 | 2.7 | 0.8 | 2.7 |
| | Particulate BOD | 0.18 | 0.06 | 2.2 | 0.9 | 1.7 |
| | NBOD[2] | 0.16 | Na | na | na | 1.8 |

[1] $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

[2] Synthesized from average BOD and cBOD determined from average k and $BOD_{ult}$ values.

**Table 15** Summary of BOD Results

| Sample | Trial | $R^2$ | K ($d^{-1}$) | $BOD_{ult}$ (mg/L) | Measure $dBOD_5$ (mg/L) | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Final Effluent | City | 0.98 | 0.11 | 14.0 | 5.9 | 2.3 |
| | UOP 1 | 0.98 | 0.13 | 15.8 | 8.9 | 2.1 |
| | UOP 2 | 0.97 | 0.07 | 18.1 | 5.2 | 3.3 |
| | UOP 3 | na | neg slope for 3 bottles | | | na |
| | UOP 4 | 0.98 | 0.12 | 36.1 | 17.4 | 2.2 |
| | Average | | 0.11 | 21.0 | | 2.4 |
| | Std. Dev. | | 0.02 | 10.2 | | |
| Mossdale | City | 0.99 | 0.09 | 7.2 | 2.7 | 2.7 |
| | UOP 1 | 0.98 | 0.16 | 6.1 | 3.5 | 1.7 |
| | UOP 2 | 0.87 | 0.04 | 10.1 | 2.0 | 5.0 |
| | UOP 3 | 0.85 | 0.08 | 5.9 | 2.0 | 3.0 |
| | UOP 4 | 0.82 | 0.06 | 7.6 | 1.9 | 3.9 |
| | Average | | 0.10 | 7.4 | | 2.5 |
| | Std. Dev. | | 0.04 | 1.7 | | |
| R-5 | City | 0.90 | 0.07 | 5.1 | 1.6 | 3.1 |
| | UOP 1 | 0.93 | 0.24 | 6.3 | 4.1 | 1.5 |
| | UOP 2 | 0.99 | 0.09 | 4.8 | 1.9 | 2.6 |
| | UOP 3 | 0.99 | 0.16 | 4.2 | 2.2 | 1.8 |
| | UOP 4 | 0.87 | 0.12 | 9.3 | 4.4 | 2.1 |
| | Average | | 0.14 | 5.9 | | 2.0 |
| | Std. Dev. | | 0.07 | 2.0 | | |

[1] $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

**Table 16** Summary of CBOD Tests

| Sample | Trial | $R^2$ | K ($d^{-1}$) | $BOD_{ult}$ (mg/L) | Measure $dBOD_5$ (mg/L) | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Final Effluent | City | 0.91 | 0.07 | 16.4 | 4.4 | 3.3 |
| | UOP 1 | 0.94 | 0.11 | 12.7 | 5.0 | 2.3 |
| | UOP 2 | 0.72 | 0.12 | 14.9 | 6.3 | 2.2 |
| | UOP 3 | 0.44 | 0.07 | 13.4 | 3.1 | 3.3 |
| | UOP 4 | 0.72 | 0.16 | 13.0 | 6.1 | 1.8 |
| | Average | | 0.11 | 14.1 | 5.0 | 2.4 |
| | Std. Dev. | | 0.04 | 1.5 | 1.3 | |
| Mossdale | City | 0.95 | 0.11 | 3.5 | 1.5 | 2.4 |
| | UOP 1 | 0.98 | 0.09 | 5.7 | 2.1 | 2.9 |
| | UOP 2 | 0.92 | 0.09 | 3.5 | 1.2 | 2.7 |
| | UOP 3 | 0.88 | 0.14 | 4.3 | 2.0 | 2.0 |
| | UOP 4 | 0.98 | 0.09 | 3.9 | 1.4 | 2.8 |
| | Average | | 0.10 | 4.2 | 1.7 | 2.5 |
| | Std. Dev. | | 0.02 | 0.9 | 0.4 | |
| R-5 | City | 0.93 | 0.11 | 2.2 | 1.0 | 2.3 |
| | UOP 1 | 0.90 | 0.15 | 5.6 | 2.7 | 1.9 |
| | UOP 2 | 0.93 | 0.05 | 4.1 | 0.9 | 4.4 |
| | UOP 3 | 0.80 | 0.08 | 3.9 | 1.1 | 2.9 |
| | UOP 4 | 0.99 | 0.11 | 3.2 | 1.4 | 2.3 |
| | Average | | 0.10 | 3.8 | 1.4 | 2.5 |
| | Std. Dev. | | 0.04 | 1.2 | 0.7 | |

[1] Estimated from k: $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

**Table 17** Summary of sBOD results.

| Sample | Trial | $R^2$ | K ($d^{-1}$) | $BOD_{ult}$ (mg/L) | Measure $dBOD_5$ (mg/L) | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Final Effluent | City | 0.98 | 0.10 | 6.1 | 2.5 | 2.5 |
| | UOP 1 | 0.88 | 0.09 | 7.9 | 2.8 | 2.7 |
| | UOP 2 | neg slope | | | 2.6 | na |
| | UOP 3 | neg slope | | | 4.7 | na |
| | UOP 4 | 0.88 | 0.12 | 12 | 5.8 | 2.2 |
| | Average | | 0.11 | 8.6 | 3.7 | 2.4 |
| | std dev | | 0.02 | 2.9 | 1.5 | |
| Mossdale | City | 0.84 | 0.09 | 2.0 | 0.8 | 2.8 |
| | UOP 1 | 0.93 | 0.10 | 3.2 | 1.5 | 2.5 |
| | UOP 2 | 0.95 | 0.08 | 5.7 | 1.9 | 3.0 |
| | UOP 3 | 0.70 | 0.08 | 3.3 | 0.8 | 3.2 |
| | UOP 4 | 0.15 | 0.01 | 25 | 0.9 | 27.7 |
| | Average | | 0.09 | 3.6 | 1.3 | 2.9 |
| | std dev | | 0.01 | 1.5 | 0.5 | |
| R-5 | City | 0.73 | 0.08 | 2.0 | 0.7 | 3.0 |
| | UOP 1 | 0.98 | 0.10 | 4.5 | 1.9 | 2.5 |
| | UOP 2 | 0.84 | 0.08 | 5.4 | 2.0 | 3.1 |
| | UOP 3 | 0.05 | 0.02 | 21 | 1.7 | 12.9 |
| | UOP 4 | 0.91 | 0.11 | 4.5 | 1.8 | 2.3 |
| | Average | | 0.08 | 7.6 | 1.6 | 3.1 |
| | std dev | | 0.04 | 7.9 | 0.5 | |

[1] Estimated from k: $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

**Table 18** Summary of sCBOD Tests.

| Sample | Trial | $R^2$ | K ($d^{-1}$) | $BOD_{ult}$ (mg/L) | Measure $dBOD_5$ (mg/L) | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Final Effluent | City | 0.79 | 0.06 | 3.8 | 1.2 | 3.7 |
| | UOP 1 | 0.88 | 0.09 | 7.9 | 1.7 | 2.7 |
| | UOP 2 | 0.95 | 0.05 | 10.6 | 1.9 | 4.5 |
| | UOP 3 | 0.78 | 0.12 | 4.9 | 2.3 | 2.2 |
| | UOP 4 | 0.74 | 0.10 | 9.5 | 3.3 | 2.6 |
| | Average | | 0.08 | 7.4 | 2.1 | 3.1 |
| | std dev | | 0.03 | 2.9 | 0.8 | |
| Mossdale | City | 0.93 | 0.07 | 7.7 | 0.4 | 3.4 |
| | UOP 1 | 0.94 | 0.09 | 2.9 | 1.2 | 2.7 |
| | UOP 2 | 0.97 | 0.07 | 3.4 | 0.9 | 3.3 |
| | UOP 3 | 0.87 | 0.12 | 3.0 | 1.3 | 2.2 |
| | UOP 4 | 0.69 | 0.08 | 2.5 | 0.9 | 3.0 |
| | Average | | 0.09 | 3.9 | 1.0 | 2.9 |
| | std dev | | 0.02 | 2.1 | 0.4 | |
| R-5 | City | 0.87 | 0.10 | 1.3 | 0.5 | 2.6 |
| | UOP 1 | 0.96 | 0.10 | 2.8 | 1.2 | 2.5 |
| | UOP 2 | 0.94 | 0.11 | 3.4 | 1.4 | 2.3 |
| | UOP 3 | 0.98 | 0.07 | 3.1 | 1.0 | 3.3 |
| | UOP 4 | 0.80 | 0.07 | 2.8 | 0.7 | 3.4 |
| | Average | | 0.09 | 2.7 | 1.0 | 2.8 |
| | std dev | | 0.02 | 0.8 | 0.4 | |

[1] Estimated from k: $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

**Table 19** Summary of Particulate BOD results (BOD – sBOD)

| Sample | Trial | $R^2$ | K ($d^{-1}$) | $BOD_{ult}$ (mg/L) | Measure $dBOD_5$ (mg/L) | $BOD_{ult}/BOD_5$[1] |
|---|---|---|---|---|---|---|
| Final Effluent | City | 0.99 | 0.20 | 6.0 | 3.6 | 1.6 |
| | UOP 1 | 0.98 | 0.11 | 11 | 4.4 | 2.4 |
| | UOP 2 | 0.61 | 0.14 | 6.0 | 3.5 | 2.0 |
| | UOP 3 | 0.00 | 0.00 | 0.0 | 13 | na |
| | UOP 4 | 0.96 | 0.13 | 23 | 11 | 2.1 |
| | Average | | 0.14 | 11.5 | 7.3 | 2.0 |
| | std dev | | 0.04 | 8.0 | 4.8 | 0.0 |
| | | | | | | |
| Mossdale | City | 0.99 | 0.10 | 5.1 | 1.9 | 2.6 |
| | UOP 1 | 0.91 | 0.10 | 5.1 | 2.0 | 2.6 |
| | UOP 2 | 0.00 | Na | na | -0.2 | na |
| | UOP 3 | 0.87 | 0.09 | 2.6 | 1.2 | 2.8 |
| | UOP 4 | 0.97 | 0.12 | 2.3 | 1.0 | 2.2 |
| | Average | | 0.10 | 3.8 | 1.5 | 2.5 |
| | std dev | | 0.02 | 1.5 | 1.1 | 0.0 |
| | | | | | | |
| R-5 | City | 0.93 | 0.11 | 2.4 | 2.1 | 2.3 |
| | UOP 1 | 0.98 | 0.23 | 2.9 | 0.1 | 1.5 |
| | UOP 2 | 0.00 | Na | na | 0.5 | na |
| | UOP 3 | 0.93 | 0.19 | 1.2 | 1.7 | 1.6 |
| | UOP 4 | 0.78 | 0.06 | 6.5 | 0.9 | 3.7 |
| | Average | | 0.18 | 2.2 | 0.9 | 1.7 |
| | std dev | | 0.06 | 0.9 | 0.9 | |

[1] Estimated from k: $BOD_{ult} / BOD_5 = 1/(1-e^{-kt})$

## Acknowledgments

The thoughtful review of the study design, data analysis, and this report by the members of the San Joaquin River TMDL Technical Committee is greatly appreciated.

Field work, data compilation and analysis was made possible with the assistance of the following University of the Pacific engineering undergraduate students:

Jennifer Dean

Andrew Etchison

Shawn Hart

Ed Herrnberger

Ingrid Johanson

Brandon Nakagawa

Jason Nikaido
Alicia Stamps

and

Lauri Wong.

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