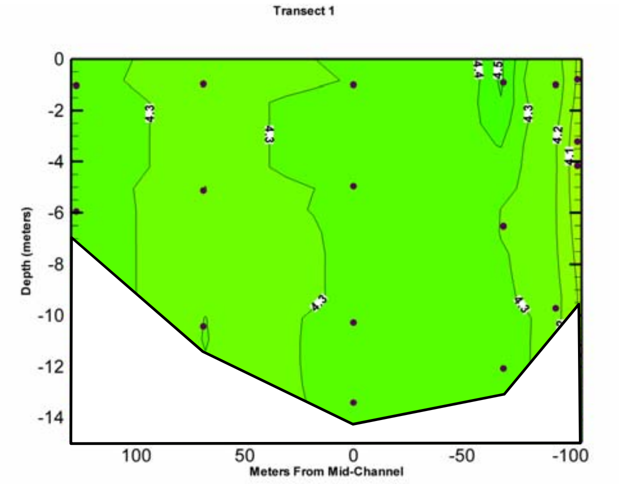
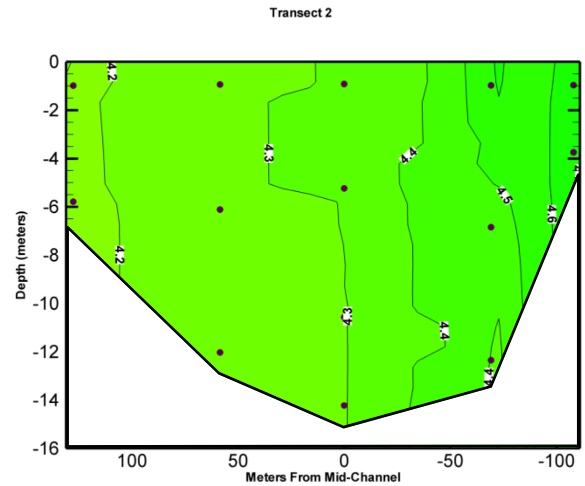
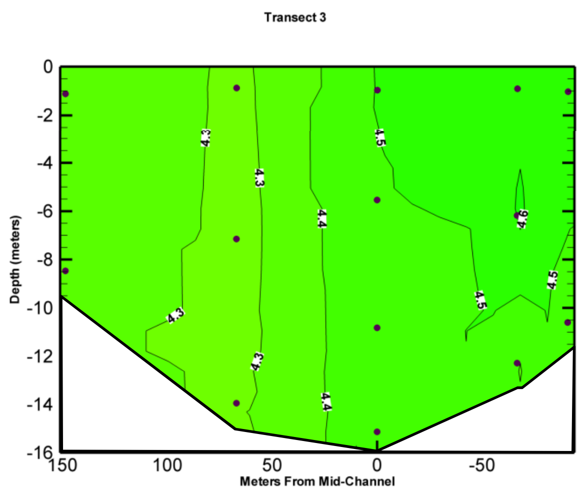
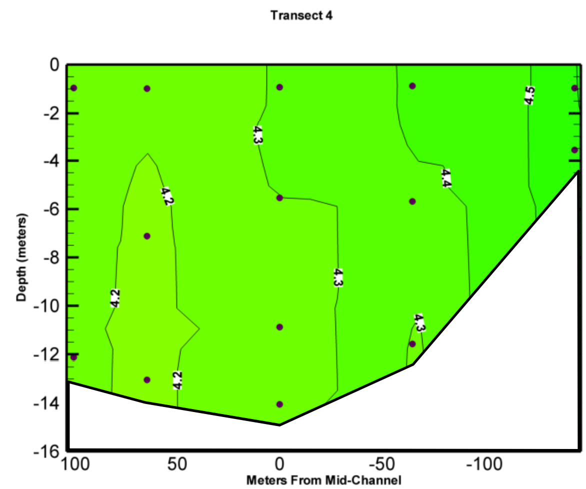
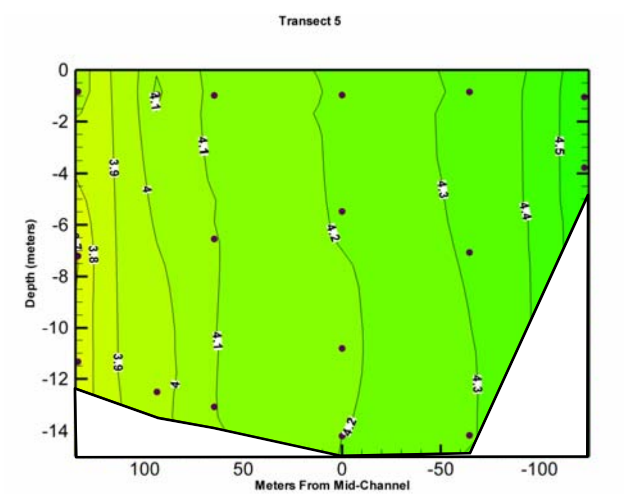




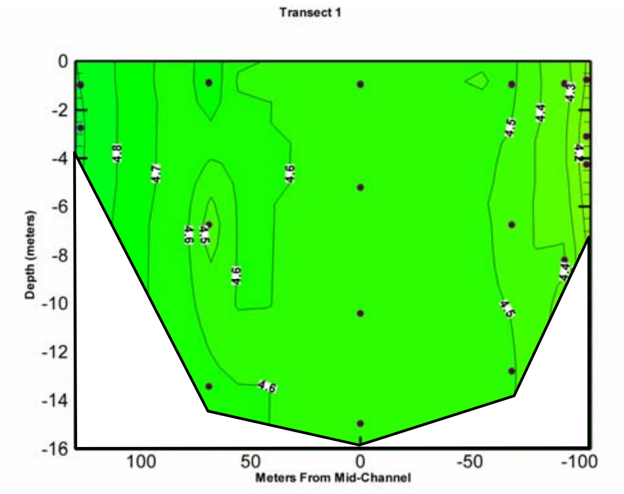


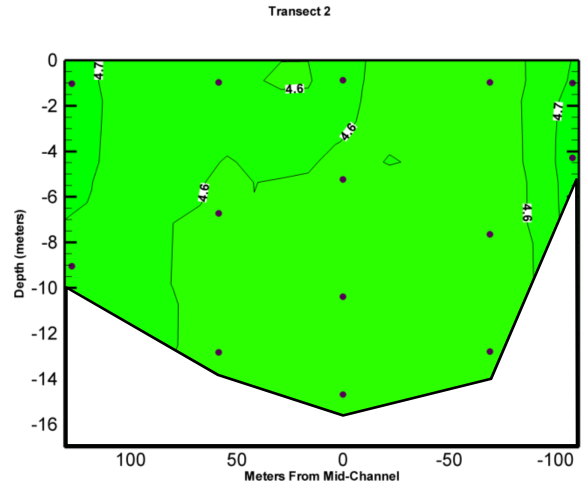


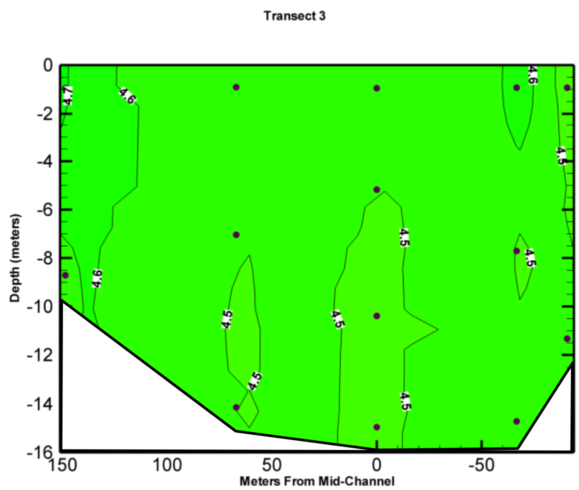


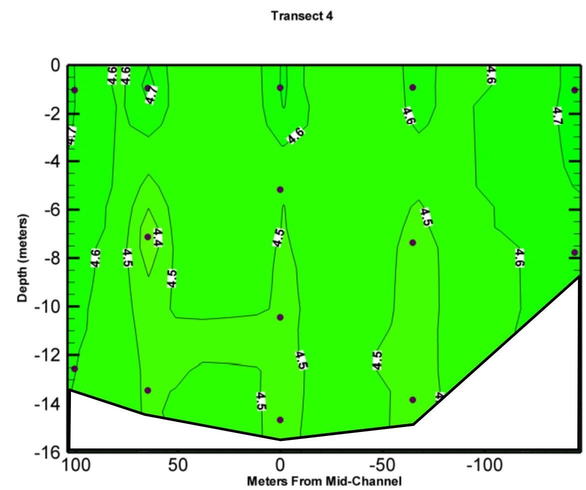
Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

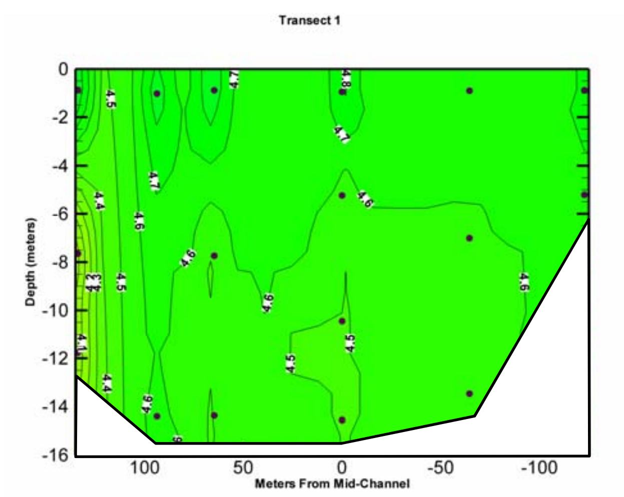
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT GEORGIA PORTS AUTHORITY SAVANNAH, GEORGIA	MACTEC	Cross-Sections DO Concentration (mg/L) High Tide 9/11/2007
		Project Number: 6110080064 Figure: 3.49











Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

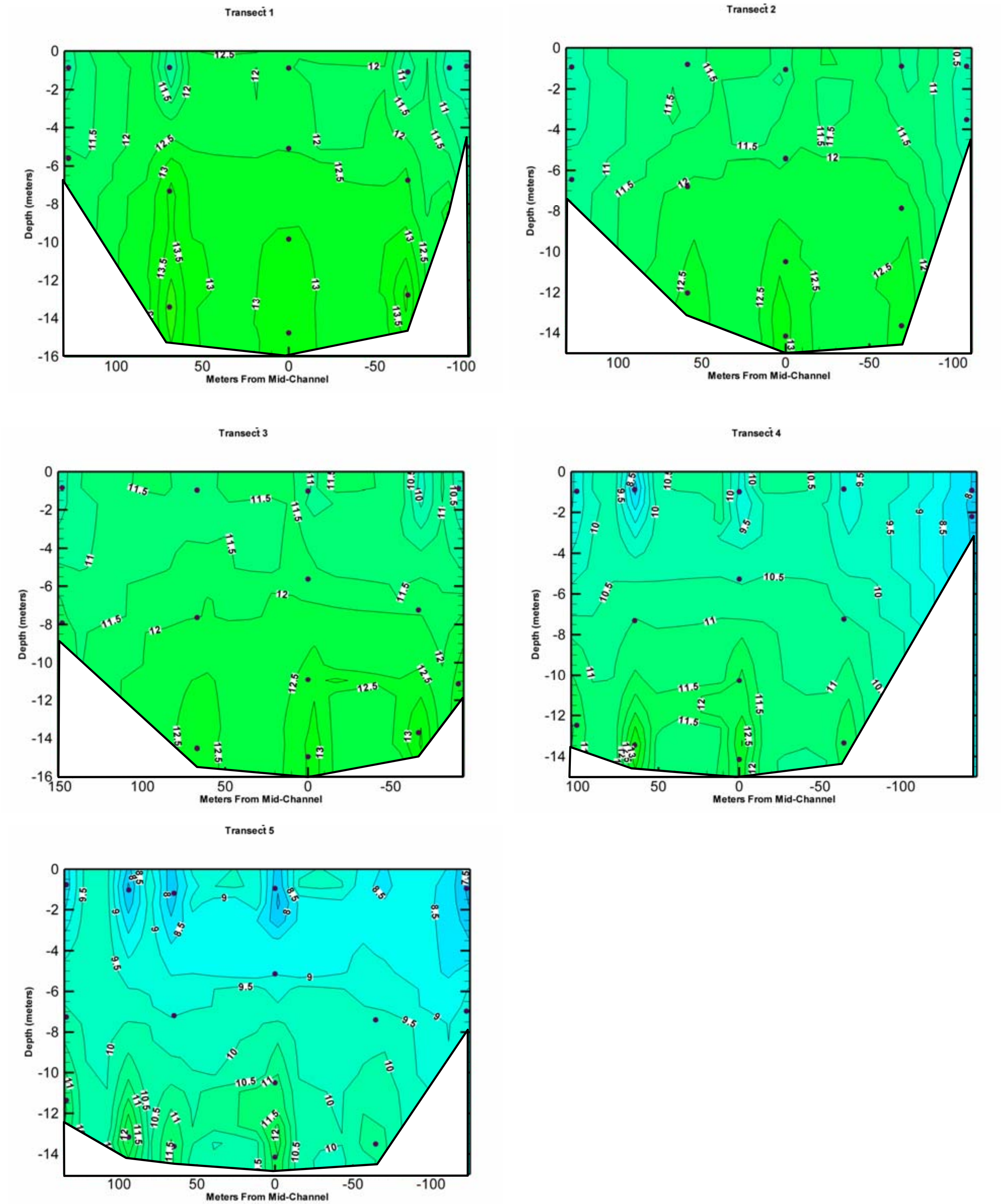
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Cross-Sections
DO Concentration (mg/L)
High Tide 9/18/2007

Project Number: 6110080064

Figure: 3.50



Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

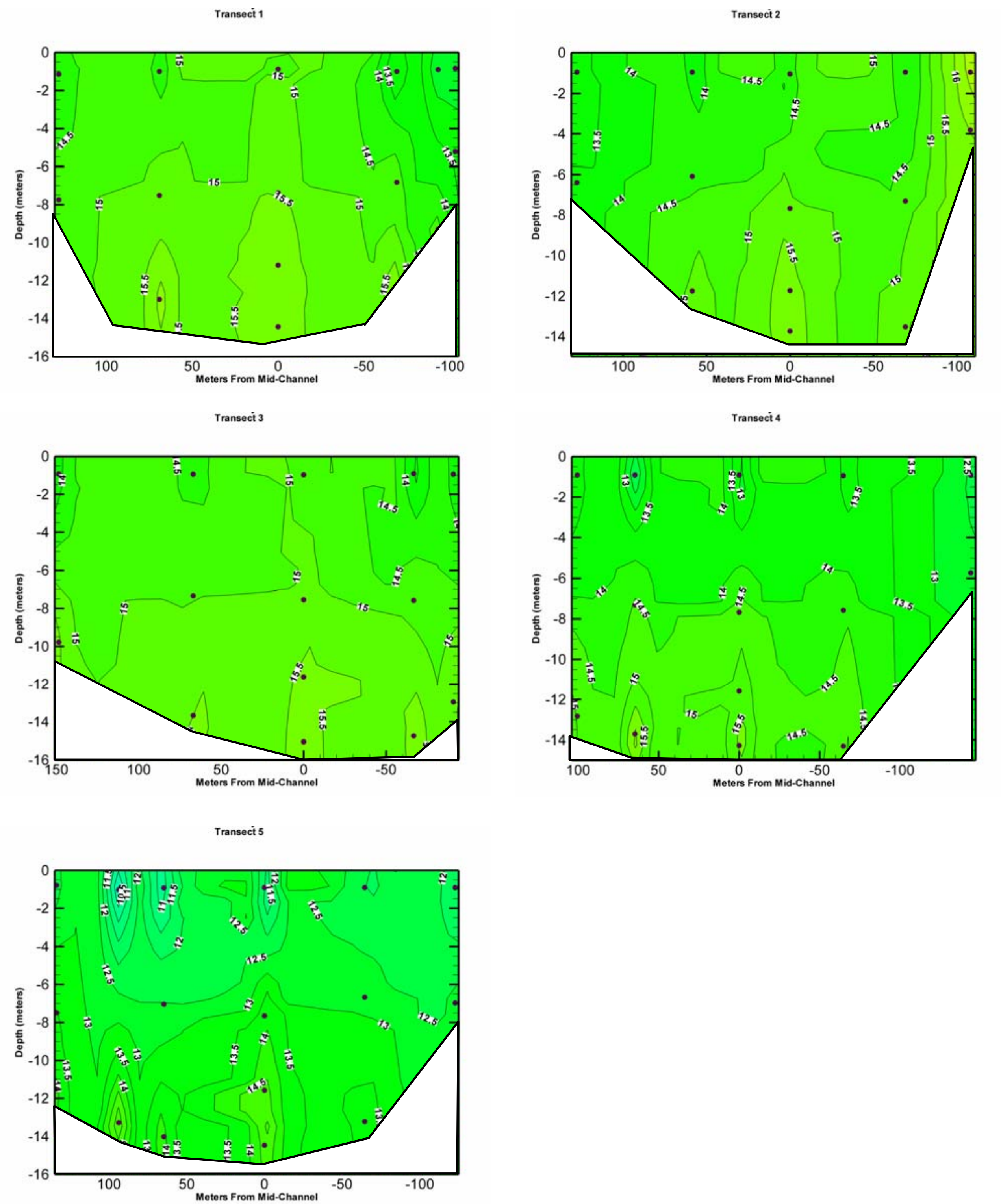
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Cross-Sections
Salinity (ppt)
High Tide 7/17/2007

Project Number: 6110080064

Figure: 3.51



Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

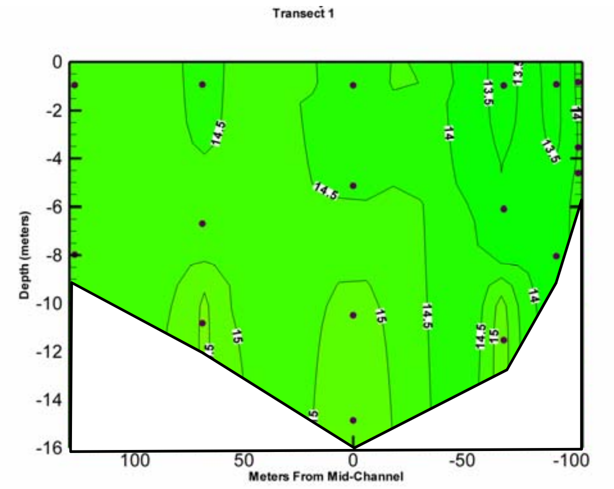
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

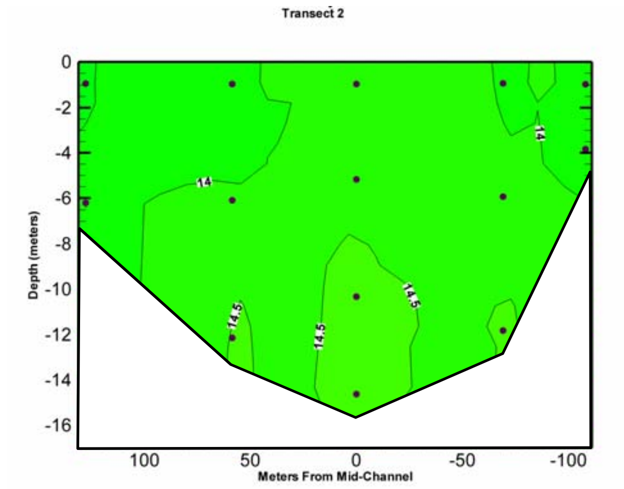
MACTEC

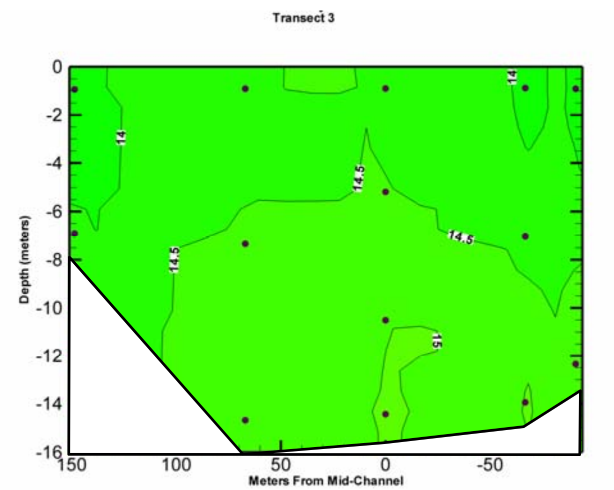
Cross-Sections
Salinity (ppt)
High Tide 8/13/2007

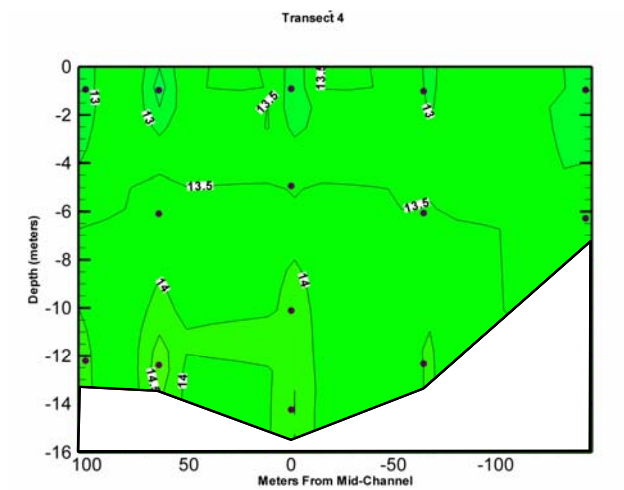
Project Number: 6110080064

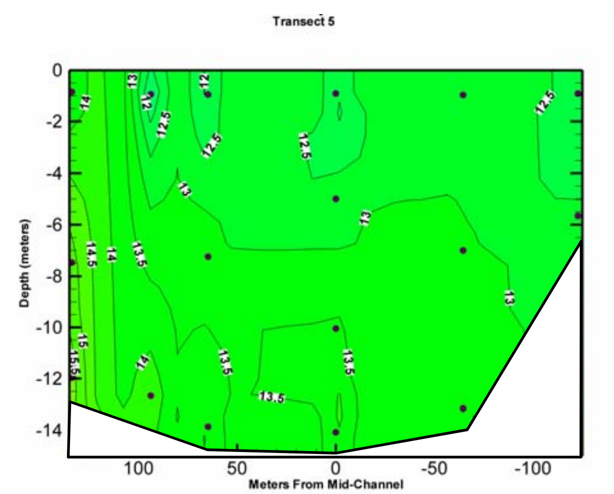
Figure: 3.52











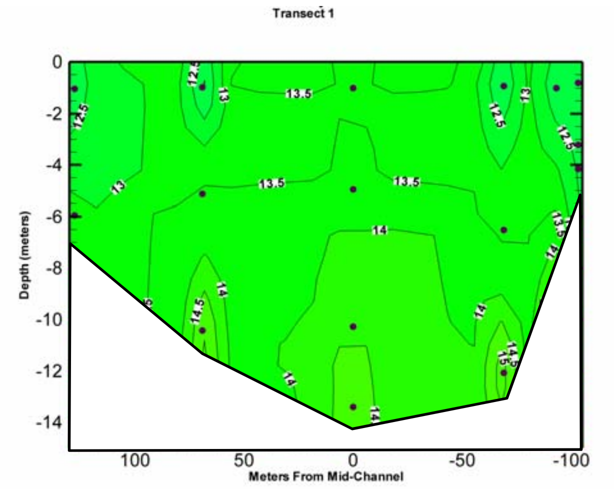
Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

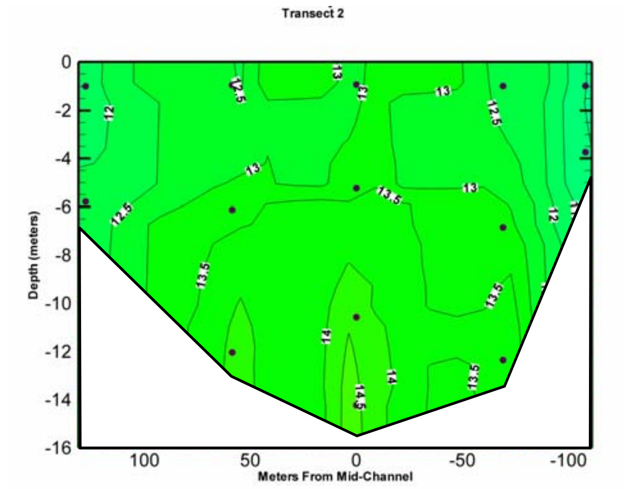
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

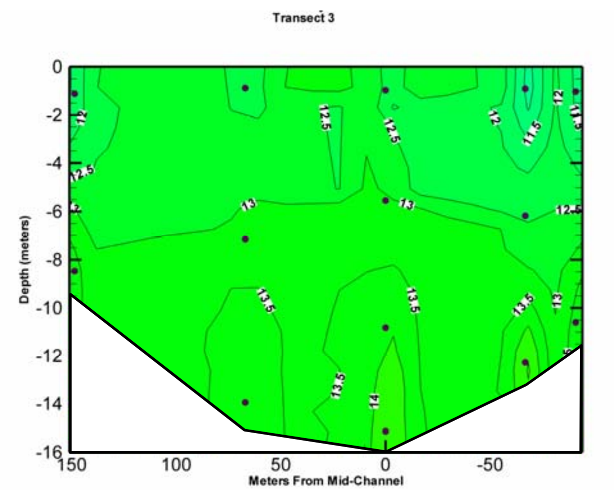
MACTEC

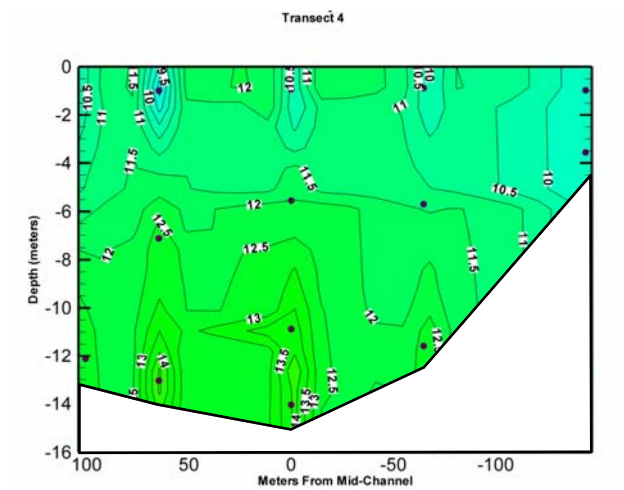
Cross-Sections
Salinity (ppt)
High Tide 8/28/2007

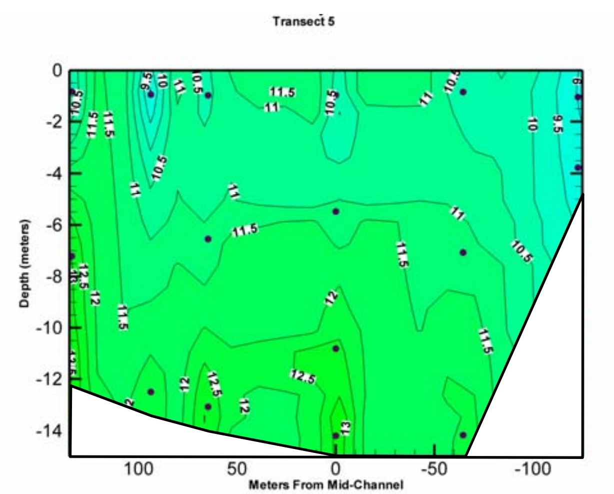
Project Number: 6110080064 Figure: 3.53











Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

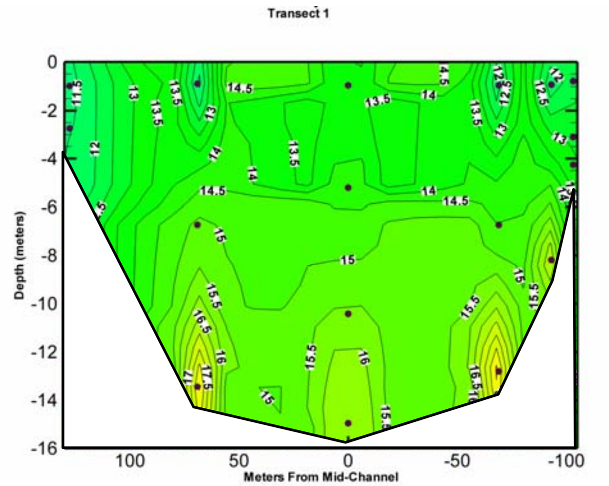
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

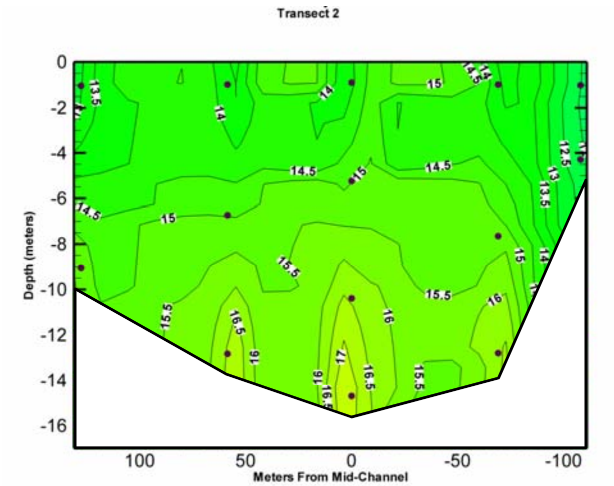
MACTEC

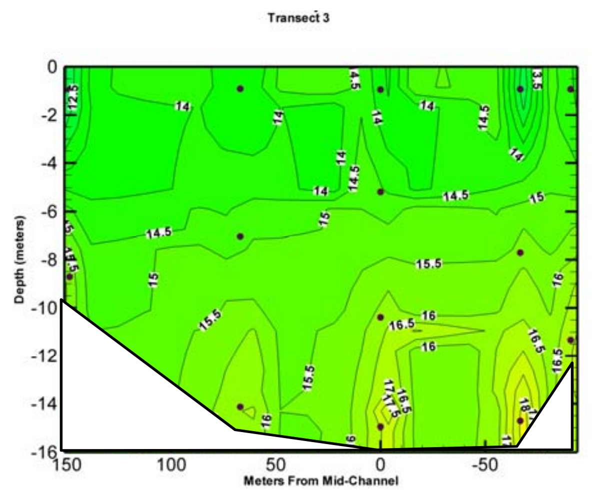
Cross-Sections
Salinity (ppt)
High Tide 9/11/2007

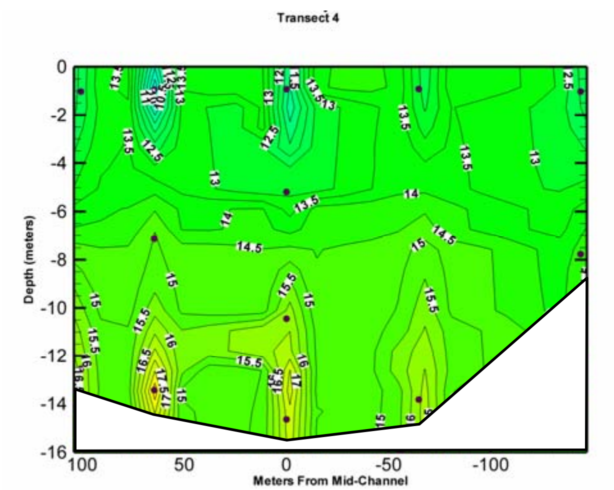
Project Number: 6110080064

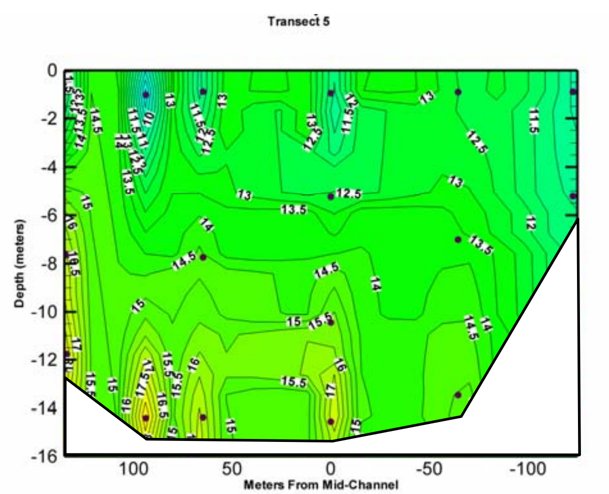
Figure: 3.54











Prepared by: LRP 8/10/09
Checked by: TRK 8/10/09

SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

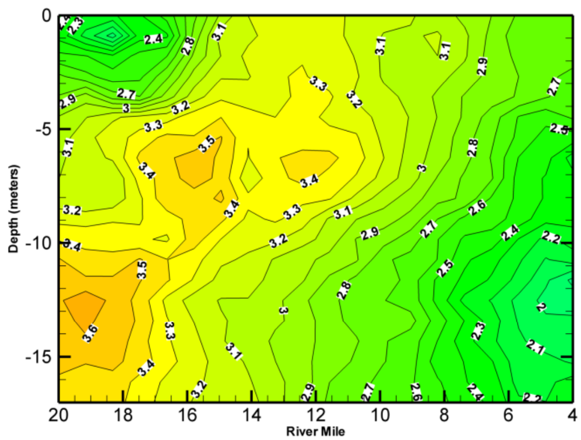
MACTEC

Cross-Sections
Salinity (ppt)
High Tide 9/18/2007

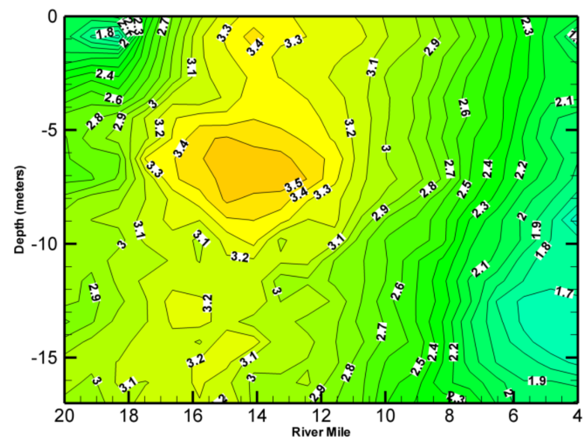
Project Number: 6110080064 Figure: 3.55

LOW TIDE

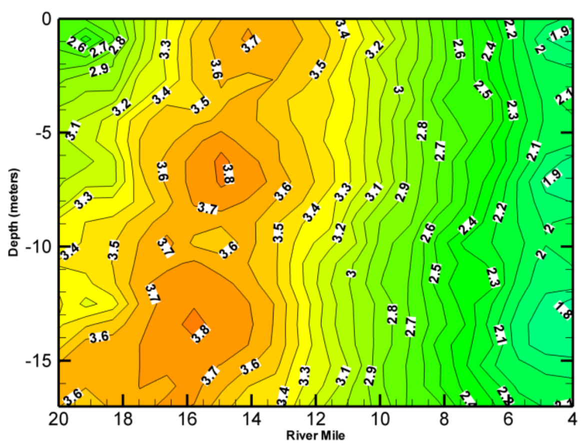
Oxygen Concentration Deficit
9/6/2007 low tide Long Run (After 30 day of ReOxygenation)



Oxygen Concentration Deficit
9/7/2007 low tide Long Run (After 31 day of ReOxygenation)

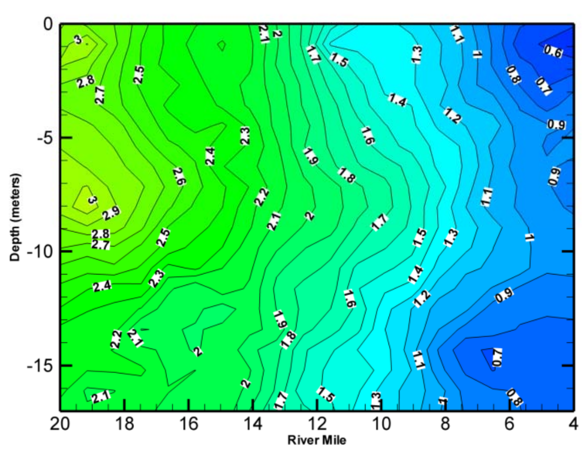


Oxygen Concentration Deficit
9/25/2007 low tide Long Run (9 days Post ReOxygenation)

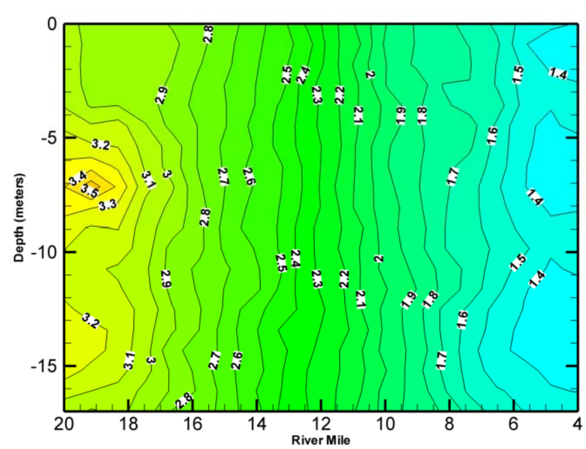


HIGH TIDE

Oxygen Concentration Deficit
9/19/2007 high tide Long Run (3 days Post ReOxygenation)



Oxygen Concentration Deficit
9/13/2007 high tide Long Run (After 37 days of ReOxygenation



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

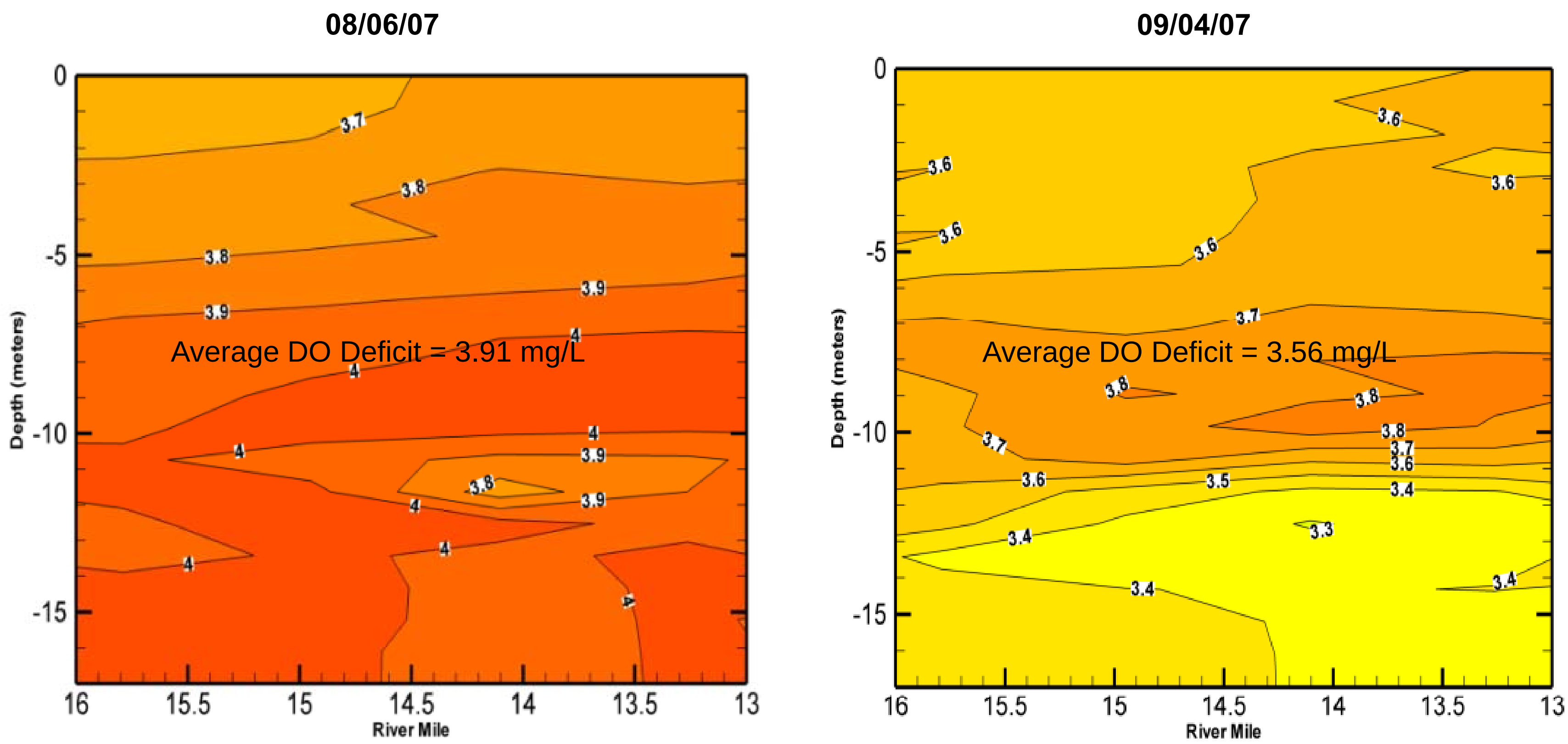
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Mid-channel
DO Deficit (mg/L)
Low and High Tide Long Run Events

Project Number: 6110080064

Figure: 3.56



Prepared by: LRP 1/14/09

Checked by: TRK 1/14/09

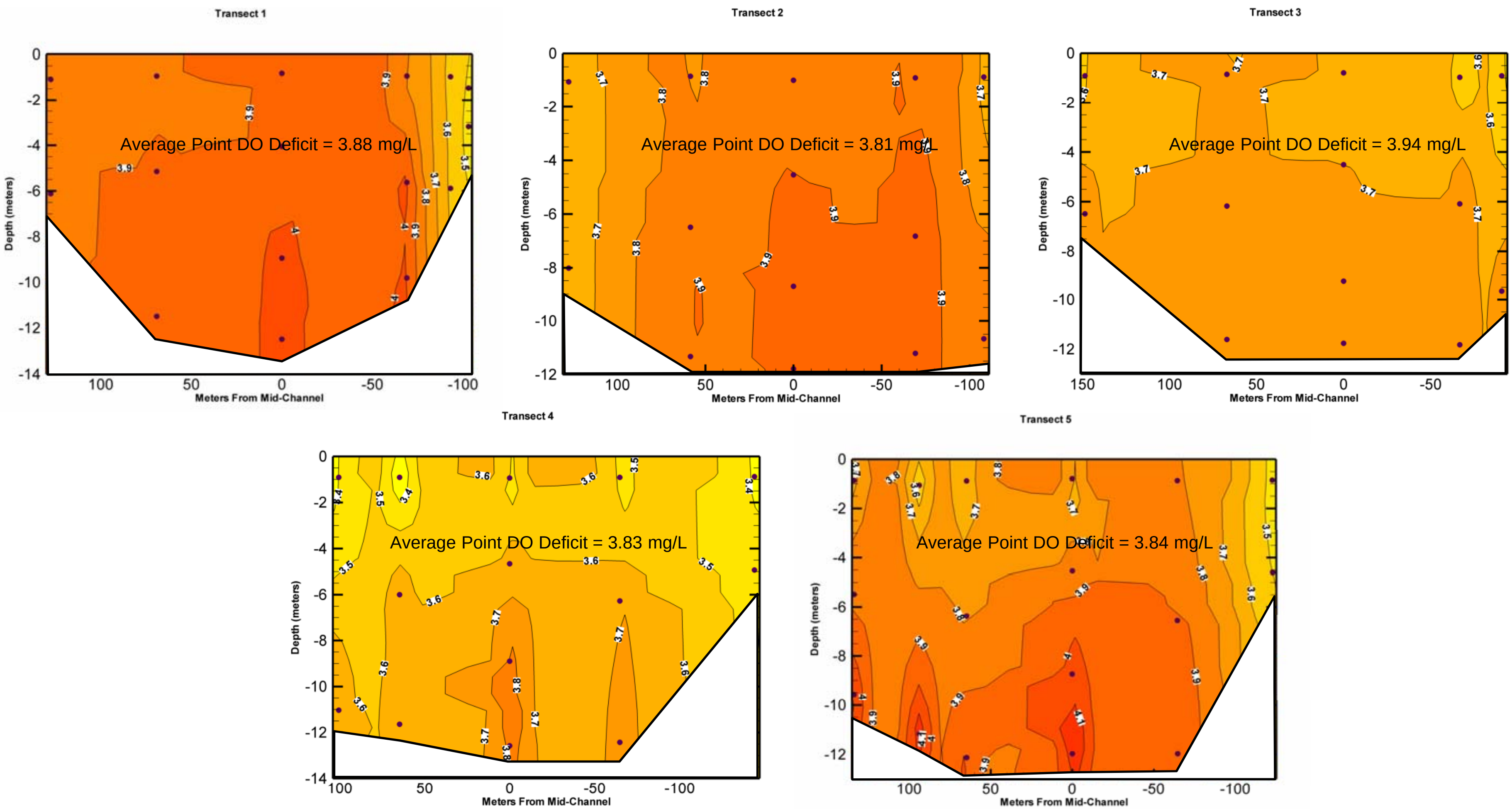
SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Mid-Channel Profiles
Similar Salinity and Tide Range Comparison

Project Number: 6110-08-0064

Figure 3.57



River Segment Average = 3.86 mg/L

Prepared by: LRP 1/14/09

Checked by: TRK 1/14/09

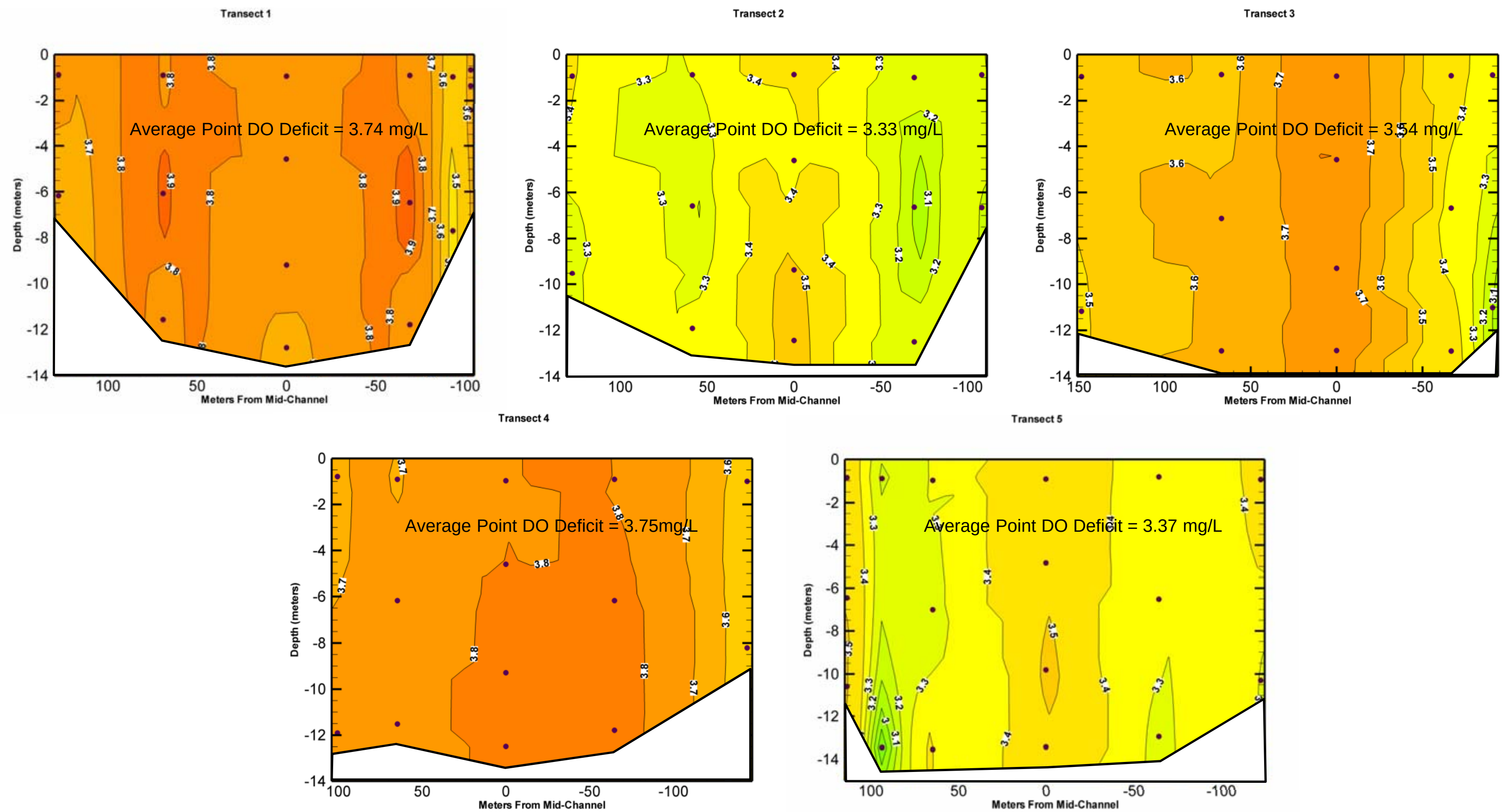
SAVANNAH HARBOR REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Cross-Sections Low Tide 8/07/2007
DO Deficit (mg/L)
Similar Salinity and Tidal Range Comparison

Project Number: 6110-08-0064

Figure 3.58A



River Segment Average = 3.55 mg/L

Prepared by: LRP 1/14/09

Checked by: TRK 1/14/09

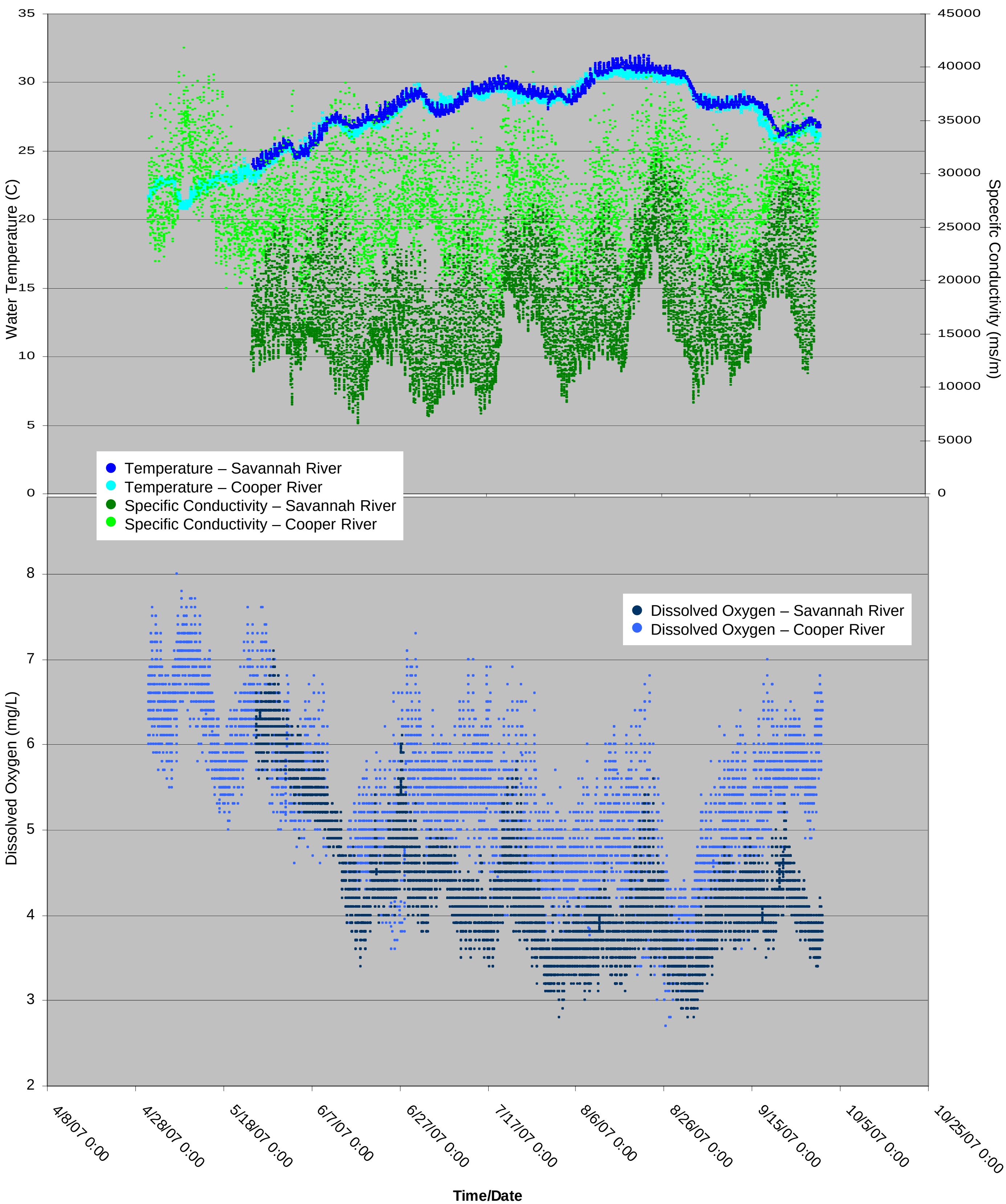
SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

Cross-Sections Low Tide 9/5/2007
DO Deficit (mg/L)
Similar Salinity and Tidal Range Comparison

Project Number: 6110-08-0064

Figure 3.58B



SAVANNAH HARBOR
REOXYGENATION DEMONSTRATION PROJECT
GEORGIA PORTS AUTHORITY
SAVANNAH, GEORGIA

MACTEC

2007 Savannah River and Cooper River Comparison

Project Number: 6110080064

Figure 3.59

APPENDICES

APPENDIX A

SAVANNAH HARBOR REOXYGENATION MULTIPLE LINEAR REGRESSION ANALYSIS

APPENDIX A – SAVANNAH HARBOR REOXYGENATION MULTIPLE LINEAR REGRESSION ANALYSIS

The method of multiple linear regression was used to investigate the interrelations of several measured parameters of the Savannah River to determine the feasibility of using these measurements to predict dissolved oxygen concentrations. This predicted value would then be used to estimate the effects of the addition of oxygen to the water by supplying an expected value (derived from factors other than the addition) to compare the actual measured values with addition of oxygen.

Multiple Linear Regression

Multiple linear regression (MLR) is a statistical method of predicting a response (dependent variable) from more than one input value (independent variables). It is directly related to the more common linear regression or least-squares line fit which predicts the dependent variable from a single independent variable ("y" from "x").

Best Model Determination

Unlike simple linear regression with one independent and one dependent variable, MLR offers models with various combinations of the multiple independent variables. For instance, if one has a system with three independent variables X1, X2, and X3, then there are seven models possible: (X1, X2, X3), (X1, X3), (X1, X2), (X2, X3), (X1), (X2), (X3). The last three are really just simple linear regressions of individual independent variables, but are also part of the MLR framework.

Since each additional variable added to the regression adds predictive power, it would seem logical to add as many variables to the model as possible and simply go with this longest model. Unfortunately, additional variables also have a negative effect by adding their noise to the mix. Intuitively, adding a variable with no interaction to the underlying relationship will add nothing to the regression model, so additional variables should be added only when they have something to contribute to the regression model. Fortunately, there is a class of methods that can be used to identify when a variable adds more to the predictive value of a regression model than it subtracts with its own noise. Best know of these is the Akaike Information Criterion (AIC). Using this metric, one can compare the predictive power of MLR models with different mixes of independent variables and identify which among them has the best information content – the most predictive power with the least amount of individual variable's noise. The

AIC rates each model in a group – the model with the lowest AIC is the "best" model within that group, but models with similar AICs are almost equally as "good". A difference of 2 points in a pair of AICs is not considered significant.

Savannah River MLR

This MLR was developed to predict expected oxygen concentration deficits (with no oxygen addition treatment) for comparison to actual measurements of oxygen concentration deficits with the addition treatment. Dissolved oxygen concentration deficits are the difference between the actual dissolved oxygen concentration and the theoretical saturated oxygen concentration. It is easier to interpret because variations in oxygen concentration simply due to temperature changes, salinity changes, and other factors can be eliminated.

The MLR was developed with data before oxygen was added to the system (before 8/5/2007).

Since the river is not a homogeneous system, models for each of two stations (US Army Corps of Engineers dock and Georgia Port Authority location) for three different depths (shallow, mid, and deep) were developed. The same independent variables were considered for each location and depth – tidal range, temperature, and salinity. These independent variables were combined in various permutations into the following candidate models:

- Tidal Range, Temperature, and Salinity
- Tidal Range and Temperature
- Tidal Range and Salinity
- Temperature and Salinity
- Tidal Range
- Temperature
- Salinity

The dependent variable was dissolved oxygen concentration deficit in all candidate models. The "best" prediction model for DO deficit was chosen based on the Akaike Information Criterion (AIC).

Best Model Predictions and Interpretations

Once a best model was chosen for a station and depth, the model was then used to predict expected DO deficits (with no additional oxygen addition). This predicted value was compared to actual measured values at various times before, during, and after the oxygen addition and the difference between predicted and measured values was determined (the "residual" – a statistical term having no relation to any chemical analysis of "oxygen residual").

These residuals were then time-plotted for visual examination for trends and graphed as box-and-whisker plots, grouped by "before", "during" and "after" to visually examine for trends in the groups.

Results for Individual Locations and Depths

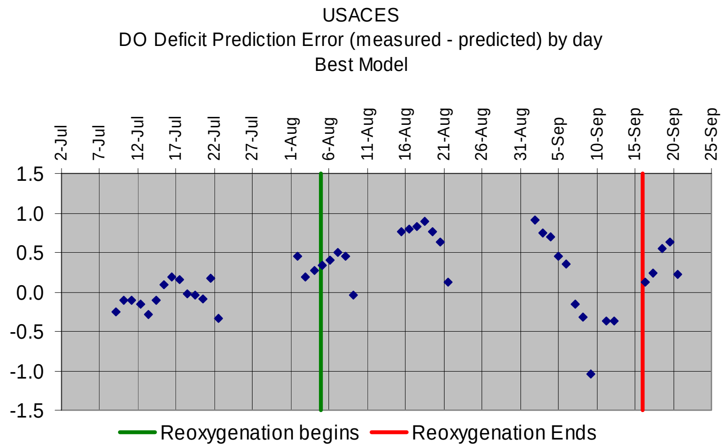
USACE Shallow Depth

In this location, salinity played a peripheral role in enhancing predictive power. The most efficient model (as determined by the lowest relative AIC) was the model including tidal range and temperature. Adding salinity did not greatly improve the model's predictive ability (multiple r-squared did not change) so the AIC increased.

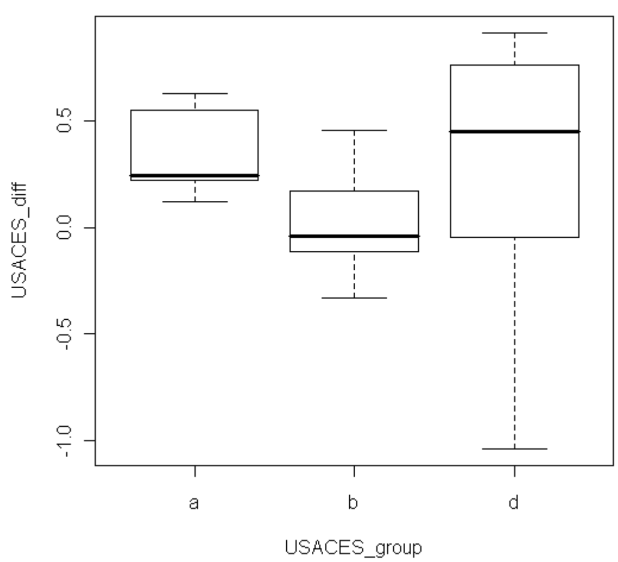
Model Parameters – USACE Shallow Depth					
Site	**Tidal Range**	**Temp**	**Salinity**	**Multiple R^2**	**AIC**
USACES	x	x	x	0.8069	5.1972
USACES	x	x		0.8069	3.19811
USACES	x		x	0.7569	7.11168
USACES		x	x	0.5606	17.17659
USACES	x			0.752	5.45076
USACES		x		0.4716	18.31354
USACES			x	0.09349	27.4877

- Best model: Tidal Range and Temperature
- Yellow indicates the model is probably not significantly worse than the model chosen

After calculating the residuals and plotting them against periods (and highlighting when reoxygenation began and ended) the following chart is produced. It appears the residuals increase once reoxygenation begins, but decrease at the end of the reoxygenation period and increase again after reoxygenation ends.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see the "before" (b) and "after" (a) reoxygenation groups are significantly different (the median line in the box does not overlap the box of the other group), while both "before" and "after" are not significantly different from "during" (d).



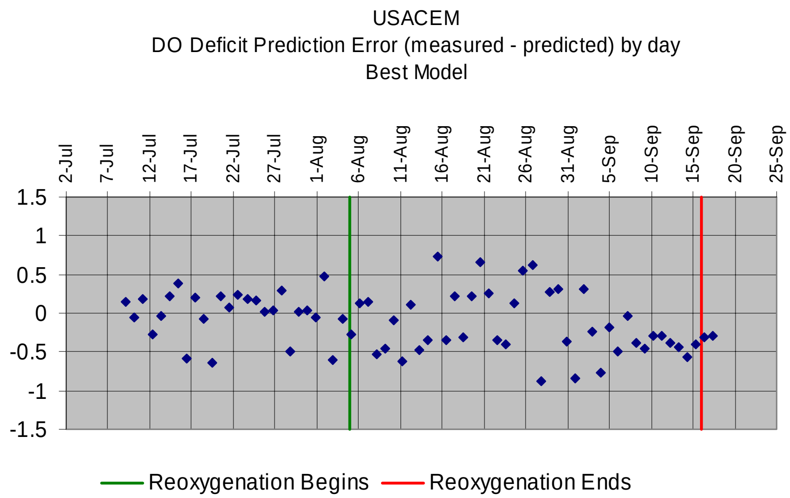
USACE Mid Depth

In this location, temperature played the major role in predictive power. The most efficient model (as determined by the lowest relative AIC) was the model including just the temperature. Adding salinity or tidal range individually did not greatly improve the model's predictive ability (multiple r-squared did not change much) so the AICs increased.

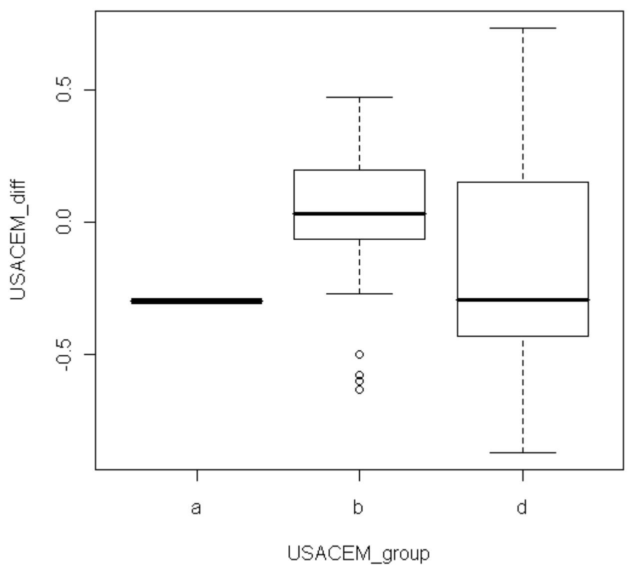
Model Parameters - USACE Mid Depth					
Site	Tidal Range	Temp	Salinity	Multiple R2	AIC
USACEM	x	x	x	0.218	18.97637
USACEM	x	x		0.2066	17.353
USACEM	x		x	0.08979	20.92367
USACEM		x	x	0.1976	17.64643
USACEM	x			0.03038	20.56743
USACEM		x		0.1942	15.75634
USACEM			x	0.03157	20.53547

- Best Model: Temperature only

Again, after calculating the residuals and plotting them against time periods (and highlighting when reoxygenation began and ended) the following chart is produced. It appears the residuals do not change much before and during reoxygenation, decreasing somewhat at the end of the reoxygenation period. Data was too sparse after the reoxygenation period to assess trends.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see the "before" (b) and "during" (d) reoxygenation groups are not significantly different, while data after reoxygenation (a) are not sufficient for meaningful comparisons.



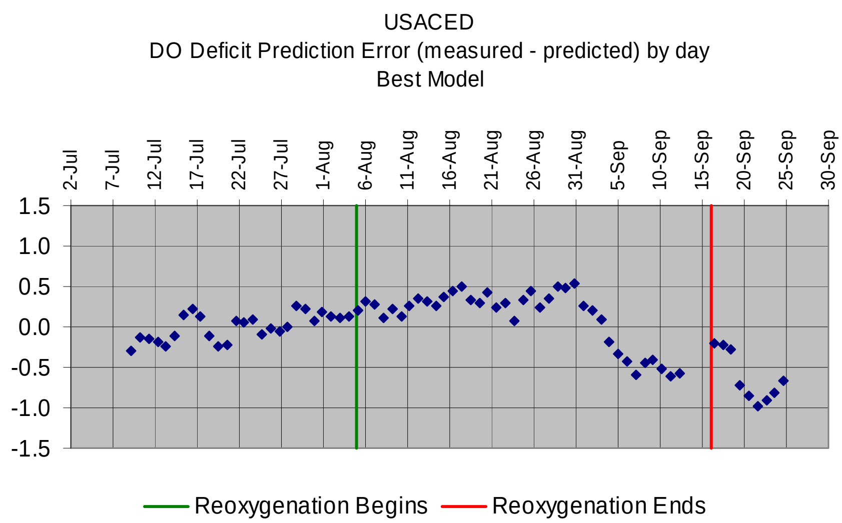
USACE Deep Depth

In this location, tidal range and temperature played the major roles in predictive power. The most efficient model was the model including the temperature and tidal range. Adding salinity did not greatly improve the model's predictive ability (multiple r-squared did not change much).

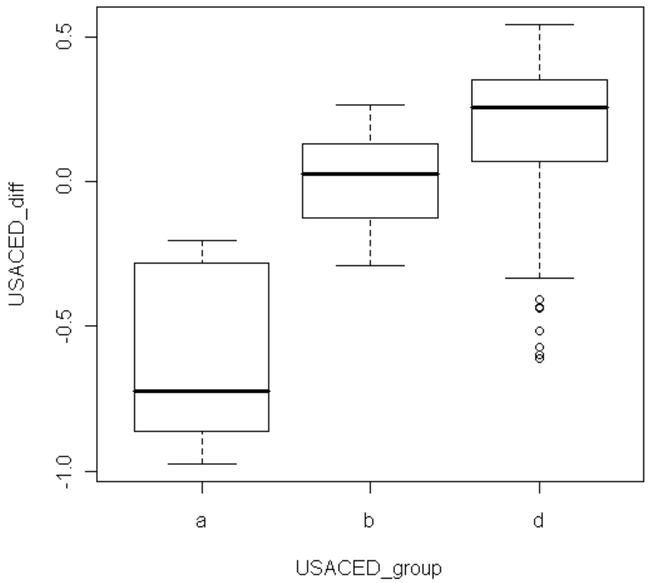
Model Parameters – USACE Deep Depth					
Site	**Tidal Range**	**Temp**	**Salinity**	**Multiple R^2**	**AIC**
USACED	x	x	x	0.7196	-13.3537
USACED	x	x		0.6979	-13.4177
USACED	x		x	0.6247	-7.77446
USACED		x	x	0.507	-0.6847
USACED	x			0.5703	-6.25525
USACED		x		0.4525	0.042281
USACED			x	0.1107	12.65427

- Best Model: Tidal Range and Temperature

Calculating the residuals and plotting them against time periods (and highlighting when reoxygenation began and ended) the following chart is produced. Much like the shallow depth, it appears the residuals increase once reoxygenation begins, but decrease at the end of the reoxygenation period and may increase again after reoxygenation ends.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see the “before” (b) and “during” (d) reoxygenation groups are significantly different with “before” being less than “during”, while data “after” reoxygenation (a) are significantly lower than both other groups.



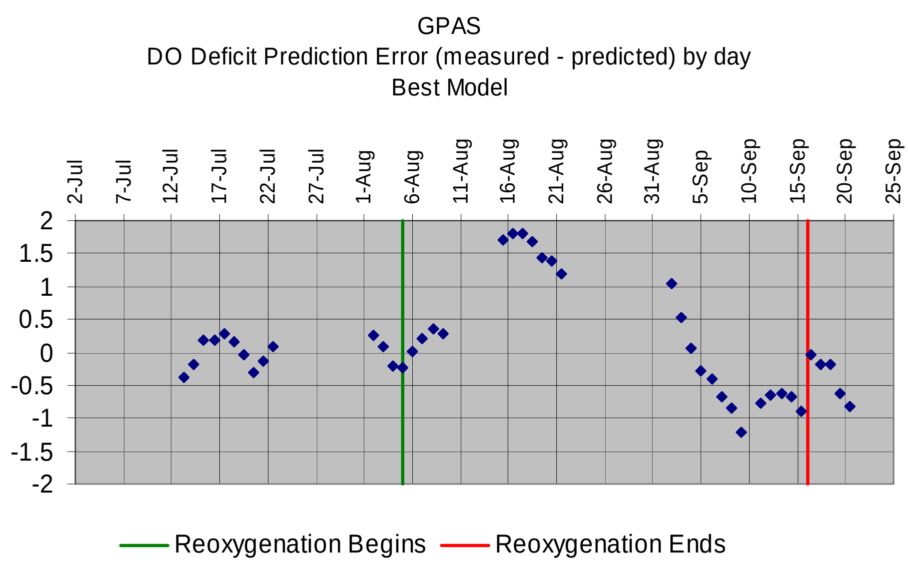
GPA Shallow Depth

In this location, salinity played a peripheral role in enhancing predictive power. The most efficient model (as determined by the lowest relative AIC) was the model including tidal range and temperature – just as in the USACE shallow location. Again, adding salinity did not greatly improve the model's predictive ability (multiple r-squared did not change) so the AIC increased.

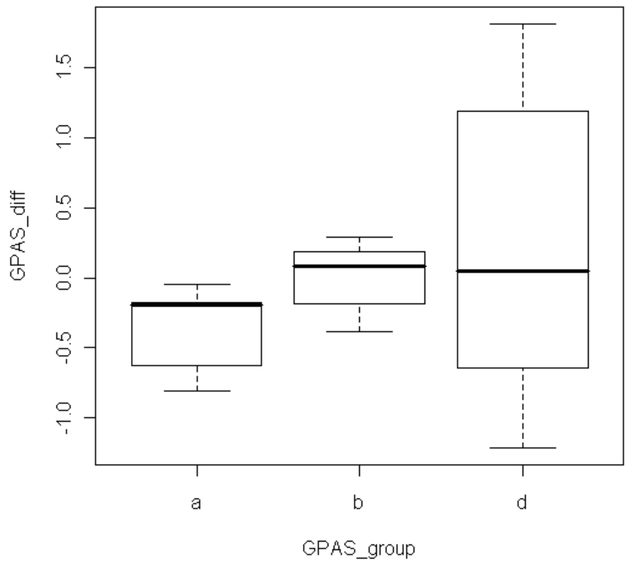
Model Parameters – GPA Shallow Depth					
Site	Tidal Range	Temp	Salinity	Multiple R^2	AIC
GPAS	x	x	x	0.8636	6.57251
GPAS	x	x		0.8589	5.01229
GPAS	x		x	0.6944	15.06292
GPAS		x	x	0.7812	10.72118
GPAS	x			0.6893	13.27697
GPAS		x		0.6972	12.94195
GPAS			x	0.1337	26.60738

- Best Model: Tidal Range and Temperature

Calculating the residuals and plotting them against time periods (and highlighting when reoxygenation began and ended) the following chart is produced. It appears the residuals increase once reoxygenation begins, but decrease at the end of the reoxygenation period and may increase again after reoxygenation ends.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see there are no significant differences among the groups.



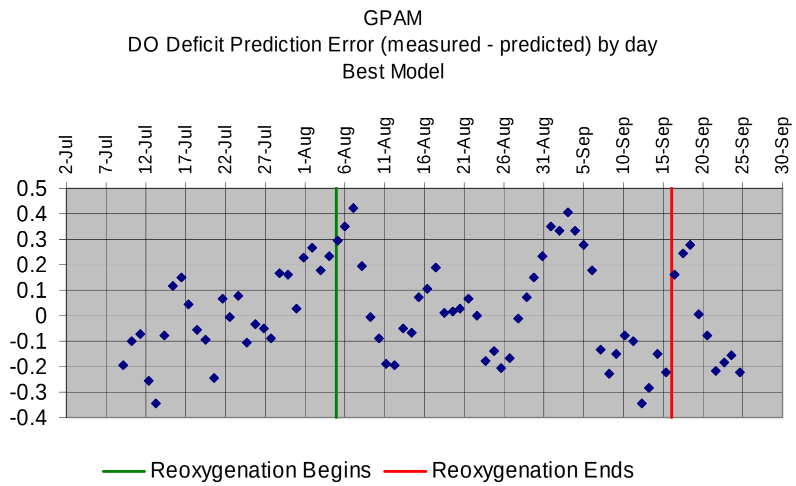
GPA Mid Depth

In this location n this location, tidal range and salinity played the major role in predictive power. The most efficient model (as determined by the lowest relative AIC) was the model including tidal range and salinity. Adding temperature or removing salinity did not greatly improve the model's predictive ability (multiple r-squared did not change) so the AIC increased

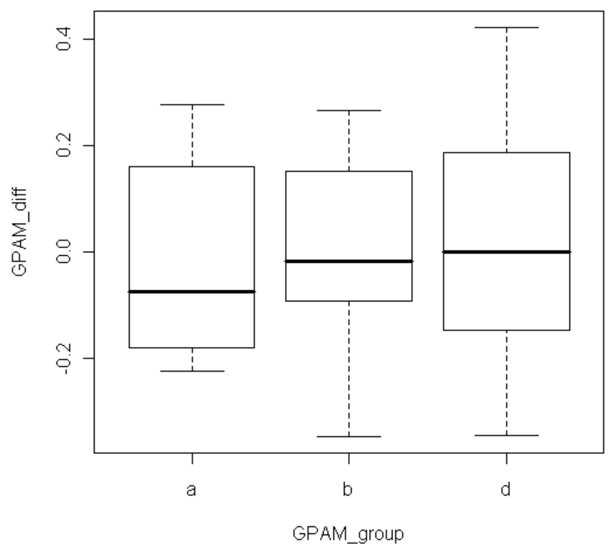
Model Parameters - GPA Mid Depth					
Site	**Tidal Range**	**Temp**	**Salinity**	**Multiple R2**	**AIC**
GPAM	x	x	x	0.576	-12.3978
GPAM	x	x		0.5315	-11.8033
GPAM	x		x	0.5719	-14.146
GPAM		x	x	0.3047	-1.53737
GPAM	x			0.5168	-13.001
GPAM		x		0.21	-0.21851
GPAM			x	0.1677	1.13849

- Best Model: Tidal Range and Salinity

Calculating the residuals and plotting them against time periods (and highlighting when reoxygenation began and ended) the following chart is produced. Much like the USACE mid depth, the residuals do not change much before and during reoxygenation, perhaps decreasing somewhat at the end of the reoxygenation period. There was also no clear difference after the reoxygenation period.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see there are no significant differences among the groups.



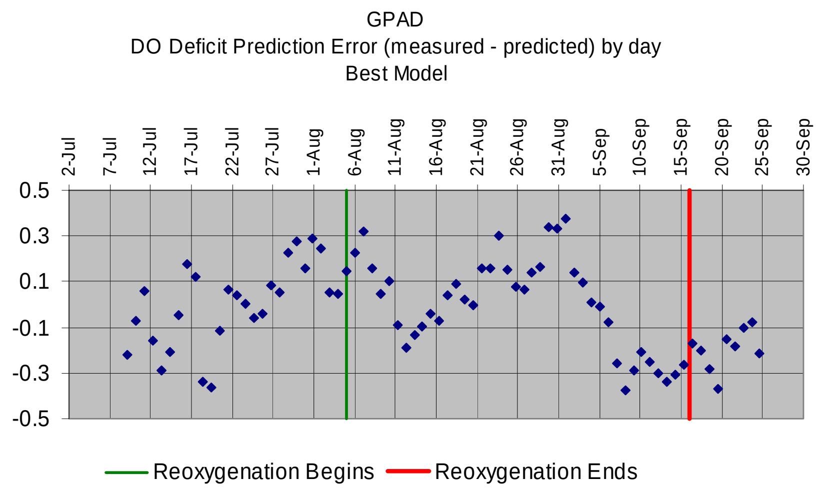
GPA Deep Depth

In this location, salinity played the major roles in predictive power. The most efficient model was the model including the temperature and tidal range. Adding the other parameters (singly or in combination) did not greatly improve the model's predictive ability (multiple r-squared did not change much).

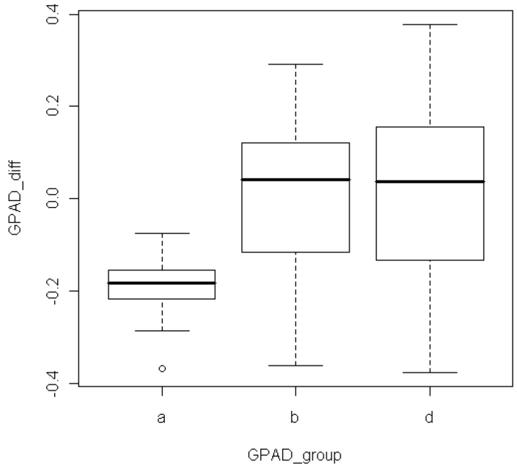
Model Parameters - GPA Deep Depth					
Site	**Tidal Range**	**Temp**	**Salinity**	**Multiple R2**	**AIC**
GPAD	x	x	x	0.3579	-7.17514
GPAD	x	x		0.3286	-8.0158
GPAD	x		x	0.3264	-7.93017
GPAD		x	x	0.353	-8.97849
GPAD	x			0.296	-8.78322
GPAD		x		0.1544	-4.01736
GPAD			x	0.3147	-9.48315

- Best Model: Salinity

Calculating the residuals and plotting them against time periods (and highlighting when reoxygenation began and ended) the following chart is produced. The residuals do not change much before and during reoxygenation, perhaps decreasing somewhat at the end of the reoxygenation period. There was a decrease after the reoxygenation period.



Looking next at box-and-whisker plots of the residuals to examine group behavior, we see there are no significant differences between “before” and “during” but a significant difference in the “after” group.



Conclusions

Due to the complexity of the river system a multiple linear regression (MLR) was used to investigate the interrelations of several measured parameters of the Savannah River to determine the feasibility of using these measurements to predict DO concentrations. The data compared included the tidal range, temperature, and salinity measured in the river system. The MLR method statistically predicted a dependent variable from more than one input value. The MLR method statistically predicted an overall effect at the USACE and GPA locations mostly dependant on tidal range. Deep monitoring locations predicted an influenced effect from temperature and tidal range at USACE and mostly a salinity effect at GPAD.

Based on this MLR analysis of the continuous near-shore monitoring data, the MLR analysis does not provide a useful means to directly quantify the relatively small expected DO effects of supplemental oxygenation during the demonstration period.

APPENDIX B

SAVANNAH HARBOR REOXYGENATION SIGNAL-TO-NOISE RATIO ANALYSIS

APPENDIX B: SIGNAL-TO-NOISE RATIO AND THE ABILITY TO DISCERN A SIGNAL

In an ideal world, every measurement taken would be perfect and without error or noise. In the real world, neither of these are true. Error can be minimized by careful sampling and analysis, but noise is a random, uncontrollable haze that obscures all measurements to one degree or another. The standard measure of this level of obfuscation is called the signal-to-noise ratio (SN). Measurements with a large SN are easy to deal with since the noise is a small fraction of the measured value – sometimes a vanishingly small fraction. On the other hand, if the SN is small, the noise may be as large as the actual signal and the resulting measurements are nearly random noise and impossible to interpret.

How small is too small? Physicist Albert Rose developed the Rose Criteria to quantify this. This criteria states the SN must be greater than 5 for all features of the signal to be detected with 100 percent certainty. This criterion was developed for electronic imaging processing, but has general signal processing applicability. In short, if the magnitude of the noise is greater than 20 percent of the magnitude of the signal, then not everything in the signal can be extracted. If the SN is much less than 5, very little of the actual signal can be seen.

Application of SN to Savannah River Oxygen Addition

During the Savannah River experiment oxygen was added to the river water and the change in oxygen concentration was measured. To measure the effect, it is necessary to ask "Is there likely enough signal generated to overcome the inherent noise of measurement and inherent noisy variability within a tidally-influenced river environment?" Calculating a SN can address this question. To generate a SN, one needs a measure of the signal strength and a measure of the noise strength.

One method to estimate signal strength is to model the known processes while ignoring noise-producing processes. (Since noise-producing processes are usually unknown, they are seldom modeled. Most models produce a "clean" signal that can be used as a best-case estimate of signal strength.) This system has already been modeled (with and without oxygen addition) by TetraTech (2009), so estimates of signal strength can be easily determined from that model.

An estimate of noise is a little more difficult to make. Since duplicate samples are not available, instantaneous differences in measurements cannot be used to estimate noise. However, regularly scheduled samples are available and an estimate of variability at time = 0 can be generated from semivariogram analysis commonly used in geostatistics (substituting time steps for distance lags). Average squared differences of measurements taken at a set timelag apart are graphed against the timelag length and a curve is fit through the points. This curve is then extrapolated back to a timelag of 0 and the variability determined. In geostatistics, this variability is termed the “nugget effect” the inherent variability of co-located samples.

With an estimate of the signal strength and the noise strength, a SN can be calculated and compared to the Rose Criterion to determine if the measurement of oxygen addition is theoretically discernable.

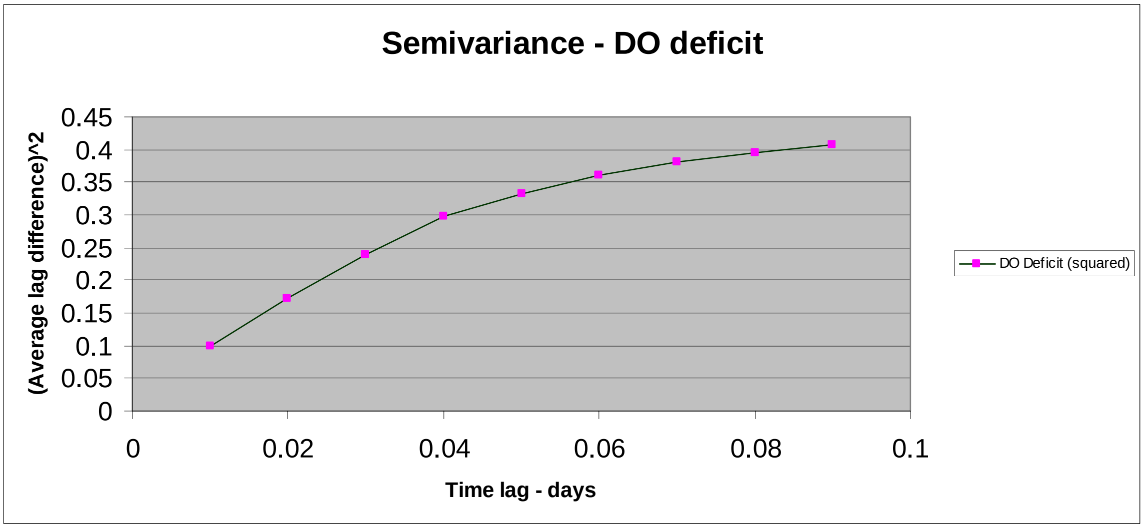
Estimate of Signal Strength

Since the model was run over many cells for many time-steps, a simplification was needed. As a bounding case, the SN at the barge’s middle depth was first estimated, assuming this to be one of the most likely locations to have a high SN. Data was extracted from Tetratech’s model runs to compare results at cell (15, 59, middle depth) for 481 time-steps with and without oxygen addition to the model. The oxygen addition to the model decreased the oxygen deficit from 1.85 to 0.03 mg/L with an average decrease of 0.28 and median decrease of 0.27 mg/L. A reasonable estimate of the average signal strength at the middle level of the barge is 0.28 mg/L.

Estimate of Noise Strength

Developing a semivariogram for a data set requires calculating squared differences for each pair of data points in the data set. For a large data set, this may be an unmanageable number, since the number of pairs increases by one-half the square of the number of data points ($n^2/2$). For the 481 time-steps of interest at the barge, middle depth, this means a total of ($481^2/2$) or nearly 116,000 differences.

This large number of differences, along with the expectation of correlation of values over much more than a tidal cycle led to initial review of lags no more than a day. Further review identified substantial homogenization of differences beyond 0.1 days. Plotting of the average difference squared (to avoid graphing problems of positive and negative differences as specified by the semivariogram process) leads to the following semivariogram figure.



The average squared lag difference at time lag 0 appears to be on the order of 0.05 for an average difference of 0.22 mg/L (square root of 0.05).

Estimate of Signal-to-Noise Ratio

Given the average estimated signal strength at one of the most favorable locations is 0.28 mg/L and the estimated average instantaneous noise strength at any location is 0.22 mg/L, calculation of the SN is straightforward:

$$SN = (0.28 / 0.22) = 1.3$$

This number is much smaller than the Rose Criterion and strongly suggests the expected size of the nearshore DO effect cannot be separately identified in the noise of the nearshore continuous measurements.

Conclusions

The signal-to-noise ratio helps decipher noticeable signals from measurements. The ratio value of 1.3 is small enough that the expected size of the DO signal due to reoxygenation in the main channel cannot be reliably separated from the baseline variability of the nearshore continuous DO measurements.

APPENDIX C

RESPONSE TO COMMENTS

Savannah Harbor ReOxygenation Demonstration Project Report Supplemental Data Evaluation Report – August 19, 2009

Response to Comments

Wade Cantrell, SCDHEC

1. *Both the near-field plume modeling and the far-field dissolved oxygen (DO) modeling are based on characteristics that vary considerably within the harbor area, so a final DO mitigation plan should include similar modeling for each proposed injection location. Depending on location, additional analysis may be needed to rule out the possibility of vertical turbulence, upward movement of the injected plume, and lower DO transfer efficiency compared to the demonstration site.*

   MACTEC understands that this modeling will be performed as part of considerations for permanent ReOx system placement.

Ed Eudaly PECONSULTING

1. *I believe that this is an excellent recommendation and support it. I realize that logistics and infrastructure are considerations in selecting the injection sites. However, the recommended modeling would be very useful in determining whether the proposed injection sites are effective in addressing the predicted impacts. I expect that this recommendation will be discussed at the upcoming meeting.*

   No response required

EPA Technical Review of the Savannah Harbor ReOxygenation Demonstration Project Reports – April 17, 2009

1. *The Savannah Harbor ReOxygenation Demonstration Project results were presented in 2 separate reports; 1) Savannah Harbor ReOxygenation Demonstration Project Report (MACTEC 2009) and 2) Savannah Harbor ReOxygenation Demonstration Modeling Report (Tetratech 2009). The three (3) main technical goals of the study, from EPA's perspective, were 1) to demonstrate that the Speece Cone Oxygen (O2) injection technology was feasible to install and use in the Harbor; 2) to determine the efficiency of*