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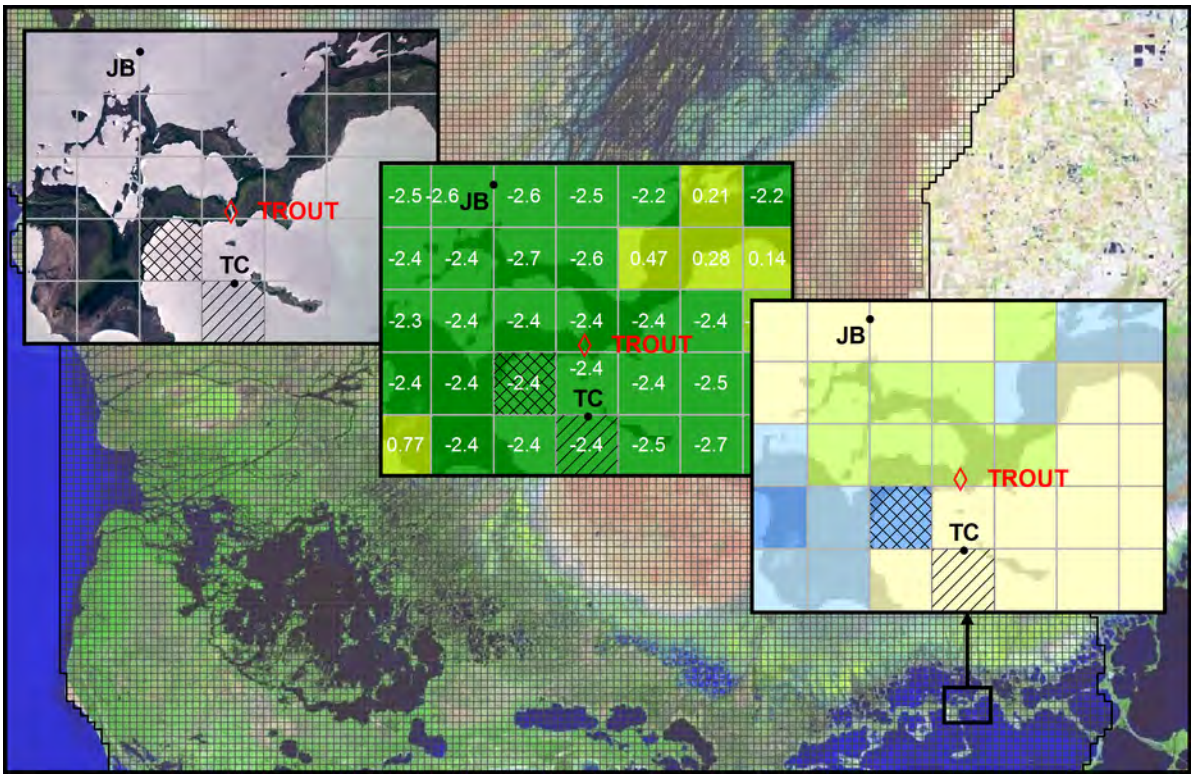
South Florida Natural Resources Center
Everglades National Park

Evaluation and Application of the TIME Model v2.0

Restoration Alternatives and Sea Level Rise in Everglades National Park



HYDROLOGIC MODEL REPORT

SFNRC Technical Series 2013:1

Cover picture shows TIME v2.0 elevation and Manning's n coefficient for cells in the Trout Creek monitoring station area. The upper left inset image shows a satellite view of Trout Creek, located within the center cell and with a width of about 25 m. Station TROUT measures flow through this channel, stations JB and TC measure stage. The TIME model grid is shown overlying the image. The model cell used to represent stage at TC is shown as striped, and the model cell used to calculate flow is shown with a crosshatched pattern. TIME model cell elevations in this area are shown in the center inset image (superimposed on the satellite image). The bottom left inset image shows frictional resistance (Manning's n) values for the model (see Fig. 83, pg. 57).

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SFNRC Technical Series 2013:1

South Florida Natural Resources Center
Everglades National Park
Homestead, Florida

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EXECUTIVE SUMMARY

Introduction

Hydrologic modeling is a tool used to analyze effects of water management alternatives on the south Florida system of wetlands, impoundments, and canals. The consequences of sea level rise are of great concern to Department of the Interior managers and have added another set of criteria to consider when evaluating water management alternatives affecting Everglades National Park (ENP). The South Florida Water Management Model (SFWMM) has been widely used to simulate hydrologic effects of these management alternatives, but the model domain does not extend into the mangrove areas of ENP. The Tides and Inflows in the Mangroves of the Everglades (TIME) model was created to simulate the hydrology of the mangrove-dominated ecotones of ENP, as well as to perform more detailed and spatially resolved hydrologic simulations. The domain of the TIME model includes the land areas of ENP and some of Big Cypress National Preserve, and extends southward into the northern portion of Florida Bay.

This report summarizes the joint project between the U.S. Geological Survey and the South Florida Natural Resources Center of the National Park Service that uses the TIME model to develop ecosystem restoration and sea level rise simulations for ENP. Analysis of preliminary simulation results necessitated an investigation of TIME v2.0 model input datasets and an evaluation of model performance in order to provide context in interpretation of results. This report contains documentation of the input datasets used in the model simulation, an evaluation of TIME v2.0 calibration run results, and an analysis of results from simulations of water management alternatives and sea level rise scenarios. The final section in this report summarizes several performance issues with the TIME v2.0 model discovered during this project and, where possible, recommendations for improvement.

The TIME Model

The TIME model consists of a coupled two-dimensional surface water and groundwater system with variable-density flow. TIME's small cell size allows for incorporation of rivers as topographic features with no need for a separate river package in the model. Variations in cell elevations are used to create preferred flow paths that define Shark Slough and Taylor Slough, and allow tidal embayments and creeks to be incorporated into the model simulations. The TIME domain was designed to include the estuarine zone of ENP. The model can solve for solute transport, allowing the salinity interface in the estuarine zone to be simulated. Coupling between the surface water and groundwater parts of the TIME model is implemented through the concept of a thin layer through which fluxes are calculated. Leakage between surface water and groundwater is computed as flow through this thin layer. In TIME v2.0 the thin layer is 0.5 m thick throughout the entire model domain. Although

TIME has 10 subsurface layers, layers 2–10 have not been determined to have any significant impact on model results from the simulations presented in this report. The initial surface water stages and groundwater heads are set to land surface elevation, and the model requires about a year of simulation time to initialize. In TIME v2.0, the salinity boundary timeseries were derived from output obtained from a hydrologic model of Florida Bay. Use of this new data in the TIME v2.0 simulation resulted in calibration run output with higher correlations to measured data along the downstream boundaries, compared to the TIME v1.0 calibration run results.

Model Performance Evaluation

Evaluation of the TIME v2.0 calibration run results were necessary because significant changes were made to the boundary datasets and hydrologic input parameters of the simulation. The calibration run performance evaluation also helps in interpretation of results from other simulations performed with the model. The TIME v2.0 performance evaluation in this report is not meant to be a comprehensive analysis; the intent is to document the findings on model performance obtained during the course of this project that were pertinent to our current and future application of the model.

Metrics used in this analysis include performance statistics for simulated groundwater stages at monitoring points compared to measured data, and are presented along with statistics calculated for the TIME v1.0 and SFWMM v5.4 simulation results. Timeseries of modeled and measured groundwater and surface water stages are presented for selected locations, and are discussed on a station-by-station basis. Timeseries of surface water and groundwater salinity from measured data and TIME v2.0 simulation results are also discussed in this manner. Model-computed flow volumes for the rivers in the domain are presented along with measured values. The time period of the TIME v2.0 calibration run simulation is 1997–99, with 1996 reserved as a warm-up period and not used in the statistics calculations.

Correlation values for TIME v2.0 model-computed groundwater stage compared to measured stage averaged about 0.88, percent explained variance (PEV) was 69, and Nash-Sutcliffe values (a measure of error relative to variance) averaged a bit less than 40. Comparison of TIME v1.0 and TIME v2.0 simulation results showed that TIME v2.0 has higher correlation and PEV in the western marl prairie and Shark Slough basins. In other basins, TIME v2.0 correlation and PEV statistics are on par with v1.0 calibration run results. The performance statistics for stage values from the TIME v2.0 calibration run were determined to be on par with the SFWMM v5.4 calibration run, where their domains overlap.

Analysis of model calibration run results for each basin revealed the following:

- In the Western Marl Prairie, the TIME v2.0 model-computed surface water and groundwater stages for most stations are consistently as much as 0.5 ft below measured values.
- In Shark Slough, surface water and groundwater stages calibrate very well in the central part of the slough for the TIME v2.0 and SFWMM simulations; performance at these stations ranks among the best within the TIME model domain. Stages in northeast Shark Slough are consistently too high in the TIME simulation, and are consistently lower than measured values in northwest Shark Slough.
- In the Rocky Glades, the TIME v2.0 simulation consistently overestimates surface water and groundwater stages in the northern areas; the SFWMM calibration run results match measured data much more closely. The seasonal low groundwater stages in the

northern Rocky Glades region are not captured in the TIME model simulation, often being off by as much as 2 ft. The SFWMM simulation was determined to be more reliable in capturing the annual lows. The TIME model-computed stages have consistently longer hydroperiods than measured stages indicate in this region. Discrepancies decreased farther downstream in this basin, with both TIME and the SFWMM simulations showing good performance at the southwestern stations.

- In the Shark River area, TIME v2.0 model-computed surface water stages at the mouth of the river are higher than measured stages by about 0.5 ft. Farther upstream, the model-computed surface water stages are generally higher than the measured stages and the model-computed recessions in the groundwater stage during the dry season are deeper than measured recessions. The model-computed surface water salinity values in this area correlate well, and typically is within 5 ppt of measured salinity values. Model-computed groundwater salinity values show a continuous decreasing trend throughout the multi-year simulation period in TIME v2.0, and are in the 30-40 ppt range at locations within the Harney and Shark rivers.

- Within Lostmans River, the TIME v2.0 model-computed surface water stage and salinity calibrated very well with measured values, but model-computed groundwater stages were persistently 1 ft above model-computed surface water stages. Farther inland these model-computed surface water and groundwater stage differences decrease. TIME model-computed surface water salinity values correlate well with measured values. Model-computed groundwater salinity values are higher than measured values at the two stations for which data were available, and did not show the expected seasonal variability, suggesting that interaction between the surface water and groundwater in the TIME model is limited. The measured salinity values indicate that some level of interaction between the two regimes does exist, with seasonal variability generally evident in both surface water and groundwater regimes.

- Chatham River stages from the TIME v2.0 calibration simulation did not capture most of the seasonal lows present in measured data. At the upstream end of the river, the model-computed stages were lower than measured values during the wet season. In the central and downstream sections of the river, the model-computed stages were higher than measured stages, and model-computed groundwater stages were consistently higher than the model-computed surface water stages. The model-computed surface water salinity values generally follow the trend of measured values, but from a later period.

- In the Whitewater Bay Basin, TIME v2.0 model-computed stages were consistently higher than measured data at gages situated in areas influenced by the marine environment, but tracked well with measured data from gages located in the wetlands. The model-computed salinity values near the TIME boundary are influenced by the prescribed boundary conditions and correlate with measured data well.

- In the Taylor Slough Basin, TIME v2.0 model-computed stages were fairly close to measured values. Model-computed surface water salinity values at Little Madeira Bay were captured well, but model-computed salinity values at Trout Creek did not reflect the dynamics of the fresh water and saltwater exchange that is evident in measured data.

Modeled flow volumes for each of the major rivers emptying into the Gulf of Mexico and Florida Bay were compared to measured flow volumes. For the west coast rivers, the

TIME v2.0 model-computed annual flow volumes were within 50% of measured values. For the Florida Bay locations, measured flow data for this time period were sparse, and model-computed results where data were available were mixed.

Simulation of Water Management Alternatives and Sea Level Rise Scenarios

Three water management alternatives were simulated: the pre-drainage condition (NSM), the current condition (Alt7r5e), and future condition with restoration (CERP0). In addition, three sea level rise scenarios were simulated with each of these alternatives: a rise of 0.0 m, 0.3 m, and 0.6 m. Six additional Alt7r5e scenarios were simulated to test the sensitivity of the TIME simulation surface water salinity output to its prescribed salinity boundaries. These simulations used boundaries fixed at 30 and 36 ppt for each of the three increments of sea level rise.

Implementation of the water management alternatives was achieved in the TIME v2.0 simulations using flow and water level output from the SFWMM and the pre-drainage version of the SFWMM, the Natural System Model, as prescribed input boundary conditions. The methodology used for simulating sea level rise in the TIME model simulations was to raise groundwater and surface water heads at the boundary cells. The boundary salinity, however, was not adjusted to account for the change to more marine conditions. This allows for fairly good simulation of stage increases due to sea level rise, but limits the ability of TIME v2.0 to simulate salinity changes in the mangrove and coastal ecotones.

Analysis of TIME v2.0 simulated effects of changes in water management indicates that increased freshwater flows and higher stages in a restored system have a larger effect on stages in upstream areas but a relatively small effect on the stages in the mangrove ecotone along the west coast. Hydroperiods can be increased by more than 1 month due to the additional flows discharging to Taylor Slough under the CERP0 alternative. Salinity in the upper mangrove ecotone is influenced the most by changes in water management. The effects of larger flows under the CERP0 alternative can also be seen in the increased flow volumes discharging through the rivers, ranging from 7 to 35% higher than the Alt7r5e volumes. The model simulation computes a salinity decrease of 2–3 ppt under CERP0 compared to Alt7r5e in the upper estuaries adjacent to the west coast rivers. Model-computed salinity shifts in Florida Bay are difficult to evaluate due to the proximity of the prescribed boundaries, but relative shifts in the embayments were simulated by TIME v2.0 to decrease 0.2 to 1.6 ppt under CERP0 compared to Alt7r5e.

The sensitivity study of TIME v2.0 model-computed salinity to prescribed boundary conditions indicates that simulation results are affected to some degree in almost all areas of the domain that are not completely dominated by freshwater. The analysis indicates that results in the riverine and mangrove ecotone areas are very sensitive to the prescribed boundary conditions. Thus, when using the TIME v2.0 model to evaluate alternatives where boundary conditions are speculative, assumptions used to generate boundary timeseries and their influence on interpretation of the results must be taken into account before arriving at conclusions.

Analysis of sea level rise scenarios under different water management alternatives indicates that less drastic changes in stages and salinity regimes would occur in a restored system as compared to the present one. CERP0 water levels are higher than Alt7r5e water levels at current sea level, and changes in hydroperiods due to sea level rise effects were not as large

under CERP0 as they were under current operations for the stations that show a response to changes in water management. The increased flows and stages in ENP due to CERP0 at current sea level would bring water levels up closer to where they would be with sea level rise and no change in water management. Increased flow from CERP0 also results in fresher water at many of the stations and may help temper the inevitable increase in salinity due to sea level rise, providing a potentially broader front in the transitional ecotone.

Performance Issues with the TIME Model

Evaluation of the TIME v2.0 calibration run results and input datasets revealed several issues with the model that may affect accuracy of computed simulation results.

- Model-computed stage and salinity values at many stations do not reflect the high level of connection between the surface water and groundwater systems present in measured data.
- The first subsurface layer defined in the model simulation averages about 20 ft thick in the mangrove areas, but has been measured to be only as much as 12 ft thick. This does not allow for simulation results that will reflect the finer-scale vertical resolution of the fresh/saltwater interface in the mangrove ecotone.
- In the mangrove-dominated areas, including the entire West Coast Ecotone, NP205 and P34 in the Western Marl Prairie, Whitewater Bay Basin (except Cape Sable), southern Shark Slough, southern Rocky Glades, NP205 and P34 in the Western Marl Prairie, and the C-111 and Florida Bay areas of the Taylor Slough Basin, average surface water and groundwater stages differed in the simulation results by 3 to 34 cm when surface water was present.
- In the Everglades, local rainfall temporarily increases surface water stages until it fills the upper aquifer layer through infiltration. Often the rainfall excess computed in the model simulation does not infiltrate after many days, even though the simulated groundwater stage is more than 1 ft below ground level.
- The TIME simulation groundwater stage results exhibit a very slow response in the ascension rate going into the wet season, which can make the surface water hydroperiod calculation ambiguous compared to the groundwater calculation.
- The TIME model simulation input datasets define preferential flow paths such as creeks and rivers through elevation differences and lowered frictional resistance values. Devising proper algorithms for simulating wetting and drying on the Buttonwood Embankment and accurate flow through the cuts in the embankment still need to be resolved. Several of the adjustments of the roughness coefficient in the TIME v2.0 simulation datasets are very location-specific. Although the calibration plots and statistics might show that a match was achieved at the specific location, accuracy of flow or stage values in neighboring cells may have been affected.
- TIME's formulation for wetting/drying of cells using cell corner elevations is an adequate method when using the code for areas with very subtle topography changes. This was the original purpose of the surface water model component used in TIME. In the relatively higher relief of the mangrove ecotone, coastal and riverbank cells often have

large corner-elevation variations, and substantial water depth can remain in the cell when the model computes it to be dry.

- TIME's computed salinity values are influenced by prescribed boundary conditions along the southern and western edges of the domain. However, the hydrologic stresses from the restoration alternatives likely reach the boundary cells, complicating interpretation of the results.
- It is not clear if groundwater salinity values reach an appropriate solution at any time during the calibration run at several stations in the model. Many of the model-computed groundwater salinity values at stations in the mangrove zone showed an increasing or decreasing trend for the entire multi-year simulation, with little or no inter-annual variation. Part of this lack of response could be due to the thickness of the first layer.

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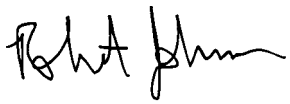
FOREWORD

Early on in the Everglades restoration process, it was recognized that a better understanding of the existing natural system and its response to restoration alternatives would be needed to help make sound restoration decisions. It was clear that the development and application of a hydrologic simulation model that could capture the fine scale aspects of the marsh hydrology as well as the dynamic relationship between the marsh and the estuarine environments would be required to provide necessary information. From this model, ecological responses could then be estimated and evaluated. It was further recognized that to parameterize this model, many field measurements would be needed. In response, a substantial effort, largely funded by the Department of Interior and executed by the U.S. Geological Survey, was made to collect the requisite data. These data included topographic information for the entire south Florida region, landscape specific evapotranspiration measurements. marsh point velocities, marsh roughness estimates, and estuarine stream flow. Acquisition of these data was a major undertaking that has enhanced not only this model development effort, but also many other physical and biological investigations over the last several years. All of these data, and more, were used to build the Tides and Inflows to the Mangrove Ecotone, or TIME model.

This coupled surfacewater and groundwater, variable density, solute transport model represents the state-of-the-art in fine scale simulation of the marsh and estuarine environment in south Florida. For the first time, a tool is available to make predictive simulations in the freshwater and estuarine environments. This simulation tool represents not the culmination, but rather a major milestone in the effort to produce simulation results that are accurate enough and at a fine enough scale to inform ecologic process models that produce results essential for ecosystem restoration planning.

Another significant environmental issue that must be considered concurrently with restoration is sea level rise. Fortunately the TIME model provides the capability to evaluate the effects of sea level rise on natural resources under current conditions as well as under restored conditions. This report represents the first application of the TIME model in a production mode driven by boundary conditions from a regional model. The application of the model is ultimately used to assess the system response to both restoration alternatives and sea level rise.

The modeling and results described in this report are products of USGS and NPS scientists and engineers who have devoted many years toward the protection and restoration of the Everglades. We hope that this report contributes to this effort.



Robert Johnson
Director
South Florida Natural Resources Center

April 2013

1 INTRODUCTION

The Tides and Inflows in the Mangroves of the Everglades (TIME) model is an application of the Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) code, which was developed by the U.S. Geological Survey (USGS) to model a coupled surface water and groundwater system with variable-density flow [Swain et al., 2004].

The domain of the TIME model includes the terrestrial areas of Everglades National Park (ENP), a portion of Big Cypress National Preserve, Florida's southern Gulf Coast estuaries, and the northern-most portions of Florida Bay (Fig. 1). The first version of the TIME model (TIME v1.0) was developed with the intention to provide some understanding of coastal freshwater flows and nutrient sources, and aid in the evaluation of ecosystem restoration alternatives [Wang et al., 2007]. The second version of the the TIME model (TIME v2.0) is a result of a joint project between the USGS and the South Florida Natural Resources Center of the National Park Service (NPS). This project focused on upgrading TIME v1.0 and evaluating and applying the new model.

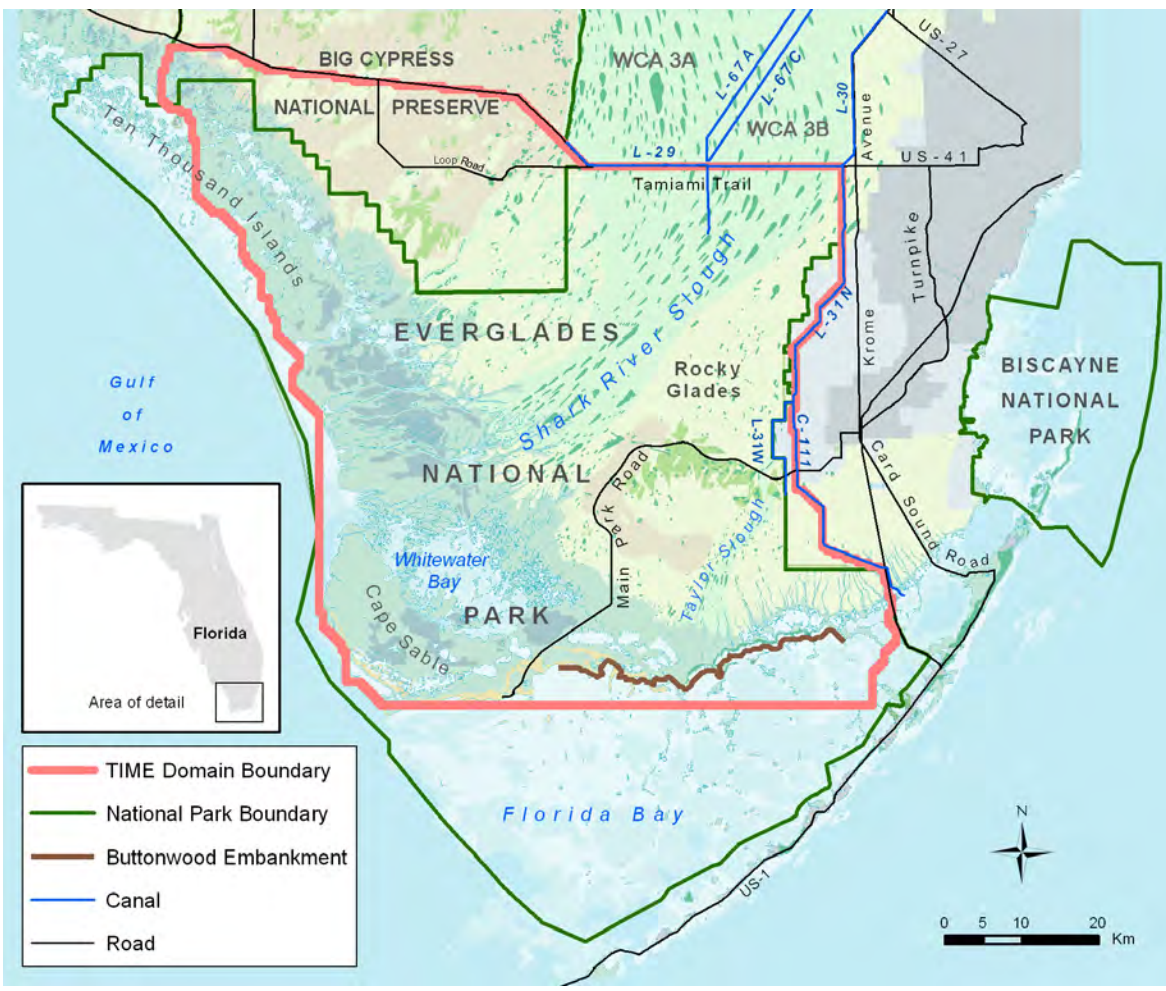


Figure 1. Location of TIME model domain in South Florida.

TIME v1.0, which used the FTLOADDS v2.2 code, was modified to accept additional boundary conditions and streamlined for improved input and output. A versioning protocol

was established to properly track changes to the TIME model code and data input sets. The version of the FTLOADDS code used for TIME v2.0 and this project is FTLOADDS v4.0. A number of significant changes were implemented in the TIME v1.0 source code and input data sets, which made it necessary to recheck calibration and evaluate the resulting output statistics of the new TIME v2.0 model. Calibration of a model refers to the process of tailoring input data to produce model output that matches a set of measured data. The current effort documented herein is an application of the TIME model to develop ecosystem restoration and sea level rise simulations for ENP.

This report documents the TIME v2.0 calibration run statistics for 1997–99 (inclusive), and the results from application of TIME v2.0 to restoration alternatives for 1990–99. The restoration scenarios modeled use three different alternatives developed for use in south Florida planning efforts, and have been previously simulated with the South Florida Water Management Model (SFWMM) and the Natural System Model (NSM). Alternatives modeled are the pre-drainage condition (NSM462), the current condition (Alt7r5e), and future condition with restoration (CERP0). The CERP0 alternative represents proposed structural and operational changes to the existing water management features along the northern and eastern boundaries of ENP.

The timescale for implementation of the Comprehensive Everglades Restoration Program (CERP) extends far enough into the future to make evaluation of sea level rise also a component of interest. Tidal cycles are anticipated to rise uniformly along the coast; therefore, those CERP components planned to benefit the resources of ENP need to be evaluated within this new context. Three main sea level rise scenarios were run on each of the alternatives: a rise of 0.0 m, 0.3 m, and 0.6 m, implemented along the model's marine boundaries. Additional model simulations were performed to test the sensitivity of the model output to prescribed coastal salinity boundaries, which was done by running TIME with marine salinity values fixed at 30 and 36 ppt.

The appendices in this report contain comprehensive plots of model simulation results as well as details about the model implementation and development. Appendix A contains plots of stage and salinity values applied as marine boundary conditions, which were derived from a simulation using the Environmental Fluid Dynamics Computer Code (EFDC) model of Florida Bay. Model output from the TIME v2.0 calibration run, SFWMM alternative runs, and sea level rise scenario runs are presented in full in Appendices B through E. Appendix F contains a memo from a previous application of the TIME model that was not published but contains relevant documentation of some of the development of TIME since described by Wang et al. [2007]. Technical code updates are documented in Appendix G.

2 MODEL DESCRIPTION

The TIME code, FTLOADDS, is a combination of two separate models that have been coupled to account for leakage and salinity flux between the two regimes. The first model, Surface-Water Integrated Flow and Transport in Two Dimensions (SWIFT2D), is a two-dimensional hydrodynamic surface water and transport model [Leendertse, 1987]. The hydrodynamic surface water representation is a necessity in modeling the coastal wetland system. The second model, named SEAWAT, is a three-dimensional groundwater model with variable density [Guo and Langevin, 2002]. The integrated code allows for the important hydrologic processes in ENP to be simulated, with the exception of the interaction between the marsh and the canal system. The drainage canals and associated structures are represented as boundary conditions in TIME, which produces some inaccuracies in the wetlands adjacent to the canals. The primary application of the model is to simulate downstream conditions in the mangrove areas of ENP, particularly the salinity responses in the near-shore wetland and coastal zones. These areas are far enough away from the canal system that the localized effects are unimportant.

The TIME model uses a 10-minute timestep for the surface water simulation and a daily timestep for the groundwater simulation. The short surface water timestep is necessary to account for tidal- and wind-driven flow and transport dynamics and can be of interest to the ecological modeling community, especially when consideration must be given to daily tidal cycles. Coupling between the two processes is done by passing a leakage quantity, including a salt flux, across a thin layer separating the surficial landscape from the aquifer.

The development of a near-shore wetland model to evaluate restoration alternatives and sea level rise scenarios was initiated in 1996 with the development of the Southern Inland and Coastal System (SICS) model [Swain et al., 2004], which simulates the hydrology of the coastal region and wetlands in ENP [Langevin et al., 2004]. The objective was to compute resultant salinity patterns and concentrations in the subtidal embayments as a function of freshwater inflows [Swain et al., 1996], which were prescribed as upstream boundary conditions derived from the output from the SFWMM model [Wolfert et al., 2004]. Once the SICS model was built and operational, the boundaries were expanded to include more of the mangrove ecotone and rivers, and thus enlarged to the west coast of ENP. The northern boundary was expanded to provide better upstream boundary conditions along Tamiami Trail. The objectives for this new FTLOADDS model, TIME v1.0, were delineated in Schaffranek et al. [2001]:

- How do the Everglades wetlands and coastal marine ecosystems respond concurrently to freshwater inflow regulation?
- What concurrent changes in wetland hydroperiods and coastal salinities are likely to occur in response to various restoration plans and management actions?
- What dynamic forcing factors, e.g., sea level rise, meteorological effects, etc., could adversely affect regulatory plans?
- What factors affect salt concentrations in the coastal mixing zone and how do they interrelate?
- What effects will upland restoration and management actions have on endangered species in the land-margin ecosystems?

Development of the SICS and subsequent TIME models involved collaborations among the staff of numerous projects within the USGS South Florida Ecosystem Program and

others, see *e.g.*, Cline et al. [2004]. Hydrologic conditions from TIME model simulations were provided to staff members utilizing the Across Trophic Level System Simulation (ATLSS) to assist in their ecological modeling efforts. The outputs of physical system models are important inputs to the suite of ecological models envisioned in the ATLSS program that compare the relative impacts of water management alternatives on the biotic components of south Florida. The objective is to provide a rational, scientific basis for ranking the water management scenarios as part of the planning process for Everglades restoration. In addition to the ecological models, the exchange between the upstream hydrologic models and the Florida Bay models (such as the hydrodynamic models TABS-MDS (also known as RMA 10), EFDC and SWIFT2D), is helpful in predicting circulation, inflow, and the movement of nutrients through the bay. FATHOM, a mass balance basin model of Florida Bay, can use inflows from these upstream hydrologic models to help predict salinity exchange among the offshore basins [Cosby et al., 2010].

As part of the Florida Bay Florida Keys Feasibility Study (FBFKFS), cosponsored by the U.S. Army Corps of Engineers and the South Florida Water Management District, the TIME model was used to simulate hydrologic conditions under varying restoration plans with the intention to help guide all aspects of restoration of freshwater flow to Florida Bay [Wang et al., 2005]. TIME output was used as boundary input in a Florida Bay version of the EFDC [Hamrick, 2006] to improve salinity approximations produced by the EFDC simulations. This task became part of the FBFKFS, and the TIME model underwent development at the same time culminating in v1.0 and published in Wang et al. [2007]. This development was also documented in a previously unpublished report promulgated in Appendix F.

The FBFKFS project used selected SFWMM alternatives and iterated these model runs between the TIME model and the EFDC. TIME model inputs were taken from SFWMM simulation output for alternatives Alt7r5e, CERP0, and 2050b0. The Alt7r5e simulation models the current condition, and the 2050b0 simulation models the future condition without implementation of CERP projects. Preliminary results presented in a meeting of the Project Delivery Team for the FBFKFS in December 2006 showed poor agreement between Alt7r5e surface water salinity and measured values for 1990–94, for both TIME and EFDC predictions.

This prompted the TIME model developers to undertake an additional calibration process which attempted to minimize and/or explain the differences between measured conditions and model results based on the Alt7r5e alternative. As a result of the FBFKFS work, the modelers identified several things that needed revision, including the model's code, topographic dataset, rainfall dataset, and initial and boundary condition datasets. Initial conditions were identified as important factors in the ability of the model to simulate the conditions of earlier years. In earlier TIME v1.0 simulations, the initial salinity had been set to zero throughout the entire domain, and the initial stages set to a level pool higher than the highest land surface elevation in the model. In TIME v2.0, the stages and salinity values are more accurate due to this effort.

2.1 Model Domain

The extent of the TIME model domain was developed to complement the existing SFWMM model domain, which did not extend into the estuarine zone (Fig. 2). TIME has the added flexibility to solve for solute transport, allowing the salinity interface to also be simulated. The model domain consists of 174 rows and 194 columns, with identical cell spacing of 500 by 500 m (1640 by 1640 ft). As shown in Figure 3, the domain extends from Tamiami Trail

as the northern boundary and the Eastern Protective Levee System defined by the L31N and C111 levees as the eastern boundary. The outflow boundaries are defined at the southern extent by Florida Bay and along the west by the Gulf of Mexico. The principal monitoring stations used to calibrate and verify the model are also shown in Figure 3, and will be used in the presentation of model output throughout the rest of this report.

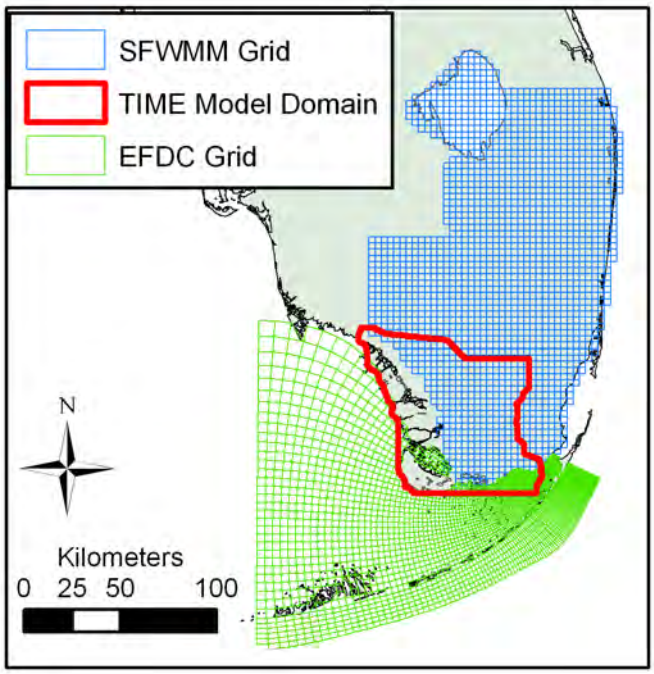


Figure 2. Model domain of SFWMM, TIME, and EFDC. The SFWMM domain extends from Lake Okeechobee in the north to the wetlands upstream of Florida Bay and the Gulf of Mexico in the south. This model is based on a 2-mile by 2-mile grid. The EFDC model simulates circulation in Florida Bay and the Gulf of Mexico and has a variable mesh grid. The TIME model domain covers the land areas of ENP, including the area between the SFWMM and EFDC grids, and can use model output from each of these models as boundary condition input.

The boundaries along the north and east side of the TIME domain correspond to distinct hydrologic divides, and sufficient information is available to use as input boundary conditions to the model. The western and southern boundaries of the domain do not correspond to hydrologic divides, but instead lie in the highly dynamic coastal freshwater/saltwater mixing zones.

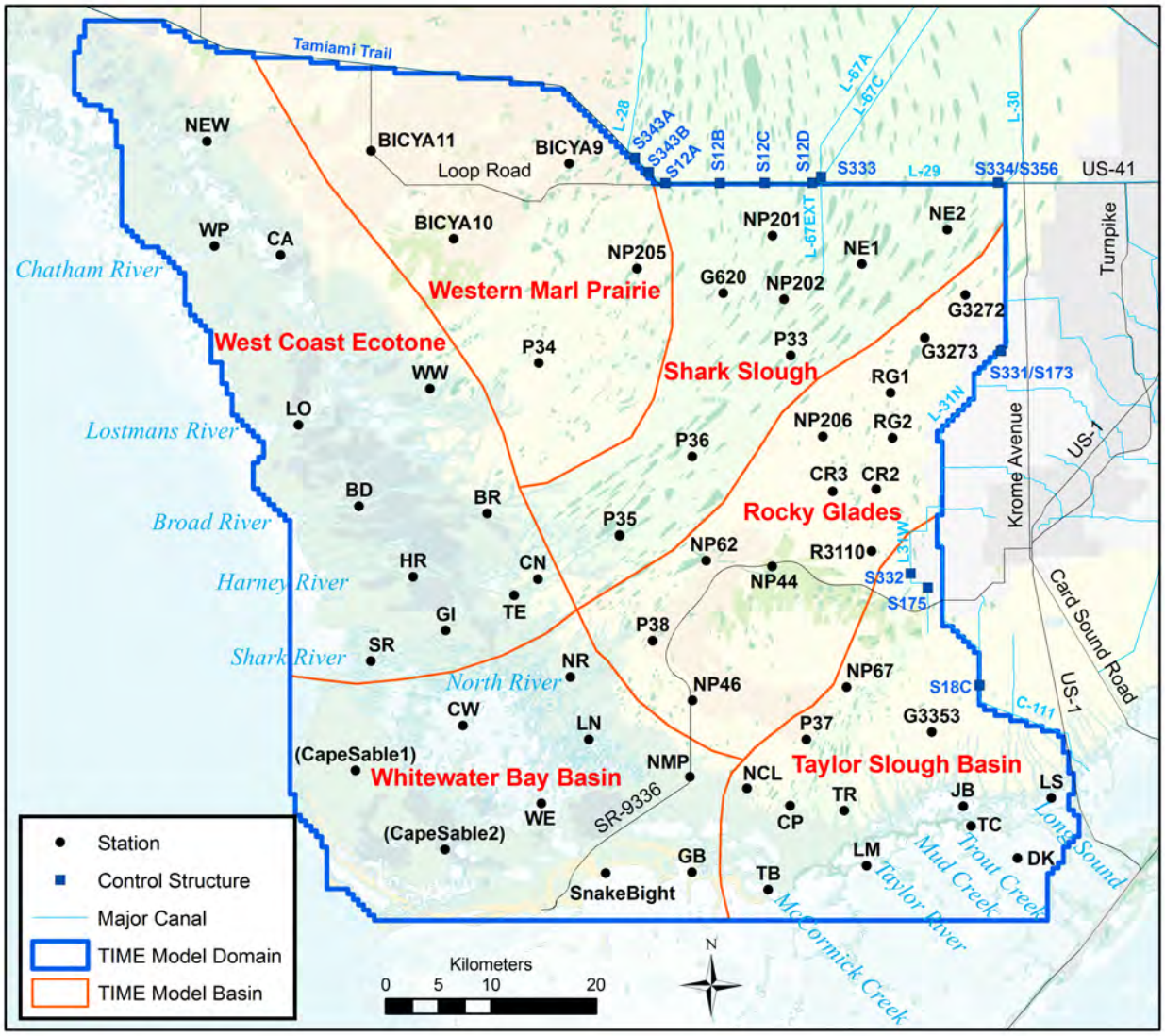


Figure 3. TIME model domain, basins, and primary monitoring stations used in this report. Stations are grouped into basins, and model results are discussed by basin. Locations CapeSable1 and CapeSable2 are not actual field monitoring stations, but model results from these locations are reported to give a more complete picture of model results and performance.

2.2 Aquifer Layers

The active cells in each of the 10 subsurface layers of the TIME model domain are shown in Figure 4. Layers 1 through 5 have identical domains. All layers have a 23 ft (7 m) thickness except for the first layer, which is of variable thickness with the bottom fixed at 23 ft below sea level. Layers 2–10 were determined to have no substantial impact on the model solution, so will not be discussed in detail in this report. The first subsurface layer thickness is shown in Figure 5; the thickest portion occurs near Tamiami Trail, and the bay and river beds are represented as the thinnest parts. In the model, the interaction between surface water and groundwater is significant only between the first subsurface aquifer layer and the surface. The results of the groundwater computations quantify an average result for salinity for the entire layer, which ranges from 13 to 33 ft (4 to 10 m) thick. In Northeast Shark Slough, the average thickness of the first subsurface layer is between 26 and 30 ft (8 to 9 m). Mangrove areas of the domain range from 20 to 26 ft (6 to 8 m), and the rivers and Florida Bay have a layer thickness of 13 to 23 ft (4 to 7 m).

Salinity fluctuations near the surface are an important component in mangrove and adjacent upstream wetland dynamics, determining the occurrence of particular vegetation landscapes. Because much of Everglades hydrology depends on the interaction between surface and near-surface water movement, the model results could benefit by incorporating a peat layer in the input dataset. Model modification efforts initiated by the USGS after completion of the project detailed in this report were underway to reduce the thickness of the upper layer to 8 ft (2.5 m) in order to more precisely model surface/near-surface dynamics.

2.3 Land Surface Elevation

The land surface elevations used in the model are shown in Figure 6 for the active part of the model domain. Elevations used in this model generally range from 9 ft above to 12 ft below NGVD 29 datum. TIME's small cell size allows for incorporation of the rivers as topographic features with no need for a separate river package. Variations in cell elevations are used to create preferred flow paths, which define Shark Slough and Taylor Slough, and allow tidal embayments and creeks to be incorporated in the model. Major west coast rivers implemented in the TIME model include Chatham River, Lostmans River, Broad River, Shark River, North River, and Harney River.

The Florida Bay area contains more subtle geographic and topographic variation than the west coast. Smaller creeks and rivers flowing into the bay are more difficult to define within the model's cell size. These outlets to Florida Bay include Trout Creek, Taylor River, McCormick Creek, Long Sound, and Mud Creek, shown in Figure 3. These waterways provide the principal means for surface flow to exit the upstream wetlands across the Buttonwood Embankment, shown in Figure 1. The Buttonwood Embankment is described in Wang et al. [2007] as being 6 inches (15 cm) higher than the surrounding marsh. In the earlier SICS model, the Buttonwood Embankment was represented by a series of hydraulic barriers [Swain et al., 2004]; in TIME v1.0 the difference in resistance between the embankment and the coastal creeks was expressed with differences in the frictional resistance and variations in land elevation. In TIME v2.0, the methodology of using the frictional resistance to define the embankment was dropped.

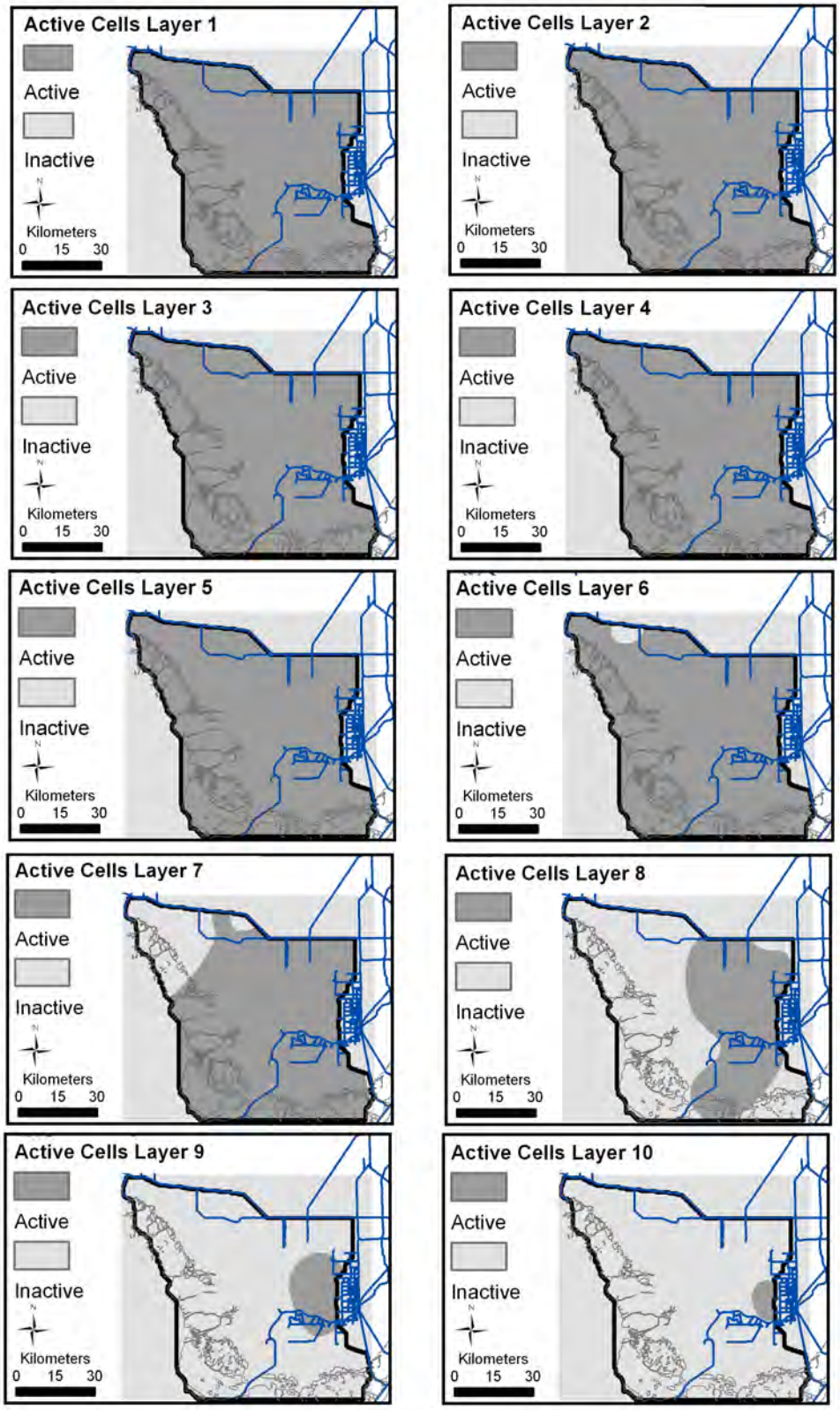


Figure 4. Active cells in layers 1–10 of TIME v2.0.

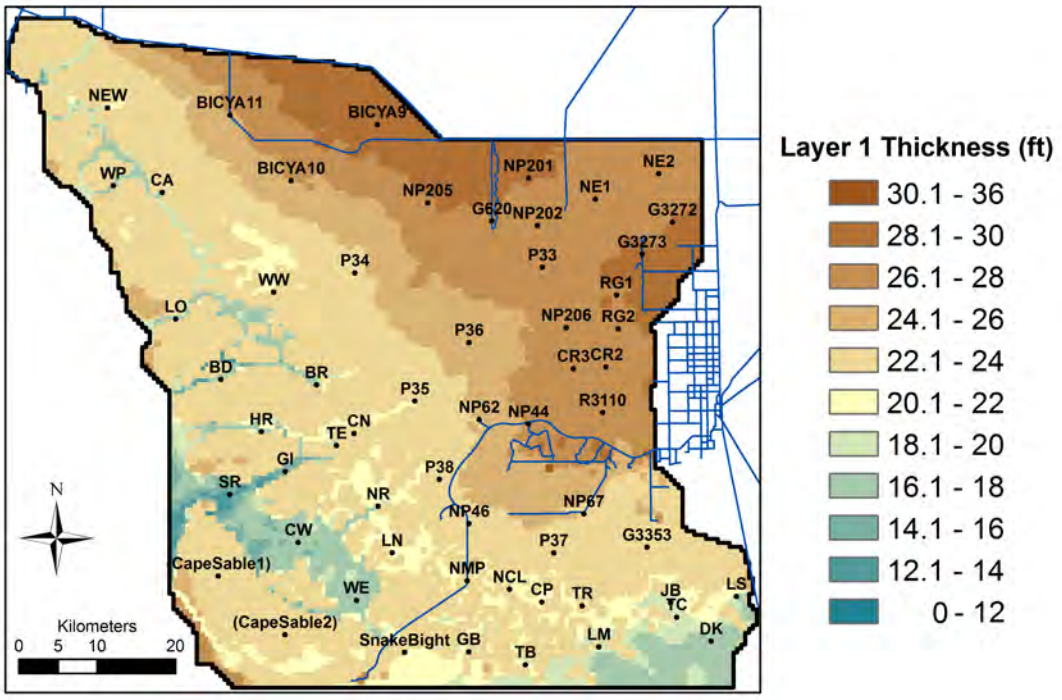


Figure 5. Thickness of first groundwater layer in TIME v2.0.

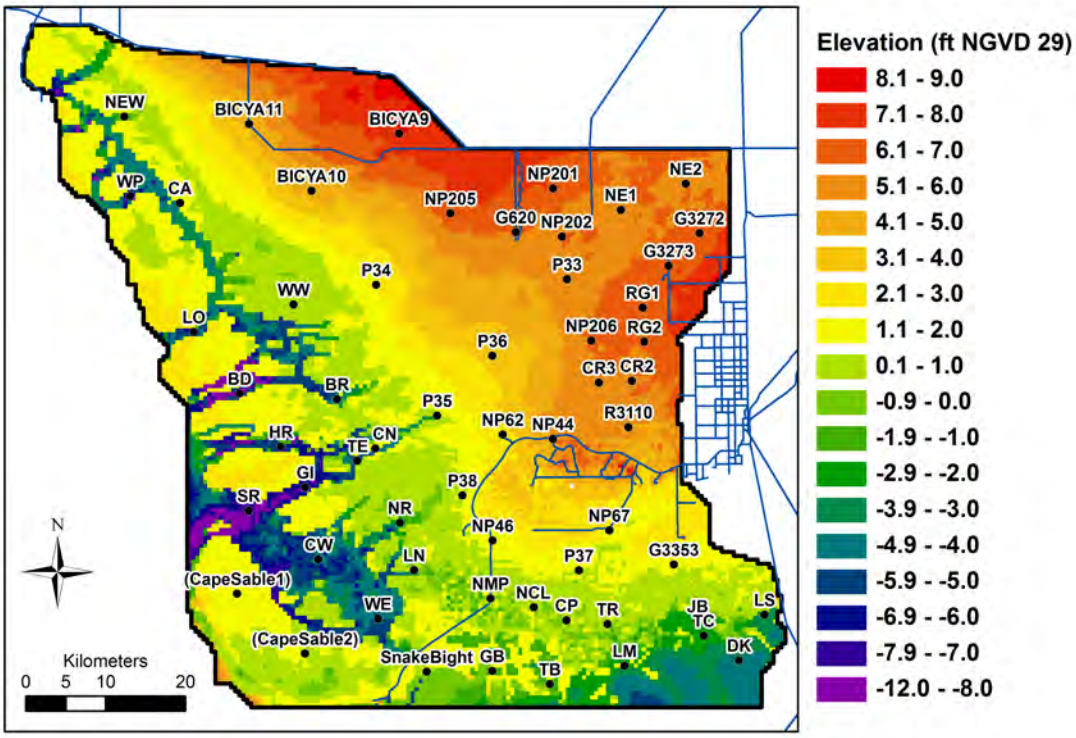


Figure 6. Land surface elevations in TIME v2.0.

2.4 Manning's Coefficient

Resistance to surface water flow between model cells is implemented using the Manning's coefficient. Higher values indicate greater resistance to flow. Values used for Manning's coefficient in the TIME model simulation are shown in Figure 7, and range from zero to two. One set of values is applied to cell flows in the north-south direction and another to the east-west direction. A description of the derivation of these datasets can be found in Wang et al. [2007].

The block-shaped areas in Figure 7 indicate areas where resistance values were modified from baseline values in the TIME calibration process. This was done to improve the match between model flow results and measured data, but the modified areas are not refined beyond their rectangular shape. At Taylor Slough Bridge, the resistance values have been lowered and are shown in the figure as a rectangle extending across the road at the southeastern entrance to ENP. Frictional resistance has in the model been increased in both directions over an area of approximately 28 square kilometers in the southeast panhandle region of the domain, just south of the C111 canal. In the Shark River, the values have been increased in an area spanning the channel in the east-west direction, and in the North River the same has been done but in the north-south direction. In both cases, the areas contain the grid cells used in the calculation of river flow volumes from these rivers. In Florida Bay, there are five cells, each representing a transect through the central part of a river or creek that empties into the bay, that have had their Manning's coefficient values increased. These cells are at the same locations as those used to calculate the river flow volumes. The effects of this implementation are further discussed in Section 3 and a detail map of the area is provided there.

2.5 Conductivity and Leakance

The TIME model simulation utilizes the concept of a thin layer to achieve coupling between the surface and groundwater parts of the model. Leakage between surface and groundwater is computed as flow through this thin layer and the upper aquifer. Resistance to flow is based on the combined conductance of the thin layer and the aquifer. The thin layer is 1.6 ft (0.5 m) thick throughout the entire domain, and is implemented as the top 1.6 ft of the first subsurface layer. The aquifer vertical leakance value is 328 ft (100 m) per day and the thin layer vertical leakance value is 16.4 ft (5 m) per day. These values are representative of the lower conductivity of the peat layer that overlies the limestone aquifer in the Everglades.

Figure 8 illustrates the hydraulic conductivity values of the 10 subsurface layers in the TIME model. Hydraulic conductivity values in the first layer are 500 m per day (m/day) for the northwest portion of the model, and 5000 m/day for the rest of the domain, including Shark Slough. The second layer has values of 5000 m/day for the eastern and extreme southern edges of the domain, and 500 m/day everywhere else. Values used in the remaining layers are either 50, 500, or 5000 m/day.

Vertical leakance values between layers in the TIME model vary between 6 and 72 m/day. Values assigned to each of the layers are shown in Figure 9. Layer 1 leakance values are less than 15 m/day for most of the domain. The far eastern boundary of the domain has a leakance value of less than 70 m/day, and the southern Florida Bay area has leakance values between 77 and 87 m/day.

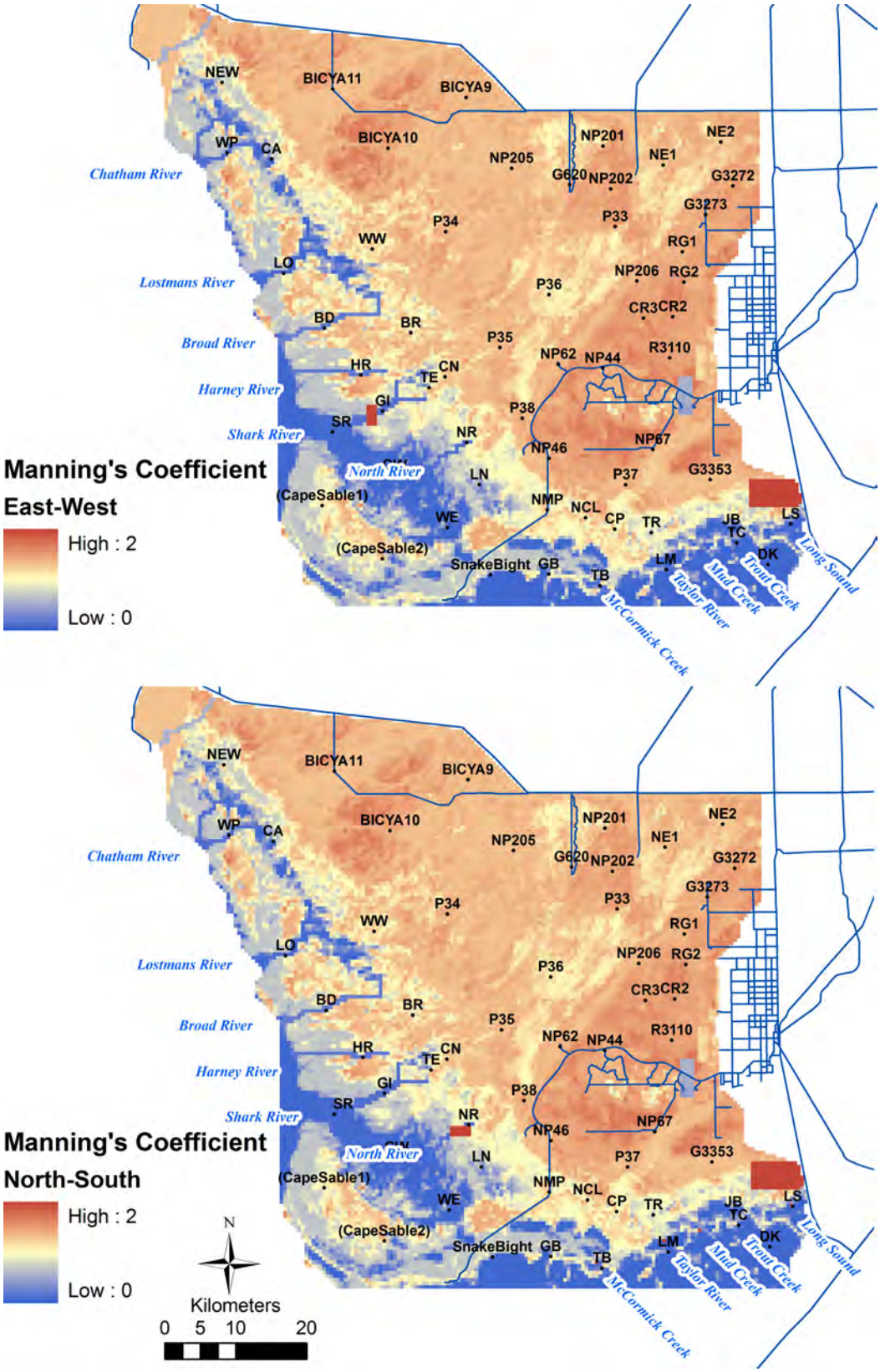


Figure 7. Manning's n coefficient in east-west direction (top) and in north-south direction (bottom) in TIME v2.0.

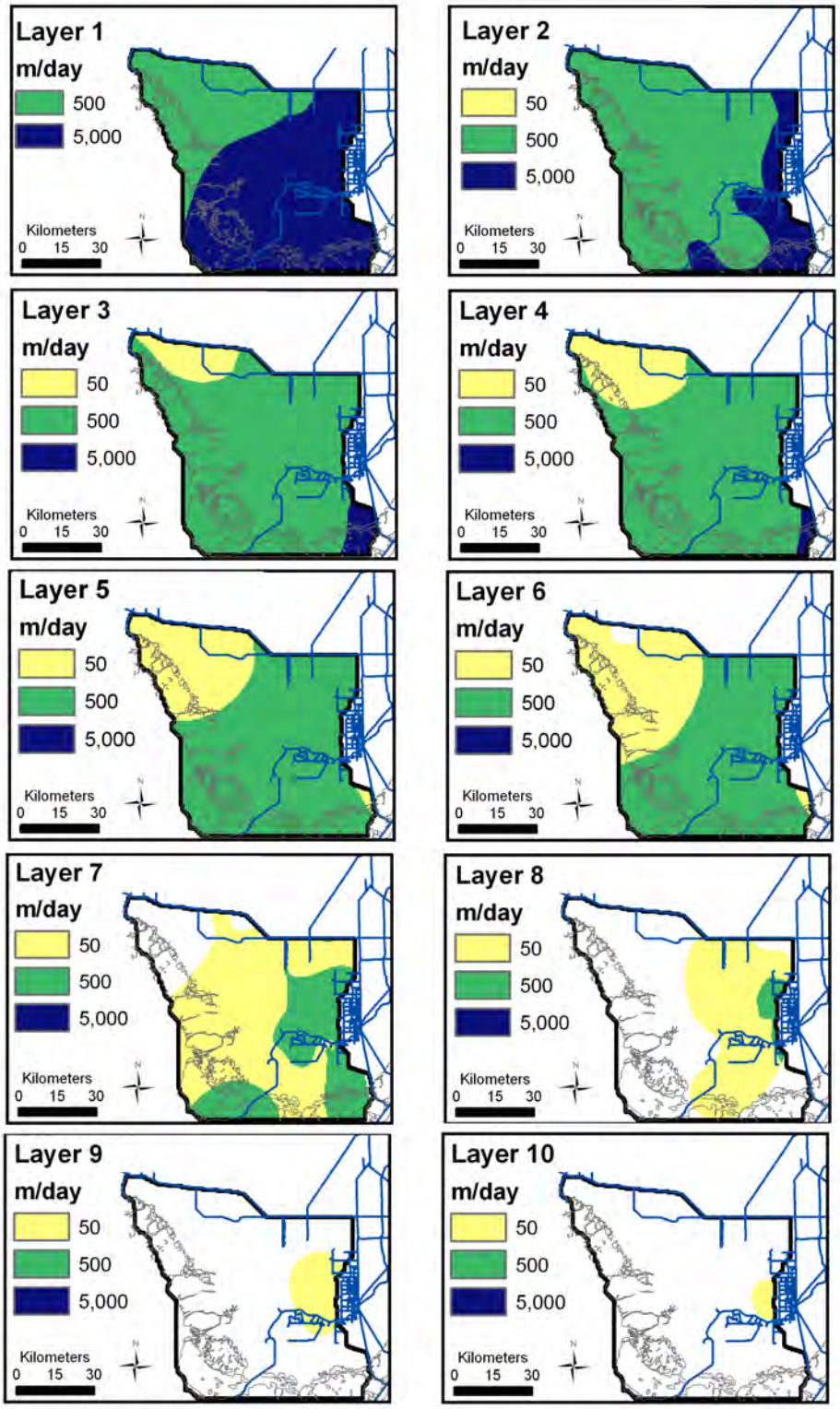


Figure 8. Hydraulic conductivity values in meters per day for layers 1–10 of TIME v2.0. Inactive cells for each layer are shown in white.

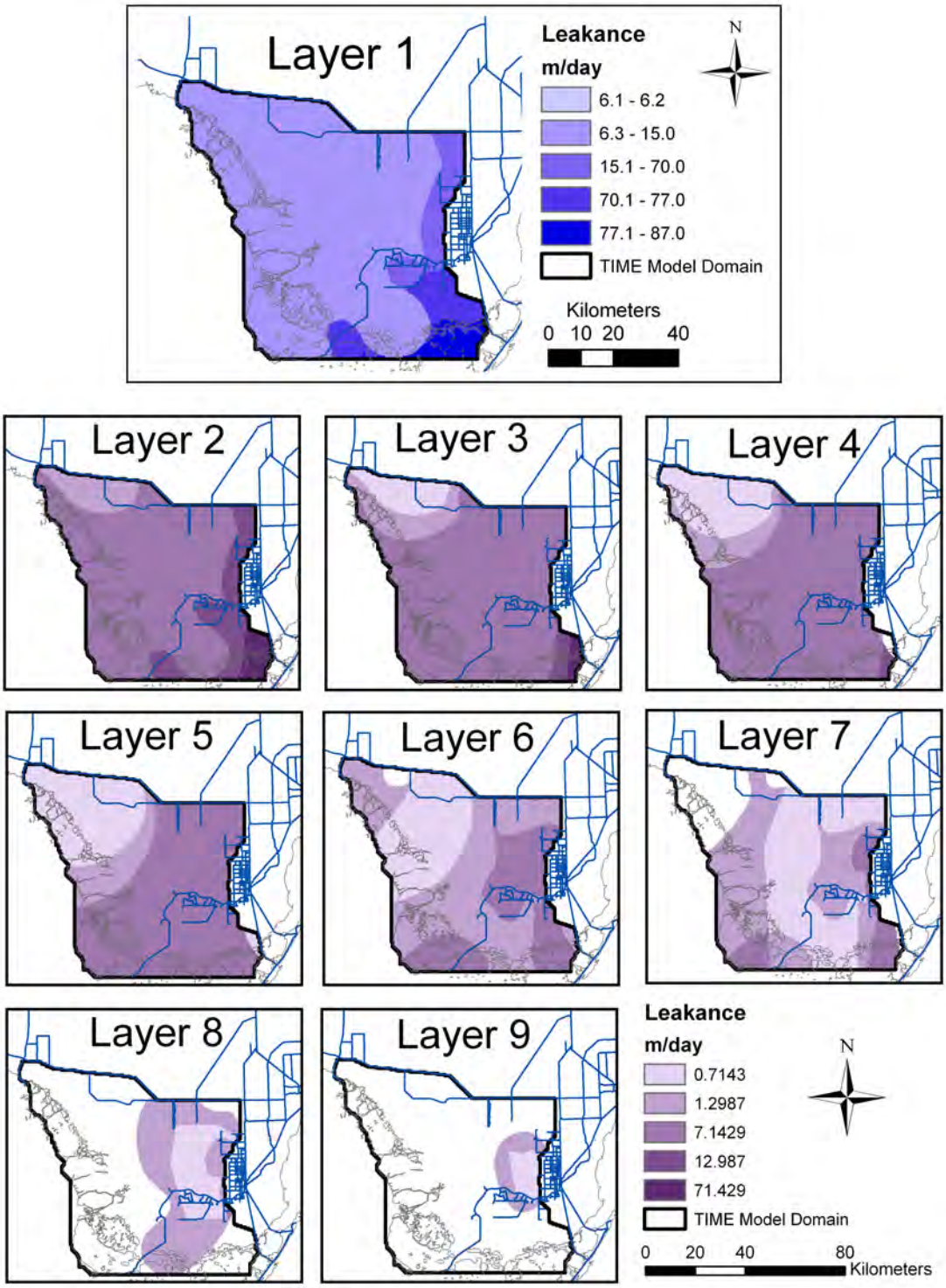


Figure 9. Leakance values in meters per day for layer 1 (top) and layers 2–9 (bottom) in TIME v2.0.

2.6 Initial Conditions

The initial surface water stages and groundwater heads in the TIME v2.0 model simulation are set equal to land surface elevation. The first-day salinity values for the surface water and groundwater layers are shown in Figures 10 and 11. Surface water salinity values range from 0 to 45 ppt, with Florida Bay and the rivers and bays of the Ten Thousand Islands having initial values from 26 ppt farther inland to 40 ppt at the outer reaches. Groundwater salinity values range mostly from 30 to 45 ppt, with some areas in the 45 to 60 ppt range for initial conditions.

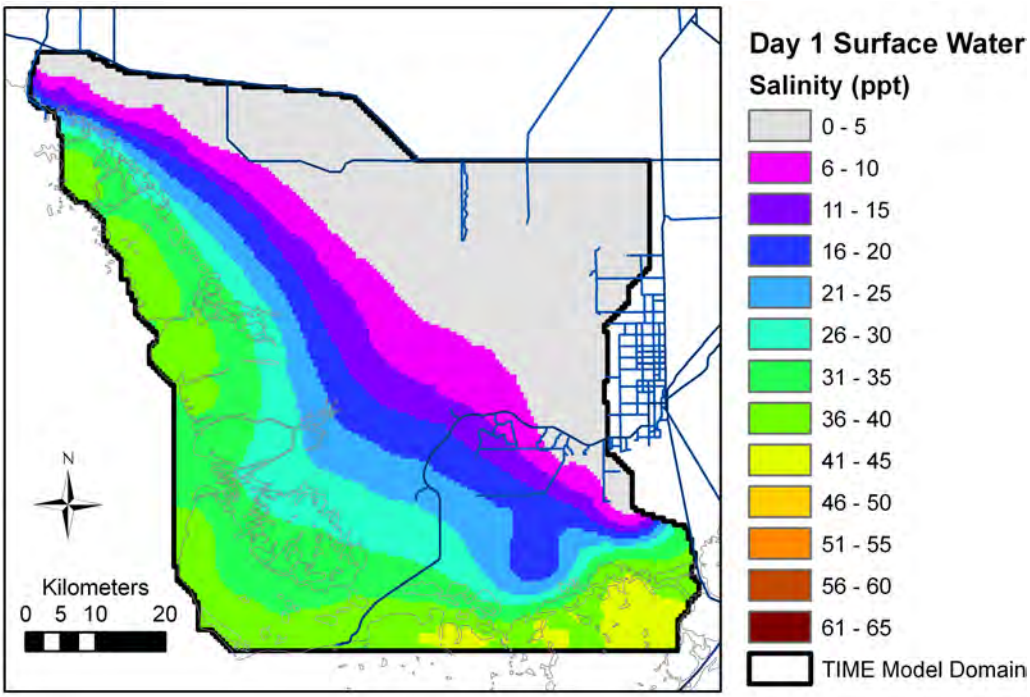


Figure 10. Model-computed surface water salinity on first day of simulation for TIME v2.0 runs. Note that these values would not apply to cells with no surface water present.

2.7 Boundary Conditions

Boundary conditions for stage and salinity are prescribed along the entire northern and eastern sides of the domain, and for marine cells along the western and southern sides.

Boundary conditions for the northern and eastern sides were derived from measured data for the calibration run and from SFWMM output for the alternative runs, and are described in sections 3.1 and 4.1, respectively.

For the southern and western sides of the domain, boundary conditions were derived from a coupled run of the TIME model and the EFDC model of Florida Bay, and were used for both the calibration and alternative runs. This section will describe this dataset. Specific alterations to the western and southern boundary conditions for sea level rise and sensitivity runs are described in section 4.

In the earlier SICS and TIME v1.0 model simulations, the downstream surface water (marine) salinity boundaries had used an annually repeating Fourier series for stage, which

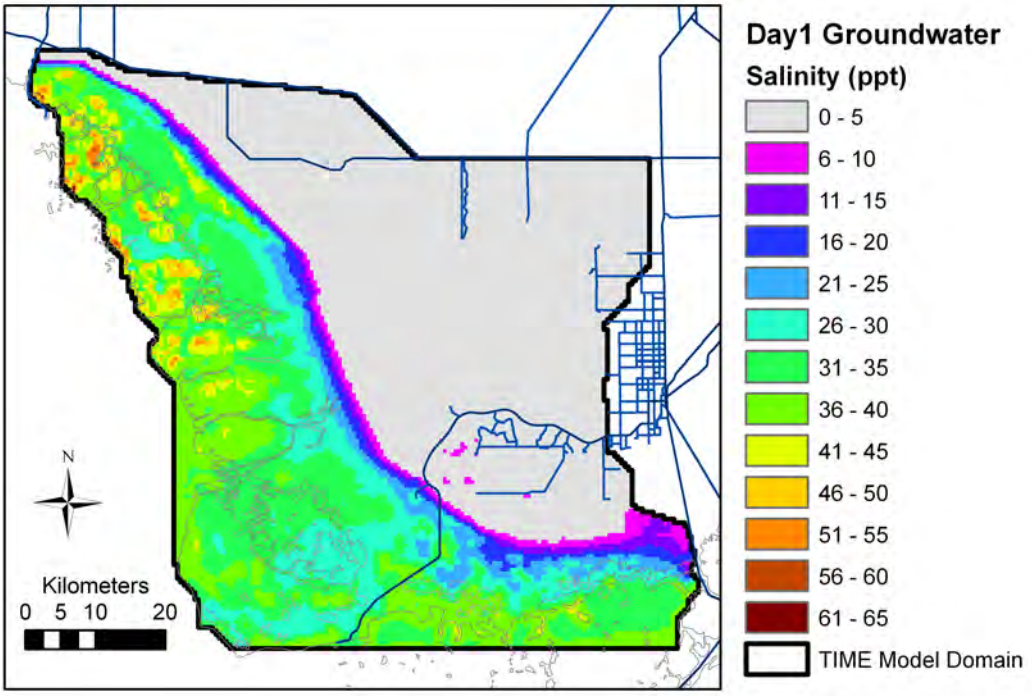


Figure 11. Model-computed groundwater salinity on first day of simulation for TIME v2.0 runs.

lacked the dynamics of the measured conditions. In the present version, TIME v2.0, downstream boundary conditions were upgraded to include the daily and seasonal variation of Florida Bay and the Gulf of Mexico. The timeseries were set according to output obtained from the Florida Bay application [Hamrick and Moustafa, 2003] of the EFDC, the domain of which is presented in Figure 2. Earlier efforts, a part of the FBFKFS, generated this dataset during attempts to couple TIME and the EFDC. Details of this earlier effort were documented and can be found in Appendix F.

The EFDC-derived datasets are applied to the TIME simulation along the marine portions of its western boundary where the rivers exit out to the sea, and along the southern boundary where it cuts across Florida Bay (Fig. 12). The surface water marine boundary conditions are applied in the discontinuous sections shown, and a no-flow boundary condition is prescribed for the boundary cells over land. The prescribed surface water stage and salinity timeseries for these western and southern boundaries are presented in Appendix A.

The use of boundaries derived from the iterative process between EFDC and TIME led to better matches with measured data along the downstream boundaries than the use of the Fourier series. Figure 13 presents comparisons of two stations influenced by the downstream boundary and shows the timeseries output for the TIME v2.0 model with the EFDC and Fourier series boundaries and measured data. The Shark River (SR) station shows the effects on stage and the Little Madeira Bay (LM) station shows the effects on salinity. Both examples show improvements in performance by using the EFDC boundary condition inputs.

For the groundwater portion of the TIME model, the stage along the marine boundaries is static and set to average sea level (0.8 ft NGVD 29), and the salinity is set to 36 ppt.

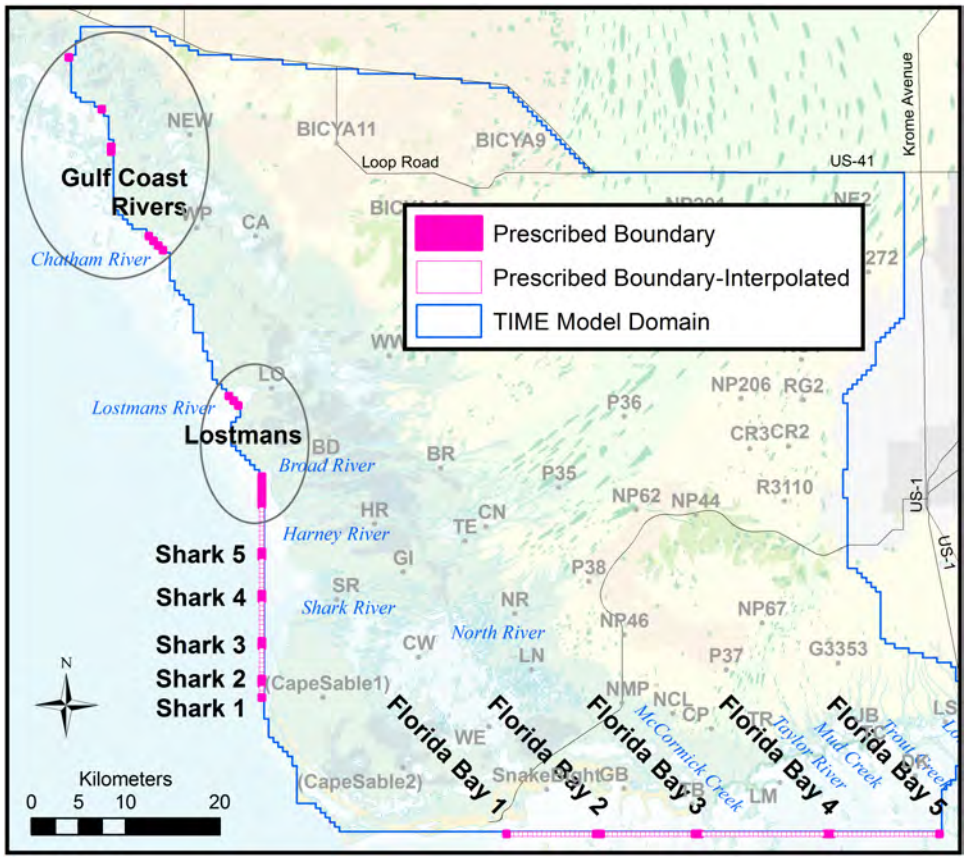


Figure 12. Locations of prescribed marine surface water boundary conditions in TIME v2.0. Timeseries are explicitly prescribed for solid-colored cells, and interpolated for the remaining boundary cells; all other cells on the south and west marine boundaries are treated as land boundaries. Description of marine boundary condition input can be found in Schaffranek [2004]. Stage and salinity timeseries for marine boundaries are provided in Appendix A.

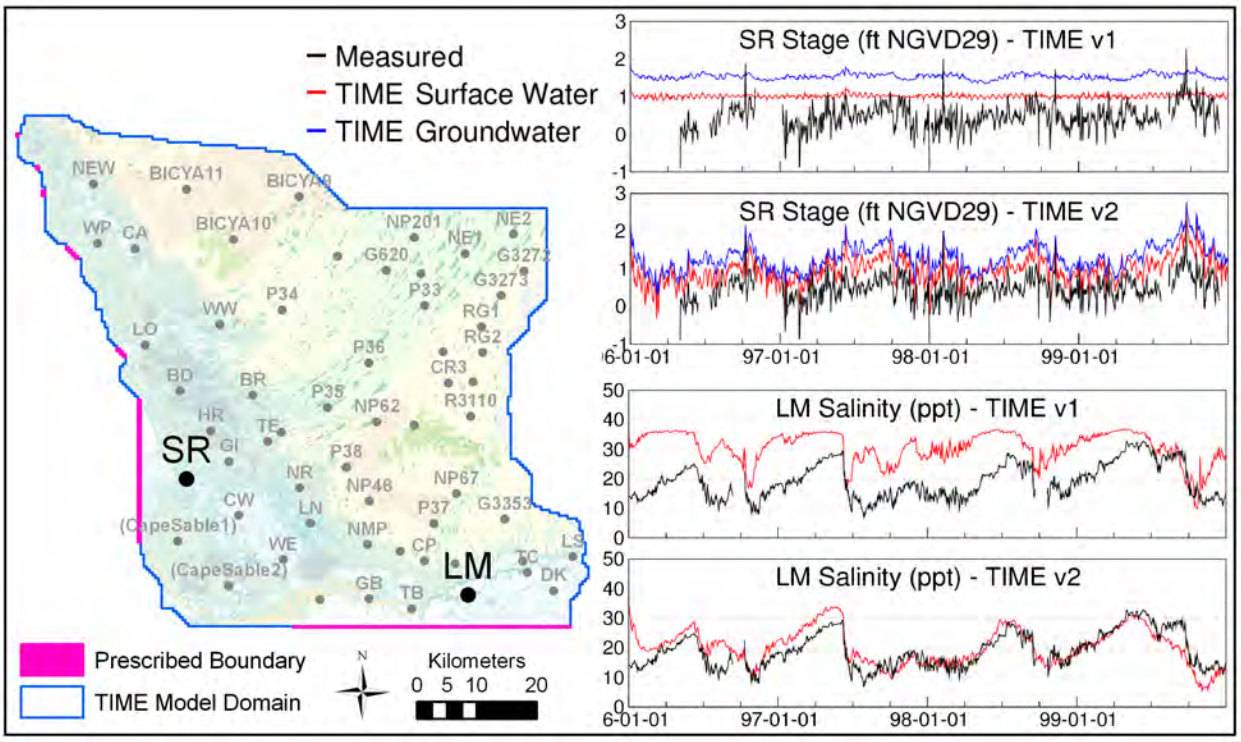


Figure 13. Effects on TIME's model-computed surface water and groundwater stage and salinity output using EFDC instead of Fourier boundary timeseries. TIME v1.0 uses a Fourier timeseries for the stage boundary and a constant salinity value of 36 ppt for the marine boundaries. As a result, SR stage for TIME v1.0 shows little variability and LM salinity values are much higher than measured values. TIME v2.0 uses boundary conditions derived from an EFDC simulation, and shows a much closer match to measured data for both salinity and stage results. EFDC-computed timeseries used in TIME v2.0 are provided in Appendix A.

3 CALIBRATION RUN EVALUATION

During development of TIME v2.0 for use in application to ecosystem restoration and sea level rise questions, several issues were encountered that made it necessary to modify model code and datasets. The most significant of these issues, as discussed in Section 2, included changes in marine boundary conditions, and interaction between the surface water and groundwater systems. As a result, an evaluation of the TIME v2.0 calibration run output was necessary. A new set of performance statistics were calculated to aid in interpretation of scenario output and uncertainty thereof. Because application of TIME v2.0 was the primary goal of the study, only a limited number of analyses were performed. These focused on providing a general assessment of how well the TIME model was performing, using daily groundwater stage, surface water salinity, and annual average river flow volumes as primary analysis criteria. An analysis of sensitivity to prescribed marine boundary salinity was also performed using one of the SFWMM alternatives as a base condition. The salinity sensitivity results are presented in Section 4.

The calibration time period for TIME v2.0 was initially the same as TIME v1.0, 1996–2002, inclusive. However, the calibration period was adjusted when it was discovered that using input datasets generated in the Alt7r5e run of the EFDC [Hamrick, 2006] and measured data yielded better calibration results along the marine boundaries. A 1-year warm-up period was also deemed necessary to allow the model to stabilize. The final TIME v2.0 calibration time period is 1997–99, inclusive.

In this section, performance statistics for the SFWMM v5.4 verification run and TIME v1.0 calibration run are also presented for comparison. Statistics for TIME v1.0 are taken from Wang et al. [2007], which used the entire 7-year time period of 1996–2002, and are reproduced here in their original form. Covariance, correlation, percent explained variance, and Nash-Sutcliffe coefficients were calculated for groundwater stage at selected stations where measured data were available. The complete set of timeseries graphics of surface water, groundwater, and salinity for all of the calibration stations are provided in Appendix B.

3.1 Boundary Condition Inputs

Boundary conditions for the southern and western marine boundaries are the same for both the TIME v2.0 calibration and alternative runs, and were discussed earlier in section 2.7. Northern and eastern boundary conditions for the calibration run consist of prescribed flows for the surface water portion of the model and prescribed stages for the groundwater portion of the model. These datasets were constructed using the measured structure flow and groundwater head data along Tamiami Trail and the Eastern Protective Levee System. Average annual surface water inflow volumes are shown in Figure 14, which are obtained from measured data and input to the model at the locations shown on the map. The majority of the surface water flows into the model domain along the northern boundary. However, after the development and application of TIME v2.0 was completed, it was discovered that input flows for the TCMON2CAR section were being assigned to inactive cells north of the model domain. The ratio of flow between the western (S12 structures) and eastern (Northeast Shark Slough) portions of northern Shark Slough is almost 4 to 1 for the modeled time period, 1996–99.

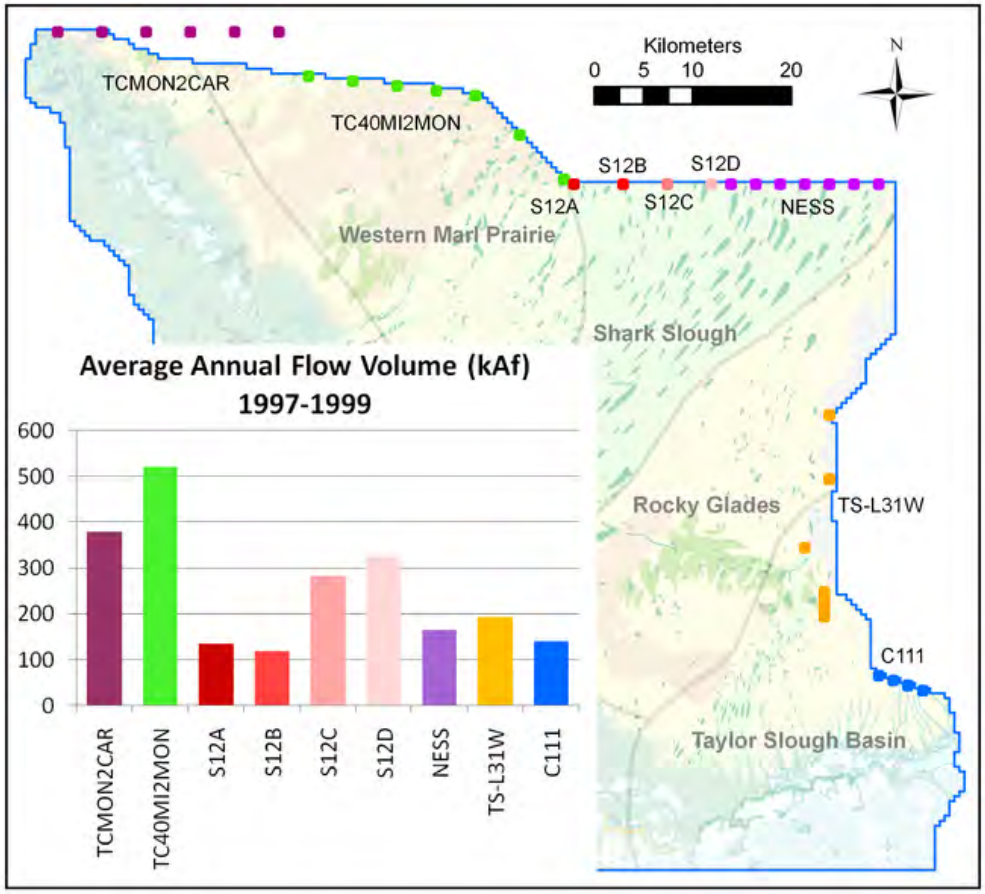


Figure 14. TIME v2.0 calibration run average annual surface water inflow volumes and respective locations of input to the model domain.

3.2 Performance Statistics

In the following analysis, groundwater stage values from TIME v1.0 and TIME v2.0 are used for calculating the model performance statistics. For selected locations, the performance statistics for surface water output from the SFWMM simulation are also presented. The SFWMM simulation rarely has differences between surface water and groundwater, and its surface water output also provides the depth below land surface; thus, usage of surface water heads from this model is comparable.

In the following paragraphs, the equations used to calculate the statistics in the data tables are defined along with a short description of their standard use. Following the tabulation of this output, interpretations of the calibration output are provided for each basin defined in Figure 3, along with the individual statistics for the selected stations within that basin.

Covariance ($CoVar$) is a measure of how much two variables change with respect to each other. The simulated and the measured daily values are subtracted from their respective

means, and the products of the resulting deviations are summed and averaged:

$$CoVar = \frac{\Sigma_{i=1}^{N}\left(h_m^i - \overline{h_m}\right)\left(h_o^i - \overline{h_o}\right)}{N}$$

where:

N	is	number of measurements
h_o^i	is	i^{th} measured stage value
h_m^i	is	i^{th} simulated stage value
$\overline{h_o}$	is	average measured stage
$\overline{h_m}$	is	average simulated stage

The covariance is useful to illustrate the fluctuations occurring in the data sets of the simulated and measured timeseries. A high covariance indicates that each dataset varies about their respective means in a similar manner.

Correlation (Cor) is defined as the covariance of the measured and simulated stages divided by the product of their standard deviations:

$$Cor = \frac{\Sigma_{i=1}^{N}\left(h_m^i - \overline{h_m}\right)\left(h_o^i - \overline{h_o}\right)}{\sqrt{\Sigma_{i=1}^{N}\left(h_m^i - \overline{h_m}\right)^2 \Sigma_{i=1}^{N}\left(h_o^i - \overline{h_o}\right)^2}}$$

The correlation is dimensionless and describes the degree to which the two data sets rise and fall in a similar manner. Because the value is unitless, a comparison of the resulting values between stations of different variance will provide a better comparison. A value of 1.0 indicates perfect correlation. The correlation and covariance describe the degree of similarity between the data sets.

The Percent Explained Variance (PEV) is defined as:

$$PEV = 100\% * \left[1 - \left(\frac{\Sigma_{i=1}^{N}\left[(h_m^i - h_o^i) - \left(\overline{h_m - h_o}\right)\right]^2}{\Sigma_{i=1}^{N}\left(h_o^i - \overline{h_o}\right)^2}\right)\right]$$

The PEV compares the variance of the residual (expressed by the numerator of the fraction) to the variance of the measured data (expressed as the denominator). This yields a percentage of the measured variability that is represented in the simulation results, where a PEV value of 100% indicates that all variance is explained.

The Nash-Sutcliffe model efficiency coefficient (NS) compares the residual squared to the measured variance:

$$NS = 100\% * \left[1 - \frac{\Sigma_{i=1}^{N}\left(h_m^i - h_o^i\right)^2}{\Sigma_{i=1}^{N}\left(h_o^i - \overline{h_o}\right)^2}\right]$$

The Nash-Sutcliffe coefficient yields a percentage of the error relative to the measured variance, and can range from negative infinity to 100%. The Nash-Sutcliffe coefficient includes a measure of bias, and is sensitive to differences between measured and computed values. A value of $NS = 100\%$ indicates there is no difference between model-computed and measured data, and a value of $NS = 0\%$ indicates that the model predictions are as accurate as the mean of the measured data. A value less than 0% indicates that the mean of the measured data is a better predictor than the model. Thus this method places emphasis on large deviations between model-computed and measured values.

The NS analysis can point the modeler to possible problems regarding measured or model-computed land surface elevations, or to problems with the accuracy of the predictive values of the model, especially those related to relationships of variances and biases (precision and accuracy).

3.2.1 TIME v1.0 and TIME v2.0

The performance statistics for both TIME v1.0 and TIME v2.0 are shown in Tables 1 and 2. Stations were selected for analysis to provide a distribution as uniform as possible throughout the domain, and are organized according to the basins defined in Figure 3. The time period of the TIME v1.0 calibration run is 1996–2002 and for TIME v2.0 is 1997–99. Performance statistics presented in this section for the two models will be for these different periods. For TIME v2.0, measured data for the selected stations are available more than 70 percent of the time for the period 1997–99, with many stations having data available greater than 90 percent of the time. Stations with more than 10 percent of measured data missing are noted in the performance results tables. TIME v1.0 statistics are reproduced from Wang et al. [2007].

In the tables, the surveyed elevation of each station is provided, as well as the average cell elevation and the elevation at which the TIME model considers the cell as dry. Where larger gradients are present, the model's average stage and elevation in its 500 by 500 meter cell may not be representative of the specific station stage within that cell.

The correlation results for TIME v2.0 are generally of high degree, indicating that the model-computed data and the measured data are fluctuating in a similar fashion during the calibration time period. Implementation of the EFDC boundaries greatly improved performance in estuarine areas, and better calibration performance relative to TIME v1.0 was noted at several of the coastal and riverine stations. Figure 15 contains spatial representations of the statistics and shows the improvements of the percent explained variance in the Western Marl Prairie and near the downstream boundaries in Whitewater Bay and Taylor Slough.

Table 1. TIME v1.0 and TIME v2.0 calibration run performance statistics for groundwater stage, Part 1. 'Cor.' is correlation, 'CoVar' is covariance in ft^2, 'PEV' is percent explained variance, and 'NS' is the Nash-Sutcliffe coefficient. Meas. Count is the number of measurements available. Elevations are in ft NGVD 29. Stations with '*' are non-marine sites that have a greater than 1 ft (or unknown) difference between modeled and surveyed land surface elevation values, and stations with '†' have more than 10 percent of measured data missing. A '-' indicates the value was not determined.

	TIMEv2(v1) Cor.	TIMEv2 CoVar.	TIMEv2(v1) PEV	TIMEv2 NS	Meas. Count	Avg. Cell Elevation	Cell Drying Elevation	Surveyed Elevation
Western Marl Prairie								
BICYA9*	0.87 (0.81)	0.33	68 (62)	63	1095	8.02	8.23	–
BICYA10*	0.86 (0.84)	0.49	73 (69)	73	1081	4.21	4.37	–
BICYA11*	0.78 (0.73)	0.47	57 (50)	55	1023	3.98	4.32	–
LOOP1T*	0.88 (0.73)	0.23	8 (22)	-390	1095	5.73	6.10	–
LOOP2T*	0.83 (0.75)	0.26	56 (48)	-23	1095	4.64	4.86	–
NP205	0.91 (0.83)	0.44	80 (68)	50	985	6.16	6.21	5.86
P34	0.91 (0.86)	0.44	84 (74)	73	1051	1.78	1.99	1.86
TMC	0.94 (0.89)	0.38	86 (77)	65	1004	–	4.01	3.89
Shark Slough								
G620	0.96 (0.93)	0.24	91 (87)	26	1062	5.94	6.03	5.81
L67XW*	0.96 (0.74)	0.28	80 (42)	69	1095	–	5.96	–
NE1	0.95 (0.85)	0.13	84 (69)	6	1095	5.73	5.77	5.85
NE2	0.93 (0.86)	0.11	84 (65)	-96	1082	5.90	5.95	5.63
NE4	0.95 (0.83)	0.15	90 (61)	49	1027	–	5.67	5.52
NP201	0.96 (0.86)	0.38	90 (72)	16	1074	6.78	6.93	6.18
NP202†	0.97 (0.96)	0.29	87 (90)	60	941	5.85	5.95	5.34
NP203	0.96 (0.92)	0.21	91 (80)	77	1056	5.37	5.52	4.44
P33†	0.95 (0.92)	0.11	85 (80)	85	958	5.50	5.56	4.89
P35*	0.93 (0.95)	0.20	84 (89)	37	1090	-1.27	0.20	0.87
P36	0.94 (0.91)	0.12	87 (80)	86	983	3.51	3.59	3.26
Rocky Glades								
A13	0.91 (0.86)	0.48	80 (73)	59	1095	–	4.76	4.72
CR2	0.89 (0.93)	0.53	71 (85)	14	1004	5.74	5.92	5.60
CR3	0.89 (0.86)	0.58	76 (74)	57	1095	5.76	5.85	5.60
CYP2*	0.82 (0.86)	0.44	53 (68)	52	1023	–	1.57	5.39
CY3*	0.79 (0.81)	0.46	41 (60)	24	1095	–	2.46	6.52
DO1	0.81 (0.86)	0.67	61 (74)	57	1093	–	3.39	3.42
DO2	0.82 (0.85)	0.67	65 (73)	54	1087	–	3.84	3.42
G1502*	0.91 (0.82)	0.26	71 (62)	-3	1095	–	6.74	8.32
G3272	0.90 (0.77)	0.22	67 (49)	-61	1087	6.57	6.71	6.85
NP206	0.88 (0.87)	0.32	60 (72)	43	1075	6.03	6.08	6.03
NP44	0.80 (0.86)	0.91	64 (72)	62	999	4.90	5.72	5.07
NP46	0.84 (0.75)	0.37	55 (50)	38	1095	1.51	1.70	1.36
NP62*	0.93 (0.82)	0.41	86 (66)	85	999	2.31	2.55	4.27
NP72	0.79 (0.85)	0.90	62 (70)	62	1076	–	4.77	4.50
NTS14*	0.85 (0.91)	1.02	70 (76)	5	998	–	6.09	4.05
P38	0.91 (0.82)	0.22	81 (67)	80	983	1.01	1.11	0.90
R3110	0.84 (0.92)	0.73	70 (82)	-8	1085	5.28	5.64	5.16
RG1†	0.91 (0.86)	0.35	65 (67)	46	794	0.32	6.35	5.04
RG2†	0.92 (0.89)	0.34	67 (78)	51	975	0.20	6.32	6.12
SP	0.88 (0.83)	0.46	77 (69)	73	1081	–	3.11	2.46

Table 2. TIME v1.0 and TIME v2.0 calibration run performance statistics for groundwater stage, Part 2. 'Cor.' is correlation, 'CoVar' is covariance in ft^2, 'PEV' is percent explained variance, and 'NS' is the Nash-Sutcliffe coefficient. Meas. Count is the number of measurements available. Elevations are in ft NGVD 29. Stations with '*' are non-marine sites that have a greater than 1 ft (or unknown) difference between modeled and surveyed land surface elevation values, and stations with '†' have more than 10 percent of measured data missing. A '-' indicates the value was not determined.

	TIMEv2(v1) Cor.	TIMEv2 CoVar.	TIMEv2(v1) PEV	TIMEv2 NS	Meas. Count	Avg. Cell Elevation	Cell Drying Elevation	Surveyed Elevation
West Coast Ecotone								
BR†	0.84 (0.90)	0.12	70 (81)	69	979	-1.74	0.96	–
CN	0.87 (0.90)	0.13	76 (76)	46	1054	-3.24	1.22	–
WW*†	0.82 (0.88)	0.13	66 (78)	-59	918	0.57	0.69	–
Whitewater Bay Basin								
CW	0.90 (0.75)	0.10	78 (13)	-128	1038	-5.39	-4.56	–
NMP*	0.84 (0.78)	0.30	30 (38)	6	1085	-0.54	1.55	–
NR†	0.77 (0.91)	0.08	58 (80)	-330	955	-2.85	-2.44	–
WE	0.83 (0.83)	0.10	64 (50)	-126	1095	-4.48	-3.82	–
Taylor Slough Basin								
CP	0.83 (0.83)	0.26	63 (67)	41	1031	-0.20	0.10	-0.11
DK†	0.81 (0.86)	0.08	65 (18)	-38	775	-4.66	-4.56	–
EPGW	0.94 (0.84)	0.13	73 (67)	73	992	–	1.19	1.03
G1251†	0.91 (0.88)	0.27	62 (71)	61	750	–	2.33	2.85
LS*	0.73 (0.72)	0.06	45 (26)	45	1056	-1.52	-1.52	–
NCL*	0.81 (0.78)	0.36	43 (59)	-20	1003	0.30	0.74	–
NP67*	0.89 (0.90)	0.50	31 (78)	-258	1080	2.16	2.35	3.47
P37	0.84 (0.86)	0.28	46 (73)	46	1094	0.98	1.09	0.95
R127*†	0.93 (0.92)	0.41	86 (84)	71	922	–	1.77	–
TSB†	0.89 (0.93)	0.64	78 (83)	67	967	–	3.19	3.58
TSH	0.91 (0.90)	0.31	73 (81)	73	1074	–	1.56	1.49

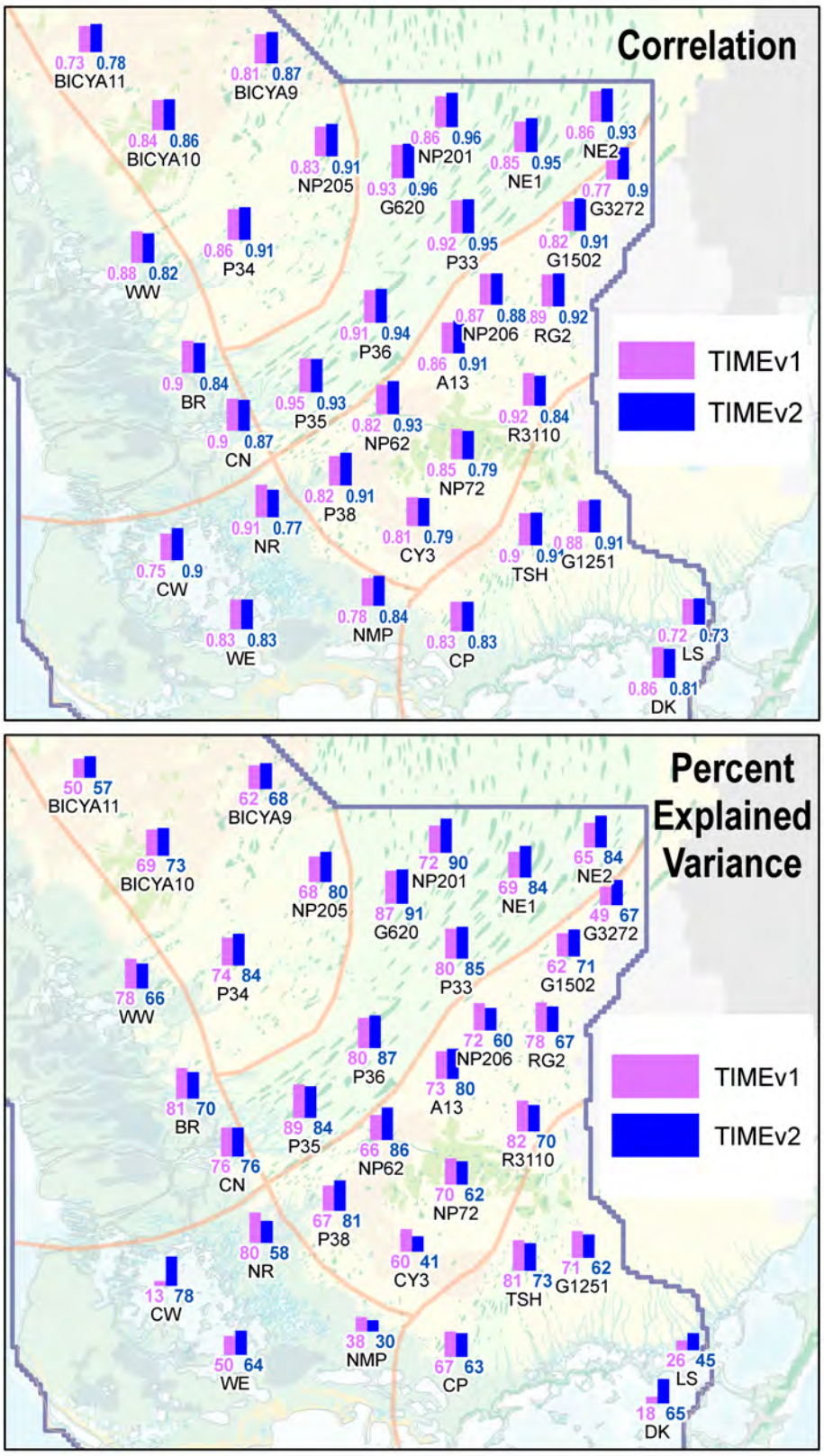


Figure 15. Groundwater stage performance statistics for TIME v1.0 and v2.0.

3.2.2 TIME v2.0 and SFWMM v5.4

Performance statistics were computed for the SFWMM v5.4 Verification Run and TIME v2.0. Care must be exercised when comparing the results because the two models use different grid cell sizes. The SFWMM and TIME cells are 2 miles and 500 m square, respectively, and the cells used to represent any particular station will report averaged values over different spatial areas. To make comparisons more relevant between TIME and SFWMM, the elevation values and cells used to compare to individual observation stations are tabulated in Table 3 and illustrated in Figure 16.

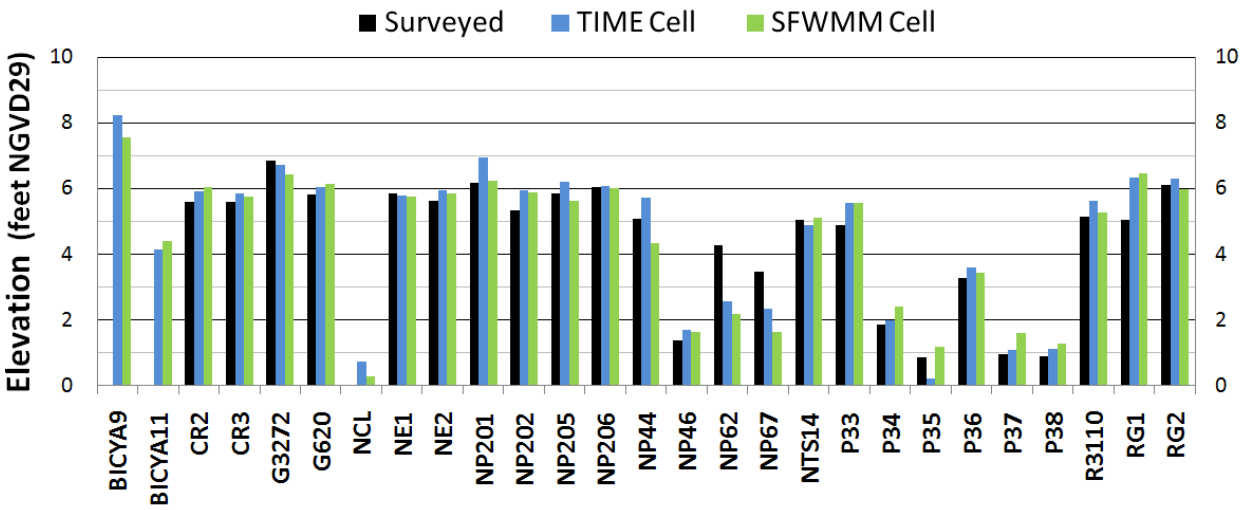


Figure 16. Simulated and surveyed station elevations (ft NGVD 29).

Performance statistics for the SFWMM v5.4 Verification Run and TIME v2.0 calibration run are shown in Table 4 for the period 1997–99. Figure 17 contains graphical representations of the performance statistics. The coastal ecotone is not modeled in the SFWMM so this area is not represented in these statistics. Generally the SFWMM has better statistics in the Rocky Glades and Taylor Slough area. This may in part be due to the difference in the model architecture. The SFWMM includes a canal/structure network interacting directly with the adjacent cells and the model is calibrated to obtain high accuracy in these areas. The performance statistics for both models are explained more completely in the section on basin specific performance (Section 3.4).

3.3 Spatial Distribution of Stage and Salinity

Animations of the gridded values for the entire modeled time period can be produced and include spatial timeseries for surface water, groundwater, and salinity distributions. These animations present a spatial view of daily values and help in assessing the patterns produced by the model. To illustrate the significant spatial patterns observed, four specific dates were identified which provide a full range of the hydrologic conditions and are shown in Figures 18 and 19. In these plots the distribution of stage and salinity are displayed and a qualitative assessment of the extent of the presence of surface water and extent of fresh water within the domain is obtained.

The spatial distribution shown in the plots ranges from dry to wet conditions. The extent of surface water and movement in the surface water salinity are readily visualized in

Table 3. Elevation values for stations used in performance statistics calculations (ft NGVD 29) for TIME v2.0 and SFWMM v5.4. Stations with '*' are non-marine sites that have a greater than 1 ft (or unknown) difference between modeled and surveyed land surface elevation values, and stations with '†' have more than 10 percent of measured data missing. A '-' indicates the value was not determined. TIME and SFWMM grid origins are each in the southwest corner of their respective domains. Surveyed elevation values were taken from Wang et al. [2007]. TIME cell elevations shown are for the southwestern corner of each cell.

Station	Surveyed Elevation	TIME Cell Elevation	SFWMM Cell Elevation	TIME Cell Location	SFWMM Cell Location
BICYA9*	–	8.23	7.57	C097,R145	C13,R23
BICYA11*	–	4.13	4.40	C059,R147	C08,R23
CR2	5.60	5.92	6.05	C155,R083	C23,R13
CR3	5.60	5.85	5.75	C147,R083	C21,R13
G3272	6.85	6.71	6.42	C172,R120	C25,R19
G620	5.81	6.03	6.14	C126,R120	C18,R19
NCL*	–	0.74	0.28	C130,R027	C19,R04
NE1	5.85	5.77	5.74	C152,R126	C22,R20
NE2	5.63	5.95	5.85	C168,R132	C25,R21
NP201	6.18	6.93	6.23	C135,R132	C19,R20
NP202	5.34	5.95	5.87	C137,R119	C20,R19
NP205	5.86	6.21	5.64	C109,R125	C15,R19
NP206	6.03	6.08	6.02	C145,R093	C21,R15
NP44*	5.07	5.72	4.34	C135,R069	C19,R11
NP46	1.36	1.70	1.64	C120,R043	C17,R07
NP62*	4.27	2.55	2.19	C123,R070	C17,R11
NP67*	3.47	2.35	1.64	C149,R046	C22,R07
NTS14	5.05	4.89	5.10	C152,R066	C22,R10
P33	4.89	5.56	5.55	C139,R109	C20,R17
P34	1.86	1.99	2.41	C091,R107	C13,R17
P35*	0.87	0.20	1.18	C106,R075	C15,R12
P36	3.26	3.59	3.43	C120,R090	C17,R14
P37	-0.95	1.09	1.59	C142,R036	C20,R06
P38	-0.90	1.11	1.28	C112,R055	C16,R08
R3110	5.16	5.64	5.27	C154,R072	C22,R11
RG1	5.04	6.35	6.47	C158,R102	C23,R16
RG2	6.12	6.32	5.97	C158,R093	C23,R14

these four examples. The surface water stage distribution in Figure 19 shows the inundation pattern from a dry to a wet condition. The narrow deep portion of Shark Slough has a long hydroperiod, and the western marl prairie inundates as local rainfall and S-12 releases take place. The eastern marl prairie and the area from Rocky Glades to Taylor Slough take longer to re-wet. The rivers are readily discerned and large dry areas occur in between the rivers, except when the entire model domain is wet.

The salinity distribution plots in Figure 19 illustrate the spatial movement of the interface across the domain. As the stage increases, the fresh/salt water interface moves inland, and the influence of the prescribed salinity boundary conditions can be readily discerned within the coastal region.

Surface water stage contours are shown in Figure 18; on March 12, 1997, the model is near the minimum water level for that dry season, and the measured data indicate the water levels are still receding. Near the end of the wet season on November 15, 1997, the stages are receding from the peak wet season and this timestep may be interpreted as representing an "average" condition.

Several above-normal rainfall days during the dry season produced the stages shown for

Table 4. Performance statistics for groundwater stage for TIME v2.0 and SFWMM v5.4 calibration runs (1997–99). 'Cor.' is correlation, 'CoVar' is covariance in ft^2, 'PEV' is percent explained variance, and 'NS' is the Nash-Sutcliffe coefficient.Stations with '*' are non-marine sites that have a greater than 1 ft (or unknown) difference between modeled and surveyed land surface elevation values, and stations with '†' have more than 10 percent of measured data missing. A '-' indicates the value was not determined.

Station	TIME Cor.	SFWMM Cor.	TIME CoVar.	SFWMM CoVar.	TIME PEV	SFWMM PEV	TIME NS	SFWMM NS
Western Marl Prairie								
BICYA9*	0.87	0.85	0.33	0.22	68	72	63	16
BICYA11*	0.78	0.84	0.47	0.51	57	63	55	63
NP205	0.91	0.80	0.44	0.23	80	62	50	-46
P34	0.91	0.92	0.44	0.44	84	84	73	83
Shark Slough								
G620	0.96	0.97	0.24	0.32	91	93	26	93
NE1	0.95	0.93	0.13	0.12	84	82	6	51
NE2	0.93	0.93	0.11	0.11	84	86	-96	79
NP201	0.96	0.97	0.38	0.44	90	94	16	-51
NP202†	0.97	0.98	0.29	0.39	87	97	60	90
P33†	0.95	0.98	0.11	0.16	85	95	85	94
P35*	0.93	0.91	0.20	0.22	84	82	37	75
P36	0.94	0.96	0.12	0.15	87	93	86	90
Rocky Glades								
CR2	0.89	0.95	0.53	1.01	71	88	14	-81
CR3	0.89	0.94	0.58	0.94	76	86	57	84
G3272	0.90	0.83	0.22	0.34	67	69	-61	65
NP206	0.88	0.97	0.32	0.75	60	93	43	92
NP44	0.80	0.86	0.91	1.04	64	74	62	74
NP46	0.84	0.88	0.37	0.31	55	76	38	67
NP62*	0.93	0.96	0.41	0.34	86	87	85	83
NTS14	0.85	0.92	1.02	1.43	70	84	5	-12
P38	0.91	0.94	0.22	0.23	81	88	80	51
R3110	0.84	0.94	0.73	1.17	70	86	-8	-122
RG1†	0.91	0.97	0.35	0.94	65	90	46	-104
RG2†	0.92	0.94	0.34	0.86	67	83	51	-263
Taylor Slough Basin								
NCL*	0.81	0.81	0.36	0.33	43	48	-20	-135
NP67*	0.89	0.92	0.50	0.36	31	82	-258	-913
P37	0.84	0.91	0.28	0.30	46	65	46	35

January 4, 1998. The coastal rivers are well defined as seasonal tidal lows draw much of the surface water away from the surrounding wetlands. The peak stages of the 1998 wet season on September 20, 1998, are shown in the contour plot with few areas not inundated.

Salinity contours for the four selected days described in the previous section are shown in Figure 19. The surficial salinity interface is clearly defined by the transition from the darker blue to lighter blue color (at around 10 ppt), and the influence of the prescribed boundary timeseries can be noticed (see Figure 12 for the boundary locations). Note that on January 4, 1998 (high rainfall in the dry season), the areas where freshwater and saltwater are mixing have moved a considerable distance downstream as compared to the other days.

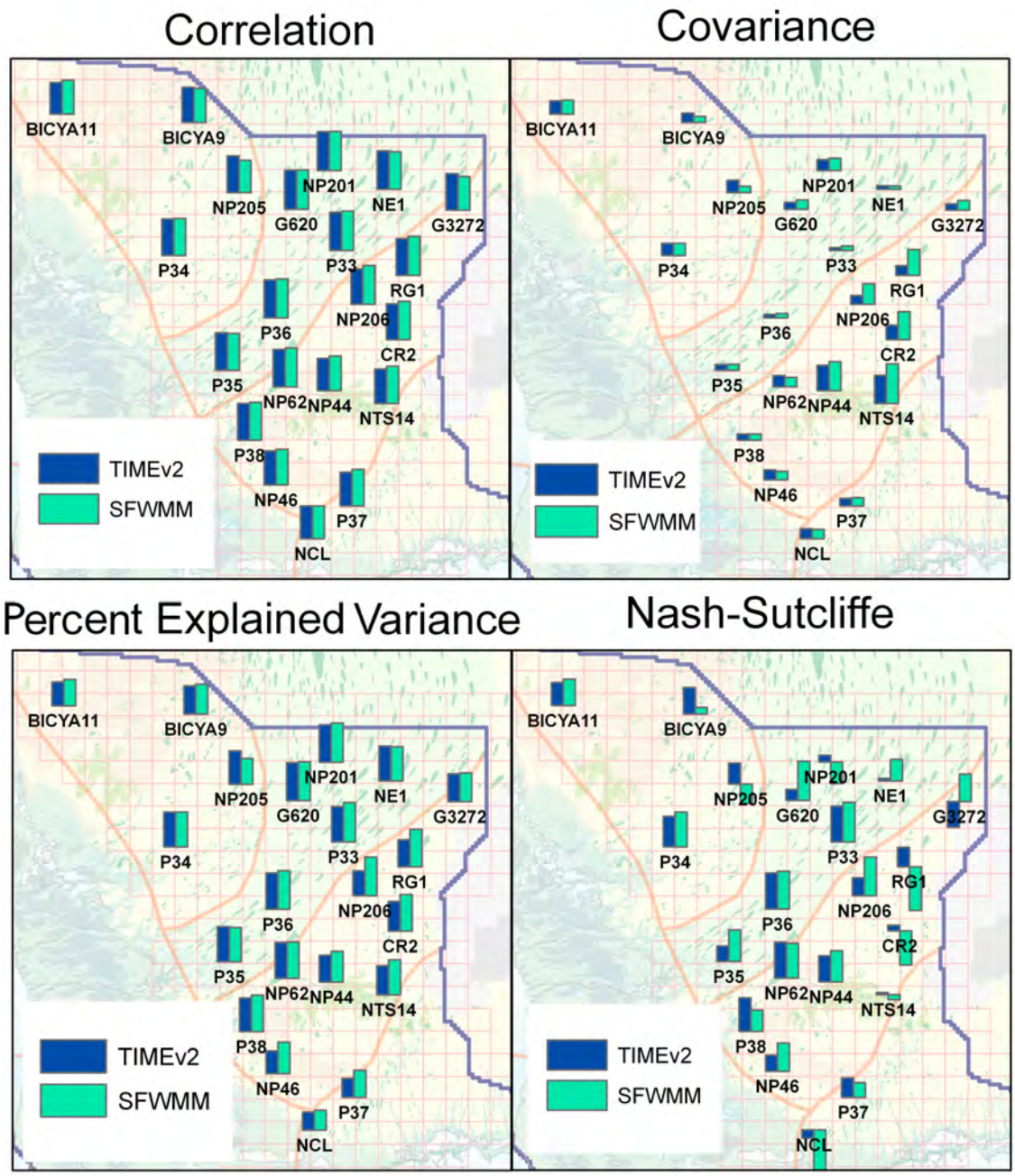


Figure 17. Relative groundwater stage performance statistics for TIME v2.0 and SFWMM v5.4. Values for statistics are presented in Table 4.

3.4 Basin Specific Evaluation of Performance

For ease in discussing model performance, regional evaluations of the statistics and output data were implemented; the TIME model domain was subdivided into six basins as shown in Figure 3. The following sections detail each of the basins individually.

During calibration, stages are analyzed and incremental adjustments made to specific model data sets. In the Everglades the interpretation of water depths is important; however,

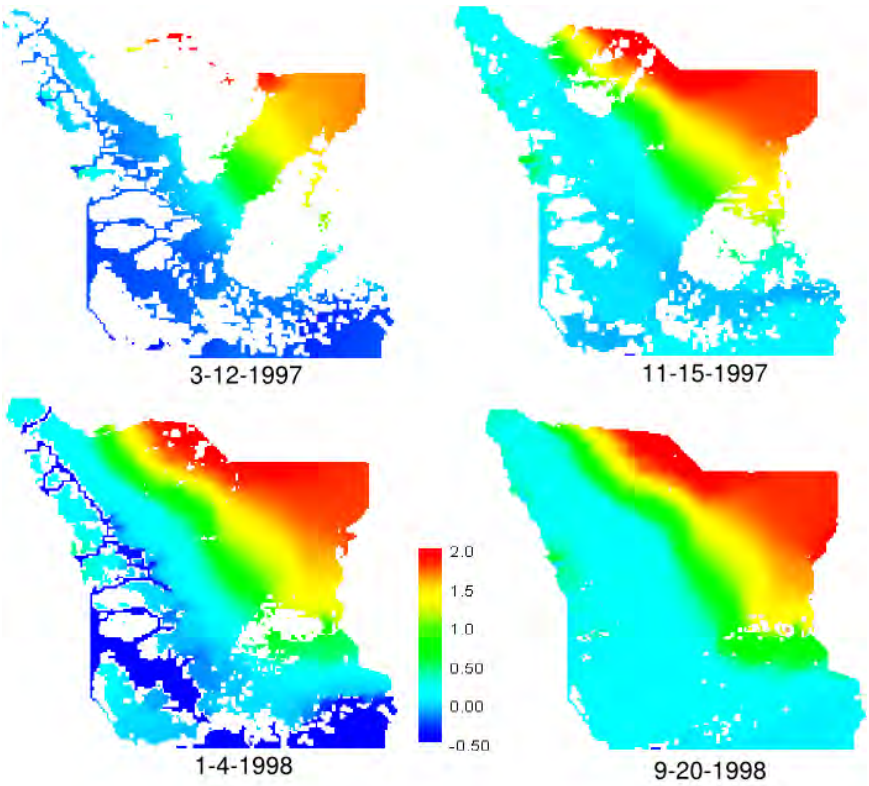


Figure 18. Surface water stage distribution (m NAVD 88) in the TIME v2.0 calibration run. The four days shown are representative of the dry season (upper left), a transitional (average) time (upper right), a day with high rainfall in the dry season (lower left), and the wet season (lower right). Dry cells are shown as white inside the model domain, as are inactive cells outside the model domain.

during calibration the stages are often used as they are a more spatially uniform statistic. As a result, the following sections concentrate primarily on stages rather than depths. The differences in grid cell elevation and land surface elevation should be considered when making decisions on the value of the calibration in specific areas and the interpretation of the scenario results.

Even though entire timeseries are presented in the graphics, the performance for the first year (1996) of the TIME model simulation is considered a warm-up period and should be ignored. Performance statistics in the graphics were calculated only for the 1997–99 time period. The complete set of graphics of the timeseries for all calibration stations may be found in Appendix B.

General trends common to all the timeseries reflect patterns in precipitation specific to 1996–99. Annual rainfall totals during this period indicate that 1996 was a dry year and 1999 a wet year. Several storm events are of note during the calibration period. Tropical Storm Mitch on November 5, 1998, caused a large storm surge on the west coast, with moderate rainfall over the model domain. Tropical Storm Harvey occurred on September 21, 1999, with 3 to 5 inches of rainfall and little storm surge. Hurricane Irene in October 1999 is the primary cause of the large rainfall total in 1999; the storm delivered between 10 and 15 inches of rain over the east side of the TIME domain. Peak stages as a result of these events can be seen in the plots in the next sections.

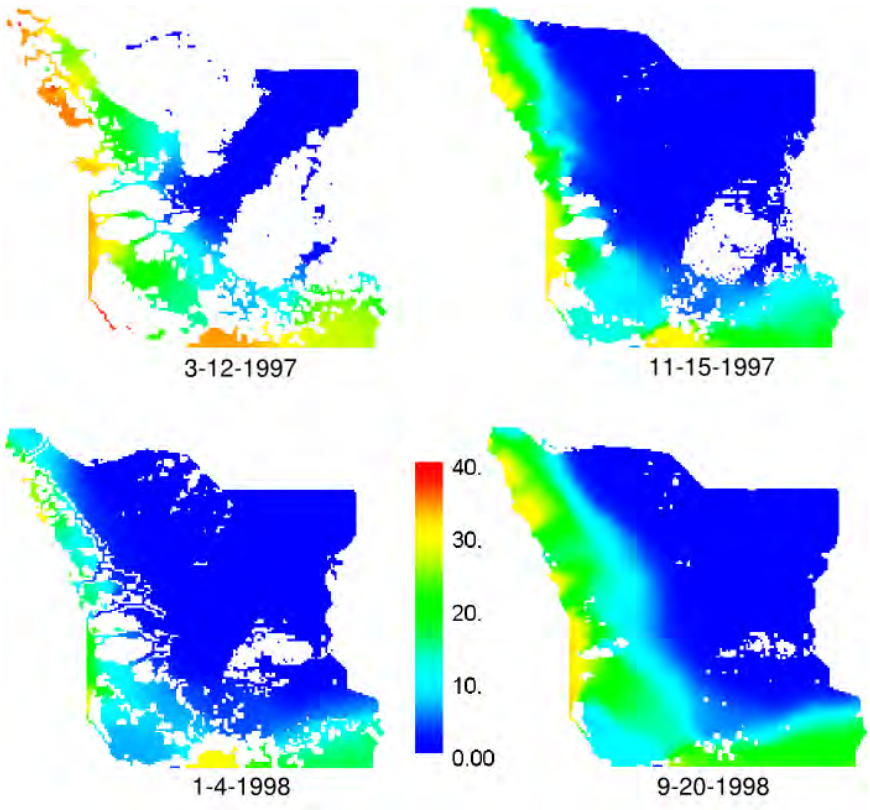


Figure 19. Surface water salinity distribution (ppt) in the TIME v2.0 calibration run. The four days shown are representative of the dry season (upper left), a transitional (average) time (upper right), a day with high rainfall in the dry season (lower left), and the wet season (lower right). Dry cells are shown as white inside the model domain, as are inactive cells outside the model domain.

3.4.1 Western Marl Prairie

This area is influenced by discharges from the structures S12A, S12B, S343A, and S343B, and contains some of the highest elevations in ENP. Representative stations include BICYA9, BICYA10, BICYA11, NP205, and P34 (see Figure 3).

BICYA9 is a dry site, surface water rarely persists, and the station is close to the northern input boundary. The TIME v2.0 model-computed stage is 0.2–0.4 ft higher than the measured data and does not capture two of the three seasonal lows. The SFWMM oscillates around the measured timeseries with differences of as much as 0.4 ft, the stages capture the seasonal low in 1998, but not in 1999. Stages at station BICYA10 calibrate well in both models, except for the lows in the dry season which are not captured well in 1998 or 1999.

Figure 20 contains the timeseries for NP205. The stages from the SFWMM calibrate poorly with as much as a 1 ft difference. The land surface elevation in the SFWMM model is 0.43 ft lower than surveyed, thus the water depths in the 2x2 model are below measured values by as much as 0.5 ft. The TIME stages are also low by as much as 0.5 ft. TIME surface water stage is higher than its groundwater head by about 0.1 ft. This station is of importance for determining surface water conditions for the Cape Sable Seaside Sparrow Population A habitat. None of the models perform well at this location, which leaves little confidence in the accuracy of the resultant hydroperiods. With TIME, the recession and ascension rates vary between surface and groundwater when above or below land surface.

The result is that hydroperiods can be substantially off which makes model results difficult to interpret. In the TIME model, during ascension periods, the difference between surface water and groundwater levels can diverge and the difference may be as large as 1 ft. This can lead to false interpretation of the rewetting event, which will in turn affect hydroperiod calculations.

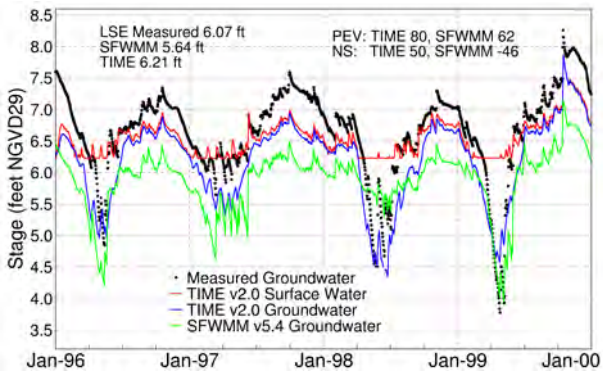


Figure 20. NP205 stage, Western Marl Prairie.

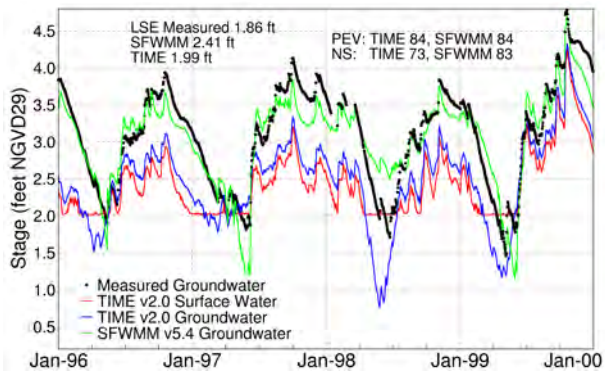


Figure 21. P34 stage, Western Marl Prairie.

At station P34, the SFWMM oscillates around the measured data (see Figure 21), with the minimum in the dry season of 1998 too high, and overshooting the low in 1997. The TIME values are too low by more than 0.5 ft. The TIME groundwater stage is 0.2 ft higher than its surface water stage at this location, indicating potential recharge of surface water by groundwater.

3.4.2 Shark Slough

The eastern section of the formerly deep-water slough is maintained by local rainfall and inflows through the culverts underneath Tamiami Trail (see Figure 3). The inflows to Northeast Shark Slough are delivered via structure S333, which is generally kept closed when water levels at G3273 on the edge of the Rocky Glades reach land surface. The subsidence that has occurred in the slough allows the central part to remain wet throughout the year, except during drought periods.

NE2 is a station in the northeast corner of the basin and is influenced by the prescribed boundary conditions at L29 and L31N in both the SFWMM and TIME models. The model-computed water levels in the TIME simulation are higher than measured values by 0.2 to 0.6 ft. In the SFWMM the model-computed stages remain much closer to measured values (see timeseries graph of NE2 in Appendix B).

The stages for NP201 are shown in Figure 22. The area is wet throughout the year, except during severe drought years. Both SFWMM and TIME stages are consistently as much as 1 ft lower than measured data. The cell elevation in TIME is only 0.05 ft higher than the surveyed elevation and dries out every year, and in SFWMM the cell elevation is 0.65 ft lower than surveyed.

Figure 23 plots the timeseries for P33, the models do very well in this area, and land surface elevation for the representative cells in the models are nearly the same as surveyed at the station site. Surface water flows in a southwest direction in the slough, from P33 to the next station, P36, which is shown in Figure 24. Both models also perform well in this area. The TIME and SFWMM capture the higher water levels well, and the SFWMM does better on the low end.

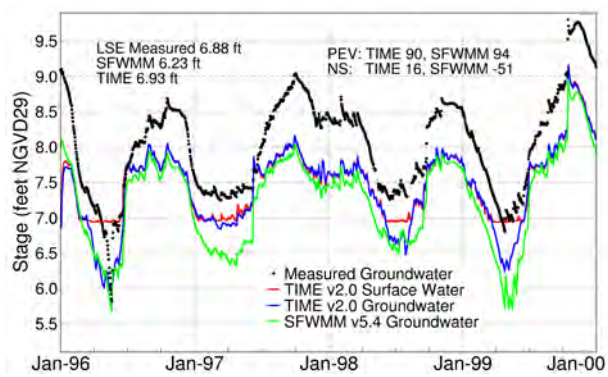


Figure 22. NP201 stage, Shark Slough.

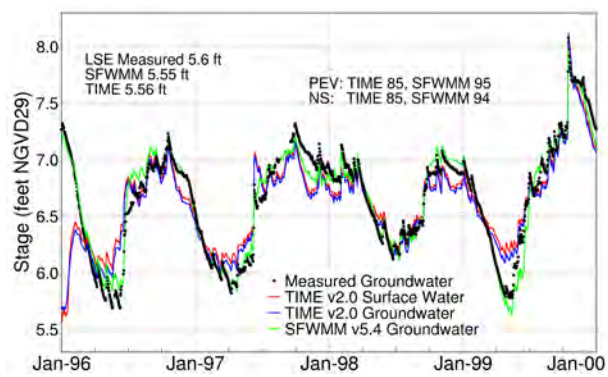


Figure 23. P33 stage, Shark Slough.

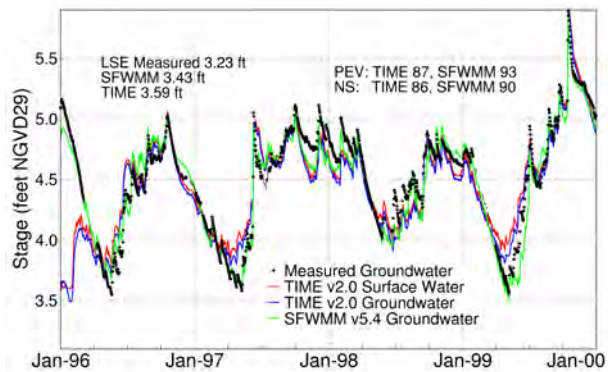


Figure 24. P36 stage, Shark Slough.

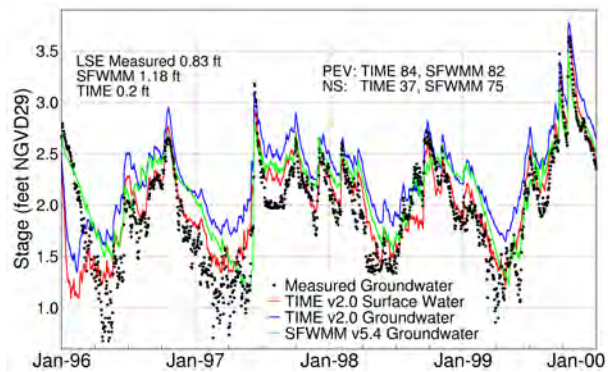


Figure 25. P35 stage, Shark Slough.

Near the appearance of navigable creeks in the landscape, leading to the Shark and Harney rivers is station P35. This station is influenced by local rainfall and by both upstream water deliveries and the effects of the Gulf of Mexico tides transmitted up the rivers. Figure 25 plots the timeseries for the measured and simulated data. This station is close to the southern boundary of the SFWMM. At P35 both models overestimate stages and underestimate variability with percent explained variance values in the lower 80s. TIME v2.0 surface water stages are closer to measured data than TIME v2.0 groundwater, and also closer than the stages in the SFWMM. The TIME v2.0 groundwater heads are higher than surface water stages by approximately 0.4 ft, indicating a region of groundwater discharge to surface water. There is a 0.6 ft difference in land surface elevation between TIME v2.0 cell and measured data, making the TIME v2.0 depths considerably deeper than the measured data. The SFWMM model has a 0.3 ft difference in elevation, also over-estimating the depth.

3.4.3 Rocky Glades

The eastern peripheral wetlands adjacent to Shark Slough are at a higher elevation and are mostly pinnacle rock with some marl deposits overlain. In the central part of this area, referred to as the Rocky Glades, local rainfall and stages in the L31N canal determine the height of the water levels. Towards the southern portion of this basin, the southern terminus of the Coastal Ridge, marsh vegetation gives way to pine forest interspersed with a few transverse glades. The pinelands are more than 1 ft higher in elevation than the surrounding area. South of the pinelands, marsh vegetation again dominates. Local rainfall

and runoff from the pinelands dominate the hydrology, with little effect from upstream water management operations.

The timeseries for the measured and model-computed stage for station G3272 are shown in Figure 26. The TIME model-computed stages are higher than the measured stages, especially during the dry season, with model-computed surface water stage consistently higher than model-computed groundwater stage. TIME model boundary conditions play an important role in determining stage in this area. The SFWMM simulated stages track measured data better than the TIME stages, but have trouble with simulating the recessions into the dry seasons. Model-computed water depth in TIME indicates complete inundation, with model-computed surface water stage between 0.5 to 1.0 ft generally present across the local region, whereas measured stage indicate that the area dries out annually.

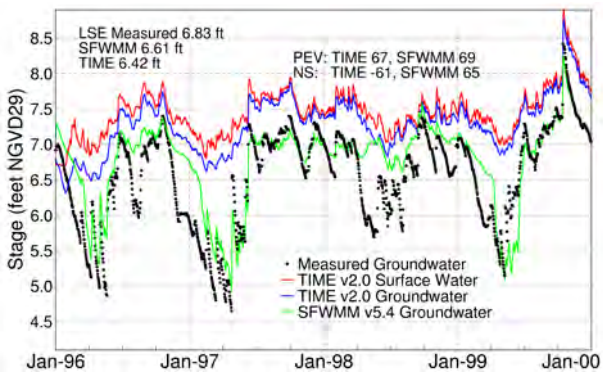


Figure 26. G3272 stage, Rocky Glades.

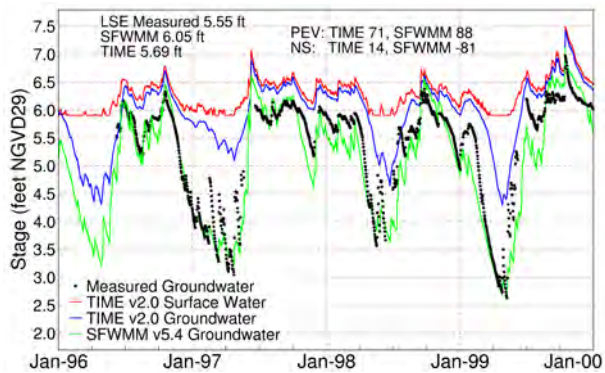


Figure 27. CR2 stage, Rocky Glades.

In the middle of the abandoned Context Road, station CR2 is situated halfway between Shark Slough and L31N; the timeseries for this station are presented in Figure 27. The area generally has 0.3–0.5 ft of surface water during the wet season, and the water level recedes to several feet below land surface during the winter months. The minimums in field measurements are not captured well by the TIME model. The SFWMM responds well in this area, capturing lows and highs; however, model-computed depths are 0.5 ft lower.

Just north of the main park road, station NP44 is located at the northern edge of the pinelands. The area has very little surface water throughout the year (Fig. 28). The land surface elevation differs between the models, yet both models do maintain groundwater conditions throughout the year. South of the pinelands, in the important Cape Sable Seaside Sparrow Population B habitat, is station NP46 (Fig. 29). Both models do well in this area, often achieving the highs and lows of the measured data.

3.4.4 West Coast Ecotone

A principal objective of the TIME model is to simulate the interface between the inland region and coastal regions. The tidal creeks and the mangrove zone of ENP are an important natural resource. Knowledge gained in understanding the dynamics of this region can help managers initiate proper structural and operational modifications to the Central and Southern Florida Project and anticipate landscape changes as a result of natural or man-made events, such as sea level rise or drainage. Several field studies conducted in recent years concentrated on this ecotone (Wanless and Vlaswinkel [2005], Anderson et al. [2010]); these investigations included the monitoring of flow through the coastal creeks (Levesque [2004]). In addition, the network of stage and salinity stations was expanded. The USGS Land-Margin

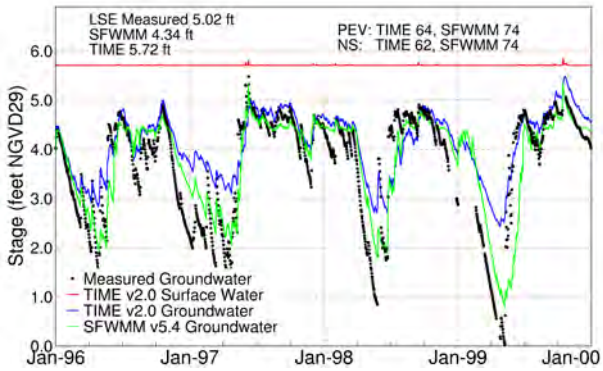


Figure 28. NP44 stage, Rocky Glades.

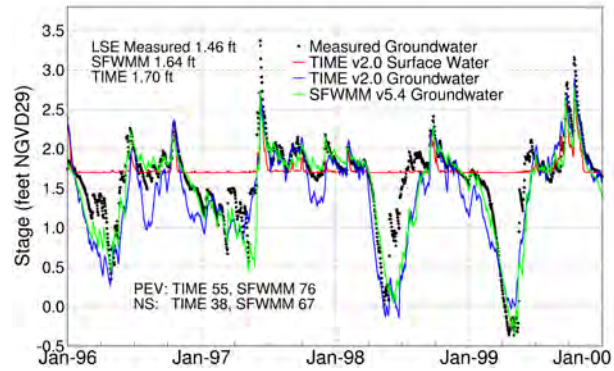


Figure 29. NP46 stage, Rocky Glades.

Ecosystem Study (LMES) has operated a network of paired surface water/groundwater gage stations within the western coastal mangrove region of ENP since 1996. Each station consists of a pair of sensors at the same geographic location, one recording surface water parameters and the other recording groundwater parameters.

These sites are aligned with three major rivers: Chatham, Shark, and Lostmans rivers. Shown in Figure 30 these stations are categorized as upstream freshwater marsh sites (CH1, SH1, LO1), transitional marsh-mangrove sites (CH2, SH2, LO2), and downstream mangrove sites (CH3, SH3, LO3). Typical site locations are shown in Figure 31, a freshwater marsh site, and Figure 32, a mangrove site.

Figure 30. West Coast Estuary station locations. The USGS Land-Margin study has three coastal monitoring transects: Shark (SH), Lostmans (LO), and Chatham (CH). The upstream freshwater marsh sites have a '1' suffix, transitional marsh-mangrove have a '2' suffix, and downstream mangrove sites have a '3' suffix. The sites follow natural drainage features formed from many tributaries flowing into main waterways: the Chatham, Lostmans, and Shark rivers. These estuarine rivers allow the tidal energy to travel upstream. In addition to these special project sites, several monitoring stations are maintained by NPS: LO, WW, P34 in the Lostmans drainage; SR, TE, HR, CN, GI, P35 in the Shark drainage; and WP, BICYA11 in the Chatham drainage.

Water levels and salinity measurements from 1996 to the present for these sites can track the movement of the freshwater/saltwater interface in the coastal Everglades. Comparisons of the measured and modeled data for these paired stations can be utilized to evaluate the TIME model predictive capability.

Figure 31. SH1 station in Shark River
(Anderson and Smith, USGS).

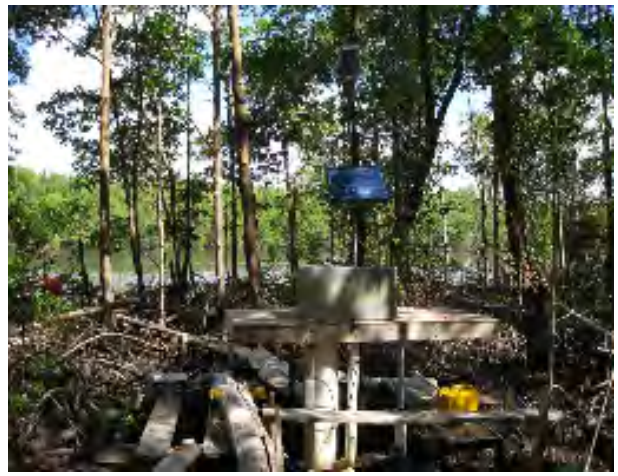


Figure 32. SH3 station in Shark River
(Anderson and Smith, USGS).

Soils and hydrodynamics

The subsurface in the coastal ecotone consists of a thick layer of peat/marl overlying limestone. Mangrove peat is primarily composed of partially decomposed roots and plant material and can be more than 15 ft thick in places (Shark River Delta). This layer extends, with decreasing thickness, from the coast to the river and marsh headwaters. Mangrove peat has lower hydraulic conductivity than the underlying limestone bed. Little field or laboratory work has been done in this ecotone to quantify the parameters needed for input to numerical models. In the TIME model, this region is not modeled as a distinct layer. Sparse data on the horizontal and vertical extent of this aquitard make it difficult to construct a reliable model.

The tidal exchange between estuary and marsh coupled with the freshwater flows and meteorological influences (*e.g.*, wind, rainfall, evaporation) dominate the hydrology of this ecotone. Tidal amplitudes have been linked to natural formation of small muck levees adjacent to the rivers causing the stages in the interior between the rivers to behave differently than the main channel.

The LMES stations located in the freshwater marsh sites are most responsive to rainfall and freshwater flows, and stations located in downstream mangrove sites are most influenced by marine conditions and tidal forcing. A study documenting these upstream and downstream dynamics is presented in Anderson et al. [2010]. The authors reported that during September, in the wet season, USGS upstream fresh (SH1) and ecotone (SH2) surface water/groundwater data and downstream marine (SH3) groundwater data showed substantial positive correlation with NPS Shark Slough (P33) data. However, during March, in the dry season, there was no substantial correlation of Shark Slough (P33) water levels with either the ecotone or marine water levels. SH1 water levels have a substantial negative correlation with P33. Downstream NPS marine gage (SR) water level data during the wet season (September) interestingly also showed a substantial positive correlation with the surface and groundwater at SH1 and SH2, and for groundwater at SH3.

Results of the study indicate that freshwater discharges and rainfall dominate both freshwater Shark Slough and Shark River Estuary during the wet season. However, during the dry season month of March, surface and groundwater levels at the ecotone (SH2) and downstream (SH3) showed positive, significant correlations with NPS marine (SR) stage, sug-

gesting more estuarine and marine influence. Shark River salinity data suggest that during September, there was no significant correlation ($p<0.001$) with surface water and groundwater at upstream (SH1), ecotone (SH2), and mid-estuary groundwater (SH3) salinity values. Lower-estuary (SH3) surface water salinity did correlate (+0.34, $p<0.008$) with downstream river salinity (SR). In March, downstream salinity (SR) showed positive correlation with surface/groundwater salinity at SH2 and SH3, but not with upstream SH1 salinity [Anderson et al., 2010]. These correlations point to the seasonal importance of the upstream flow and tidal regimes; during the wet season, upstream fresh water flows abate the influence of the tidal cycling and the intrusion of saline water upstream.

Coastal areas: Stages in the Shark and Harney rivers

The details for each shallow aquifer well in the USGS LMES paired surface water and groundwater station set (SH1, SH2, SH3, SH4, and SH5) located in the Shark and Harney rivers are presented in Table 5. Upstream station SH1 is proximate to NPS stage gage P35, an ecotone station. Station SH1 experiences no tidal effects in either surface water or groundwater. Saline conditions are not observed in the surface water and only modestly saline conditions exist in the groundwater (<2 ppt). Station SH2 has a tidal signature in both surface and groundwater, but only experiences tidal flooding under extremely high tides or storms. SH2 is adjacent to NPS stage gage TE. Coastal marsh station SH5 has a groundwater tidal signal (tidal pumping), but the surface water shows no tidal signature. SH4 and SH5 are adjacent to NPS stage gage HR. Downstream mangrove station SH3 is tidal and the mangrove forest typically floods daily. SH3 is approximately 3 km from NPS stage gage SR. The open channel/bay NPS stage and salinity data complement the mangrove/marsh shallow aquifer and surface water levels and salinity provided by SH3 to better define Shark Slough/Shark Estuary hydrodynamics. Both the NPS and USGS gages have a common height reference (VGPS) to provide for direct comparison. The locations are shown in Figure 33.

Near the mouth of the river is the monitoring station SR, recording surface water stage and salinity fluctuations in the Shark River. Figure 34 shows the SR station measured surface water stage with the TIME v2.0 calibration run surface water stage and groundwater stage timeseries. TIME v2.0 model-computed groundwater stages are more than 1 ft higher at the river cross-section than the measured stages; this head difference occurs at most river cell locations in the western region of the domain. Note that the model-computed surface water stages are as much as 0.5 ft lower than model-computed groundwater stages. The tidal signal at the SR field station is about 5 ft, which is not shown in the graphics of daily averages.

Situated in the mangrove forest, the paired USGS surface water/groundwater gage SH3 is 30 m from the south bank of the Shark River channel. The timeseries for 1998–99 is shown in Figure 35 with the model-computed and the measured data. Both the surface water and groundwater stages in the measured data have oscillations during certain time periods exceeding 1 ft, responding to the river water level fluctuations at SR (see timeseries for SR in Figure 34). These oscillations are not seen in the TIME simulation results; instead, there is a stronger seasonal oscillation. Groundwater in the field is generally lower than the surface water by as much as 0.2 ft. Hourly measurements show a strong tidal signal with as much as a 1 ft daily cycle, and the groundwater has a leading 2-hour phase shift. Farther upstream, the GI station monitors the river stage and both measured and model-computed data show fair correlation, with the measured data showing larger variability (see Appendix B). The

Table 5. USGS-LMES paired groundwater/surface water station well log (Anderson and Smith, USGS). Sample screens are 0.02 slotted PVC.

USGS-LMES Station Name	Average Surface Elevation ft NAVD 88	Land Type	Groundwater Well Depth (approx.)	Sediment Layer Depth (approx.)	Sediment Layer Type	Limestone Layer Depth (approx.)	Sample Screen Length
Shark 1 (SH1) freshwater marsh	-0.32	slough	11 ft	4 ft	Sawgrass muck	7 ft	5 ft
Shark 2 (SH2) coastal ecotone	-0.52	marsh	12.5 ft	6 ft	Mangrove peat	6.5 ft	7 ft
Shark 3 (SH3) coastal mangrove	0.27	forest	24 ft	16 ft	Mangrove peat	8 ft	5 ft
Shark 4 (SH4) coastal mangrove	0.37	forest	14 ft	9 ft	Mangrove peat	5 ft	5 ft
Shark 5 (SH5) coastal marsh	0.16	marsh	16 ft	9.5 ft	Sawgrass muck - Mangrove peat	6.5 ft	5 ft
Lostmans 1 (LO1) freshwater marsh	-0.05	prairie	8 ft	2 ft	Marl	6 ft	5 ft
Lostmans 2 (LO2) coastal ecotone	-0.66	marsh	5 ft	2 ft	Marl	3 ft	2.5 ft
Lostmans 3 (LO3) coastal mangrove	1.17	forest	24 ft	12 ft	Mangrove peat	12 ft	5 ft
Lostmans 4 (LO4) coastal marsh		marsh	14 ft	9 ft	Mangrove peat	5 ft	5 ft
Chatham 1 (CH1) freshwater marsh		prairie	8 ft	1.5 ft	Sawgrass muck	6.5 ft	5 ft
Chatham 2 (CH2) coastal ecotone		marsh	14 ft	6 ft	Mangrove peat	8 ft	5 ft
Chatham 3 (CH3) coastal mangrove		forest	16 ft	7.5 ft	Mangrove peat	8.5 ft	5 ft

tidal signal is still strong at this location; the measured data indicate that a greater than 2 ft signal is present.

The transitional marsh-mangrove area is represented by SH2 and nearby river station TE. Gauge CN is located farther upstream, near the end of navigable waters of the Shark River. Figure 36 is a plot of the 1997–99 measured and model-computed stage data for station SH2. Both surface water and groundwater for SH2 are higher in the model simulations than the measured data, with as much as a 0.5 ft difference between surface water and groundwater stage. The measured data do not show much difference between the two stages, except during dry periods when surface water is higher. In the hourly measurements SH2 groundwater has a leading 2-hour phase shift. TE has a measured tidal signal as high as 1.5 ft, and CN as high as 1 ft. The effects of fresh water flows are noted at these stations during the summer wet season, with stages generally higher and tidal ranges generally reduced to 0.1–0.3 ft. The model-computed surface water stages for both CN and TE show dry land surfaces throughout the calibration period (see Appendix B).

The timeseries for the stage at the freshwater marsh site SH1 is shown in Figure 37. This station is non-tidal; the model-computed data are generally higher than the measured data, approaching each other during periods of ascension. Both model-computed and measured data indicate little difference between surface water and groundwater. The calibration timeseries for the P35 station is shown in Figure 25 in the section on the Shark Slough Basin. This station is downstream of SH1 and shows a larger difference than SH1 between TIME v2.0 model-computed surface water and groundwater, with groundwater higher.

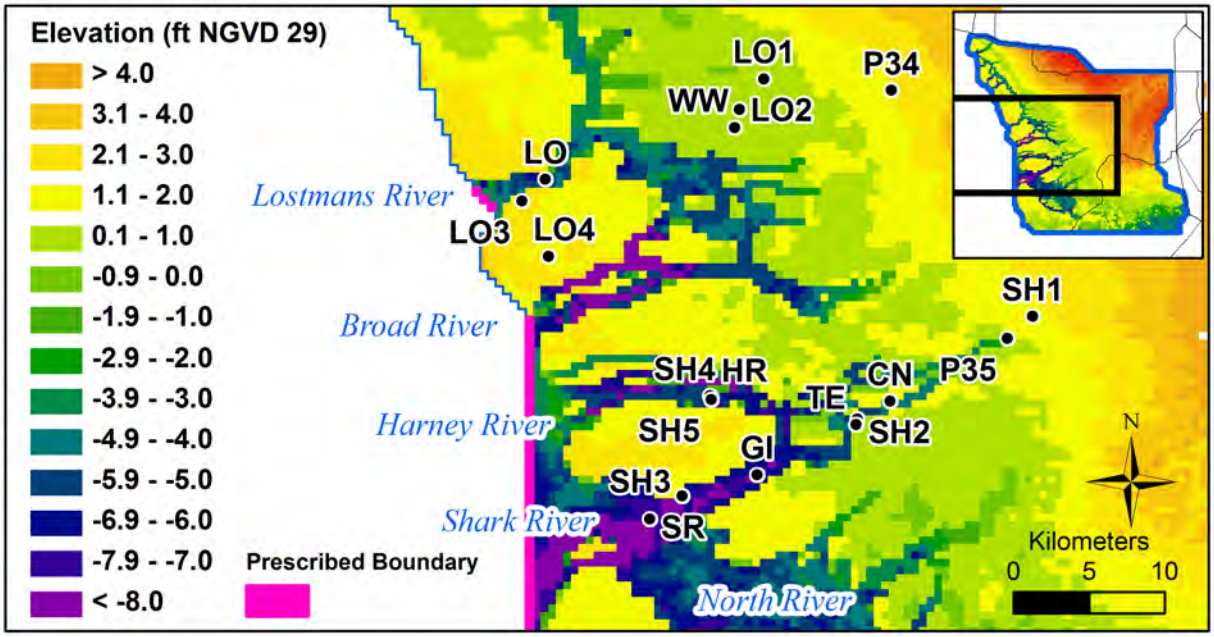


Figure 33. Shark and Lostmans river monitoring station locations, shown with the TIME v2.0 gridded land surface elevations and prescribed marine boundary input locations. In the Shark River estuary, upstream sites SH1 and P35 are freshwater marsh, transitional marsh-mangrove sites are SH2 and SH5 (coastal marsh) and TE and CN (river), and downstream marine sites are SH3 and SH4 (mangrove) and GI, HR, and SR (river). In Lostmans River estuary, upstream sites LO1 and P34 are freshwater marsh sites; transitional marsh-mangrove sites are LO2 and LO4 (coastal marsh) and WW (river), and downstream marine sites are LO3 (mangrove) and LO (river).

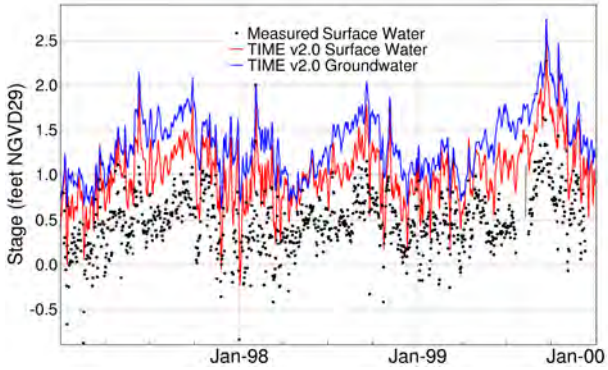


Figure 34. SR stage, Shark River.

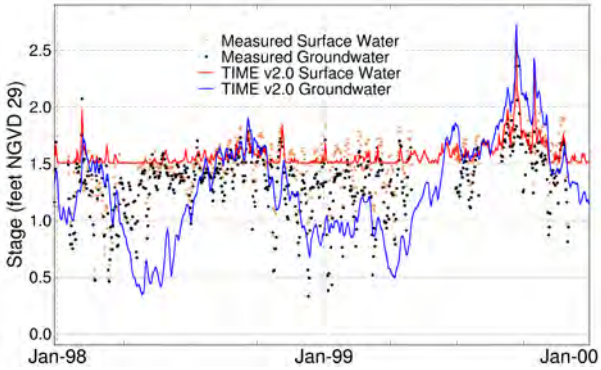


Figure 35. SH3 stage, Shark River.

On the Harney River, the ENP monitoring station HR was complemented by SH4, a mangrove station, and SH5, a station in the nearby sawgrass. The plots for SH5 and HR are shown in Figures 38 and 39. HR, SH4, and SH5 fall within the same grid cell. The cell location used in the TIME model for HR, SH4, and SH5 is one cell south of the actual location. In 1998 and 1999 the groundwater stage at SH5 draws down more during dry periods in the model simulation than is measured. TIME model-computed values overestimate the SH5 stage level during all wet seasons. The measured data at HR and SH5 show large fluctuations in stage throughout the year, so these stations probably correlate well with offshore fluctuations in sea level in addition to local influences due to rainfall. The TIME v2.0 boundary condition for the Harney River area is shown in Appendix A.

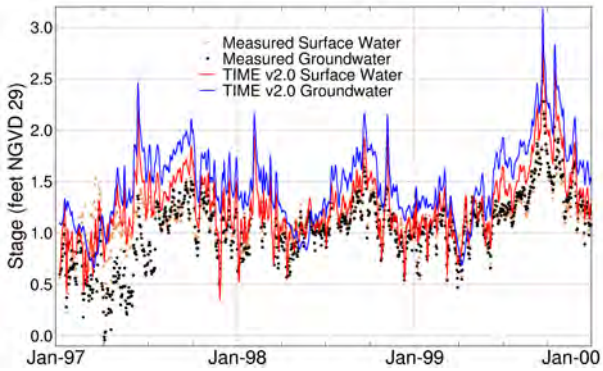


Figure 36. SH2 stage, Shark River.

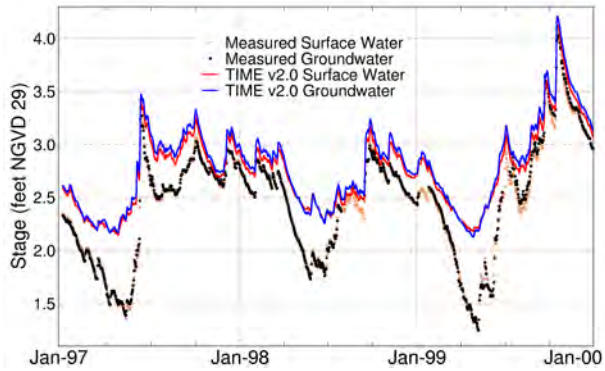


Figure 37. SH1 stage, Shark River.

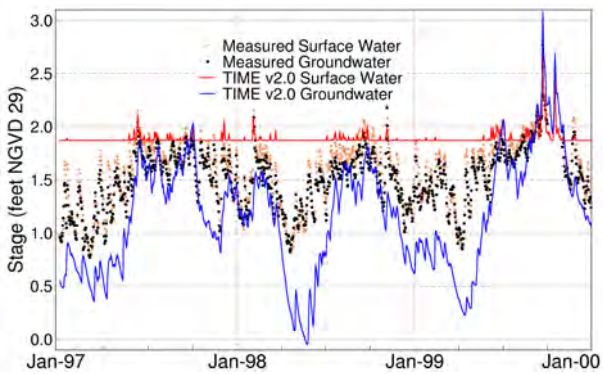


Figure 38. SH5 stage, Harney River.

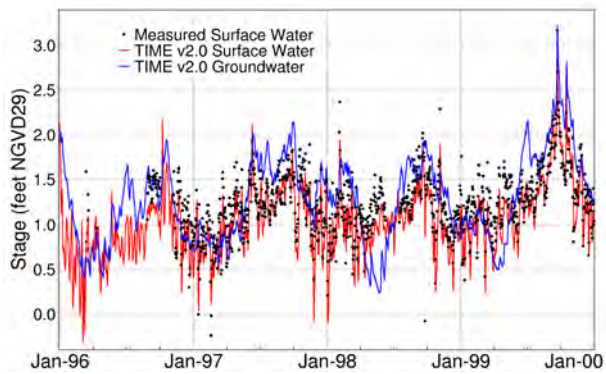


Figure 39. HR stage, Harney River.

Coastal areas: Salinity in the Shark and Harney rivers

Salinity for upstream surface water and groundwater is measured at the paired stations SH1 and SH2; a comparison of measured groundwater salinity with the output of the TIME v2.0 model is provided with a caveat: the model layer 1 aquifer is 7.12 m (15 ft) thick at the SH1 location and 5.23 m (11 ft) thick at SH2. The salinity is depth-averaged through this layer in the model, thus not an indication of the near-surface salinity variation provided by the field groundwater sites (SH2 measures average salinity at a depth of between 5 and 12 ft). Figures 40 and 41 show the model-computed and measured data, both of which are in the range of 0 to 15 ppt. The results show marine salinity influences traveling via the surface water to these freshwater marsh sites, although the measured data have a low steady salinity value. Groundwater salinity values simulated in the model shows a steady decline during the model time period.

Just downstream from SH1, the salinity at the SH2 site shows the marine influence in the surface water, and the measured data also show this seasonal fluctuation. The groundwater salinity values are depth averaged in the model simulation and show the entire thickness to be very saline (between 32 and 34 ppt), which, however, does not mean that the near-surface salinity cannot be lower. The near-surface field record below the 6 ft thick peat layer shows salinity fluctuations, indicating some transport from the surface or via lateral contributions during dry periods. Because this thick peat layer is not represented in the model simulation, the model-computed and measured data are perhaps not directly comparable.

Figures 42 and 43 contain the timeseries for salinity at the Harney and Shark river monitoring stations. The field stations record the river salinity only. The model-computed

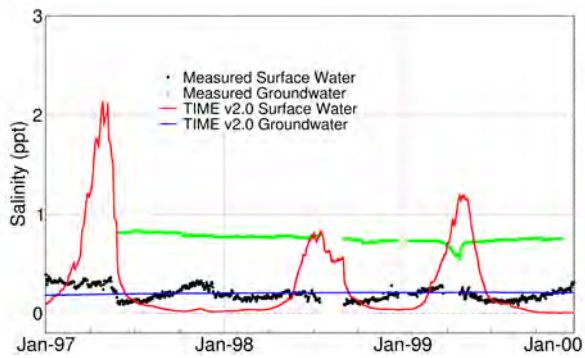


Figure 40. SH1 salinity, Shark River.

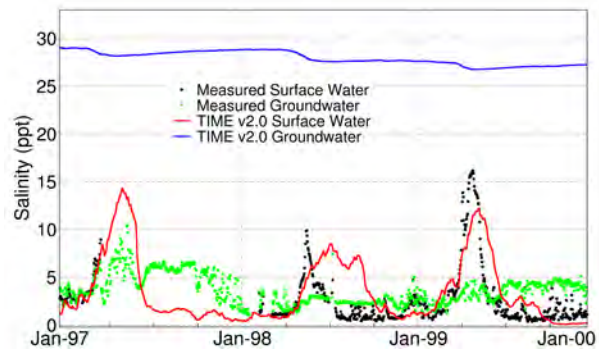


Figure 41. SH2 salinity, Shark River.

data at these stations show a generally declining trend for the model period. The measured and model-computed data both show the marine seasonal influence.

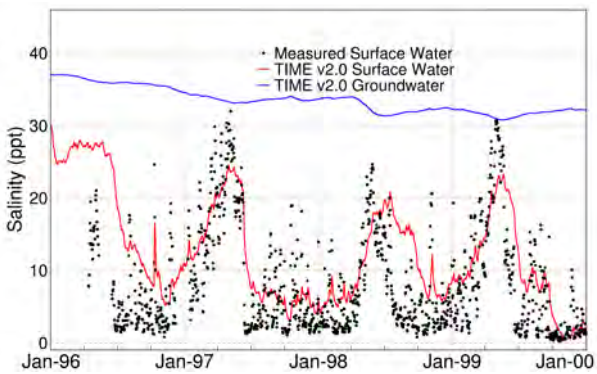


Figure 42. HR salinity, Harney River.

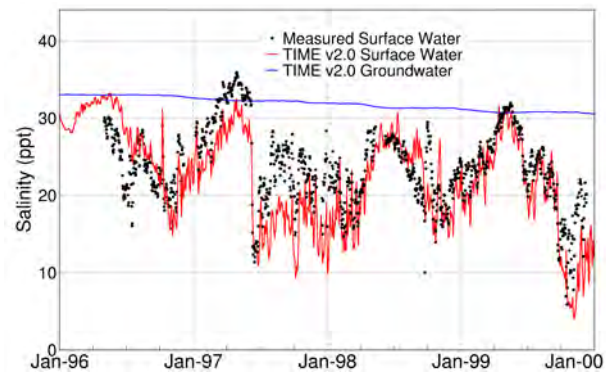


Figure 43. SR salinity, Shark River.

Coastal areas: Stages in the Lostmans River

The upstream source for the Lostmans River Estuary watershed is flow across the Big Cypress National Preserve (BICY). This watershed is bounded by a northeast/southwest karst feature, named Rattlesnake Ridge, to the east, and to the north by Loop Road. During the time period used in this analysis there were no BICY water gages upstream of the Lostmans River Estuary model region. Gages useful to the model calibration were USGS LMES paired stations LO1 (upstream), LO2 (ecotone), LO3 (downstream mangrove), and LO4 (downstream marsh) in combination with NPS stage gages P34 (freshwater marsh), WW (tidal creek), and LO (downstream tidal), all shown in Figures 30 and 33. Shallow aquifer well details can be found in Table 5 for USGS LMES paired stations.

Drainage from the area upstream of monitoring station P34 feeds the headwaters of Lostmans River (Fig. 30). Near the headwaters of distinct creeks in the landscape is station LO1, located in a seasonally wet marl prairie and adjacent to a small hardwood hammock (near the BICY/ENP boundary). Both station LO1 surface water and groundwater have non-tidal signals. Nearby, NPS stage gage P34 is located 5 km due east of station LO1. Paired station LO2 is located northeast of Rocky Creek Bay in a tidal coastal marsh (*Eleocharis* spp. and shrubby mangrove). NPS stage gage WW is located in a small creek, northeast of Rocky Creek Bay and 1 km southwest of station LO2.

Located near the mouth of Lostmans River are NPS stage gage LO, and USGS mangrove (LO3) and coastal marsh (LO4) stations. NPS gage LO has been operating since 1998. Adjacent to Johnson Creek (south of First Bay, Lostmans River) is located USGS paired station LO3. It is situated 30 m from the creek bank in a mangrove forest and 0.5 km north of Johnson Mound. Station LO3 is tidally influenced and is located on high ground so does not experience daily tidal flooding.

LO4 is a paired coastal marsh station that was discontinued. It is located in a large coastal Spartina marsh (*Spartina patens*). There is a tidal groundwater signal, even though the gage is not near a tidal water body and receives little to no tidal flooding.

Figure 44 is a plot of the measured data for station LO with the TIME v2.0 model-computed surface water and groundwater timeseries for the calibration period. The measured data at LO show the stage is tidal with a range as high as 2.5 ft. The model-computed surface water stages track measured data very closely. Model-computed groundwater, however, is as much as 1 ft higher. In the model simulation, most river cells investigated show a larger difference between surface water and groundwater than adjacent marsh cells. This relationship is not reflected in the measured data, which show groundwater and surface water levels to be much closer.

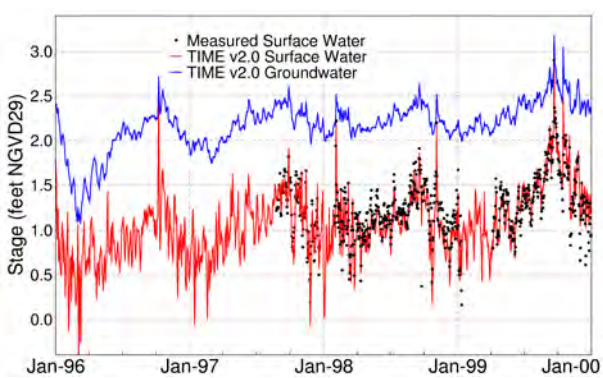


Figure 44. LO stage, Lostmans River.

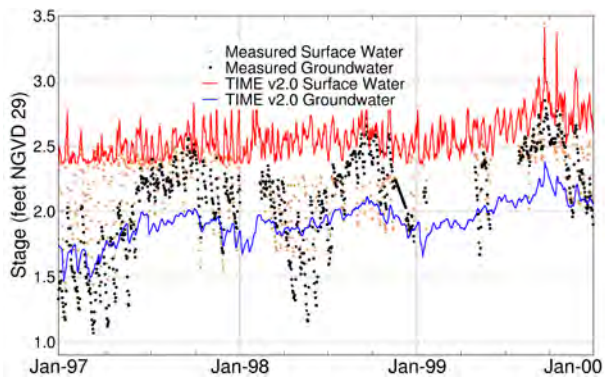


Figure 45. LO3 stage, Lostmans River.

Figure 45 shows the stages for station LO3 model-computed and measured data. The surface water stage simulated in the model is 0.5 ft higher than simulated groundwater stage. The measured stages of the surface water are generally lower. It is important to note that the model-computed surface water level at LO3 is generally 1.5 ft higher than at LO.

Figure 46 provides the timeseries for station LO4. This station is situated far away from river and tidal influences, thus the source of water in the region is primarily local rainfall. The TIME v2.0 surface water data do not rise as much as the measured data during the wet season.

The station LO2 measured surface water levels are tidal with a range of 0.1 ft. Generally the model-computed surface water and groundwater are slightly higher than the measured data (Fig. 47). In the model simulation, groundwater is consistently higher than surface water by 0.1–0.2 ft.

The stage at station LO1 fluctuates according to upstream flows and local rainfall, in wet as well as dry seasons. Measured data show a distinct difference between the surface water and groundwater stages in the early portion of the record, until mid-1998 (see Figure 48). After this time, the record shows only a small difference between surface water stages and groundwater stages. The TIME simulated surface water stage and groundwater stage at station LO1 are consistently below the measured data (as much as 0.5 ft). Gener-

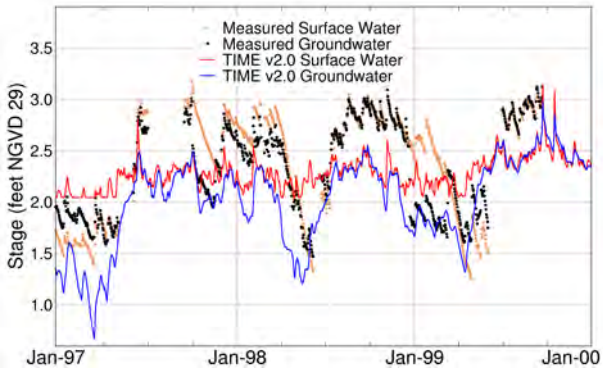


Figure 46. LO4 stage, Lostmans River.

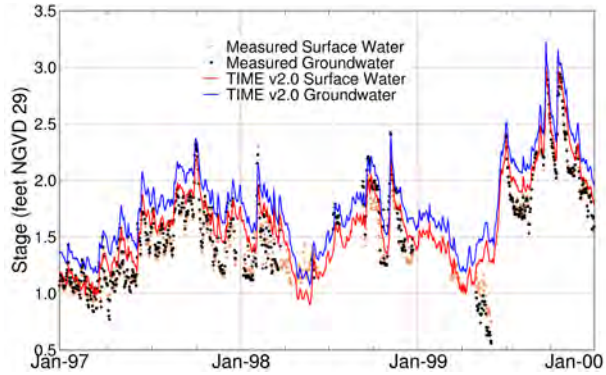


Figure 47. LO2 stage, Lostmans River.

ally where there is a separation between surface water stage and groundwater stage in the measured data, the surface water is higher, however the TIME v2.0 model-computed data were determined to be generally reversed close to the coast.

At the WW station, Figure 49, measured surface water stages show a seasonal cycle (summer high) and a daily tidal range of as much as 0.3 ft. The model-computed data show groundwater stage higher than surface water stage by 0.2 ft. Peaks in measured and TIME v2.0 model-computed surface water stage are generally close, but measured data indicate that water recedes during the dry season by as much as 0.8 ft.

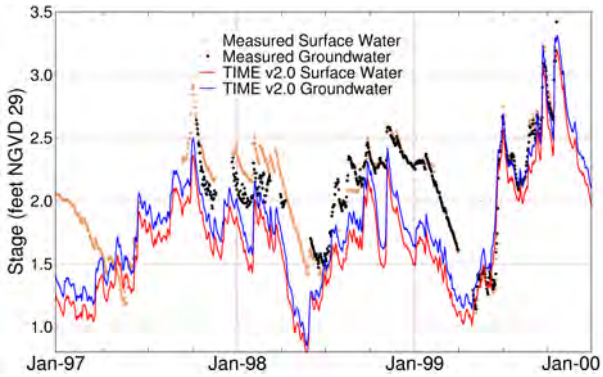


Figure 48. LO1 stage, Lostmans River.

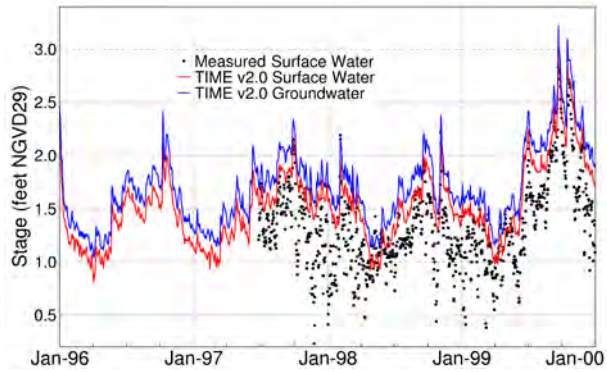


Figure 49. WW stage, Lostmans River.

Coastal areas: Salinity in the Lostmans River

At station LO, the results of the TIME v2.0 model simulation of surface water salinity correlate well with the measured data, Figure 50. Model-computed groundwater salinity showed little variation throughout the time period.

Shallow aquifer well details are contained in Table 5 for all the Lostmans USGS LMES paired stations. The LO2 station surface water salinity is highly variable (3–15 ppt), whereas groundwater salinity, also highly variable, is greater (5–20 ppt). Station LO2 reflects the immediate marsh to creek dynamics better than station LO1. Like Station LO1, station LO2 also has a shallow marl sediment layer (about 2 ft in depth) with very dense underlying limestone, restricting groundwater and surface water mixing.

During the period of comparison (1996–99), station LO3 measured salinity data, especially for surface water, were not usable. Although station LO3 groundwater salinity, which

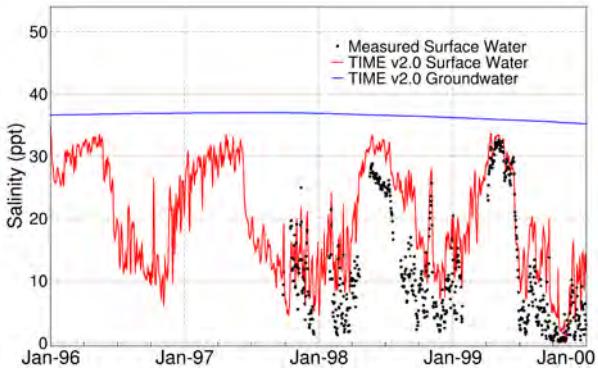


Figure 50. LO salinity, Lostmans River.

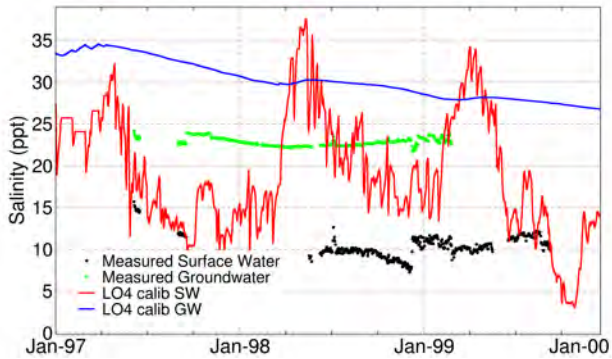


Figure 51. LO4 salinity, Lostmans River.

averaged 34 ppt during 1997–99, and station LO4 groundwater salinity, which averaged 17 ppt, had missing and erroneous data, it was observed that the groundwater salinity was relatively stable and consistent in range for the time period. Surface water salinity levels for station LO4 (1998–99) were indicative of an interior coastal marsh (similar to station SH5). Surface water salinity values ranged from 0.5–17 ppt. During the rainy season, the surface water salinity declined through rainfall dilution and increased through evaporation during the dry season. The groundwater salinity values simulated by TIME v2.0 for this station showed a consistent decreasing trend; and the model-computed surface water salinity ranged from almost fresh to saline by the end of the dry season (Fig. 51).

The Willy Willy (WW) station is at the end of the navigable waters of the Lostmans River drainage and exhibits a large range in salinity. The TIME v2.0 model simulation of surface water salinity picks up the highs and lows, although ascensions and recessions are more abrupt in the measured data (Fig. 52). The paired station LO1 is located within a freshwater marsh site and the TIME v2.0 model simulation shows substantial fluctuation in surface water salinity (Fig. 53). Surface water at the LO1 station is fresh, but with underlying groundwater salinities which range from 5–12 ppt. The marl sediment is 1–2 ft in depth and the underlying limestone is very dense, restricting vertical mixing of groundwater and surface water. The gage at station WW is located in the river and the gage at station LO1 is in the wetland. Groundwater salinities from the measured data indicate that LO1 is very close to the salinity interface: fresh surface water, but brackish groundwater.

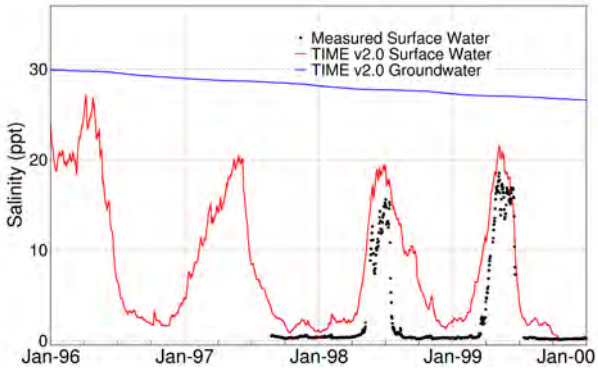


Figure 52. WW salinity, Lostmans River.

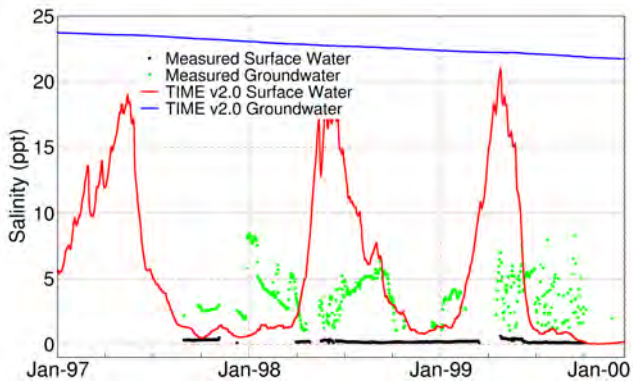


Figure 53. LO1 salinity, Lostmans River.

Coastal areas: Stages at Chatham River

The Chatham River drainage receives surface water from the Big Cypress watershed, which flows through the Loop Road culverts at the northern boundary of the model domain, past the area surrounding station BICYA11, and reaches the headwaters of the Chatham River near CH1. Relevant stations for this drainage area are BICYA11, CH1, CH2, CH3, CA, and WP shown in Figure 54.

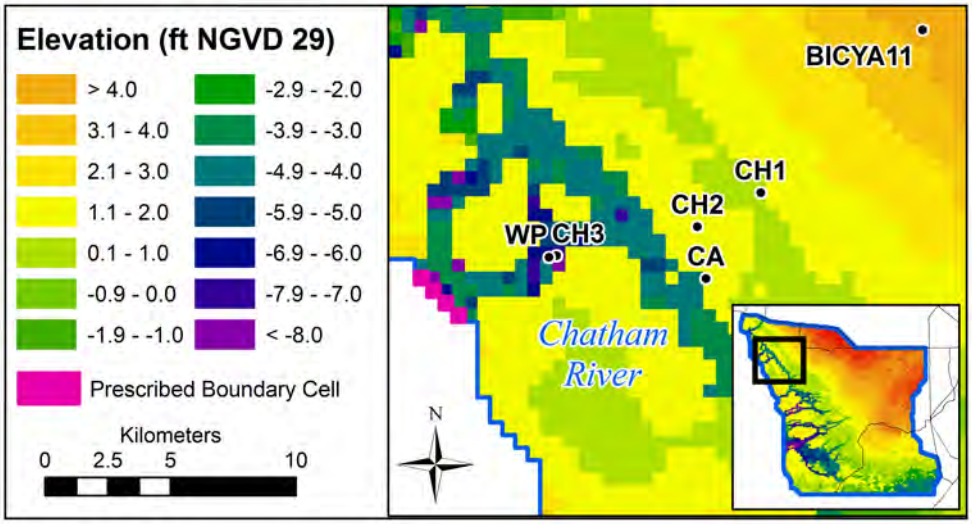


Figure 54. Chatham River monitoring station locations, shown with the TIME v2.0 gridded land surface elevations and prescribed marine boundary input locations.

The paired station CH1 is located in a freshwater short-hydroperiod marsh adjacent to the BICY/ENP boundary, called the Stairsteps region. The transition zone station CH2 is located in scrub mangrove and coastal marsh near Deer Island and Cannon Bay. Data collection at this site was discontinued in 2006 due to lack of financial support. The monitoring station CA is maintained by NPS and measures stage and salinity. Within the coastal river mangroves is located the paired station CH3, across the Chatham River from the Watson Place Campground and the NPS stage gage WP.

Results from the paired station, CH1 are shown in Figure 55. The measured surface water stage and groundwater stage match closely; however, TIME v2.0 model-computed groundwater stages are 0.3 ft higher than the model-computed surface water stage.

CH2 is a transitional station in coastal marsh; there is a difference between groundwater and surface water stages in the measured data (Fig. 56). The surface water is tidally influenced and the thickness of the overburden suggests some disconnect between the two regimes, with a stronger tidal signal in the groundwater. The TIME v2.0 output indicates that the cell goes dry in early spring and that there is 0.2 ft difference between the surface water and groundwater regimes.

The back-country bays which separate the freshwater uplands from the coastal prairies and mangrove ecotone are interconnected via numerous small creeks. The Chatham River cuts through the coastal prairie and stations CH3 and WP are located in this region (Figs. 57 and 58). Data from station CH3 in the mangroves show large variability in both groundwater stage and surface water stage, indicating the strong connection with the Gulf of Mexico. The model-computed data are always higher than measured data. The Chatham River station

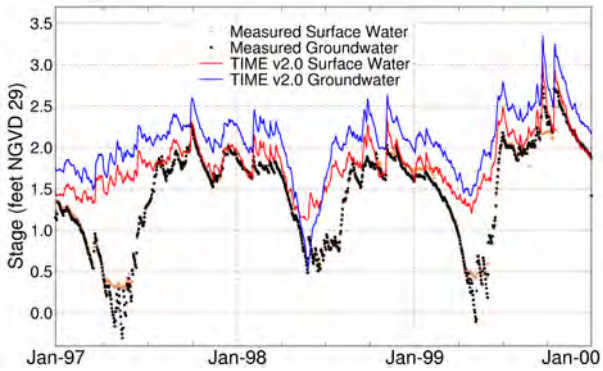


Figure 55. CH1 stage, Chatham River.

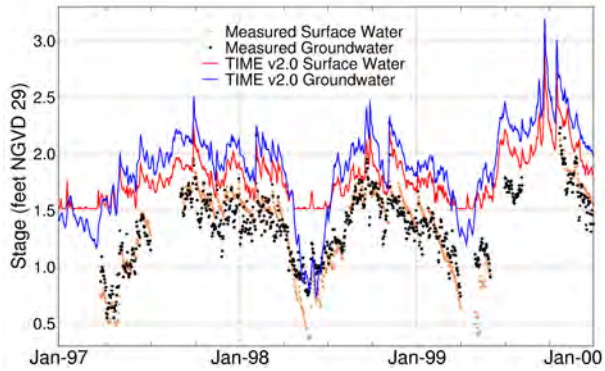


Figure 56. CH2 stage, Chatham River.

WP was installed after 1999, so a comparison with measured data at this river location is not possible. The surface water stage from the model simulation is lower than the groundwater stage from the model simulation, approximately 0.7 ft.

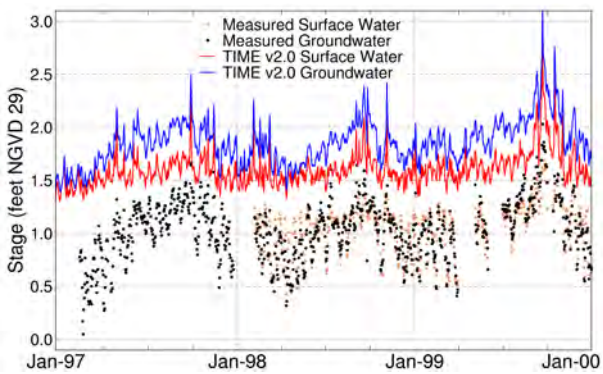


Figure 57. CH3 stage, Chatham River.

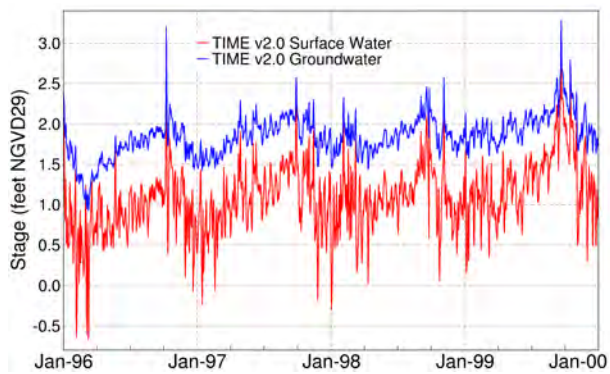


Figure 58. WP stage, Chatham River.

The timeseries for the upstream station BICYA11 is shown in Figure 59; the TIME v2.0 simulation results for surface water stage and groundwater stage are nearly identical and as much as 0.5 ft lower than measured data during the wet season. The SFWMM simulation results track well with the measured data during the wet seasons. Both models underestimate the magnitude of the recession in the dry seasons.

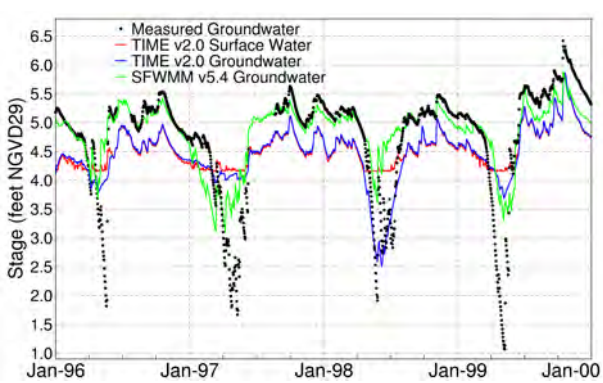


Figure 59. BICYA11 stage, Big Cypress.

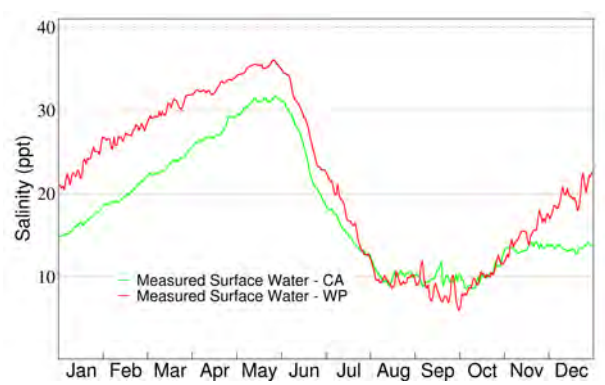


Figure 60. Chatham & Watson Place salinity.

Coastal areas: Salinity at Chatham River

Field data collection for salinity at both station CA and station WP began after the model calibration period. To facilitate a comparison with the model output, daily averages throughout the annual cycle were produced using data collected during 2000–2008, and are shown in Figure 60. CA has lower salinity in the dry season because it is farther upstream and the area receives rain and upstream flows, although WP is more affected by marine influences. The model output for these stations is shown in Figures 61 and 62; the variability is similar to the measured data. The model-computed surface water salinity values for the CA station follow the general pattern of the measured data. Model-computed salinity at station WP may reflect more marine influence, although it is probable that the prescribed near-shore boundary conditions strongly influence this bay station. Groundwater salinity values at both sites suggest little interaction between the surface water and groundwater.

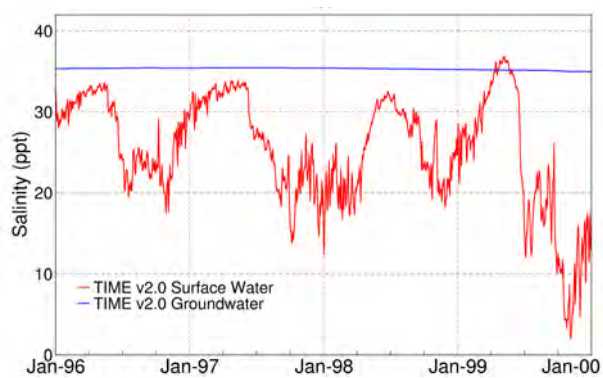


Figure 61. WP salinity, Chatham River.

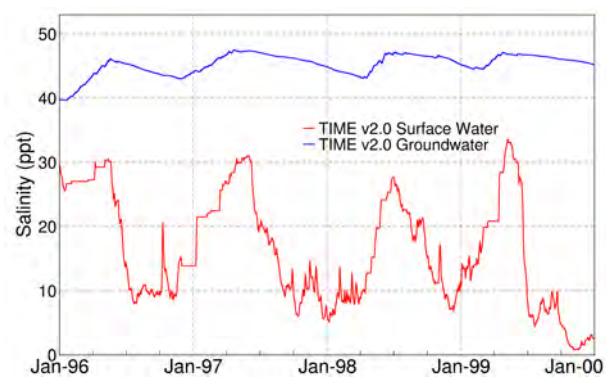


Figure 62. CA salinity, Chatham River.

3.4.5 Whitewater Bay Basin

The outflow from the eastern flank of Shark Slough discharges into the rivers leading to Whitewater Bay. The primary component of the local water budget is precipitation, especially in the southern parts of this area. An internal broad estuary separates the Cape Sable region from the freshwater wetlands in the upper part of this basin (see map in Figure 3). A small northern portion of the basin is represented in the SFWMM (Fig. 2).

The CW station is located in Whitewater Bay and is influenced by Gulf of Mexico tidal fluctuations and local bay seiching. Figure 63 provides a timeseries plot of the measured and TIME v2.0 model-computed stage. The model-computed groundwater stage is approximately 0.2 ft higher than computed surface water stage, and model-computed surface water stage is as much as 0.2 ft higher than measured data.

The model-computed timeseries of stage for a location (labeled as CapeSable2) in the interior of the Cape Sable region is shown in Figure 64. Measurements are not collected in this area, so the CabeSable1 and CapeSable2 locations were created to examine model output here. The model output indicates that stages at this location fluctuate seasonally about 1.5 ft. There is some surface water present during the wet periods, providing at least a short hydroperiod every year.

Along the park road, south of the pinelands and into a marsh with small cypress stands, the NMP station is located on the banks of Nine Mile Pond near SR-9336. The area is wet during most of the summer months, Figure 65. Land surface elevation for the SFWMM is

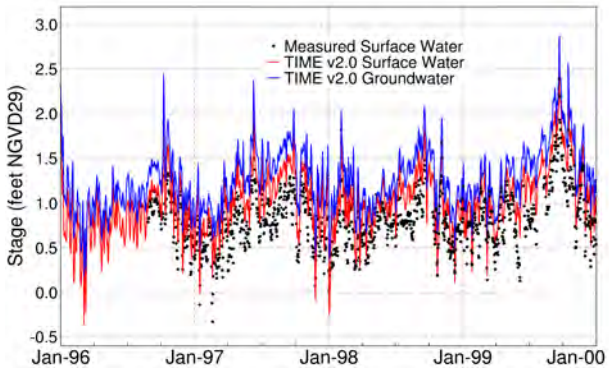


Figure 63. CW stage, Whitewater Bay.

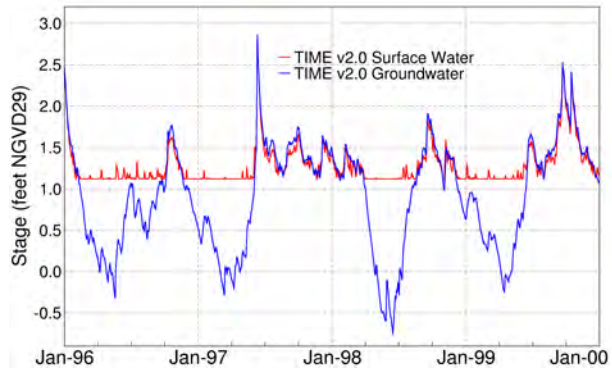


Figure 64. CapeSable2 stage, Whitewater Bay.

substantially lower than surveyed and the TIME model. Both SFWMM and TIME v2.0 over-predict the magnitude of the recession in 1998 and 1999.

In the northern part of the Florida Bay estuary is Garfield Bight, a shallow bay influenced by the vagaries of Florida Bay water levels. Plots of measured and model-computed data for station GB are shown in Figure 66. This location responds more to the marine than the upstream freshwater environment. SFWMM and TIME stages are both lower than measured data.

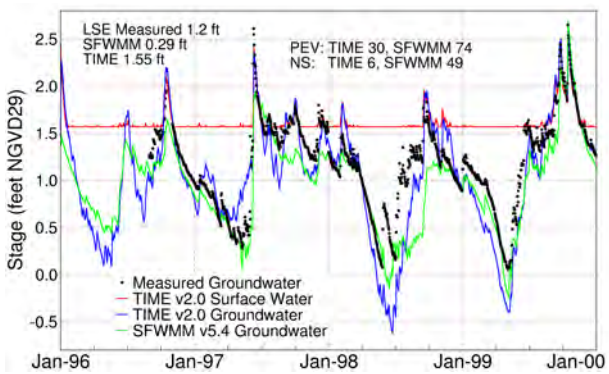


Figure 65. NMP stage, Whitewater Bay.

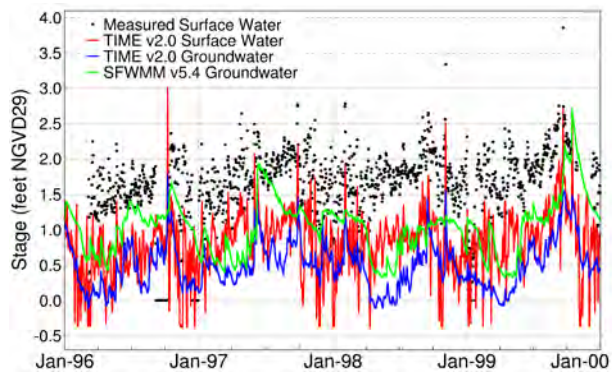


Figure 66. GB stage, Whitewater Bay.

The Whitewater Bay region is represented by the CapeSable1 and CapeSable2 locations and the GB station in Figures 67 and 68. In the TIME model, when the water table falls below the land surface, surface water salinity values remain constant at the value of the last active time step. Upon re-inundation the computation of salinity may have a completely different value, leading to blockiness in the timeseries output. The state in between may be considered as undefined. As in several other locations, CapeSable2 has high groundwater salinity (45 ppt) which declines during the model time period to 35 ppt. The average model salinity is within an acceptable range for a transitional landscape where the vegetation is shifting to more saline-tolerant types [Wanless and Vlaswinkel, 2005].

The Garfield Bight (GB) salinity timeseries shows a wide range in the measured data, with hypersaline conditions in the end of the dry season. The TIME model-computed surface water salinity does not quite capture these extremes, but retains more of the characteristics of the prescribed boundary conditions. The model-computed groundwater salinity remains close to its prescribed constant value of 36 ppt.

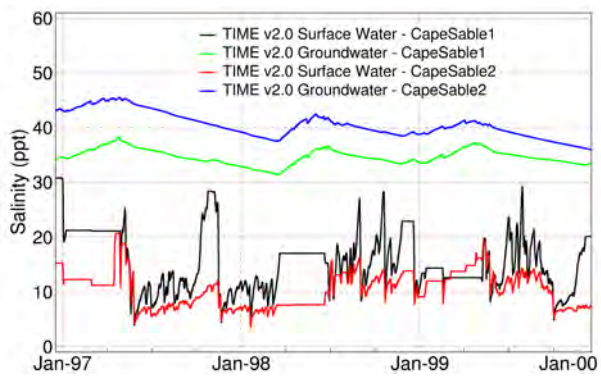


Figure 67. Cape Sable salinity.

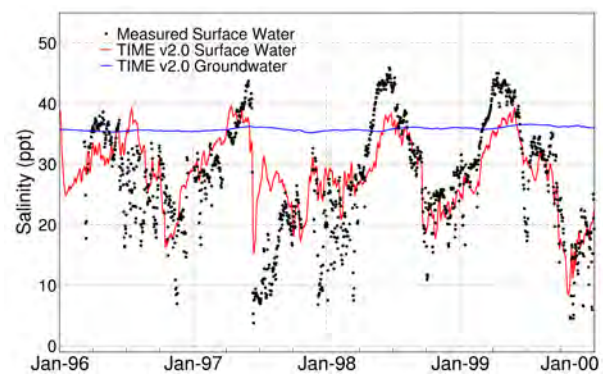


Figure 68. GB salinity, Whitewater Bay.

3.4.6 Taylor Slough Basin

Near the end of the South Dade Conveyance System, the L31N canal discharges to Taylor Slough, and the C111 canal discharges to the Eastern Panhandle of ENP. Taylor Slough begins as a narrow channel in the Frog Pond and broadens south of the park road (SR-9336). Its waters eventually reach the Craighead Pond area where some of the flow discharges via rivers and groundwater into northeast Florida Bay. During large storm events, the area collects local rainfall and upstream flows, and surface water occasionally flows over the shallow Buttonwood Embankment (location shown in Figure 1).

The uplands adjacent to Taylor Slough are represented by the two stations G3353 and P37 (see Figure 3). The data for G3353 are presented in Figure 69, the TIME v2.0 groundwater stage is higher than the surface water stage by as much as 0.4 ft, and the surface water stage is about 0.3 ft higher than the measured stage. The output from the SFWMM model oscillates around the measured data, and matches highs and lows well. The surveyed land surface elevation is 0.86 ft, pointing to a long hydroperiod, not captured effectively in the TIME and SFWMM output, where the modeled land surface elevation is 0.6 ft higher.

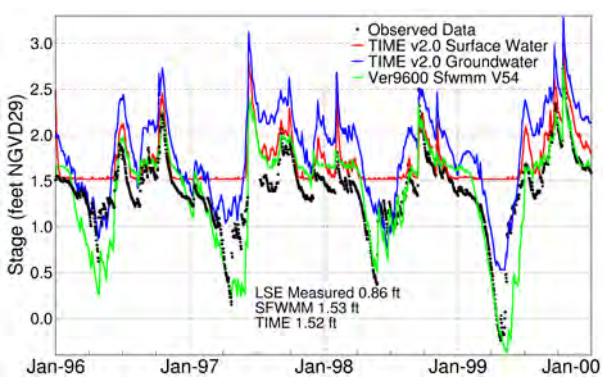


Figure 69. G3353 stage, Taylor Slough.

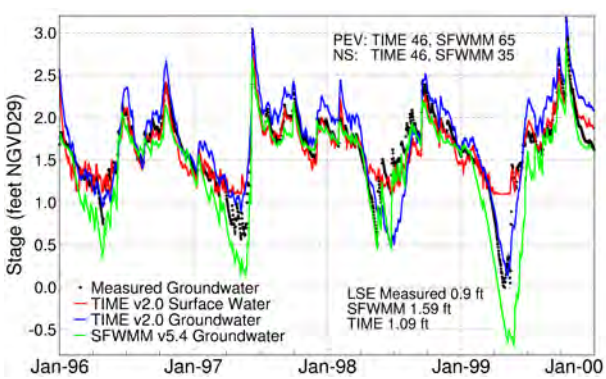


Figure 70. P37 stage, Taylor Slough.

P37 is on the western flank of Taylor Slough and is shown in Figure 70. The TIME 2.0 and SFWMM model-computed surface water stages match with the measured data, except for dry periods when the SFWMM is generally lower than measured stage. The SFWMM model-computed land surface elevation is 0.5 ft higher than surveyed, so the model simulation underestimates hydroperiods.

Along the western side of this basin is the Craighead Pond area, represented by the station

CP. The measured and model-computed data for this location are shown in Figure 71. The area seldom dries out and generally has 1 ft of water on the landscape. The TIME v2.0 model-computed stages track fairly well with the measured stages. In the SFWMM model output, water levels are mostly lower than measured data and dip well below ground surface during dry seasons.

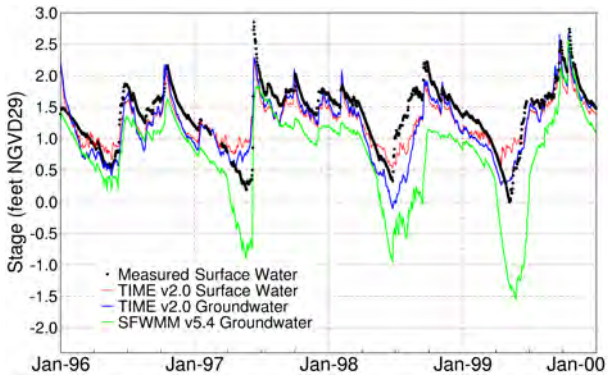


Figure 71. CP stage, Taylor Slough.

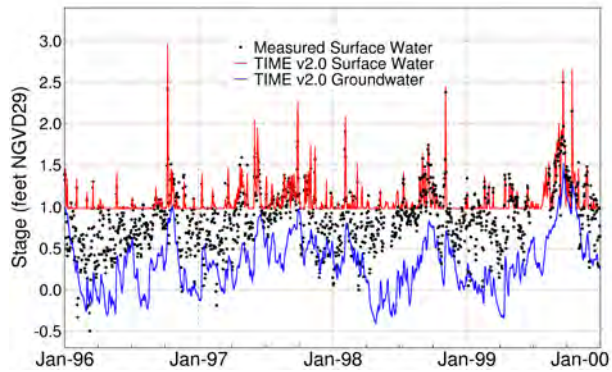


Figure 72. TB stage, Taylor Slough.

West of Garfield Bight is Terrapin Bay, a shallow area in the upper estuary of Florida Bay. The Terrapin Bay station (TB) responds more to Florida Bay conditions than flows from upstream wetlands. The measured and TIME v2.0 stage plots for TB are shown in Figure 72. When surface water is present in this model cell, the model-computed stage tracks well with measured values. In the model simulation, when the water level falls below the land surface, the groundwater stage is as much as 0.8 ft lower than measured data.

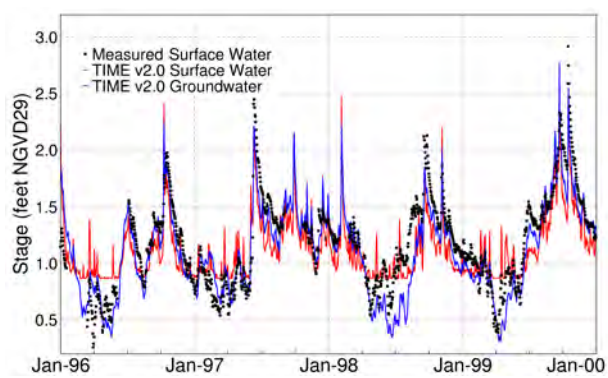


Figure 73. TR stage, Taylor Slough.

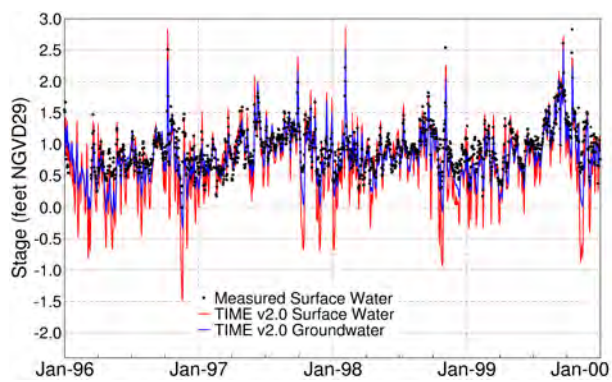


Figure 74. TC stage, Taylor Slough.

Taylor Slough connects to Taylor River in the eastern part of its drainage, represented by the station TR. The TIME cell location chosen to represent this river site dries during the winter months, but surface water stage tracks fairly well with the measured data during other times (Fig. 73). During these dry periods, the groundwater head captures the lows in the measured data.

The NPS station in Trout Cove, TC, is located south of a major outlet through the Buttonwood Embankment. The measured data and TIME v2.0 model output are shown in Figure 74. The model-computed surface water stage has larger fluctuations between minimum and maximum than measured data, although the model-computed maxima are generally close to measured data. Model-computed groundwater stage has a lower range than model-computed surface water stage.

The station LM records salinity in the water flowing into and out of Little Madeira Bay, a partially confined upper estuary of Florida Bay. The broad opening across the ridge, where the station is located, allows upstream fresh water and local rainfall to flow out into the bay.

The timeseries shown in Figure 75 indicates that the match between model-computed surface water stage and measured stage values is good. Model-computed groundwater salinity shows a continuous decline during the calibration time period. The measured data for station TC, Figure 76, show large salinity fluctuations due to the constant exchange of waters between a partially confined Joe Bay and Florida Bay. The TIME v2.0 model-computed surface water salinity output does not show this strong signal. The station exhibits a seasonal pattern which is captured in the TIME model simulation output.

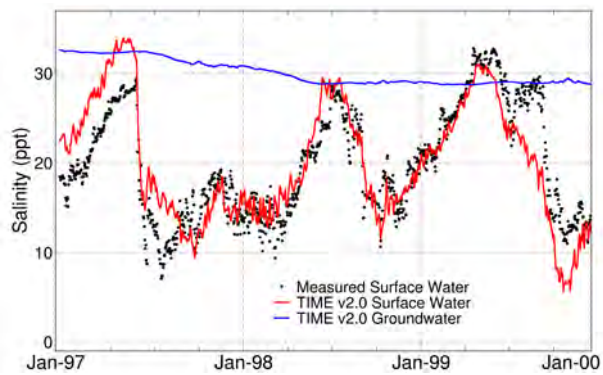


Figure 75. LM salinity, Taylor Slough.

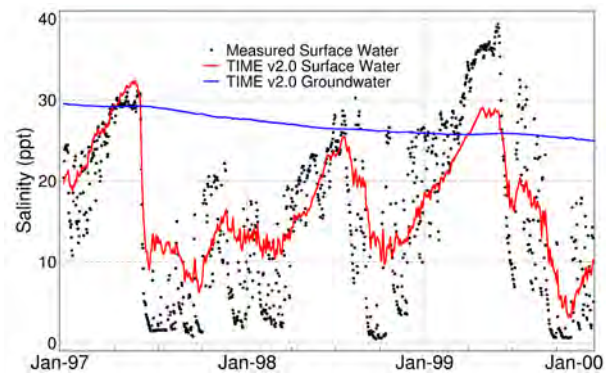


Figure 76. TC salinity, Taylor Slough.

3.5 River Flow Volumes

3.5.1 Gulf Coast Rivers

Rivers are defined in the TIME v2.0 model by paths of lower elevation cells, and flow rates are calibrated by adjusting frictional resistance values (Manning's n). The Gulf Coast rivers include Chatham, Lostmans, Broad, Harney, Shark, and North river (Fig. 77). The locations of the specific cells used in the TIME model flow calculations for these rivers are indicated in the figure. The Lostmans River site uses a transect of five grid cells to calculate river flow volumes, the North River site uses two cells, and Chatham, Broad, Harney, and Shark rivers each use one cell. The location of each field station for which flow data were available during the calibration time period also is shown in Figure 77.

Frictional resistance (Manning's n) is used to alter the modeled river outflow velocities to enable a closer match to measured flow data. Figure 78 shows the Manning's n values used in the east-west flow calculations of the model cells. The Manning's n coefficient along the entire length of the river channels is lower, with the exception of Shark and North rivers, where there are large localized increases in resistance at the monitoring location. For Shark River, this is shown as a rectangular block of constant color in the figure. A similar large n value is present in the north-south direction for the North River flows, whose Manning's n coefficient is shown in the lower half of Figure 7 on page 11.

Figure 79 plots model-computed average annual discharge rates. At the sites for which measured data were available for more than 90% of the year, the discharge rates are also plotted. Flow measurements were available for Harney River in 1998, and Shark River for 1998 and 1999. The TIME v2.0 model-computed discharge rates are generally within 50%

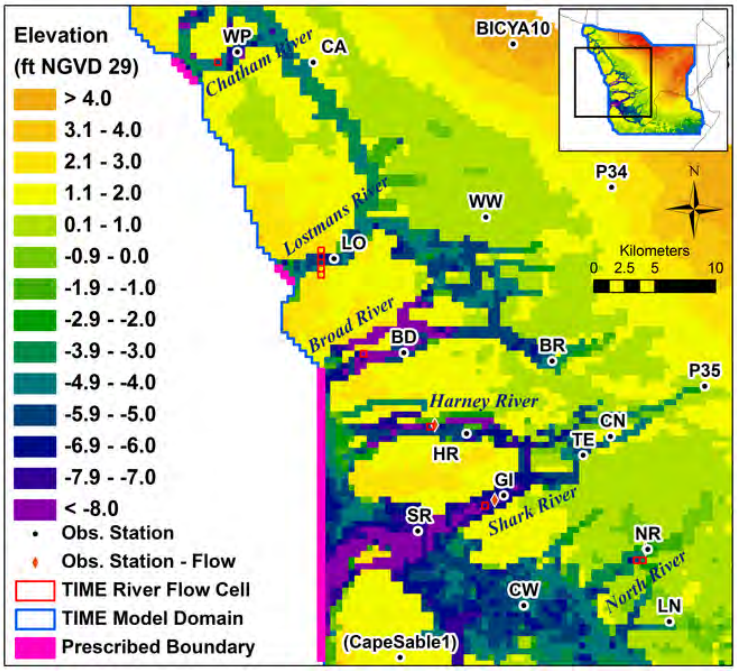


Figure 77. Gulf Coast rivers field stations, flow cells, prescribed boundaries.

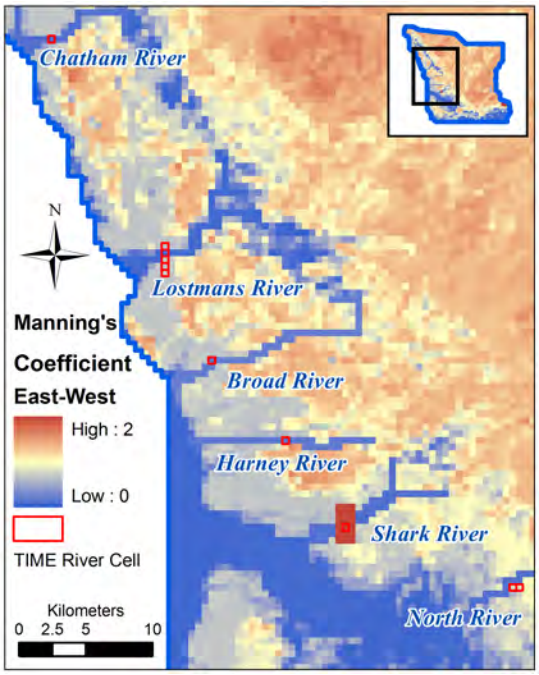


Figure 78. Gulf Coast rivers Manning's n coefficient.

of the measured discharge rates of Harney and Shark rivers along the Gulf Coast. Lostmans, Broad, and Chatham rivers have the highest flow rates, and Harney, Shark, and North rivers have much less discharge. All rivers have their largest model-computed average flow rates during the last year of the simulation, a result of the high rainfall from Hurricane Irene, and have their lowest flow rates in 1996.

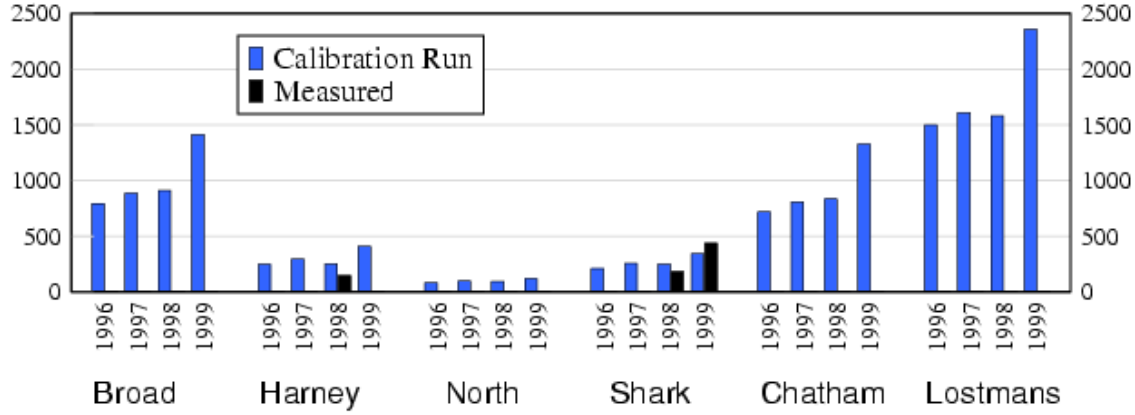


Figure 79. Gulf Coast average annual river flow rates (in cfs) for TIME v2.0 calibration run, 1996–99. Flow measurements are shown for field stations where there is more than 90% of the data present for the year.

Discharge measurements available for the calibration time period of 1997–99 for five estuarine rivers along the southwest coast have been published in Levesque [2004]. The river discharges are a significant component of the flow into the Gulf and can be two to three times the flow through the S12A, B, C, and D structures (locations shown in Figure 3). It is interesting to note that during the period of record the measured river discharges led the

discharges through the S12s by one month. The majority of the flows through the rivers is contributed by rainfall in the immediate upstream basin, but downstream of the S12s. The TIME v2.0 output for Harney and Shark river flows is similar in magnitude to values in Levesque [2004], however the other rivers could not be directly compared with this data because of differing measurement locations.

3.5.2 Discharge into Florida Bay

Figure 80 shows the locations of the TIME v2.0 cells used for calculation of flow volumes of McCormick Creek, Taylor River, Mud Creek, Trout Creek, and Long Sound. Cells selected to represent creek flows in the model are near the actual field locations where flow is measured. These creeks and rivers are more difficult to model than the Gulf Coast rivers - most have widths that are smaller than the model cells and involve much more subtle variations in topography.

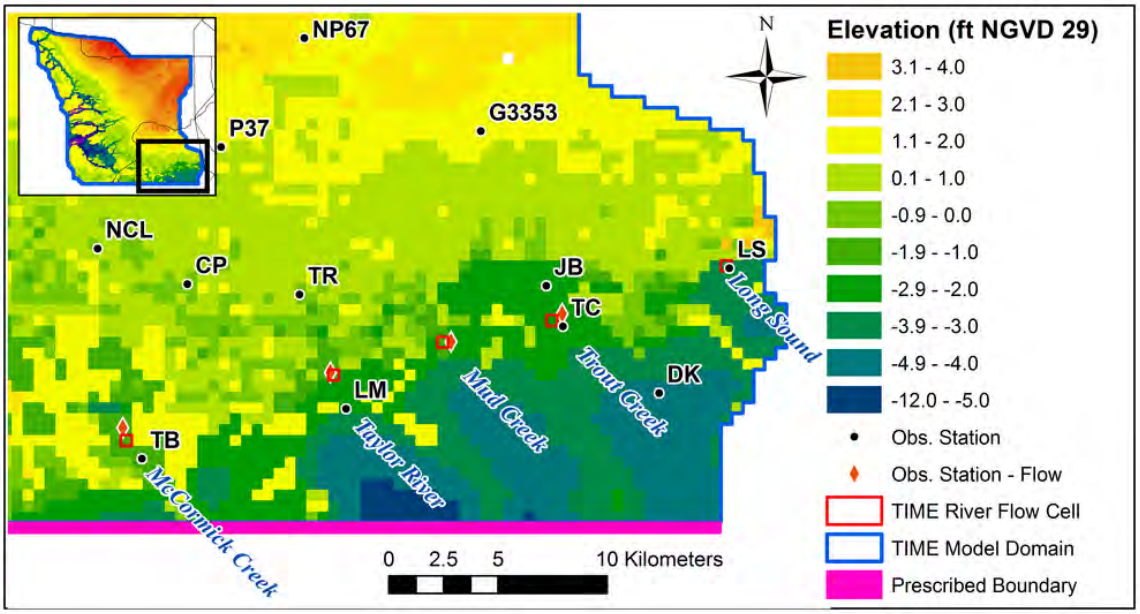


Figure 80. Florida Bay river cells and field stations.

The model topography does not create flow paths that are as well-defined at each of the creeks as it does for the Gulf Coast rivers. Variations in frictional resistance (Manning's n) is used to slow the flow specifically at each of the monitoring cell locations, similar to the approach used in the Shark and North rivers. Manning's n values for this area are shown in Figure 81. A secondary influence in areas where there is little cell-to-cell change in topography is that a higher Manning's n coefficient will also serve to deflect the flow around the cell. Figure 81 shows a large area of increased friction south of the C111 canal, to force much of the surface flow farther west, into Taylor Slough.

In this region storm deposition has created ridges, collectively known as the Buttonwood Embankment, which prevent direct surface water flow into Florida Bay except during high upstream water conditions. Model-computed and measured flows near these actual discharge points are presented in Figure 82. The greatest flow occurs through Trout Creek in the measured data, with the model-computed flow an order of magnitude less. McCormick

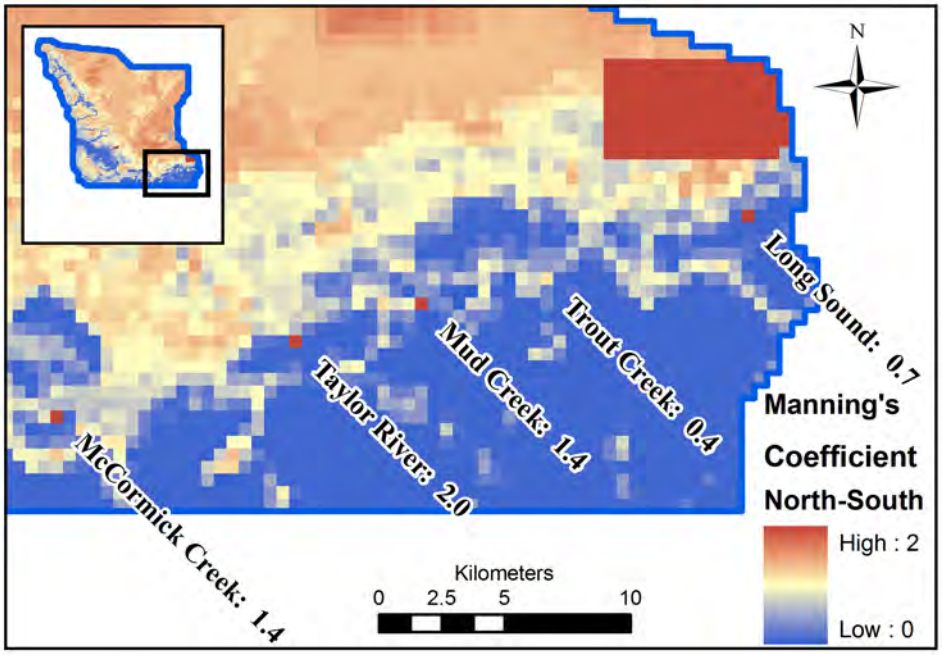


Figure 81. Florida Bay rivers Manning's n coefficient.

Creek and Taylor River model-computed flows were within 75% of measured flow volumes, and Mud Creek model-computed values were only about 10% of measured values.

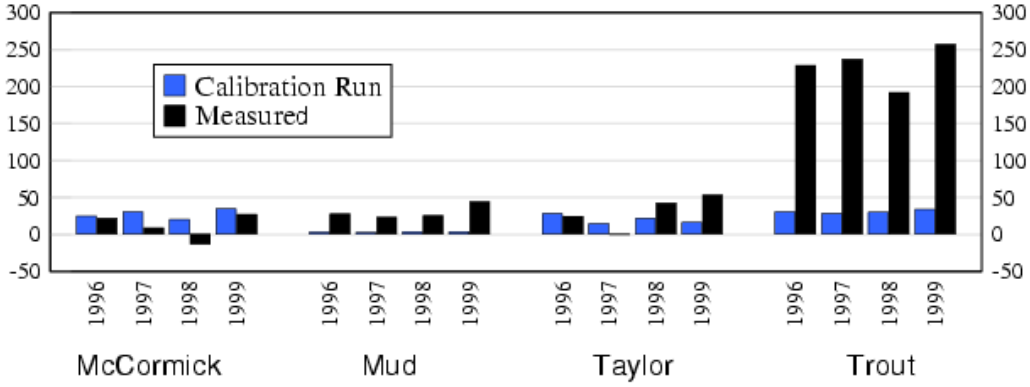


Figure 82. Florida Bay average annual river flow rates (in cfs) for TIME v2.0 calibration run, 1996–99. Flow measurements are shown for field stations where there is more than 90% of the data present for the year.

The back-country bays leading to the creeks are mostly confined by a narrow, slightly higher elevation mud bank and are difficult to model or analyze due to the dynamics of the surface water between the upland areas and Florida Bay; salinity values can fluctuate sharply and often in response to rainfall and wind [Baratta, 1991]. An example of the complexity of the landscape is the Trout Creek area connecting Trout Cove with Joe Bay, shown in Figure 83. This figure shows the frictional resistance (Manning's n) and topography surrounding the modeled Trout Creek area, a channel about 25 m in width, which is the main outlet for Joe Bay to Trout Cove. The cross-hatched cell is the cell used for the flow measurements (field station TROUT in Figure 83) and the hatched cell corresponds to the

field location of the stage measurement gage TC (stage and salinity timeseries for TC are shown in Figures 74 and 76). The friction coefficient in the flow measurement cell is set to a large value to aid calibration for this location. The Buttonwood Embankment downstream of Joe Bay is represented by increased frictional resistance (higher Manning's n) but not by increased elevation.

The panels in Figure 83 illustrate the complexity of the embayments and much detail work would be needed to simulate this area with the appropriate elevations and frictional resistance (Manning's n) values.

3.6 Calibration Summary

Groundwater stage performance statistics were calculated for the TIME v1.0, TIME v2.0, and SFWMM v5.4 model simulations at selected stations across the TIME domain. TIME v2.0 simulation correlation values averaged about 0.88, percent explained variance was 69, and Nash-Sutcliffe values averaged a bit less than 40 (Nash-Sutcliffe values below zero were not included in this average).

Comparison of TIME v1.0 and TIME v2.0 showed TIME v2.0 has better correlations and PEV in the Western Marl Prairie and Shark Slough basins. In other basins, correlation and PEV statistics are on par with v1.0. Statistics were not calculated for most stations in the mangrove ecotone, but visual inspection of the timeseries shows that TIME v2.0 is better than TIME v1.0 due to implementation of new boundary conditions.

Comparison of TIME v2.0 and SFWMM v5.4 simulation results showed that for stations in the overlapping domain, correlation was about the same between the models, average PEV was 71 for TIME v2.0 and 81 for SFWMM v5.4, Nash-Sutcliffe was in the 40s for both (not including negative values). Neither the SFWMM v5.4 nor TIME v2.0 were determined to predict stages consistently better than the other in any given basin. For example, in the Rocky Glades the SFWMM simulation had higher correlation and PEV but the TIME simulation had much better NS values.

Timeseries analysis of regional model performance showed that in the Western Marl Prairie, at station NP205 and P34, TIME v2.0 calibration run surface water and groundwater stages are consistently as much as 0.5 ft below measured values. In Shark Slough, model-computed stages calibrate very well at P33 and P36 for the TIME v2.0 and SFWMM models, and performance at these stations ranks among the best within the TIME model domain. Model-computed surface water stages at NE1 and NE2 are consistently too high in TIME, but the SFWMM model-computed surface water stage tracks well at NE2. Station NP201 performance statistics have high values for both models, but model-computed stages are consistently lower than measured values by about 1 ft.

The seasonal low groundwater stages in the Rocky Glades region were not captured by the TIME model simulation, often being off by 2 ft. Discrepancies decreased farther from the eastern boundary. The SFWMM simulation was determined to be much more reliable in capturing the annual lows. The result is that the TIME model-computed hydroperiods are consistently longer than measured data indicate in this region.

In the Shark River area, stages were over-predicted by about 0.5 ft in the TIME v2.0 surface water model simulation for the SR station. Farther upstream, the simulated surface water is generally higher than measured data, and the model shows deeper recessions in the groundwater during the dry season. Downstream in the Shark River the model-computed salinity correlates well; predicted salinity values are typically within 5 ppt of measured data.

For the Lostmans drainage, the model-computed groundwater salinities are much higher than measured salinities. Furthermore, the model-computed groundwater salinities do not show the expected seasonal variability. This seems to suggest that within the model simulation, interaction between the surface water and groundwater is limited. The measured data indicate some level of interaction between the two regimes, with seasonal variability generally evident in both surface water stage and groundwater stage. At Lostmans River (LO) the TIME v2.0 model-computed surface water stage and salinity were very good.

Model-computed Chatham River stages did not capture most of the seasonal lows. At the upstream end of the river the model-computed stages were lower than measured data during the wet season. In the central and downstream sections of the river the model-computed stages were higher than measured stages, with model-computed groundwater stage being consistently higher than its surface water stage. The model-computed surface salinity data generally follow the trend of measured values but from a later time period.

In the Whitewater Bay Basin, model-computed stages were consistently higher than measured data at gages influenced by the marine environment, but tracked well with measured data in the wetlands. The model-computed salinity values near the boundary are influenced by the boundary conditions.

In the Taylor Slough Basin, model-computed stages were fairly close to measured stages, especially at P37. Model cells corresponding to the field locations for TB and TR did not reflect the marine environment, therefore were not directly comparable. Model-computed surface water salinity at LM is captured well, but model-computed surface water salinity at TC does not show the dynamics of the fresh-saltwater exchange occurring through Trout Creek.

For the west coast locations where river flow volume measurements were available, the TIME v2.0 model-computed river flow volume was within 50% of measured values. For the Florida Bay locations, results were mixed. Measured flow data for this time period are sparse.

Overall, the calibration of the TIME v2.0 model is on par with the SFWMM where the two domains overlap. However, the calibration review revealed some issues with the performance of the TIME model that may be of importance depending on the intended use of the model. TIME v2.0 was determined to be better suited for system-wide analysis, instead of a specific detailed local application. In the following application section of this report, analyses and comparisons are presented for different scenarios of sea level rise and upstream boundary conditions. This application section is intended to demonstrate use of TIME v2.0 in the assessment of regional impacts. It is at this level of analysis that we expect the model to have greatest validity.

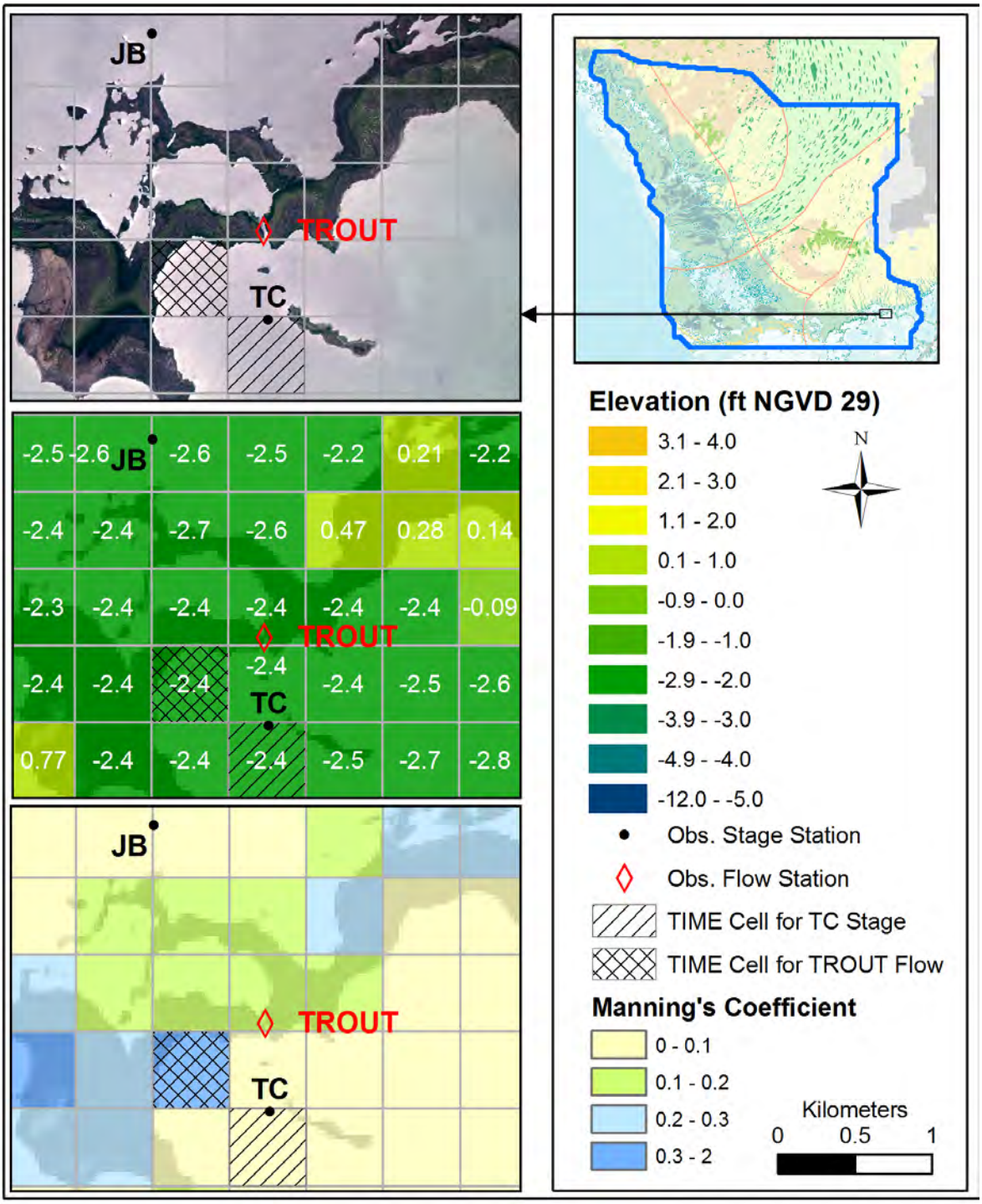


Figure 83. TIME v2.0 elevation and Manning's n coefficient for cells in the Trout Creek monitoring station area. The upper left image shows a satellite view of Trout Creek, located within the center cell and with a width of about 25 m. Station TROUT measures flow through this channel, stations JB and TC measure stage. The TIME model grid is shown overlying the image. The model cell used to represent stage at TC is shown as striped, and the model cell used to calculate flow is shown with a crosshatched pattern. TIME model cell elevations in this area are shown in the center left image (superimposed on the satellite image), and show a three-cell-wide depression in the area at -2.4 ft. The bottom left image shows frictional resistance (Manning's n) values for the model (also superimposed over the satellite image), which indicate that the cell used for flow calculations has one of the highest values for flow resistance in the area.

4 APPLICATION TO WATER MANAGEMENT ALTERNATIVES AND SEA LEVEL RISE

Extensive modeling has been done utilizing the South Florida Water Management Model (SFWMM) to simulate effects of proposed water management strategies on the south Florida system of wetlands, impoundments, and canals. The SFWMM is used to evaluate ENP hydrology, particularly inflows and resulting stages, but the effects of various alternatives on coastal and near-coastal areas in ENP have not yet been successfully modeled. The consequences of sea level rise on ENP are of great concern to Department of the Interior managers and have added another set of criteria to consider when evaluating water management alternatives. ENP predominantly consists of topography below 6 ft NGVD 29, and will be most sensitive to effects of sea level rise. Because the West Coast Ecotone, Whitewater Bay Basin, and lower Taylor Slough Basin are not modeled within the SFWMM's domain, the TIME model was created to simulate the hydrology of these mangrove-dominated ecotones and salinity regimes, as well as to provide a more detailed and spatially resolved hydrology. The analysis presented in this section will focus on the evaluation of the aforementioned areas, in an effort to provide a better understanding of how different water management alternatives and sea level rise scenarios will interact, notwithstanding the issues mentioned in the calibration section.

The application of the TIME v2.0 model used flow and water level output from SFWMM and the pre-drainage version of the SFWMM, the Natural System Model (NSM), as prescribed input boundary conditions along the northern and eastern boundaries of TIME. The three alternatives that were simulated, the natural system, the current condition (Alt7r5e), and the CERP buildout (CERP0), provide a range of alternatives to evaluate under varying levels of sea level rise. For each of these alternatives, scenarios representing current sea level and a 0.3 m and 0.6 m increase in sea level were evaluated. The change in sea level was implemented using a vertical shift to the tidal cycle along the coastal boundaries. In addition, 0.15 and 1.5 m increases were evaluated for the Alt7r5e alternative.

The evaluation of the TIME v2.0 calibration run indicated performance on par with the SFWMM. In the following analysis, results are presented in the form of comparisons among scenarios, and higher confidence is placed on the relative results rather than the absolute values. Timeseries of localized results are presented to illustrate specific points.

During model evaluation, it was clear that the prescribed marine boundaries significantly influenced the salinity values in the mangrove ecotone. To quantify the sensitivity of the model to the placement of the coastal boundaries, six additional Alt7r5e scenarios were run using surface water salinity boundaries fixed at 30 and 36 ppt for each of the three increments of sea level rise.

The final set of simulations evaluated is:

- Current condition runs (SFWMM v5.4.1 Alt7r5e):
  - 0.0 m sea level rise
  - 0.15 m sea level rise
  - 0.3 m sea level rise
  - 0.6 m sea level rise
  - 1.5 m sea level rise
  - 0.0 m sea level rise with boundary at 30ppt
  - 0.3 m sea level rise with boundary at 30ppt

  - 0.6 m sea level rise with boundary at 30ppt
  - 0.0 m sea level rise with boundary at 36ppt
  - 0.3 m sea level rise with boundary at 36ppt
  - 0.6 m sea level rise with boundary at 36ppt
- CERP buildout runs (SFWMM v5.4 CERP0):
  - 0.0 m sea level rise
  - 0.3 m sea level rise
  - 0.6 m sea level rise
- Pre-drainage condition runs (NSM v4.6.2):
  - 0.0 m sea level rise
  - 0.3 m sea level rise
  - 0.6 m sea level rise

The inflow and outflow boundary conditions for each alternative are as follows:

- Northern and Eastern (upstream) TIME boundaries:
  - Surface water inflows derived from SFWMM cell-to-cell overland flows
  - Groundwater heads derived from SFWMM cell stages
  - Surface water and groundwater salinity values set to zero
- Western and Southern (downstream) TIME boundaries (same as Calibration Run):
  - Surface water stage and salinity output from the TIME-EFDC Alt7r5e run
  - Groundwater heads at mean sea level (-0.2 m NGVD 88)
  - Groundwater salinity values at 35 ppt

This analysis will discuss the input along the boundaries and the general methodology for converting the SFWMM inputs to TIME boundary conditions. Results for the sea level rise scenarios run with the SFWMM and NSM alternatives will be presented through comparisons of stages, hydroperiods, flow, and salinity.

Timeseries output from all runs is included in Appendices C through E, sorted by basin, for each station shown in Figure 3. Appendix C includes stage and salinity results for the Alt7r5e sea level rise runs. Appendix D includes results of the Alt7r5e salinity sensitivity runs under differing levels of sea level rise. Appendix E includes the salinity results of the Alt7r5e, CERP0, and NSM runs at current and increased sea level. As in the calibration run, prescribed salinity values based on the EFDC timeseries are used along the outflow boundaries, and are shown in Appendix B.

4.1 TIME Inputs for Water Management Alternatives

To incorporate water management alternatives into the TIME model boundary conditions, daily flow and water level data were extracted from the SFWMM and NSM models immediately downstream of where their grids intersect the TIME's northern and eastern boundaries. The TIME model utilizes stage data for prescribing the groundwater boundaries and uses flow data for the surface water boundaries.

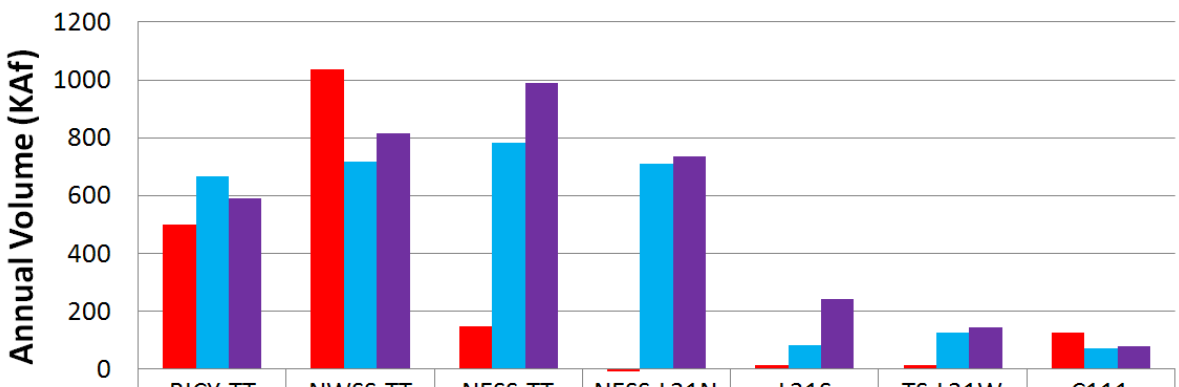
Previous efforts at assigning surface water and groundwater boundary conditions to TIME using SFWMM output (also referred to as the 2x2) had problems with accurately quantifying the surface water flows and seepage input to the model. The complexities of the

SFWMM structure and its naming and accounting system for surface water and groundwater flows, cell seepage, canal seepage, reservoir seepage, structure flows, and relative placement and connections among these elements, warranted a new and simplified approach. For this effort, a method was created where only the cell-to-cell surface water flows and groundwater stages were used, thereby avoiding the need to account for structure flows, canal over-banking, and canal and reservoir seepage.

To avoid these problems, 2x2 cells used for input to TIME were selected such that they were located inside the TIME domain. Cells chosen were downstream of all the structures, canals, and reservoirs in the 2x2. That ensured that all flows were accounted for, and can be applied to all SFWMM and NSM alternatives the same way. Because the TIME surface water component uses flow inputs and the groundwater component uses stage inputs, the relevant data are obtained from the same set of SFWMM cells. For each TIME boundary cell, groundwater stages were assigned based on the corresponding upstream 2x2 cell. Surface water flows were input to the TIME model at their closest upstream boundary location.

4.1.1 SFWMM and NSM Surface Water Inflows

The L29 levee along Tamiami Trail blocks the historical unconstrained slough, though spillways allow some water to flow into ENP. The surface water flows that now enter ENP are controlled entirely by gates with specific flood control operation schedules and rules. Average yearly surface water flows input to TIME from the SFWMM alternatives are shown in Figure 84, based on the boundary sections defined in Figure 85. Figure 85 also shows which 2x2 cell-to-cell boundaries were used to extract flows.



	BICY-TT	NWSS-TT	NESS-TT	NESS-L31N	L31S	TS-L31W	C111
Alt7r5e	500	1036	149	-10	15	14	126
CERP0	667	718	784	710	82	125	72
NSM	592	814	990	735	242	144	80

Figure 84. TIME average annual surface water inflow volumes from SFWMM and NSM simulations used in alternative and sea level rise runs. Locations of BICY-TT, NWSS-TT, NESS-TT, etc. can be found in Figure 85. (Note that this plot does not show groundwater flow volumes, which are computed by the model from prescribed groundwater stages).

The Alt7r5e alternative was chosen to represent current (1990–2000) conditions for this study. Specific features in this SFWMM alternative include: the Interim Operational Plan with Cape Sable Seaside Sparrow operational constraints, the L29 desired flow volume which provides 45% of the flow through the S12 structures to Western Shark Slough, with the

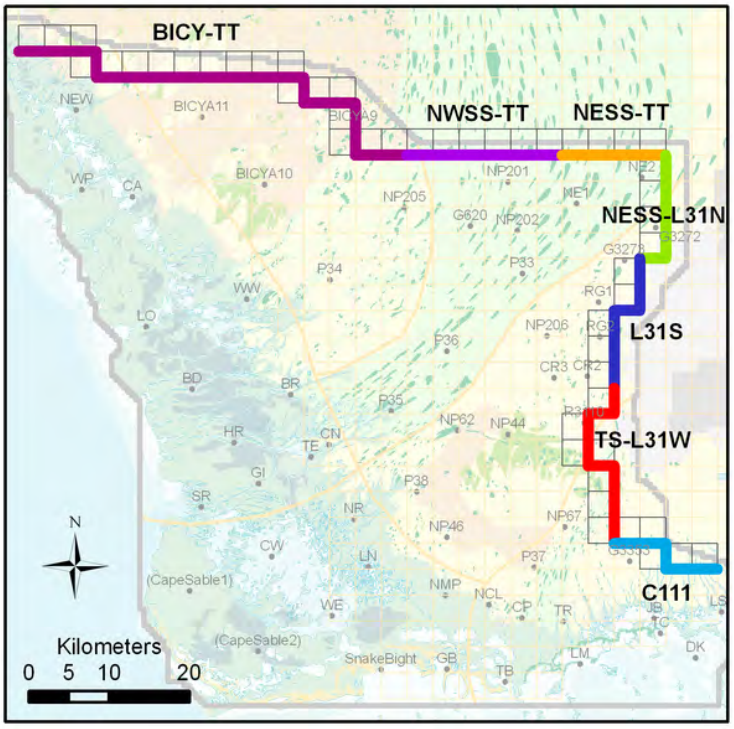


Figure 85. TIME surface water inflows transect location map. These transects indicate where model-computed flow and stage values were extracted from the SFWMM and NSM simulations and then applied to the northern and eastern boundaries of the TIME model for alternative and sea level rise runs. Transects were chosen so that they were downstream of all SFWMM canals, reservoirs, and structures. Figure 84 shows surface water flow volumes input to the TIME model.

remainder passing through S333 for release through the culverts to Northeast Shark Slough. This flow division rarely occurs in the field due to constraints imposed when the stage at the trigger well, G3273, reaches the land surface or the L29 canal reaches maximum stage imposed by roadbed concerns. In this alternative, structures S331 and S173 in L31N operate under the Angel's Well criteria, Taylor Slough structures S332 and S175 remain closed, and the C111 detention areas are present (U.S. Army Corps of Engineers [2002]). The Panhandle area receives flood control discharges as well as Minimum Deliveries via S18C.

In the CERP alternative, the L28 levee has been removed, which allows more flow to move westward and enter the model domain in the Big Cypress area. This can be seen in the BICY transect flow volumes, where CERP0 has an average of 667 Kaf per year, and NSM and Alt7r5e are 592 and 500 Kaf per year, respectively. In this alternative L29 is also removed, allowing for unconstrained surface water flow into ENP across Tamiami Trail. Two large pump stations (S356s) along northern L31N pump water directly into Northeast Shark Slough. Seepage collection and back-pumping into detention areas west of the southern portion of L31N and upper C111 are implemented.

The Natural System Model (NSM v4.6.2) uses the processes from the SFWMM but with the entire canal and structure network removed. Some reconstruction of the original topography and landscape units were implemented in this version of the NSM. Topography within the TIME model was not altered for this alternative.

A consequence of using this methodology for exchange of simulated flows between model scenarios is a shift in location of the flow lines. The cell flows from the SFWMM are well within the TIME domain, thus the SFWMM flows were shifted back towards the TIME boundaries.

4.1.2 SFWMM and NSM Groundwater Stage

The SFWMM and NSM model-computed groundwater stages used as input to TIME for each of the alternatives are shown in Figures 87 through 88 for selected cells along the boundary, which are shown in Figure 86. The northern boundary of the TIME model is the Tamiami Trail (TT). To the north of this boundary lies Water Conservation Area 3 on the eastern side and Big Cypress National Preserve on the west. Along the Big Cypress section of Tamiami Trail, the prescribed groundwater stages at the BICY-TT1 cell (Fig. 87) are the least influenced by water management operations because no operable structures are present in the area, and the numerous culverts under the Big Cypress section of Tamiami Trail allow flow to pass unimpeded. The timeseries of stage in Figures 87 and 88 show the relationship among the three alternatives. At the BICY-TT2 cell in Big Cypress, stages in the area are influenced by operations at several upstream gates. The dry-season recession leads to the lowest simulated depths in the Alt7r5e alternative (see BICY-TT2 in Figure 87). In this area in the CERP0 simulation surface water stage is very close to the NSM simulation surface water stage, an objective which CERP tries to accomplish.

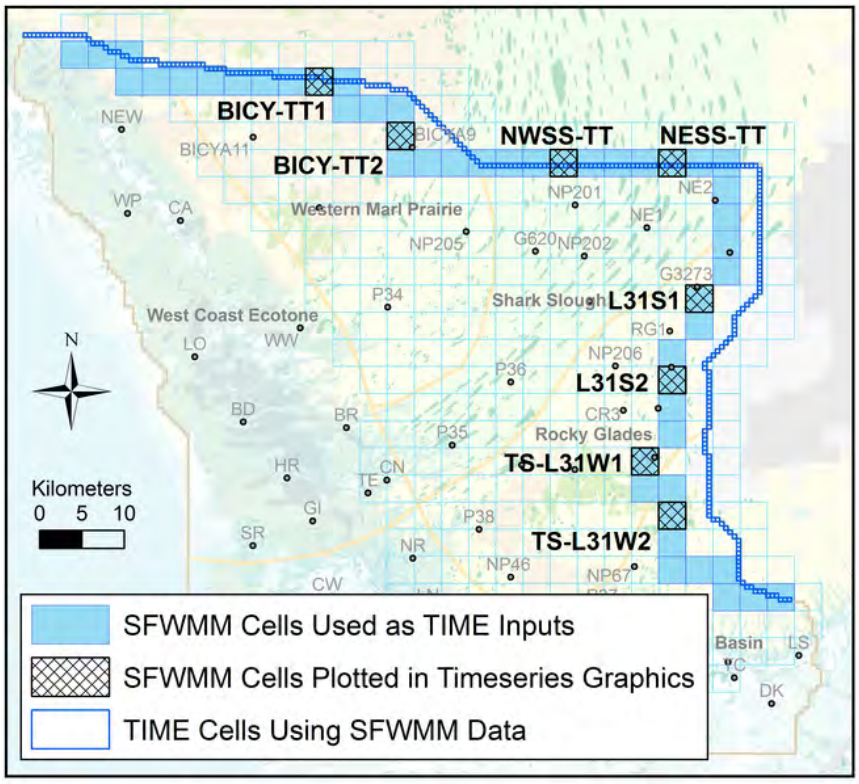


Figure 86. Location of SFWMM groundwater cells used as stage inputs to the TIME groundwater model. Stage timeseries from selected cells marked with crosshatching are plotted in Figures 87 and 88. Also shown are the TIME boundary cells that use the SFWMM cell stages.

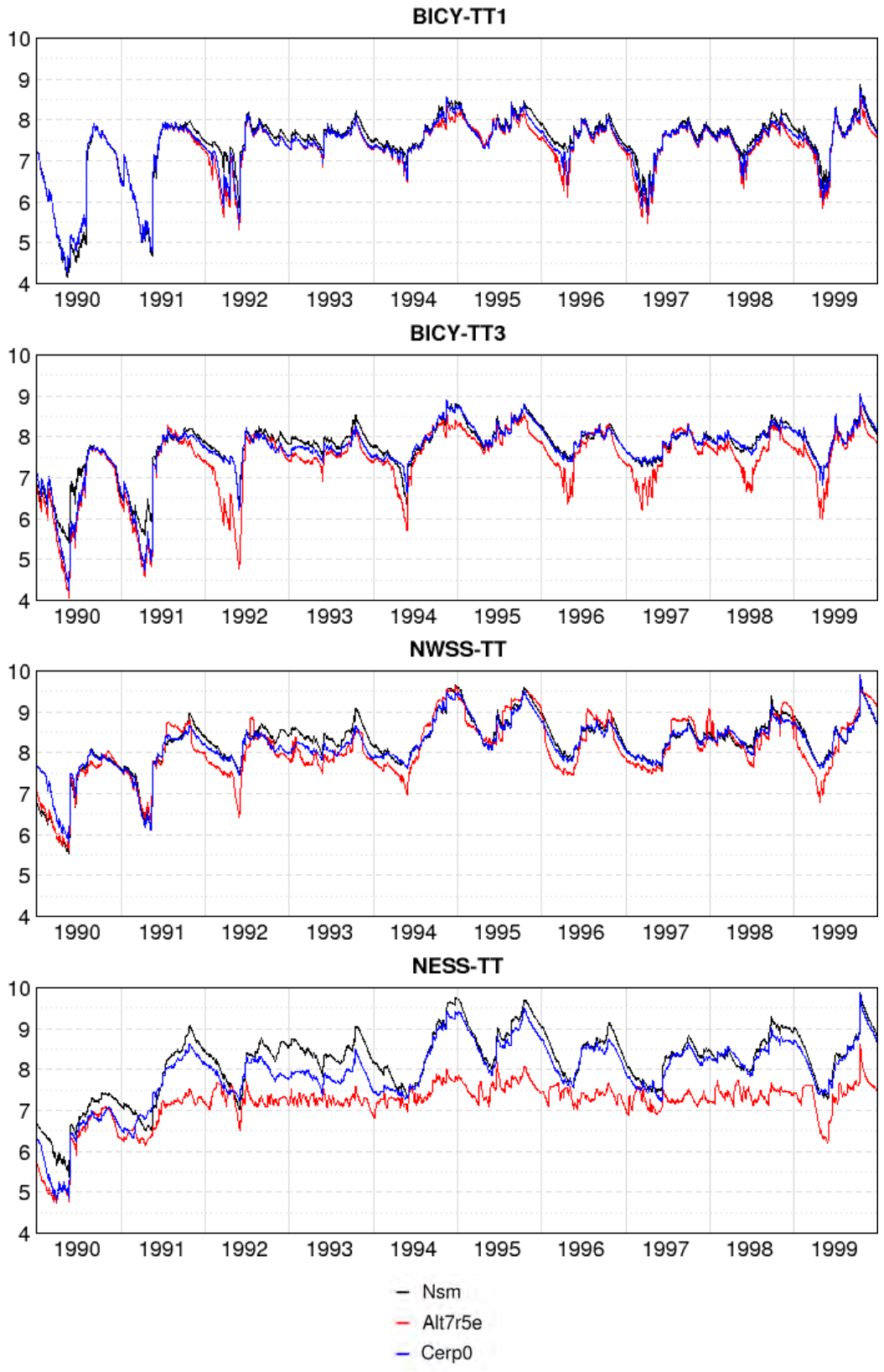


Figure 87. Northern TIME boundary groundwater stage inputs for representative cells (ft NGVD 29). Locations of these cells are shown in Figure 86.

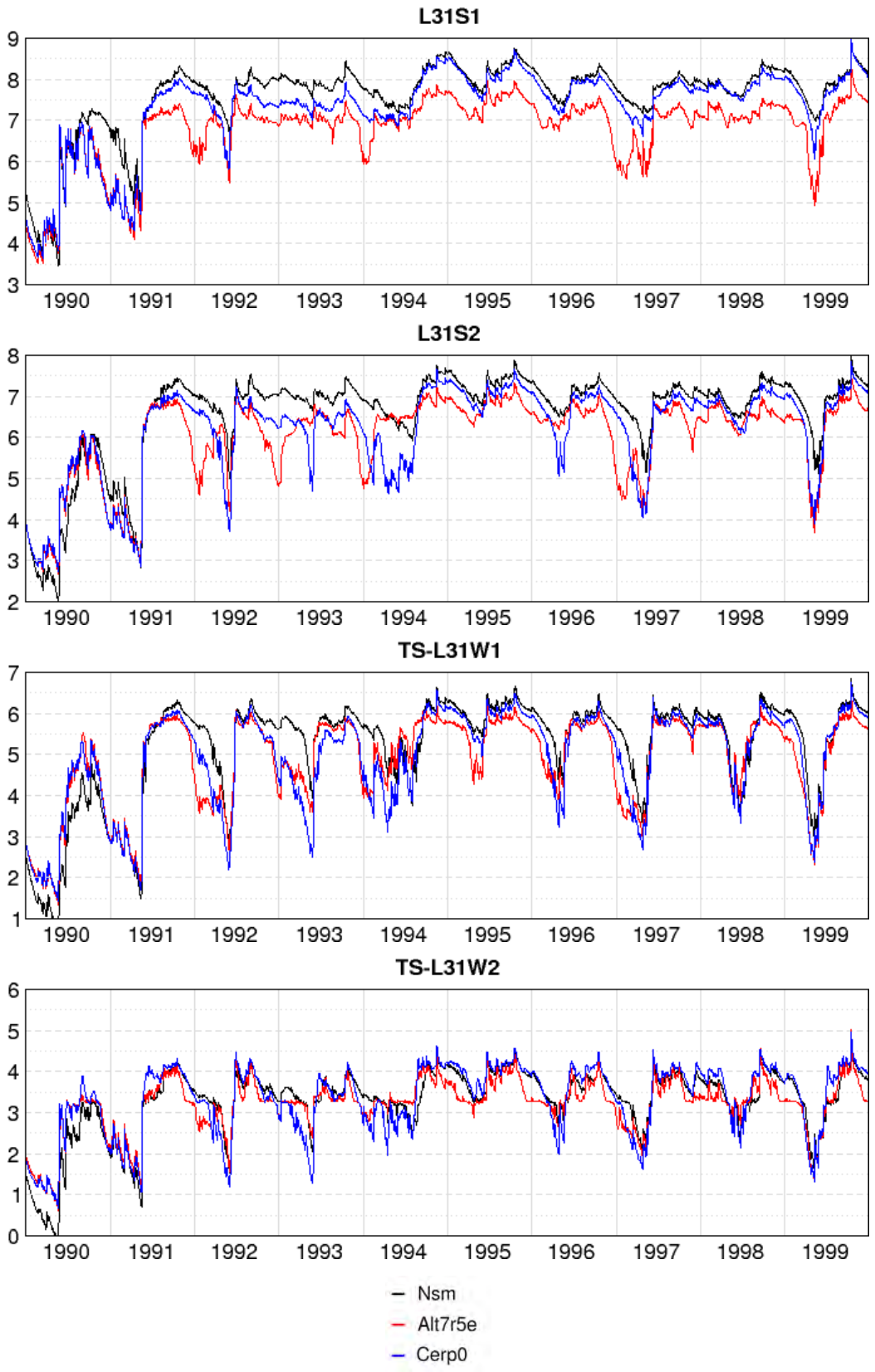


Figure 88. Eastern TIME boundary groundwater stage inputs (ft NGVD 29) for representative cells. Locations of these cells are shown in Figure 86.

ENP's northern boundary is divided into Northeast Shark Slough and Northwest Shark Slough headwaters. In Northwest Shark Slough, the water level is primarily controlled by the water level in Water Conservation Area 3A as well as flows through the S12 structures under Alt7r5e operations. Here the Alt7r5e alternative has higher peaks and recedes to lower levels than the other two alternatives (NWSS-TT in Figure 87). CERP0 and NSM stages are very similar for the last 5 years of the simulation, and for the first 5 years NSM generally has increased depths. In Northeast Shark Slough, the striking difference among alternatives is a result of the influence of the L29 canal (NESS-TT in Figure 87). In Alt7r5e, the canal stage is kept below a specified maximum to prevent it from destabilizing the Tamiami Trail roadbed. In the CERP0 and NSM alternatives, the L29 canal is not present. Although the CERP0 depths are not quite as great as NSM levels, the variability of depths has been restored and significant improvements can be seen in the timeseries.

Stages along the eastern boundary of ENP are influenced by operations of the L31N, L31W, and C111 canals, and a set of water detention areas (generally located between the L31S2 and L31W2 cells in Figure 88) that receive water from the L31 canal through pumps. At cell L31S1 (Fig. 88), Alt7r5e water levels recede to much lower levels than in the CERP0 and NSM alternatives. In the last 5 years of the simulation, NSM and CERP0 depths are fairly close (CERP0 recedes to a lower level than NSM), and in the first five years, NSM is generally higher than CERP0 by 0.5 ft. L31S2 depths (Fig. 88) recede to similar low stages in both Alt7r5e and CERP0; NSM levels often are higher. Stages in cell TS-L31W1 (Fig. 88) have similar magnitude in their ranges during most years for all alternatives. Alt7r5e recessions happen much more quickly than in CERP0, and CERP0's recessions are faster than in the NSM alternative. At TS-L31W2 (Fig. 88), depths in Alt7r5e are kept at a constant level most of the time. CERP0 and NSM depths are similar and have more gradual recessions after peak events.

4.2 TIME Inputs for Sea Level Rise Scenarios

Several evaluation runs were performed with TIME v2.0 to model sea level rise. Sea level was raised by 15 cm, 30 cm, 60 cm, or 1.5 m for the entire duration of the simulation for the Alt7r5e scenario. Sea level increases of 30 cm and 60 cm were also applied to the NSM and CERP0 runs and the runs for Alt7r5e salinity sensitivity. Stage increases greater than 1.5 m require much more extensive modifications to the boundary conditions and other input data sets, and were not attempted with the TIME model.

4.2.1 Stage Inputs

Implementation was accomplished by raising all groundwater elevations in the general head boundary input file that were below the new sea level up to the new sea level elevation. For example, the model uses -0.2 m NAVD 88 as average sea level, so for a 30 cm sea level rise the marine boundary groundwater heads would be set to 0.1 m (10 cm) NAVD 88 for the entire simulation. Also, northern and eastern boundary groundwater stages below 0.1 m would be set to 0.1 m, so that no boundary heads would be below the new sea level. Stages already above the new sea level elevation were not changed. Flow values input to the surface water model along the northern and eastern boundaries were kept the same.

Tidal surface water elevations along the southern and western boundaries were uniformly raised by the amount of sea level rise through the use of a new feature available in TIME v2.0. The amount of sea level rise is prescribed in the main input file, and is then added in

the model (at runtime) to the marine surface water heads. The offset is applied uniformly for the entire duration of the simulation.

4.2.2 Salinity Inputs and Sensitivity Analysis

For sea level rise runs, prescribed boundary salinity values along the southern and western boundaries were not changed to enable a direct comparison among the scenarios. Because the TIME model domain follows the coastline on these sides, it cannot accurately predict salinity changes as a result of sea level rise in these areas without being fully coupled to another model that extends further into the marine environment. With the increasing stages predicted under sea level rise, the values for salinity are likely to be different, and the implementation of the southern and eastern boundaries would need to be changed to represent a continuous marine boundary.

To obtain an estimate of how far into the model domain the prescribed boundary salinity values will affect the predictive capability of the TIME model, a sensitivity analysis was conducted by modeling a complementary set of sea level rise runs where the boundary salinity values were held at fixed values of 30 and 36 ppt. These results are presented in Section 4.6 on page 74.

The resulting output from the Alt7r5e run, created by iterating TIME and EFDC model runs, is used in this project as the boundary condition input for TIME for all alternatives evaluated during this project: Alt7r5e, CERP0, and NSM. The stage and salinity timeseries for the relevant monitoring stations are presented in Appendix B.

4.3 Sea Level Rise and TIME Topography

Much of the land area of ENP is less than 6 ft above sea level. The continuation of rising sea levels will impact vast areas and continue the shift in ENP's estuarine ecotones to more saline types. The installation of tide gages has provided less than 100 years of record; the data indicate that the slow rate of ascension (4 cm per 100 years) that has persisted for the last 3000 years is increasing. Numerous projections of sea level rise exist in the literature, ranging from static predictions in which sea level rise rates do not change, to complex dynamic approximations where additional feedback mechanisms are considered. A wide range of predictions for 2100 is documented in Gleason [2009], from 1 ft to more than 20 ft.

The Miami-Dade Climate Change Task Force [2008] projects as much as a 60 inch (1.5 m) sea level rise by 2100 if there is an increase in the rate of melting of the polar ice sheets. Bindoff and Willebrand et al. [2007] predict a 7 to 23 inch (0.2 to 0.6 m) sea level rise by 2100. The Intergovernmental Panel on Climate Change (IPCC) synthesis report offers projections of sea level following a linear increasing trend analogous to that of recent decades. Increases based on assumptions about future behavior of ice sheets and glaciers, as a result of global warming which might originate from anthropogenic activities, are also considered in the literature. These analyses are complex and often speculative; the human induced increases are superimposed on a longer timescale (geologic) natural oscillation that has not yet been captured in tidal and temperature records, but perhaps are hinted at through proxies.

Current worldwide rates of rise for stable areas around the globe are shown in Figure 89 and the long-term trend for the Key West gage is shown in Figure 90. Investigated by Maul and Martin [1993], the long-term trend for increases in sea level at Key West continues at 2.24 mm per year which is equivalent to 0.73 ft in 100 years.

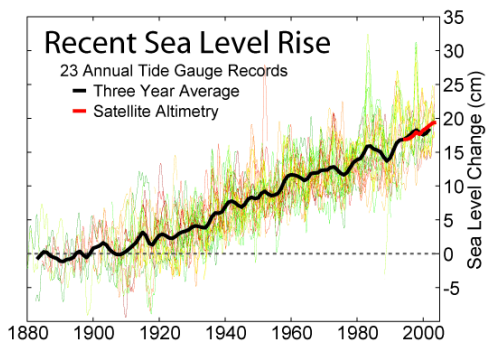


Figure 89. Recent worldwide sea level rise
Source: WikipediA [2010].

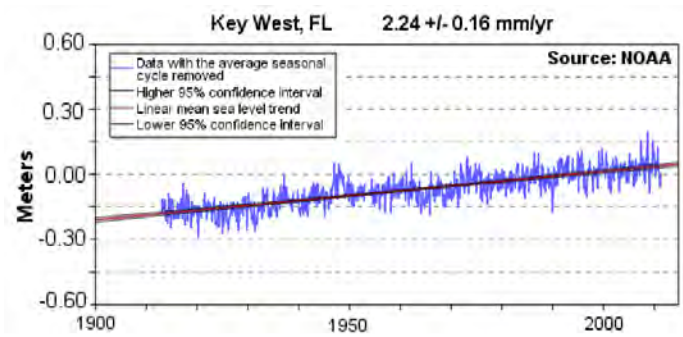


Figure 90. Key West tide data
Modified from: of National Marine Sanctuaries [2011]

Impacts on the coastal ecotone depend as much on total quantity of rise as they do on the rate of rise. The mangrove forests are underlain by decaying mangrove vegetation, with storm sediments added to the mix. If new soil formation keeps pace with sea level rise, the ecotone will change gradually as the upland areas become inundated. The coastal margin will continue to prograde unless the rate of sea level rise exceeds the ability for oyster bars to develop and mangrove recruitment becomes inhibited. It has been estimated that mangrove survival is not possible under sea level rise rates greater than 0.75 ft per 100 years, assuming no additional deposition [Ellison and Stoddart, 1991].

4.3.1 Static Analysis

The topography in TIME v2.0 shown in Figure 6 can be used to calculate static inundation patterns with various scenarios of sea level rise. Average sea level in the TIME model is -0.2 m NAVD 88 and the seasonal fluctuation in the Gulf of Mexico is about 0.50 m. By splitting this range equally between a maximum and a minimum tide, we can derive three tide elevations: a minimum (-0.45 m), average (-0.20 m), and maximum (0.05 m) condition from which to determine the effects of rising sea level over the TIME topography. Identifying the contour line for the three tide conditions with the two sea level rise scenarios (+0.3 and +0.6 m) is straightforward, and the results for the minimum are shown in Figure 91, for the average in Figure 92, and for the maximum in Figure 93. The dark blue is the current tide level at 0 cm sea level rise, and the light blue colored swath is the additional area inundated due to the sea level rise scenario for that condition.

In this analysis, and in the TIME model, the topography is not changed. During the relatively long time period that sea level may rise to the 60 cm value used as a maximum in this report, the soil dynamics in the coastal zone will likely change. Unless peat deposition keeps pace with rising sea level, the present peat soil will be eroded. As a consequence, surface elevations will drop to the level of the bedrock, providing a much different ecotone than can be inferred from the plots. For example, in the plot of maximum sea level with 0.6 m rise shown in Figure 93, the outlying islands will likely have disappeared.

4.3.2 Dynamic Analysis

The static analysis presented in Section 4.3.1 estimates the extent of inundation under 30 and 60 cm sea level rise at a minimum, average, and maximum tidal condition using only

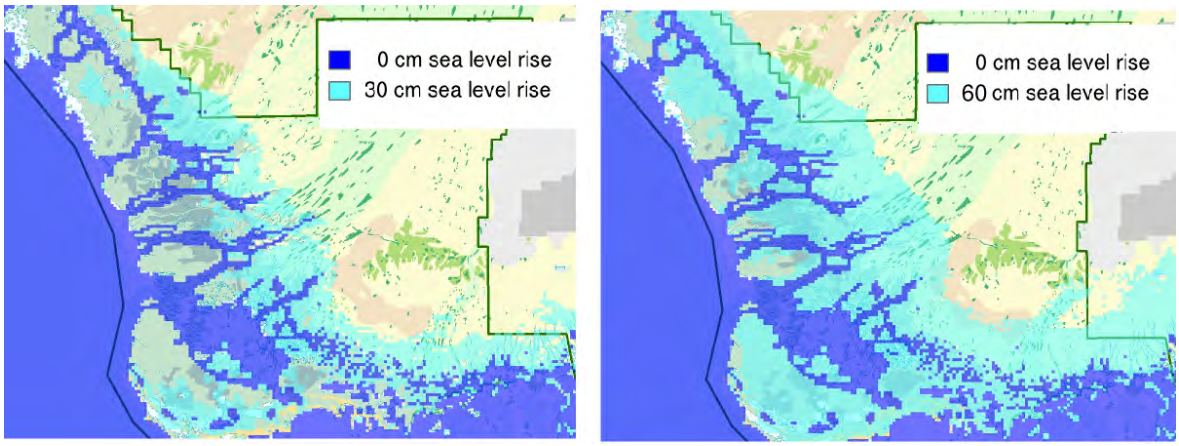


Figure 91. Inundation pattern calculated using minimum annual low tide and TIME v2.0 land surface elevations. Area inundated under current sea level is shown as dark blue; additional area inundated under 30 cm rise (left) and 60 cm rise (right) is shown as light blue.

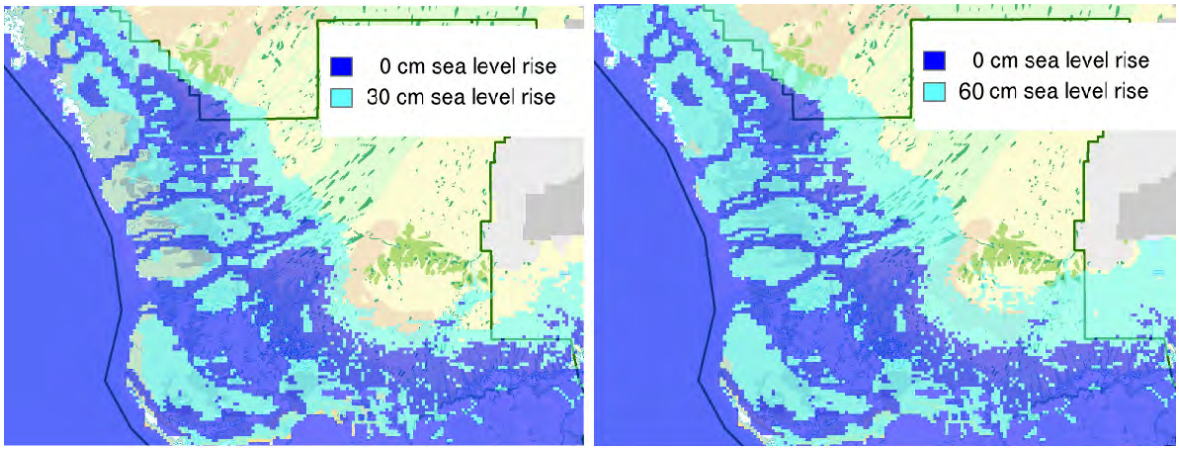


Figure 92. Inundation pattern calculated using average annual tide and TIME v2.0 land surface elevations. Area inundated under current sea level is shown as dark blue; additional area inundated under 30 cm rise (left) and 60 cm rise (right) is shown as light blue.

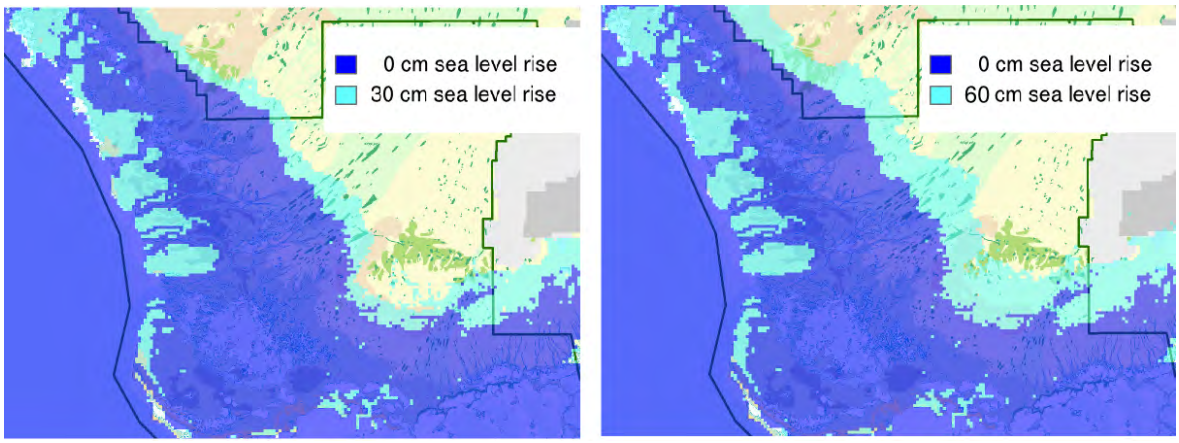


Figure 93. Inundation pattern calculated using maximum annual high tide and TIME v2.0 land surface elevations. Area inundated under current sea level is shown as dark blue; additional area inundated under 30 cm rise (left) and 60 cm rise (right) is shown as light blue.

model topography. For this dynamic analysis, three simulation days were chosen from the Alt7r5e model run to represent a range of conditions from dry to wet periods.

Three days representing dry (March 12, 1997), average (November 15, 1997), and wet (September 20, 1998) conditions were selected based on a general stage pattern observed from timeseries graphs. Higher correlation with upstream conditions was considered more important than capturing downstream tidal conditions to be able to tease out any spatial patterns under different flow conditions. The dates have a normal tide level for the dry (-0.23 m) and the average (-0.25 m) condition, and slightly above normal tide level for the maximum (-0.06 m) condition.

Spatial plots were created for these three specific dates, in which depth values greater than 15 cm (representing inundated areas) are shown as a dark blue color (Figs. 94, 95 and 96). The additional area inundated due to 30 and 60 cm sea level rise is shown in the figures as a medium blue color. The model results indicate that the sea level increases simulated in the dynamic TIME model show a similar pattern to the results obtained from the static analysis presented in Section 4.3.1. The static analysis, however, lacks the stage and salinity response in the marsh.

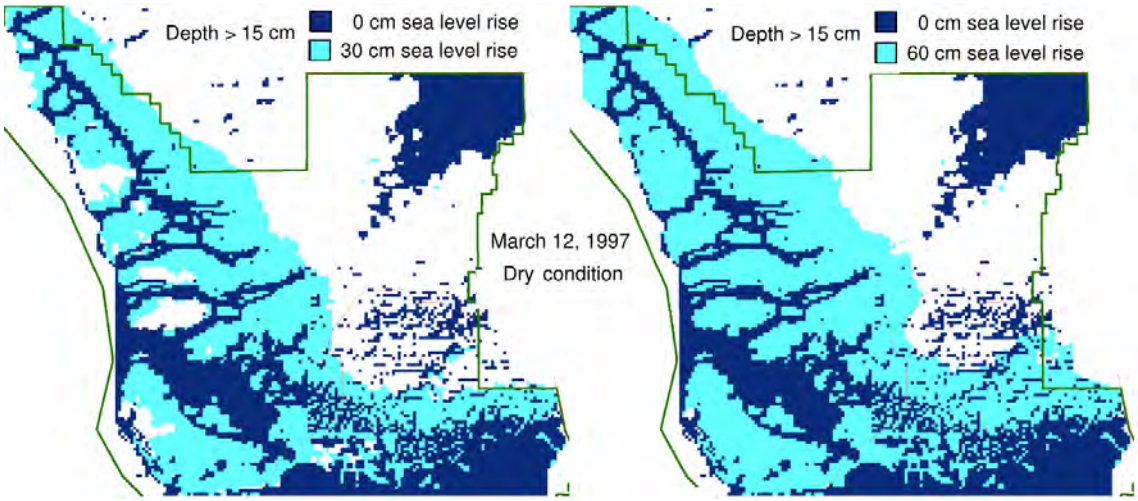


Figure 94. Inundation pattern under a dry condition using TIME v2.0 dynamic simulation and land surface elevations.

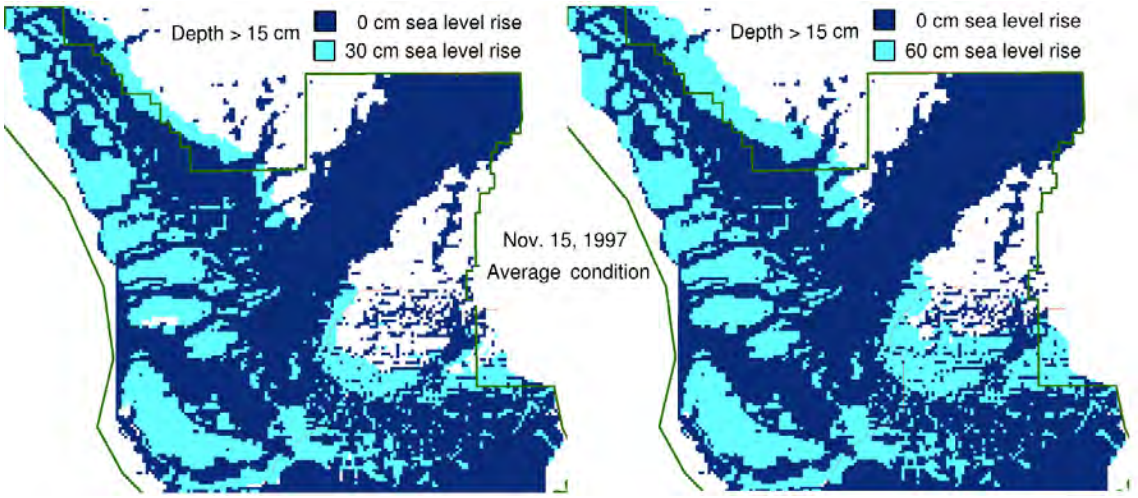


Figure 95. Simulated inundation pattern under an average condition using TIME v2.0 dynamic simulation and land surface elevations.

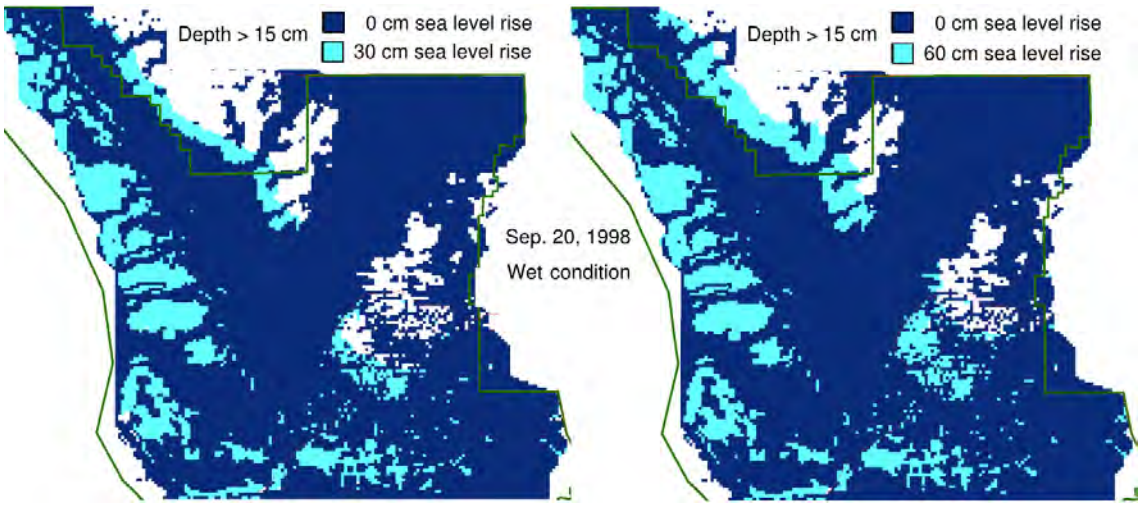


Figure 96. Simulated inundation pattern under a wet condition using TIME v2.0 dynamic simulation and land surface elevations.

4.4 Stage and Salinity for Different Alternatives

The three selected alternatives, Alt7r5e, CERP0, and NSM, provide a range of surface water flows for analysis, with NSM providing the most flow into ENP, followed by CERP0, and then Alt7r5e. To illustrate the effect of these various flow inputs, a transect aligned with the central flowway of Shark Slough is used (Fig. 97). Along this transect the surface water stages and surface water salinity values from TIME for the alternatives Alt7r5e and CERP0, at four different locations, are plotted. The effects on water depths immediately downstream of the input boundary are most pronounced, but diminish farther downstream. Station NE2 is the farthest upstream, and the most directly influenced by water management decisions. CERP0 stages are as much as 1 ft higher than Alt7r5e, reflecting the additional flows prescribed at the boundary. Station P36 is midway down the slough, in the center of the model domain. Here the differences between stages for both alternatives are often closer to 0.5 ft. At stations GI and SR, stages are not only influenced by water flowing downstream through Shark Slough but also by the marine environment. Tidal forcing can be seen in these stage plots, and is most prominent at the farthest downstream location, SR.

Even though the stages at a particular station may be very similar for different alternatives, the salinity regimes can be quite different. The higher upstream stages in CERP0 diminish in the downstream direction but the increase in flows pushes the salinity front seaward. This is shown in the plots of surface water salinity for GI and SR in Figure 97. The average salinity under Alt7r5e at the GI station is 16 ppt, and at SR is 26 ppt. Under CERP0, the average for GI is 11 ppt and for SR is 22 ppt. The average decrease in salinity by moving from Alt7r5e to CERP0 water management alternatives is 5 ppt at GI and 4 ppt at SR. The prescribed boundary salinity timeseries west of the SR station is the same for both alternatives.

SR is heavily influenced by the boundary conditions. Because the increase in flows is expected to lower the salinity at the boundary, it is difficult to determine the magnitude of the salinity response. This effect is also applicable for the salinity timeseries under increasing levels of sea level rise. A sensitivity analysis was performed to address this question and is presented in Section 4.6.

4.5 River Flow Volumes for Different Alternatives

Rivers and creeks in ENP play an important role in regulating salinity values in the estuarine environments of the West Coast Ecotone and Florida Bay. Successful modeling of salinity values in Florida Bay is highly dependent on accurate estimates of flow from ENP uplands. The USGS has installed numerous continuous flow gages in northern Florida Bay at the entrances to the creeks and rivers, and results from the early years of this study can be found in Hittle et al. [2001]. The USGS gage data are presented in Section 3 of this report.

A comparison of flows at these sites can be made among the three different water management alternatives which were used for input to the TIME model. The downstream outflows from these runs were compiled and examined for evidence of influences on flow volume by water management. Figure 98 tabulates the annual average flow volumes through the model's river cell locations in the West Coast region. Differences of as much as 20% can be noted between the Alt7r5e and CERP0 alternatives. Chatham River has the largest flows and shows the closest agreement between CERP0 and NSM, with NSM having slightly higher flows than CERP0. Moving farther south along the Gulf Coast, modeled flow volumes decrease. The Harney, Shark, and North rivers have the least amount of flow of all the rivers

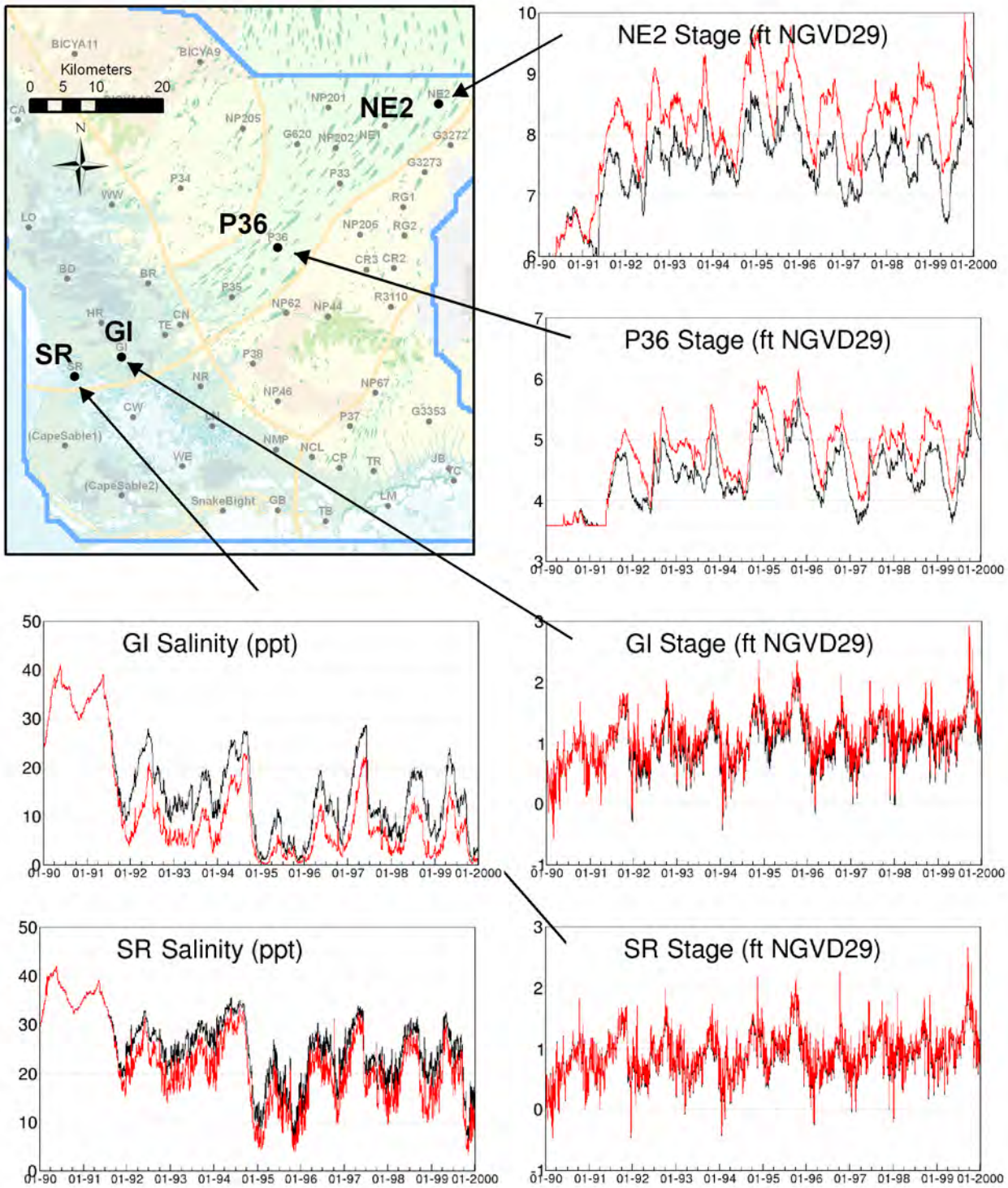


Figure 97. Shark Slough surface water stage and salinity for CERP0 (red) and Alt7r5e (black) for selected stations along a transect down Shark Slough. Differences in stage between Alt7r5e and CERP0 (plots on right) are largest in the northeast and decrease moving down the slough. Differences in salinity between Alt7r5e and CERP0 are greatest in the upstream areas and decrease downstream and toward the model boundaries.

in this region. In the model calibration run, model predictions for flow in the Harney and Shark rivers were within 25% of measured annual average values. For the other rivers, the difference in these predictions cannot be quantified because flow gages were not installed in the rivers until after the calibration time period.

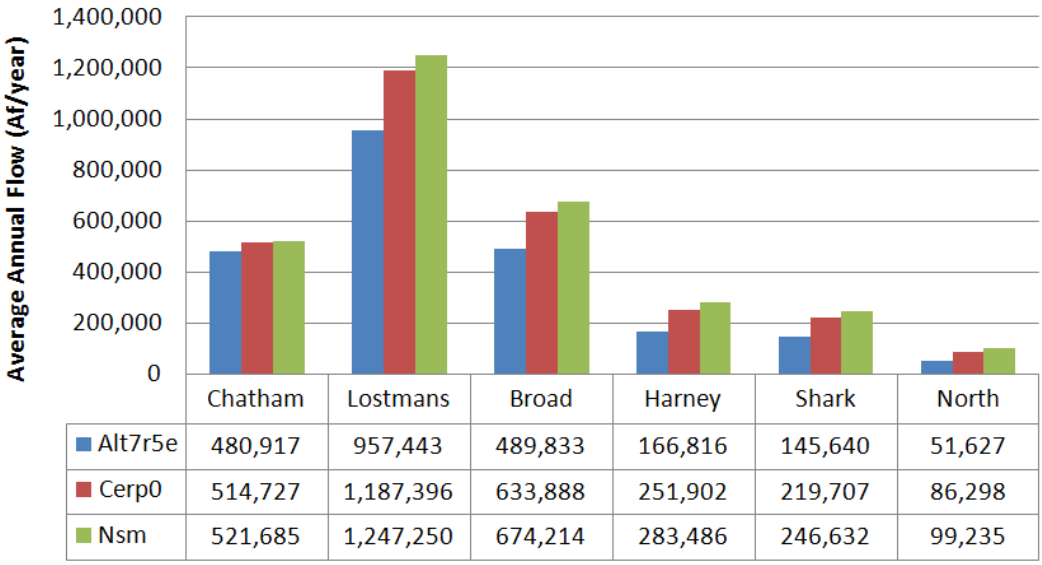


Figure 98. West Coast average annual river flow volumes for water management alternatives, 1990–2000. River implementation in TIME is shown in Figure 78.

Outflow through the river and creek cells to Florida Bay for the three alternatives are tabulated in Figure 99. Florida Bay surface water inflows are substantially less than west coast flows, but still some differences can be quantified among water management scenarios. Again, NSM has the highest rates of flow, CERP0 flows are predicted to be about 90% of NSM, and Alt7r5e flows are between 50% and 75% of NSM. There is a high degree of uncertainty in these results. As discussed in Section 3.5, the implementation of these rivers in the model was determined to need improvement. The topography in this area is much more subtle and determining flow paths in this area becomes more difficult. At the Taylor and McCormick stations, the TIME model calibration run predicted flows that were roughly half of those measured during the same years, and underestimated flows at Mud and Trout Creeks by about 90%.

4.6 Sensitivity of Salinity Values to Prescribed Marine Boundary Conditions

The current domain of the TIME v2.0 model has prescribed marine salinity boundaries that should be influenced by changes in freshwater flows, as well as sea level rise, due to their proximity to the coastline. To quantify the potential change in predicted salinity values due to variations in boundary conditions, two sensitivity runs were performed. The first run set the marine groundwater and surface water salinity values at the boundaries to 30 ppt for the entire simulation, and the second run set the boundary to 36 ppt. The results from these two runs were then compared to see how far and by how much a change in average annual surface water salinity extended into the domain. This analysis was performed using the

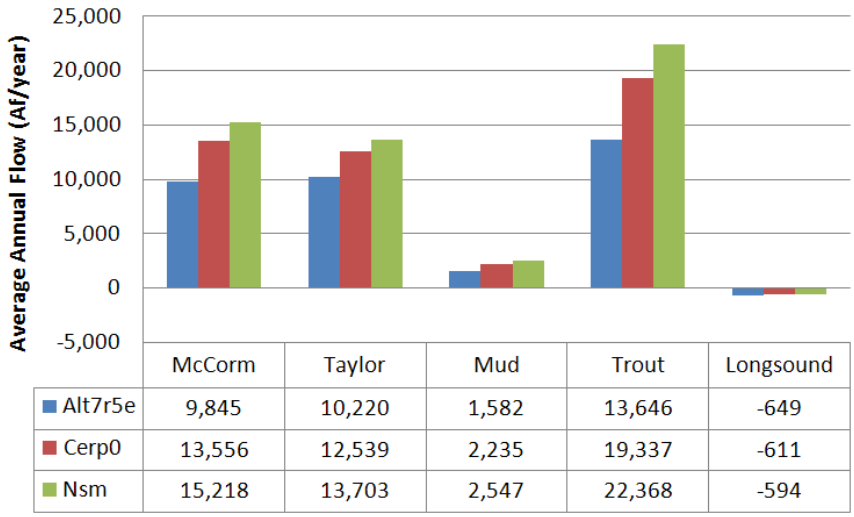


Figure 99. Florida Bay average annual river flow volumes for water management alternatives, 1990–2000. River implementation in TIME is shown in Figure 81.

Alt7r5e inputs. In addition, to evaluate how sensitive the model was to prescribed boundary salinity values under sea level rise scenarios, this 30–36 ppt analysis was also performed with 30 and 60 cm sea level rise increments. The modeled salinity results from this study are provided in Appendix D for all stations.

An example comparison of the three different salinity boundary conditions is illustrated in Figure 100 for the Central Southern Shark River boundary location, shown as 'Shark4' in the map in Figure 101. The timeseries in the plot shows the prescribed boundary salinity values at this location, for a reference on the magnitude of variability. For the sensitivity analysis, the simplified approach of using static boundary conditions instead of a variable timeseries was deemed appropriate as a method to gain some insight into the influence of boundary salinity values on the model solution. These static timeseries are shown as the 30 and 36 ppt lines in Figure 100. The sensitivity analysis compares the resultant 10-year average salinity values for different locations within the TIME domain under different sea level rise scenarios. The differences between 10-year average salinity values with a 36 ppt boundary and with a 30 ppt boundary were used to quantify the degree of influence the boundary has at different upstream locations in the model.

Because of the very general nature of this study, even though many of the boundary cells previously over land would be inundated with the applied sea level rise, the set of cells the marine boundary conditions were applied to was not changed. Figure 12 on page 16 shows the marine boundary cells where the salinity values are prescribed; all other boundaries are treated as land boundaries for the sea level rise runs presented in this report.

In Figure 101 the average annual salinity results are presented along a transect extending from the boundary into the domain. The timeseries for the selected stations in the accompanying plots indicate the degree of influence that the different implementations have in the domain. As designed, the 10-year average difference between the 30 and 36 ppt runs remains at 6 ppt at all marine boundary cells. Farther away from the prescribed marine boundary, the difference between 30 and 36 ppt runs decreases, until eventually there is no sensitivity far upstream in the sloughs. At the Shark River (SR) station, a distance of 8 km from the boundary, the 10-year average salinity values between the 30 and 36 ppt runs differed by 4.56

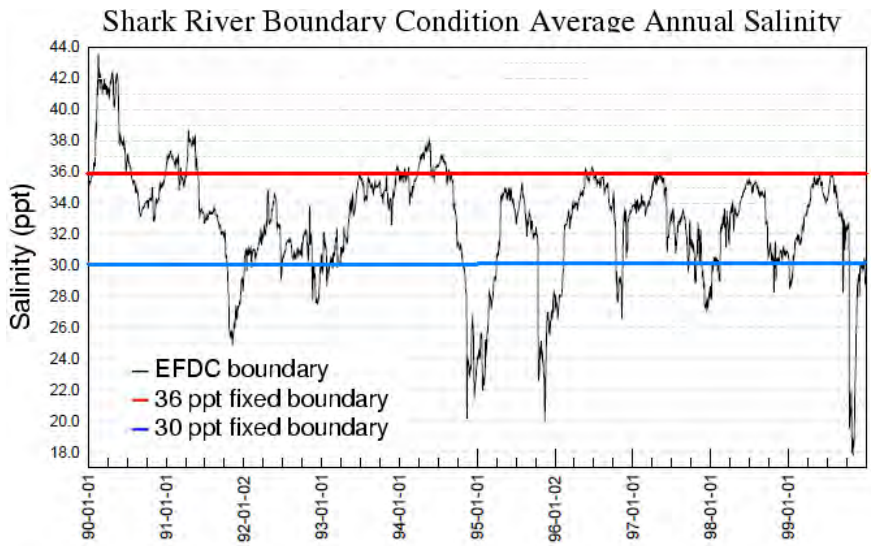


Figure 100. Central Southern Shark River prescribed boundary salinity for sensitivity analysis. The red and blue lines are the 36 ppt and 30 ppt static salinity values used as the input boundary conditions for the entire simulation period. The black line is the prescribed salinity value timeseries used in the model alternative simulations, shown for reference. This location is the Shark4 site shown in the map in Figure 101.

ppt. The scaled result then indicates that for each 1 ppt change in annual average boundary conditions, SR will have a 0.76 ppt change. Farther upstream, a distance of 23 km from the boundary, the TE station shows less sensitivity, with only a 1.32 ppt change between runs. Therefore, the normalized TE annual average salinity is predicted to increase about 0.2 ppt for each 1 ppt increase in the boundary condition.

A spatial overview of the results of the sensitivity study (aimed at quantifying the amount of uncertainty in prescribed marine boundary salinity values) is shown in Figure 102. The results of the salinity sensitivity study indicate that the stations in the northeastern portion of the domain, mainly the freshwater sites of the Western Marl Prairie, Shark Slough, and the northern Rocky Glades, are not influenced by boundary conditions. The stations influenced the most by boundary conditions are in the West Coast Ecotone, Whitewater Bay Basin, and southern Taylor Slough Basin, with the northern Florida Bay stations being the most sensitive. Predicted average annual surface water salinity at stations on the southern and western sides of the domain will increase by between 0.5 ppt and 1 ppt for every 1 ppt increase in boundary salinity. The LM station in northern Florida Bay is influenced the most, increasing 0.95 ppt for every 1 ppt increase at the boundary. The Western Marl Prairie sensitivities are generally less than 0.05 ppt for each 1 ppt boundary change, and the southern Rocky Glades sensitivities range from 0.16 to 0.02 ppt. Figure 103 shows the results of the same sensitivity study at sea level rise amounts of 30 cm and 60 cm. Appendix D presents the complete timeseries results for all stations under each increment of sea level rise.

4.7 Changes Due to Water Management and Sea Level Rise

The three alternatives Alt7r5e, CERP0, and NSM were each run with current sea level and also two scenarios of sea level rise, 30 cm and 60 cm. A comparison of the hydroperiods and salinity regimes for these model runs is presented in the next sections.

4.7.1 Hydroperiod Patterns

This section will present a comparison of hydroperiods among alternatives at 0 and 60 cm sea level rise. A discontinuous hydroperiod is defined as the total number of days per

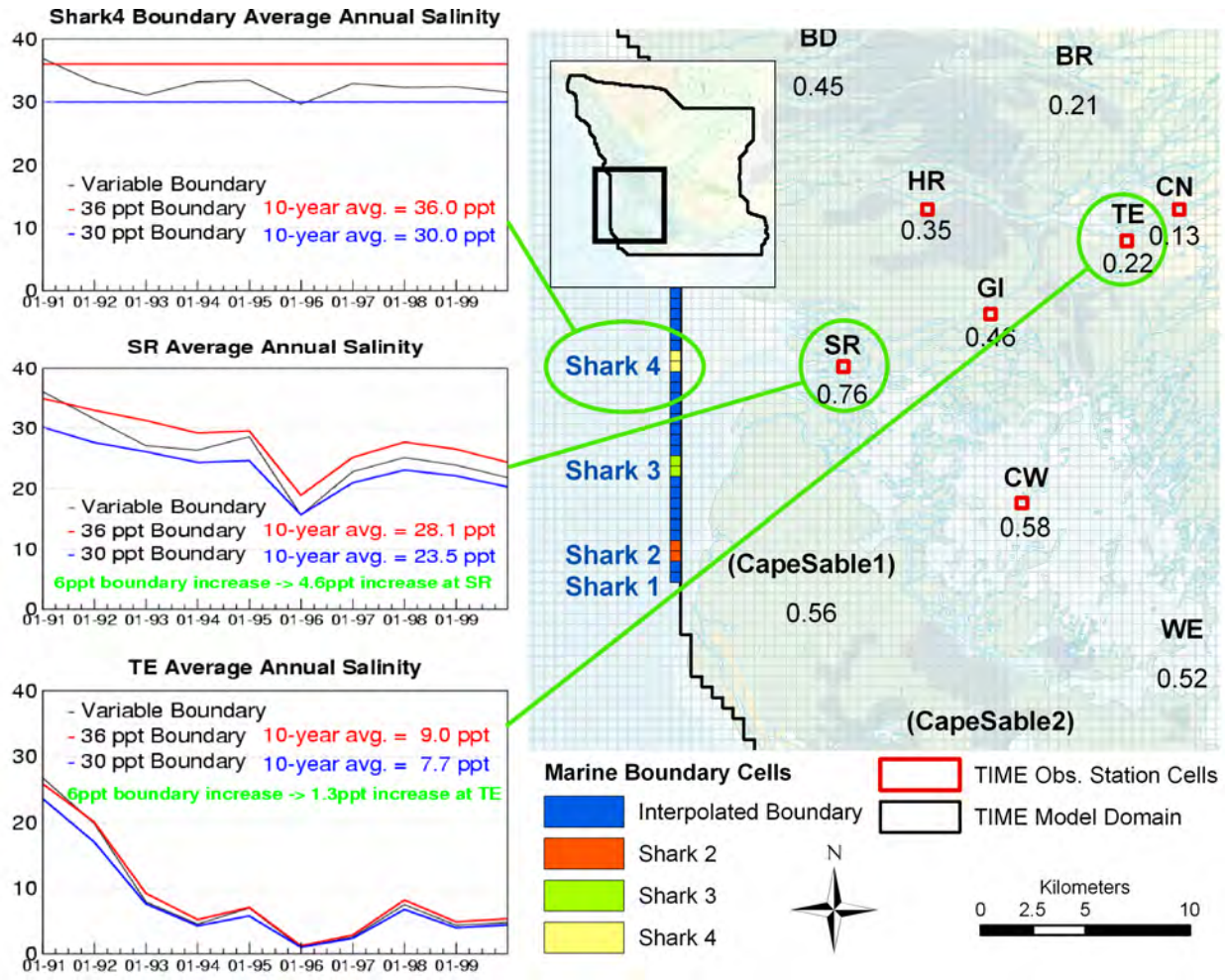


Figure 101. Salinity sensitivity example calculation for TIME v2.0 salinity sensitivity study. The timeseries in the above plots show 1-year averages, however only the 10-year averages were used to quantify the sensitivity in the analysis. The blue timeseries is the 30 ppt fixed-boundary Alt7r5e run, the red timeseries is the 36 ppt boundary run, and the black timeseries is the annual average EFDC boundary values, shown here for reference only. Sensitivity values were calculated as the difference between change in input boundary salinity compared to the difference in salinity seen at the station.

calendar year a given area is inundated, and is calculated in this analysis using the modeled groundwater head. Utilizing the output from the surface water portion of the model would result in slightly different hydroperiods for many stations and considerations would have to be made for detention depths. The following analysis of groundwater-derived hydroperiods is presented to emphasize differences among alternatives rather than absolute hydroperiod values.

Figures 104 through 107 show the average annual discontinuous hydroperiods for stations located throughout the TIME domain. The four runs are the Alt7r5e and CERP0 alternatives with no sea level rise and 60 cm sea level rise scenarios. The 365-day contour lines shown in these figures are essentially the same for Alt7r5e and CERP0 under no sea level rise, and are also similar for Alt7r5e and CERP0 under the 60 cm sea level rise run. Hydroperiods for the areas of complete inundation under this sea level rise are influenced primarily by tidal level changes and not by water management decisions on the scale of

Figure 102. Sensitivity of Alt7r5e average annual surface water salinity values to changes in static prescribed boundary conditions at current sea level. Values depict magnitude of change (in ppt) that is seen in specific locations with each 1 ppt change in boundary condition salinity values; *i.e.*, a value of 0.5 ppt at a station within the domain would indicate that a change of 4 ppt in boundary condition would manifest as 2 ppt change at that location, and would also indicate that a boundary change of 6 ppt would cause a 3 ppt change at that location.

CERP (salinity changes are discussed in Section 4.7.2). Evidence of hydroperiod differences among alternatives can be seen in the location of the 200-day contour lines. In CERP0 the upland areas of the Western Marl Prairie and the Rocky Glades have longer hydroperiods than Alt7r5e in both the 0 cm and 60 cm sea level rise scenarios.

The hydroperiod analysis was computed only for the discrete points representing station locations. These stations were divided into three groups based on the response to sea level rise: stations with discontinuous hydroperiods that will become completely inundated, stations that will increase their average hydroperiod, and stations that will not see hydroperiod changes due to sea level rise. These response regimes are shown in Figure 108. The two middle sections define areas where changes in hydroperiod are predicted to occur, with the blue area representing the area of complete inundation, and the pink area representing the area of partial inundation under 60 cm of sea level rise. These regimes are fairly similar for all alternatives, with the specific differences among alternatives discussed below on a station-by-station basis.

Hydroperiods for stations that become completely inundated from 60 cm sea level rise are shown in Figure 109 for Alt7r5e, CERP0, and NSM. The plot shows that whereas all these stations become inundated, some station's hydroperiods were more sensitive to changes in water management than others. For example, WW, CapeSable1, and CapeSable2 stations

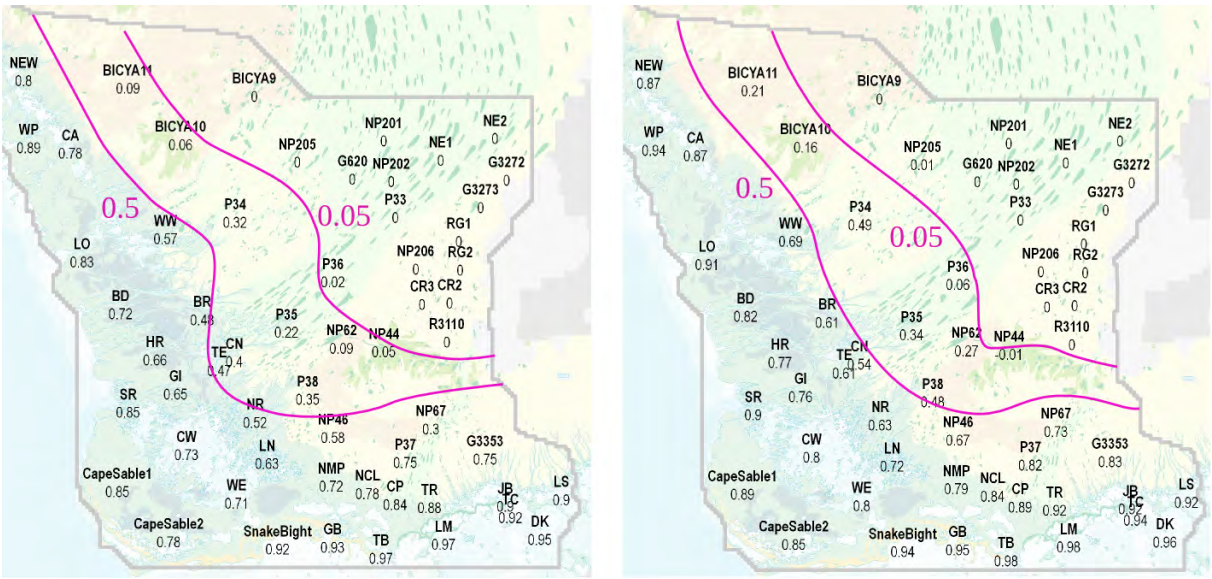


Figure 103. Sensitivity of Alt7r5e average annual salinity values to changes in static prescribed boundary conditions with sea level rise of 30 cm (left) and 60 cm (right). Values depict magnitude of change (in ppt) that is seen in specific locations with each 1 ppt change in boundary condition salinity values; *i.e.*, a value of 0.5 ppt at a station within the domain would indicate that a change of 4 ppt in boundary condition would manifest as 2 ppt change at that location, and would also indicate that a boundary change of 6 ppt would cause a 3 ppt change at that location.

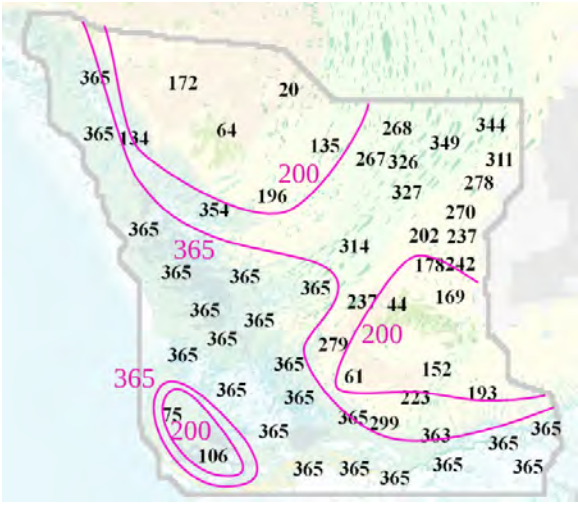


Figure 104. Alt7r5e with no sea level rise average annual discontinuous hydroperiods derived from groundwater stages.

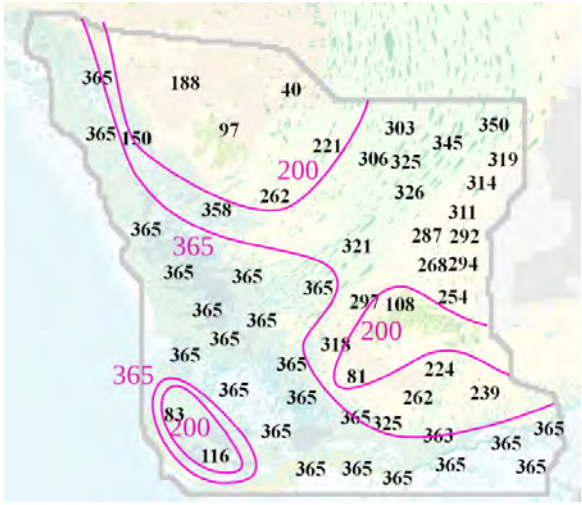


Figure 105. CERP0 with no sea level rise average annual discontinuous hydroperiods derived from groundwater stages.

had almost no sensitivity to water management changes, and hydroperiods at these locations were primarily influenced by sea level rise (these stations have the black bars for all alternatives at roughly the same value for each scenario). The remaining stations shown in the figure have different hydroperiod responses to water management at current sea level but all still become inundated with 60 cm sea level rise. For these areas, the model indicates that there is some ability to manage hydroperiods, and therefore be able to try and manage the speed of transition from one hydraulic and salinity regime to another.

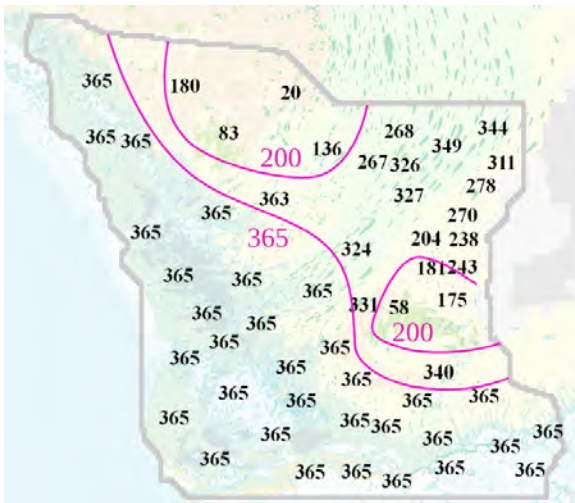


Figure 106. Alt7r5e with 60 cm sea level rise average annual discontinuous hydroperiods derived from groundwater stages.

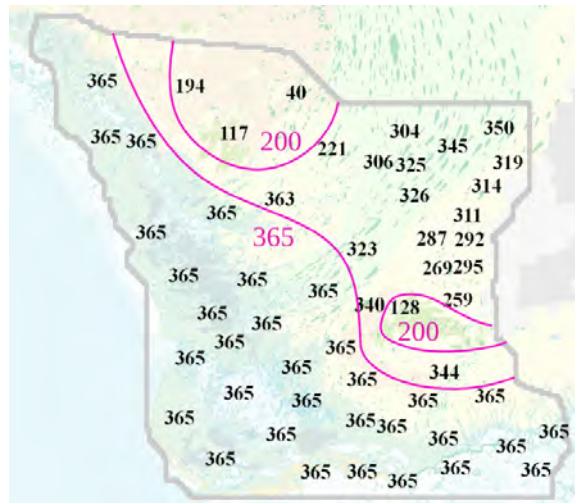


Figure 107. CERP0 with 60 cm sea level rise average annual discontinuous hydroperiods derived from groundwater stages.

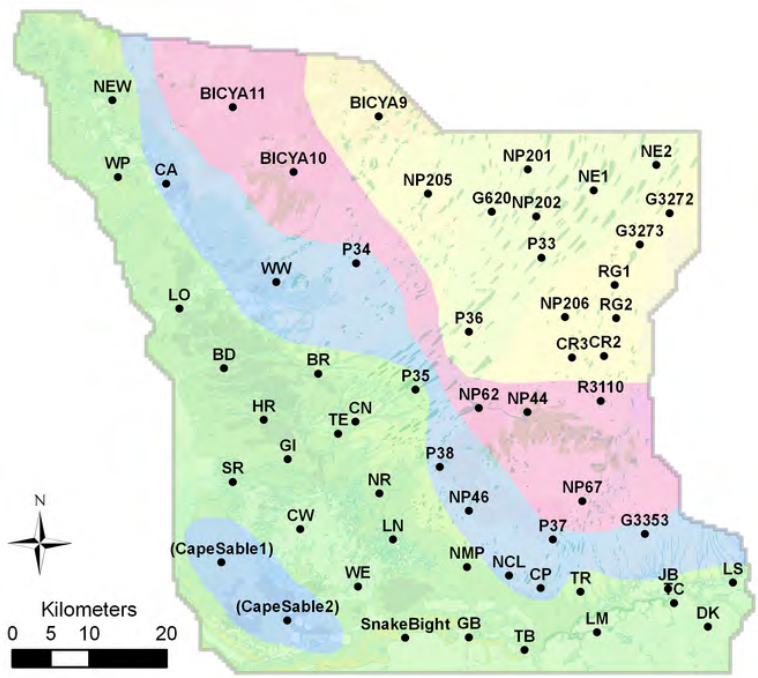


Figure 108. Response regimes of stations to 60 cm sea level rise under Alt7r5e. Green areas are completely inundated with no sea level rise, blue areas will become completely inundated with sea level rise, pink areas will have increased discontinuous hydroperiods with sea level rise, and yellow areas will not have their discontinuous hydroperiods affected with sea level rise. Response regimes for CERP0 and NSM are fairly similar to Alt7r5e, with specific differences among alternatives quantified in Figures 109 and 110.

At higher elevations some stations are not completely inundated with sea level rise, but they will see hydroperiod changes nonetheless. The hydroperiods for these stations are shown in Figure 110. Almost all show sensitivity to water management alternatives and only some show sensitivity to sea level rise. Stations in the bar chart with hardly any blue coloring have no sensitivity to sea level rise, and stations such as NP62 and NP67 show sensitivity to both.

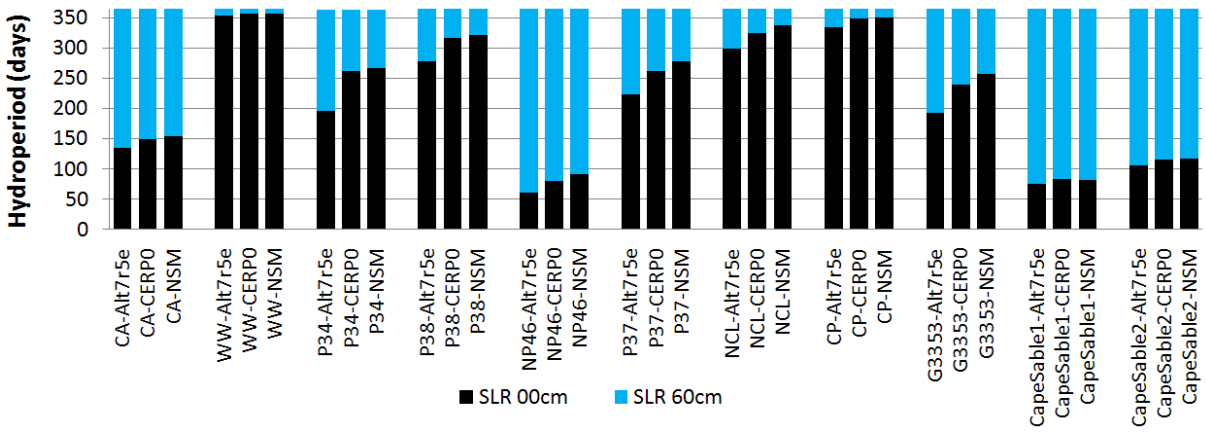


Figure 109. Average annual discontinuous hydroperiods of stations inundated with 60 cm sea level rise, in days. Calculated from daily groundwater stages for the 3652 days of the 10-year simulation, all stations have 365-day hydroperiods at 60 cm sea level rise (shown in blue), and have varying hydroperiods without sea level rise (shown in black).

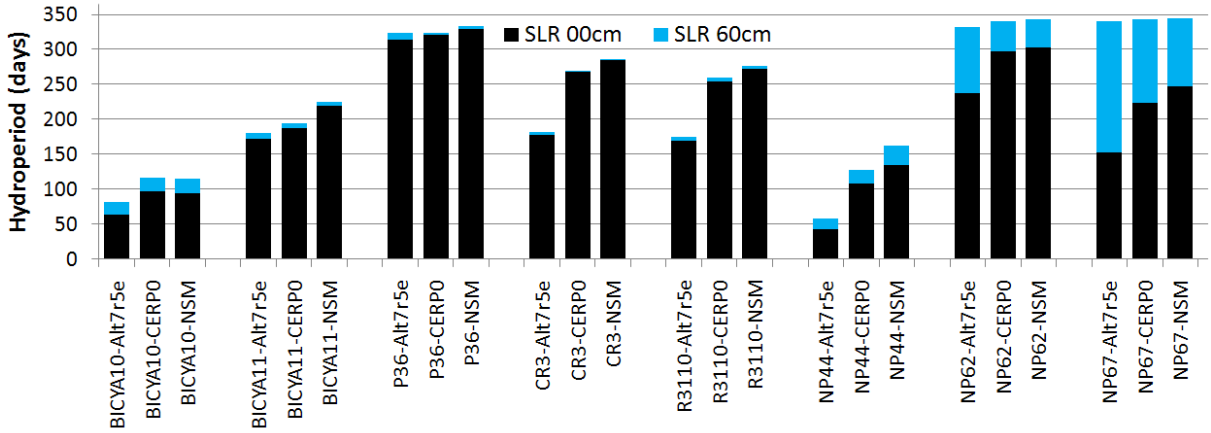


Figure 110. Average annual discontinuous hydroperiods of stations semi-inundated with 60 cm sea level rise, in days. Calculated from daily groundwater stages for the 3652 days of the 10-year simulation.

4.7.2 Surface Water Salinity Changes

As hydroperiods in ENP change due to sea level rise and water management, those stations influenced by sea level rise will also see changes in salinity. Figure 111 shows average annual surface water salinity values for stations that are completely inundated after 60 cm sea level rise. For all stations (except SnakeBight) the average annual salinity values for Alt7r5e, CERP0, and NSM will increase with rising sea level. Stations DK, JB, LM, LS, and TC near the southeastern boundary of the model, and WP and SR on the Gulf Coast, show the smallest increases in salinity under each water management alternative due to sea level rise. The decreased signal could partially be an artifact of their proximity to the boundary. Stations BD, BR, CN, CW, GI, LN, LO, NR, P35, SR, TE, and WE show larger differences between salinity values due to water management alternatives with 60 cm sea level rise as well as current levels. At BR, CN, and TE the relative increase in salinity with 60 cm sea level rise under Alt7r5e is greater than under CERP0 and NSM. At stations such as LM,

TC, and WP the change in salinity is the same under each alternative.

Figure 112 shows average yearly salinity values for stations that become completely or partially inundated with 60 cm sea level rise. These stations have lower overall salinity values, but greater changes due to sea level rise.

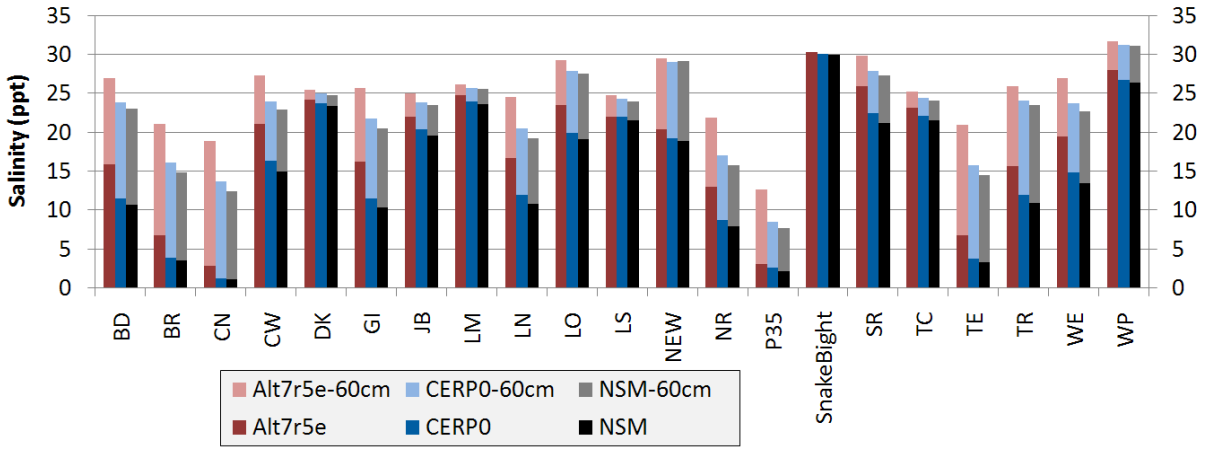


Figure 111. Average annual surface water salinity values of marine and inundated stations.

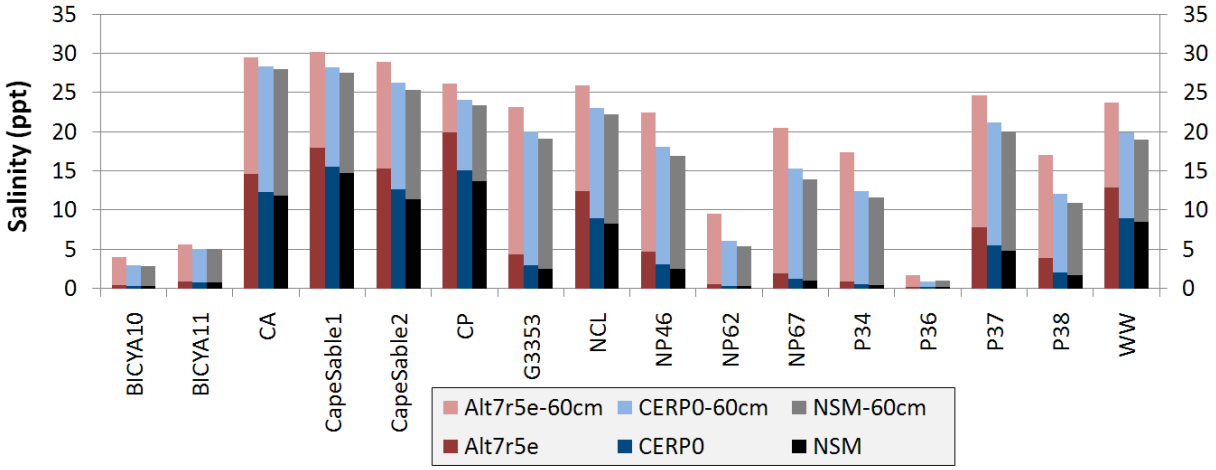


Figure 112. Average annual surface water salinity values of non-inundated stations.

Figure 113 shows a timeseries of groundwater stage at Craighead Pond (CP) under sea level rise scenarios of 0, 15, 30, 60, and 150 cm, and Alt7r5e water management rules. With sea level increases, the range of stages decreases, eventually the water level variation becomes the same as the marine water level, which is prescribed as a tidal signal. The stage curves for 30, 60, and 150 cm are virtually identical in range and variability except for a vertical offset. The curves for current sea level and a 15 cm rise exhibit the greater range.

The effect of increases in sea level on the salinity timeseries is shown in the lower half of Figure 113. This figure shows that predicted surface water salinity values at CP increase on average but decrease in range as the station becomes more inundated with salty water and increases its connection with the open ocean. TIME model results show that average salinity values at all near-shore stations will be higher under 60 cm of sea level rise for all three alternatives, and overall, average salinity values for Alt7r5e are higher than for CERP0, with no sea level rise and also with 60 cm sea level rise.

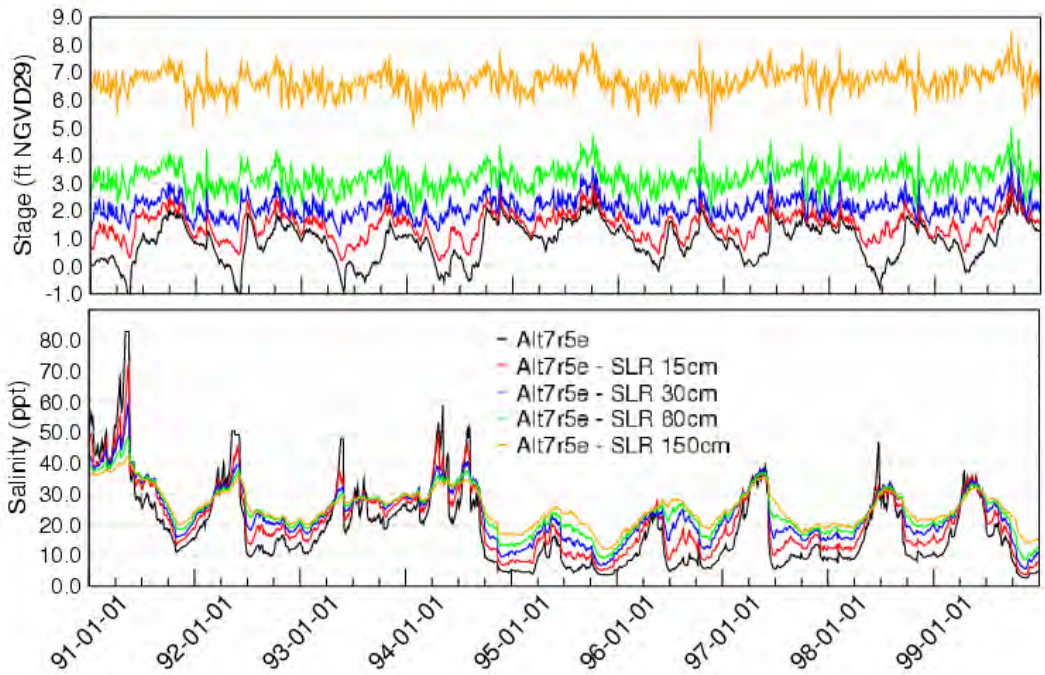


Figure 113. CP groundwater stage and surface water salinity for Alt7r5e.

CP salinity values also exhibit two general categories of behavior. The first is seen in 1991–95, where the current conditions cause more drastic hypersalinity events than under sea level rise. The second is in 1995–98, where the hypersalinity events are less drastic under current conditions but increase with sea level rise. Although many stations do have both types of salinity behavior, in general the stations in the Western Marl Prairie, West Coast Ecotone, eastern Whitewater Bay Basin, and western Rocky Glades fall in the second category. Stations generally in the first category include NEW in the northwest corner of the domain, the CapeSable stations in the southwest corner, and stations in Taylor Slough.

Daily salinity values from the different model runs were used to generate exceedance curves for several selected gages, shown in Figures 114 and 115, under current and 60 cm sea level rise scenarios. The first group of stations were chosen on a transect down Taylor Slough. Upstream in the slough, stations NP67 and P37 show how increases in sea level will increase salinity values overall, and will result in a bigger salinity increase under Alt7r5e than CERP0. The CP station is opposite in that sea level rise will decrease the differences among alternatives. Station CP also shows distinctly the decrease in hypersalinity events with sea level rise in the plot where dotted and solid lines cross in the 0–10% range.

Station TB shows that there is no difference between the alternatives themselves at 0 or 60 cm, but at current sea level the station is wet only 45% of the time. The TB station was determined to be one of the most sensitive to changes in boundary conditions, and therefore the model results have the least confidence for this area. Overall, the stations with modeled salinity profiles showing the least sensitivity to sea level rise are in Florida Bay, and model results in this area do not properly take into account the change in dynamics and salinity regimes because they use the same set of boundary salinity values for all alternatives. Another important process not modeled by TIME that increases uncertainty is that deeper inundation of Florida Bay will alter the hydrodynamics drastically, especially if sedimentation rates do not keep up with sea level rise.

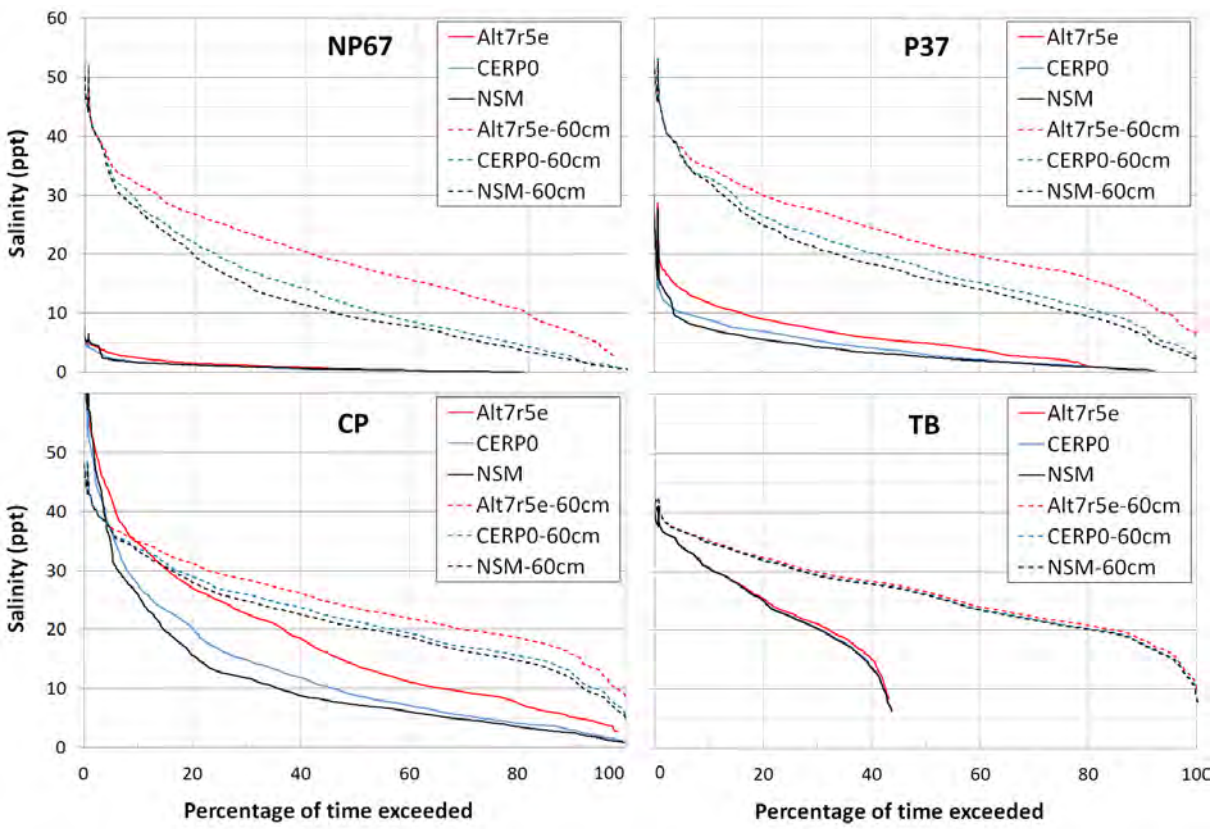


Figure 114. Salinity exceedance curves for Taylor Slough stations

Stations P35, CN, GI, and SR, along a transect down Shark Slough, are shown in Figure 115. The salinity values at the farthest upstream stations show that the effects of water management decisions here have greater impact than downstream. For station SR, the Alt7r5e/0cm salinity distribution is close to the NSM/60cm distribution, which indicates that to achieve a natural salinity regime under sea level rise, the salinity values at SR should remain about the same as they are now.

4.8 Summary

Scenario and alternative implementation

The methodology introduced for converting SFWMM and NSM output to TIME input is useful in that it can be applied to all NSM and SFWMM model runs that do not have new water management features within the ENP boundaries. It is a scripted tool so does not need user oversight when coupling the models. The drawback to this method is that flows along the edges of the TIME domain (especially the northeast corner) can be shifted laterally from their original location, and some of the dynamics in stage fluctuations resulting from bordering canal and detention area stage changes may be dampened.

The methodology for simulating sea level rise in the TIME model raises groundwater and surface water heads at the boundary cells, but does not adjust the boundary salinity

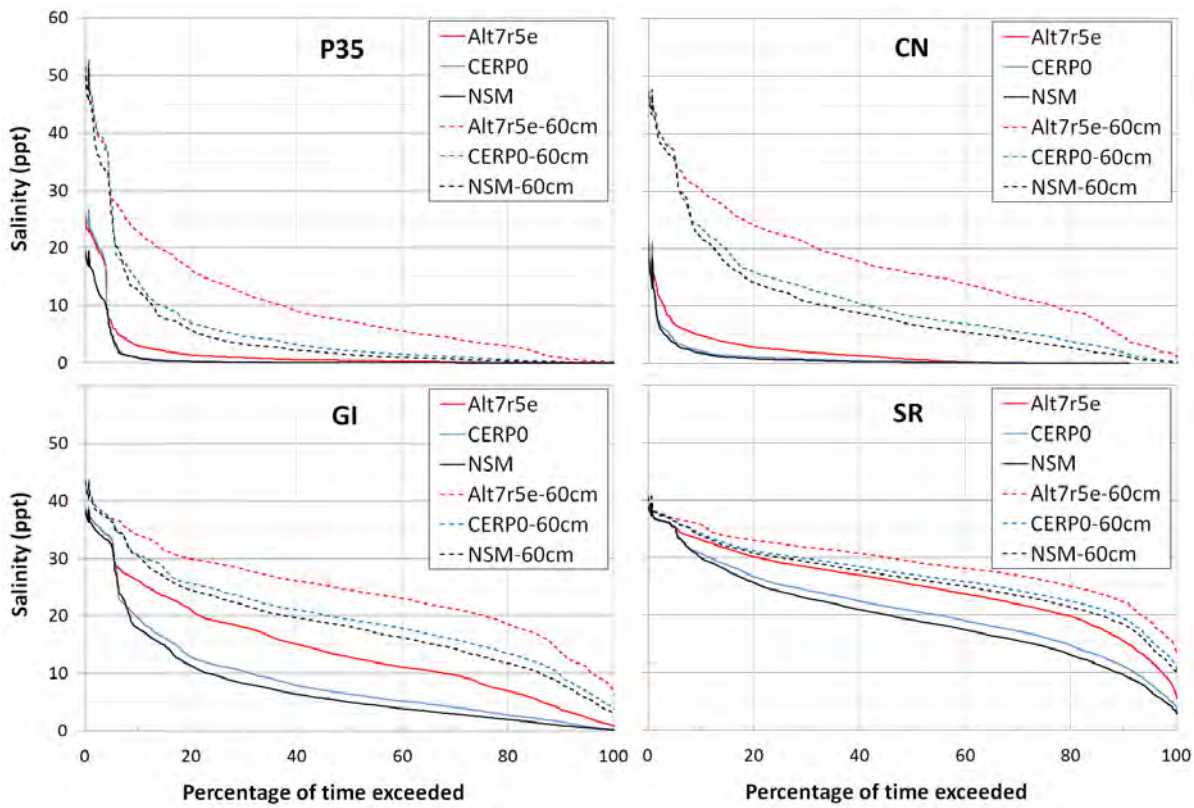


Figure 115. Salinity exceedance curves for Shark Slough stations

values to account for the change to more marine conditions. This allows for fairly accurate simulation of stage increases but limits the ability to predict salinity changes in the mangrove and coastal ecotones due to sea level rise. A static and dynamic study of sea level rise in the model domain indicates that the combination of tidal range and land surface elevation will determine the extent of inundation in many areas, but if dynamic prediction of stages in the sloughs is necessary, a dynamic model run is needed. The extraction of depth and hydroperiod output from TIME is complicated by the model's calculation technique for determining when a cell goes dry, and therefore station-specific results must be examined on a site-by-site basis for validity.

Effects of prescribed boundaries on model output

Sensitivity of modeled salinity values to prescribed boundary conditions indicate that results are affected in almost all areas of the domain that are not completely dominated by freshwater. The sensitivity analysis indicates that the riverine and mangrove ecotone solutions for alternatives and scenarios are very sensitive to the prescribed boundary conditions. Thus, salinity changes due to implementation of different water management alternatives combined with sea level rise could not be adequately investigated. Although degrees of influence were calculated in the sensitivity study, a more thorough approach would be to run simulations with different inputs to determine at what distance from the coast the boundary conditions have no effect.

A sensitivity analysis of the 10-year average surface water salinity values to two static salinity boundary conditions was performed on the Alt7r5e alternative at 0 cm, 30 cm, and 60 cm sea level rise. At current sea level, cells upstream of and including BICYA11, BICYA10, P34, P35, NP62, and NP67 had less than 0.1 ppt change in average annual salinity for each 1 ppt change in boundary conditions. At 30 cm sea level rise the cells upstream of and including BICYA11, BICYA10, P36, NP62, NP44, and R3110 had less than 0.1 ppt change in average annual salinity for each 1 ppt change in boundary conditions. At 60 cm sea level rise the cells upstream of and including BICYA9, NP205, P36, NP44, and R3110 had less than 0.1 ppt change in average annual salinity for each 1 ppt change in boundary conditions. Cells downstream of these had more than 0.1 ppt change in average annual salinity, increasing in magnitude the closer to the boundary they are. The analysis indicates that when using the model to evaluate alternatives where boundary conditions are speculative, assumptions used to generate boundary timeseries and their influence on the results must be taken into account before arriving at conclusions.

Upstream water management effects

The analysis indicates that increased freshwater flows and higher stages in a restored system have a larger effect in upstream areas, but a relatively small effect on the stages in the mangrove ecotone along the West Coast. Hydroperiods can be increased by more than one month due to the additional flows discharging to Taylor Slough under the CERP0 alternative. Salinity values in the upper mangrove ecotone are influenced the most by changes in water management. The effects of the larger flows under CERP0 can also be seen in the increased flow volume discharging through the rivers, and ranges from 7 to 35% higher than the Alt7r5e volumes. The model output predicts a decrease of 2–3 ppt under CERP0 compared to Alt7r5e in the upper estuaries adjacent to the west coast rivers. Predictions of salinity shifts in Florida Bay are difficult to evaluate, due to the proximity of the prescribed boundaries, but relative shifts in the embayments were predicted to decrease 0.2 to 1.6 ppt under CERP0 compared to Alt7r5e.

Upstream water management alternative effects with sea level rise scenarios

CERP0 water levels are higher than Alt7r5e at current sea level, and changes in hydroperiods due to sea level rise effects were not as substantial under CERP0 as they were under current operations for the stations that show a response in groundwater stages to water management decisions. The increased flows and stages in ENP due to CERP0 bring water levels up closer to where they will be with sea level rise and no change in water management, and the increased flow also results in fresher water at many of the stations. The increased flow under CERP0 may help temper the inevitable increase in salinity due to sea level rise, providing a potentially broader front in the transitional ecotone.

5 RECOMMENDATIONS

The dynamic modeling of the estuaries and adjacent mangrove ecotone is important to be able to assess the effects on species and community composition as a result of modifications to upstream water management and higher downstream tidal ranges. The reduction of historical freshwater flows has increased near-shore salinity and resulted in a decline in coastal productivity. As stabilization and restoration efforts modify the timing and distribution of inflows to ENP, the effects of these alterations need to be fully understood. An important tool in the evaluation of operational and structural alternatives is numerical hydrologic modeling programs.

Hydrologic models are a simplification of the actual physical processes and their interactions, the accuracy of the calibration determines how useful the model is for simulating alternatives. Many of the targets and performance measures are based on the needs of the ecological community, thus the level of accuracy needed in the model-computed flows, stages, and salinity values should be within the range of variability acceptable to ecological analysis and models. TIME was specifically developed to address these needs in the coastal ecotone.

The evaluation of TIME v2.0 revealed several issues with the calibration. The following sections summarize the issues discovered during this effort.

5.1 Groundwater component

The bottom of the first aquifer layer in the model is fixed at -7.5 m NAVD 88. The first subsurface layer in the TIME model therefore averages about 20 ft thick in the mangrove areas. In the field, these peat layers are as much as 12 ft thick. As a result, the model does not allow for finer scale vertical resolution of the near-surface fresh/saltwater interface in the mangrove ecotone.

Model results at many stations do not reflect the high levels of connection between the surface water and groundwater systems present in measured data. Infiltration from surface water to the groundwater is very rapid in south Florida's limestone aquifer. Large separations between surface water and groundwater stage for extended periods of time have not been observed. Model results show many stations with persistent differences between surface water and groundwater stage. This could be a local natural phenomenon but at most of the locations the difference is much larger than what is thought to occur naturally in the area.

Areas with smaller differences between model-computed surface water stages and model-computed groundwater stages include the BICY stations in the Western Marl Prairie, and near the boundaries in northern Shark Slough, the northern Rocky Glades, the western-central Taylor Slough basin, and Cape Sable. Average surface water and groundwater stages for these areas were within 2 cm of each other when surface water was present.

In the mangrove-dominated areas, including the entire West Coast Ecotone, NP205 and P34 in the Western Marl Prairie, Whitewater Bay Basin (except Cape Sable), southern Shark Slough, southern Rocky Glades, and the C-111 and Florida Bay areas of the Taylor Slough Basin, the 4-year average surface water and groundwater stages, as computed by the model, differed by 3 to 34 cm when surface water was present.

In the Everglades, local rainfall temporarily increases surface water stages until infiltration fills the upper aquifer layer. Often the model-computed conditions in which the rainfall excess does not soak in for many days, even though the groundwater stage is more than 1 ft below ground. An example of this behavior can be seen in the figure of NP205 surface water and groundwater stage in the month of May 1999 (Fig. 116).

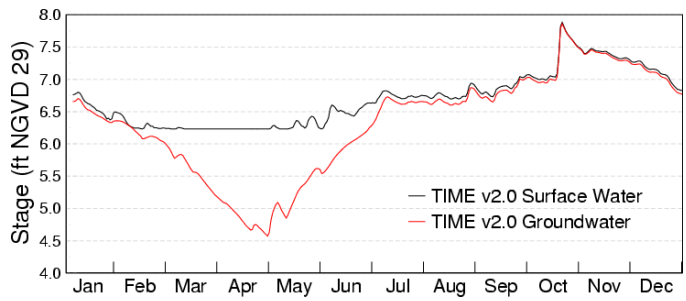


Figure 116. TIME v2.0 calibration run NP205 surface water stage (red) and groundwater head (black) in feet NGVD 29 for 1999. Land surface elevation is around 6.25 ft, shown in the graphic as the minimum surface water stage. In the month of May, several rainfall events occurred causing water levels to rise above the surface. These increases in water level, which infiltrate into the ground fairly quickly in the field, persist in the model much longer. Another issue illustrated by this dataset can be seen: In the beginning of June the model shows surface water at the site, but the groundwater level does not rise above the land surface elevation until the beginning of July.

The TIME model also exhibits a very slow response of the groundwater ascension rate going into the wet season; surface water in the spring of 1999 is endemic, but groundwater lags behind for several weeks. In this case the hydroperiods will be about a month longer in the surface water calculation compared to the groundwater calculation.

5.2 Implementation of rivers and Buttonwood Embankment

The rivers are an important component of the mangrove ecotone. TIME does not have a separate river package so defines flow paths through cell elevation and frictional resistance values. Flow rates are calculated by integrating exchange between cells. Fresh water flow volumes are important to maintain desired salinity ranges in the upper estuaries of Florida Bay. Devising proper algorithms to take care of the wetting/drying issues on the Buttonwood embankment and simulating accurate flow through the cuts needs to be resolved.

In simulations, the roughness coefficient is used to slow down or speed up the overland flow, and the values will generally reflect a particular surface condition (soil or vegetation). During calibration, adjustments are often made to achieve a match with known conditions, such as flow or stage measurements, while retaining a strong relationship to the landscape. Several of the adjustments in the TIME model are very location-specific, where there is a desire to exactly reproduce the particular flow or stage measurements of a monitoring station. Plots of the Manning's coefficient show this at Taylor Slough, the lower C-111 basin, and most of the rivers. Although the calibration plots and statistics might show that a match was achieved at the specific location, accuracy of flow or stage values in neighboring cells may have been affected.

5.3 Placement of model monitoring stations

The minimum surface water depth at which a cell goes dry is different for each cell in the model, which has to do with the way dryness is calculated: The four corners of each cell have different elevations. The average of the four elevations is used to determine the depth of water in the cell, but the highest elevation is used to determine when the cell dries. This formulation was an acceptable method when using the code for areas with very

subtle topography changes, SWIFT2D's original purpose. In the application to the mangrove ecotone, however, coastal and riverbank cells often have large corner-elevation variations, and substantial water depth can remain in the cell when effectively dry.

5.4 Marine boundary

TIME model predictions are influenced by prescribed boundary conditions along the south and west edges of the domain. Because the focus of the TIME model is the coastal mangrove region of the Everglades, this area needs to be free of influence by the outflow boundary conditions in order to produce valid output.

If TIME can successfully be coupled with a working Florida Bay and West Coast model (perhaps EFDC), the computed results near the boundaries may improve, especially with different alternative and scenario runs. If TIME boundaries are expanded farther into the marine environment, the salinity values for initial and boundary conditions could be set to Gulf defaults, also improving the near-shore solution.

5.5 Initial conditions

Initial salinity conditions can be seen in the figure for salinity at station WE (Fig. 117). The initial surface water salinity is set to 32 ppt, but the measured value is closer to 3 ppt. Measured and model-computed surface water salinity values do not converge until well into the 4-year calibration run. The initial groundwater salinity for WE is set close to 30 ppt and shows a decreasing trend throughout the model run.

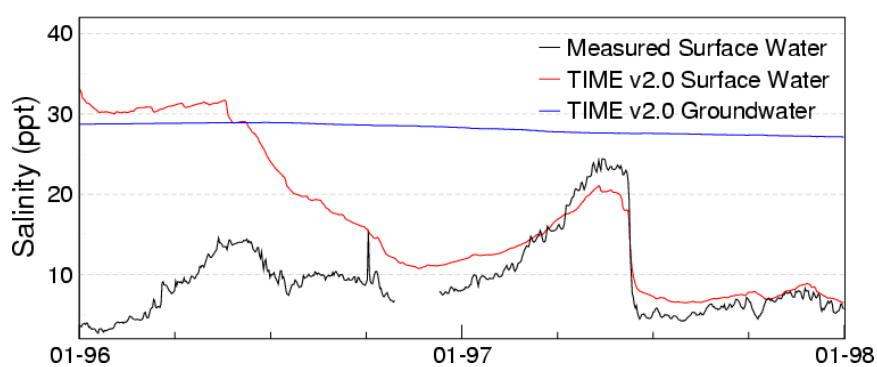


Figure 117. Station WE measured salinity and TIME v2.0 calibration run surface water and groundwater salinity, 1996–98. Model-computed groundwater salinity values do not reach an equilibrium point during the first 2 years of the simulation, and do not show a seasonal signal. Model-computed surface water salinity values take more than a year to approach measured values, partially due to the initial salinity values chosen for this area.

It is not clear if groundwater salinity at several stations reaches an appropriate solution at any time during the calibration run for this and several other stations. Many of the model-computed groundwater salinity values at stations in the mangrove zone showed an increasing or decreasing trend for the entire 4-year simulation, with little or no inter-annual variation. Part of this lack of response could be due to the thickness of the first layer.

5.6 Model stability

Model stability problems are typically associated with faulty boundary conditions or algorithm problems, and should not manifest in model runs when the model is within its intended range of simulations or applications. For the simulations presented in this report, instability problems occurred only at the SnakeBight station in the CERP0 alternative. Figure 118 illustrates a spike in groundwater stage from 0.5 ft to 3.8 ft NGVD 29 during the course of 1.5 months in the CERP0 alternative run; such spikes did not occur in the other alternative runs (NSM and Alt7r5e). The prescribed inputs for the three alternatives differ only in the flow and stage timeseries along the northern and eastern boundaries of the domain.

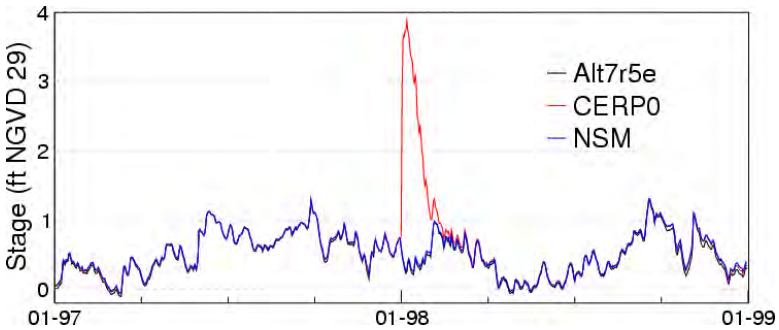


Figure 118. TIME v2.0 groundwater stage at SnakeBight station for NSM, Alt7r5e, and CERP0 alternatives showing instability on 1/1/1998 in CERP0 run. The southern boundary conditions are the same for all of the runs, only the flows and stages at the northern and eastern boundaries are changed among alternatives.

5.7 Documentation

There is no comprehensive documentation of the TIME model and its input and output files. Documentation exists for many of its component models, but not all parts of the component models are active in TIME. It is helpful that all of the input files (except for the hot-restart file) have been changed to ascii format, allowing the user easy access to the input data. We recommend a full set of version-specific documentation be created for this model. Documentation is especially needed of the connection between the surface water and groundwater models, including the thin layer. We also recommend that a complete set of compiler options be documented and supplied with the model code.

LITERATURE CITED

Anderson G.H., K.E. Bahm, R.J. Fennema, E.D. Swain, K.M. Balentine, and T.J. Smith III. 2010. A paired surface-water/groundwater monitoring network in the western coastal mangrove Everglades provides water level and salinity data for analysis and model validation [abstract]. In: GEER 2010, Greater Everglades Ecosystem Restoration, The Everglades: A Living Laboratory of Change, Planning, Policy and Science, Naples, FL, July 12–16, 2010, University of Florida and U.S. Geological Survey, p. 7. [URL: http://www.conference.ifas.ufl.edu/GEER2010/pdf/Abstract%20BOOK.pdf]

Baratta A.M. 1991. The effects of wind, rain and water releases on the water depth and conductivity of Florida Bay. Master's thesis, Department of Civil and Environmental Engineering, Florida International University, Miami, Florida.

Bindoff N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Qur, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan. 2007. Observations: Oceanic climate change and sea level. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Cline J.C., J.J. Lorenz, and E.D. Swain. 2004. Linking hydrologic modeling and ecologic modeling: An application of adaptive ecosystem management in the Everglades mangrove zone of Florida Bay. In: C. Pahl-Wostl, S. Schmidt, A.E. Rizzoli, and A.J. Jakeman (eds.). International Environmental Modelling and Software Society (iEMSs) 2004 International Conference, June 14–17, 2004, University of Osnabrck, Germany. Transactions of the 2nd Biennial Meeting of the iEMSs. [URL: http://www.iemss.org/iemss2004/pdf/biocomplexity/clinlink.pdf].

Compaq Computer Corporation. 1999. Compaq Fortran language reference manual: AA–Q66SD–TK. Houston TX.

Cosby B.J., F.E. Marshall, and W.K. Nuttle. 2010. FATHOM (version 6.10) model structure and salinity simulation. Report to Everglades National Park from University of Virginia, Cetacean Logic Foundation, Inc., and Eco-Hydrology. CESI Cooperative Agreement Number H5284–07–0076, http://www.cetaceanlogic.org/publications.

Ellison J.C., and D.R. Stoddart. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. Journal of Coastal Research 7:151–165.

Gleason P.J. 2009. Sea level rise (SLR) projection. Presentation by the Science and Technical Subcommittee, Broward County, Florida, May 21, 2009. Accessed February 23, 2012, at http://www.broward.org/NaturalResources/ClimateChange/Documents/052109_sealevelsprojection_cctf_pjg_rev2.pdf

Guo W., and C.M. Langevin. 2002. User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow. U.S. Geological Survey Open-File Report 01–434, 77 p.

Hamrick J.M. 2006. The Environmental Fluid Dynamics Code theory and computation; Volume 3; Water Quality Module. Prepared for the U.S. Environmental Protection Agency, Office of Research and Development, by Tetra Tech, Inc., Fairfax, Virginia.

Hamrick J.M., and M.Z. Moustafa. 2003. Florida Bay hydrodynamic and salinity model analysis. Abstract, Joint Conference on the Science and Restoration of the Greater Everglades and Florida Bay Ecosystem "From Kissimmee to the Keys," April 13–18, Palm Harbor, Florida. [URL: http://conference.ifas.ufl.edu/jc/fb.pdf, p. 22].

Hittle C., E. Patino, and M. Zuker. 2001. Freshwater flow from estuarine creeks into northeastern Florida Bay. U.S. Geological Survey Water-Resources Investigations Report 01–4164, 32 p.

Langevin C.D., E.D. Swain, and M.A. Wolfert. 2004. Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. U.S. Geological Survey Open-File Report 2004–1097, 30 p.

Leendertse J.J. 1987. Aspects of SIMSYS2D, a system for two-dimensional flow computation. Rand Corporation Report R–3572–USGS, Santa Monica, California, 80 p.

Levesque V.A. 2004. Water flow and nutrient flux from five estuarine rivers along the southwest coast of the Everglades National Park, Florida, 1997–2001. U.S. Geological Survey Scientific Investigations Report 2004–5142, 92 p.

Maul G.A., and D.M. Martin. 1993. Sea level rise at Key West, Florida, 1846–1992: America's longest instrument record? Geophysical Research Letters 20:1955–1958.

McDonald, M.G. and A.W. Harbaugh. 1988. Chapter A1: A modular three-dimensional finite-difference ground-water flow model, Book 6, Modeling Techniques. U.S. Geological Survey Techniques of Water-Resources Investigations Report, TWRI6–A1, Washington. [URL: http://pubs.water.usgs.gov/twri6a1]

Miami-Dade Climate Change Task Force. 2008. Statement on sea level in the coming century. Technical report, Science and Technology Committee, Miami-Dade County, 9 p.

NOAA. 2010. Historical tide data for Key West. Graphic published online, accessed website and graphic October 2010. [URL: http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8724580%20Key%20West,%20FL&type=Historic+Tide+Data].

Office of National Marine Sanctuaries. 2011. Florida Keys National Marine Sanctuary condition report 2011. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 105 pp.

Schaffranek R.W. 2004. Simulation of surface-water integrated flow and transport in two dimensions: SWIFT2D users manual: U.S. Geological Survey Techniques and Methods, book 6, chap. 1, section B, 115 p.

Schaffranek R.W., H.L. Jenter, C.D. Langevin, and E.D. Swain. 2001. The tides and inflows in the mangroves of the Everglades Project. U.S. Geological Survey and University of Miami proposal abstract, accessed February 23, 2012, at http://sofia.usgs.gov/projects/time/timeabfb2001.html.

Swain E.D., M. Lohmann, D. Garces, and M.A. Stewart. 1996. Southern Inland and Coastal Systems (SICS) model development. U.S. Geological Survey project webpage, accessed February 23, 2012, at http://sofia.usgs.gov/projects/index.php?project_url=sheet_flow.

Swain E.D., M.A. Wolfert, J.D. Bales, and C.R. Goodwin. 2004. Two-dimensional hydrodynamic simulation of surface-water flow and transport to Florida Bay through the Southern Inland and Coastal Systems (SICS). U.S. Geological Survey Water Resources Investigations Report 03–4287, 56 p.

U.S. Army Corps of Engineers. 2002. Final environmental impact statement, Interim Operational Plan (IOP) for Protection of the Cape Sable Seaside Sparrow, Miami-Dade County, Florida. [URL: http://hpm.saj.usace.army.mil/issueweb/Sparrow/fiopeis.htm].

Wang J.D., E.D. Swain, M.A. Wolfert, and C.D. Langevin. 2005. Hydrodynamic modeling FBFKFS, SICS and TIME model boundary inputs to Florida Bay hydrodynamic model. Progress Report 4, Final TIME Calibration Status Report, U.S. Geological Survey and University of Miami.

Wang J.D., E.D. Swain, M.A. Wolfert, C.D. Langevin, D.E. James, and P.A. Telis. 2007. Application of Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) to simulate flow, salinity, and surface-water stage in the Southern Everglades, Florida. U.S. Geological Survey Scientific Investigations Report 2007–5010, 114 p.

Wanless H.R., and B.M. Vlaswinkel. 2005. Coastal landscape and channel evolution affecting critical habitats at Cape Sable, Everglades National Park, Florida. Final report to Everglades National Park from University of Miami, accessed March 21, 2012, at http://www.nps.gov/ever/naturescience/cesires02-1.htm.

WikipediA. 2010. Recent Sea Level Rise. Graphic uploaded to WikipediA. Accessed October 2010, unreferenced, Wikimedia Foundation Inc. [URL: http://en.wikipedia.org/wiki/Current_sea_level_rise].

Wolfert M.A., C.D. Langevin, and E.D. Swain. 2004. Assigning boundary conditions to the Southern Inland and Coastal Systems (SICS) model using results from the South Florida Water Management Model (SFWMM). U.S. Geological Survey Open-File Report 2004–1195, 30 p.

Wolfert, M.A., E.D. Swain, and J.D. Wang. 2006. Utilizing the TIME model to simulate Comprehensive Everglades Restoration Plan (CERP) scenarios for Florida Bay and Florida Keys Feasibility Study (FBFKFS), p. 249. Technical report, Greater Everglades Ecosystem Restoration Conference, June 5–9, 2006, Lake Buena Vista, Florida.