A Tracer Investigation of

Aerated Water Dispersion and Tidal Exchange in

the San Joaquin River and Stockton Ship Channel

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Introduction

This tracer study was conducted to determine the transport behavior of water oxygenated at the jet aeration facility operated by the Port of Stockton. This work was performed in conjunction with an investigation of the aerator efficiency conducted by Jones & Stokes. Aeration has been identified as a potential solution to the severe dissolved oxygen deficits observed in the San Joaquin River and the Stockton Deep Water Ship Channel (DWSC) near the Port of Stockton. Knowledge of the movement and mixing of water in the San Joaquin River will assist with proposed plans to further investigate the viability of expanding aeration facilities. Specifically, these results will aid with locating and sizing of the demonstration project aerator.

The tracer dye study was performed in the San Joaquin River on September 1 and 2, 2004 to evaluate the dispersion and tidal movement of water aerated at the Port of Stockton. A 25-hr injection of rhodamine WT was conducted at the jet aeration facility located near the confluence of the San Joaquin River and the DWSC near the Port of Stockton. The tracer was introduced to the aerated water to track its movement and mixing. The spatial distribution of the rhodamine was tracked with a boat-mounted fluorometer and global positioning system (GPS). Water quality measurements of dissolved oxygen, electrical conductivity, water temperature, pH, turbidity, instrument depth, and water depth were also simultaneously recorded during the tracer monitoring.

This study was performed to answer several questions that will assist with the sizing, location and spacing of future aeration facilities and whether the benefits of the existing jet aerator can be measured directly. The specific questions that address these issues follow.

- Will aerated water released on the bank of the San Joaquin River mix laterally across the channel to influence dissolved oxygen deficits across the entire river?

- Will the aerated water mix completely with depth to affect the greatest dissolved oxygen deficits typically observed near the channel bottom?

- What is the longitudinal movement of the aerated water during a 25-hr tidal cycle?

- Can increases of dissolved oxygen be measured when the existing jet aerator at the Port of Stockton is operated continuously?

Methods and Materials

Rhodamine WT dye (Keystone Pacific Division, Santa Fe Springs, CA) was introduced to the San Joaquin River at the Port of Stockton aerator on September 1, 2004. The tracer injection started at 16:15 on September 1 and continued until 17:20 on September 2. The movement of the dye within the San Joaquin River was monitored throughout the injection and again on September 3. The location of the aerator is shown in Figure 1.

The tracer injection was conducted with the diffuser system shown in Figures 2 and 3 to uniformly disperse the rhodamine WT within the upwelling water at the aerator. The aerator injected water with entrained air from jet nozzles at a water depth of approximately 20 ft. Air not dissolved in the jet stream rises rapidly to the surface as bubbles and creates a strong upflow current. As shown in Figure 3, the red tracer was sprayed into the upwelling aerated water that was then laterally carried away at the water surface. Prior to releasing the dye into the San Joaquin River a trash pump operating at approximately 25 gpm diluted the concentration of rhodamine. The intake of the trash pump suction hose was placed at a depth of approximately 15 ft below San Joaquin River water surface. The tracer was injected into the suction hose at a rate of 23 mL/min before being laterally distributed into the upwelling current with the 2-in diameter PVC diffuser manifold. The diameter of the holes in the PVC diffuser was _ in and spaced approximately every 6 inches. The injection of rhodamine WT into the trash pump suction hose was accomplished with a Masterflex peristaltic pump (Cole-Parmer Instrument Co., Vernon Hills, IL). The dye was pumped at a concentration of 228 g/L as rhodamine WT (undiluted 20 percent dye solution by weight) at 23 mL/min. Dilution of the dye by the air bubble induced lateral current was sufficient to reduce the concentration in the San Joaquin below 12 μg/L within 50 ft of the diffuser.

The concentration of rhodamine WT dye tracer and the corresponding location and depth was measured from an 18-foot aluminum outboard boat. A schematic diagram of the monitoring system is shown in Figure 4. The boat speed was typically limited to 2-3 mph during the dye tracking. The dye concentration was measured with a SCUFA III fluorometer (Turner Instruments, Sunnyvale, CA) calibrated with standards diluted with tributary water collected at a depth of 2 feet prior to the dye injection. A solid secondary standard was also used to periodically check the calibration of the SCUFA. The SCUFA III also measures turbidity and temperature, the two parameters used to adjust the raw fluorescence reading to a tracer concentration. During this study the internal correction for turbidity effects was not sufficient to eliminate this interference. Therefore, rhodamine WT concentrations were adjusted manually using fluorescence-turbidity curves developed with measurements of San Joaquin River water without tracer. Instrument depth was determined with a 600XL water quality sonde (YSI, Inc., Yellow Springs, OH) fixed to a weighted, PVC frame at the same elevation as the SCUFA. The YSI sonde also provided water temperature, dissolved oxygen and electrical conductivity data. Coordinate locations for each dye measurement were determined by a Garmin GPS Map 238 Sounder (Garmin

International, Inc., Olathe, KS) with a two second sampling frequency and reported position accuracy of less than 10 ft (position measurements when stationary generally do not vary more than 15 ft). This instrument also measures water depth by sonar with a measured accuracy of approximately 1 ft. The four instruments were interfaced to a desktop computer via serial ports and RS232 communication protocols. Data was collected simultaneously from each instrument every two seconds and time-stamped using data acquisition software developed with Matlab (Version 7.0, The MathWorks, Inc., Natick, MA).

Results and Discussion

Figure 5 exhibits the flow and stage of the San Joaquin River on September 1 and 2, 2004. Within the study area, the San Joaquin River is tidal. Flood tide flows measured at the Garwood Gage were approximately 2000 cfs, while maximum ebb flows were as high as 3000 cfs. The net river flow for September 1 and 2 was 582 and 451 cfs, respectively. As shown in Figure 5, the injection of rhodamine WT was initiated at the start of a flood tide and ended approximately 25 hours, one tidal cycle, later. Due to the net flow downstream during this study, the time at which flow reverses in the San Joaquin River lags the slack tide by about 1 hour. Near-field and far-field observations of the dye movement are discussed in the following sections.

The terms upstream and downstream are used in this report to describe the transport of the dye relative to the location of the rhodamine injection at the aerator. Reversals of the San Joaquin River net flow occasionally occur in the study area; however, for this report, upstream is defined as the direction toward the USGS Garwood gage and downstream is toward the Department of Water Resources water quality station at Rough and Ready Island (RRI) shown earlier in Figure 1. Positive distances on all figures are in the downstream direction.

Near-field mixing of rhodamine WT

Immediately after the start of the dye injection on September 1, longitudinal traverses were performed within 50 feet of the dye diffuser to characterize the lateral surface flow induced by the jet aerator. Measurements were performed at 1 ft intervals to a depth of 4 ft, the approximate vertical extent of the lateral surface flow. As shown in Figure 6, the concentrations of rhodamine WT varied between 4 and 12. The simple average of these measurements within plume was 6.6 µg/L. Applying mass conservation to this system yields an estimate of 450 cfs for the lateral surface flow induced by the jet aerator ($C_{in}Q_{in} = C_{lat}Q_{lat}$, where C_{in}=228 g/L, Q_{in}= 23 mL/min). However, the dye was injection on only one side of the lateral current induced by the rising air bubbles, the total upwelling current is 900 cfs, twice the calculated flow.

The dissolved oxygen, water temperature, pH, and turbidity of the lateral surface flow are shown in Figures 7a, b, c, and d. The dissolved oxygen of the dyed water in the plume is approximately 0.5 mg/L higher than adjacent waters. While Figure 7b suggests that an increase in dissolved oxygen associated with the jet aerator was observed, the initial dissolved oxygen concentration prior to aeration by the rising bubbles is uncertain. Figure 7c indicates that water temperatures are also higher within the lateral surface flow by approximately 0.2ºC. The turbidity and pH data also show a distinct difference for water within and outside the dyed plume.

Comparing these water quality measurements in the lateral surface flow from the aerator with data collected farther away suggest that the DWSC may be the origin of the water drawn to the aerator jet. These data are presented later in Figures 8a,b,c, and d. A comparison of the temperature, pH and turbidity in the lateral surface flow from the aerator with water measured at 18 ft in the DWSC at a distance 100 to 250 ft downstream of the aerator are similar. This suggests that the source of the upwelling flow came from the about the same depth as the aerator at the time of the measurements and the much colder water observed below 25 feet in the DWSC was not drawn up into the bubble inducted current. The dissolved oxygen concentration measurements shown in Figure 8a suggest that the water drawn into the aerator bubble upflow range from about 3.5 to 4.5 mg/L. Unfortunately, this variability is too great to provide for an accurate estimate of the dissolved oxygen enhancement associated with the aerator.

Longitudinal measurements were performed throughout the water column in front of the aerator to compare whether elevated concentrations of dissolved oxygen were correlated with rhodamine WT concentration. Figure 9a and b presents the rhodamine WT dye and dissolved oxygen concentration profiles measured along the centerline of a 1200 ft river segment. As expected, most of the dye is located within the upper 5 ft of the water column and is moving upstream of the aerator due to the flood tide. The dyed, aerated water is also shown to be relatively well mixed within the upper 15 ft of the water column after moving upstream only 200 ft. Relatively uniform rhodamine concentrations were observed at distances greater than 1000 ft upstream of the aerator. During this first flood tide, the rhodamine WT concentration was observed to be approximately 1.5 µg/L. This observation was also used to estimate the flood tide flow, Q_r, at approximately 2000 cfs ($C_{in}Q_{in} = C_rQ_r$, where C_{in}=228 g/L, Q_{in}= 23 mL/min). This flow estimate is consistent with the flood tide flows measured at the USGS Garwood gage shown earlier in Figure 5.

Also seen in Figure 9b is the movement of colder bottom water of the DWSC moving up into the San Joaquin River during this flood tide. During this study, river temperatures above the DWSC were consistently lower than the surface waters of the DWSC. As shown later in Figures 18 and 19, the cooler aerated, dyed water would sink below the water surface upon entry to the DWSC and move near the channel bottom during the successive ebb tide flow.

Figures 10a and b provide a comparison of the rhodamine WT and dissolved oxygen concentration profiles. Dissolved oxygen concentrations in the DWSC, downstream of the aerator, varied from 6 mg/L at the surface to 3 mg/L below depths of 25 ft. Elevated dissolved oxygen concentrations originating from the jet aerator are not clearly evident in Figure 10b. As shown by the channel bottom profile, the aerator is located at the transition of the DWSC and the San Joaquin River. Water quality was observed to be highly variable at this location due to the mixing of surface and bottom waters of the DWSC and the operation of the aerator. A sharp transition in dissolved oxygen between the DWSC and the San

Joaquin River above the aerator masks any clear indication of increased dissolved oxygen concentrations associated with jet aerator. A comparison of the temperature and dissolved oxygen in Figures 9b and 10b does indicate that the regions of elevated dissolved oxygen are associated with the warmer waters from the DWSC. In addition, the jet aerator was oxygenating water drawn from a depth of approximately 18 ft that contained dissolved oxygen concentrations lower than the surface waters of the DWSC. Thus, even an increase in the dissolved oxygen concentration of 1 or 2 mg/L from the jet aerator would be difficult to observe when injected into waters with approximately the same dissolved oxygen concentration. The aerator would have had to be capable of raising the dissolved oxygen concentration to levels exceeding 6 mg/L to be seen clearly in Figure 10b.

Far-field observations of longitudinal rhodamine WT movement

The rhodamine WT longitudinal profile after the end of the first flood tide is shown in Figure 11. Tracer concentrations increase above the aerator and stabilize at about 1.5 μg/L after 1000 ft of transport. Between 2000 and 8000 ft the dye concentration falls to about 1.2 μg/L before peaking again at 1.8 μg/L. This dip and spike appears to be associated with the variable flood tide flow and is consistent in the flow record measured at the USGS Garwood Bridge gage (see Figure 5). The front of the rhodamine WT plume is observable in Figure 11 between 8,000 and 16,000 ft. The upper extent of the aerated, dye movement during this flood tide appears to be approximately 16,000 ft upstream of the jet aerator. Traces of dye may be observed as high as 22,000 ft upstream, however, turbidity interference may be responsible for these concentrations at the 0.1 to 0.2 μg/L level.

Also shown in Figure 11 are the dissolved oxygen and pH measurements recorded at the end of the first flood tide. Both profiles are consistent with the dye measurements. For example, the mid-point of the DO front is located at approximately 16,000 ft. However, the dissolved oxygen and pH profiles show evidence of DWSC water reaching approximately 25,000 ft upstream. This higher upstream influence is probably associated with dispersion caused by multiple tidal cycles and lower net river flows measured during the previous week, yielding greater upstream tidal movement. The net flow on August 29 was 278 cfs compared to 582 cfs measured on September 1 at the start of the rhodamine WT release.

The longitudinal rhodamine WT profiles measured at selected slack tides during the 25-hr injection and on Sept 3, 24 hours after the end of the dye release are presented in Figure 12. The highest dye concentrations were observed at the end of the second flood tide during the morning of September 2. The increased concentration of dye from the end of the first flood tide to the end of the second flood tide is caused by multiple dosing of the water as is passes back and forth in front of the aerator during successive flood and ebb tides. The profile measured during the afternoon at the end of the ebb tide was conducted near the end of the 25-hr rhodamine WT injection. The lower magnitude of the dye concentration observed downstream of the aerator is associated with the higher ebb tide flows (see Figure 5) that provide greater dilution of the injected rhodamine WT. The end of the ebb tide profile indicates that the extent of the downstream transport of the dyed, aerated water was approximately 10,000 ft after 24 hours. A final longitudinal transect was performed during the afternoon of September 3, about 24 hours after the end of the dye injection. This dye profile shows a downstream movement of about 2000 ft, greater attenuation of the maximum concentration, and a spreading of the plume associated with dispersion over another tidal cycle.

During flood tides the rhodamine WT tracer was also observed to travel approximately 1600 ft up the Stockton Ship Channel, toward the Turning Basin, as shown in Figure 13. These data were recorded approximately 2 hours before the high slack tide during the morning of September 2. Rhodamine concentrations increased slightly with depth, indicating that tidal flood flow toward the Turning basin was greatest near the channel bottom. The farthest extent of tidal excursion up the Stockton Ship Channel measured during this tracer study was about 2000 ft, just beyond the Wine Slip at the Port of Stockton.

Figure 14 presents the extent of the dyed, aerated water movement measured during this study. The tracer was detected from approximately 3 miles above the DWSC to 2 miles downstream of the DWSC within the 2 days of the start of the dye release. Movement up the Stockton Ship Channel toward the Turning Basin was less than 0.5 mile.

As discussed earlier, the water passing the jet aerator received multiple doses of oxygen and rhodamine WT during the 25 hr injection period. The profiles presented in Figure 14 indicated that at least 2 dosings were evident in the observations recorded at the end of the flood and ebb tides on September 2. To estimate the number times dyed water was dosed on September 1 and 2 the movement of a parcel of dyed water was calculated using the flows recorded at the USGS Garwood gage. Shown in Figure 15 is the calculated excursion of water dyed at the start of the 25 hr injection period. These calculations were performed using average cross-sectional San Joaquin River areas above and in the DWSC of 1900 and 13000 ft^2, respectively. Each time the excursion line passes the aerator at location 0 ft, a dose would be received. As shown in Figure 15, the movement of dye was calculated to travel approximately 15,000 ft upstream of the aerator during the first flood tide. This travel distance is consistent with the observed dye transport. Following the excursion curve shows that this parcel would pass the aerator at least 2 times before being carried downstream of the aerator. The second flood tide may return the dyed parcel back to the jet aerator at 9:00 on September 2 for the third dose and final dose. If net flows were less than the 582 and 451 cfs measured for September 1 and 2, then at least 4 dosings would occur. Conversely higher net flows would yield only 2 aeration dosings. This analysis illustrates the influence of net flow on the number of possible aeration dosings. The excursion estimates are sensitive to the channel cross-sectional area of the San Joaquin River above the aerator, which is not constant as assumed here. A more accurate analysis should be performed with a water quality model and accurately measured channel geometry.

Far-field lateral mixing of rhodamine WT

Measurements along lateral transects were performed between the longitudinal measurements to evaluate the extent of lateral mixing of the dyed, aerated water. The locations of three lateral concentration profiles are shown in Figure 16 for the DWSC. The measurements of each of these profiles was performed during the last ebb tide of the tracer injection on September 2.

The rhodamine WT and dissolved oxygen profiles for the Stockton Channel cross-section are presented in Figures 17a and b. A vertical tracer concentration gradient is evident in Figure 17a where values vary from 1.0 µg/L near the channel bottom to 0.1 µg/L at the water surface. This gradient was measured during an ebb flow and is greater than observations recorded at high slack tides shown earlier in Figure 13. The vertical dye concentration gradient shown in Figure 17b is associated with surface water flowing downstream from the Turning Basin during the ebb tide. Figures 13 and 17a suggest that flow enters the Stockton Ship Channel along the lower water column during flood tides and flows out during ebb tides as a surface flow.

Also shown in Figure 17a is the extent of lateral mixing across the Stockton Ship Channel after 18 hours of dye injection. Near the sediment bottom, rhodamine WT concentration are greatest near the Port of Stockton dock, but are relatively uniform across the channel. This uniformity diminishes as the depth decreases and is probably caused by the ebb surface flow discussed earlier . As shown in Figure 17b, dissolved oxygen concentrations are generally uniform across the channel, but decrease from 4.6 mg/L at the surface to 3.2 near the bottom. No correlation between dye concentration and dissolved oxygen is evident when comparing Figures 17a and b. This is probably due to the greater variability of dissolved oxygen in the water column caused by factors including photosynthesis, respiration, and oxygen demanding substances relative to the increase of dissolved oxygen in the dyed water associated with the jet aerator.

Figure 18 exhibits rhodamine WT and dissolved oxygen profiles at the middle cross-section located about 3000 ft downstream of the jet aerator. The greatest rhodamine WT concentrations were measured below 20 ft depths. This appears to be caused by the transport of the cooler, dyed water flowing into the DWSC and moving downstream along the channel bottom. As shown in Figure 18a, at a given depth the dye concentration was relatively uniform, indicating lateral mixing of the dyed, aerated water across the DWSC. Similar to the dissolved oxygen profile for the Stockton Channel shown in Figure 17b, the lowest dissolved oxygen concentrations were associated with the highest dye concentrations. Again, channel biochemical processes influencing dissolved oxygen exert a greater influence than the jet aerator and prevent the measurement of increased dissolved oxygen concentrations. However, the presence of the highest rhodamine WT concentrations in the lower water column indicates that the aerated water is transported to the areas of greatest dissolved oxygen deficit.

The farthest downstream cross-sectional measurements were performed at Lt 45, approximately 6500 feet downstream of the jet aerator. As presented in Figure 19, the highest rhodamine concentrations were observed in the middle of the channel at a depth of approximately 20 ft and show where flows are highest in the channel cross-section. At shallow depths, little of the dye was measured near the Rough and Ready Island dock; significantly higher concentrations were measured near the opposite bank. However, below the depth of 15 ft, the dye has spread laterally across the full channel. As with the other cross-sections presented earlier, no correlation between the dye concentration and increased dissolved oxygen was observed. Similar to other observations, waters with the highest dye concentrations often exhibited the greatest dissolved oxygen deficit.

Conclusions

Within the 25-hour rhodamine WT injection, the longitudinal transport of the dyed, aerated water in the San Joaquin River during flood and ebb tides were observed to be approximately 16,000 and 10,000 ft, respectively. During this period, on days with net river flows of approximately 500 cfs, the dyed water received at least 2 doses and perhaps as many as 4 doses of air and rhodamine WT. Lateral mixing in the DWSC was generally sufficient to transport the dyed, aerated water across the channel within the first 24 hours. These observations suggest that the existing aeration facility is capable of supplying oxygen to a relatively long DWSC reach, approximately 2 miles in length extending from the Port of Stockton jet aerator to the confluence with the Calaveras River.

Transport of the aerated water up the Stockton Ship Channel toward the Turning Basin and downtown Stockton was limited to approximately 1800 ft. This observation suggests that the Turning Basin will not be a significant sink for aerated water and also indicates that additional aeration facilities may be necessary to efficiently address dissolved oxygen deficits in the Stockton DWSC above Channel Point. Lateral mixing was also shown to be sufficient to deliver the aerated water across the channel to the opposite bank indicating that aeration facilities could be located on one side of the channel if the aerated water possessed sufficient momentum to facilitate significant near-field mixing.

The high variability of dissolved oxygen where the San Joaquin River transitions from the DWSC to the upper river prevented detection of increased dissolved oxygen concentrations associated with the jet aerator. The jet aerator was designed to raise the dissolved oxygen in the channel by 0.2 mg/L. Measurements of dissolved oxygen after September 2 at the DWR RRI station suggest that the exertion of oxygen demanding substances exceeded the ability of the jet aerator to reverse the deficit trend.