FINAL TASK REPORT

TASK 7 - SIMULATING AND FORECASTING SALINITY IN FLORIDA BAY: A REVIEW OF MODELS

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Simulating and Forecasting Salinity in Florida Bay: A Review of Models

EXECUTIVE SUMMARY

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 models.

This report reviews models for which information is currently available on a broad basis (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.

A summary table presenting general model information and a summary evaluation table is included with this Executive Summary. In the evaluation table the Florida Bay Science Program model evaluation factors have been used and a score of 1 to 5 has been assigned to each model for each factor, with 1 being poor and 5 being excellent in application.

Summary of Salinity Models and Supporting Hydrologic Models Currently in Use For Simulating Florida Bay and Southwest Gulf Coast Salinity (Table 6 in report).

Model Name	Model Type	Simulated Parameters	Spatial Domain	Grid Size	Simulation temporal domain
SFWMM[1]	Freshwater Hydrology	Stage, Flow	Everglades	3.2km X 3.2km	1965-2000, daily
PHAST[2]	Wetland Basin	Flow	Lower Everglades and Mangrove Zone	regional	1965-2000, monthly
MLR[3]	Statistical	Salinity	Florida Bay, Whitewater Bay, southwest Gulf coast, Manatee Bay, Barnes Sound	N/A	1965-2000, daily
Four Box[4]	Mass Balance	Salinity	Florida Bay	regional	1993-1998, monthly
FATHOM[5]	Mass Balance	Salinity	Florida Bay, Manatee Bay, Barnes Sound	open-water basins	1965-2000, monthly
EFDC[6]	3-D Hydrodynamic	Salinity	Florida Bay, Whitewater Bay, southwest Gulf coast, Manatee Bay, Barnes Sound	variable	1965-2000, daily
SICS/TIME[7]	2D/3D Coupled surface and groundwater	Stage, Flow, Salinity	Florida Bay (SICS), southwest Gulf coast (TIME)	0.3km X 0.3km (SICS, 0.5km X 0.5km (TIME)	1996-2000, daily
SoFLA-HYCOM[8]	3-D Hydrodynamic ocean circulation model	Flow magnitude and direction	Gulf of Mexico, Florida Straits	6-7km X 6-7km	?

[1] http://www.sfwmd.gov/org/pld/hsm/models/sfwmm/index.html
[2] Nuttle and Teed 2002, Nuttle 2004
[3] Marshall, 2005
[4] Nuttle et al. (2000)
[5] Cosby et al. 1999, Nuttle et al. 2000, Cosby et al 2004
[6] Hamrick and Moustafa, 2003
[7] Swain, et al 2004 (SICS), Langevin, et al 2002 (TIME)
[8] Kourafalou, 2005

Summary evaluation of Florida Bay salinity and hydrology models using the Florida Bay Science Program evaluation factors (PMC 2000). Models with asterisk (*) are freshwater hydrology only models. Score is from 1=lowest to 5=highest (Table 7 in report).

Model	Portability	Validity	Fidelity	Focus	Ease of Use
SFWMM*	2	5	3	4	3
PHAST*	3	4	3	3	5
MLR	5	5	5	5	5
Four Box*	3	4	4	3	5
FATHOM	3	5	4	5	4
EFDC	2	5	3	5	3
SICS/TIME	2	5	4	5	3
SoFLA-HYCOM	2	3	?	3	3

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1 INTRODUCTION

1.1 General

Ecological forecast models play an essential role in efforts to restore and preserve natural resources. This role is analogous to the role that hydrologic forecast models have played in the management of water resources for human benefit (Lettenmaier and Wood 1993). 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 models. In south Florida, the Everglades and estuarine ecosystems in Everglades National Park have been altered by water supply and flood protection for agricultural and urban activities (CROGEE 2002). The restoration effort for these ecosystems is currently centered on the activities of the Comprehensive Everglades Restoration Plan (CERP).

For CERP, ecologists and water managers use salinity forecasts as one tool to evaluate the expected benefits and impact of restoration activities. These benefits and impacts to coastal ecosystems are reflected in potential future changes in wetland communities, estuarine water quality, and coastal fisheries that are expected for water management activities and for alternative management scenarios. Forecasts provide managers with quantitative information needed for evaluation of alternative actions under consideration and to choose the course of action that best meets objectives.

The study area for this review of models includes the freshwater marshes and mangrove eco-tone areas of the Everglades, the estuarine and near-marine basins of Florida Bay, the estuarine areas of Whitewater Bay, and the estuaries the discharge into the southeastern-most portion of the Gulf off Mexico (Gulf coast). The hydrologic features in the upstream Everglades that are important to salinity modeling include Shark River Slough, Taylor Slough, and the C-111 Canal system.

The ability to forecast how Everglades restoration will affect the ecology of Florida Bay, Whitewater Bay, and the Gulf coast of south Florida depends on first being able to forecast how changes in regional water management alter the bay's salinity. Changes in salinity reflect changes in the amount or timing of the net supply of freshwater to an estuary, i.e. the sum of rainfall plus inflow minus evaporation, hydrodynamics and mixing, and exchange with the ocean. Salinity is a key characteristic of physical conditions (including water quality) in estuarine and coastal ecosystems; it affects the composition and spatial distribution of vegetative communities and life history of most animal species. Because salt is a conservative tracer, changes in salinity signal possible changes in the concentrations of other substances, such as nutrients and contaminants that enter estuarine and coastal waters through the inflow of freshwater or mixing with the coastal ocean.

This report reviews models for which information was currently available (June 2006) for forecasting salinity in Florida Bay. This constitutes part of the work being performed by the Cetacean Logic Foundation, Inc. for Everglades National Park (ENP) with support from the Critical Ecosystem Science Initiative (CESI) program. The purpose of this study is to update information in a similar report compiled for Everglades National Park by The Cadmus Group (Nuttle 2002). The present work expands the coverage of the earlier report by incorporating the recent improvements in hydrology and salinity modeling including statistical, mass balance, and hydrodynamic models.

1.2 Background

In general, the formulation and application of forecasting models serve three roles. First, the formulation and development of predictive models helps to confirm a common understanding of the system and its behavior in response to changes in driving processes.   Second, the predictive model functions as one of the primary mechanisms for investigating possible future structure and behavior of the system that can may result from proposed restoration activities. Finally, predictive models are used to understand uncertainties about the present and future state of the system and the variation in driving processes, and translate these into corresponding uncertainties of meeting restoration goals.

Forecasting ability increases with improved scientific understanding through the synthesis of research results. Therefore, formulation and refinement of predictive models serves an essential function in the development of knowledge through research and in the application of that knowledge toward the practical goals of ecosystem restoration. This is the motivation for building predictive salinity models for the southern Everglades and Florida Bay region.

Recurrent patterns in the data, such as the annual cycle of wet and dry seasons, are predictive in their own right in the mode of a null model. The underlying assertion of a null model is that the mechanisms driving the phenomenon will continue unchanged. Models used in restoration planning must go beyond the description of a null model, if only to test the proposition that the null model is or is not the best model for describing the observed data.

1.2.1 Approaches to Simulation and Forecasting

Making accurate forecasts of salinity in Florida Bay, the mangrove transition zone of the Everglades, Whitewater Bay, and the Gulf coast estuaries depends on knowledge of patterns of salinity variation in the past and of the underlying driving processes that produced them. Forecasts derive from the driving processes and a representation of the relationship between these processes and salinity in the bay. For Everglades restoration, driving processes include water management alternatives that affect freshwater inflow to the estuaries from the Everglades, tied to different proposed management strategies.

There are two general approaches currently employed to construct salinity models. The first is empirical and relies on accurately describing observed salinity variations. Analysis of the available data identifies basic patterns that characterize the phenomenon of interest. The second is mechanistically-based and relies on accurately portraying the processes that drive changes in salinity. Typically, a numerical model describes the physical relationship between driving processes and 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, including descriptive analysis and correlation, are employed in the empirical approach. These techniques help in understanding the relationship between driving processes and resulting salinity variation and can be used in deriving a mathematical description embodied in a linear combination model. Correlation does not necessarily establish a causal link between characteristics of the ecosystem and the driving processes that incorporate the effects of human activities. However, descriptive analysis and correlation are the foundation for models capable of reproducing patterns of variation. Descriptive analysis also serves to diagnose bias and other problems related to the methods of observation and measurement. Patterns identified through descriptive analysis and correlations provide clues to the underlying mechanisms by their proximity in time and space.

Both regression and time series modeling techniques have been applied to models for Florida Bay salinity. Regression models exploit linear relationships in records of driving processes and systems response. A number of statistical modeling tools are available, ranging from simple linear regression to more complicated analytical techniques such as multivariate regression, linear transfer function models, and frequency domain models. Time series models utilize the distribution of variation with time and serial correlation to model system behavior. By nature, useful time series models require enough data such that the variation over time can be adequately analyzed statistically. Classical time series modeling begins by allocating the variation in a set of data ordered by time into different components, such as mean, trend, seasonal, etc. Times series models also include an explicit representation for irreducible error represented ideally as uncorrelated white noise error term.

The mechanistic approach relies on knowledge of the physical processes that influence estuarine salinity. The structure of mechanistic models reflects this understanding. Explicit mathematical representation of cause and effect based on general physical principles means that a mechanistic model can predict the behavior of the system beyond the range that has been observed. For this approach, there are various models that exhibit different levels of complexity depending on the detail employed in the numerical description of the processes at work.

Mechanistic models have only been developed for Florida Bay and the southern Everglades mangrove zone. Mechanistic models include both relatively simple 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 ignore momentum effects which are negligible at time steps greater than daily. Complex mechanistic models are based on the solution of simultaneous differential equations of continuity and hydrodynamics (momentum). A hydrodynamic forecast model is used where additional temporal and spatial detail or coverage are required for forecasts.

1.2.2 Forecast Uncertainty

Uncertainty in salinity forecasts falls into the category of “Knowledge Uncertainty” (NRC, 2000a). Knowledge uncertainty encompasses sources of uncertainty from imperfect knowledge of processes, model structure, model parameter values and data used as input in generating the forecasts. These sources of uncertainty are often not independent of each other. Uncertainties in the data can be derived in part from the mismatch between the temporal and spatial scales represented by the model and the scales on which data are collected. And finally, the uncertainty in the data contributes to the uncertainty in the optimally selected model parameters. All sources of uncertainty must be considered when evaluating alternative approaches or making improvements to forecasting.

Uncertainty in forecasts can be characterized by various statistics calculated from the differences between measured and forecast values of salinity, i.e. the set of residuals (*R*). For this study, five error statistics are reported:

average error (avg e),
root mean squared error (rmse),
average absolute error (abs e),
coefficient of determination (r^2), and
model efficiency (eff).

The average error, the average of *R*, measures bias between simulated and observed values; a mean error of zero means no bias. Even if the average error is zero there can still be significant differences between simulated and observed values; these differences may simply cancel out in the calculation of the average error.

The root mean squared error and the average absolute error are measures of the deviation between simulated and observed values, reported in the units of the simulated variable. The root mean squared error (RMSE) is calculated as the square root of the mean of the squared residuals (MSE). The average absolute error is calculated as the mean of the absolute values of the *R* values. These measures better reflect the expected magnitude of the difference between calculated and measured salinity at a particular location and time.

Model efficiency and the coefficient of determination, R-squared, or R^2 are similar. The coefficient of determination measures the fraction of the variance in the observations that can be explained by a linear transformation of the simulated salinity values; therefore it is a measure of the correlation between the simulated and observed values. In contrast, model efficiency is calculated from the mean square error normalized by the variance of the observed salinity:

$$\boldsymbol{eff} = 100 * (1 - \mathrm{MSE} / \mathrm{Var(obs)}) \qquad 1$$

where MSE is the mean of the squared residual errors and Var(obs) is the variance of the observed salinity data.

Model efficiency, also known as the Nash-Sutcliffe efficiency (c.f. Nash and Sutcliffe 1970, Weglarczyk 1998), can be interpreted broadly as the percentage of the variance in the data that is accounted for directly by the model. A model efficiency of zero indicates that the model accounts for no more of the variation than does the mean of the data. An efficiency of 100 indicates that the model accounts for all of the variation in the data. However, model efficiency can take on negative values if, for example, the model produces a biased estimate of the data. In this case, the mean of the data offers a better forecast than the model.

1.3 Previous Report

The salinity modeling status report by Nuttle (2002) reviewed and evaluated work prior to 2002 that could be applied to forecast salinity in the coastal mangroves of Everglades National Park and in Florida Bay. The report focused on approaches for formulating models needed to support the development and application of ecological performance measures. The goal was to identify an approach for linking coastal salinity prediction to changes in Everglades hydrology that could be implemented quickly and so satisfy the immediate need for predictive tools in planning. Different approaches were evaluated based on both predictive ability and practical considerations related to needs of the multi-agency planning process for ecosystem restoration in south Florida.

Accordingly, Nuttle (2002) evaluated the alternative approaches to forecasting salinity in Florida Bay based on the following set of practical requirements drawn from experience in the Florida Bay Science Program (PMC 2000):

Portability – The model chosen should be widely available for evaluation and application.

Validity – The predictive capability of the model must be generally known and accepted.

Fidelity – The model must be consistent with understood mechanisms of cause and effect within the limitations of the underlying approach to prediction.

Focus – Model predictions must relate directly to the ecosystem attributes defined as performance measures.

Ease of use – Model results must be able to be obtained quickly within the typically short time period allotted for analysis of alternatives within the planning process.

The Nuttle (2002) report recommended adopting the mass balance modeling approach, and this recommendation led to the development of the aggregated wetland basin hydrology and estuarine basin salinity model (PHAST) for ENP, and more recently used as a planning tool for the Biscayne Bay Coastal Wetlands Project (Nuttle 2005).

1.4 Objectives and Scope of this Study

Resource managers need reliable salinity forecast models to use in evaluating the benefits of alternative project designs for water management through the CERP program. As planning progresses and the understanding of the system matures, modeling activities will focus more on assuring the predictive capability of the model. For example, the future activities of the SFWMD Interagency Modeling Center will extend to reviewing modeling needs and advising project management teams on the application of models used for planning activities of individual CERP projects (CERP 2004).

This CESI task report provides general information about the options currently available from models that can be applied at sub-regional levels. The models that will be described in this task report will have the following characteristics:

The primary models that will be reviewed are salinity models; Everglades freshwater hydrology models are included to the extent they have been utilized with the salinity models being described;

Status of modeling efforts will be reported as of June 30, 2006;

Salinity models for the southern Everglades mangrove zone, Florida Bay, Whitewater Bay, and the southwest Gulf coast areas only will be reviewed (the subject area for this CESI project);

Information will be gathered primarily from abstracts and papers that are available from the sofia.usgs.gov website, the evergladesplan.org website, the latest Greater Everglades Ecosystem Restoration (GEERS) conference proceedings, the latest Florida Bay Science Program conference proceedings, and from personal communications; and

Models reviewed will include models currently in use by ENP as well as models not currently being used by ENP that have the potential for use.

2 SALINITY PATTERNS AND PROCESSES

2.1 Salinity Variation

Salinity in south Florida estuaries varies with time, and this variation can be expressed on a wide range of scales. In general, salinity varies with the annual wet and dry seasons driven by the regional precipitation and temperature patterns of sub-tropical south Florida. Salinity also responds to episodic meteorological events such as tropical storms and cold fronts. In addition, salinities in south Florida estuaries are influenced by interannual El Nino/La Nina cycles and by decadal variability in precipitation driven by Atlantic Ocean multi-decadal forcing.

A preliminary analysis of historical data from the Salinity Synthesis database (Robblee et al. 2001, Nuttle et al. 2000) shows that for the past few decades Florida Bay has behaved as a marine lagoon with, on a few occasions, salinities as high as 70 psu reported in central Florida Bay. During drought years of this period, salinity typically exceeded 40 psu over most of the Bay. Although estuarine, i.e. mesohaline, conditions in the open-water areas of Florida Bay are rare in recent history, precipitation has increased since the mid-1990's as has happened in the past when there is a change in the Atlantic Multidecadal Oscillation (AMO) a regional climate indicator (Enfield, et al 2001). Lowered salinity conditions are also associated with episodic events such as hurricanes and tropical storms or with other periods of above average rainfall, for example in 1994-1995. Increased water releases from the C-111 canal can also lower salinity across the Bay during relative dry years, as occurred 1983-1985.

Spatially within Florida Bay, salinity variability is greatest in the northeast and decreases to the west. Boyer et al. (1997) and Boyer and Jones (2001) have described a decadal trend in monthly salinity values collected by Florida International University (FIU)'s Southeast Environmental Research Center (SERC) in Florida Bay from 1989-1999. Over this interval salinity in the eastern, central and western region declined 13.6, 11.6, and 5.6 psu respectively, but this "trend" is due largely to very high values during the 1989-1990 drought and is not descriptive of substantial interannual variability. Following the wet period of 1994-1995 salinity increased, tropical storms in 1999 induced a salinity decrease, and data from the drought years of 2000 and 2001 show an increase. Therefore, the effect of precipitation patterns and episodic events can be traced in the salinity record.

In the estuaries of Whitewater Bay and the Gulf coast salinity variation has been affected by the same climatic factors as Florida Bay. However, the impact on salinity variation in these estuaries has been caused more by the decrease in freshwater supply to Shark River Slough than by water management features such as the C-111 Canal. The trend, if any, in salinity in these estuaries over the past decade has not been studied as it has in Florida Bay.

2.2 Driving Processes

Salinity in the study area reflects the shifting balance between the inflow of fresh water, the continual exchange of water with the coastal ocean and the Gulf, variation in evaporation, and physical circulation effects. The interplay of these hydrologic drivers creates a transition zone of increased salinity with distance downstream, from an upstream freshwater body to a marine downstream water body. The inflow of lower density fresh water from the Everglades dilutes the salinity in the estuary and moves the transition zone toward the bay, while exchange with the coastal ocean or Gulf replaces diluted estuarine water with water of higher salinity and greater density. As a consequence, changes in estuarine salinity, both in time and in space, are driven by the variation in three basic processes: the net supply of fresh water, the processes that drive mixing within the estuary (wind, geomorphological features, hydraulic effects), and the exchange of salinity with the coastal ocean.

2.2.1 Net Freshwater Supply

Net freshwater supply in Florida Bay and Whitewater Bay is the sum of rainfall over the area plus the inflow of fresh water through the coastal mangroves from the Everglades minus evaporation from the bay. Rainfall and evaporation dominate the freshwater budget in Florida Bay, but inflow from the Everglades is comparable in magnitude to the difference between rainfall and evaporation. For the Gulf coast estuaries, freshwater supply is dominated by the upstream contribution from Shark River Slough. An annual water budget for Florida Bay has been constructed using 31 years of salinity, hydrology and climate data (Cosby et al. 2005, Nuttle et al., 2000; 2001). From 1965-1995, annual runoff from the Everglades was one fifth of the annual direct rainfall into the Bay, and annual evaporation slightly exceeded annual rainfall. The freshwater budgets for Whitewater Bay and the Gulf coast estuaries has not been studied in detail.

On a seasonal basis rainfall, evaporation, and wetland inflow are not in phase. However, the overlap of rainfall and inflow and the opposition of evaporation lead to a strong seasonal pattern of salinity in Florida Bay (lowest in the fall, highest in the spring). Inter-annual variations in salinity appear to be affected primarily by fluctuations in rainfall both over the Everglades and over Florida Bay. These fluctuations influence salinity in the bay directly and also indirectly through variations in inflow to Florida Bay from the southern Everglades. Relative to the available data on rainfall and inflow of surface water, little is known directly about the rate of evaporation and its variation seasonally, year-to-year and spatially within the bay. Nuttle et al. (2001) describe an investigation that is designed to provide mean rates of evaporation and its variation both spatially and temporally in Florida Bay.

Freshwater inflows from Trout Creek and Taylor River (the two largest tributaries to Florida Bay) have significant influence on salinity patterns and variability in northeast Florida Bay. Low salinity values can be found near the creek mouths during the wet season, and strong gradients can occur in northeast Florida Bay.

In the fall, when sea level is relatively high, inter-basin exchange within the Bay is enhanced resulting in more of the inflowing fresh water to northeast Florida Bay reaching the central basin. When freshwater inflow to northeast Florida Bay is reduced by drought or water management practices, hypersaline conditions often develop in the central region during the dry season. Runoff from large tropical storm events can raise water levels in the mangroves and inject fresh water into the central region; this occurred notably following Hurricane Georges in 1998 (see Hurricane Georges Workshop report available at http://www.aoml.noaa.gov/flbay/hurgeocoverpage.html) and tropical storm Harvey and Hurricane Irene, both in 1999.

No large-scale effects of groundwater on salinity have been observed, but observing this input is made more difficult by the fact that the primary groundwater input is thought to be saline (Price et al. in press, Price 2001, Sutula et al. 2001). Estimates of groundwater discharge directly into the bay vary over orders of magnitude (from 1 to 16 cm/d) with higher values obtained during the dry season (Top et al., 2001; Corbett et al., 1999). Anecdotal evidence reports the existence of local springs and these have been observed by scientists in nearby Biscayne Bay within a few hundred meters of the shoreline (J. Proni, pers. comm.).

2.2.2 Exchange Processes

In northeast Florida Bay and the open water areas west (behind) the Florida Keys the lunar tides have only limited influence on driving the exchange of water with the adjacent coastal waters of the Atlantic Ocean and the Gulf of Mexico. The shallow bathymetry of the bay attenuates the influence of tides in the central and northeast regions of the bay. Here, wind-driven flows and longer term fluctuations in sea level are the dominant drivers of mixing and exchange processes. However, in the western open water areas and along the Gulf coast (including Whitewater Bay) the tidal influence also plays a role.

Wind-driven flows can affect salinity in Florida Bay both directly and indirectly. Direct effects include advection of the freshwater plumes discharging from the coastal creeks. Indirect effects include redirection of low salinity plumes from the Shark River Slough discharge into Gulf of Mexico waters into western Florida Bay. D. Smith (2001), Johns et al. (2001), and R. Smith et al. (2001) have recently shown that storm events cause significant and long-lasting (~months) changes in salinity patterns and turbidity in Florida Bay. In combination with upstream water management releases (due to flood control restrictions), storms can affect salinity by discharging pulses of fresh water into Florida Bay and the Gulf of Mexico even in the dry season. Tropical storms can cause Everglades water levels to rise rapidly, and then recede slowly as fresh water is discharged from upstream areas into northeast Florida Bay. Nor'easters drive large quantities of fresh water out of the Everglades into Florida Bay, usually during the dry season.

Fluctuations in sea level also affect exchange and mixing processes. First, annual sea level variations propagate throughout the bay essentially without attenuation. Annual changes in sea level within Florida Bay are on the order of 20 cm, representing the exchange of about 20 percent of the bay's total volume with surrounding coastal waters. Changes in water levels of this magnitude over the shallow topography have the potential to modulate the magnitude and patterns of exchange driven by wind and tides. During periods of low sea level, connections between adjacent basins are restricted thereby minimizing overbank exchange. Higher water levels facilitate the mixing of fresh water entering the northeast region from the Everglades across the shallow banks into the central and south regions of the bay.

Additionally, the increase in the elevation of higher density salt water relative to the lower density freshwater moves the broad transition zone between fresh and salt water bodies towards the upstream (inland) areas, until the increasing freshwater levels in the Everglades in the wet season can overcome the pressure created by salt water elevation and density in Florida Bay. In drought periods when freshwater inflow to the Everglades and direct rainfall are limited, saline water brought into the shallow near-shore embayments is not washed out, and high evaporation rates at the end of the dry season (late spring to early summer) can create hypersaline conditions in the near-shore areas.

2.2.3 Boundary Salinity

Flow from the rivers and tidal creeks along the southwest Florida coastline (primarily from Shark River Slough) can reduce salinities in the estuaries along the Gulf coast, the western perimeter of Florida Bay, and in its westernmost basins. Remote river discharges, i.e. the Mississippi River can be transported by coastal and boundary currents along the Florida Shelf to different parts of the south Florida coast (Lee et al., 2001a; 2001b; Ortner et al., 1995). Since most mechanistic models utilize the Gulf of Mexico as a boundary condition changes in salinity due to influence from distant sources can be a source of uncertainty in some cases and at certain times.

2.3 Available Salinity Data

In all instances, uncertainty in salinity modeling and forecasts depends on the available data. The amount and quality of the data available can affect the description of the variation in the driving processes and the resulting variation in salinity which may limit the predictive capacity of any model (CERP 2002). The models reviewed in this report rely on several important datasets that have been assembled by a number of agencies. Most models utilize data for some but not all of these processes to forecast salinity. The type and complexity of model governs the data that are used for model development and simulation.

The ENP Marine Monitoring Network (MMN) stations collect salinity and other data in Florida Bay and the southwest Gulf coast waters at 15 to 60 minute increments, which are averaged to reported hourly and daily values (http://www.sfnrc.ever.nps.gov/). The entire hydrologic monitoring network within Everglades National Park includes 62 freshwater sites (Physical Monitoring Network) throughout the marsh and 37 marine/estuarine sites (MMN). At the freshwater sites, the oldest stations have been operating since 1949. For the MMN, salinity measurements began to be collected in 1988. Parameters measured include water level, rainfall, water temperature, and salinity. Collection of data is automated and the data are transmitted to a base station using telemetry. According to the website information, these data are used to determine the effect of the Central and Southern Florida Flood Control Project on the ENP natural resources, and to characterize the park's water resources. Details about these data can be found in Everglades National Park (1997a,1997b, 2001, 2003), and Smith (1997, and 1998).

As a separate effort, the Southeast Environmental Research Center (SERC) at Florida International University (FIU) collects monthly salinity data as part of a grab sample monitoring program that has been on-going since the early 1990s. This long-term program monitors water quality in the coastal waters of south Florida. This program visits 24 stations in Florida Bay and 21 stations along the southwest coast on a monthly basis. Water samples are analyzed for salinity along with a suite of nutrient and other water quality parameters. The report by Jones and Boyer (2001) summarizes the data and discusses long-term trends in water quality on a regional basis (http://serc.fiu.edu/sercindex/index.htm). There is also synoptic salinity data available, some of it recorded as data collected with a study other than salinity. Historical salinity data (prior to the mid-1980's) exist (Robblee et al, 2001), but continuous records are spotty (Nuttle et al. 2000). A description of some of the historical salinity data can be found in Orlando, et al (1998).

The South Florida Water Management District (SFWMD) collects stage data in the Everglades, and stage and flow data at each of the structures that are a part of the water management system of the Central and South Florida (C&SF) Project, including structures that affect freshwater delivery to ENP (http://www.sfwmd.gov/org/ema/dbhydro/index.html). The United States Geological Survey (USGS) collects flow data in the tidal creeks that flow into Florida Bay through ENP, and salinity data in some of the near-shore embayments (http://sofia.usgs.gov/).

To these data other time series data can be added, including wind and rain data from the National Weather Service (Southeast Regional Climate Center – (http://water.dnr.state.sc.us/climate/sercc/climateinfo/historical/historical_fl.html), and water level and tide data collected long-term at Key Westand Naples,and for shorter periods at other south Florida locations from the National Ocean Service (http://tidesonline.nos.noaa.gov/). Off-shore sea surface elevation data which are used for boundary conditions for some mechanistic models are available through the CMAN / SEAKEYS programs (http://www.ndbc.noaa.gov/cman.php; http://www.coral.noaa.gov/cman/cman_menu.html). Evaporation estimates are often based upon the work of German (2000), or Nuttle (2001). Evaporation estimates have also been made by SFWMD for use with the South Florida Water Management Model (SFWMM) (Abtew, et al 2003).

2.4 Estimating Inflow from the Everglades to Florida Bay

Methods used to estimate fresh water inflow to Florida Bay from the Everglades deserve special attention because inflow is an important parameter for mechanistic salinity models, and can be incorporated into statistical models. Fresh water entering Florida Bay from the Everglades flows as diffuse overland flow, canal flow, and ground water. These various flow paths link water management activities of the Central and Southern Florida Project to the coastal ecosystems of South Florida. Understanding how changes to water management and restoration of the Everglades hydrology affect the ecology of the coastal ecosystems depends on information about this hydrological link between flow and salinity. Only in the last ten years have these flows been studied in detail.

There are eight estuarine creeks along the northern boundary of northeast Florida Bay. The U.S. Geological Survey has monitored flow and salinity continuously in five of these creeks since 1996. In addition to monitoring in the five creeks, Hittle et al. (2000) published empirical relationships for estimating instantaneous flow in three ungauged creeks from flow measurements in Taylor River (TR) and West Highway (WH) creek. Except for these empirical relationships, there appears to be no information from direct measurements on the magnitude of the ungauged discharge of fresh water from the Everglades directly into Florida Bay.

Everglades freshwater hydrology models such as the SFWMM do not directly estimate flow into Florida Bay. For that purpose, wetland basin models have been developed to estimate fresh water inflow into most areas of the estuarine and near shore areas in south Florida. For example, Walker (1998) implemented a set of watershed hydrology models in Everglades National Park to estimate nutrient loads to estuarine and nearshore waters. The PHAST models (Nuttle and Teed 2002, Nuttle 2004) cover the three wetland sub-basins in the Taylor Slough C111 wetland basin where discharge measured by the USGS in estuarine creeks can be used to verify the calculated wetland discharge. PHAST. Nuttle (2005) implements a series of wetland basin models as part of a screening tool for initial planning of the Biscayne Bay Coastal Wetland CERP project.

The most widely used freshwater hydrology model for south Florida was developed by the SFWMD and is called the South Florida Water Management Model (SFWMM), also known as the 2X2 model for the two mile by two mile (3.2 km X 3.2 km) grid size of the model. The SFWMM simulates the hydrology and the management of the water resources system from Lake Okeechobee to Florida Bay. It covers an area of 7600 square miles using a mesh of square cells.

The domain of this model stretches from Lake Okeechobee to the mangrove zone in Everglades National Park. The model utilizes inflows from Kissimmee River, and accounts for runoff and demands in the Caloosahatchee River and St. Lucie canal basins.

For each cell, the model simulates rainfall, evapotranspiration, infiltration, overland water flows, groundwater flow, canal flow, canal-groundwater seepage, levee seepage and groundwater pumping as well as water management control structures. SFWMM runs incorporate both current and proposed operational programs for structures in the water management system for urban, agricultural, and environmental water demands in south Florida. To evaluate water management alternatives for CERP, the SFWMM simulates Everglades hydrology on a daily basis using climatic data for 1965-2000 as model input. The model has been calibrated and verified using observed water level and flow data in the Everglades (http://www.sfwmd.gov/org/pld/hsm/models/sfwmm/index.html). Applications of the SFWMM have included the Initial CERP Update (ICU), the Restudy, the Lower East Coast Water Supply Plan, and the development of operational protocols for Lake Okeechobee. The SFWMM has been used by ENP for the Interim Structure and Operation Procedures (ISOP), the Interim Operation Procedures (IOP), and the Combined Structure and Operation Procedures (CSOP) evaluations (Santee, et al; 2003).

For FATHOM salinity modeling for minimum flows and levels for Florida Bay, an alternative approach was taken to constructing the inflow data (Cosby, et al 2005). Components of the wetland water budget are estimated from the available regional hydrological and climatic data. Freshwater inflow was estimated from the estimated water budget as monthly average flows. This alternative approach maintains the framework of the wetland water budget for combining information from long-term data sets. Uncertainty over the amount of ungauged fresh water inflow, inflow that occurs in addition to that measured by the USGS creek monitoring network, is dealt with explicitly in the manner of an unknown parameter in the salinity calculations (Cosby et al. 2005).

Hydrodynamic models under construction by the United States Geological Survey (USGS) and the SFWMD in conjunction with their ongoing measurement programs are expected to reduce the uncertainty concerning surface water discharges into Florida Bay. Hydrodynamic transport models have been developed that are capable of being linked to upland management models to address the impact of fresh water inflows on salinities and the conveyance of nutrients and contaminants to Florida Bay and southwest coastal estuaries. Langevin et al. (2002) of the USGS have developed a coupled surface / groundwater model of the southern Everglades (SICS / TIME) that is capable of simulating flow into the coastal embayments of northern Florida Bay in response to naturally occurring hydrologic events in the wetlands and the effects of upland management practices on fresh water releases.

The total groundwater discharge to the Everglades surface water regime on an annual basis for the entire SICS model domain is on the order of only one cubic meter per second (E. Swain, pers. com). This is a small contribution that can be ignored for some calculations. This estimate is based on analysis of the average net groundwater discharge calculated for each node of the SICS model within the Taylor Slough and C111 wetland basins. Net figures for groundwater exchange in the period 1995 through 1999 show patterns of upwelling to the surface in the upper reaches of Taylor Slough, north of Old Ingram Highway.

3 STATISTICAL MODELS

3.1 Regression Models

The first documented attempt to use statistical methods to establish the relationship between upstream hydrology and downstream salinity of Florida Bay and the Gulf coast estuaries is attributed to Durbin Tabb (1967). Tabb (1967) observed a close relationship between salinity and the elevation of the water level at two wells in ENP (P-35 and P-38) and one well in Homestead. Simple linear regression methods were used (including lagged values) to develop salinity prediction tables that were compared to observed data, and the correspondence was considered to be acceptable.

After the work by Tabb (1967), attempts were made to develop statistical relationships between water levels in monitored wells in the Everglades and Florida Bay salinity, primarily by the SFWMD using data that were collected monthly (Scully, 1986). Other statistical evaluations of salinity variation using correlation evaluations, simple linear regression models, and analysis of variance followed, including Cosby (1993). Though the performance of simple linear models was reasonable for salinity at some stations in Florida Bay nearest the mangrove fringe area, the effects of wind, tide, and local meteorological conditions, particularly at open Bay locations, limit the ability of the simple linear regression relationships to satisfactorily simulate salinity (Marshall, 2000). The use of other time-series modeling techniques, such as seasonal autoregressive integrated moving average models (SARIMA) that are robust to outliers and seasonality, was suggested as an improvement for simulation.

Nuttle (1997) was the first to implement more sophisticated statistical techniques using monthly data that included monitored C-111 Canal structure flows and rainfall. The resulting updated transfer functions solved some of the statistical problems that were associated with the initial simple linear models (such as a non-constant variance), but use of the models for predictive purposes was hampered for by the transformations needed to stabilize the non-constant variance of the monthly input data.

The conceptual model for the south Florida coastal aquifer system explains the relationship between estuarine and coastal shelf salinity, hydrology in the upstream watershed, and meteorology in the region. For this coastal aquifer system there is a dynamic balance between fresh and salt water bodies with a salinity transition zone from freshwater to sea water (Pandit, et al 1991). In south Florida, the salinity transition zone is wide because of the relatively small difference between upstream freshwater stage and downstream estuary water level. In most of the coastal aquifer examples in the literature, the focus of analysis is the water table aquifer, with the primary concern being the location of the transition zone as a water supply issue of saltwater intrusion. For salinity modeling in an estuary the focus is the salinity in the interface transition zone.

The Ghyben-Herzberg principle describes the location of this interface as function of the height of the freshwater surface in the watershed relative to the height of the sea surface above a common datum and the relative density of the water masses. In shallow estuaries like Florida Bay and Whitewater Bay wind can also cause the interface to translocate and mix. Therefore, Marshall (2002) hypothesized a correlation between salinity levels and these three factors (watershed water level or elevation, sea surface elevation, and wind), which is confirmed by a correlation analysis including lagged values on the order of days. However, each of these forcing factors (fresh water elevation, wind, and sea surface elevation) has a different pattern of variability over time

The MLR salinity models of Marshall (2002) used SFWMM model output for water levels in the Everglades and available long-term data for wind and sea surface water level to produce estimates of daily salinity for the 1965-2000 period. Although rainfall in the upstream watershed is an important hydrologic parameter for seasonal salinity variation, rainfall at monitoring stations in the Everglades are not highly correlated with salinity at the daily level. Instead, the stochastic effect of rainfall falling on the Everglades is integrated by the coastal aquifer system and expressed adequately in stage data.

The original MLR salinity models were developed for Joe Bay, Little Madeira Bay, Terrapin Bay, Garfield Bight, and North River (Marshall 2002). For the Interim Operating Plan (IOP) Congressional report, an additional station (Long Sound) was added (Marshall, 2002). Then, the second phase of the CESI project extended the spatial extent of MLR models to Highway Creek, Taylor River, Whipray Basin, Duck Key, Butternut Key, and Bob Allen Key (Marshall 2004).

In 2005, the Southern Estuaries Sub-team of RECOVER used the 12 existing MLR salinity models and developed new models for Gunboat Island, Shark River, Clearwater Pass, and Whitewater Bay, Barnes Sound and Manatee Bay (Middle Key station). By the end of 2006, statistical salinity models will be developed for the remaining stations in Florida Bay and on the Gulf coast. Figure 1 presents the MMN station locations with MLR salinity models.

A number of error statistics were computed (Marshall 2005) in order to quantify the uncertainty in the simulations produced by the MLR salinity models (See Tables 1 and 2). In general, the salinity in the near-shore embayments (Joe Bay, Little Madeira Bay, Terrapin Bay, and Garfield Bight) is observed to be more variable on a day-to-day basis than the salinity at the open water stations. Because of this, the development of MLR salinity models was more difficult and the R^2 and Nash-Sutcliffe Efficiency values are slightly lower compared to the open water MLR salinity models.

Error statistics indicate that the daily resolution MLR salinity models are capable of explaining on-the-order of 70 – 80% of the variation in salinity. However, individual daily residuals can sometimes be large. At the weekly average level, large residuals are uncommon. This grouping of similar models by goodness-of-fit statistics follows closely the groups presented in Orlando et al (1998) from an archival salinity data set.

3.2 Time Series and Frequency Domain Models

Most of the statistical modeling of salinity completed prior to 2002 was done with monthly data. Marshall (2002) investigated the development of time series statistical models using daily time series data. Daily variability in salinity is valuable to a variety of biologists, because daily variability captures the “flashiness” of the system relative to changes in salinity.

When Marshall (2002) tried to apply SARIMA time series models to Florida Bay salinity, it was found that there were fewer limitations with multivariate linear regression (MLR) models for coupling with SFWMD model output to produce 36-year simulations. Therefore, Marshall (2002) adapted a SARIMA technique using cross-correlation coefficient analysis to efficiently identify significant variables and lagged values with MLR salinity models.

Nuttle and Marshall (unpub., 2005) applied spectral analysis to examine long-term salinity records from Florida Bay. Spectral analysis can be used as a diagnostic tool of system behavior by examining the characteristic spectral density function for Florida Bay salinity. Peaks in the spectral density function of salinity at periods of 12.5 hours and 25 hours signal the importance of diurnal and semi-diurnal tidal forcing on a number of estuarine processes such as water level, velocity of flow, and salinity. In addition to the information provided by peak values, trends in the spectral density function are also important. For example, a 5/3 slope found in the spectral density function for certain characteristics of marine ecosystems reveals the influence of turbulent mixing processes (Levine 1996). Changes in spectral density function slope can signal a change in the mode of behavior, such as between Eulerian and Lagrangian turbulence (Seuront el al. 1996), or in the underlying processes that control ecosystem structure and function (Holling 1992, 1996). The results obtained for Florida Bay indicate that although tides and wind-driven water movement are important over the short term, the variation in the supply of fresh water to the bay contributes significantly to changes in salinity over time scales greater than about a month. Spectral analysis allowed this change in the pattern of salinity variation with increasing time scale to be seen, an important finding for salinity modelers.

Figure 1: Map showing the location of Marine Monitoring Network stations with MLR salinity models (from Everglades National Park).

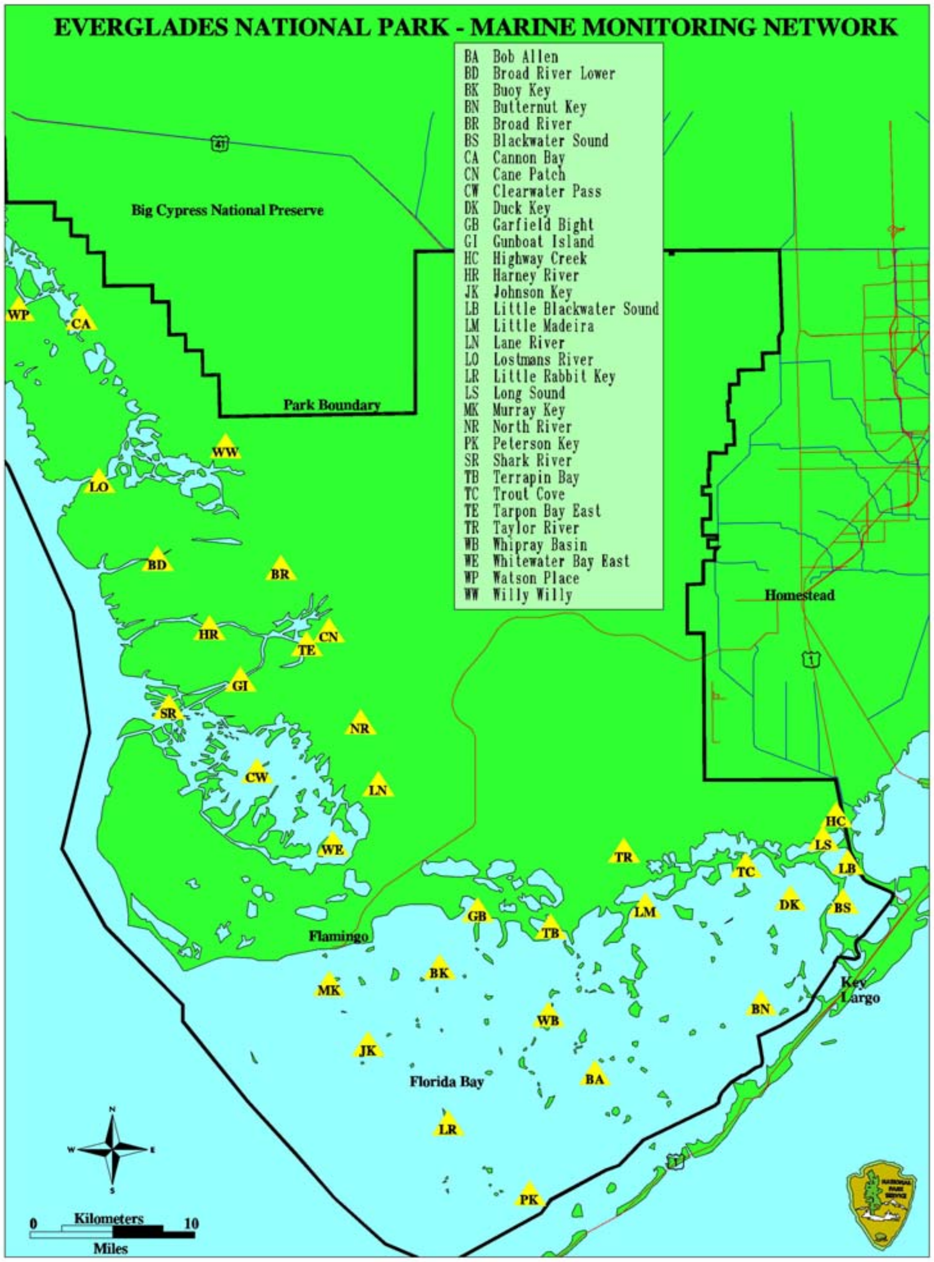


Table 1. Comparison of Model Uncertainty Statistics for IOP / CESI MLR Salinity Models (Marshall, 2004).

station	mse psu^2	root mse (rmse), psu	adj R-sq	mean error, psu	mean abs error, psu	max abs error, psu	Nash-Sutcliffe Effcy
Joe Bay	25.8	5.1	0.75	-0.14	3.7	20.6	0.76
Little Madeira Bay	40.1	6.4	0.65	-0.66	5.1	22.6	-0.96
Terrapin Bay	32.6	5.7	0.75	-0.99	5.4	5.4	0.67
Whipray Basin	7.2	2.7	0.8	0.11	2.2	10.1	0.77
Duck Key	9.7	3.1	0.71	-0.18	2.27	14.4	0.71
Butternut Key	10.7	3.3	0.65	0.1	2.7	11.3	0.66
Long Sound	15	3.9	0.8	0.31	2.7	18.9	0.81
Taylor River	21.4	4.6	0.78	-0.49	3.6	22.9	0.78
Highway Creek	18.2	4.3	0.81	-0.95	3.7	17.7	0.76
Little Blackwater Sound	14	3.7	0.75	-0.14	2.9	15.7	0.76
Bob Allen Key	7.2	2.7	0.79	0.3	2.1	9.2	0.81

Table 2. Comparison of Model Uncertainty Statistics for Southern Estuaries Sub-team MLR Salinity Models (Marshall, 2005).

station	mean square error	root mse	adj R-sq	mean error	mean abs error	max abs error	relative mean error	relative mean abs error	relative mean square error	Nash-Sutcliffe Effcy.
Garfield Bight	37.9	6.15	0.68	-0.36	4.75	21.1	-0.012	0.16	0.06	0.89
Clearwater Pass	11.60	3.40	0.85	-0.12	2.72	10.82	-0.01	0.16	0.08	0.85
Whitewater Bay	9.60	3.10	0.74	0.46	2.90	10.60	0.04	0.26	0.06	0.88
North River	14.30	3.80	0.77	0.56	3.23	17.92	0.08	0.45	0.04	0.92
Gunboat Island	11.50	3.40	0.85	1.03	3.02	13.28	0.09	0.27	0.05	0.89
Shark River	6.30	2.50	0.82	-0.11	2.02	9.11	0.00	0.08	0.06	0.89
Middle Key	6.88	2.60	0.74	-0.22	2.20	11.33	-0.01	0.09	0.16	0.71
Manatee Bay Stage	9.50	3.10	0.69	0.02	2.07	12.86	0.00	0.09	0.17	0.70

4 MECHANISTIC MODELS

4.1 Mass Balance (Box) Models

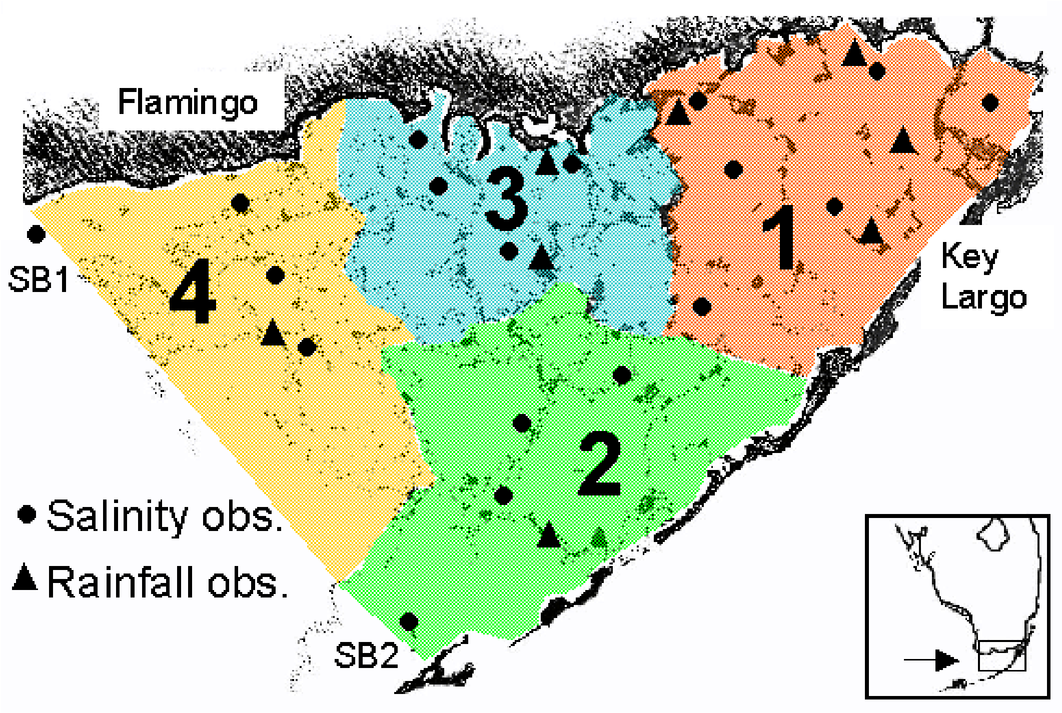
4.1.1 Four Box Model of Florida Bay

Nuttle et al. (2001) implemented a mass balance model in Florida Bay for the purpose of estimating evaporation. This model calculates salinity using monthly time steps from variation in the net supply of freshwater to and water exchange between each of four regions in the bay, Figure 2, and exchange with the Gulf of Mexico. The regions used in this model correspond to the regions defined from similarities in water quality (Boyer et al. 1997) and other attributes of the Florida Bay ecosystem. Rainfall and salinity used to drive the model are measured in the bay. Freshwater runoff is estimated from measured flows in Taylor Slough and the C111 canal that discharge into the mangrove wetlands north of the Florida Bay.

The four-box model by Nuttle et al. (2001) has been calibrated against salinity data for the period 1993 through 1995 and validated by comparison with salinity data in the period 1996 through 1998, Figure 2. Monthly salinity and rainfall data were aggregated within each region. Salinity at SB1 and SB2 provide boundary conditions for exchange with regions 2 and 4. Freshwater runoff also enters region 1. Evaporation and exchanges between regions were estimated by optimization. The standard error of prediction is about 2 ppt across all four regions. Calibration of the model produces estimates for the unknown seasonal evaporation rates and the exchange rates between basins and with the Gulf of Mexico. These exchange rates can be used to investigate residence times in the Bay, information that is needed to understand the processes that control nutrient concentrations and plankton blooms in the bay.

Nuttle et al. (2000) employ two different box models. One is the annual averaged version of the four-box model described above, which was used to estimate mean annual evaporation from Florida Bay. The other, FATHOM (described below), divides the Bay into about 40 basins based on morphology, and estimates exchanges between basins using tide-driven hydraulic calculations. FATHOM has been applied to analyze the influence of changing runoff into Florida Bay (Nuttle et al. 2000), but the calculated exchange rates and resulting residence times have yet to be validated by comparison with observation.

Figure 2: The box model divides Florida Bay into four regions based on observed patterns in water quality (Boyer et al 1997, Nuttle et al. 2000).



4.1.2 PHAST

The Nuttle (2002) report recommended adopting the mass balance modeling approach, and this recommendation led to the development of the aggregated wetland basin hydrology and estuarine basin salinity model (PHAST) for ENP, and more recently used as a planning tool for the Biscayne Bay Coastal Wetlands Project (Nuttle 2005). The domain of the PHAST models encompasses three wetland sub-basins in the Taylor Slough C111 wetland basin and the adjacent estuarine basins Long Sound, Joe Bay, Little Madeira Bay and Terrapin Bay. The PHAST models have been applied by Everglades National Park to simulate changes in salinity as a performance measure of restoration in the development of a spoonbill habitat suitability index model (Lorenz 2005) and in modeling studies to support development of minimum flows and levels criteria for Florida Bay (Cosby et al. 2005).

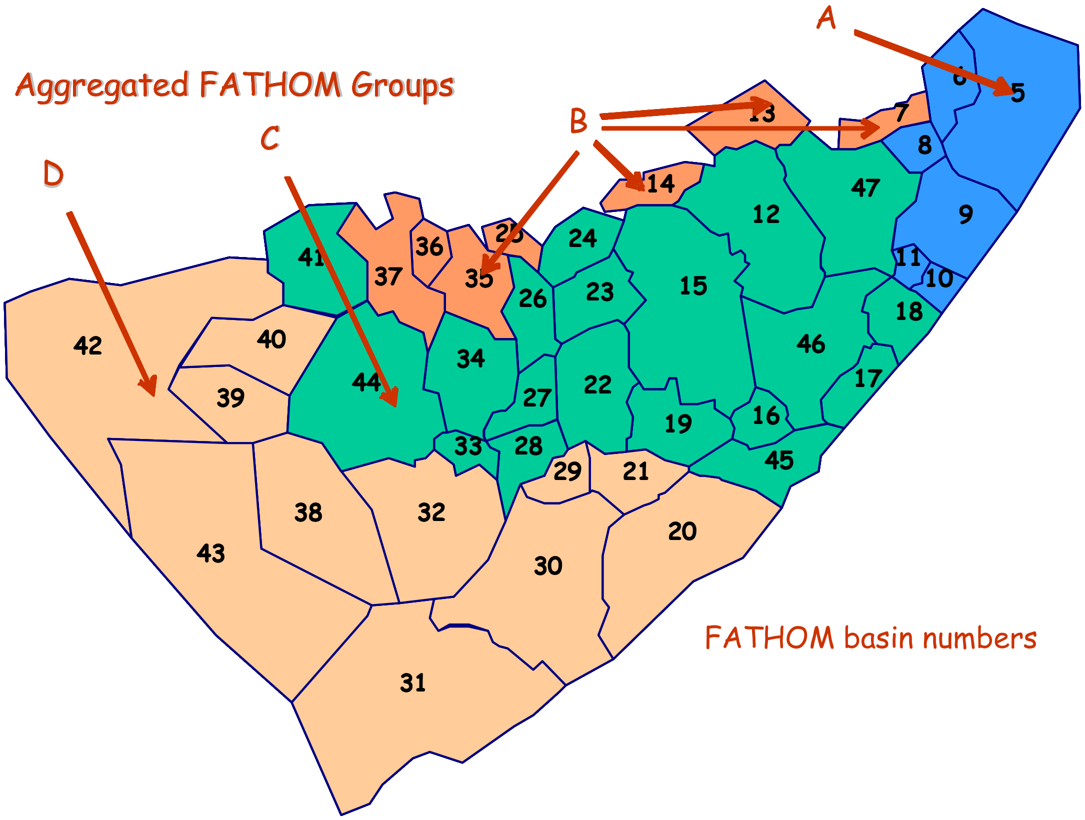
4.1.3 FATHOM

FATHOM is a dynamic, spatially explicit, mass-balance model designed to investigate the response of salinity in Florida Bay to runoff, climate, and variation in salinity on the Florida Shelf (Cosby et al. 1999, Nuttle et al. 2000, Cosby et al 2005). The model maintains a running account of the water and salt budgets in each of 41 well-mixed basins within the bay, Figure 3. Circulation within Florida Bay and exchange with the Florida Shelf are controlled by the network of shallow banks. The basins defined by these banks offer a natural framework for mass-balance accounting.

FATHOM represents Florida Bay as a collection of well-mixed basins. Circulation and exchange are driven primarily by tides imposed along the western boundary. At each time step, the model solves for uniform, hydraulic flow across each bank based on the depth, width, and frictional roughness of the bank and water levels in the upstream and downstream basins. By this mechanism, tidal forcing at the boundary propagates into the bay and drives the exchange of water and solutes among the basins. Solute fluxes are then calculated from water fluxes and the salinity of water on each bank. Details of the representation of flow over the banks and the hydraulic equations are given in Cosby et al. (1999).

Despite the model's computational simplicity, FATHOM requires highly detailed information about the bathymetry in Florida Bay. Bathymetric data are entered into a GIS database that classifies the depth for every 20 by 20 meter rectangle in the bay.

Figure 3: Map identifying the basins and the aggregated regions used in FATHOM for salinity calculations.



There is no direct simulation of wind shear on the water surface in FATHOM. Salinity calculated by FATHOM represents a time-averaged value with a period of about one month. Even though circulation and exchange in the model are driven by tides, data on other processes such as rainfall and freshwater inflow are provided as monthly values. The assumption of basins as well mixed imposes constraints on the time scale on which salinity calculations can be taken as comparable to observations at any particular location.

Bay-wide inputs required by FATHOM include time series of rainfall and evaporation for each basin in the bay. The model structure allows these inputs to be specified individually for each basin to reproduce spatial gradients in these forcing functions. In practice, however, observed data are not sufficient to support more than a regional approach to the spatial distribution of climate inputs. Instead, the bay must be divided into a few regions for each of which climate inputs are applied uniformly to the model to make long-term forecasts of salinity. Groundwater inputs to the basins can also be specified, but these have not been employed in the simulations performed for this project.

For FATHOM time series of freshwater inflow volumes are required at the terrestrial boundaries of the bay. Inflow is specified as an input separately into each of the boundary basins along the Florida Bay coastline. Along the keys, inflows of fresh water are small, and these are not included in the FATHOM inputs. In addition to the runoff data at the terrestrial boundaries, FATHOM requires tide, sea level and salinity time series to set the open water boundary conditions for the bay. The model allows these boundary conditions to vary spatially along the boundaries.

For the Florida Bay minimum flows and levels (MFLs) modeling for SFWMD, the bathymetry of Florida Bay was updates and freshwater inflows were improved using USGS observations and a sensitivity analysis approach. This effort produced 31-year (1970-2002) historical reconstructions of salinity in each of the 41 FATHOM basins. The salinity reconstruction for Little Madeira Bay was used as input to ecological models.

Error statistics for the FATHOM MFL base case calibration / verification run (1991-2000) are presented in Table 4 for monthly simulations. While not directly comparable, root mean squared error, absolute error, and r^2 for FATHOM are similar to the same statistics for the MLR daily salinity models (Tables 1 and 2). Average error is higher and efficiency values are less for FATHOM MFL base case model compared to daily MLR salinity models.

Table 3. : Error statistics for salinity simulations by FATHOM for the MFL base case model with monthly measurements over the period 1991 through 2002. (adapted with permission from Cosby, et al 2005).

station	root mse (rmse), psu	adj R-sq	mean error, psu	mean abs error, psu	Nash-Sutcliffe Effcy
Long Sound	4.3	0.9	1.9	3.4	0.77
Joe Bay	7.7	0.8	-1.9	5.6	0.56
Little Madeira Bay (mouth)	4.2	0.9	1.3	3.3	0.76
Park Key	3.7	0.9	2.0	3.1	0.77
Duck Key	3.7	0.9	-1.6	3.0	0.76
Butternut Key	3.5	0.9	-0.2	2.8	0.90
Garfield Bight / Rankin Bight	5.9	0.7	1.5	4.5	0.43
Whipray Basin	4.5	0.8	0.2	3.6	0.58
Rabbit Key Basin	2.6	0.7	0.0	1.9	0.51

4.2 Hydrodynamic Models

4.2.1 Initial Hydrodynamic Modeling Efforts

There were various preliminary detailed modeling efforts in the 1990's that were associated with Florida Bay restoration projects which were not carried forward. Examples include models developed or described by Wang et al (1994) and Wang (1998), Sheng et al (1995), and Cerco et al (2002). Because these modeling efforts are no longer active they were not included in the model summary, but they are worthy of note. Because of the spatial extent of the RMA-10-WES model developed by the US Army Corps of Engineers Waterways Experiments Station, it is discussed below.

The RMA-10-WES model is a two-dimensional version of a finite element hydrodynamic model that was used by the US Army Corps of Engineers in 1996 to simulate circulation in Florida Bay, and to be coupled with a water quality model, CE-QUAL-ICM (Cerco, et al; 2002). The RMA-10-WES grid mesh that was developed for Florida Bay consists of 19253 triangular elements and 40609 nodes, stretching from Barnes Sound to the Gulf of Mexico north of Johnston Key. When RMA-10-WES was coupled to CE-QUAL-ICM a number of issues surfaced. In addition, the grid for RMA-10-WES did not match the CE-QUAL-ICM grid. Several attempts were made to adapt the RMA-10-WES output for water quality use. Overall, the end result was not usable, and no documentation of any further effort could be found. The RMA-10-WES Florida Bay modeling activity by the Corps was notable because it was the first attempt in south Florida to link a hydrodynamic model to a water quality model, and it exposed the problems that have to be faced in that regard.

4.2.2 EFDC

The Environmental Fluid Dynamics Code (EFDC) is a hydrodynamic model that is used to simulate surface water systems in one, two, and three dimensions. EFDC is composed of stretched or sigma vertical coordinates and Cartesian or curvilinear, orthogonal horizontal coordinates to represent the physical characteristics of a water body. The code solves three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable-density fluid. Dynamically-coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. The EFDC model allows for drying and wetting in shallow areas by a mass conservation scheme.

The SFWMD EFDC model grid domain includes Florida Bay and extends westward into the Gulf of Mexico to the 81.9-degree latitude. The model was configured using NOAA and USGS bathymetry. Open boundary conditions include tides and sea level, salinity, and temperature. Surface heat exchange is accomplished using spatially-varying wind and atmospheric data. Estimates of inflows, salinity, and temperature for canal, creek and river discharges are used for model input along northern Florida Bay and the eastern Gulf of Mexico.

The most current information on the EFDC model development as presented in the first draft of a calibration report to SFWMD in September, 2005 describes the a new multi-level grid for Florida Bay. This study describes the calibration of the hydrodynamic component of the EFDC model, building on the previous studies. In addition this new model configuration was used for a historical simulation from 1996 through 2002. The model calibration in this draft report describes the ability of the model to simulate sea level and currents frequencies at tidal and sub-tidal resolution, as well as temperature and salinity.

The new EFDC model has several grid resolutions. The coarse grid is shown by Figure 4. The EFDC grids consist of two configurations. One grid stops at the coast in northeast Florida Bay (nominal coast model), while the other configuration incorporates the mangrove area north of the Bay which is hydraulically connected to the open water areas of northeast Florida Bay (wetland model). According to the authors of the draft report, both configurations of the model performed well at reproducing observed sea level and currents at tidal frequency resolution. However, the grid that includes the mangrove zone is described as better in predicting the low frequency variation in water surface level in the northeast part of Florida Bay, including episodic events such as tropical storms.

As shown by Table 3, both grids (nominal coast model = NM, wetland model = WM) perform well in predicting salinity. According to Tetra Tech, Inc. (2005), the model is capable of reproducing seasonal variation as well as the extreme inflows that are caused by tropical storms. The smaller grid configuration (NM) apparently predicts better because groundwater is excluded, and there are problems depicting some mangrove zone features such as the Buttonwood embankment. Compared to daily MLR salinity models (Tables 1 and 2), monthly FATHOM model (Table 3), and the USGS SICS model (see below), daily salinity simulations by EFDC to-date contain significantly greater uncertainty (error) than the other 3 model systems. It is noted that the EFDC model development activity is on-going.

The EFDC modeling effort confirmed the physical processes at work in Florida Bay. For example the model shows that there is a shift in the tidal regime from macro-tidal in the western areas to micro-tidal in the central and eastern / northeast parts of the Bay. This transition is attributed to the mud banks that are said to attenuate tidal frequencies. In the east and in the central region sub-tidal frequency variations from the Gulf of Mexico and the Florida Straits and local winds are the primary water level drivers.

Because of the potential for problems specifying the open boundary conditions future EFDC efforts will utilize the ocean circulation model SoFLA-HYCOM (see below). This current draft report describes the initial work incorporating these boundary conditions. Additionally the surface and groundwater model TIME (see below) will be used in the future to simulate freshwater inflows to the mangrove zone.

Figure 4. Domain of the EFDC model, coarse grid (from TetraTech, 2003)

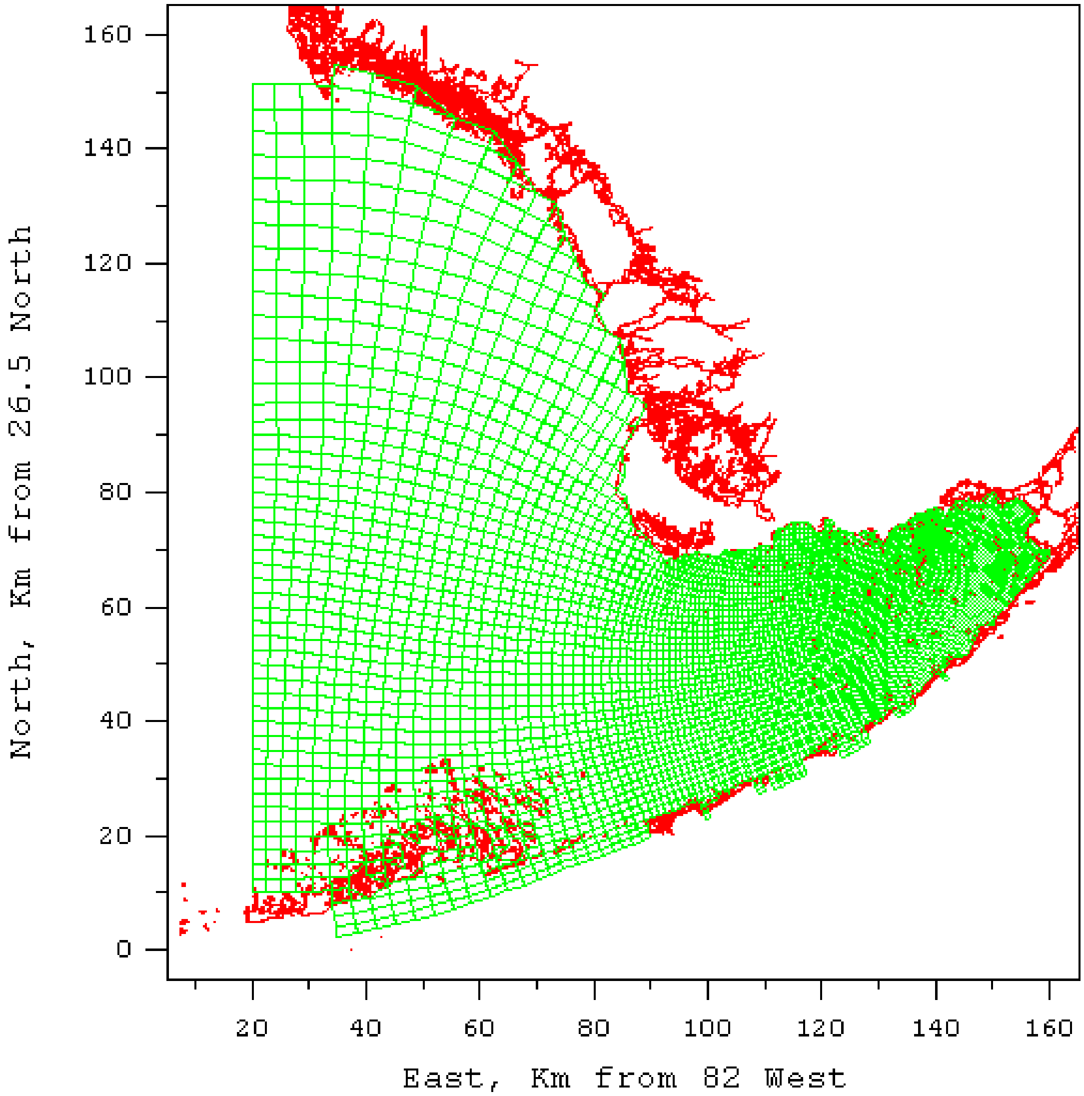


Table 4. Error statistics for EFDC salinity simulations at ENP MMN stations (Tetra Tech, Inc. 2005), nominal coast model = NM, wetland model = WM.

Station	Relative Error, PSU, NM	Relative Error, PSU, WM	Absolute Relative Error, PSU,NM	Absolute Relative Error, PSU,WM	Root Mean Squared Error, NM	Root Mean Squared Error, WM
Trout Cove	11.32	-3.57	11.34	6.27	14.18	8.08
Duck Key	1.64	-0.05	2.55	3.37	3.28	4.11
Little Madeira Bay	-2.35	-1.00	3.61	6.01	4.31	7.20
Butternut Key	0.13	-0.07	3.26	4.41	3.93	5.27
Terrapin Bay	-2.82	-1.10	5.27	5.67	6.46	7.15
Whipray Basin	2.04	3.30	3.40	4.64	4.04	5.64
Bob Allen Key	0.24	0.88	2.82	3.46	3.53	4.39
Garfield Bight	1.64	12.14	4.89	13.38	6.32	15.11
Buoy Key	2.29	6.26	4.63	7.36	5.70	9.13
Peterson Key	-1.15	-1.02	2.27	2.31	2.89	2.94
Murray Key	0.89	2.80	3.63	4.25	4.39	5.61
Johnson Key	1.10	2.71	3.80	4.59	4.69	5.97
Little Rabbit Key	-0.22	0.69	3.16	3.57	4.03	4.77
Shark River	4.46	4.78	5.14	5.38	5.88	6.10

4.2.3 SICS / TIME

The USGS has developed the Southern Inland and Coastal System (SICS) model (Swain et al 2004) and the Tides and Inflows in the Mangrove Ecotone (TIME) model (Langevin et al 2002). SICS has a smaller-domain and different grid-cell size than TIME, and there are other code differences. SICS and TIME adapt the USGS SWIFT2D two-dimensional hydrodynamic surface-water model coupled with SEAWAT, a three-dimensional ground-water model, to estimate freshwater flow and solute transport (including salinity) in the southern Everglades. The USGS developed a coupling model (FTLOADDS) to connect the two models.

The SICS model domain encompasses the Taylor Slough area and northeastern-most part of Florida Bay with a 305-m grid resolution (Figure 5). The TIME model has a coarser resolution (500 m) than SICS, but covers a larger area, including Shark and Taylor Sloughs, the Gulf of Mexico, and northern-most part of Florida Bay. Both models use the Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) computer code to couple surface water flow, groundwater flow, and solute transport. Both models produce flows, stages, and salinities in the wetlands and underlying aquifer system. The SICS and TIME simulations have been produced primarily for the 1996 through 2002 period.

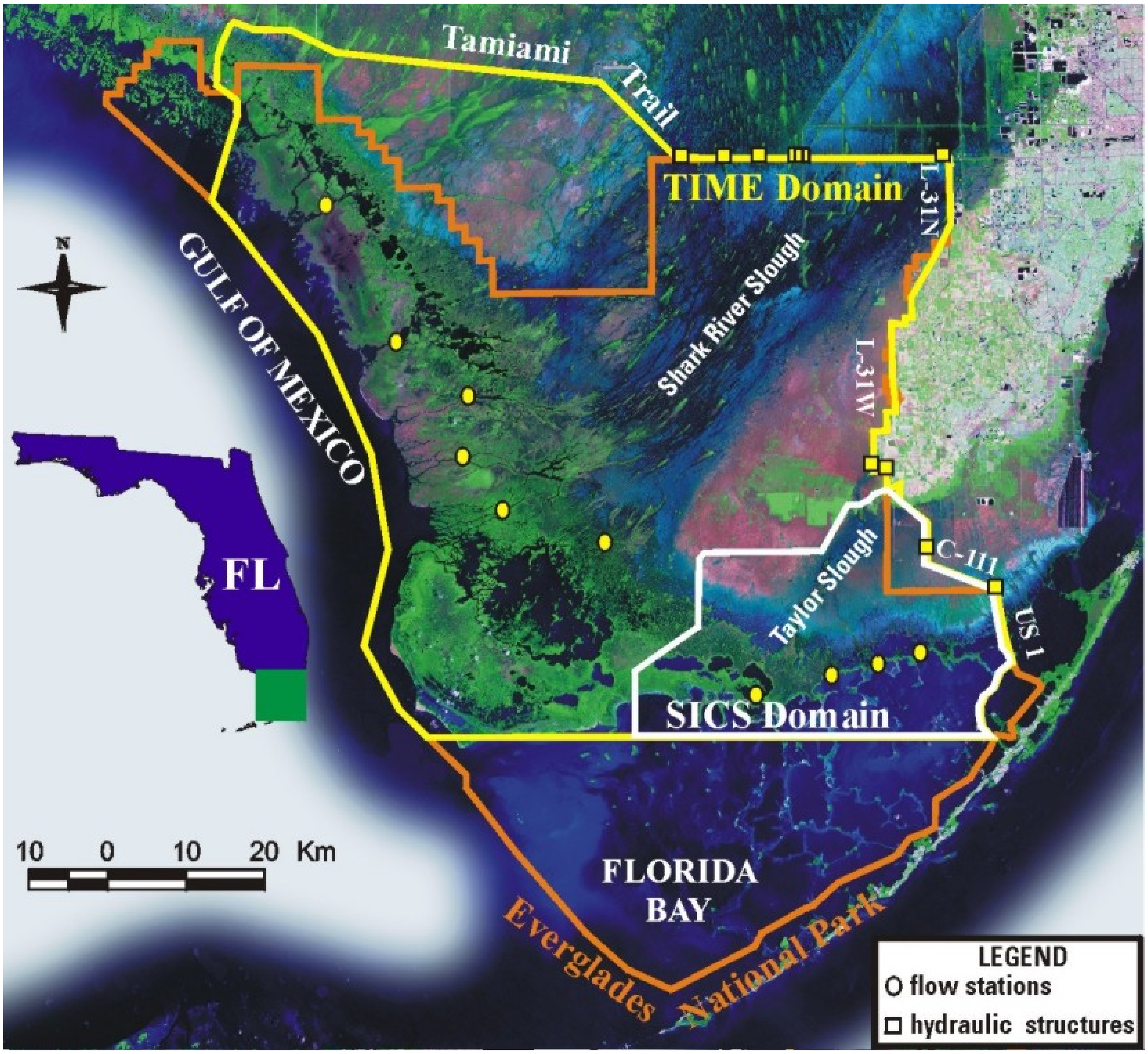
The SICS model can be driven by the SFWMM through the use of SFWMM stage values for SICS boundary conditions which allows for accurate prediction of freshwater flows to Florida Bay under restoration conditions. The SICS model has also produced salinities for use with the ATLSS models (Across Tropic Level System Simulation) to assess restoration effects on fish populations (Langevin et al, 2004a; Cline et al, 2006).

The SICS model has also been used for making daily salinity simulations near the coastal creeks that are being monitored by the USGS. Calibration statistics are presented in Table 3 from Langevin, et al 2004b. The SICS model was found to be better at simulating monthly salinity values ($r^2 = 0.76$) than daily salinity values ($r^2 = 0.67$) at Trout Creek.

Table 5. Error statistics for salinity for the calibration run of the USGS SICS model of Florida Bay and the adjacent coastal wetland (Langevin, et al 2004b)

Station	Mean Error	Mean Absolute Error	Root Mean Squared Error	N
McCormick Creek	2.76	7.14	9.43	2508
Mud Creek	2.10	3.95	5.08	2421
Trout Creek.	2.33	4.86	6.45	2529
Taylor River	4.95	6.35	7.70	2515
West Highway Creek	-1.43	4.60	5.57	2512

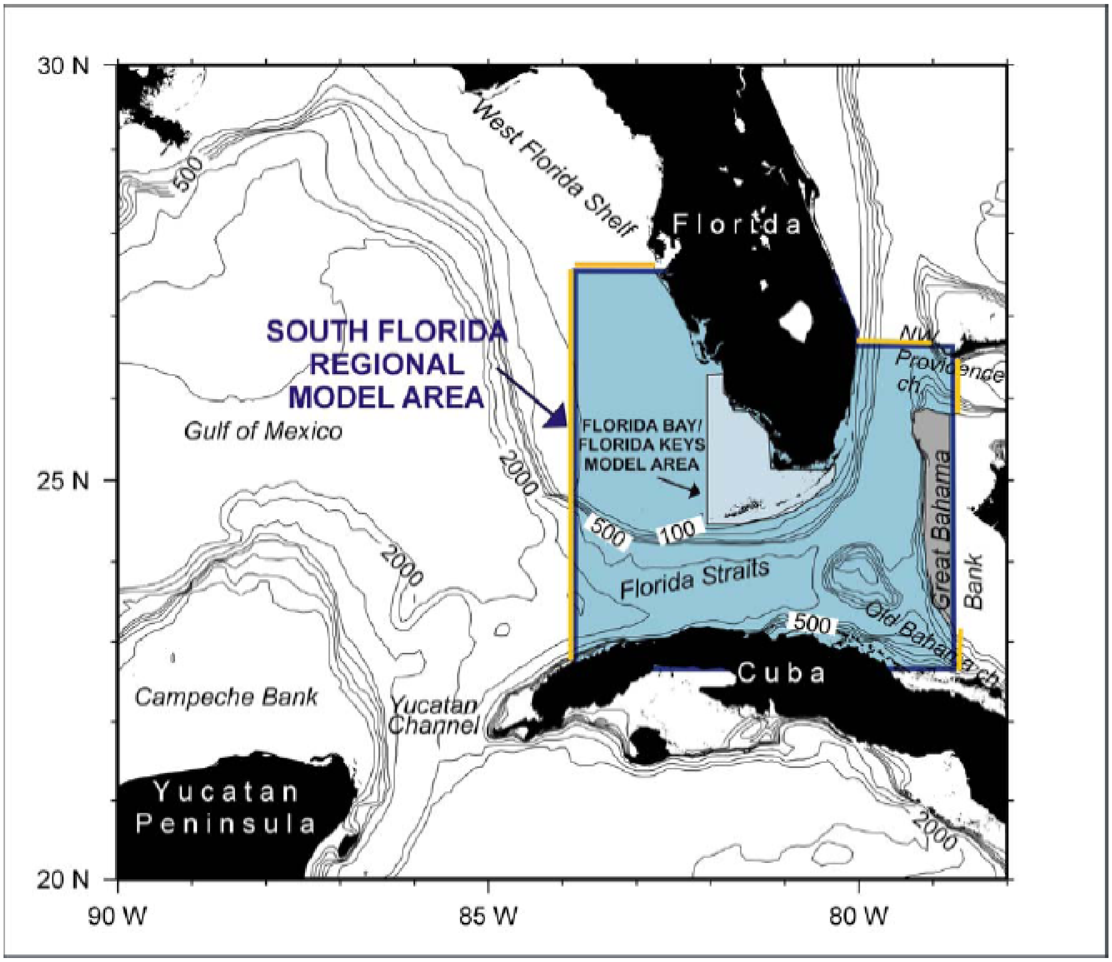
Figure 5: South Florida satellite image showing SICS and TIME model domains (USGS).



4.2.4 SoFLA-HYCOM

SoFLA-HYCOM is a three-dimensional hydrodynamic ocean circulation model for the south Florida coastal system with a domain that includes Florida Bay, the Florida Keys reef tract, and the southwest portion of the Florida shelf as shown by Figure 6. The model was developed to connect the south Florida estuaries and near-shore marine waters to the open-sea areas of the Florida Straits and the Gulf of Mexico. The South Florida (SoFLA) adaptation of the Hybrid Coordinate Ocean Model (HYCOM) simulates the complex circulation patterns of the seas in this region, including the interaction of coastal and offshore effects. SoFLA-HYCOM is coupled with larger scale models of the North Atlantic through nesting. The model is capable of resolving low salinity waters from remote sources, the prevailing Florida Current, the wind-driven southwestward flow along the Florida Keys, eddies that have been observed between the Florida Current and the Keys reef tract, and freshwater flows from rivers into Florida Bay and the Gulf coast estuaries (Kourafalou, 2005).

Figure 6. Map showing the domain of the SoFLA-HYCOM model (Kourafalou, 2005)



5 SUMMARY AND DISCUSSION

Considerable progress has been made in the development and refinement of salinity models since the report in 2002 by the Cadmus Group (Nuttle, 2002). The information presented herein reports on the current status of models that have been used to simulate the salinity in Florida Bay and in the backwaters of the southwest Gulf coast. The two primary salinity data sets used for modeling 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.

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. Therefore, freshwater hydrology and wetland basin models have been developed to simulate the south Florida conditions required for use with salinity models. For statistical models, hydrology of the Everglades is described by the stage levels that are used as input for salinity simulating and forecasting.

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 input are not fully available. This increases the level of uncertainty in the salinity estimates produced by hydrodynamic models. 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.

For salinity, the following models were presented and discussed:

1. Multivariate linear regression (MLR) models,
2. A four-box Florida Bay mass balance model;
3. FATHOM, a 41-basin dynamic mass balance models of Florida Bay;
4. RMA-10, a full three-dimensional hydrodynamic model of Florida Bay;
5. EFDC, a full three-dimensional hydrodynamic model of Florida Bay;
6. SICS/TIME, an integrated ground and surface water models that simulates hydrology in the Everglades and salinities in the near shore embayments of Florida Bay and the estuaries on the Gulf coast, and

7. SoFLA-HYCOM, a three-dimensional ocean circulation model that simulates circulation and salinity on the Gulf shelf, in the Florida Straits, and on the Keys reef tract.

A summary of general information about each of these models, except RMA-10, is presented in a Table 6. The RMA-10 model is no longer in use.

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

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

Each of the models that were assigned a score for acheiving the desired result of each modeling factor (Table 7). 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 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.

To-date, the most widely used models for developing historical recreations and simulating salinity regimes for the evaluations of water management alternatives are the FATHOM mass balance model and the MLR salinity models. Because of their relative simplicity, development has occurred before full hydrodynamic model development has been completed. 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 SICS/TIME and EFDC, is continuing, and use for historical salinity reconstructions and simulations is likely within the next several years.

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 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 and 8):

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.

It can be seen that 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. It can also be seen that 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.

6 FINDINGS

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).

Table 6. Summary of Salinity Models and Supporting Hydrologic Models Currently in Use For Simulating Florida Bay and Southwest Gulf Coast Salinity

Model Name	Model Type	Simulated Parameters	Spatial Domain	Grid Size	Simulation temporal domain
SFWMM[1]	Freshwater Hydrology	Stage, Flow	Everglades	3.2km X 3.2km	1965-2000, daily
PHAST[2]	Wetland Basin	Flow	Lower Everglades and Mangrove Zone	regional	1965-2000, monthly
MLR[3]	Statistical	Salinity	Florida Bay, Whitewater Bay, southwest Gulf coast, Manatee Bay, Barnes Sound	N/A	1965-2000, daily
Four Box[4]	Mass Balance	Salinity	Florida Bay	regional	1993-1998, monthly
FATHOM[5]	Mass Balance	Salinity	Florida Bay, Manatee Bay, Barnes Sound	open-water basins	1965-2000, monthly
EFDC[6]	3-D Hydrodynamic	Salinity	Florida Bay, Whitewater Bay, southwest Gulf coast, Manatee Bay, Barnes Sound	variable	1965-2000, daily
SICS/TIME[7]	2D/3D Coupled surface and groundwater	Stage, Flow, Salinity	Florida Bay (SICS), southwest Gulf coast (TIME)	0.3km X 0.3km (SICS, 0.5km X 0.5km (TIME)	1996-2000, daily
SoFLA-HYCOM[8]	3-D Hydrodynamic ocean circulation model	Flow magnitude and direction	Gulf of Mexico, Florida Straits	6-7km X 6-7km	?

[1] http://www.sfwmd.gov/org/pld/hsm/models/sfwmm/index.html
[2] Nuttle and Teed 2002, Nuttle 2004
[3] Marshall, 2005
[4] Nuttle et al. (2000)
[5] Cosby et al. 1999, Nuttle et al. 2000, Cosby et al 2004
[6] Hamrick and Moustafa, 2003
[7] Swain, et al 2004 (SICS), Langevin, et al 2002 (TIME)
[8] Kourafalou, 2005

Table 7. Summary evaluation of Florida Bay salinity and hydrology models using the Florida Bay Science Program evaluation factors (PMC 2000). Models with asterisk (*) are freshwater hydrology only models. Score is from 1=lowest to 5=highest.

Model	Portability	Validity	Fidelity	Focus	Ease of Use
SFWMM*	2	5	3	4	3
PHAST*	3	4	3	3	5
MLR	5	5	5	5	5
Four Box*	3	4	4	3	5
FATHOM	3	5	4	5	4
EFDC	2	5	3	5	3
SICS/TIME	2	5	4	5	3
SoFLA-HYCOM	2	3	?	3	3

Figure 7. A comparison of observed salinity (SERC), monthly average salinity (MMN), and simulations by FATHOM and MLR salinity models (monthly average) at Long Sound.

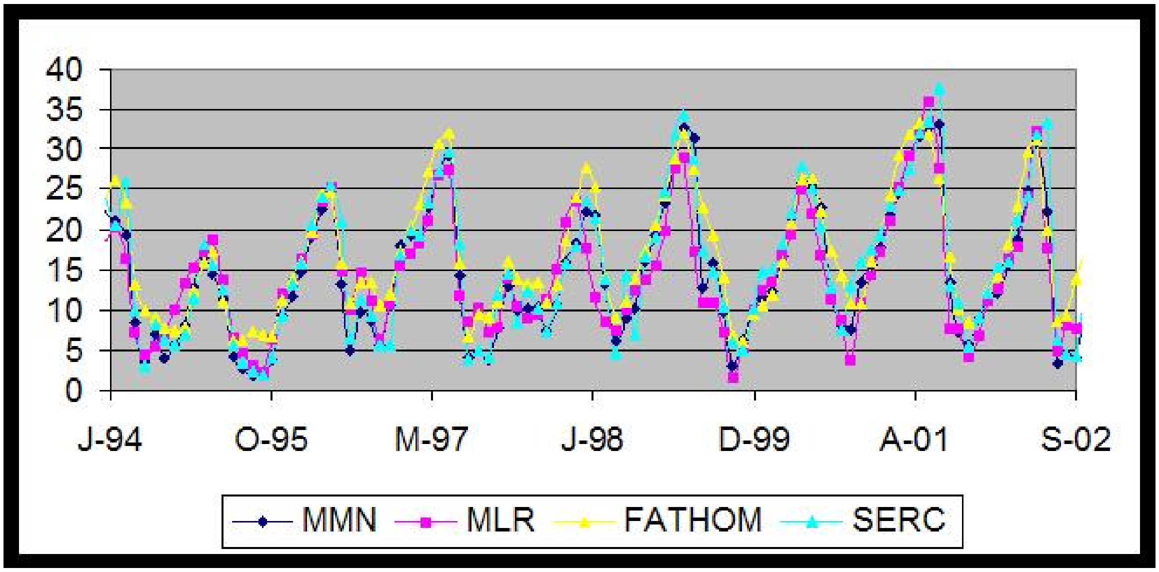
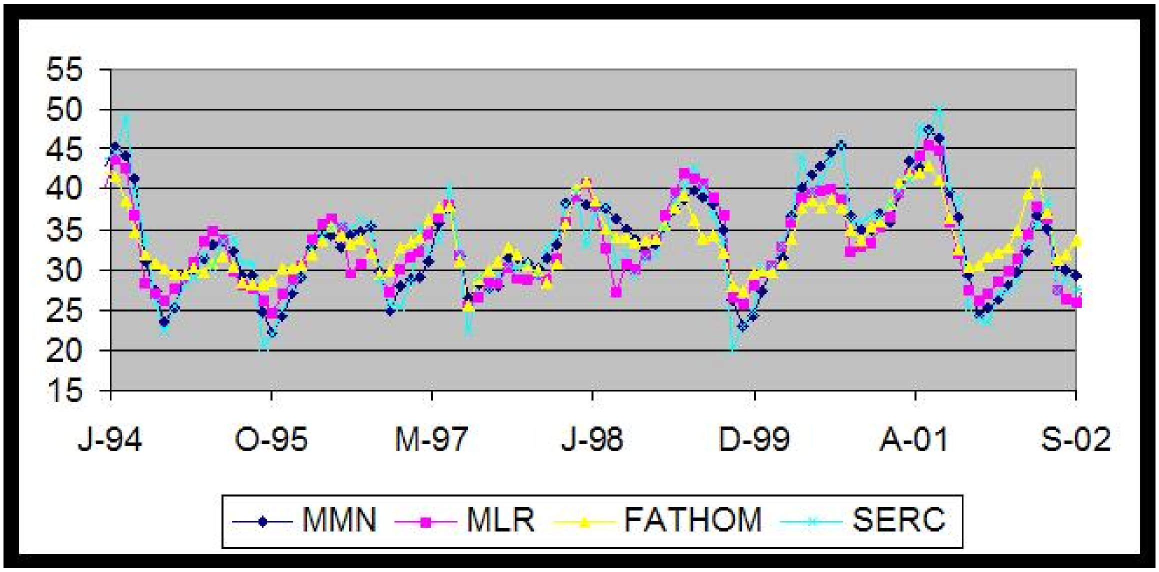


Figure 8. A comparison of observed salinity (SERC), monthly average salinity (MMN), and simulations by FATHOM and MLR salinity models (monthly average) at Whipray Basin.



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