# FINAL PROJECT REPORT

# SALINITY SIMULATION MODELS FOR FLORIDA BAY AND THE SOUTHWEST GULF COAST, EVERGLADES NATIONAL PARK

Cooperative Agreement Number CA H5280-05-0006
Between
The United States Department of the Interior National Park Service
Everglades National Park
And
Cetacean Logic Foundation, Inc.

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August 6, 2008

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**CESI Project No. CA H5284-05-0006 for Everglades National Park**

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Abstract

A Critical Ecosystem Studies Initiative (CESI) project, Cooperative Agreement Number CA H5280-05-0006 was completed as a continuation project by Cetacean Logic Foundation, Inc. (CLF) for Everglades National Park (ENP). The goal of this project was the characterization and simulation of the salinity regime in Florida Bay and the estuaries along southwest coast of the Gulf of Mexico (Gulf) within the Park. This research provided important information regarding the link between the downstream salinity in the estuaries of ENP and the upstream freshwater hydrology of the Everglades. In all fifteen (15) tasks were completed.

Evaporation surrogates were investigated to determine if inclusion of evaporation would improve the simulative capabilities of multivariate linear regression (MLR) salinity models. Correlation analysis showed that evaporation surrogates were correlated with other independent variables, which likely means that the parameters that were selected by the stepwise process were already expressing the effects of evaporation. It was concluded that there were no substantial reasons to include evaporation in the MLR salinity models. Based on this, the existing MLR models remained unchanged and the new models will not include evaporation as an independent variable.

The FATHOM mass-balance model was upgraded to include additional basins so that the total number of basins or “cells” is now 58. The new basins are intended to improve the initial mixing of freshwater inflows, and improve the fit of the model compared to the 47-basin configuration. While the 58 basin configuration is an improvement, the geometry of the basin domain must be fully evaluated in the context of the other model input parameters, in particular the spatial distribution of freshwater flows to the central part of the bay.

An additional fifteen MLR salinity models were developed, which means that there are daily MLR salinity models throughout Florida Bay and the upstream mangrove areas, in the Whitewater Bay area and the upstream mangrove areas, in the Shark River discharge estuary, along the upper Gulf coast in the Ten Thousand Islands area, and in Barnes Sound / Manatee Bay. Inferences can now be made about the models based on the model development process and the resulting MLR salinity models.

Historical reconstructions were developed for stage data using regression models to extend the observed data encompass the full period of the evaluations being made for CERP, 1965 – 2000. In this manner, historical reconstructions of salinity are possible through the MLR salinity models. Additionally, the Interagency Modeling Center at the South Florida Water Management District coded the models into programs that can be readily accessed for alternative analysis for Comprehensive Everglades Restoration Plan activities.

MLR salinity models were used with historical reconstructions and a paleo-based salinity time series data as input to a pink shrimp growth dynamics model. Whipray Basin and Johnson Key historical salinity reconstructions were utilized to help calibrate the pink shrimp simulation model using existing data. The MLR salinity models were coupled with the pink shrimp model to simulate growth and survival as the response of pink shrimp (*Farfantepenaeus duorarum*) to changing salinity and temperature. This proof-of-concept task showed that the two models could be coupled.

When all of the current salinity models in use for south Florida estuaries were evaluated (not just MLR salinity models), it was found that considerable recent progress had been made in the development and refinement of salinity models. From the analysis performed it was seen that the most complex models are the least portable and are rated lowest for ease of use. With respect to validity, all models rated high because most models are well-documented. For model fidelity, daily MLR salinity models have the best performing error measures, followed by SICS / TIME, and monthly FATHOM MFL base case models. Statistical and mass balance models will likely remain in use for planning-level decisions on a regional basis. Where possible, it appears that it will be less-expensive and time-consuming to utilize both statistical and mass balance models together as multiple lines of evidence and corroboration compared to utilizing only one hydrodynamic model for regional evaluations.

A flow estimate procedure was developed for the purpose of estimating the flow needed to meet the performance measures of the Florida Bay and Florida Keys Feasibility Study. The procedures established a quantifiable link between salinity in the downstream waters and the upstream hydrology (stage and flow), a link that had previously not been quantified. This flow procedure was used outside of this project to estimate the pre-drainage hydrology in the Everglades and salinity in Florida Bay using paleoecological information from sediment cores retrieved by the USGS from Florida Bay.

A preliminary study of the mangrove lakes area within the ENP found that this region has highly variable salinity that may be important in providing information on restoration alternatives. Preliminary models suggest that this region of the Florida Bay transition zone behaves differently with respect to salinity than other areas of Florida Bay and should be investigated further.

# I. Introduction

This Project Report describes all of the activities that were completed for the current Critical Ecosystem Studies Initiative (CESI) project, Cooperative Agreement Number CA H5280-05-0006. This is a CESI continuation project that was originally initiated by Cetacean Logic Foundation, Inc. (CLF) for Everglades National Park (ENP) in 2002. The goal of this on-going CLF research is the characterization and simulation of the salinity regime in Florida Bay and the estuaries along southwest coast of the Gulf of Mexico (Gulf) within the Park. It is intended that this research yield information regarding the link between the downstream salinity in the estuaries of ENP and the upstream freshwater hydrology of the Everglades.

There were 15 tasks in the latest contract modification, as follows:

Task 1 – Investigate the use of surrogates for evaporation to improve the simulative capabilities of MLR salinity models.

Task 2 – Run the FATHOM MFL model with SICS/TIME input and compare to observed data.

Task 3 – Complete the development of MLR salinity models at MMN stations not previously modeled.

Task 4 – Assist ENP with implementation of the FATHOM model that was developed for the SFWMD MFL project.

Task 5 – Investigate the coupling of pink shrimp models with MLR salinity models, and investigate other ecological models that may benefit from the use of MLR salinity simulations.

Task 6 - Coordinate with the IMC to incorporate the new MLR models in the recently developed post-processing tool.

Task 7 - Update the 2002 report by The Cadmus Group by incorporating the improvements in statistical modeling accomplished by CESI activities.

Task 8 - Develop a methodology for using SARIMA models to fill data gaps in salinity, stage, water temperature, and freshwater flow to Florida Bay

Task 9 - Estimate the Flow Regime Required to Meet the Florida Bay and Florida Keys Feasibility Study Salinity Performance Measures.

Task 10 – Implement the ENP Version of the SICS/TIME Model for Use with the MLR and FATHOM Salinity Models.

Task 11 - Develop historical reconstructions for the longest period possible for the MLR salinity models in northeast Florida Bay.

Task 12 – Evaluate the feasibility of developing MLR salinity models for the mangrove lakes region north of Garfield Bight and Terrapin Bay.

Task 13 – Prepare and submit a manuscript for publication in a refereed journal.

Task 14 – Prepare draft and final reports.

Task 15 - Attend and Conduct Meetings

All of these tasks were the subject of individual Task Reports that describes in detail the activities that were involved with a particular task. Those task reports are incorporated herein by reference (see Reference section). This Final Project Report summarizes the tasks that were performed and evaluates the project as a whole, as required by the contract.

## II. Methods and Findings by Task

Task 1 – Investigate the use of surrogates for evaporation to improve the simulative capabilities of MLR salinity models (Marshall, 2008a)

Evaporation is thought by most scientists and hydrologists to have a significant effect on salinity variation in Florida Bay, and this effect is thought to have a greater impact in the open water areas of Florida Bay and at certain times, particularly during the dry season and at the beginning of the wet season. Reliable, continuous data on Florida Bay evaporation do not exist for the period of MLR salinity model calibration and verification. Additionally, historical direct measurements of daily evaporation variability over the period for which SFWMD 2X2 model simulations are available do not exist. Therefore, this task focused on the evaluation of the correlative ability of evaporation surrogates that are known to be available over the 31- and/or 36-year period of the assessments that are being made.

Quantities that were evaluated included air temperature at Key West and Miami, relative humidity, cloud cover, sea water temperature, and the difference between air and sea water temperature. A time series correlation analysis was used to evaluate surrogates for evaporation. The significance level for inclusion in the MLR salinity models is 0.999, which means that an evaporation surrogate must be highly correlated to salinity to be included in the models. In a similar manner, local rainfall measured at the MMN stations was investigated as a potential candidate independent variable.

One of the primary objectives of this task was to re-visit consideration of evaporation as a candidate independent variable for MLR salinity models. In previous model development activities, the focus has been to find enough existing observed data to develop sound MLR salinity models at a high level of significance for long-term salinity simulation use. There are no long-term data available in the inventory of existing evaporation data for the south Florida region, though there are synoptic studies. Relative to the amount of observed data and the length of record for Everglades water levels, Key West sea surface water level, and wind (at Miami and Key West), the observed evaporation data are practically non-existent, particularly in Florida Bay and the mangrove fringe of he southwest Gulf coast. Therefore, evaporation was not included amongst the candidate independent variables during the first MLR salinity model development tasks. However, it is well-established through water budget estimates and observations of hypersaline conditions that evaporation plays an important role in determining the salinity regime in parts of Florida Bay and in areas along the southwest Gulf coast.

Various methods for estimating evaporation were examined. The SFWMD (Abtew et al, 2003; Irizarry-Ortiz, 2003) and others (Price et al, 2005) have found success using a self-calibrating method of estimating solar radiation, the key

component of evaporation, and using it with maximum and minimum air temperature values to estimate the potential evapotranspiration, which can, in turn, be used as an evaporation surrogate for MLR salinity model tasks. A preliminary investigation using salinity data from a limited number of stations showed that there was some correlation between salinity and Joe Bay potential evapotranspiration computed using the “Simple” method.

Therefore, SAS© code was written to compute an estimate of potential evapotranspiration using the Simple method at each of the 19 stations that currently have MLR salinity models. Solar radiation was estimated using the latitude of the station and the time of the year. Temperature difference was based on the maximum and minimum daily air temperature value measured at the Key West weather station, which has a record of daily air temperature much longer than the 1965-2000 period needed for CERP evaluations. Historical reconstructions for the 1965-2000 period using the Simple method simulations indicate that during the period 1985 – 1992, a drought period, etp was higher than the previous 19 years. During this period salinity values, in general, over the Bay were also high. However, the high salinity period of the early 1970’s is not expressed distinctly in the etp values. This was a period of low flow and the average evaporation contributed to the hypersaline conditions during that period.

A salinity model development activity was then undertaken in which the estimated potential evapotranspiration (etp) was submitted to the step-wise model development process along with the parameters that had previously been determined to be the best independent variables for salinity simulations at each station. In all but 3 of the 19 cases, etp was shown to be a significant independent variable, sometimes replacing other independent variables and sometimes becoming an added independent variable. However, in all case where etp replaced an existing independent variable, the independent variable that was replaced only explained a small portion of salinity variability (usually less than 1%), usually being a lagged value, and the etp replacement also only explained a small portion of salinity variability. For some models the goodness-of-fit improved with the inclusion of the etp, and for others the replacement by etp degraded the adjusted-$R^2$ and root mean square error values. The greatest model improvement occurred at Butternut Key, where the new model with etp explained an additional 5% of the variation in salinity, with about 3% explanatory improvement at Bob Allen Key and Manatee Bay, based on adjusted-$R^2$ values. When etp was an added independent variable, such as at Terrapin Bay, model adjusted-$R^2$ and RMS error values were reduced because the model now included additional terms that did not explain enough additional salinity variability to overcome the penalty of additional terms added to the regression model.

Additionally, the model development results using this evaporation surrogate were somewhat inconclusive at the open water stations where it was expected that evaporation would improve the models even if no improvement was seen at the near shore stations. Although model improvement was seen at Butternut Key

and Bob Allen Key with very slight improvement at Whipray Basin, etp was not a significant independent variable at Duck Key. Additional investigation with other open water salinity models (to be developed in the future) may prove that evaporation should be one of the independent variables in open water MLR salinity models. However, a comparison of the simulated values for salinity at Butternut Key indicates that the model with etp does no better at estimating high salinity values than the MLR salinity model that does not include etp.

Based on these results, it does not appear that including evaporation computed from the "Simple" method in the MLR salinity models is useful and that the models that have already been derived and are currently in use produce salinity simulations that are very similar to the salinity simulations produced by models that include evaporation surrogates.

With respect to rainfall directly on the Bay as compared to rainfall measured at a land-based meteorological station that may be remote to the Bay, previous attempts to correlate daily rainfall with salinity have not produced satisfactory models. For one reason, at the daily level, rainfall is an almost all-or-none discontinuous quantity, not a continuous independent variable like Everglades stage, sea surface elevation, and wind. In some manner, Everglades stage and sea surface elevation indirectly expresses the effect of rainfall accumulation. Because it is thought that rainfall on Florida Bay is spatially variable, to utilize direct rainfall as a candidate independent variable requires at least regional estimates of rainfall over a long-term period, or indirect data and a transfer function to relate rainfall at other stations to rainfall at a location on the Bay. The long term rainfall data that are available at Royal Palm, Flamingo, and Tavernier were used to produce a multivariate linear regression for rainfall measured at Joe Bay weather station. Since the fit of the model at the daily level was poor, it was not considered acceptable for use with MLR salinity models as a rainfall surrogate. However, when the daily values are aggregated into monthly totals, a much better and acceptable multivariate linear regression model can be produced (adjusted-$R^2$ = 0.68). Rainfall is spatially discrete at the daily time step but becomes somewhat continuous at the monthly step.

Therefore, even if daily rainfall at the Joe Bay weather station turned out to be a significant independent variable, it is not possible to extend the period of data by using the daily rainfall at other long-term weather stations because a reasonable transfer model can not be developed. Previous attempts to use daily rainfall to model salinity have also not been successful, though there is potential at the monthly resolution.

<u>Task 2 – Run the FATHOM MFL model with SICS/TIME input and compare to observed data</u> (Marshall, 2008b)

Task 2 was initiated when the MFL FATHOM model (47-basin configuration) was used with runoff input from TIME output. The TIME output that was used was the

FTLOADDS version 3.1 code and input files for run 157 were provided to ENP by USGS TIME developers. The input data to FATHOM was reviewed by Dr. Jack Cosby to ensure that the input parameters were being specified properly when TIME output is coupled to FATHOM. Runoff estimates were provided to the project team by ENP to produce salinity simulations throughout Florida Bay. The FATHOM salinity output using the TIME 157 runoff was compared to the salinity output from FATHOM generated by the MFL Base Case run. The FATHOM configuration used for this comparison was the original 47-basin model domain.

The TIME-based salinity simulations were compared to SERC and MMN observed data at a monthly resolution. When the TIME-based salinity simulations were compared to the observed data (both datasets) a number of discrepancies were noted. A comparison of the inflows showed that the TIME runoff estimates are lower than the observed values. Therefore, though this task was successful in that the output from the TIME model was coupled with the 47-basin configuration of FATHOM to produce reasonable salinity estimates, it was not successful in producing reasonable simulations from TIME output.

As an additional task, an updated bathymetry for a new 58-basin configuration of FATHOM was delivered by ENP to Dr. Cosby in early June 2007. The new bathymetry was processed to prepare the input files for FATHOM. The new bathymetry files were compared to the original bathymetry files in a detailed quality assurance check to assure that bathymetry of the unaltered basins was not affected. The new bathymetry files were then used in a simulation of the MFL base case for comparison with simulation of the same inputs using the 47 basin version of FATHOM.

The bathymetry for the new 58 basin configuration of FATHOM was installed using a hybrid approach (as in the SFWMD MFL study) and benchmark tests for the installation were completed. The benchmarks consist of a series of simulations for which the model has been run in the old 47 basin configuration and for which model outputs and diagnostics are known. When applied to the new basin configuration, the benchmarks assure that the installation of the additional basins did not inadvertently alter other aspects of the model structure.

The overall model performance in simulating salinity with 58 basins is degraded compared to the 47 basin simulation. In general, the model efficiencies are smaller for the SERC sites in the northeast bay (but are essentially unchanged in the rest of the bay).

This negative result is not unexpected. In changing one set of inputs, it is reasonable to expect that other inputs might need to be adjusted in turn. The SFWMD MFL run (to which these new simulations were compared) was the “best” of a number of runs performed as part of a sensitivity analysis in that project. Changing the basin configuration has shifted the relative sensitivity of other inputs to the model. To be rigorous, it will be necessary to repeat the sensitivity analysis to examine the new pattern of effects of all inputs. A recent

paper published by Nuttle et al (2007) suggests that evaporation should be increased by about 20% over that used in the SFWMD Florida Bay MFL FATHOM modeling activity.

The new basin configuration runs successfully and corrects (at least partially) the conceptual problem of the location of the flow inputs from Trout Creek. In general, the model efficiencies are smaller for the SERC sites in the northeast bay, but are essentially unchanged in the rest of the bay. To analyze this result, it will be necessary to repeat the sensitivity analysis to examine the new pattern of effects of all inputs. However, modification of the model in this manner is beyond the scope of this task. Another CESI project is currently being initiated to begin this process.

Task 3 – Complete the development of MLR salinity models at MMN stations not previously modeled (Marshall, 2008c)

The year one CESI project focused primarily on the development of models for Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight, North River, and Whipray Basin. The IOP exercise updated some of those models and added a new model for Long Sound, Duck Key, and Butternut Key. The second year CESI project added new MLR salinity models for Taylor River, Highway Creek, Little Blackwater Sound, and Bob Allen Key. Work for the Southern Estuaries Sub-team developed new models for Whitewater Bay East, Clearwater Pass, Shark River, and Gunboat Island.

For this task, new MLR salinity models were developed using the longest period of data available at the remaining physical monitoring stations in the ENP MMN. Most of these stations are within the influence of Shark River Slough or relatively more distant from the Everglades in the open water areas of Florida Bay. The MMN stations for new models are Broad River, Buoy Key, Broad River Lower, Cane Patch, Harney River, Johnson Key, Lane River, Lostmans River, Little Rabbit Key, Murray Key, Peterson Key, Tarpon Bay East, and Willy Willy.

The models presented herein for the ENP MMN stations, when added to the models previously prepared (Marshall, et al 2003a; 2004 and Marshall, 2003b; 2005), complete salinity model development for the MMN and provide a method of estimating salinity throughout all of the estuarine areas of Everglades National Park. While there are other salinity models available for salinity estimates in Florida Bay (FATHOM, EFDC, Nuttle's Four-box Model, SICS/TIME) the MLR salinity models developed by this study and the previous studies are the only salinity models available for Whitewater Bay, Shark River estuary, and upper west Gulf coast areas that are capable of producing a 36-year time series simulation. All of the MLR salinity models include the link to the upstream, freshwater hydrology of the Everglades through the stage independent variable, and include the important factors of sea surface level and wind variation.

The initial MLR salinity models that were previously developed were in water body areas of specific interest. When the first models were developed they were shown to be capable of reasonably estimating daily salinity such that alternatives for CERP projects could be evaluated through the use of the SFWMD 2X2 model. However, it was noticed in the early modeling that the models are sensitive to both local and regional conditions. The models presented herein provide additional evidence that the parameter selection process is capable of selecting independent variables that represent the relative effects of both local and regional conditions.

For the stations that are located in Whitewater Bay, the Shark River Slough estuary, and along the northernmost Gulf coast in ENP, the use of the daily average sea surface elevation from the Naples, Florida station (ID No. 8725110) instead of the data from the Key West station (ID No. 8724580) improved model fit by about 3-5%. For the Florida Bay stations along the western boundary with the Gulf, both Key West and Naples data were significant. However, the Naples data are predicted values prior to 1995, so Key West water level was used for model development purposes as in the past.

Additional details on model development can be found in Marshall, et al (2003a; 2004) and Marshall (2003b; 2005; 2008c). The daily salinity models that were developed for this task and the associated adjusted-$R^2$ value are shown below by sub-region. All independent variables in these models are significant at the 99.9% level, except for Cannon Bay (95% significance level).

Central Florida Bay

Buoy Key = 24.82836 – (1.13942 cplag4) + (0.23472 terbay) + (0.14891 terbaylag4), adj-$R^2$ = 0.79

Western Florida Bay

Murray Key = 50.44369 – (3.15719 p33) + (0.14449 terbaylag4), adj-$R^2$ = 0.51

Johnson Key = 53.13962 – (3.53830 p33) + (0.09932 ltmadlag4) + (0.07948terbaylag4) + (0.04843 vwndmia) + (0.55111 kwwatlev), adj-$R^2$ = 0.55

Little Rabbit Key = 51.31785 – (3.18926 p33lag1) + (0.19900 ltmadlag4) + (0.59864 kwwatlev), adj-$R^2$ = 0.46

Peterson Key = 39.76767 – (1.57570 p33lag4) + (0.25200 ltmadlag1) - (0.04663 uwndkwlag1) - (0.06325 vwndkw) + (0.08712 vwndmia), adj-$R^2$ = 0.56

Whitewater Bay

Lane River = 56.42862 – (1.46788 p35lag2) – (2.82488 p33)
- (4.71551 np206lag4) – (0.07508 uwndkwlag1) – (0.13990 vwndkwlag1)
- 0.05170 vwndmialag3), adj-$R^2$ = 0.77

Shark River Slough Estuary

Cane Patch = 7.86280 – (1.20972 np206lag4) + (0.23731 vwndmia),
adj-$R^2$ = 0.42

Tarpon East = 22.18537 – (1.02605 p33lag4) – (2.23641 np206lag4),
adj-$R^2$ = 0.57

Harney River = 51.09667 – (2.84042 p35lag4) – (6.12109 np206lag2)
– (0.22464 vwndkw) - (0.11811 vwndkwlag1) – (0.17356 uwndmia)
+ (2.45632 kwwatlevlag1), adj-$R^2$ = 0.72

Broad River = 20.82753 – (3.11717 np206lag4) - (0.05780 vwndkwlag1),
adj-$R^2$ = 0.53

Broad River Lower = 73.21431 – (4.82197 p35lag3) – (4.03692 p33)
- (4.15505 np206lag2) - (0.31452 vwndkw) – (0.22519 uwndmia)
+ (0.28467 uwndmialag2) + (0.10788 vwndmialag3)
+ (4.41540 kwwatlevlag2), adj-$R^2$ = 0.74

Upper West Coast

Willy Willy = 19.10483 – (2.23072 pa8lag2) – (2.23460 pa11lag2), adj-$R^2$ = 0.71

Lostmans = 43.18695 – (6.08870 pa8lag2) – (3.11218 pa11lag2)
– (0.14135 vwndkw) + (3.25077 kwwatlevlag1), adj-$R^2$ = 0.76

Cannon Bay = 38.12839 – (5.57603 pa8lag2) – (1.88696 pa11lag2),
adj-$R^2$ = 0.68

Watson Place = 41.54103 – (9.59506 pa8lag1) – (0.10461 uwndkw)
– (0.23667 vwndmia) adj-$R^2$ = 0.86 (Provisional model, limited data),

Task 4 – Assist ENP with implementation of the FATHOM model that was developed for the SFWMD MFL project (Marshall, 2008d)

The objective of this task was for the FATHOM consultant (Dr. B. J. Cosby) to meet with ENP to review and discuss the current use of FATHOM and to review up to five (5) FATHOM input files provided by ENP. The FATHOM consultant interpreted the output and provided the findings of the analysis in a report. Listed below are the notes from those meetings and the results of the discussions.

Sept 2006 Meetings.

- Met with ENP staff at SFNRC office in Homestead.
- Delivered FATHOM model and all MFL base simulation inputs.
- Conducted a 2-day workshop to instruct ENP staff in the implementation of the FATHOM model.
- Instructed ENP staff in the preparation of inputs for the FATHOM model so that the output of the SICS/TIME model could be used as an input to FATHOM.
- Instructed ENP staff in the post-processing of FATHOM output, particularly the comparison of simulated salinity to observed salinity.
- Collected MMN data from ENP staff to prepare spreadsheet for comparison of FATHOM salinity to MMN observations. (meeting also related to Task 2)

September 2006 through July 2007 Activities.

- Participated in phone calls and exchanges of model inputs and outputs through ftp sites to assist ENP staff in the implementation FATHOM with SICS/TIME outputs.
- Examined and debugged FATHOM outputs produced by ENP staff. Advised ENP staff on procedures for adapting the SICS/TIME output to FATHOM.
- Posted a spreadsheet to the ENP ftp site for comparison of FATHOM output to MMN observed data.

July 2007 Meetings.

- Met with ENP staff in Homestead to review the data and programs developed and exchanged over the preceding 10 months.
- Discuss the new 58 basin configuration of FATHOM. (meeting also related to Task 2)

FATHOM MFL model output was compared to MMN observed data as part of the exercise of assisting ENP with full implementation of the FATHOM MFL model. Simulated salinities from those runs were compared to observed salinity for the period 1991-2002 in the following plots. Two observed salinity datasets are used, the SERC dataset and the MMN dataset. Coordination and assistance in use of the post-processing routines from the software to produce the comparisons of simulated salinity to MMN data is one of the objectives of this task.

Comparisons are in the form of selected statistics of goodness-of-fit for all FATHOM basins for which observed data are available, and in the form of time series plots of simulated and observed salinities for selected basins. Full details of these statistics and plots for all pertinent basins are included in the spreadsheets delivered to ENP.

In general, there are few substantive differences when FATHOM MFL base case output is compared to either SERC or MMN data. The spatial coverage of the SERC data is broader than the spatial coverage of the MMN data set. The temporal coverage of the MMN data is broader then the temporal coverage of the SERC data because the MMN data are gathered more frequently than the SERC data, and the period of record is longer at most MMN stations.

From the statistics that were prepared it is noted that the values for efficiency for SERC and MMN data are similar but values of $R^2$ for SERC comparisons during the dry season are lower than MMN data. When the basins are grouped, the $R^2$ values for the MFL base case compared to the MMN data are lower than the comparisons to the SERC data. Exceptions to this are grouped basins C and D during the wet season.

The most significant accomplishment of this task was to assist ENP with implementing the FATHOM MFL software at South Florida Natural Resources Center. New spreadsheets were developed to analyze FATHOM results relative to ENP MMN data as well as SERC data.

<u>Task 5 – Investigate the coupling of pink shrimp models with MLR salinity models, and investigate other ecological models that may benefit from the use of MLR salinity simulations</u> (Marshall, 2008e)

A simulation model of growth and survival was developed by Browder et al. (2002) to predict the response of pink shrimp (*Farfantepenaeus duorarum*) to changing salinity and temperature. This model has been applied in Florida Bay and other south Florida estuaries (Browder et al. 2005). Response variables include: average growth rate, average survival rate, and potential harvest (which integrates both growth and survival). In addition, the model provides estimates of the number of individuals at 30-day intervals, relating directly to density, once scaled in the calibration.

The pink shrimp stimulation models for Whipray Basin and Johnson Key was calibrated using part of the data from Robblee (unpublished) 18-station data set for juvenile pink shrimp in Florida Bay and observed and simulated salinity data for western Florida Bay and north-central Florida Bay. This allowed comparison of observed pink shrimp density and density-related output from the pink shrimp model. The model was used with the predicted paleosalinity regimes for Whipray Basin and Johnson Key to predict pre-drainage shrimp densities for Johnson Key and Whipray basins.

The data requirements for the shrimp model and the mechanism for using the various salinity runs were determined through discussions with pink shrimp modelers. It was arranged that the PI would provide salinity time series data (daily) for four scenarios. The Whipray Basin simulations had previously been generated. However, the Johnson Key models were not developed until recently and processing was necessary to prepare the Johnson Key models for use.

The following data were sent to Joan Browder:

1. Whipray Basin observed salinity, April 6, 1989 - Dec 31, 2000.
2. Whipray Basin reconstructed salinity, January 1, 1965 – December 31, 2000
3. Whipray Basin paleo-based salinity, January 1, 1965 through December 31, 2000
4. Whipray Basin NSM 4.6.2-based salinity, January 1, 1965 – December 31, 2000
5. Johnson Key observed salinity, March 13, 1989 - Dec 31, 2000
6. Johnson Key reconstructed salinity, January 1, 1965 – December 31, 2000
7. Johnson Key paleosalinity salinity, January 1, 1965 through December 31, 2000
8. Johnson Key NSM 4.6.2 salinity, January 1, 1965 – December 31, 2000.

The data were sent by the Principal Investigator to Joan Browder (NOAA) and the pink shrimp model (Browder at al, 2002) was utilized for a number of preliminary runs, including the following:

1. Historical reconstruction salinity data (Marshall, 2007a),
2. Natural System Model-based (NSM 4.6.2) salinity from MLR model,
3. Paleo-based salinity from MLR model (Marshall, 2007b),
4. the average of reconstruction and NSM 4.6.2-based salinity (r+n/2), and
5. the average of NSM 4.6.2-based and paleo-based salinity (n+p/2).

These runs were intended to span the range of salinity values that were being examined at Whipray Basin and at Johnson Key.

Output produced by the pink shrimp model for Whipray Basin and Johnson Key include proportion of daily survival, average growth in mm/day, and potential harvest in tons kg/year. Although present and reconstructed salinity regimes in

the two basins differ, certain generalities apply to both basins regarding the simulated responses of pink shrimp to the various scenarios. Pink shrimp responses are lower (i.e., less favorable) under the paleo-based salinity scenario in the case of growth, survival, and potential harvests in Whipray Basin and in the case of survival and potential harvests in Johnson Key Basin. In contrast, growth rate was substantially higher for the paleo-based salinity regime compared to reconstitution salinity in Johnson Key Basin in these simulations. With the one exception, responses varied little among the reconstruction, NSM, and (r+n/2) scenarios. The (n+p/2) regime response was intermediate in responses between the paleo-based salinity regime and the other three scenarios.

Looking only at potential harvests which is an integrating parameter, in both Whipray Basin and Johnson Key the response to the paleo-based salinity scenario was higher than the response to the other scenarios in only two of the 36 years, 1971 and 1989, generally recognized as exceptionally “dry” years in the long-term south Florida rainfall records. The poorest responses were in the years 1966, 1968-1970, 1995-1997, and 1999, recognized as “wet” years in south Florida.

Differences in responses to the reconstruction, NSM, and (r+n)/2, were examined in more detail by calculating means and quartiles of the time series of responses. NSM had the highest mean growth rates and (r+n)/2 had the highest mean survival rates and potential harvests. The quartiles showed their most striking differences between paleo-based salinity regime and the other scenarios. Differences among scenario responses increased inversely with quartile, causing the minimum to show the largest differences among scenarios.

As another way of making comparisons, yearly differences between July-of-the-year responses were made. According to annual averages, both NSM and (r+n)/2 outperform the reconstruction by a small margin in simulated growth rate, survival rate, and potential harvests. Based on the number of years, both NSM and (r+n)/2 outperform the reconstruction in growth rate and potential harvests in both basins. In survival rate, (r+n)/2 outperforms the reconstruction in both basins, and the reconstruction outperforms NSM in both basins.

This task was a proof-of-concept exercise that focused on the coupling of statistical salinity model output with pink shrimp models. Therefore, the results consist of output from the shrimp model with limited interpretation.

<u>Task 6 - Coordinate with the IMC to incorporate the new MLR models in the recently developed post-processing tool</u> (Marshall, 2008f)

The objective of this task was to make the new models that were developed as a part of this CESI project (Task 3) available to the IMC for incorporation into the salinity simulation routine used by the Southern Estuaries Sub-team of RECOVER for evaluation of CERP alternatives. The new models that were

developed in Task 3 were transmitted to the IMC staff. The PI assisted the IMC with review of the final product. This task was a perfunctory task that was intended to help the agencies that rely on the MLR salinity models to analyze CERP alternatives as part of the performance measure evaluations. All models developed for Task No. 3 of this CESI project have been imported by the IMC.

Task 7 - Update the 2002 report by The Cadmus Group by incorporating the improvements in statistical modeling accomplished by CESI activities (Marshall, 2008g)

A report prepared for ENP by the Cadmus Group (Nuttle, 2002) described the current (at that time) status of model development for correlative and mechanistic models. Since then, improvements and updates have been incorporated into the modeling procedures, hence that status report on modeling tools was outdated. The PI coordinated with the author of the 2002 report (William K. Nuttle) to update this information, and compare MLR salinity models and mass balance models (ex. FATHOM). The 2002 report was updated at the beginning of this project to include recent advancements in salinity models. The report was updated again as one of the final tasks for inclusion in the final report to include additional advancements made during this project, and by others.

The two primary salinity data sets used for salinity modeling in Florida Bay are:

(1) the SERC/FIU long-term monthly grab sample data set, and
(2) the ENP marine monitoring data set with observations at 10 to 60 minute intervals.

Other hydrologic and climate data sets are used as they are needed for model development and for model input for simulations.

For this analysis, models were reviewed for which information was available on a broad basis in June 2006 for simulating and forecasting salinity in Florida Bay, Whitewater Bay, and the Gulf coast estuaries. For the salinity evaluations that have taken place thus far, there have been two general approaches to constructing such models. The first is empirical and relies on accurately describing observed salinity variations and correlative relationships. The second is mechanistic-based and relies on accurately accounting for the physical processes that drive changes in salinity. In both approaches the accuracy of the forecasts is limited by the data available to describe patterns of salinity variation and the driving processes.

Various statistical techniques can be employed in the empirical approach, the simplest being descriptive analysis. Both regression and time series modeling techniques have been applied to derive models for Florida Bay and Gulf coast salinity. Regression models exploit linear relationships in records of driving processes and systems response. Time series models utilize the serial

correlation that is present in many hydrologic parameters. The statistical models that have been developed thus far for Florida Bay and the Gulf coast estuaries are based on a coastal aquifer conceptual model and have been used successfully for evaluating water management alternatives and for performance measure development.

Mechanistic salinity models for south Florida estuaries include both mass-balance models and more complex hydrodynamic models. Mass balance models of salinity, in their discretized numerical form, are similar in form to autoregressive time series models. Mass balance models account for the inputs and outputs of water from basins delineated by geomorphologic features. Mass balance models have been used for ecological evaluations and for minimum flows and levels modeling.

Hydrodynamic models have been developed for both Everglades hydrology and the salinity in the downstream estuary. Hydrodynamic models are based on the solution of simultaneous differential equations of continuity and hydrodynamics (momentum) in one, two, or three dimensions, and can be used for both surface and groundwater applications. Hydrodynamic models have been used for modeling the freshwater portion of the Everglades / Florida Bay hydrologic system for about the past decade, and are in the process of being updated with better data and techniques. Only recently have hydrodynamic models been available that are capable of adequately simulating the salinity regime in south Florida Bay and the mangrove / salinity transition zone. Work is currently underway on the Florida Bay hydrodynamic models, while work on hydrodynamic models for the transition zone of the Gulf coast estuaries is still in preliminary stages.

The following salinity model evaluation factors from the Florida Bay Science Program (PMC, 2004) were utilized:

1. portability,
2. validity,
3. fidelity,
4. focus, and
5. ease of use.

Each of the models that were assigned a score according to how well they achieved the desired result of each modeling factor. The scale of scoring is from 1 = poor to 5 = excellent. For some models it was not possible to provide a score for a particular factor.

From this summary (Table 7-2) it can be seen that the most complex models are the least portable and are rated lowest for ease of use. With respect to validity, all models rated high because the models are well-documented. Models that simulated salinity were rated highest for focus because salinity performance

measures are the use for most of the salinity models. Finally, for model fidelity, daily MLR salinity models have the best performing error measures, followed by SICS / TIME, and monthly FATHOM MFL base case models.

Additionally, a comparison was made of observed salinity data and forecasts made by MLR and FATHOM salinity models by plotting the following data for Long Sound and Whipray Basin for the period April, 1994 through October 2002 (Figures 7-1 and 7-2):

1. MMN observations averaged to monthly,
2. SERC monthly grab sample observations,
3. FATHOM monthly average estimates from SFWMD MFL work, and
4. MLR daily estimates averaged to monthly values.

The MMN monthly average and SERC grab sample observations correspond well, with fewer deviations at Long Sound than at Whipray Basin. It is important to note that the sampling locations for these two programs in these water bodies are not the same. Both FATHOM and MLR salinity models simulate monthly average salinity in both basins well. The MLR models appear to perform slightly better for Long Sound compared to FATHOM, and noticeably better at Whipray Basin, though the difference in the simulations by the two modeling procedures is small. These plots indicate that both the MMN and SERC data sets can be used interchangeably at the monthly level. It also shows that both FATHOM and MLR salinity models are capable of providing reasonable estimates of salinity at these stations.

Task 8 - Develop a methodology for using SARIMA models to fill data gaps in salinity, stage, water temperature, and freshwater flow to Florida Bay (Marshall, 2008h)

Autoregressive, moving average (ARMA) models for stage, salinity, temperature, and flow were first evaluated for filling data gaps. ARIMA models were developed to take advantage of serial correlation, and particular the power of autocorrelation (correlation to the previous time-period value). The evaluation determined that the SAS© PROC ARIMA procedure is relatively inflexible meaning that utilization of multivariate methods provides a better overall process for filling data gaps compared to ARIMA models. After testing ARIMA models on stage and salinity and determining that the simulations were unreliable, further use of ARIMA models for temperature and flow was eliminated from the task.

Linear interpolation is another method of filling gaps that is common. Linear interpolation is generally considered to be acceptable if the gap is small (1-5 days), the day-to-day change is small, and there are no inflection point in the missing data. Larger gaps (in time) create a chance that an event of some kind may occur, which would change the rate of increase or decrease in a parameter (stage, salinity, temperature, flow) such that linear interpolation was no longer

accurate for filling gaps. Similar to ARMA modeling, no additional time was spent evaluating linear interpolation for filling gaps in hydrologic or physical data after evaluating stage and salinity.

Multivariate linear regression (MLR) models proved to be the most successful technique for simulating hydrologic and physical data when there are gaps in the observed data record. MLR models were constructed from same-type data that was available from neighboring stations. Determining the candidate stations that would work best as an independent variable in an MLR model was straight-forward, accomplished through the use of a correlation matrix and step-wise development of the regression model. For stage and flow, use of the intercept term produced the best model, while a model with no intercept was best for salinity and temperature. However, use of a no-intercept model is only appropriate under certain circumstances, when one is confident that the distribution of values for the observed data and the distribution of values for the gap-filling data are equivalent, and the means are equal, which is rarely if ever known.

In addition, stage, salinity, and flow benefited from the inclusion of wind in the model. However, the benefit of including wind terms in a temperature model was very small, perhaps because the level of correlation with neighbor stations was so high with temperature. In all cases where wind was a significant parameter in the MLR model, the wind parameters generally only explained on the order of 1-5% of the variability in the dependent variable.

The use of multiple independent variables generally increased the explanatory capability of the model compared to a univariate model by about 1-5% for stage, 3-5% for salinity, and 3-5% for flow. The $R^2$ value for univariate temperature models was over 0.86 so multivariate modeling was not needed. The $R^2$ value for MLR models ranged form a high of 0.99 for salinity (Long Sound) to 0.78 for stage (P33).

The conclusions of this effort to determine if time series models could be useful for filling gaps in time series data for stage, salinity, temperature, and flow are clear –ARIMA models are not very useful for this purpose. This in-depth analysis of ARIMA models brought to the surface the level to which this procedure relies on the availability of past values of the dependent variable, which are not available when the data gap exceeds one day for daily data. ARIMA models work reasonably well for gaps of 2-3 days particularly when the range of the data in the 2-3 day period is near the mean value for time series. However, the ability of ARIMA models to provide highly accurate one-step forward predictions using the serial correlation in the data means that ARIMA models should be considered for use as a predictive tool for water management system operation when the data are not missing.

Similarly, the obvious limitations of linear interpolation limit the use of this technique to small gaps. From the limited analyses done, it appears that gap-size limit for linear interpolation is about 5 days in duration for the 4 parameters of interest. Beyond a 5-day window, the chance that an event will occur that modifies the rate of change increases such that the use of linear interpolation may not be reliable.

Multivariate linear regression (MLR) models proved to be useful for filling data gaps in stage, salinity, and flow. Based on the limited sample of this evaluation MLR models appear to be able to explain about 85-95% of the variability in the stage, salinity, and flow data, and wind measured at Key West and Miami appears to be useful in modeling by explaining up to 5% additional variation over models that do not include wind. However, models that include wind tend to have a large number of independent variables even at the 0.999 level of significance, which may be the result of cross-correlation effects between independent variables.

In the case of temperature, the correlation of neighbor stations as independent variables to the dependent variables was so high that MLR models did not provide sufficient benefit to justify MLR use. Instead simple univariate linear regression models were more than adequate. The use of bottom measurements to model top measurements at the same station (and vice versa) provides an advantage over the use of neighbor data as an independent variable.

Based on this analysis the flexibility of MLR models was shown to be useful for filling data gaps. MLR models have the added advantage of being transparent and easy to understand by a wide audience. The use of neighbor independent variables and wind data in MLR models for filling data gaps is recommended when simple regression models are considered to be inadequate.

Task 9 - Estimate the Flow Regime Required to Meet the Florida Bay and Florida Keys Feasibility Study Salinity Performance Measures (Marshall, 2008i)

Linear regression techniques were used to develop models for flow at the S-12, S-18C, S-197, and S-175 structures as a function of observed stage at the statistically significant stations in the Everglades. These models are the same as the hydraulic rating curves used for weirs, gates and other flow control structures. These techniques were used to establish relationships between the primary and secondary stage (water level) variables in the various MLR models. Model goodness-of-fit statistics was computed and verification of all models was performed using observed data for comparison.

At least one salinity model was assigned to each FBFKFS zone in northeast Florida Bay, Zones 1, 2, 3, 5,and 14. For each of the zones, plots of the FBFKFS requirements were used with plots of the NSM salinity simulation made for the Southern Estuaries sub-team to establish a salinity regime at a particular

monitoring station that meets the performance measure requirements to the greatest extent possible. The NSM time series was adjusted by adding or subtracting an equal amount to each NSM value over the 36-year period 1965-2000. In this manner, the NSM simulation was only be used to simulate the day-to-day salinity variation, not the magnitude of the salinity estimate. A well-documented statistical procedure called inverse prediction (Neter et al 1990) was used with the salinity models to establish a stage regime at the primary regression model stations - Craighead Pond (CP), P33, and EVER7, using observed water level and the previously developed regression models for the secondary stations.

Then the flow regression models (hydraulic rating curves) developed previously were used to estimate the required flow regime at the S12, S18C, S197, and S-175 structures for the 36-year simulation period 1965 through 2000. This was done for each of the zones, Zones 1, 2, 3, 5, and 14.

This proof-of-concept exercise has shown that a suite of linear regression models and statistical techniques can be used to estimate the flow requirements at three locations in the Everglades hydrologic system for a particular salinity regime. In this case, the Florida Bay / Florida Keys Feasibility Study salinity targets were used with NSM 4.6.2 and MLR salinity models (Marshall 2004, 2005) to develop a FBFKFS daily salinity regime for eight locations in Florida Bay that were spread across several FBFKFS zones. Observed values of salinity and stage were regressed to produce salinity (independent variable) as a function of stage. Then the models were turned around to use stage as the independent variable. In this manner simulated time series were generate at CP and EVER7 from the FBFKFS salinity regimes. From CP and EVER7, flow at TSB and S18C are estimated using other regression models. An additional set of regression models produces stage at P33 from stage at CP, then P33 is used to estimate flow at S12T.

The daily simulated flow values can show large differences at times when compared to daily observed values, particularly at high flow values. However, the statistical power that comes from large data sets, such as the ones used in this study (about 2500 values used for model development and about 12,500 for FBFKFS runs) allows these simulations to be used best in a monthly average or daily average value mode. In this mode, with simulations made daily and then averaged to monthly mean or daily average value over the simulation period, the modeling procedure appears to work well. This means that the simulated daily values should be interpreted as long-term averages, over periods that have experienced a wide range of climatic conditions.

When the modeling procedure is used to simulate the flows required to meet various FBFKFS targets, the difference between the simulated FBFKFS target flows and observed flows is substantial. The TSB, S18C, and S12T observed average values were found to be about 50%, 80%, and 56%, respectively, of the

FBFKFS target flows. This reflects the findings of Smith, et al (1988) using fluorescent techniques with coral banding on a piece of coral from near Peterson Key. These authors found that flow to northeast Florida Bay was reduced about 56% from historical conditions.

Task 10 – Implement the ENP Version of the SICS/TIME Model for Use with the MLR and FATHOM Salinity Models (Marshall, 2008j)

This investigation makes use of two modeling systems (SICS and TIME) developed by the USGS for simulating the hydrology and hydraulics of the Everglades (Langevin et al 2004a). The output of these modeling systems includes water depth values that can be converted to stage and used with the MLR salinity models to simulate salinity in Florida Bay.

ENP obtained a copy of the SICS code in 2006 which was provided to the PI. The PI analyzed some examples of SICS output before the attention in the modeling effort turned to the further development and use of the TIME model. The PI was able to produce stage output from the SICS model using post-processing programs provided to ENP and the PI by the USGS. When the TIME model began to be used, the SICS post-processing tools were no longer applicable and the PI relied on ENP to provide post-processing files for input to the MLR salinity models.

A calibration / verification run from TIME (157 run) was made available to compare with observed data for stage. ENP provided stage output from the TIME 157 model run that has been corrected for model bias, relative to the NGVD29 datum. This adjusted TIME 157 run output (stage) was compared to the observed stage data, then used with MLR salinity models to produce salinity simulations, as present below.

The MLR salinity models used for simulating salinity using the adjusted TIME 157 run stage values for Joe Bay, Little Madeira Bay, and Terrapin Bay come from Marshall et al, 2004 and for Garfield Bight the models are from Marshall, 2005.

When the bias-adjusted TIME 157 stage data were used for the MLR salinity model input there are periods with missing data because the TIME data are post-processed for the surface water module, only (see discussion below). When the conditions become dry enough for the simulated water level to drop below the elevation of the monitoring station, the stage elevation is a groundwater output, which is not currently produced by the post-processing tools.

This task was the first task initiated for this part of the on-going CESI project, and the last to be finished. Mostly this was caused by the evolution of the SICS domain into the TIME domain, and the difficulty of the USGS in making the code revisions that were needed. However, it appears that the TIME model is now running dependably. Even so, stage output data are not provided by the post-processing tools when the simulated water levels dropped below the ground

surface elevation. The ground water stage output is produced by the groundwater model, SEAWAT while surface water stage is produced by the SWIFT2D model. Output is only available from the SWIFT2D model at the surface cells using the post-processing tools available at the time of the analysis. An integrated time series of stage is needed to be able to fully couple TIME and MLR salinity models.

When the TIME 157 stage data are compared to the observed stage the data are similar for both models during the wet season, but the dry season values show various levels of divergence. The greatest divergence of TIME 157 and observed dry season values is seen at NP62; the least divergence is seen at P33.

When both of these input data sets are used with wind and Key West water level data in the MLR salinity models, the comparison plots the salinity produced using the TIME 157 data and salinity produced using the observed data are similar. The exception may be Joe Bay, but there are many missing values for the dry season. EVER6 in the Joe Bay model input had many dry season missing values from the TIME output. All salinity simulations were affected by missing dry season data from TIME 157. Given the differences seen in the stage comparison plots, the similarity of the salinity simulations is somewhat surprising.

It is concluded that the TIME output may serve as input to MLR salinity models and the resulting salinity simulations are similar to salinity produced using the SFWMM output for similar modeling scenarios.

Task 11 - Develop historical reconstructions for the longest period possible for the MLR salinity models in northeast Florida Bay (Marshall, 2008k)

The SFWMD used the Taylor River MLR salinity model from a previous CESI project for their Florida Bay MFL work. As part of that work a historical salinity reconstruction was developed for the period 1970 through 2003. Salinity measurements have only been collected at the Taylor River site by ENP since 1988. The Taylor River MLR salinity model was used to extend the salinity time series back in time to 1970, which is when the C-111 Canal system came on line. To do so required using other MLR models to also extend certain input parameters.

Using the same methodology used by the PI at Taylor River for the SFWMD MFL activities, a historical salinity reconstruction was developed at MMN stations in northeast Florida Bay (Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight, Long Sound, Highway Creek, Little Blackwater Sound, Duck Key, Butternut Key, Whipray Basin, and Bob Allen Key). A spectral analysis was then performed using the historical reconstruction to determine if the dominate frequencies in the observed data also appeared in the modeled data.

The purpose of this task was to prepare time series of salinity that extended back in time until January 1, 1970 which is beyond the beginning of the period of record for the MMN stations. In some cases, for example Joe Bay, Little Madeira Bay, Long Sound, and Highway Creek, the period of record begins in 1988. By comparison, the Bob Allen Key period of record doesn't begin until 1997. The primary tool for filling in the gaps - internally in the continuously-monitored observed data but also in the period prior to the date of data collection - are multivariate linear regression models for salinity that have been used successfully to-date for CERP performance measure evaluations. For CERP use, the South Florida Water Management Model (2X2 Model) providing the stage inputs and observed data were utilized for wind and Key West water level input parameters.

The 2X2 Model data begin on January 1, 1965. The observed wind and Key West water level data used for the MLR salinity simulations begin on the same date. For this CESI task it was beyond the scope of work to obtain additional wind or Key West water level data prior to 1965. Therefore, the earliest point in time that the reconstructions can begin with this data set is January 1, 1965. For the Florida Bay Minimum Flows and Levels modeling (ECT, 2005) the historical reconstruction from 1965 to 1970 was not particularly useful since the construction of Tamiami Trail in the current configuration including the S-12 structures was completed in the 1960's and water levels for next decade reflect an area in transition. Initial operations of these facilities interrupted almost completely the flow of water into Shark River Slough. However, due to intervention by ENP, additional flows to the Park were augmented through operational activities beginning in about 1970. This limitation was also realized for the historical reconstructions using the FATHOM model in Florida Bay and for the MLR model for Taylor River for the Florida Bay Minimum Flows and Levels (ECT, 2005). For these reasons, the historical reconstructions in this task begin on January 1, 1970 and end on December 31, 2000.

For the historical reconstructions to be useful, there must be confidence that the simulations prior to the observed data represent a reasonable estimate of the salinity regime that occurred during the period of the reconstruction. Occurrence of extreme high and low salinity values can be used to test the responsiveness of the models. For four of the MMN stations (Joe Bay, Little Madeira Bay, Long Sound, and Highway Creek) there are good examples of both high and low extremes in the observed record. For example, during the drought year of 1989, salinity values were recoded over 50 psu (Joe Bay), 70 psu (Little Madeira Bay), and 40 psu (Long Sound and Highway Creek). As a comparison to a simulated situation, at Bob Allen Key monitoring began in September 1997, meaning that the salinity values of the Bob Allen Key reconstruction in 1989 were from the MLR model. The plots show that simulated salinity at Bob Allen Key exceeded 60 psu in 1989, and values above 60 psu in the Bob Allen Key reconstruction are only seen in the reconstruction 2 others years, 1971 and 1974. In fact, all of the reconstructions show an increase in salinity during this drought period of the

1970's, which means that the reconstructions are sensitive to dry period conditions.

At the other end of the salinity scale, lowest salinity values in the observed record of these 4 stations are seen in 1995 and the following years, though low salinity values at these stations during the observed record are much more common than high salinity values. At Bob Allen Key the simulated 1995 and 1996 salinity values are also low, as are the observed values in 1997 (when monitoring began) and in the ensuing years.

Comparisons of salinity reconstructions at the open-water stations with salinity at the near shore stations indicates that there are times when high salinity conditions develop at the near shore stations in the spring at the end of the dry season, but the salinity conditions at the open-water stations remain at average levels. However, for some years (1971, 1974, and 1989 through 1991) the highest salinity values in the reconstruction are seen at both near shore and open-water locations. It appears that the dry conditions must reach a certain level of severity (or perseverance) before the open-water stations begin to experience hypersaline conditions. In average years, the highest salinity value of the year is about 20 psu higher at Bob Allen Key compared to Long Sound. However for the years of the highest salinity values when hypersaline conditions were recorded or simulated at both locations, the difference in the highest salinity values of the year at these two stations is only about 10 psu.

Comparison of the spectral density plots for observed data and reconstructed data for the period prior to the observed period of record (POR) shows that the reconstructed time series have similar periodicities to the observed data, though some differences at some of the stations is noted as follows:

Because the number of values used to compute the spectral density function for the longer periods is limited to about 20 or less, the differences between the observed POR and the reconstruction (pre-) POR are not considered to be significant. The important information is the recurring seasonality in the observed data is being expressed in the simulated reconstructions.

In addition, it appears that the near shore stations are subject to relatively significant cyclic forcing that is not on the order of yearly, semi-annually, or quarterly intervals. The open-water stations do not show the same behavior in the spectral density function plots.

The near shore locations appear to be subject to hydrologic forcing that is more complicated than Little Madeira Bay, Whipray Basin, Duck Key, Butternut Key, and Bob Allen Key, as expressed in the number of secondary maxima seen in the spectral density function plots of the near shore stations at the more frequent periods (low values of period). In addition, at Whipray Basin, Duck Key, Butternut Key, and Bob Allen Key the value of the spectral density function does

not increase to a secondary maximum at higher periods, as is seen in the plots of the near shore stations, including Little Madeira Bay. In the case of Joe Bay, Terrapin Bay, Long Sound, Highway Creek, and Little Blackwater Sound, the value is still increasing significantly at 1000 days. For Little Madeira Bay and Garfield Bight the spectral density function value has leveled off at a relatively high value at 1000 days. At Whipray Basin, Duck Key, Butternut Key, and Bob Allen Key the spectral density function levels off at a lower value of period.

This analysis shows that the reconstructions comprised of observed data and simulations using MLR salinity models and other statistical relationships provide a reasonable estimate of the historical conditions since 1970. These historical reconstructions of salinity are intended for use with ecologic models such as available fish models (ENP and others), pink shrimp models, and seagrass models by other researchers.

Task 12 – Evaluate the feasibility of developing MLR salinity models for the mangrove lakes region north of Garfield Bight and Terrapin Bay (Marshall, 2008l)

Work is currently underway in the Florida Bay mangrove lakes region to study submerged aquatic vegetation as part of a CESI project. As part of this project physiochemical data are being acquired.

At the time of this evaluation, two reports had been filed to record project progress: Semi-annual Progress Report - October 18, 2006; and Annual Progress Report – March 23, 2007. Both of these reports were reviewed. Temperature and salinity data are presented for the period April/May 2006 – January/February 2007 for 8 stations in the region. These data were analyzed for use with the development of MLR salinity models to determine if there is the potential to link the salinity of this region to the hydrology that affects it, the freshwater marsh of the Everglades.

Equipment problems affected the collection of continuous salinity data at the beginning of the project. Continuous salinity data were made available from June 27, 2006 through August 28, 2007, approximately 13 months. To begin the analysis, simple statistics were computed for all three salinity modeling stations. Then the data from Seven Palms Lake, The Lungs, and West Lake were used to prepare correlation matrices using the salinity data, stage data from upstream locations in the Everglades freshwater marsh, wind vectors from the Long Key C-Man station, and water level elevation from the Long Key C-Man station. Using guidance in parameter selection from the information in the correlation matrix, preliminary MLR salinity models were developed using stepwise regression procedures to explore the potential for MLR salinity model development once additional data have been collected.

The highest Pearson correlation coefficient for correlation with salinity was P33 for all stations. However the correlation coefficient was positive for P33 and

West Lake, seemingly indicating that higher values of P33 stage were related to higher values of salinity in West Lake. Positive correlation coefficients are also seen for CP at both Seven Palms Lake and at West Lake. The correlation coefficients for CP at Seven Lakes Palms and West Lake show a medium level of correlation but they are opposite in sign. Comparison of the correlation matrices shows that the correlation coefficient values were similar to the unlagged values.

Preliminary models were developed for all three stations using the stepwise linear regression procedure. The significance level for including an independent variable in the model had to be set at 0.999 similar to other MLR salinity models to reduce the number of parameters in the model to a reasonable level. At the 0.950 significance level there were between 15 and 20 independent variables in the model. There is an additional benefit in setting the significance level at 0.999 – all independent variables in the final model are highly significant.

This was an initial exercise at preparing MLR models with this data. All parameters chosen by the SAS© stepwise procedure are reported. Though there is only limited data available at this time from this project, it appears that the salinity data being collected ultimately will be useful for salinity modeling. The mangrove and lakes area of the north central part of Florida Bay where the salinity measurements are being taken represents an area with few monitoring stations. If extended continuous monitoring shows the salinity range seen for the limited monitoring, then this is an important area for monitoring because (1) salinity is being measured across a large salinity range, (2) hypersalinity is being measured, and (3), salinity values are not dropping to 0 ppt. At these locations, restoration in the form of additional freshwater flows towards western and central Florida Bay will be most noticeable, as will lower flows (if that occurs) and increased salinity due to sea level rise. Since these stations do not go to zero they are useful for simulating changed conditions due to restoration or other alterations to freshwater flow and stage. If paleoecological investigations could be extended into this area, it may be useful for estimating the conditions before freshwater flow alterations around the turn of the 20$^{th}$ century.

The preliminary modeling activities suggest that the data from these three stations should be capable of producing reasonable MLR salinity models using stage, wind, and water level parameters. The models produced herein are preliminary models prepared for analysis only. These models illustrate important relationships and should NOT be used for predictive purposes without further analysis. However, this initial evaluation suggests that this further analysis will yield models with $R^2$ values in the 0.55 to 0.80 range.

Task 13 – Prepare and submit a manuscript for publication in a refereed journal (Marshall, 2008m)

Although the work performed over the past several years on developing the salinity models for the MLR network has produce several project reports and a number of presentations at conferences and seminars, a formal paper presenting the development work has not been submitted to a scientific journal and subjected to peer review. The purpose of this task is to produce a manuscript that is suitable for submittal and review by a refereed journal, such as Estuaries and Coasts, Water Resources Research, or ASCE Proceedings. The paper discusses the development of statistical models for the estimate of salinity, stage, and flow; and presents the models and findings for an estimate of flow needed for restoration purposes. Included in this task are site visits to each of the monitoring stations in the Everglades where water levels are being measured, and to the salinity monitoring stations that have not yet been visited.

The manuscript was reviewed by two reviewers. The most constructive criticism is contained in the additional comments of one of the reviewers, as follows:

"It needs much further work on the writing and format although I would encourage the author to pursue this avenue as I think there does exist in it a novel approach of the use of paleoecological data and the ability to link inferred values with modeled events."

On the first submittal, the manuscript was not recommended by the Editor for publishing in *Estuaries and Coasts*. The primary reason for this recommendation was the lack of information on the paleoecological activities that lead to the development of the paleosalinity regime by others. As a result of this Lynn Wingard of the USGS and Patrick Pitts of the USFWS became co-authors and the paper has been re-written.

At the time of publication of this final report, the revised manuscript has been through several re-writes, and has been formally reviewed by Tom Cronin and Debra Willard of the USGS Reston office. It was re-submitted for publication by *Estuaries and Coasts at* the end of June, 2008.

**T**ask 14 – Prepare draft and final reports.

Draft task reports were prepared by CLF for review by ENP. Comments on the draft reports were received and discussed with the COTR. Revisions were then made to finalize the final task report. Each task report has been provided as an appendix.

The information in the task reports was summarized in this draft project report, and interpreted. Once comments have been received, a final project report will be submitted.

Task 15 - Attend and conduct meetings

The Principal Investigator scheduled, attended, and conducted on-site meetings on a roughly bi-monthly basis Off-month telephone discussions were held to discuss progress, needs, schedule and other project items. Other telephone and electronic communications took place as-needed between the scheduled meetings.

Nine project meetings were held at the ENP office in Homestead. Summary meeting notes for each meeting were prepared and are provided in an appendix.

Bi-annual and annual progress reports were prepared and presented that were comprised of excerpts from the task reports completed to-date, as well as information on tasks that were still underway and had not yet reached the point of preparing a task report. The final project report represents the final bi-annual and annual progress report.

## III. Discussion of Overall Project Findings

Salinity is a fundamental and key characteristic of the physical conditions of estuarine and coastal ecosystems. Salinity affects water quality, the make-up and spatial distribution of vegetative communities, and the life history of most animal species in these ecosystems. Simulations and forecasts of salinity are an important tool in the assessment of ecological resources in the Everglades, Florida Bay, and the estuaries on the Gulf of Mexico (CROGEE 2002). Water managers use forecasts to evaluate the expected benefits and impacts of ecosystem restoration activities. Ecosystem restoration involves aspects of adaptive management (NRC 2004), uncertainty analysis (CERP 2002), and risk assessment (Thom et al. 2004), and these all rely on the application of predictive tools such as statistical models.

The Everglades / Florida Bay hydrologic system is unique because of the vast area of freshwater marshes underlain by porous substrate that stores runoff before it enters the estuarine zone, as well as the spatial extent of estuarine conditions in Florida Bay. Standard riverine hydraulic models can not account accurately for the spatial and temporal variation in stored water and dispersed flows in the Everglades. Instead freshwater hydrology and wetland basin models have been developed that simulate the south Florida hydrology required for use with statistical salinity models. For the MLR salinity models, the hydrology of the Everglades is described by the stage levels that are used as model input with wind and sea surface elevation conditions for salinity simulating and forecasting.

This project has been a continuation of statistical salinity model development and application. The findings of the tasks that were completed, summarized above, are discussed further below.

There were several project tasks related to the further refinement and upgrading of the MLR salinity model development methodology, and to the development of additional models at MMN stations that were not previously included in the analysis. These similar tasks included Task 1 (evaluation of evaporation surrogates), Task 3 (development of new models), Task 6 (IMC coordination for new models), and Task 12 (evaluation of data from the mangrove lakes).

The evaluation of evaporation surrogates was developed as a task to determine if there were indirect measures of evaporation that could be used to improve the MLR salinity models. Evaporation had not been included in the models because there are few measurements of observed evaporation, much less a time series of daily values for 31- or 36-years. The only method for computing evaporation that accommodated the need for this long-term simulation through the use of data that were available was the SFWMD Simple Method, which is used for the SFWMM. While the method produced what seemed to be reasonable estimates of daily evaporation, demonstration of coherence with observed data could not be shown. Even so, when evaporation estimates from the Simple Method were

used for model development, little improvement of the fit of the MLR salinity models to observed data was seen. Correlation analysis showed that the evaporation estimates were correlated with other independent variables, which likely means that the parameters that were selected by the stepwise process were already expressing the effects of evaporation. For example, both stage and sea surface elevation record the reduction of water level due to evaporation. It was concluded that there were no substantial reasons to force the inclusion of evaporation in the MLR salinity models if simulative ability of the model is not improve. Based on this, the existing MLR models remained unchanged and the new models described below will not include evaporation as an independent variable.

Building on the success of the MLR models in the previous CESI projects, an additional fifteen MLR salinity models were developed, thereby completing the development of MLR salinity models for the MMN stations. Because of the work completed on this project there are currently daily MLR salinity models for the following regions of south Florida:

- Florida Bay and the upstream mangrove areas,
- Whitewater Bay area,
- Shark River estuary,
- the upper Gulf coast in the Ten Thousand Islands area, and
- Barnes Sound / Manatee Bay.

Inferences can now be made about the models based on the model development process and the resulting MLR salinity models.

All of the MLR salinity models for the MMN stations along the western open-water boundary of Florida Bay included P33, either un-lagged or with a 4-day lag, as well as salinity in the near-shore embayments of Little Madeira Bay and Terrapin Bay. The importance of P33 provides evidence of the link between the Shark River discharge and the western boundary stations as has been theorized by researchers who have examined circulation patterns in this area. All of the Shark River estuary salinity models included NP206, lagged.

Previous salinity model development efforts in Florida Bay showed that P33 and Craighead Pond (CP) were the primary stage stations in explaining the salinity variation. The additional Shark River estuary models indicate that NP206 is the primary station for explaining salinity variation at the MMN stations in the Shark River estuary. It is important to note that the selection criteria for inclusion of a parameter in the model was very high, 0.999, meaning that the consistent selection of independent variables as the most significant in explaining salinity variability provides additional evidence that certain stations are primary.

Wind vectors and sea surface elevation were important at a secondary level in explaining salinity variability at almost all stations. Each of these patterns shows

that the MLR salinity models are reflecting the important driving forces for salinity in a way that seems to make physical hydrologic and hydraulic sense.

The error statistics generated for the new salinity models indicate that, in general, the $R^2$ value for the new models is between 0.50 and 0.75 and the root mean square (RMS) value for all models is between 2-3 psu, with higher values for some of the models that are driven by the stage in Big Cypress National Preserve. These models perform as well and better than other salinity models that have been previously developed from ENP Marine Monitoring Network salinity data.

The development of these additional MLR salinity models for the remaining stations in the MMN means that salinity models are now available for all of the estuarine areas within ENP. This means that CERP alternatives can now be examined for their effect in all of the estuaries, providing a complete picture of the potential for restoration. In a general manner the development of all MMN models have shown that there is a definitive link between the upstream hydrologic conditions in the freshwater marshes of the Greater Everglades and the estuaries into which the freshwater is being discharged, be it north or east of Cape Sable. This also means that the restoration of the estuarine areas within Everglades National Park can only happen with the restoration of freshwater levels and volumes in the Greater Everglades.

The use of MLR models was also investigated by evaluating the data being gathered for a CESI project in the mangrove lakes area near Garfield Bight. Though the data are limited at this time due to operational difficulties, these data show promise for use in an area that may be important in recording restoration due to the variability of the salinity that extends over the full range of 0 – 35+ psu.

Applications involving the MLR salinity models comprised the majority of the remaining tasks. Historical reconstructions (daily estimates) of salinity were developed for eleven MMN stations using the MLR salinity models for the period 1965-2000. A small number of stage monitoring stations have a period of record that extends back in time beyond about 1985, including P33. Univariate (simple) linear regression models for stage at a location in the Everglades with very good fit to observed data are possible due to the cross-correlation that exists between stage measurements. Therefore, the stage input data were extended through the use of simple regression models. Wind and sea surface elevation (observed) are available for the entire period and were also used for the historical reconstructions.

All of the reconstructions were consistent in expressing the higher salinity conditions that existed during the extended drought periods of the early 1970s and 1980s. Spectral analysis of the reconstructions showed that there may be some minor errors in the historical reconstructions, but there are generally too few observations to determine any aberrant patterns. The historical

reconstructions will have the most value as input to ecological models as will be demonstrated further in this discussion.

Another application of MLR salinity models and other statistical models that was accomplished for this project was the use of historical reconstruction and paleo-based salinity time series data as input to the pink shrimp growth dynamics model developed by Browder et al (2002). This task was a proof-of-concept exercise that focused on the coupling of statistical salinity model output with pink shrimp models. The results consisted of output from the shrimp model with limited interpretation.

Another application of MLR models was the use of univariate and MLR models to fill gaps in stage, salinity, tidal creek flows, and water temperature data when it was determined that SARIMA models were only useful for gaps of one to about three values. The conclusions of this effort to determine if Autoregressive Moving Average (ARIMA) models could be useful for filling gaps in time series data for stage, salinity, temperature, and flow are clear: ARIMA models are not very useful for this purpose. This in-depth analysis of ARIMA models brought to the surface the level to which this procedure relies on the availability of past values of the dependent variable, which are not available when the data gap exceeds one day for daily data. ARIMA models work reasonably well for gaps of 2-3 days particularly when the range of the data in the 2-3 day period is near the mean value for time series. However, the ability of ARIMA models to provide highly accurate one-step forward predictions using the serial correlation in the data means that ARIMA models should be considered for use as a predictive tool for water management system operation when the data are not missing.

Similarly, the obvious limitations of linear interpolation limit the use of this technique to gaps that are less than 5 days in duration for the 4 parameters of interest. Beyond a 5-day window, the chance that an event will occur that modifies the rate of change increases such that the use of linear interpolation may not be reliable.

Multivariate linear regression (MLR) models proved to be useful for filling data gaps in stage, salinity, and flow. Based on the limited sample of this evaluation MLR models appear to be able to explain 85-95% (sometimes more) of the variability in the stage, salinity, and flow data, and wind appears to be useful in modeling by explaining up to 5% additional variation over models that do not include wind. However, models that include wind tend to have a large number of independent variables even at the 0.999 level of significance.

In the case of temperature, the correlation of neighbor stations as independent variables to the dependent variables was so high that MLR models did not provide any benefit. Instead simple univariate linear regression models were highly adequate. The use of bottom measurements to model top measurements

at the same station (and vice versa) provides an advantage over the use of neighbor data as an independent variable.

Based on this analysis the flexibility of MLR models was shown to be useful for filling data gaps. MLR models have the added advantage of being transparent and easy to understand by a wide audience. The use of neighbor independent variables and wind data in MLR models for filling data gaps is recommended when simple regression models are considered to be inadequate.

Another model application was the use of statistical models (both univariate and MLR) to estimate the flow needed to meet the performance measures for the Florida Bay and Florida Keys Feasibility Study. It was concluded that the procedure using a suite of univariate linear regression models can be successfully used to simulate long-term average flow conditions (monthly mean and annual average). The procedure takes advantage of the statistical power in a large number of observations with which to develop models and a large number of input values for simulations.

According to this analysis, the current flows through the S-18C and S-12T structures and TSB are well below the flows needed to meet the FBFKFS salinity targets. However, the flows currently delivered to the S-18C structure are closer to the target than the flows needed at S-12T and TSB, because of the water management operations at these structures.

Both MLR salinity models and the FATHOM mass-balance model were coupled with the output from the SICS / TIME model being developed by the USGS showing that these models can be coupled, though not directly at this time. The use of modeled input data for salinity simulations by mechanistic models is necessary because the standard period for evaluations of water management alternatives spans a 36-year period, and observed data for some model inputs are not fully available. The use of a 36-year period for south Florida simulations is warranted by the significant difference in wet and dry periods over years to decades, and the ecological implications of anthropogenic alterations that may only be expressed over longer periods of change in the salinity regime.

When the status of the current salinity models for Florida Bay were evaluated, it was found that considerable progress had been made in the development and refinement of salinity models since the report in 2002 by the Cadmus Group (Nuttle, 2002). To-date, the most widely used models for developing historical recreations and simulating salinity regimes for the evaluations of water management alternatives and ecological modeling are the MLR salinity models and the FATHOM mass balance model. Mass balance and MLR salinity models have already been applied in a number of ways and are still being refined. However, the development of hydrodynamic models, particularly the USGS TIME and the EFDC Florida Bay model by SFWMD, is continuing.

By design hydrodynamic models are intended for detailed and spatially discrete applications because of the effort and cost to calibrate, validate, and run large-scale hydrodynamic models for regional scenarios. Statistical and mass balance models will likely remain in use for planning-level decisions on a regional basis. Where possible, it appears that it will be less-expensive and time-consuming to utilize both statistical and mass balance models together as multiple lines of evidence and corroboration compared to utilizing only one hydrodynamic model for regional evaluations.

A comparison of observed salinity data and forecasts made by MLR and FATHOM salinity models by plotting the data for Long Sound and Whipray Basin. This comparison showed that both FATHOM and MLR salinity models are capable of providing reasonable estimates of salinity in Florida Bay. Additionally it was shown that ENP MMN and SERC (FIU) data sets can be used interchangeably at the monthly level.

Based on this review of the current status (June, 2006) of the models available for simulating and forecasting salinity in Florida Bay, Whitewater Bay, and the Gulf coast estuaries, it is found that MLR salinity models, FATHOM, and the SICS / TIME models appear to be providing the most reasonable estimates of salinity at the time of this report, with corroborating results for salinity variation at the limited locations that were evaluated. In addition, these three models, and the EFDC model if model fidelity can be improved, meet most of the salinity modeling goals of the PMC (2004).

Task 13 produced a manuscript that was submitted to *Estuaries and Coasts* and peer reviewed. The paper discussed the development of statistical models for the estimate of paleoecology-based salinity, stage, and flow. The paper presented the models and findings. The manuscript was reviewed by two reviewers, but revision were requested. Both reviewers considered the lack of information on the paleoecological data as a flaw, even though both reviewers commented favorably on the use of paleo-data and modeling as a novel approach worth pursuing further. Because of this the PI collaborated further with a paleoecologist and an estuarine ecologist to provide the background that the reviewers consider necessary. As of the date of this report, a revised manuscript has been submitted to *Estuaries and Coasts*.

When all of the tasks of this project are considered as a whole it is clear that most tasks worked well. The accomplishments of the tasks that worked well are summarized briefly below:

- The evaluation of the use of evaporation surrogates showed that evaporation was an important factor is explaining the variation in salinity within Florida Bay when the correlation between evaporation surrogates and salinity was considered. However, of all of the components of the water budget of Florida Bay, evaporation is the most difficult to directly

measure and is most frequently utilized in some sort of derived manner from other more easily quantified parameters. It was recommended that evaporation surrogates not be included in MLR salinity model development as the new models are being developed.

- The FATHOM mass-balance model was upgraded to include additional basins so that the total number of basins or “cells” is now 58.
- With respect to the development of new models, the work that was done completed the job of salinity model development at all MMN stations.
- All of the MMN MLR salinity models have been coded by the IMC and are available for CERP and any other applications.
- The FATHOM model developer met with ENP staff to insure that the model inputs were being applied appropriately. This assistance validated the model use and allowed ENP staff to have confidence in the predictions.
- The MLR salinity models were successfully coupled with pink shrimp growth and survival models in a proof-of-concept exercise. The interpretation of the output from the ecological model is on-going.
- The status of salinity modeling evaluation provided valuable information to ENP staff on the level of development of salinity models. The best models according to the model error statistics were the MLR salinity models, the Florida Bay Four Box model, FATHOM, SICS/TIME, and EFDC.
- The flow estimate procedure that was developed for the purpose of estimating the flow needed to meet the performance measures of the Florida Bay and Florida Keys Feasibility Study may be the task that has, to date, been the most successful. An application of the developed procedures followed as the Southern Estuaries Sub-team realized the commissioned the PI to develop a paleo-based salinity regime estimate.
- The historical reconstruction procedure was developed to extend the observed data to include the full period of the evaluations being made for CERP, 1965 – 2000.
- The mangrove lake salinity study showed that this area of highly variable salinity may be important in providing information on restoration alternatives because of the large range in salinity at the three stations that are being monitored.
- Though it required an extended effort, a revised journal manuscript has been submitted for the paleoecological adaptation of the flow estimation scheme. This was accomplished through additional collaboration between others involved in the analysis and has been submitted to *Estuaries and Coasts*.

While most tasks worked very well there was one task that was only partially successful, subject to being improved with some additional work that was beyond the scope of this project. Task 8 evaluated the use of seasonal autoregressive moving average models (SARIMA) to fill in gaps in observed data. It was found that autocorrelation (serial correlation) is prevalent in south Florida hydrologic and climatologic data. However, it is difficult to incorporate it into models that are

capable of hindcasting as is needed for south Florida restoration evaluations. Even so, the utility of multivariate linear regression models to fill in gaps (as was seen for historical reconstructions, task 12) was shown as MLR models were capable of providing reasonable estimates of salinity, stage, temperature, and (to a lesser extent) flow.

## IV. Recommendations

Because this was a research project, follow-on projects and tasks beyond the current scope of work were identified as some of the tasks evolved. This follow-on work is discussed briefly below.

- Additional historical reconstructions

The historical reconstructions provide temporal evidence of past hydrologic conditions, both natural and anthropogenic. The use of historical reconstructions was shown through the Florida Bay MFL modeling work for the SFWMD (Hunt et al, 2005). The spatial extent of this evidence can be extended through the development of additional MLR salinity model reconstructions at the other MMN stations that were not a part of this project. The historical reconstructions are needed by the ecological modelers because some of the evidence of past ecological conditions comes from synoptic studies and anecdotal data that are infrequent. The historical reconstructions provide a way to bring those data into the analysis. Additionally, a body of data collected by Roblee (unpublished) on salinity from synoptic studies and anecdotal data would become useful with additional spatial coverage for historical salinity reconstructions.

- Work with other paleoecologists to verify the paleo-based salinity regime

The next CESI project (currently underway) includes work with Evelyn Gaiser of FIU. That task should be expanded to include the 3 additional stations USGS sediment cores that are being interpreted by Lynn Wingard of the USGS, because that paleoecological data can be used with ENP Marine Monitoring Network salinity data stations nearby –. Bob Allen Key holds the most promise.

The concept for the additional work is to develop the new regression relationships between Bob Allen Key, Little Madeira Bay, and Little Rabbit Key salinity and the primary upstream stations (primarily CP and P33), then use the transfer functions that have already been developed to estimate flow into Shark River Slough and Taylor Slough, stage at other stations in the Everglades (for hydroperiod calculations), and salinity in Florida Bay, all as was done previously.

The tasks involved are generally: (1) development of the salinity regime using the paleo data including coordination with Wingard and Pitts; (2) development of regression models for application of the paleo-salinity data to estimate upstream stage for a given salinity; (3) application of the existing models to estimate flow, hydroperiod, and salinity; and (4) interpretation of the results.

Then the results from all of the Florida Bay paleoecological analyses - Whipray Basin, Bob Allen Key, Little Madeira Bay, Little Rabbit Key, and Gaiser's work – should be combined into a manuscript with multiple authors. It will have a broadened spatial basis in paleoecology and a good description of the

interpretation of the paleoecological work that went into the establishment of the basis for the paleosalinity regime(s) that will be developed.

- Prepare manuscript for the MLR salinity models

There are now MLR salinity models for all stations in Florida Bay, Whitewater Bay, Shark River estuary, upper western Gulf coast (Big Cypress Preserve area), and Barnes Sound / Manatee Bay. The limited number of MLR salinity models that were available proved valuable in CERP alternative evaluations and for other analyses. However, the MLR salinity models have not been peer reviewed nor are they all readily available in one source for use by other researchers. At the present, given the lack of success in developing a comprehensive hydrodynamic model of Florida Bay, the MLR salinity models and FATHOM are the best tools available for salinity in the study area. It would be a relatively straight-forward task to document the MLR salinity model development procedure in a manuscript that would be well suited for process-oriented journals.

- Continue work with pink shrimp model

The output of the pink shrimp model coupled with observed salinity data, NSM 4.6.2, and paleo-based salinity was thought-provoking and needs further interpretation, which requires coordination with the shrimp modelers. It is recommended that the PI continue working with the shrimp modelers, perhaps to expand the spatial extent of the simulations using other MLR salinity models. If the paleoecological studies can be broadened as recommended above, the confidence in the paleo-based salinity regime being used with any ecological modeler will improve.

- Utilize the MLR salinity models with other ecological models

The historical reconstructions of salinity and the paleo-based salinity simulations can be used for freshwater fishes and other aquatic fauna and wading bird ecological models and Habitat Suitability Indices (HSI). The daily time step and the long period of the simulations (36 year) will allow the uncertainty in the historical simulations to be accurately characterized. The historical simulations can be analyzed by comparing the simulated conditions for wet, dry and normal rainfall years.

The models that have been produced by this and previous CESI studies provide: (1) a historical simulation of salinity and hydrology over the past 30-40 years, and (2) pre-drainage salinity and hydrology at key locations in Florida Bay and the Everglades. The developed salinity and hydrologic regimes can be coupled with ecological models and HSIs to improve and upgrade the indicators being used for evaluation and assessment performance measures. Assistance to and coordination with the researchers who have developed the ecological models and the developers of the indicators and performance measures should be part

of this effort to ensure that the simulation data are appropriately applied, and to assist with the interpretation of the results. The output of the coupling of the historical reconstruction of salinity and hydrology and the ecological models can be compared to observed conditions to provide a more complete baseline and to verify ecological models.

- Utilize TIME stage output with MLR salinity models and FATHOM

At this point, it appears that TIME is ready for use. However the post-processing tools to utilize the output are not fully developed. When this data becomes available it can be coupled with the MLR salinity models to provide a better tool for analysis of CERP alternatives and for other restoration studies.

- Continue working with mangrove lakes researchers

The limited work that was done with the mangrove lake data (because the project has just begun) shows much promise for these stations. This area is an important transition zone between fresh and salt water and may provide the most information for assessment of restoration projects based on the wide range of salinities that were observed.

## V. References

Includes all references used for this project. See task reports in the appendices for references related to a specific task.


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