the O2 transferred from the O2 tank to the water column – i.e., the Overall O2 Transfer
Efficiency (OOTE); and 3) to determine if the Savannah Harbor Model can simulate the
O2 injection impacts.

a. **Goal 1** *– Feasibility of Speece Cone technology was successfully demonstrated,*
however it was also shown that items, such as pumps, can break down and
routine maintenance is needed. A back up system to operate during these down
times will be needed.

Operation and maintenance plans and activities would be part of a permanent
installation. Additional considerations for backup systems will be part of system
design and installation. This information is provided in the Recommendations
section (Section 5.0) in the "Savannah Harbor ReOxygenation Demonstration
Project Report Supplemental Data Evaluation Report".

b. **Goal 2** *– Determination of the overall O2 transfer efficiency was not fully*
determined. The Savannah Harbor ReOxygenation Demonstration (MACTEC
2009) report provided the theoretical efficiency but the monitoring data collected
was not adequate to determine the actual efficiency. In previous meetings, Dr.
Speece provided a detailed explanation of the Speece Cone theory and practical
operations; these details were not and should be included in the report. Also the
Savannah Harbor ReOxygenation Demonstration (MACTEC 2009) report
references other Speece Cone applications but provided no supporting
documentation. Reports of the other Speece Cone applications should be
included as appendices.

Additional case studies on Speece Cone Operation and a section write-up was
received from Dr. Speece and provided in Appendix D of "Savannah Harbor
ReOxygenation. A description of the Speece Cone technology is also provided in
Section 2.3.1 of the report". A report on uses of supplemental oxygenation by
Dr. Speece was provided in the "Identification and Screening Level Evaluation of
Measures to Improve Dissolved Oxygen in The Savannah River Estuary,
Savannah Harbor Expansion Project & Savannah Harbor Ecosystem Restoration
Study Chatham County, Georgia" dated June 2005 (MACTEC, 2005). This

report is provided as Appendix E in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

c. *Expected efficiency of a well-operated O2 system can range from 70 percent to nearly 100 % (NCASI 2008 – Measurement of Oxygen Transfer Efficiency of Aeration and Oxygenated Systems Installed in Lakes and Rivers). Given this range, the assumption of a 90 % OOTE is on the high side and an estimate of 80 % would be more realistic especially without additional monitoring data that shows a higher efficiency is applicable. This OOTE is an important factor, as illustrated in the modeling report. Appendix C of the Savannah Harbor ReOxygenation Modeling (Tetratech 2009) report shows that the difference between 70 % and 90 % OOTE can be more than 0.1 milligrams per liter (mg/L) DO added to the system.* **Goal 3** *– The mixing zone model and the Harbor model (Tetratech 2009) with O2 injection provided good insight on how the oxygen is distributed throughout the harbor; however the monitoring data collected was not sufficient to provide a conclusive model calibration. Based on other studies and the models' capabilities, oxygen injected into the Harbor can be simulated fairly accurately if the OOTE is known. If an OOTE of 70 percent to 80 percent is used the models can be used to determine the amount of O2 that must be injected to mitigate the impacts of the various deepening alternatives.*

The dissolved oxygen transfer capacity for a specific Speece Cone is a function of three factors: (1) Henry's Law governing gas solubility for the given temperature and pressure inside the cone, (2) the oxygen gas mass-flow rate delivered to the top of the cone and (3) the water flow rate through the cone.

Henry's Law governs the dissolved oxygen concentration exiting the cone while the cone geometry and water flow rate are configured to provide ample detention time inside the cone for the oxygen-to-water transfer to equilibrate in accordance with Henry's Law. However, as a practical matter it has been found that about 10 percent of the oxygen gas added to a Speece Cone will not dissolve in the cone but will inevitably "drag through" the cone with the water flow and exit the bottom of the cone as fine oxygen bubbles. This inherent drag-through effect means that the nominal maximum oxygen transfer efficiency for a Speece Cone

(from cone inlet to cone outlet) is 90 percent. So long as the oxygen gas flow rate supplied to the cone is maintained at or below 110 percent of the Henry's Law oxygen solubility limit for the prevailing temperature and pressure inside the cone, the inlet-to-outlet oxygen transfer efficiency will hold at the nominal 90 percent level.

If still more excess oxygen gas is added to the cone, going beyond 110 percent of the controlling Henry's Law solubility limit, that further excess amount of oxygen gas will not dissolve and will instead accumulate inside the cone and be periodically "belched" from the cone discharge as coarse bubbles. In order to operate at the nominal 90 percent oxygen transfer efficiency, the cone must not be loaded with more oxygen gas than 110 percent of the Henry's Law dissolved oxygen limit for the prevailing temperature and pressure inside the cone.

If less than 110 percent of the Henry's Law dissolved oxygen limit is added to the cone as oxygen gas, less overall oxygen mass will be dissolved to the water exiting the cone but the inlet-to-outlet oxygen transfer efficiency will still hold at the nominal 90 percent. To simultaneously obtain the maximum amount of oxygen transfer from a cone while still maintaining maximum transfer efficiency (i.e., 90 percent) would require close and continuous control of the oxygen gas flow rate to just below 110 percent of the prevailing Henry's Law solubility limit. As an alternative to operating at the very edge of the Henry's Law design envelope, a conservative design operating comfortably below the 110 percent Henry's Law solubility threshold would likely be easier to operate while maintaining the maximum inlet-to-outlet transfer efficiency.

For the demonstration system the oxygen gas flow rate to the cones was typically greater than 110 percent of the Henry's Law solubility limit in order to transfer the maximum possible oxygen to the river at the expense of reduced inlet-to-outlet transfer efficiency. An added site-specific consideration for the ReOx demonstration system configuration was the small additional amount of oxygen locally transferred to the river water column from the excess oxygen bubbles released to the river at the ReOx injection depth of 33 feet.

Assuming the upriver land-based Speece Cones can be sized and operated below 110 percent of the Henry's Law solubility limit, an overall inlet-to-outlet oxygen transfer efficiency of 90 percent should be achievable. Conservatively assuming 80 percent as the inlet-to-outlet transfer efficiency seems reasonable for design purposes. Developing a reliable means (i.e., instrumentation) for monitoring very-high, end-of-pipe DO concentrations in the submerged cone-discharge pipe would (in combination with oxygen gas flow and water flow monitoring) allow continuous monitoring of inlet-to-outlet oxygen transfer efficiency. This information is provided in Section 2.5 in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

2. *Once a land based Speece Cone O2 System is installed, adequate additional monitoring needs to be completed to determine the actual Speece Cone OOTE for the Harbor. Once a good OOTE has been determined, the amount of O2 injected can be adjusted to take in to account this lower or higher OOTE. Also an OOTE margin of safety (5 to 10%) should be included in the calculation.*

Engineering design considerations generally employ the use of conservative assumptions and safety factors. As stated above, use of a conservative OOTE of 70 to 80 percent would be appropriate for design purposes. Once permanent installations are implemented, then actual OOTE may be determined and system operations adjusted as needed. Lessons learned from the Demonstration Project have provided insight into procedures to measure high concentrations of DO to calculate the OOTE. This information is provided in the Recommendations Section 5.0 in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

3. *An adequate monitoring study would be a study similar to those completed for other O2 injection systems (NCASI 2008) and following the guidelines GaEPD proposed in their 2007 comment letter. The study would be focused on characterizing the near field mixing of the O2 injection using a rhodamine dye release over one or two tidal cycles and lots of DO measurements.*

EPD and EPA recommendations for sampling were incorporated into the monitoring program for the ReOx Project Demonstration. Monitoring limitations necessitated by the

location of the ReOx Demonstration system would not be as much of a constraint for the permanent systems as they are likely to be placed upstream of the King's Inland Turning Basin. Lessons learned during operation of the ReOx Project have provided considerable insight on monitoring techniques and requirements that may be incorporated into a sampling and analysis program for the permanent systems. Adequate monitoring of permanent systems would be needed to optimize system performance and operations. In-field monitoring would include measurements to calculate oxygen transfer efficiency, mixing zone studies, tracer studies, instream DO monitoring, among other considerations. Recommendations from state and federal agencies would be used to prepare and conduct a permanent system sampling program. This information is provided in the Recommendations Section (Section 5.0 in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

Letter to Sandra Tucker, U.S. Fish and Wildlife Service from Paul A. Conrad, USGS dated April 13, 2009

1. *The project goal, as stated in the January 2008 report "…was to prove that the DO mitigation amount of 20,000 pounds per day (ppd) could be added during the summer critical season and that the resulting instream DO response could be determined through instream DO monitoring." I assume that the goals of the project remain the same. The ReOx demonstration project was able to demonstrate the feasibility of operating the Speece Cones but was unable to determine the resulting instream DO response through the instream DO monitoring network.*

MACTEC's analysis of the near-shore continuous monitoring data does not provide quantification of the contribution of the ReOx demonstration system on the baseline variability of DO in the harbor. Though MACTEC did see DO response through measured data taken in the deepest parts of the River by boat during low and high tide sampling events. But to just stop there is to overlook an important point or "lesson learned". The ReOx demonstration system was designed and configured to add supplemental DO as a jetted point source directed at a downward angle into the main navigation channel as deep as possible because that is where seasonal minimum DO concentrations are expected in the river. However, because of practical access and navigation safety constraints the continuous DO monitors could not be positioned in the

main channel but were instead located along shore in the channel "overbank" sections that flank each side of the deeper navigation channel. Given this physical configuration of the injection point and the continuous monitors, the maximum supplemental DO effect would be expected in the deep channel where the DO was added as a point source while the minimum DO effect would be expected in the near-shore overbanks where the continuous monitors were situated.

Tetra Tech provided MACTEC the Savannah River Model results extraction for the DO percentiles under the injection model and no injection model, the Delta DO percentiles, and the Salinity percentiles (Tetra Tech 2009) provided as Table C.1. Consistent with this expected cross-section distribution of the DO effect discussed above, the DO model simulates the maximum average (50th percentile) model effect size ratio of 2.38 in the deeper main-channel cells at the injection location of the model and simulates the minimum average DO effect size ratio of 0.30 in the flanking shallow overbank cells (Figure C.1). At the deepest model cells of the River, an effect size ratio of 1.74 or greater was simulated in the model from the upstream GPA Berth transect 63 location to the downstream U.S. Army Corps of Engineers (USACE) Dock Transect 57 which supports the lesson learned that the measured DO data at the deepest locations have a greater chance of measuring the ReOx system effects.

Table 3.1 of the Report has been updated to include an Effect Size Analysis for the Continuous Monitoring points. See Comment 5 below for more detail.

While continuous monitors could not be installed in the main navigation channel, there were a limited number of semi-synoptic DO "snapshots" taken (by boat) as DO cross sections and main-channel centerline DO profiles during select slack-tide conditions. These periodic cross-section and centerline snapshots offer insight about DO effects observed in the river but they are not amenable to statistical analysis as are the near-shore continuous data. But just because such graphical DO cross-section isopleths or "pictures" are not amenable to statistical analysis does not mean they are faulty or not useful, nor does it mean they are "anecdotal" in the pejorative sense. Figure C.2 shows the date sequence of DO and salinity cross sections taken just downstream from the ReOx barge location for the sampled low-slack tides and Figure C.3 shows just downstream from the barge for the high-slack tides. This before-during-after sequence of ReOx

injection monitoring data graphically shows the DO effects of the supplemental oxygen addition. See Response to Comments number 9 below for further discussion.

It now seems a bit ironic that such copious amounts of continuous data are available for multiple near-shore overbank monitoring points where only minimal effects are expected while only periodic slack-tide snapshots are available in the main channel where maximum effects are expected. In retrospect, routine DO cross sections manually taken on a daily schedule throughout the demonstration period could have been a more useful monitoring plan, with substantially less effort devoted to the near-shore continuous monitors.

2. *We understand the DO mitigation system for the deepening project will consist of multiple ReOx installations located upriver, well beyond the upstream limits of the deep navigation channel. At such upriver locations, and without the access and safety constraints associated with the deep navigation channel, continuous monitors might be better positioned within the river cross section. Alternatively, the role for continuous monitors might be better suited to end-of-pipe configurations complemented with periodic DO cross sections across the channel. This information is provided in the Recommendations Section (Section 5.0 in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report". One recommendation in the Executive Summary is that if ReOx systems are used for DO mitigation that data should be collected "…to monitor the effects to water quality in an adaptive management approach." This reviewer would strongly recommend that an instream data collection network and monitoring plan be developed from the "lessons learned" from the inadequate data collection and data analysis used for the 2007 demonstration project.*

The Monitoring Plan for the ReOx project was reviewed by state and federal agencies and comments from those agencies were incorporated prior to implementing the study. However, lessons learned have shown that additional in-stream monitoring including implementing alternative methods for oxygen transfer efficiency monitoring, near-field mixing zone monitoring, and more frequent and detailed mid-channel and transect monitoring would have been helpful. Development of the monitoring program needed to develop an adaptive management approach would include considerations as continuous

monitoring, regular instream measurements, dye studies, mixing studies, etc. Lessons learned during the ReOx Project have provided insight to monitoring requirements and monitoring techniques. Recommendations from state and federal agencies would also be used in development of the sampling program for operation management of the permanent ReOx systems. This information is provided in the Recommendations Section (Section 5.0 in the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

3. *Figure 2.4 presents an analysis of theoretical change in oxygen concentration resulting from the oxygen injection from a simple steady-state mass balance. It is unclear how the data for figure 2.4 were computed. The value for seawater salinity (St), the average salinity in the target tidal segment, is not provided, and the resulting value of effective seawater flow rate in test segment (Qs), effective seawater flow in the target segment, is not given. I assumed that the daily streamflow values for Clyo were used in computing the theoretical increases in DO concentrations. (A note on the figure indicated missing data at the Clyo gage. The flow record is complete and is available at http://wdr.water.usgs.gov/wy2007/pdfs/02198500.2007.pdf.) Were daily values of Sts used and daily values of Qs computed for the values shown in Figure 2.4? How did the value(s) for Q_s compare with Clyo and daily flow values for the target location from the EFDC model? Plots of the Clyo flows, computed flows for the target segments, flows from the EFDC model, and salinity at the target segment would have been helpful.*

MACTEC used the median tidal day measured salinity values averaged from the monitors placed on the barge to monitor influent water quality. Data gaps in this data record resulted in the data gaps noted in Figure 2.4. The note on Figure 2.4 was incorrect stating that the Clyo flow data were missing. Figure 2.4 has been replaced. Additionally, to fill in data gaps, median daily salinity data were averaged from the deep and intake barge monitors. Also, in the original   Figure 2.4, an estimated average oxygen load to the system of 27,000 lbs per day was used to calculate the theoretical increase in DO concentration. This input parameter has been replaced by the measured load to the river (as measured by the Speece Cone instrumentation) as presented in Figures 2.2 and 2.3. Other input data and resulting calculated values for Q_S, total seawater flow rate (Q_{TF}), and instream oxygen concentration (C_{DO}) have been provided as Table 2.2. This information

is provided in Section 2.4 of the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

4. *The variable selection for the multiple linear regression analysis is very limited given the complexities of the system. In estuarine systems, such as Savannah Harbor, DO concentrations are a result of constantly changing streamflow, changing tidal conditions, and changing meteorological conditions including wind direction and speed, rainfall, and atmospheric pressure. The models only used three possible inputs; tidal range, temperature, and salinity. Inputs of Clyo streamflows, water levels, harbor tidal range, harbor water levels, wind speed, and wind direction were not investigated. Also it was not stated whether 15-minute data or daily data were used to develop the models. From the residual plots provided, it appears that daily data was used. If daily data were used, the size of the dataset to develop the regression models was greatly reduced. Many of the residual plots show a 7-day cyclical pattern that would indicate that the tidal cycles were not adequately characterized as an input to the models. Due to the limited variables used in the models and the limited presentation of model performance (plots of measure and computed values were not presented and only two model performance statistics were presented), it is difficult to evaluate whether the empirical modeling approach would have provided any information on DO effects.*

As stated, there are many factors that affect the DO in natural systems. Multiple linear regression analyses were conducted on the variables with the expected greatest natural effect on the DO response in Savannah Harbor. Had correlations been identified in these analyses additional more detailed approaches including analysis of the 15-minute data records and additional variables would have been conducted. That does not mean that additional insight to the DO response might be discovered if in-depth regression analyses were conducted. However, due to the inherent "noise" in the data caused by these numerous contributing factors, it was determined that gleaning effects from additional analyses would likely prove to be inconclusive. This information is provided in Section 3.2.1 of the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

5. *The conclusion of the signal-to-noise analysis is that the effect of the ReOx system on the near shore DO cannot be reliably separated from the DO measurements. If this analysis was done for other cells in the model, could it provide some guidance for designing an effective data-collection network? An "effect size" analysis was done and it was concluded that the variability of the DO data would mask the small effect ReOx system because the standard deviation of the measured data and the mean of the expected effect were of the same order of magnitude. Would the standard deviations also be of the same order of magnitude for other locations in the river and not only the near shore? If so, would it indicate that the effect of the ReOx system could not be measured? What are the implications for the profiling and transect data? What are the implications for the recommendation "...to monitor the effects to water quality in an adaptive management approach"?*

For purposes of this analysis, the relative DO "effect size" at a particular location is the dimensionless ratio of the average DO increase (mg/L) attributed to supplemental oxygenation at that location divided by the standard deviation of the DO (mg/L) at that location over the demonstration period. As the effect size decreases, it becomes increasingly more difficult to independently discern or "tease out" the supplemental DO effect from the baseline DO variability of a continuous data set.

Given the nature of adding supplemental oxygen to a highly dynamic tidal system like Savannah harbor, there is no upstream control point available for baseline DO monitoring as might otherwise be the case for a free-flowing non-tidal river. However, the Savannah Harbor DO modeling results for the simulated ReOx demonstration period do show how the DO effect size varied as a function of relative position in the river cross section. Figure C.1 shows the model-simulated average (50th percentile) DO increase from supplemental oxygenation, the simulated DO standard deviation, and the resulting simulated effect-size ratio in each of the 11 model cross-section cells; five main channel cells flaked on each side by three overbank cells. As expected, the largest simulated delta DO (0.62 mg/l) is in the deep main channel cell where the oxygen was added and the smallest simulated delta DO (less than 0.2 mg/L) is in the shallow surface cells.

Table 3.1 compares the observed DO standard deviation for the near-shore continuous monitoring points with the simulated DO standard deviations for the corresponding

overbank cells from the model. The measured DO standard deviations are typically greater than the model-simulated DO standard deviations for the corresponding overbank model cell where the continuous monitors were located near shore. This difference seems reasonable given that the model simulates spatial averages in 3D model cells and the model does not attempt to capture all of the dynamic DO processes that add up to give more DO variability in real-word continuous data than in simulated model results that tend to be smoother.

Table 3.1 of this supplemental report presents 5 columns corresponding to a continuous monitoring location. Column 4 presents the calculated effect size ratio using the actual measured continuous data for the standard deviation where as column 5 presents the calculated effect size ratio using the model-simulated standard deviation. In column 4 the greatest effect size should be seen at the Barge Deep location at 1.03. Where as the model predicted the greatest effect size ratio also at the Barge Deep location (1.24) as well as the USACE dock deep location (1.08) (USACE Deep and USGS Savannah). The second best location for simulated effect size was at the Georgia Ports Authority (GPA) Deep location (0.87). Both methods (simulated and measured standard deviation) identify deep locations for the largest effect size. Using the measured standard deviation for the effect size calculation, the maximum effect size ratio is 1.03, which means the average simulated delta DO is only marginally greater than the measured standard deviation for DO concentration.

Of course, the notion of a DO effect size for continuous monitoring purposes is quite site specific in a large tidal system like the Savannah River. The same amount of supplemental oxygen added upriver where there is less induced tidal flow would result in a greater DO effect size for the same standard deviation and the local DO effect size at any monitoring point will be a function of where the point is positioned in the cross section relative to the point of oxygen injection.

6. *The "Analysis of Central Tendency for Tidal Days" assumes that days with similar salinity conditions also have identical dissolved-oxygen conditions. With the known complexities in estuarine DO dynamics, this appears to be an overly simplifying assumption. Has this approach been used in other estuaries or was it developed to quantify the effects of the demonstration project? If it has been used in other systems, please provide references of the applications.*

This simplifying analysis was performed to show that generally trends in the system showed improvement in DO concentrations over time in the Savannah Estuary. The intent was not to quantify the impact of the ReOx system. The time periods selected had similar salinities and tidal ranges. These periods were selected to reduce the inherent variability of the data so that more subtle DO effects might be identified.

7. *Unfortunately, the spacing of the sampling location for the near field mixing zone monitoring network were too far apart to provide much information on near field mixing (fig. 3.19). Only two of the 18 sampling locations show elevated DO concentrations. Had the sampling locations been closer together, there would have been better definition of the DO plume and more information on the gradients between the high DO concentration and well mixed conditions.*

The near-field DO monitoring event conducted at the ReOx barge location was a one-time reconnaissance-level sampling in response to a concern raised in the field that too much DO might be a problem for aquatic life in the immediate vicinity of the oxygenated discharge. The near-field sampling consisted of vertical DO profiles taken on a coarse grid in the river just outboard from the ReOx barge. The resulting data depicted on Figure 3.19 reflect the maximum observed DO concentration from each vertical profile and the prevailing DO concentrations calculated for the two Speece Cone discharges. For purposes of drawing the near-field two-dimensional DO isopleths for Figure 3.19, a local DO background (baseline) of 3.53 mg/L was selected based on concurrent DO concentrations measured at the GPA dock deep and mid-depth location on 8/9/2007 at 12:30PM average. This one-time sampling event was not designed or intended to characterize the near-field DO plume for modeling purposes so much as it was to simply look for the relative maximum DO concentrations in the plume vicinity. Based on requests from the agencies to assess mixing conditions, these data were contoured to provide an assessment of near-field mixing. Additional monitoring and mixing-zone analyses would be needed once permanent ReOx systems are installed. This information is provided in Section 3.3.1 of the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report".

8. *In my review of the initial report, I noted that one would expect that the DO deficit would improve from August 7 until about August 28, based the timing of the tidal cycle. Likewise, one would expect the DO deficit to worsen sometime between August 28 and September 5. This phenomenon can be seen in the low- and high-tide mid-channel profiles (figs. 3.20 and 3.22). It is also seen in the salinity plots (fig. 3.21) where increasing salinity concentrations between profiles indicates an improving DO deficit conditions and decreases salinity concentrations indicate a worsening condition. The changing DO deficit condition cannot be attributed to the ReOx system as is implied in the discussion in this section of the report.*

Sections 3.3.2 and 3.3.3 discuss the trends noted on the mid-channel low- and high-tide profiles and state, "Comparison of the DO deficit plots mentioned above to the salinity plots (Figure 3.21A and Figure 3.21B) indicate that some of this layering may be attributed to higher salinities of the deeper layers." It is agreed that significant improvements in DO conditions can be attributable to lunar driven tidal and salinity cycles. However, as discussed in the report, there are noted variations in the DO deficit transects in the vicinity of the ReOx system not noted prior to or after system operation.

9. *The river transect plots do show gradients across the channel. Although the gradients are larger during the operation of the ReOx system (fig. 3.25), mild gradients across the channel can also be seen in some of the transects before the operation of the ReOx system (figs. 3.23 and 3.24). Although the gradients provide some evidence of the influence of the ReOx demonstration project, it is only anecdotal evidence. A quantification of the amount of the transect variability that is natural and the amount that is attributable to the ReOx system is not provided. Plots of the salinity distributions for the transects would have been helpful, as was done with the mid-channel low-tide profiles, to see if any of the DO gradients are attributable to salinity gradients.*

Transect data were collected at the request of EPD and EPA to assess the possible effect of the system in areas where continuous monitors could not be deployed. Evidence of system operation as depicted in the transect plots were measured and measurement instrumentation performance were quality assured by checks with Winker DO analyses. Data collection was designed to take snapshots of the river response. Within any one event water quality in the river from upstream to downstream at the five transect

locations would have been similar as shown in the pre- and post-system operation periods. Additionally, the transect plots for low tide DO concentration and salinity have been added to the "Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report" as Figures 3.29 to 3.40.   High tide DO concentration and salinity have been added to the report as Figures 3.46   to 3.55.

Fourteen measured dissolved oxygen and salinity concentrations from Transect 2 before (8/7/2007) and after (8/10/2007) oxygen injection were imported into Tecplot 10 and interpolated into a grid of 400 data points using inverse distance interpolation. This interpolation method generates values on a regular grid from a weighted average of nearby points. Being an average, this method does not necessarily produce the actual data value where sample locations and grid points are co-located. In addition, there is some smoothing of the original data so that grid minimum and maximum values may not be as large or small as the original data. The interpolated DO concentrations were plotted against interpolated salinity before and after injection (Figure C.4). Before injection, a linear relationship exists between dissolved oxygen and salinity representing very little disturbance to the river.   After injection, a disturbance has been created between the relationship of DO and salinity due to increased DO concentrations. Figures C.2 and C.3 also compare DO concentration and salinity before and after oxygen was added to the system. Salinity and DO patterns before oxygen injection are similar on 7/10/2007 and 8/7/2007. During injection, salinity patterns remain similar while DO patterns differ as shown Figures C.2 and C.3 for low and high tides, respectfully, suggesting a disturbance in the system caused by the ReOx injection system. After the injected oxygen was shutdown on 9/16/2007, the low and high tide transects just upstream of the injection location return to similar patterns as prior to the injection period.

10. *In a meeting on original ReOx Demonstration Project report in Atlanta, the comment was made that the "…profiles are right, the interpretation is wrong" (oral commun., Larry Neal, May 27, 2008). A section is needed in the Supplemental Report to address the misinterpretation the DO data in the first report. Without this clarification, someone could read the two reports and assume that statements from the Executive Summary in the first report are the proper interpretation of the data, such as "…the ReOx system operation reduced the mid-channel average low tide DO deficit along the three-mile*

target segment by about 0.6 mg/L.." and "…independent cross-channel transect monitoring…showed an average DO deficit reduction of about 0.7 mg/L." Such an assumption would be incorrect.

MACTEC agrees that the findings presented in the Savannah Harbor ReOxygenation Demonstration Project Report dated January 8, 2008 did not take into account the inherent variability in water quality caused by lunar driven tidal cycles. MACTEC has added a statement in the executive summary and the introduction of the Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report to that effect.

APPENDIX C

TABLES

Table C.1
Savannah River Model Results

Cell Model Location	DO 50th Percentile (mg/l) - Injection Model		DO 50th Percentile (mg/l) - No Injection Model		50th Percentile Delta DO (mg/L)	Salinity Percentile (ppt)
(I, J, K)	50%	St Dev	50%	St Dev	50%	50%
13,63,1	4.18	0.48	4.03	0.49	0.15	5.81
14,63,1	4.13	0.48	3.97	0.5	0.16	5.98
15,63,1	4.11	0.46	3.94	0.48	0.17	5.81
13,63,2	3.85	0.36	3.66	0.39	0.19	9.09
14,63,2	3.84	0.37	3.66	0.39	0.18	8.7
15,63,2	3.89	0.42	3.65	0.46	0.24	7.61
13,63,3	3.53	0.31	3.26	0.35	0.27	13.9
14,63,3	3.58	0.3	3.34	0.34	0.24	13.3
15,63,3	3.73	0.37	3.46	0.44	0.27	9.16
14,63,4	3.17	0.21	2.77	0.25	0.4	17.83
14,63,5	2.95	0.24	2.46	0.26	0.49	19.54
13,59,1	4.24	0.55	4.07	0.55	0.17	6.49
14,59,1	4	0.44	3.86	0.45	0.14	6.78
15,59,1	4.01	0.39	3.84	0.4	0.17	6.39
13,59,2	3.82	0.33	3.63	0.35	0.19	9.07
14,59,2	3.75	0.3	3.56	0.31	0.19	9.61
15,59,2	3.84	0.37	3.53	0.38	0.31	8.98
13,59,3	3.54	0.27	3.31	0.29	0.23	12.87
14,59,3	3.5	0.24	3.22	0.26	0.28	14.75
15,59,3	3.84	0.42	3.32	0.32	0.52	10.65
14,59,4	3.31	0.26	2.69	0.23	0.62	19.47
14,59,5	3.03	0.24	2.55	0.24	0.48	20.96
13,57,1	4.2	0.56	4.03	0.56	0.17	7.11
14,57,1	3.85	0.39	3.7	0.4	0.15	7.57
15,57,1	3.96	0.37	3.79	0.38	0.17	7.36
13,57,2	3.8	0.31	3.6	0.32	0.2	9.65
14,57,2	3.72	0.27	3.53	0.27	0.19	10.06
15,57,2	3.77	0.3	3.54	0.3	0.23	9.54
13,57,3	3.48	0.25	3.26	0.25	0.22	13.28
14,57,3	3.44	0.21	3.14	0.26	0.3	15.4
15,57,3	3.58	0.25	3.31	0.24	0.27	11.04
14,57,4	3.1	0.25	2.72	0.26	0.38	20.67
14,57,5	3.02	0.23	2.62	0.26	0.4	21.64

Data from TetraTech 2009

Prepared By: LRP 08/10/09
Checked By: TRK 08/17/09

Notes:
Refer to Figure C.1 for Model Cell Locations   DO - Dissolved Oxygen
St Dev - Standard Deviation   ppt - parts per thousand
I - Location in the River Transect
J - Transect Location
K - Depth Layer
I=13, I = 14 - Overbank
I=15 - Main Channel
I=15, J=59 - location of the barge
J=57 - Corps Dock (downstream of injection)
J=58 - transect downstream of injection
J=59 - transect with D.O. injection
J=60 - upstream transect
J=63 - GPA Berths (upstream of injection)

APPENDIX C

FIGURES

GPA Berth (Model Cell Transect 63)

Cell 13	Cell 14	Cell 15
1	$\dfrac{0.15}{0.48} = 0.31$	$\dfrac{0.16}{0.48} = 0.33$	$\dfrac{0.17}{0.46} = 0.37$
2	$\dfrac{0.19}{0.36} = 0.53$	$\dfrac{0.18}{0.37} = 0.49$	$\dfrac{0.24}{0.42} = 0.57$
3	$\dfrac{0.27}{0.31} = 0.87$	$\dfrac{0.24}{0.30} = 0.80$	$\dfrac{0.27}{0.37} = 0.73$
4		$\dfrac{0.40}{0.21} = 1.90$	
5		$\dfrac{0.49}{0.24} = 2.04$	

City of Savannah

Hutchinson Island

ReOx Injection Location (Model Cell Transect 59)

Cell 13	Cell 14	Cell 15
1	$\dfrac{0.17}{0.55} = 0.31$	$\dfrac{0.14}{0.44} = 0.32$	$\dfrac{0.17}{0.39} = 0.44$
2	$\dfrac{0.19}{0.33} = 0.58$	$\dfrac{0.19}{0.30} = 0.63$	$\dfrac{0.31}{0.37} = 0.84$
3	$\dfrac{0.23}{0.27} = 0.85$	$\dfrac{0.28}{0.24} = 1.17$	$\dfrac{0.52}{0.42} = 1.24$
4		$\dfrac{0.62}{0.26} = 2.38$	
5		$\dfrac{0.48}{0.24} = 2.00$	

USACE Dock (Model Cell Transect 57)

Cell 13	Cell 14	Cell 15
1	$\dfrac{0.17}{0.56} = 0.30$	$\dfrac{0.15}{0.39} = 0.38$	$\dfrac{0.17}{0.37} = 0.46$
2	$\dfrac{0.20}{0.31} = 0.65$	$\dfrac{0.19}{0.27} = 0.70$	$\dfrac{0.23}{0.30} = 0.77$
3	$\dfrac{0.22}{0.25} = 0.88$	$\dfrac{0.30}{0.21} = 1.43$	$\dfrac{0.27}{0.25} = 1.08$
4		$\dfrac{0.38}{0.25} = 1.52$	
5		$\dfrac{0.40}{0.23} = 1.74$	

Scale :

1 inch horizontal $= 125$ ft

1 in vertical $= 25$ ft

Key : $\dfrac{\text{Model}\,\Delta\,\text{DO (mg/L)}}{\text{Model Std Dev (mg/L)}} = $ Model Effect Size

Source : Δ DO and Standard Deviation from Tetra Tech 2009

Prepared by: LRP 7/9/09
Checked by: TRK 7/9/09

**SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION
PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA**

MACTEC

Effect Size of Model Cell Transects
for Injection Period
(8/8/2007 – 9/15/2007)

Project Number: 6110080064

Figure: C.1

7/10/2007 DO Concentration
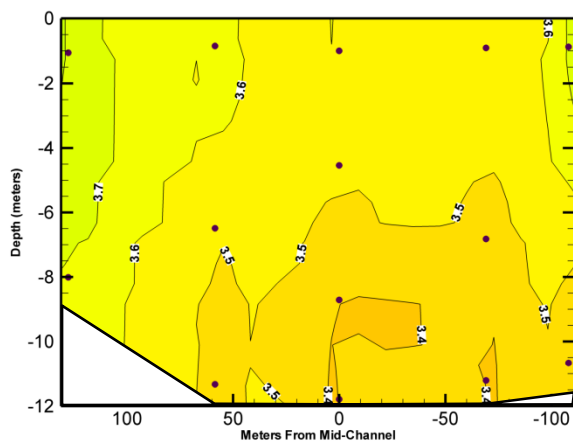
7/10/2007 Salinity Concentration
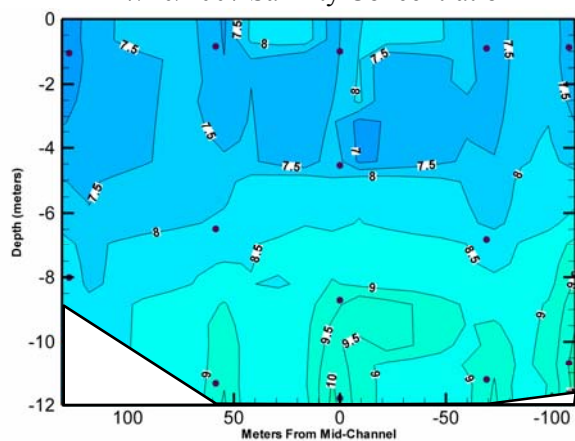
8/7/2007 DO Concentration
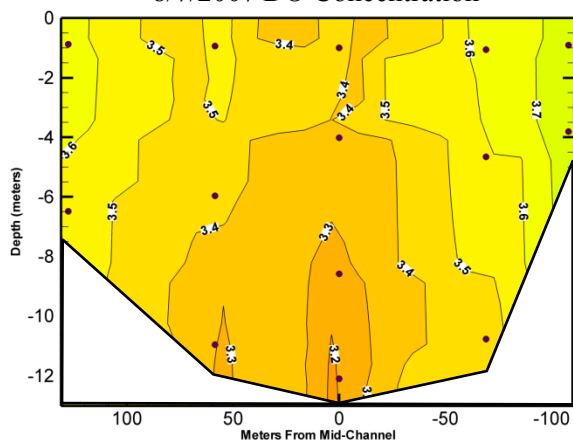
8/7/2007 Salinity Concentration
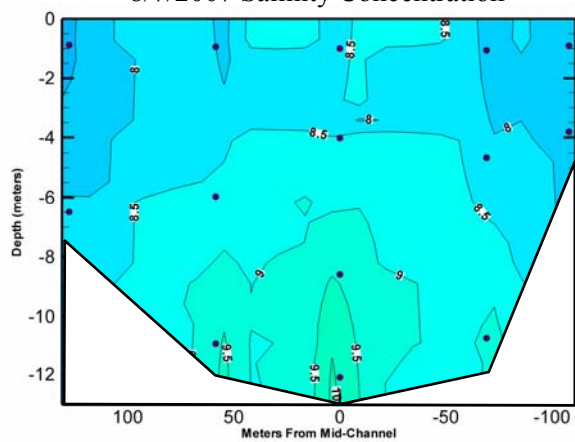
8/10/2007 DO Concentration
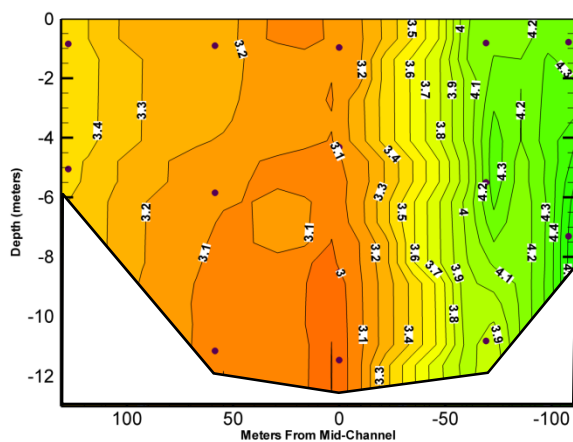
8/10/2007 Salinity Concentration
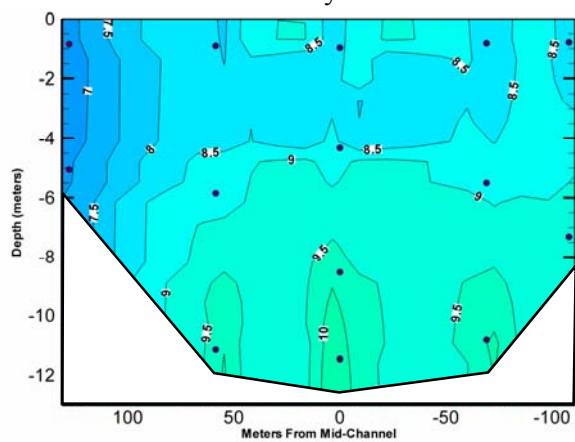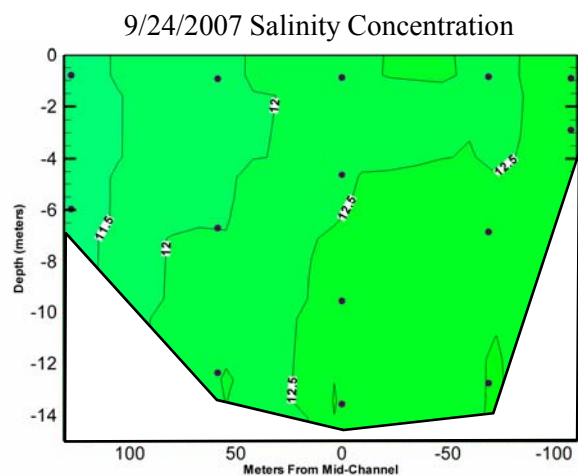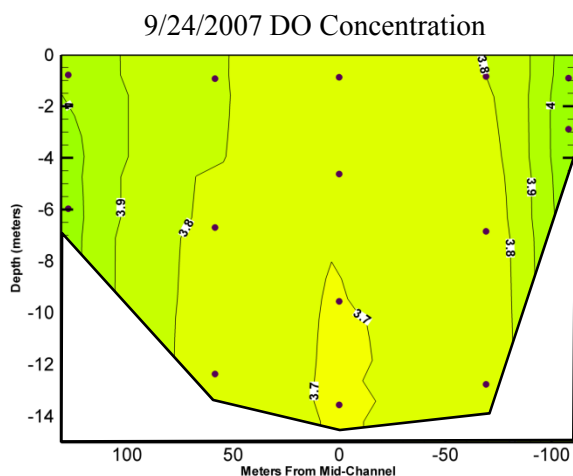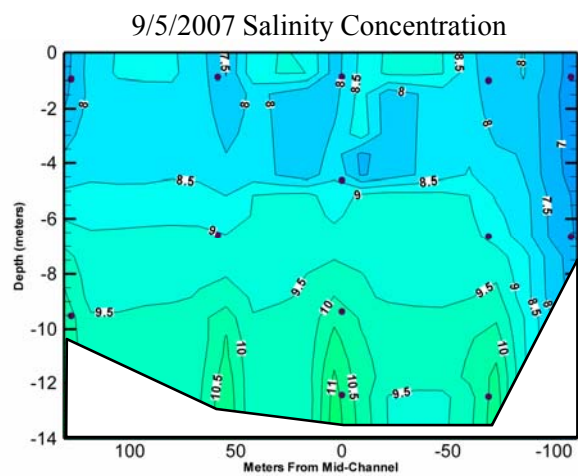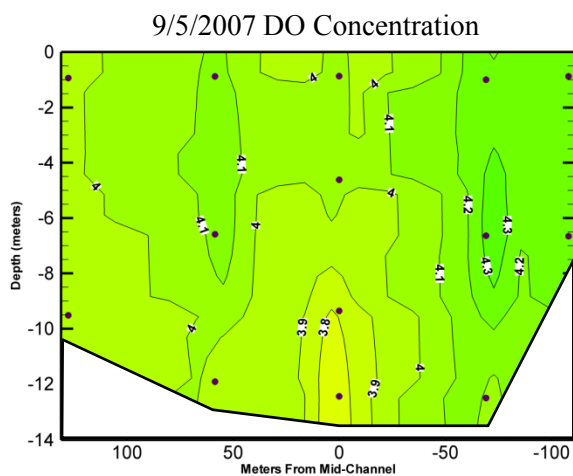
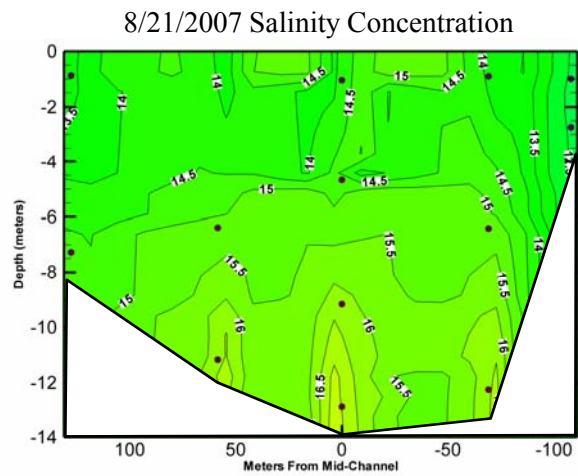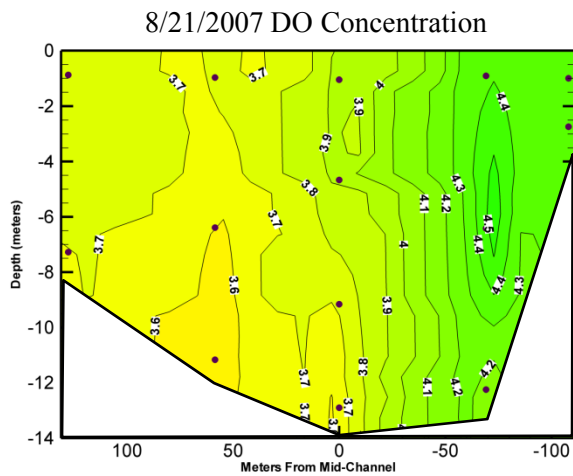Prepared by: NTG 11/16/07
Checked by: JTP 11/16/07

**SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION
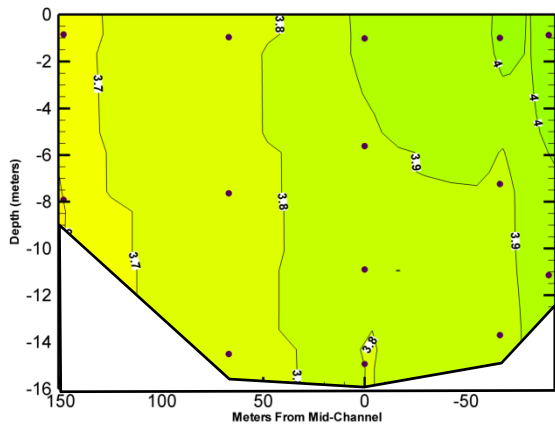PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA**

MACTEC

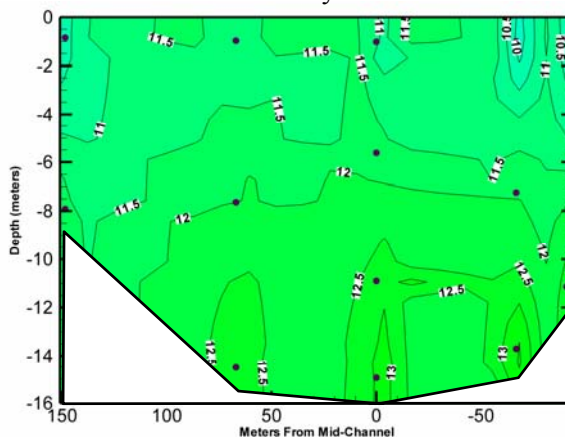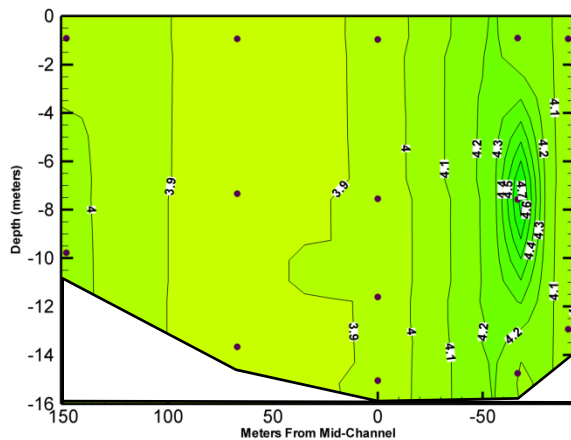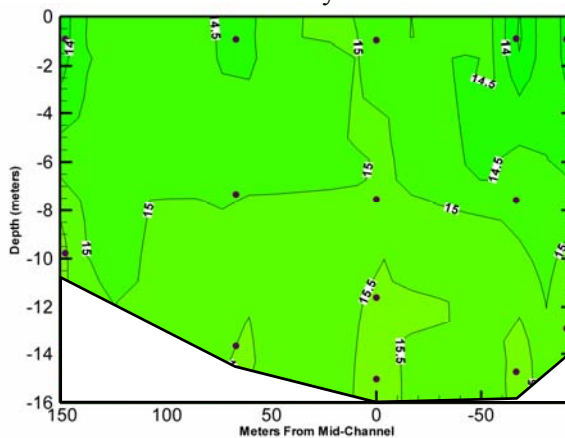Transect 2
DO Concentration and Salinity
Low Tide Event

Project Number: 6110080064

Figure: C.2

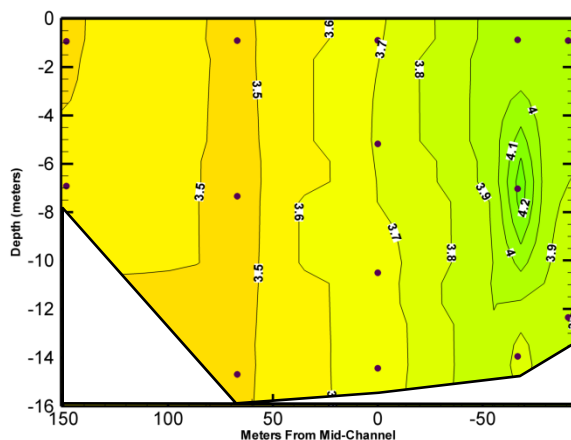8/21/2007 DO Concentration
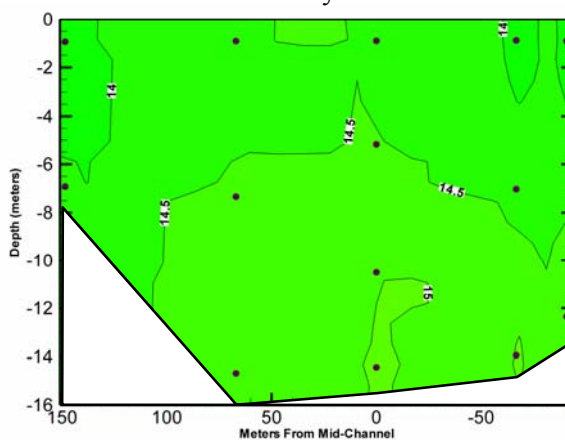
8/21/2007 Salinity Concentration

9/5/2007 DO Concentration

9/5/2007 Salinity Concentration

9/24/2007 DO Concentration

9/24/2007 Salinity Concentration

Prepared by: NTG 11/16/07
Checked by: JTP 11/16/07

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PROJECT
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SAVANNAH, GEORGIA**

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Transect 2
DO Concentration and Salinity
Low Tide Event

Project Number: 6110080064   Figure: C.2

7/17/2007 DO Concentration

7/17/2007 Salinity Concentration

8/13/2007 DO Concentration

8/13/2007 Salinity Concentration

8/28/2007 DO Concentration

8/28/2007 Salinity Concentration

Prepared by: NTG 11/16/07
Checked by: JTP 11/16/07

**SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION
PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA**

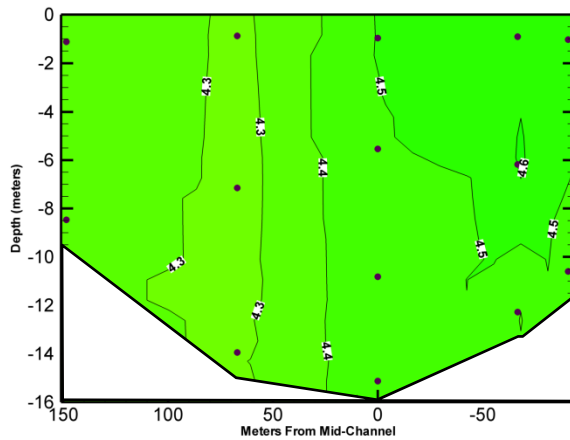**MACTEC**

Transect 3
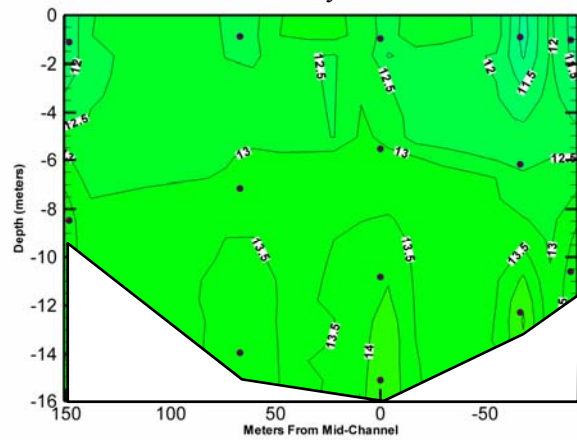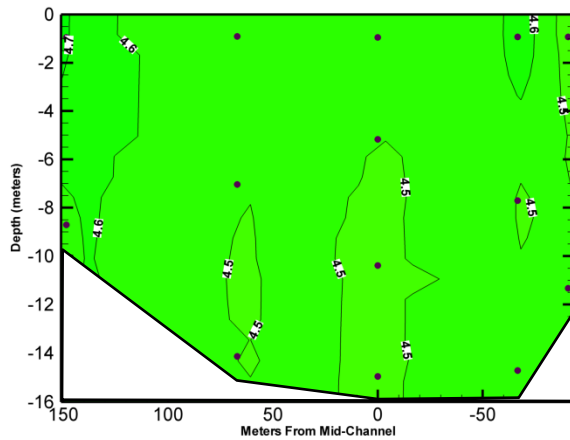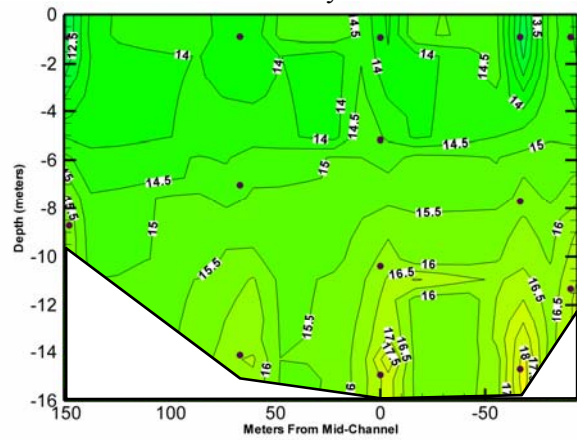DO Concentration and Salinity
High Tide Event

Project Number: 6110080064

Figure: C.3

9/11/2007 DO Concentration

9/11/2007 Salinity Concentration

9/18/2007 DO Concentration

9/18/2007 Salinity Concentration

SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT GEORGIA PORTS AUTHORITY SAVANNAH, GEORGIA	MACTEC	Transect 3 DO Concentration and Salinity High Tide Event
		Project Number: 6110080064 Figure: C.3

Transect 2: 08/07/07 – Isopleth Grid Nodes
(Before DO Injection)

Transect 2: 08/10/07 – Isopleth Grid Nodes
(with DO Injection)

Note: Inverse Distance Interpolation has a smoothing effect on data point minimums, maximums, and gradients
ppt   parts per thousand
DO   dissolved oxgyen
mg/L milligrams per liter

Prepared by: LRP 7/28/09
Checked by: MET 7/28/09

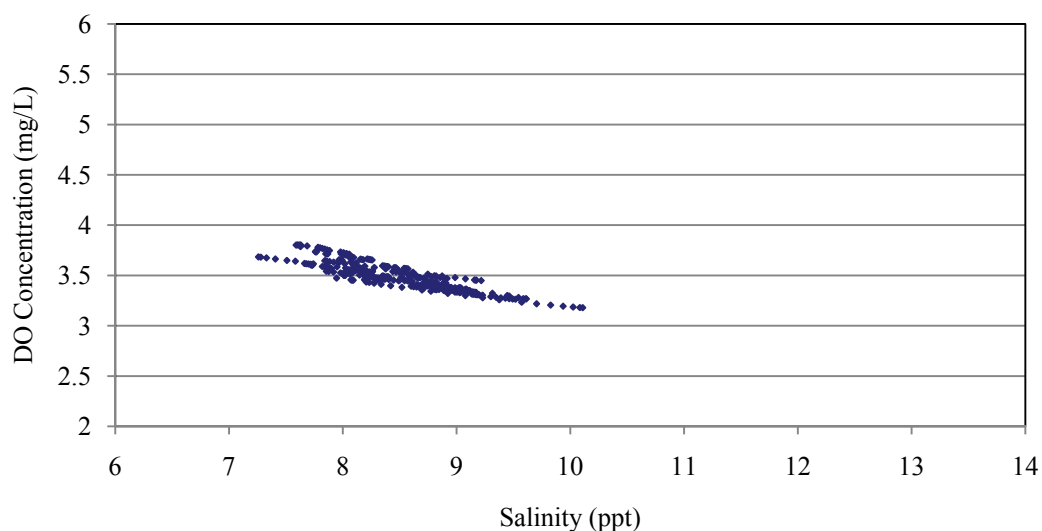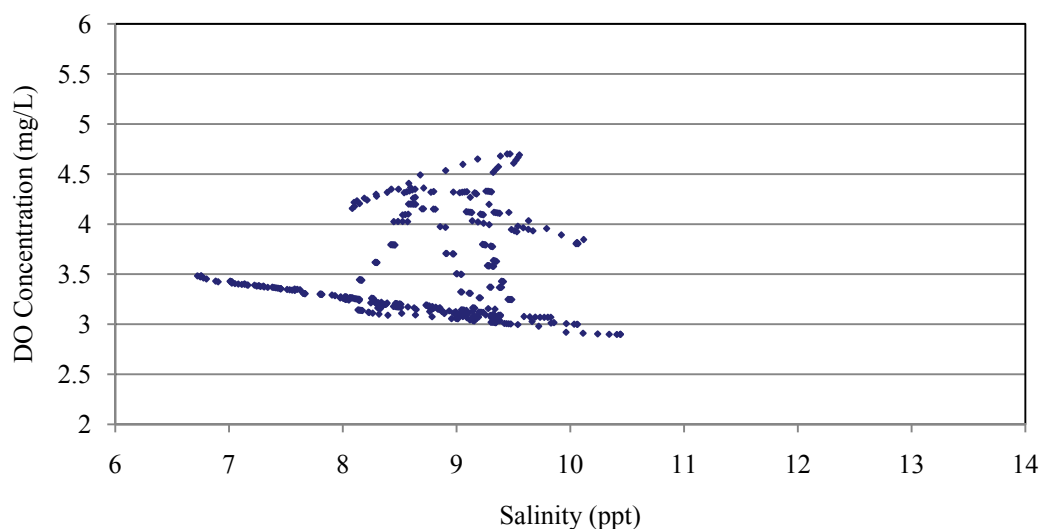| **SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT GEORGIA PORTS AUTHORITY SAVANNAH, GEORGIA**	**MACTEC**	Comparisons of Interpolated Field Measurements from Transect 2 Before and After Oxygen Injection Isopleths
		Project Number: 6110080064 Figure: C.4

APPENDIX D

SPEECE CONE CASE STUDIES

Principles of Oxygen Absorption.

Oxygen is a very insoluble gas and therefore high absorption efficiency is required since it is a valuable commodity. To achieve this high absorption efficiency, a prolonged contact time is required of the gas with the water - on the order of 100 seconds. Since fine bubble diffusers generate bubbles that have about 1 ft./s rise velocity it would take an impoundment over hundred feet deep to achieve efficient absorption of free rising oxygen bubbles. In the 1970s, a pure oxygen absorption pilot test was conducted for the Corps of Engineers for Richard B. Russell dam which is about 140 feet deep and this efficiency of O_2 bubble absorption vs depth was determined.

The technology to dissolve pure oxygen at elevated concentrations in open bodies of water less than 100 ft deep, has to be carefully selected. The most promising gas transfer system for efficiently dissolving pure oxygen into Savannah Harbor was determined to be the Speece Cone.

Speece Cone.

The Speece cone consists of a conical vessel, narrow at the top and an expanding cross section. The small conical diameter at the top facilitates a high inlet velocity, which continually shears the oxygen into small bubbles creating an intense bubble swarm, through which all the water must pass. The expanding cross section of the cone progressively decreases the downward velocity of the water until at the bottom, this velocity is less than the buoyant velocity of the gas bubbles. Consequently, the bubbles cannot escape at the top of the cone due to the high inlet velocity and they cannot escape from the bottom due to the low exit velocity. In effect the bubble swarm is trapped in the cone to achieve the efficient oxygen absorption efficiency required. This trapped bubble swarm creates a very high gas area to water volume ratio with much surface for gas transfer in the cone. In the Speece Cone the oxygen is thus efficiently dissolved into the water as it passes through the bubble swarm.

The gas transfer equation is:

$dc = k_L (A/V)(C_{sat} - C_{act}) dt$
        The term $k_L (A/V)$ is often combined into the term k_2.
        kL – gas transfer coefficient
        A – gas surface aea
        V – volume of water
        Csat – D.O. saturation concentration
        Cact – D.O. of water passing through the cone

Air has an O_2 solubility of about 9 mg per liter per atmosphere in water, while pure oxygen has a solubility of about 45 mg per liter per atmosphere in water.

A given Cone has a maximum volume of bubble swarm (corresponding to a maximum O_2 injection rate) which can be maintained and thus a maximum design capacity (tons D.O./day) to dissolve oxygen. Below that maximum design capacity the oxygen dissolution is always over 90% efficient. Any O_2 above the maximum design capacity is pushed out of the bubble swarm and this excess addition of oxygen gas is not dissolved. Thus the efficiency of oxygen absorption is 90% from zero to maximum design capacity oxygen injection rate and anything above that is carried out the discharge in undissolved bubbles.

It is important to recognize that the oxygen absorption within the cone is very efficiently achieved and therefore the discharge contains oxygen in the dissolved form with less than 10% small or micro bubbles of undissolved gas in the discharge.

The O_2 transfer capacity of a given cone is a function of the pressure, temperature and salinity inside the column. The pressure inside the column can be increased by placing the cone deeper in the water column or by placing a throttling valve on the discharge of the cone to generate backpressure within the cone. Placing the column, deeper under the water surface allows the pressure in the cone to be increased without increased energy expenditure.

The specific energy consumption is approximately 300 kWh per ton of oxygen dissolved when pressurization is by the water column. Whenever pressurization is achieved by pumping against a throttling valve on the discharge the specific energy consumption increases to 1000 kWh per ton of D.O. regardless of how high the pressure is because the discharge D.O. increases in proportion to pressure.

The pressure inside the cone corresponds to the depth at which the cone is submerged. Since C_{sat} is a function of pressure, C_{sat} for pure oxygen and 34 ft submergence would be 90 mg/L. In a cone submerged 34 ft below the surface in 20°C water and discharging at that depth, the D.O. in the discharge will be about 70 mg/L which is only 80% of Csat (90 mg/L) . Therefore there is no potential for effervescent loss of D.O. since it is below saturation.

However, when a cone is operated with pressurization by a discharge throttling valve, the discharge D.O. can be much above 100% saturation compared to the ambient discharge pressure. In such a case, potential effervescence is possible and must be prevented.

Prevention of Effervescent Loss of D.O.

There is a common misconception that if water contains dissolved gas that's over 100% saturation that it always instantly effervescences out of solution. This misconception is generally based upon the phenomena of the effervescence in a Coke bottle or the dissolved air flotation unit process.

Effervescence requires two conditions. One it requires time. A bottle of Coca Cola is saturated with about 500% carbon dioxide, and it takes about two hours for it to lose that

carbon dioxide (go flat) after the Coke bottle is opened under quiescent conditions. Second, effervescence requires a certain threshold gas saturation concentration – well above 100% saturation - before effervescence will occur. The Columbia River for instance, flows 80 miles at 130% saturation without measurable loss of dissolved gas. Dissolved air flotation units normally operate at about 600% saturation in the discharge.

Retention of the high D.O. concentration in solution is a key design feature of the cone system operating with throttling valve pressurization. This is achieved primarily by an efficient diffuser system on the discharge of the cone, which dilutes the very high D.O. in the cone discharge (above 100 mg/L) within about 1 second, with Savannah Harbor water, which has less than about 5 mg per liter of D.O. Thus, effervescent loss of high D.O. concentrations is precluded and retention of the oxygen in the dissolved form is efficiently achieved.

Speece Cone Installations.

Logan Martin Dam.
Weyerhaeuser Oklahoma.
Newman Lake Washington.
Camanche Reservoir California.
Orange County Force Main.
Kentucky Force Main.
Fishers Indiana Force Main.
Denver Water Marston Reservoir.

Publications

Publications describing successful 15 year old Speece Cone installations are included for Camanche Reservoir and Newman Lake. Extensive documentation of the performance of the Logan Martin installation in 1990 was made which demonstrated that at design conditions, 90% oxygen absorption efficiency was achieved in this field scale prototype.

IMPROVING WATER QUALITY
THROUGH LAKE OXYGENATION
AT
CAMANCHE RESERVOIR

Rodney Jung, James O. Sanders, Jr. and H. Hubert Lai
East Bay Municipal Utility District
Oakland, California

Introduction

East Bay Municipal Utility District (EBMUD) built Pardee Reservoir in 1929 on the Mokelumne River in the Sierra foothills near Jackson, California. Water from the 1,500 square kilometer (577 sq. mi.) Mokelumne River watershed in the Sierra Nevada is diverted from Pardee Reservoir to supply its 1.3 million customers in the East Bay region of the San Francisco Bay area. In 1964, Camanche Reservoir was built about 16 kilometers (10 mi.) downstream of Pardee Reservoir (Figure 1). Camanche Reservoir measures 545 million cu. meters (417,100 acre-feet) of maximum volume and 41 meters (135 feet) of maximum depth. Camanche Reservoir is used for flood control, flow regulation for downstream irrigation users, protection of instream resources, recreation and hydroelectric power generation. The Lower Mokelumne River flows from Camanche Dam to the Delta of the Sacramento and San Joaquin Rivers. The river supports several introduced and native fishes, including Chinook salmon and steelhead trout.

The Mokelumne River Fish Facility was built in 1964 at the base of Camanche Dam to mitigate for the loss of river spawning habitat caused by the creation of the reservoir. The California Department of Fish and Game operates the fish facility as a cold water hatchery for Chinook salmon and steelhead trout. Its water supply comes directly from Camanche Reservoir releases.

Camanche Reservoir is typical of a eutrophic lake, stratifying thermally in the late spring in three layers: a warmer, less dense epilimnion, the deeper, colder hypolimnion, and the intermediate thermal gradient in the metalimnion. When the temperatures at the surface start to get colder in the autumn, the reservoir thermal structure breaks down and overturns in the late fall.

Purpose of Hypolimnetic Oxygenation System

Droughts during 1987 to 1990 caused downstream fish losses from poor water quality. Immediately after the 1987 fish facility loss and continuing to date, EBMUD carried out a series of actions to identify and mitigate the water quality conditions detrimental to fish in the hatchery and in the Lower Mokelumne River.

Studies carried out by EBMUD in 1988 and 1989 identified the factors in fish losses to be seasonal hypolimnetic anoxia causing toxic levels of hydrogen sulfide in Camanche Reservoir. Decaying organisms and plant material near the bottom of the reservoir

consumed oxygen, usually depleting the oxygen in the deep, cold water layer by the mid-summer. With extended periods of oxygen depletion or anoxia, hydrogen sulfide would be generated from the bottom sediments. Besides the hydrogen sulfide problem, maintaining the cold waters of the hypolimnion was also critical to the survival of the developing fish at the hatchery and the downstream river.

Alternatives and Design Considerations

Recommendations from consultants balanced fishery needs with the water supply needs. They included: increased water flows, changes in reservoir and hatchery operations, enhancement of the river habitat and facility improvements to permanently improve the quality of the water released from Camanche Reservoir to supply the fish facility and the Lower Mokelumne River (Figure 2). Alternatives evaluated for facility improvements included: hypolimnetic aeration, multi-level intake structures, applying potassium permanganate plus aeration or diversion from Pardee Reservoir. These alternatives were eliminated due to practical, reliability or feasibility problems. Hypolimnetic oxygenation was recommended as the most cost-effective and feasible alternative to eliminate hydrogen sulfide without disrupting the cold water layer and without impacting the reservoir operations for EBMUD's water supply needs.

Professor Richard Speece of Vanderbilt University provided the conceptual design of the Hypolimnetic Oxygenation System (HOS) which utilized an inverted cone to supersaturate a sidestream of cold water from the hypolimnion with over 100 mg/L of dissolved oxygen. The "Speece Cone" design uses a manifold system to disperse the supersaturated sidestream to the hypolimnion in the deep parts of the reservoir. The cone itself acts as a counter-current oxygen contact chamber designed to maximize the oxygen transfer while minimizing generation of bubble plumes in the reservoir. A hydrodynamic study of the system determined that the HOS could operate without affecting the thermal stratification of the reservoir. The recommended system of two Speece Cones would have the capacity to add 8 mg/L to a 23 cubic meters per second (800 cfs) discharge with a pool depth of 30 meter (100 ft.). The design provides 7 mg/L to meet water quality requirements for fisheries in the river and 1 mg/L to oxidize the hydrogen sulfide before release. The system can operate as needed, usually from May until November.

In 1993, EBMUD awarded a $1.2 million design-build contract to install one Speece Cone as a demonstration project. The site, elevation and the HOS facilities are shown on Figures 3 and 4. The system went on-line in July 1993. It has been operated intermittently every year since then to improve the water quality and fisheries in Camanche Reservoir, the Mokelumne River Fish Facility and the Lower Mokelumne River. The current system with one Speece Cone can feed from 2 to 5.7 cu. standard cubic meters per minute of oxygen (70 to 200 scfm) depending upon the depth of water over the Speece Cone. A 127 kW (170 h.p.) submersible pump, with a discharge of 1.0 cu. meter per second (35 cfs) consumes about half of the current operating cost. The manifold shown in Figure 4 actually has 150 5-centimeter (2-inch) diameter ports installed with ball valves. Currently, 100 of those ports are open, balancing pump efficiency with minimized bottom scour disturbance.

2

Effect on Water Quality

Both watershed runoff and the operation of the HOS has affected the water quality of Camanche Reservoir. Although the HOS facility was designed for critical drought years with low runoff volumes, the years since installation of the HOS have been wet or normal runoff years. Still, the impact of the HOS on Camanche Reservoir can be seen around the facility.

Dissolved Oxygen Distribution

For the year of installation, 1993, Figure 5 shows dissolved oxygen (DO) near the bottom of the reservoir and the increase of DO after the oxygen feed started. The response in the immediate vicinity of the HOS unit can be seen within a few days. For 1996, the period when the unit was shut off, August 19 to September 7, the oxygen decay rate was almost twice of the original decay rate, i.e., 0.12 vs. 0.07 mg/L/day (Figure 6). Whether this was due to greater oxygen demand coming from upper layers or blooms, was not determined. For 1997, the low oxygen levels near the bottom may be explained by the pump rotating backwards during that period. The submersible pump was replaced in 1997 with a new pump. After correcting the pump rotation, the oxygen level increased quickly (Figure 6), though some of the increase may be due to inflow increases.

Dissolved oxygen profiles for late summer (Figure 7) compare conditions in the water column with (1993, 1994, 1996, 1997) and without (1992 and 1995) the oxygen feed system. The HOS unit was operated in 1995, but started at a later time of year due to high runoff conditions. The addition of oxygen with the Speece cone operating typically increased the dissolved oxygen levels near the bottom up to an elevation 15 meters (50 feet) higher. Figure 7 contrasts this plume of oxygen with the 1992 oxygen profile without oxygen addition. For the 1997 oxygen profile in Figure 7, oxygen was added essentially as a large bubble diffuser for about one month at that time, with increased levels at the thermocline depth, i.e., 10 meters (33 feet). After correcting the pump rotation, the oxygen profile returned to the shape similar to the one in 1996.

Though the 1997 oxygen profile indicated no oxygen at the very bottom just before correcting the pump rotation, the oxidation-reduction potential (ORP) did not go below 300 millivolts. Typically, hydrogen sulfide formation in 1992 did not occur until the ORP decreased below 100 millivolts. Since hydrogen sulfide was difficult to measure, EBMUD measured ORP along with sniffing of the bottom water samples by the sampling crew to monitor the presence of H_2S.

For a horizontal view, Figures 8 and 9 indicate the distribution of dissolved oxygen in a longitudinal section of the reservoir. Figure 8 illustrates (not to scale) the extent of the oxygen plume after 40 days of oxygen addition. The extent of plume can be observed over 10,000 feet away. Approximately 270 metric tons (300 tons) of oxygen were added for that calendar year. Figure 9 shows the depletion of the oxygen plume 20 and 29 days after stopping the oxygen feed. The system was designed to oxidize hydrogen sulfide as the bottom waters moved toward the dam discharge. Bench scale tests estimated that at

3

least 24 hours are needed to oxidize hydrogen sulfide within the oxygen plume. The extent and location of the observed oxygen plume indicated that it was more than sufficient for that purpose.

Nutrient Levels
All nutrient levels decreased in the hypolimnion since the HOS started operating in 1993. Ammonia levels in the hypolimnion decreased as much as two orders of magnitude after oxygen addition (Figure 10). To a lesser extent, nitrate levels also decreased in the hypolimnion. Figure 11 illustrates the decreased phosphate levels (ortho and total) by about one order of magnitude to the 0.02 mg/L range in the hypolimnion during the summer months. The 1995 season was the exception since the HOS was not operated until October due to the very high runoff that year.

Algal Growth
As an indicator of algal growth, the Secchi depth readings for the past eight years indicated increasing clarity as shown Figure 12a. Taking the average summer Secchi depth readings from those data, Figure 12b shows a correlation with time. Although no dry or low runoff years have occurred since operation of the HOS facility, the greater Secchi depths are consistent with decreased nutrient levels.

Chlorophyll maximum levels indicate a downward trend since 1993 (Figure 13). These levels indicate fewer incidents of algal blooms. The levels of total phosphate prior to fall turnover and the average annual chlorophyll concentrations during the following year, appear to correlate well (Figure 14). The availability of phosphate released from the sediments (internal load) contributes to the algal biomass for the next growing season. The exception occurred during the transition period of 1992 to 1993, since the HOS unit was first operating in 1993. The regression line indicated that without the HOS unit in operation, record high levels of chlorophyll would have been expected.

Dilution
The past five years have been relatively wet ones and the storage volume in Camanche Reservoir reflects the trend (Figure 15). Therefore, these findings so far are preliminary since a design year or a dry water year with low runoff leading to low reservoir volumes would likely change the response to the HOS unit. With less water inflow and lower releases, the demand for oxygen may exceed the capacity of the demonstration unit (one-half of the design capacity). More years of operation during such dry years would help to determine the capacity of the HOS unit and its resulting water quality changes.

Turbidity
Initially, during the first two years of operation, the turbidity of the waters released by the Camanche Dam appeared to increase when the HOS unit was operating. The cause was most likely to be due to greater zooplankton activity, due to the greater oxygen available for habitat. The last three years, turbidity in the reservoir at the release elevation is shown on Figure 16. In 1995, when the HOS unit was off, the turbidity rose by itself in the mid-summer. Turbidity at sites 5.3 and 3.5 kilometers (3.3 and 2.7 miles) upstream

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from the dam also were in the same range and exhibited a similar trend. With the same turbidity trend away from the HOS unit and often with higher levels, the use of the HOS unit does not appear to increase turbidity on its own.

Findings
- Use of a hypolimnetic oxygenation system to eliminate hydrogen sulfide and increase oxygen levels for the river below the dam was found to a practical solution.
- Dissolved oxygen levels increased as expected along the bottom of the reservoir to form a plume 15 meters (50 feet) thick and extending about 3 kilometers (1.9 miles) upstream.
- Without the effective use of the Speece Cone dissolving the sidestream water, the dissolved oxygen near the bottom was lower than usual, though appearing to avoid complete anoxia.
- As a side benefit of operating the oxygenation system, the increased oxygen levels helped to decrease the release of nutrients from the sediments, especially ammonia, orthophosphate and total phosphate and to lesser extent, nitrate.
- As expected from lower nutrient availability, the Secchi readings increased after operation of the hypolimnetic oxygenation system.
- As expected from lower nutrient availability, the chlorophyll levels decreased after operation of the hypolimnetic oxygenation system.
- Turbidity near the release elevation appeared to increase during the mid-summer. But the increase could not be attributed to the HOS unit only, but likely due to some other activity throughout the entire reservoir.

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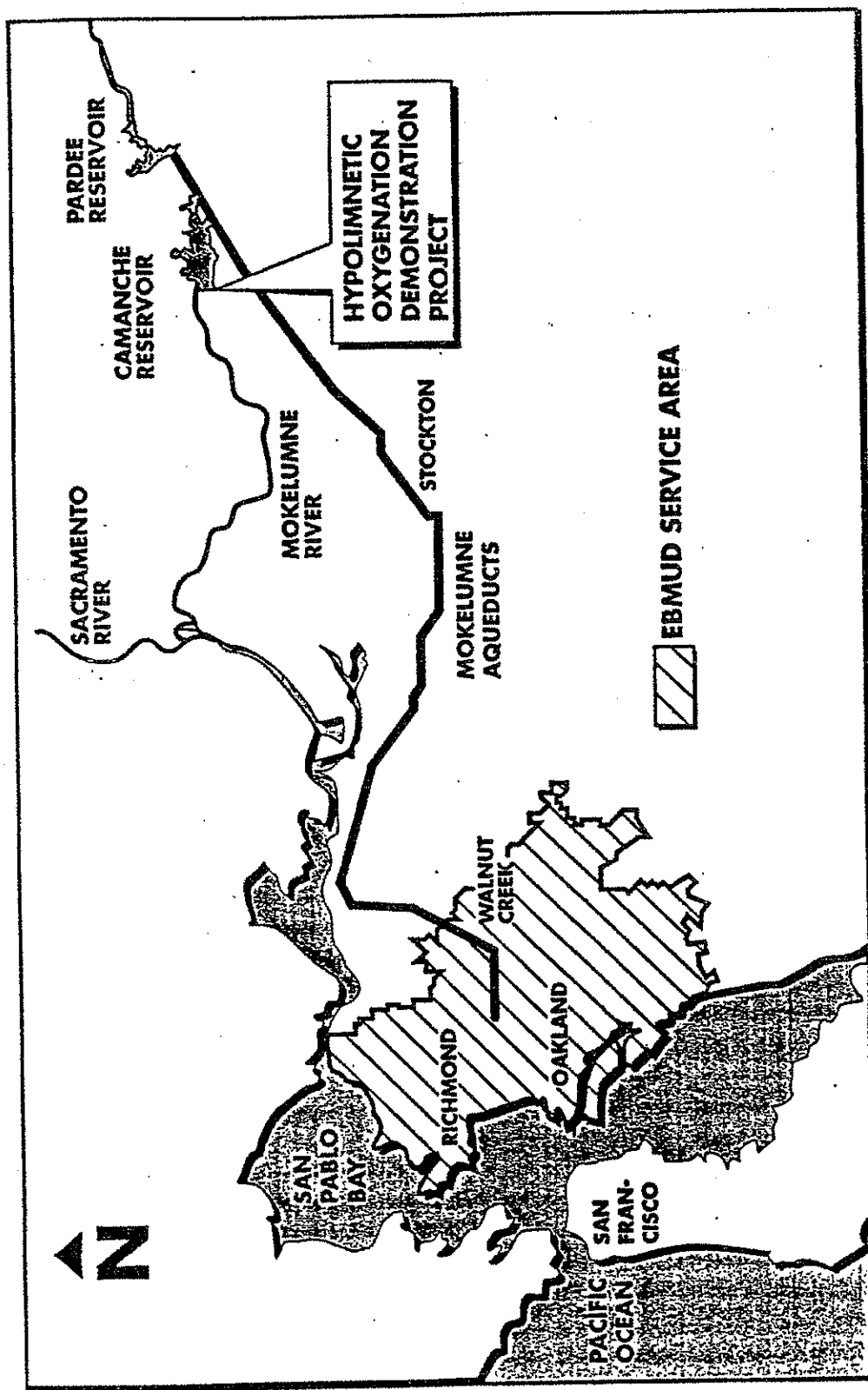
Figure 1 Camanche Hypolimnetic Oxygenation Demonstration Project Location

Figure 2

CAMANCHE HYPOLIMNETIC OXYGENATION DEMONSTRATION PROJECT SITE PLAN