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Salinity-Based Performance Measures Project:

Report #1: Review and Evaluation of Hydrologic Modeling Tools for the Coastal Mangroves and Florida Bay

prepared for

Everglades National Park

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Executive Summary

Freshwater flowing as diffuse overland flow and groundwater links coastal ecosystems of South Florida to the Everglades marshes and to the water management facilities of the Central and Southern Florida Project. Attempts to anticipate what effects changing water management and restoring the hydrology of the Everglades will have on the ecology of coastal mangroves and Florida Bay necessarily requires information about this hydrological link. However, these areas are not represented in the regional hydrology models routinely used for water management planning. It has only been recently that these flows have been studied.

This report reviews and evaluates recent work on the hydrology and salinity of the coastal mangroves in Everglades National Park and Florida Bay and recommends an approach to formulating predictive models for use as performance measures. This evaluation is based on predictive ability and practical considerations related to needs imposed by the multi-agency planning process that guides ecosystem restoration in South Florida. The goal for this report is to identify an approach that can be implemented quickly so to satisfy the immediate need for predictive tools to in planning.

The focus is on predicting salinity in the coastal mangroves and Florida Bay. Salinity is an intermediate link between changes in Everglades hydrology and the ecological effects of these changes in estuarine areas. This report considers three basic approaches to prediction: descriptive analysis, correlation, and mechanistic models. Evaluation of these approaches recognizes the trade off between predictive ability and practical considerations of implementation.

This report recommends developing mass balance models to simulate the effects of changing Everglades hydrology on the hydrology and salinity of the coastal mangrove zone and Florida Bay. Preliminary results already obtained in the application of mass balance models in the Everglades and Florida Bay give confidence that this approach can be used to simulate hydrology (levels and flows) and estuarine salinity. The implementation of mass balance models is compatible with and supports the development and implementation of more comprehensive hydrologic and hydrodynamic models. At the same time, the simpler mass balance models provide managers with a practical, predictive tool to meet their immediate needs.

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Introduction

The Comprehensive Everglades Restoration Plan (CERP) directs federal and state resource managers to restore the hydrology of the Everglades in South Florida, particularly in Everglades National Park. CERP offers the best opportunity to resolve the conflicts between water management for agriculture and urban development and the hydrologic conditions needed to sustain the natural systems protected within Everglades Park. These conflicts date from before the establishment of the Park in the 1940s. Since the completion of the Central and Southern Florida Project in the 1960s, attention has focused mainly on the amount and timing of water deliveries to the Park and on the effects of canal levels on areas along its eastern boundary.

In addition to providing a clear mandate and the resources to resolve these issues, CERP also establishes a framework for adaptive management. Adaptive management refers to an approach to planning and program management designed to direct the redevelopment of water management toward meeting ecological restoration goals defined throughout the region. Everglades National Park is working to implement the mechanisms of adaptive management, including building the decision-support tools required for ecological assessment.

Florida Bay, the adjacent mangrove swamps and the mangrove estuaries north of Cape Sable occupy about two thirds of the area of Everglades National Park. However, little scientific knowledge of the hydrology and ecology of these areas existed before about fifteen years ago. Beginning in late 1980s and continuing into the 1990s, alarming changes occurred in the ecology of Florida Bay. Concern over the severity of these changes and the future trajectory of the affected ecosystems spurred a comprehensive program of research into the hydrology, hydrodynamics and ecology of Florida Bay. At the same time, a separate program of research began investigating the effects of global change, including changes in sea level, climate and water management, on the coastal mangroves within Everglades Park. Results from these multiple-agency, interdisciplinary research programs will be useful to managers.

This report begins the process of assembling the recently acquired scientific knowledge of Florida Bay and the coastal mangrove zone into a set of environmental assessment tools. The immediate goal of this work is to extend the predictions of existing hydrologic simulation models into the coastal mangrove zone and out into Florida Bay. This report reviews and evaluates different approaches to predicting changes in hydrology and surface water salinity in the coastal mangrove zone and in Florida Bay. Based on this information, this report recommends an approach to formulating a set of hydrologic and salinity models that can serve as screening tools in assessing alternatives for hydrologic restoration in Everglades National Park.

Background

Hydrologic simulations based on predictive models form the backbone of water resource planning. Water resource planning in South Florida currently relies on simulations performed with the South Florida Water Management Model (2x2 model) that is maintained by the South Florida Water Management District. The domain for this model covers the Everglades Protected Area (roughly the former extent of the Everglades south of the Everglades Agricultural Area), the southwest coast, and the developed areas along the southeast Florida coast between Jupiter

and Florida City. A related model, the Natural Systems Model (NSM) provides benchmark simulations of “historical” hydrologic conditions in the region. Both of these models are principally regional planning tools, and as such output from these models (water flows and levels) serve as the point of departure for the sub-regional ecological assessments.

Current practice is to simulate the regional hydrologic response under proposed structural and/or operational changes for the 31-year period 1965 through 1995. Model outputs at prescribed locations are then examined to assess each management alternative with respect to various operational and ecological constraints and objectives. The 2x2 model and NSM are well-described elsewhere, e.g. Fennema et al. (1994), and the details of their operation and application will not be dealt with further in this report.

Hydrologic flows and water levels in coastal mangrove zone of Everglades Park are not simulated by the current regional hydrology models. The model grids for the 2x2 model and the NSM do not cover the mangrove zone fully, even though plots of model output sometimes show full coverage. The conditions used to represent these coastal boundaries within the models must be regarded as approximations, at best. Essentially, these deficiencies have excluded the coastal mangrove zone and, downstream, Florida Bay from the integrated assessment of water management alternatives with the 2x2 and NSM hydrology models.

The need to integrate the coastal mangrove zone and Florida Bay into the assessment of water management alternatives motivates the present work. The ultimate solution will be to extend the domain of the hydrologic simulation models so that they include the coastal mangrove zone and couple with estuarine hydrodynamic and water quality models to simulate conditions in Florida Bay. Indeed, a team in the US Geological Survey is pursuing the long-term goal of implementing a coupled surface water and groundwater hydrology model in the coastal mangrove zone (Schaffranek et al. 2001). However, linking the hydrology of sheet flow in the Everglades freshwater marshes with tide-driven channelized flow in the coastal mangroves presents a significant challenge for the modelers that will not soon be solved.

Objective and approach

This report reviews and evaluates simulation models that have been used, are being used, and might be used to extend results of hydrologic simulations obtained by the 2x2 model and NSM into the coastal mangrove zone and Florida Bay. In general, the models considered here do not involve the implementation of fully articulated, coupled surface and groundwater numerical codes. However, the physical principles underlying the fully articulated hydrologic models can still be applied.

Experience suggests that a trade off occurs between practicality and predictive ability, and so the selection of a modeling approach must strike a balance between the two. For example, while there is little question that mechanistic models based on a full articulation of conservation of mass and momentum, i.e. hydraulic and hydrodynamic models, would function best in predicting response to radical changes to water management, practical considerations currently prevent the application of these models to routine assessment in the immediate future. This report seeks to identify a modeling approach that can be implemented quickly so to meet the immediate needs of the Park for a planning and assessment tool.

This review relies on published abstracts of the 1999 and 2001 Science Conferences of the Florida Bay Science Program, reports of various workshops sponsored by the Florida Bay Science Program on the general topic of simulation modeling, and personal knowledge of the relevant research. Several individuals were contacted directly to obtain recent information on their work. Finally, a draft of this report was reviewed with staff at Everglades National Park. The recommendations reflect additional information obtained as a result of this review.

Basis for Evaluating Models

Adaptive management within CERP relies on performance measures that track observable attributes of the ecosystems in region. An ecological performance measure consists of an ecological indicator that measures the ecosystem attribute, a restoration goal for the indicator, and the capacity to predict how the indicator will respond to specific restoration activities. In planning for CERP, i.e. the Restudy, assessment of various options relied mostly on hydrological performance measures, such as matching flows and hydroperiods derived from the NSM simulations at critical locations throughout the region. The 2x2 model provided the predictive capability needed to investigate the hydrological consequences of alternative management scenarios. The implementation of CERP now requires the development of performance measures with explicit ecological endpoints.

Properties of an ecological indicator

An ideal ecological indicator has some specific characteristics. First, the indicator must be an integrative measure of overall ecosystem function, not one that narrowly measures a peripheral component or secondary process. Second, the indicator must be responsive; that is it should be possible to see measurable changes over a relatively short period of time. Third, the indicator should behave in a way that is consistent with the hypothesized mechanics of the ecosystem; that is, it should not be necessary to suspend one's understanding of the ecosystem in order to interpret changes in the indicator. Finally, it should be possible to predict quantitatively how the indicator (i.e. the ecosystem) will respond to changes in water management as distinct from other sources of variation.

Importance of salinity

Formulation of predictive salinity models will be a critical milestone in the progress toward linking water management decisions with ecological indicators in the coastal mangrove zone and Florida Bay. Salinity is one of the main factors that influences the structure and function of estuarine ecosystems; freshwater discharge and the associated nutrient loading are also important (McIvor et al. 1994). Therefore, salinity forms a link in the causal chain intermediate between changing hydrological conditions in the Everglades and the ecological response in estuarine areas.

Paleoecological studies in Florida Bay reveal changes in the salinity regime coincident with the beginning of efforts to divert water out of the northern portion of the Everglades during the first half of the 20th Century. Some scientists point to changes in the amount, timing and distribution of freshwater discharge in the Florida Bay related to these and more recent water management activities as the cause of the ecological changes seen in the late 1980s and early 1990s.

Changes in salinity will occur in advance of ecological changes, and thus salinity serves as a physiochemical indicator of restoration success. Hydrologic simulation models for the coastal mangroves and Florida Bay, at a minimum, must account for the effects on salinity of changes in the hydrology of the freshwater wetlands inland in Everglades National Park. This much is

required to provide a basis for ecological performance measures in the coastal mangroves and Florida Bay.

Three approaches to prediction

Planning restoration activities requires an ability to anticipate how the ecosystem will respond to specific, proposed changes in water management. Ecological performance measures provide the ability to forecast the effects of changing Everglades hydrology on the coastal mangroves and Florida Bay. This is the practical motivation for building predictive models for this region. Predictive ability increases with improved scientific understanding through the synthesis of research results. Therefore, formulation and refinement of predictive models serves both an essential function in the accumulation of knowledge through research and in the application of that knowledge toward the practical goals of water management.

Predictive ability builds in stages. Hobbie (2000) describes a progression of five stages in estuarine science that begins with analysis of observations and ultimately leads to the use of simulation models based on detailed representation of physical processes, biogeochemistry and ecology. Each stage makes possible a different approach to prediction, and predictive ability improves through subsequent stages. This review focuses on the first three stages: descriptive data analysis, correlation, and the formulation of simple mechanistic models.

Descriptive analysis identifies basic patterns in the data that describe the phenomenon of interest. Here, this is the record of salinity observations in the coastal mangrove zone and Florida Bay. Descriptive analysis lays the foundation for constructing models capable of reproducing these patterns of variation. Descriptive analysis also serves to diagnose bias and other problems related to the methods of observation and measurement. Patterns provide clues to the underlying causal mechanisms by their proximity in time and space. Recurrent patterns in the data, such as the annual cycle of wet and dry season, are predictive in their own right in the mode of a null model. Of course, the underlying assertion of a null model is that the unspecified mechanisms driving the phenomenon will continue to operate unchanged.

Correlation formalizes the search for a similarity in patterns indicative of causal mechanisms underlying the phenomenon. Correlative analysis is employed both as a screening technique to identify potential cause and effect relationships and as the first test of hypothesized relationships. A number of statistical tools can be used, ranging from simple linear regression to more complicated analytical techniques such as multivariate and time series statistical procedures. The empirical models that result from this stage of analysis often are employed as predictive tools. However, correlation alone does not indicate that a cause and effect relationship exists.

Mechanistic models attempt an explicit representation of the causes and mechanisms underlying a phenomenon. Usually this will be in the form of a mathematical model based on representation of one or more fundamental principles. At a minimum, mechanistic hydrologic models employ the principle of mass conservation. Hydraulic and hydrodynamic models employ both the conservation of mass and conservation of momentum. Models of water quality employ the laws of chemistry, and so on. Explicit representation of cause and effect based on general principles increases confidence in the ability of a model to predict the behavior of the system beyond the range that has been observed.

Practical considerations

Practical considerations arise from limitations on the resources available first to formulate and validate predictive models and second to apply these as simulation tools in the multi-agency environment within which the planning for restoration takes place. Time is the primary limiting resource; predictive tools are needed immediately for planning and assessment of operations related to the Modified Water Deliveries and the C111 projects. Also limiting are the knowledge and data available to formulate the models and the level of experience and expertise of agency staff who must apply the models and interpret their results.

Practical considerations impose certain requirements on the models that are not directly related to their grounding in science. The Florida Bay Science Program sponsored a workshop in May 2000 to review the practical requirements related to implementation of a hydrodynamic model for Florida Bay (PMC 2000a). The practical requirements described below are drawn from the results of that workshop.

Portability – The model should be widely available for evaluation and application. This requirement extends also to the documentation and data needed to apply the model. Simulation models that require specialized computing equipment, e.g. access to parallel processing or a supercomputer facility, effectively are not widely available.

Validity – The predictive capability of the model is generally known and accepted. Recent comments by the National Research Council on the Keys carrying capacity study (NRC 2002) reinforce the importance of model validation. An important aspect of validation is the existence of a data set that is generally accepted to represent the variation in the system that the model is intended to explain.

Fidelity – The model is consistent with understood mechanisms of cause and effect – within the limitations of the underlying approach to prediction. This condition reflects one of the characteristics of an ideal ecological indicator. This also challenges model builders to become familiar with, and extend, the current state of understanding of the ecosystem.

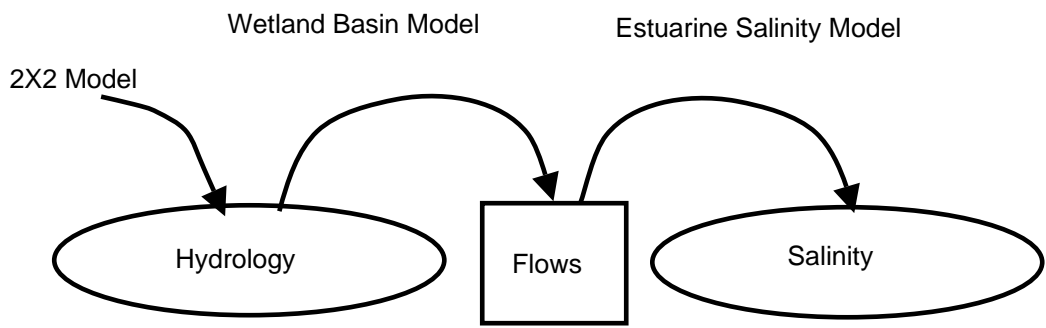
Focus – Model predictions relate directly to the ecosystem attributes defined as performance measures. Salinity is physical attribute of mangrove and estuarine ecosystems that links to other, biological components of these systems. However, different attributes of salinity variation may have different ecological effects. Linking different attributes of salinity to ecological indicators might be best approached using different models rather than relying on a single predictive model for salinity.

Ease of use – Model results can be obtained quickly within the time allotted for analysis of alternatives. Generally, this has meant that simulation results should be available within 24 hours, including staff time needed to load in a new scenario and interpret the model output. Typically, scenarios will involve simulation of 31 or 36 years; the standard period in the Restudy was 1965 through 1995. Alternatively, if a monte carlo approach is used to map ecosystem response in a probabilistic sense, then models must be capable of iteratively rerunning a large number of simulations with randomized inputs. Attention must be paid to the computational facilities needed to run the models and to the presentation of simulation results.

Results of another workshop on salinity modeling (PMC 2000b) recommend a focus on predicting freshwater flow into Florida Bay from the coastal mangroves, Figure 1. Salinity is affected directly by changes in freshwater discharge, and salinity is only indirectly affected by water levels in the Everglades through the relationship between water level and discharge. Ninety percent of the discharge from the coastal mangroves occurs through small creeks entering the northeast portion of Florida Bay. Sheet flow accounts for the remaining ten percent, and groundwater discharge is believed to deliver little or no freshwater to Florida Bay, in spite of the fact that high fluxes of groundwater have been measured in the Bay (Corbett et al. 1999).

Attention to estimating freshwater flow at the coast supports the development and implementation of other models for circulation, salinity and water quality in Florida Bay. Any model based on the implementation of a mechanistic modeling approach, such as a hydrodynamic model will require freshwater flows as a boundary condition. The Florida Bay Science Program is assembling data from the 1994 through 2000 for use in calibrating and validating hydrodynamic and water quality models of the Bay. Measurements of direct freshwater inflow do not exist for this entire period. This requires attention to be paid to reconstructing historical freshwater discharge into Florida Bay, both directly from Taylor Slough and C111 and indirectly from Shark River discharge.

Figure 1: Recommended scheme for linking Everglades hydrology to the coastal mangrove zone and salinity prediction in Florida Bay.



Review

Research on the connection between Everglades hydrology and salinity in the coastal mangroves and Florida Bay dates back at least 35 years to the Durbin Tabb's work (Tabb 1967). This section reviews the principal studies that provide the basis for extending hydrologic predictions into the coastal mangroves and Florida Bay. Discussion of the results of these studies is organized by the underlying approach, i.e. descriptive analysis, correlation and mechanistic models, and by geographical setting.

For purposes of this report, the estuarine portion of Everglades Park is divided into three regions: the coastal mangroves downstream of Shark Slough and along the southwest coast, the coastal mangroves downstream of Taylor Slough/C111, and Florida Bay. These areas differ in their hydrology, surficial geology and vegetation communities. As a result the motivation, approach and progress in understanding the connection between hydrology and salinity in each region also has been different.

Discharge structures and culverts crossing Tamiami Trail form headwaters within Everglades National Park of the Shark Slough drainage. Surface water in Shark Slough flows generally southwest to Whitewater Bay and the Gulf of Mexico through the Shark and Harney rivers. Rivers north of the Harney River have their headwaters in Big Cypress Preserve. Long Pine Key and the main Park road to Flamingo form a surface water divide that separates Shark Slough from the Taylor Slough/C111 basins. Some hydrologic communication may occur between these basins as groundwater flow or as surface water during periods of extreme high water.

The Taylor Slough/C111 basin discharges into Florida Bay from headwaters in the rocky glades near the main entrance to Everglades Park, west of Homestead. Surface water flow in the Taylor Slough/C111 basin is divided between flow following the natural course of Taylor Slough, south of the Park road, and flow from canals, principally as overflow from the C111 canal in the eastern portion of the basin. The flow in Taylor Slough proper has its source as rainfall on the rocky glades area of the Park and in the discharge of the S332, S332D pump stations.

Florida Bay receives freshwater runoff directly from the Taylor Slough/C111 basin, mostly in the northeastern portion of the Bay. However, rainfall is the major source of freshwater, about ten times the volume of runoff received directly from the Taylor Slough/C111 basin. Runoff from Shark Slough also reaches the western portions of Bay through a coastal current that flows south from the mouth of the Shark River.

Descriptive analysis

Robblee et al. (2001) describe an ongoing effort to compile all existing salinity data for Florida Bay and the mangrove estuaries of the southwest coast. This comprehensive compilation includes two data sets that are being compiled in separate on-going monitoring programs. Everglades National Park (2001) reports results from marine monitoring stations (instrumented platforms), and Jones and Boyer (2001) report results of Florida International University's Estuarine Water Quality Monitoring Program (monthly surveys). NOAA (1996), Boyer et al.

(1997), Nuttle (1997) and Everglades National Park (2001) describe different aspects of salinity variation in the coastal mangroves and Florida Bay.

Table 1: Studies providing descriptive analysis of salinity data

Shark Slough	Taylor Slough/C111	Florida Bay
Nuttle 1997 – proportion of salinity variation in mean seasonal plus trend component and in high frequency (tidal) and low frequency components.	Nuttle 1997 – proportion of salinity variation in mean seasonal plus trend component.	NOAA 1996 – review and analysis of historical salinity.
Jones and Boyer (2001) – annual report of the coastal water quality monitoring conducted by FIU.	Jones and Boyer (2001) – annual report of the coastal water quality monitoring conducted by FIU.	Boyer et al.1999 – description of patterns and trends in water quality data for three zones.
Robblee et al. (2001) – compilation of historical salinity data	Robblee et al. (2001) – compilation of historical salinity data	Jones and Boyer (2001) – annual report of the coastal water quality monitoring conducted by FIU.
Everglades National Park (2001) – data summary of Everglades Park’s marine monitoring network.	Everglades National Park (2001) – data summary of Everglades Park’s marine monitoring network.	Robblee et al. (2001) – compilation of historical salinity data
		Everglades National Park (2001) – data summary of Everglades Park’s marine monitoring network.

The quantitative record of salinity in Florida Bay begins in 1908 (Robblee et al. 2001). To date salinity observations have been gathered from seventy-two published and unpublished studies; however the data coverage is sufficient to discern trends only since about 1955.

Regular monitoring was initiated by Everglades Park in the early 1980s. Bay-wide coverage began in 1988, and it has been expanded to include continuous (10 minute interval) monitoring of conductivity, temperature and water level at 18 stations in Florida Bay and 15 stations along the southwest coast. Everglades National Park (2001) is the latest in a series of data reports that start with 1993. These data reports provide basic statistics on each of the monitored parameters on a daily, weekly, monthly and annual basis.

Beginning in the early 1990s, the Southeast Environmental Research Program at Florida International University (FIU) initiated a long-term program to monitor 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 among a suite of nutrient and other water quality parameters. Jones and Boyer (2001) is the latest in a series of annual summaries for this monitoring program. These reports include a summary of the data and discuss long-term trends in water quality on a regional basis.

Two studies have analyzed salinity data from Florida Bay and the southwest coast to describe spatial and temporal patterns and trends. Boyer et al. (1997) apply multivariate statistics to the analysis of the FIU water quality data set and identify three zones of similar influence within Florida Bay and two zones in the coastal mangroves along the southwest coast. The three zones identified in Florida Bay are similar to subdivisions of the Bay that have been identified by others based on bottom morphology, benthic fauna and other factors.

NOAA (1996) reports results of a comprehensive analysis of entire historical salinity database for the period 1955 through 1994 in Florida Bay. The NOAA study employed a number of statistical techniques to describe spatial patterns and temporal trends, time series characteristics and correlation with regional hydrology. The report identifies ten zones within the Bay and attempts to correlate long-term changes in salinity and the variation in salinity with periods of significant change in the regional hydrology. The analysis stops short of developing predictive models for salinity based on hydrologic variables

Nuttle (1997) analyzes salinity data, for the period 1991 through mid-1997, from fourteen of the FIU monitoring locations, Figure 2, and from eight locations of the Everglades National Park marine monitoring network along the southwest coast. Nuttle (1997) characterized the proportion of the variation in monthly salinity observations that corresponded to the mean seasonal pattern plus any linear trend in the data, Table 2. Using the continuous data from the Everglades National Park monitoring platforms, Nuttle (1997) analyzed these data to determine the relative contribution of tidal and subtidal (low frequency) processes to the total variation in salinity. These results showed only a small proportion of variation associated with higher frequency processes, so the conclusion was that the monthly data from the FIU data set could be used to derive the transfer functions. These analyses were conducted to characterize temporal patterns in the salinity data as preparation for deriving a set of predictive equations, transfer functions.

Figure 2: Location of salinity data (numbered) and Everglades hydrology data used by Nuttle (1997) to derive transfer functions for salinity prediction. These salinity data are from the monthly observations compiled by Florida International University.

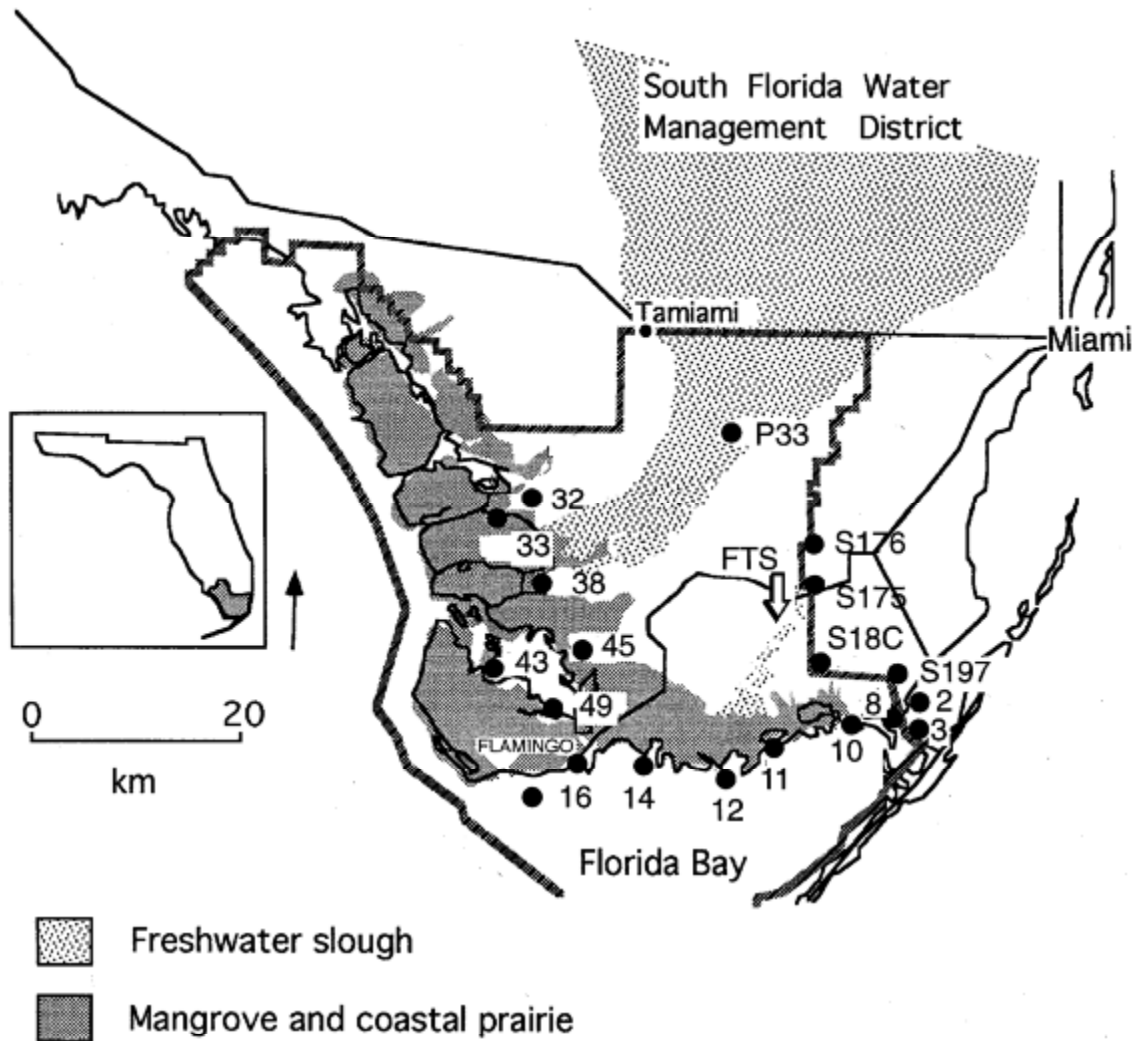


Table 2: Proportion of variation in monthly salinity described by mean seasonal pattern and trend (from descriptive analysis) compared to the variation described by the derived transfer functions (Nuttle 1997)

Station	Location	Season +Trend
2	Middle Key	0.35
3	Manatee Bay	0.42
8	Long Sound	0.62
10	Joe Bay	0.59
11	Little Madeira	0.59
12	Terrapin Bay	0.54
14	Garfield Bight	0.36
16	Murray Key	0.40
32	Cabbage Islands	0.36
33	Broad River	0.37
38	Tarpon Bay	0.46
43	West Marker 34	0.40
45	North River Mouth	0.43
49	Southeast Marker 1	0.39

Correlation

Correlation models linking estuarine salinity to Everglades hydrology have shown apparent success. For this reason and for reason of their ease of application, correlation models have been applied widely to forecast the effects of water management on salinity in the coastal bays of Florida Bay, Table 3. Tabb (1967) was the first to use correlation to investigate causes of salinity variation in Florida Bay and adjacent coastal areas. He developed linear regression models relating salinity in the coastal bays downstream from Taylor Slough/C111 to groundwater levels in Homestead and models relating water levels in Shark Slough to the position of the salinity front in the mangrove estuaries of the southwest coast. Tabb's work remains influential, i.e. McIvor et al. (1994).

SFWMD (1986) recalibrated Tabb's relationships for salinity in the coastal basins downstream of Taylor Sough/C111 following the completion of the South Dade Conveyance System. This water management project changed the hydrology of the region surrounding the Homestead well.

Table 3: Studies investigating empirical correlation between salinity and hydrology data

Shark Slough	Taylor Slough/C111	Florida Bay
<p>Tabb 1967 – correlation of salinity and position of salinity front with P35 at various locations.</p> <p>Nuttle 1997 – multiple regression models of salinity at 6 mangrove estuarine sites.</p>	<p>Tabb 1967 - correlation of salinity with P38 and S196 well and four coastal locations.</p> <p>SFWMD 1986 – linear regression for five locations.</p> <p>SFWMD 1997 – linear regression based on P33 level for salinity at four sites.</p> <p>Nuttle 1997 – multiple regression models of salinity at 8 coastal sites.</p> <p>Marshall 2000, 2001 – linear regression model for four coastal sites.</p>	<p>Tabb 1967 – correlation of salinity with P38 and S196 well and four bay locations.</p>

SFWMD (1997) derived a set of linear regression models for salinity in the coastal bays downstream of Taylor Slough/C111 based on water levels at P33, see Figure 2. The P33 salinity regression models were developed as a tool to evaluate estuarine impacts during the Restudy. Subsequently the P33 regressions were used to develop the Lower East Coast Water Supply plan and in other studies, c.f. VanLent et al. 1999.

Nuttle (1997) formulated a number of multiple regression models, Figure 2, linking estuarine salinity to a suite of hydrologic measures, including both water levels and flows, Table 4. These relationships were intended for use in the Restudy, but they never found wide use.

The dependence on simple linear regression models for predicting effects of water management on estuarine areas of South Florida has stimulated critical review of these models. Marshall (2000, 2001) finds a number of faults with the P33 regression models; some of these are reviewed in the next section of this report. Marshall (2000) recommends alternative regression models for salinity values downstream of Taylor Slough/C111. Apparently, the South Florida Water Management District and CERP have adopted a different set of regression models, based on water levels at NP67 (Rudnick, pers. comm).

Marshall (2001) extends his earlier critique of regression models and recommends the use of more sophisticated correlative analysis to the problem, i.e. time series modeling of daily hydrology and salinity. These recommendations are being pursued in work supported by Everglades National Park.

Table 4: Hydrologic parameters included in multiple regression models of salinity by Nuttle (1997) and Marshall (2000).

Variable	Description
SEND	salinity at end of month interpolated from FIU data set
SLKW	mean sea level at Key West (m) deviation from mean 1991-1996
EAVG	monthly mean pan evaporation for Flamingo (cm)
PFLAM	Flamingo precipitation (cm)
FTS	monthly vol. of flow in Taylor Slough (1000 m ³)
F18C	monthly vol. of flow at S18c (1000 m ³)
F197	monthly vol. of flow at S197 (1000 m ³)
F176	monthly vol. of flow at S176 (1000 m ³)
LS176	mean monthly level at s176 (m)
LS175	mean monthly level at s 175 (m)
LP33	mean monthly level at p33 (m)

Mechanistic models

Research aimed at developing and applying mechanistic models has pursued two radically different approaches. These are the aggregated representation of hydrology and salinity in mass-balance models and the detailed representation of tide and wind-driven water movements in wetland hydraulic and estuarine hydrodynamic models, i.e. SWIFT2D (Swain and Langevin, 2001) and the RMA-10 model (Kim et al. 1999). Both efforts have produced operational models, but these have not yet been used in the analysis of hydrologic restoration alternatives.

Mass balance models

Box models by Walker (1998), Nuttle et al. (Nuttle et al. 2000, Cosby et al. 1999, Nuttle et al. 2001), and Twilley (<http://www.uclouisiana.edu/~rrt4630/mangrove-restudy.htm>) apply mass balance calculations to the analysis of wetland hydrology, Florida Bay salinity, and salinity of Shark River, respectively. In all cases, these models incorporate simplified representations of water flow that are parameterized by matching model prediction to observed hydrology and salinity.

Table 5: Studies employing a mechanistic approach to modeling hydrology and salinity

Shark Slough	Taylor Slough/C111	Florida Bay
<p>Walker 1998 – aggregated watershed model to estimate discharge to coast.</p> <p>Bolster and Saiers 2001 – simplified surface water hydraulic model for Shark Slough (non-tidal area).</p> <p>Schaffranek et al. 2001 – TIME coupled hydrodynamic/transport surface-/ground-water model is under development.</p> <p>Twilley (website) – box model of Shark River.</p>	<p>Walker 1998 – aggregated watershed model to estimate discharge to coast.</p> <p>Swain and Langevin 2001, Wolfert et al 2001 – implementation of SWIFT2D and SEAWAT (groundwater model).</p>	<p>Nuttle et al. 2000, Cosby, Nuttle and Fourqurean 1999 – FATHOM, salinity estimated from tidal mixing across shoals separating 40 basins.</p> <p>Kim et al. 1999 – salinity simulated in hydrodynamic model of Florida Bay and adjacent coastal areas.</p> <p>Nuttle et al. 2001 – box model of salinity with four regions, monthly time step.</p>

Walker (1998) implemented a set of watershed hydrology models in Everglades National Park. These are used to estimate water and nutrient fluxes into the coastal mangroves. The models construct monthly water budgets for several wetland basins, Figure 3, based on data provide by the 2x2 hydrology model. The aggregated discharge from each basin is assumed to be related to mean water depth by a generalized power law. The parameters of this power law were estimated by fitting simulated water depths to observations. Over the long term, the mean outflow from the basins must be correct, assuming that the data on other terms in the water balance are accurate. The parameters of the flow model control the variation of estimated flows around the long-term mean value. Walker lacked the outflow data necessary to validate his watershed models, but he did find that predicted outflows were correlated with salinity in the coastal bays in the Taylor Slough/C111 area, Figure 4.

Figure 3: Delineation of the drainage areas used by Walker 1998 to model monthly discharge of freshwater into the coastal mangrove zone. (from <http://www.walker.net/flabay/obsflow.htm>)

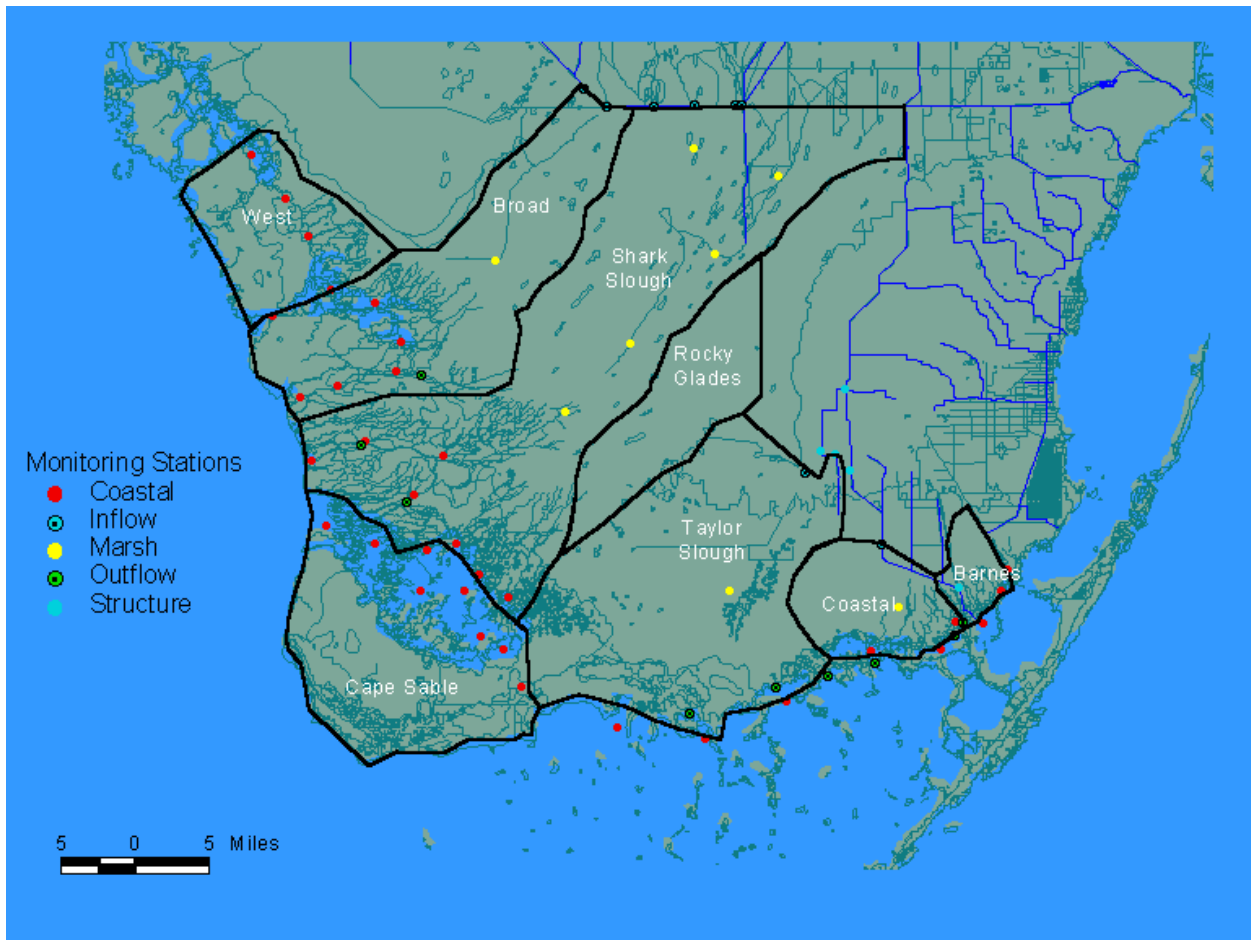
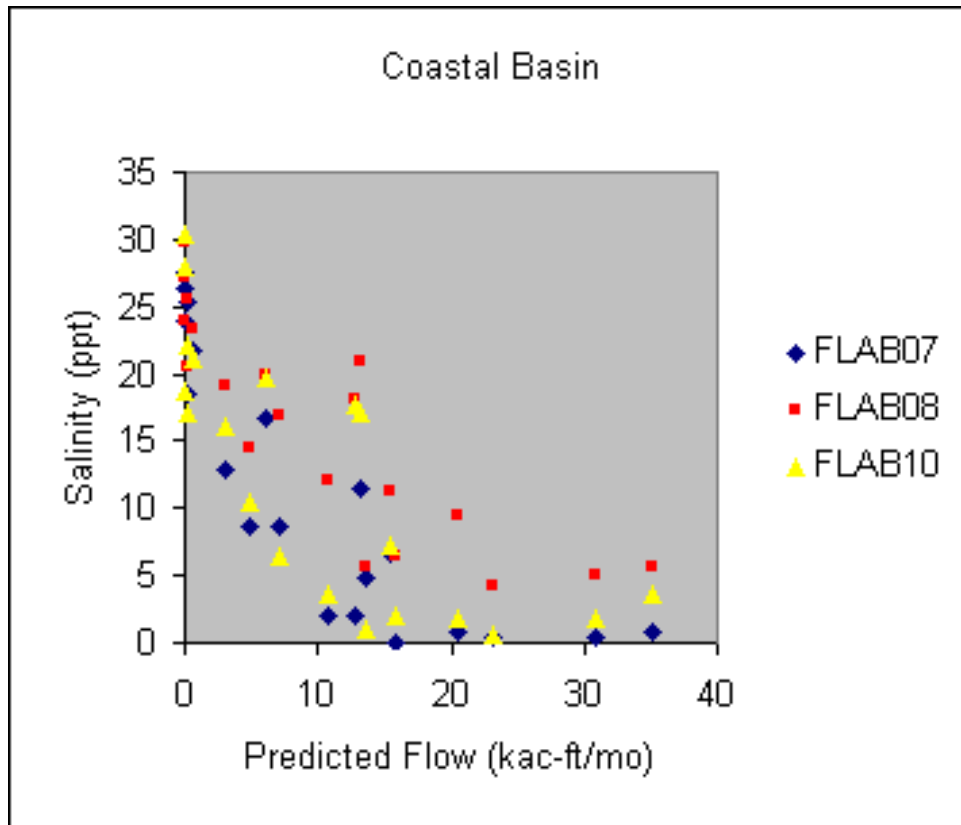


Figure 4: Monthly salinities in coastal bays compared to simulated freshwater discharge for the Coastal drainage basin using a watershed model (Walker 1997, <http://www.walker.net/flabay/obsflow.htm>)



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 5, 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 6. 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 essentially the annual averaged version of the four-box model described above, which they use to estimate mean annual evaporation from Florida Bay. The other, **FATHOM** (Cosby et al. 1999), divides the Bay into about 40 basins, based on its morphology, and estimates exchanges between basins based on 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.

Twilley (<http://www.uclouisia.edu/~rrt4630/mangrove-restudy.htm>) models salinity in the Shark River using boxes representing upper and lower reaches along the channel. The model includes the effects of advection, estimated from long-term records of freshwater flow, and dispersion determined by calibration. This is one of a set of models under development as part of a study of mangrove forest dynamics.

Other mechanistic models

In contrast to the box models, the detailed hydraulic and hydrodynamic models by Bolster and Saiers (2001), Schaffranek et al. (2001), Swain and Langevin (2001), Wolfert et al. (2001) and Kim et al. (1999) employ explicit representations of the momentum balance, as well as mass balance. These models provide a more detailed representation of flows and salinity than the aggregated, box models, but parameterization of the flow equations requires additional information about the physical characteristics of the aquifer, vegetation, and bottom roughness.

In principle, the hydraulic and hydrodynamic models under development can provide the predictive capability needed by resource managers. As a practical matter, applying these models in planning mode represents a significant undertaking. Further research is needed to support needed refinements in the hydrologic models because the data are incomplete that are needed to describe the transition from sheet flow in the Everglades to channelized flow in the tidal, estuarine areas, especially on the west coast. The following provides a brief description of

Figure 5: The box model divides Florida Bay into four regions based on observed patterns in water quality (Boyer et al 1997, Nuttle et al. 2000). Monthly salinity and rainfall data are 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 are estimated by optimization.

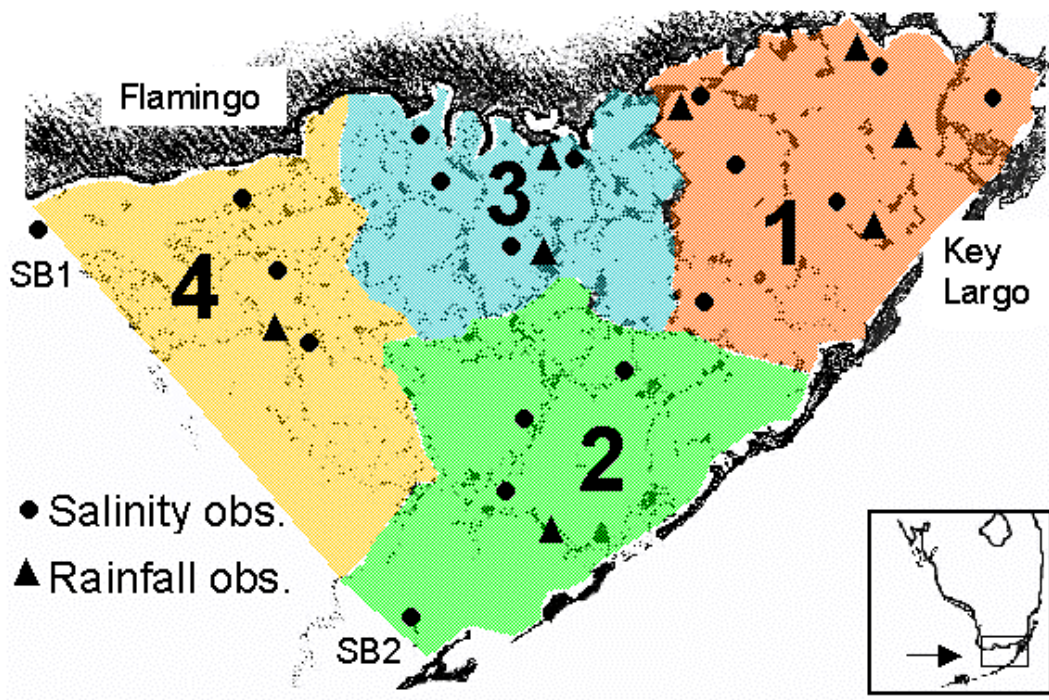
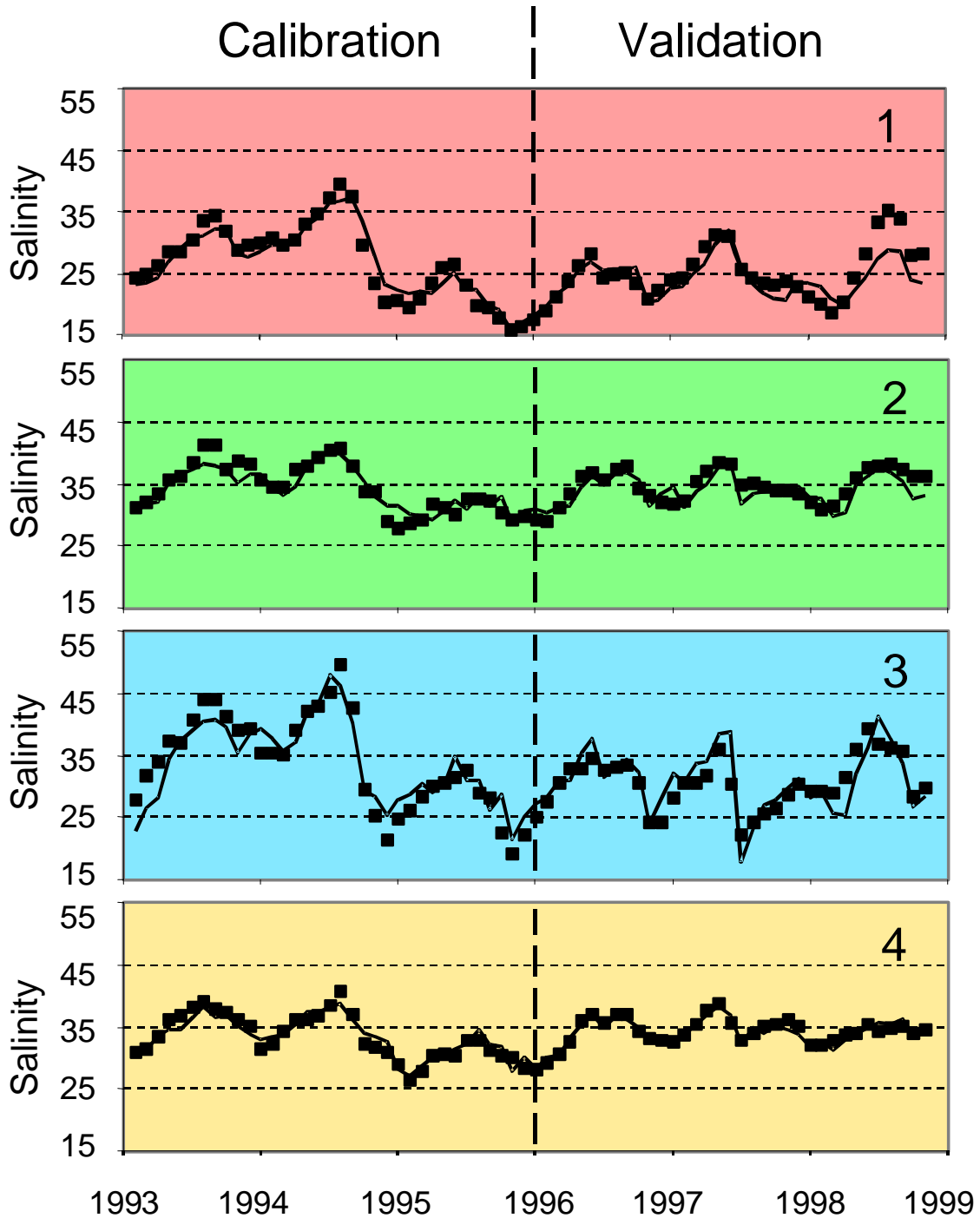


Figure 6: Box model calculations reproduce observed variation in regional salinity in Florida Bay with a standard error of 2 psu overall. The model was calibrated to fit salinity data in the first half of the data set. Comparison of predictions with salinity values in the second half of the data set test the predictive power of the model. The model error is the same for both periods. Panel numbers refer to region in model.



hydraulic models in use and under development. However, evaluation of these models falls outside of the scope of this report.

The ***South Florida Water Management Model*** (2x2 hydrology model) predicts water balances for South Florida on a uniform grid (2 x 2 mile cells). The model produces output at a daily time step for Calendar Years 1965-1995, but simulations do not take into account the changes in water management over this period. Output from the 95Base run of the Everglades Restudy most closely approximates current watershed and water-management conditions. The spatial resolution in the 2x2 model may not be sufficient to characterize the distribution of runoff into estuarine areas. The basic water-budget calculations performed by the model, however, should be reasonably accurate (Walker 1998). The model compiles useful estimates of spatially distributed rainfall and evapotranspiration rates over most of ENP for the 1965-1995 period.

The ***Everglades Landscape Model*** (ELM; <http://www.sfwmd.gov/org/wrp/elm/>) is a regional scale ecological model designed to predict the landscape ecological response to different water management scenarios in south Florida. ELM simulates changes to the hydrology, soil & water nutrients, periphyton biomass & community type, and vegetation biomass & community type in the Everglades region. ELM employs its own hydrologic simulation code, but it depends on the 2x2 model for inputs at the boundaries. The hydrologic simulation within ELM is calibrated to match the results of the 2x2 hydrology model. Extension of ELM into the coastal mangrove zone faces the same challenges as extension of the 2x2 hydrology model, but it would require the addition of a mangrove vegetation module to the present model.

The U.S. Geological Survey has made progress in implementing and calibrating a 2-D surface water hydraulics model spanning the coastal mangroves zone in the Taylor Slough/C111 area (***SICS***; Swain and Langevin 2001), and a similar effort is underway to expand coverage to include the coastal mangroves of the southwest coast (***TIME***; Schaffranek et al 2001). The SICS model has produced a two-year simulation (August 1996 to July 1998) of mangrove hydrology that matches measured creek flows at the monitoring points on Alligator, McCormick, Taylor, Mud, Trout and West Highway creeks. Current efforts are to add groundwater hydraulics into the SICS model and extend the simulation period to 1995 through 2000.

Bolster and Saiers (2002) recently have reported progress on implementing a 2-D wetland surface water model for a 27 km long transect in Shark Slough. The model implements a power law equation of flow with depth that has been used successfully in other types of wetlands. Results obtained by this approach suggest that reasonable accuracy in matching the fluctuation of water levels can be achieved with relatively simple numerical models and assuming uniform characteristics for rainfall, evaporation and vegetation. It is not known whether the authors intend to extent this approach into the coastal mangrove zone.

The U.S. Army Corps of Engineers, Jacksonville District Office, has supported the implementation of regional hydrology models with coverage in Everglades National Park (i.e. <http://sofia.er.usgs.gov/sfrsf/rooms/hydrology/modeling/>) and a hydrodynamic model for Florida Bay (Kim et al. 1999). The present status of these models could not be determined.

Evaluation

This section evaluates the utility of the three different approaches to prediction with respect to demonstrated predictive ability and the practical requirements for planning and assessment of restoration activities. Predictive ability has two aspects. First is the inherent accuracy of the model in representing the linkages between cause and effect. This is needed for the model to be capable of forecasting the response of hydrology and estuarine salinity while fundamental changes are being made in the distribution of surface flows in the Everglades. Second is the ability of the model to explain observed variations in hydrology and estuarine salinity, as demonstrated through validation against observations. The confidence among intended users earned by validation is an essential factor in establishing the utility of a predictive model.

Descriptive analysis: necessary but not sufficient

Descriptive analysis reveals the mean temporal, i.e. seasonal, and spatial patterns in the variation of salinity. As a predictive tool, mean patterns of variation serve as a null model, i.e. the best guess of what the salinity will be when all other things are held constant. Historic patterns of salinity variation are predictive only to the extent that the future resembles the observed past. The objective for restoration is to restore the hydrology of the Everglades to pre-development conditions, i.e. conditions last seen prior to about 1920. However, the compilation of historical salinity data does not provide a record useful for analysis prior to about 1955 (Robblee et al. 2001). Therefore descriptive analysis alone is insufficient for the present purpose.

Knowledge of spatial and temporal patterns of salinity variation obtained from descriptive analysis is valuable for three reasons. First, spatial and temporal patterns in the data suggest which processes may be driving the variation, and they rule out others. For example, lower mean salinity values and a high degree of variability occurring on short timescales in the coastal bays along the north shore of Florida Bay, compared with stations out in the Bay, indicate the possible influence of freshwater runoff from the Everglades. On the other hand, the high degree of correlation among variations in salinity in adjacent basins that are known to receive different amounts of runoff argues for the influence of a regionally coherent factor, such as the seasonal rainfall cycle.

Second, the characteristic spatial and temporal scales imbedded in the salinity data indicate the resolution that is needed to accurately characterize salinity by monitoring and in simulation modeling. Nuttle (1997) addressed the influence of tidal processes on salinity in the mangrove estuaries downstream of Shark Slough. Salinity variation at this frequency is missed by the monthly sampling frequency used to compile a long-term data set, and in fact the monthly data may have been biased by this unsampled process. Examination of the proportion of variation occurring at high frequencies in a continuous record of salinity showed that monthly sampling was sufficient to capture greater than ninety percent of the variation in salinity at these sites.

Finally, the mean pattern of variation serves as the appropriate null model when validating predictive models based on either correlation or mechanistic modeling approaches. For example, Nuttle (1997) found that the mean seasonal pattern accounted for about half of the variance (correlation coefficient ~ 0.7) in monthly salinity values in the coastal mangrove zone, Table 6.

The remaining variance is explained by the combined influence of year-to-year natural, i.e. climatic, variation and the effect of water management activities. For a predictive model to be useful for guiding water management decisions, it must explain significantly more than the proportion of variation accounted for by the mean seasonal pattern

Table 6: Correlation obtained by regression relationships for Joe Bay salinity compared to correlation with mean seasonal pattern in salinity

Study	Calibration Period	Correlation Coefficient
Tabb (1967), Homestead well	1.2 years	-0.91
SFWMD (1986), Homestead well	8 years	-0.66
SFWMD (1997), P33	7 years	-0.77
Marshall (2000), P33	9 years	-0.79
Marshall (2000), S18C	9 years	-0.74
Marshall (2000), Taylor S.	9 years	-0.75
Mean seasonal pattern	9 years	0.76

Descriptive analysis does not provide the predictive ability needed to forecast the future effects of changing hydrology on the coastal mangroves and Florida Bay. This is because the objective of descriptive analysis is to describe the patterns of observed variation, and this necessarily limits analysis to existing conditions. However, this is important information that is needed to support the development of predictive models.

Correlation: vulnerable to error

Correlation leads to the development of predictive models by comparing patterns of variation in salinity with the variation in other related phenomena, e.g. hydrology. If a cause and effect relationship exists, as there certainly must be between hydrology and estuarine salinity, then a high degree of correlation provides the basis for accepting the resulting models, e.g. regression equations, as a predictive tool. However, correlation is also vulnerable to spurious results, as when the phenomena are related by the common influence of a third phenomenon. In this case, correlation alone does not provide sufficient basis for prediction.

Linear regression models have been widely applied to forecast salinity in near shore areas of Florida Bay. These models relate salinity to water levels at a gage located inland. For example, the Central and South Florida Project Restudy and the Lower East Coast Water Supply Plan both relied on a linear regression between salinity in several coastal bays and water levels at gage P33, located about 30 miles inland in Shark Slough, Figure 2. Ease of application, general acceptance of their validity due to an underlying cause and effect mechanism, and a high degree of correlation between patterns in salinity and in water levels all contribute to wide acceptance and use of regression models for salinity forecasts in the planning process.

Reliance on predictive models derived from correlation requires vigilance because the fidelity of the model to cause and effect must be established by other means. Tabb (1967) came to the conclusion that surface water in Shark Slough was physically unconnected to the coastal bays in

Florida Bay; and therefore water levels north and west of Long Pine Key, including P33, cannot be used for salinity forecasts in Florida Bay. Other critics of the P33 relationship have noted it unlikely that hydrology at P33 would have an instantaneous effect on salinity, as implied by the regression equation, due to the large distance of separation and low flow velocities characteristically found in Shark Slough. Marshall (2000) found that parameters of the regression equation linking salinity to water levels at P33 appear to be sensitive to water management operations in the region. This is not a desirable characteristic for a predictive model applied to planning water management activities.

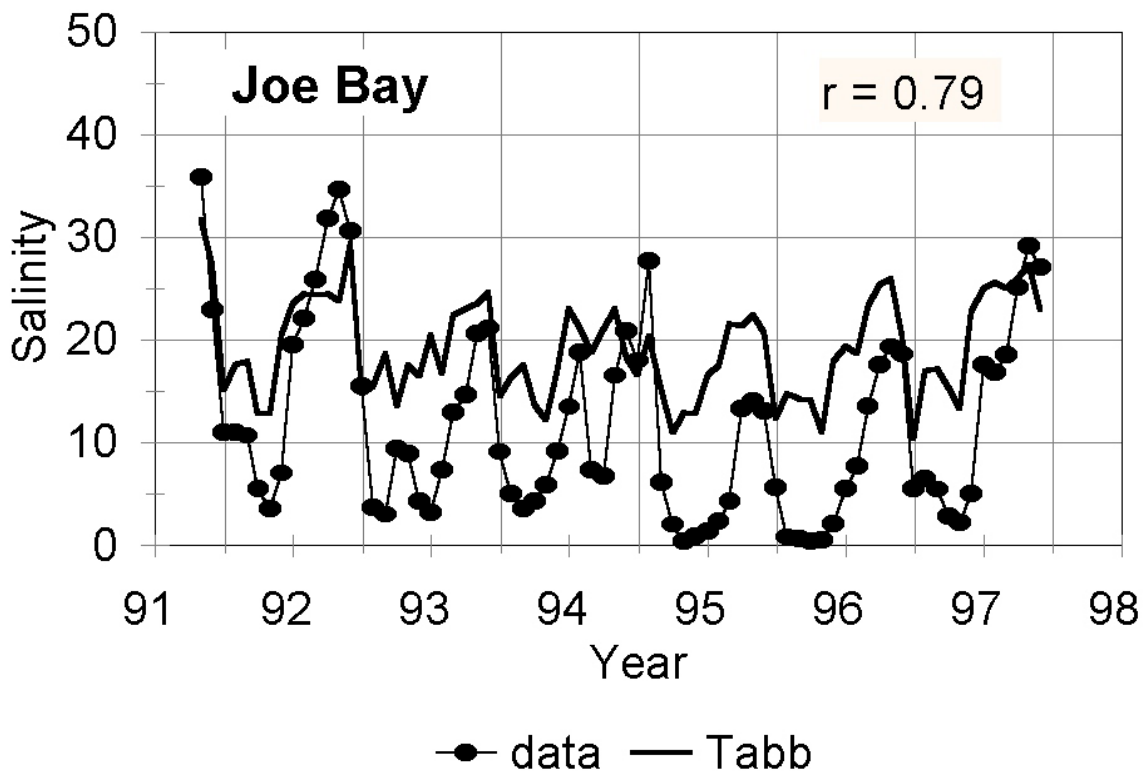
Yet, how does one explain the high degree of correlation one typically finds between near shore salinity and inland water levels, Table 6? The high degree correlation between salinity in the coastal bays of Florida Bay and water levels in Florida Bay is perhaps explained by the pervasive influence of regionally coherent climate. This casts the seasonal variation in climatic processes (rainfall and evaporation) in the role of the causal factor common to Everglades hydrology and salinity. This is a viable alternative to the hypothesis that changing water levels cause fluctuations in salinity through the physical mechanism of sheet flow and canal flows discharging along the coast.

Evidence for the alternative hypothesis is offered by the comparison of the correlation obtained by the regression models for Joe Bay salinity and the correlation of salinity to the mean seasonal pattern, Table 6. In all cases but one, the correlation of salinity with water level is the same as the correlation with the seasonal pattern. The implication is that water level observations contain no information about the salinity at Joe Bay beyond this mean seasonal pattern. Tabb's (1967) relation achieves a higher correlation perhaps because it is based on fitting only one annual cycle.

Application of Tabb's regression to "forecast" contemporary salinity values illustrates how a regression with a high degree of correlation can nonetheless fail to describe critical mechanisms affecting hydrology and salinity in the region. Tabb's regression equation is based on salinity and water level measurements made in the late 1960s. In Figure 7, contemporary salinity values are estimated by applying Tabb's regression equation to water levels measured in the same well during the recent period 1991 through 1997. Corresponding measurements are plotted on the same graph.

The correspondence between the regression results and observation is not good. Predicted salinity values exceed observations by about 10 ppt and the amplitude of seasonal variation is damped. However, the degree of correlation between salinity and groundwater levels remains high (correlation coefficient ~ 0.79) for the recent period. Therefore, a new regression model could be derived that would provide fair match to the observations, but this new regression equation would remain vulnerable to the same failing that caused Tabb's relation to fail when projected forward 30 years.

Figure 7: Simulated salinity values for Joe Bay compared to recently observed values. Simulated values are based on the linear regression model derived by Tabb with groundwater data from the period 1964-1966. A high degree of correlation remains between Joe Bay salinity and groundwater elevations, but the failure of Tabb's relationship to predict future salinity values is apparent.



Beginning in the late 1970s, and continuing until about the mid-1980s, the implementation of the South Dade Conveyance System increased flood protection and altered the hydrology of the region east of the headwaters of Taylor Slough and north of the C111 canal where it crosses Route 1 to the Florida Keys. One effect of these water management activities has been to raise mean groundwater levels and attenuate their seasonal fluctuations in the vicinity of the Homestead well, Figure 8.

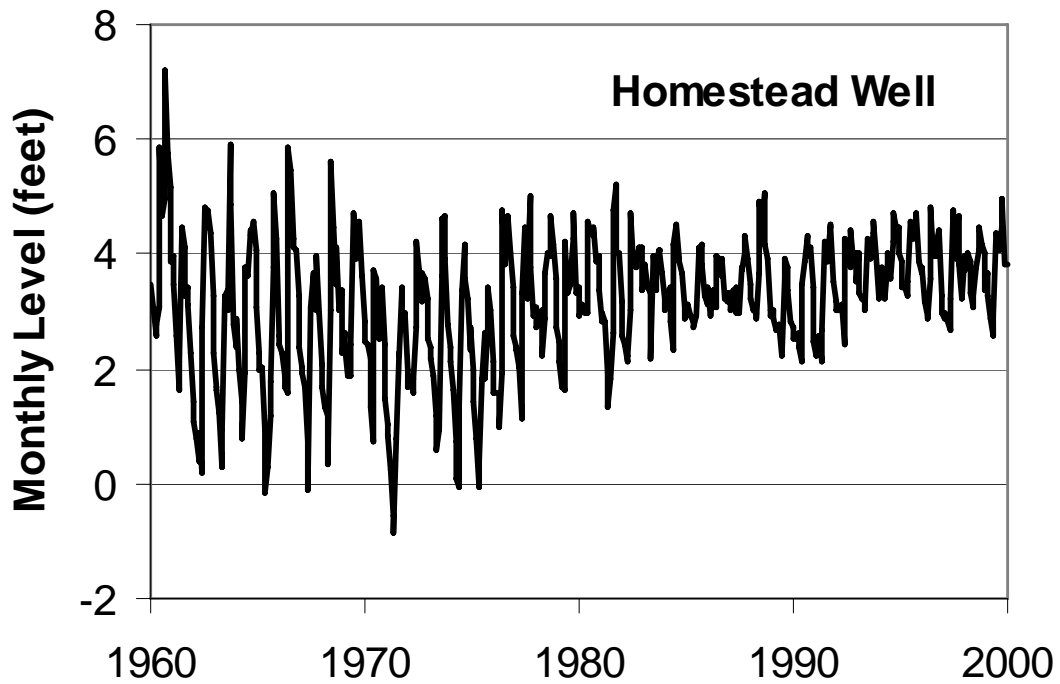
The record of water levels for the Homestead well records the effects of purposeful changes in inland hydrology over a significant portion of the watershed for the Taylor Slough/C111 area. However, it is apparent from the mismatch between Tabb's regression and contemporary salinity values, Figure 7, that the changes to the hydrologic conditions attributable to changes in water management in this area are not connected to salinity in the coastal bays of Florida Bay, at least to the degree suggested by Tabb's regression.

In conclusion, linear regression models developed for salinity in the coastal bays downstream of Taylor Slough/C111 lack fidelity to cause and effect, and they should not be used to forecast salinity changes in the mangroves and near shore regions of Florida Bay. Possibly the new regression model recently adopted for use by the South Florida Water Management District offers an improvement over other regression models, Table 6, in this respect, but this remains to be confirmed. Regression models have been unsuccessful in modeling salinity variation at locations in Florida Bay located away from the coast, Tabb (1967). Marshall (2001) reviews sources of difficulty to the application of regression models for salinity in the coastal mangroves and Florida Bay. He finds that the data display seasonality, autocorrelation and cross-correlation that are handled more appropriately in other types of empirical models, such as autoregressive models. It may be that these approaches can be more successful as predictive models for salinity.

Mechanistic models: mass balance

Results obtained so far in the application of mass-balance models are encouraging that this approach can be used to construct predictive models useful for planning and evaluation of water management activities related to Everglades restoration. The wetland hydrology models by Walker (1998) illustrate how the simulation results obtained by the 2x2 hydrology model can be interpreted and extended into the coastal mangrove zone. The results obtained in validation of the four-box model of Florida Bay indicate that this approach holds promise for predicting salinity in Florida Bay, Figure 6. However, the implementation of mass-balance models as planning and evaluation tools must recognize the limitations inherent in the predictive capability of these models and the deficiencies apparent in the existing mass-balance models.

Figure 8: The failure of Tabb's relationship can be traced to a shift in mean water levels in the Homestead well that occurred between 1980 and 1985. Tabb's regression model is based on groundwater levels measured in the later 1960s. Since then, a shift in groundwater levels occurred in response to structural and operational changes in water management associated with completion of flood control and drainage works in southern Miami-Dade County. The predictive models used to in conjunction with performance measures must be able to capture the effects of such changes.



Limitations inherent in the mass-balance approach relate to the aggregated nature of the models, their calibration, and validation against measured flows. Mass-balance models aggregate both explicitly, i.e. by representing the average salinity within large areas of Florida Bay, and implicitly by the parameters chosen to represent flow and storage characteristics. Aggregation limits the precision with which these models can represent localized and rapid changes in hydrology and salinity. As a result, the predictive capability of these models is highest for the monitoring locations used in calibration. Validation of flows, determined by calibration, is also a problem since flow data are relatively few and the data are not directly comparable to the aggregated flows represented in the models.

Deficiencies apparent in the existing hydrology and salinity models relate to the selection of regions employed for the mass balance calculations, characteristics of the data used for calibration, and unknown terms in the water and salt mass-balances. Walker's (1998) definition of wetland watersheds, Figure 3, generally follows the surface topography that was available at the time that he formulated the models. The delineation of these watersheds should be reviewed in light of more accurate topographic data that have recently become available. The structure of the salinity models by Nuttle et al. (2000, 2001) and Twilley (<http://www.ucs.louisiana.edu/~rrt4630/mangrove-restudy.htm>) should be reviewed in the areas of the coastal bays (northern Florida Bay) and the estuarine channels along the southwest coast. Much of the recent salinity data in Florida Bay and along the southwest coast has been collected as monthly grab samples. This introduces the possibility of introducing spurious variation due to aliasing if variation at tidal frequencies is high. Nuttle (1997) illustrates how salinity data from Everglades Park's monitoring platforms can be analyzed to assess this source of error.

Finally, both the hydrology and salinity mass balance models are vulnerable to errors arising from the unknown contribution of groundwater flow. There is also the question of how flow in Shark Slough might affect salinity values along the western boundary of Florida Bay. At present both of these effects are effectively ignored in the models due to lack of information. Recent research addresses the influence of groundwater flow on the water balance in the Taylor Slough/C111 area (Harvey et al. 2000, Price 2001). The significance of groundwater should be reviewed in the mass-balance hydrology and salinity models in light of these recent results. It may be possible to bound the influence of the discharge from Shark Slough on salinity values west of Florida Bay using results of investigations of estuarine plumes elsewhere.

On balance, a mass-balance approach to modeling hydrology and salinity in the coastal mangroves and Florida Bay satisfies most of the practical concerns. The models themselves are not computationally intensive, and it will be possible to implement them on computers that are commonly available. As a result, mass-balance models will be widely available within the multi-agency planning process and potentially easy to use. Mass-balance accounting provides a valid physical basis for linking inland hydrology to hydrologic and salinity conditions in the coastal mangroves and Florida Bay, albeit with recognized limitations. Attention will be required to validating the models against the available observations. The U.S. Geological Survey has compiled an approximately 6-year record (since 1996) of estimated net flow in the tidal creeks entering Florida Bay that will be useful in validating wetland hydrology models in the Taylor Slough/C111 area. The requirement for validation is not unique to this approach.

Recommended Approach

This report recommends using mass balance models to simulate the effects of changing Everglades hydrology on the hydrology and salinity of the coastal mangrove zone and Florida Bay. Preliminary results already obtained by other applications of mass balance models in the Everglades and Florida Bay give confidence that this approach can be used to simulate hydrology (levels and flows) and estuarine salinity. William Walker (1998) has implemented wetland basin hydrology models to estimate the flows needed to calculate nutrient loading to the coastal mangroves based on water balance data provided by the 2x2 model. For salinity, the mass balance modeling approach has been successful in simulating the seasonal and interannual variation of salinity in Florida Bay (Cosby et al. 2000, Nuttle 2001).

This approach breaks up the problem of linking conditions at inland and coastal estuarine sites by estimating freshwater flow at the coast, Figure 1, and separates the simulation of seasonal and inter-annual variation from the simulation of discrete “events.” By breaking the problem in half spatially, this approach implements lessons learned in earlier efforts to implement salinity models in Florida Bay (PMC 2000a, 2000b).

Limitations on the capacity of aggregated, mass balance models to simulate rapid changes in salinity can be compensated for by using a different modeling approach to predict the salinity response to short-term “events.” Other modeling approaches, e.g. time series models such as SARIMA (Marshall 2001) may prove useful in linking the causes of rapid fluctuations in hydrology to their effects on estuarine salinity and ecology.

Tasks

Implementation of a mass-balance approach to predicting freshwater discharge to and salinity in the coastal mangroves and Florida Bay can be broken down into the following tasks:

1. ***Identify wetland basins and estuarine indicator locations*** – Boundaries of the wetland basins will be delineated based on recent, detailed topography and recognized flow patterns. To the extent possible, basin boundaries should be drawn to correspond to the grid of the 2x2 model to facilitate coupling with the regional hydrologic simulations. Links to ecologic indicators, such as crocodile nesting habitat or wading bird foraging habitat will also be noted. Estuarine basins will be delineated in the coastal mangrove zone downstream of the wetland basins, and GIS analysis will be used to obtain basin areas and hypsometric relations. In Florida Bay, decide between using the higher resolution FATHOM model (40 basins) and the four-box mass balance model.
2. ***Assemble and describe salinity data*** – Salinity data will be assembled for each estuarine basin and analyzed to describe features, such as inherent time scales of variation, that are characteristic for each basin. Information will be gathered on salinity thresholds, ranges, etc. that link salinity with ecological indicators in each basin. Categorize which ecological indicators are driven by changes in the mean and seasonal and interannual

salinity variation and which indicators are driven by short term “events.” Identify the period of data to be used for calibration and validation of the salinity models.

3. ***Assemble water balance data*** – Wetland water levels, evapotranspiration, rainfall and surface inflow data will be assembled for each wetland basin. Determine whether the rainfall and evapotranspiration estimates used in the 2x2 model are sufficient for calibration and validation of the wetland basin models, as Walker (1998) has done. (Note: this may restrict the calibration and validation to the period prior to 1996 at the cost of not being able to then use more recent salinity data and measurements of discharge in mangrove creeks.) Determine how to handle the contribution of groundwater flow to the water budgets in wetland basins and discharge to estuarine basins. In Florida Bay, review and modify if desired estimates of regional rainfall and evaporation in existing work, and extend the period of data to correspond with periods selected for the wetland and estuarine basins. Assemble additional data as needed to characterize short-term variations in salinity, such as occurrence of emergency canal discharges for flood control.
4. ***Formulate, validate wetland basin models (stage and related discharge)*** – Wetland basin models will be calibrated against wetland water levels (variation in water storage) and validated against measured flows, including estimates of ungaged surface and groundwater flows, and salinity in coupled estuarine basins.
5. ***Formulate, validate estuarine basin models (salinity)*** – Mangrove salinity models will be calibrated and validated using observed salinity data, using separate portions of the salinity record as Nuttle (2001) has done for the mass balance model in Florida Bay (Figure 6). The mass balance modeling approach used by Nuttle (2001) in Florida Bay (see appendix) will be used primarily to simulate changes in the seasonal and interannual salinity patterns. It is anticipated that simulating changes in short term events will be carried out separately, using a different approach.
6. ***Implement models as assessment tools*** - Wetland basin models and mangrove salinity models will be implemented as assessment tools with a suitable user interface. Coupling with output of the 2x2 model is covered under this task.

Significance

The recommended approach offers a practical means of predicting discharge and salinity in the mangrove coastal zone and Florida Bay. The application of these models requires only moderate computational facilities, and these models can be implemented within a decision-support framework. Accuracy of the models depends on how well they describe fluxes and storage of water and salt and on the adequacy of the data used for calibration and prediction. The underlying principal of mass conservation is shared with more comprehensive hydrologic and hydrodynamic models. Therefore, the implementation of mass balance models is compatible with and supports the development and implementation of more comprehensive hydrologic and hydrodynamic models. At the same time, the simpler mass balance models provide managers with a practical, predictive tool to meet their immediate needs.

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