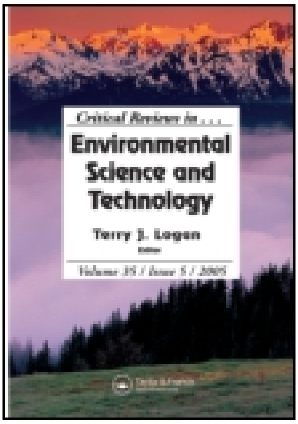

Critical Reviews in Environmental Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/best20

Use of Hydrologic and Hydrodynamic Modeling for Ecosystem Restoration

Jayantha Obeysekera [a] , Laura Kuebler [a] , Shabbir Ahmed [b] , Miao-LI Chang [a] , Vic Engel [c] , Christian Langevin [d] , Eric Swain [d] & Yongshan Wan [a]

[a] South Florida Water Management District, West Palm Beach, FL, USA
[b] U.S. Army Corps of Engineers, Jacksonville, FL, USA
[c] Everglades National Park, Homestead, FL, USA
[d] U.S. Geological Survey, Reston, VA, USA
[e] U.S. Geological Survey, Fort Lauderdale, FL, USA

Available online: 19 Feb 2011

To cite this article: Jayantha Obeysekera, Laura Kuebler, Shabbir Ahmed, Miao-LI Chang, Vic Engel, Christian Langevin, Eric Swain & Yongshan Wan (2011): Use of Hydrologic and Hydrodynamic Modeling for Ecosystem Restoration, Critical Reviews in Environmental Science and Technology, 41:S1, 447-488

To link to this article: http://dx.doi.org/10.1080/10643389.2010.531226

Critical Reviews in Environmental Science and Technology, 41(S1):447–488, 2011

ISSN: 1064-3389 print / 1547-6537 online
DOI: 10.1080/10643389.2010.531226

Use of Hydrologic and Hydrodynamic Modeling for Ecosystem Restoration

JAYANTHA OBEYSEKERA,[1] LAURA KUEBLER,[1] SHABBIR AHMED,[2] MIAO-LI CHANG,[1] VIC ENGEL,[3] CHRISTIAN LANGEVIN,[4] ERIC SWAIN,[4] and YONGSHAN WAN[1]

[1]*South Florida Water Management District, West Palm Beach, FL, USA*
[2]*U.S. Army Corps of Engineers, Jacksonville, FL, USA*
[3]*Everglades National Park, Homestead, FL, USA*
[4]*U.S. Geological Survey, Reston, VA, USA*
[5]*U.S. Geological Survey, Fort Lauderdale, FL, USA*

Planning and implementation of unprecedented projects for restoring the greater Everglades ecosystem are underway and the hydrologic and hydrodynamic modeling of restoration alternatives has become essential for success of restoration efforts. In view of the complex nature of the South Florida water resources system, regional-scale (system-wide) hydrologic models have been developed and used extensively for the development of the Comprehensive Everglades Restoration Plan. In addition, numerous subregional-scale hydrologic and hydrodynamic models have been developed and are being used for evaluating project-scale water management plans associated with urban, agricultural, and inland costal ecosystems. The authors provide a comprehensive summary of models of all scales, as well as the next generation models under development to meet the future needs of ecosystem restoration efforts in South Florida. The multiagency efforts to develop and apply models have allowed the agencies to understand the complex hydrologic interactions, quantify appropriate performance measures, and use new technologies in simulation algorithms, software development, and GIS/database techniques to meet the future modeling needs of the ecosystem restoration programs.

Address correspondence to Jayantha Obeysekera, South Florida Water Management District, 3301 Gun Club Road, MSC 750, West Palm Beach, FL 33406, USA. E-mail: jobey@sfwmd.gov

KEYWORDS: hydrology, hydrodynamic, modeling, Everglades, restoration

I INTRODUCTION

The natural hydrology of southern Florida has been greatly altered through drainage, construction, urbanization, and agriculture to an extent that the Everglades is now one of the most threatened ecosystems in the nation. Today, the water management system in South Florida encompasses 18,000 square miles and consists of over 1,800 miles of levees and canals, about 200 major water control structures, and nearly 30 major pump stations. The present system can no longer effectively provide for environmental and water supply needs of the present population; therefore, it requires modification to restore the remnant Everglades (Figure 1) and meet the needs of the predicted increase of population from about 6 million to 12–15 million by 2050. The planning and implementation of unprecedented projects for restoring the Kissimmee-Lake Okeechobee-Everglades system are underway. Hydrologic modeling for analyzing alternatives and providing design information for restoration projects has become essential for the success of ecological restoration efforts while meeting the water needs of the urban population and agricultural regions.

The unique hydrology of South Florida, with its flat topography, high water tables, sandy soils, high transmissivity of the surficial aquifers, and complex coastal systems makes the southern Florida water management system one of the most complex in the world. Simulation models have become the only feasible means to estimate regional, subregional, and local impacts of proposed water management plans in South Florida. Since the 1970s, several federal and state agencies have been involved in the code development, implementation, and application of hydrologic simulation models. The primary agencies include the South Florida Water Management District (SFWMD), the U.S. Army Corps of Engineers (USACE), the National Park Service (NPS), and the U.S. Geological Survey (USGS). Most hydrologic simulation models developed elsewhere in the country or the world are not directly applicable to the unique hydrologic conditions of South Florida. New simulation models at various spatial and temporal scales have been developed to simulate hydrologic processes on land and in wetlands, canals, and receiving water bodies such as estuaries and bays in South Florida.

Regional-scale (system-wide) hydrologic modeling using the SFWMD's South Florida Water Management Model (SFWMM) has provided information for decision making for over three decades. This modeling tool includes the important components of the terrestrial phase of the hydrologic cycle, as well as the system operating procedures. This tool has been used extensively

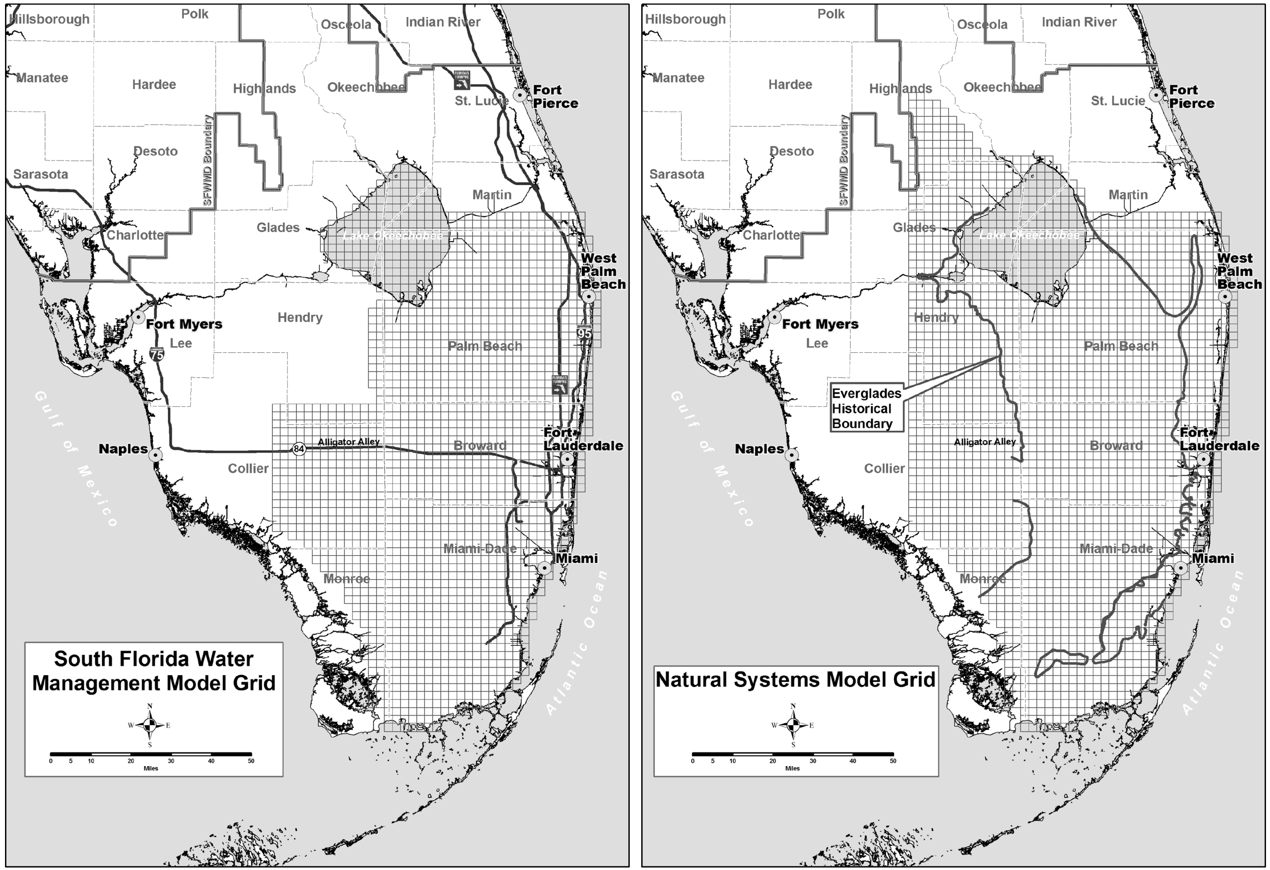

FIGURE 1. South Florida locations and the boundaries and the gridded portions of (a) the South Florida Water Management Model (SFWMM) and (b) the Natural System Model (NSM).

for the development and system-wide evaluation of the Comprehensive Everglades Restoration Plan (CERP). Numerous subregional-scale hydrologic and hydrodynamic models have been developed for evaluating water management plans associated with urban, agricultural, and inland and coastal ecosystems. These include but are not limited to groundwater models based on an enhanced version of MODFLOW, watershed and estuarine models that integrate surface and groundwater discharges into coastal estuaries and bays, and numerous hydrologic simulation models to evaluate the performance of restoration projects. Project-scale models have been used to provide critical information for both planning and design by simulating the project features at a high resolution and allowing the inclusion of local processes important for such applications. Due to the complex interactions of both groundwater and surface water systems, models of all scales are inherently complex, both in input as well as in internal structure.

Efforts are underway to develop the next generation hydrologic modeling tools necessary for evaluation of unprecedented infrastructure and operational alternatives being considered for the restoration program. Synthesis of all modeling efforts to date is beyond the scope of this paper. The following is a brief summary of key regional-scale modeling tools, subregional models and their applications, and hydrologic and hydrodynamic models used for evaluating impacts on coastal systems, as well as the next generation tools under development for meeting future needs of restoration programs. We conclude with key findings to date as well as future challenges in meeting modeling needs of Everglades restoration and water management.

II SYSTEM-WIDE HYDROLOGIC MODELING

The water resources system in South Florida is extremely complex. Future improvements to the system are expected to increase the complexity by making unprecedented changes. The interaction between the system components, both spatially and temporally, requires comprehensive system-scale models which incorporate the effects of operations in one part of the system on other components elsewhere. Regional-scale or system-wide models are the only way to incorporate such complex iterations.

Two primary, system-wide hydrologic simulation models have been used to analyze Everglades restoration alternatives, the South Florida Water Management Model (SFWMM) and the Natural Systems Model (NSM), both of which have 2 × 2 mile model grids. The SFWMM is a regional-scale hydrologic model (Figure 1) that simulates physical processes (coupled surface water and groundwater) in the natural or altered and engineered systems (canals, structures, and reservoirs) in South Florida (South Florida Water Management District [SFWMD], 2005a). This model, originally developed in the late 1970s and early 1980s, has evolved significantly to include simulation capabilities that have allowed evaluation of complex restoration and other water management alternatives. Major components of the hydrologic cycle simulated in SFWMM include rainfall, evapotranspiration, overland flow, groundwater flow, canal flow, and seepage beneath levees. Additionally, the model simulates operations of the Central and South Florida Project as well as the major water wellfields in the urbanized east coast, impoundments such as reservoirs and Stormwater Treatment Areas (STAs), canals, pump stations, and other water control structures. The ability to simulate key water shortage policies affecting urban, agricultural, and environmental water supplies allows the investigation of trade-offs among conflicting uses (Tarboton et al., 2001). The model uses a daily time step although internally smaller times steps are used for such transient processes as overland flow, and it can be run for a period of simulation as long as 41 years. Details of the model can be found in SFWMD (2005a).

SFWMM continues to be the primary system-wide hydrologic modeling tool used for evaluating system changes to meet evolving water management challenges. It has also been used for operational planning, not only for the development of operating rules for Lake Okeechobee but also as a tool for making operating decisions for providing water supply and maintaining flood control. The operating rules now include climate outlook at seasonal and multiseasonal scales. In 2005, the model was peer reviewed by a national panel of experts (SFWMD, 2005b), and they concluded that the SFWMM was an appropriate tool for planning and operation of the South Florida system and that the model was robust and performed satisfactorily.

Another regional-scale hydrologic model is used to set water depth restoration targets for the remnant Everglades is the NSM (Figure 1). This model simulates what is believed to be the hydrologic response of a predrainage Everglades system using the same rainfall, potential evapotranspiration, and tidal boundaries of the SFWMM. The use of both models together provides meaningful comparisons between the managed system of the SFWMM with the conditions of the original undeveloped system of the NSM. Although the NSM cannot be calibrated in the same way as the present managed system model, it has served as a valuable tool for determining the hydropatterns that resembled the predrainage Everglades system.

Experience in Applications

In the design and analysis of water resources plans and projects for CERP, computer models are used to analyze existing and simulate possible future conditions. Planners and scientists then analyze these conditions to determine planning options that are likely to offer the greatest benefits or least impacts. These models provide important information for planning by providing input to decision-making by experienced engineers, planners and managers (Loucks, 1992). Moreover, models are one of a number of tools used to design project components.

More specifically, a particular modeling scenario is assumed to be static with respect to the facility plans, operating criteria, land use and land cover conditions, and the water demands. One scenario represents baseline and alternatives represent possible system configurations and operations. These scenarios then are subject to a variety of hydrologic conditions extracted from a recent historical period of record, often 1965–2000. The SFWMM is used to evaluate the performance of the plan with respect to varying hydrologic conditions, while the NSM is often used to represent the original conditions.

Analysis of project alternatives often relies on performance measures that represent project objectives in the form of quantitative criteria. Models allow quantification of hydrologic conditions (i.e., water levels and flows) that can be presented as performance measures and provided, along with other critical information such as costs and physical constraints, to decision makers.

The SFWMM was the primary planning tool used for developing the 1999 Central and South Florida Comprehensive Review Study (U.S. Army Corps of Engineers, 1999). After initial screening, formulation of baseline conditions, and definition of performance measures, each of the simulated alternative plans went through a process of alternative formulation and design, regional-scale modeling, publication on the Internet, and evaluation before the next alternative was formulated (Tarboton et al., 2001). This iterative process helped build consensus among stakeholders and develop a plan that included lessons learned from previous iterations and incremental improvements.

Operational Planning Applications

Seasonal and multiseasonal operational planning of major water resources systems requires a careful evaluation of likely future scenarios of water and environmental conditions that influence management objectives. It is common practice to use computer simulation models to determine likely outcomes of short- and long-term management options. The SFWMD uses position analysis as a form of risk analysis that can forecast uncertainties associated with a specific operating plan for a basin over a period of many months conditioned on the present state (e.g., reservoir storages) of the system (Cadavid et al., 1999; Hirsch, 1978; Smith et al., 1992; Tasker and Dunne, 1997). The SFWMD relies on generating a large number of possible time series (season or multiple seasons in length) of the hydrologic variable of interest (e.g., stages or flows) using the same initial conditions and broad ranges of meteorological conditions that may occur in the future but cannot be forecast accurately. Probable future meteorological conditions may be derived using such methods as (a) extended streamflow prediction (Day, 1985), (b) historical data, and (c) stochastic simulation models (Tasker and Dunne, 1997).

During the past decade, position analysis concepts developed by the SFWMD have been used with increasing effectiveness to assess risks associated with seasonal and multiseasonal operations of the water management system and to communicate the projected outlook to decision makers, agency partners, stakeholders, and the public. While SFWMD has used position analysis chiefly to project the expected stage of Lake Okeechobee, it has also used the technique for other impoundments, including the Water Conservation Areas (WCAs; see Figure 1). Monthly position analysis has become an important tool for making operational decisions that may have implications for multiple seasons.

III SUBREGIONAL MODELING

In this paper, a subregional model is defined as a numerical model with a higher spatial resolution than that of the 2 × 2 mile SFWMM and usually represents a subarea of a regional model. Two examples of subregional models are the Everglades Agricultural Area (EAA) MODFLOW Model with a cell resolution of 500 × 500 ft and the Lower East Coast Subregional (LECsR) Model, which has a cell resolution of 704 × 704 ft.

Many subregional groundwater models have utilized the modular finite-difference groundwater flow model, MODFLOW (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988) and more recently the three-dimensional, variable-density, saturated groundwater flow model, SEAWAT (Langevin et al., 2007). Two groundwater models, EAA MODFLOW Model and LECsR Model are based on different versions of MODFLOW. These models and their applications to CERP are discussed herein.

Everglades Agricultural Area (EAA) MODFLOW Model

One of the storage projects under CERP is the EAA reservoir. The objectives of the project are to capture, move, and store regulatory releases from Lake Okeechobee. This reservoir is the largest of all the reservoirs proposed in CERP. Under this project, a storage area approximately 30,000 acres in size with a 12.5 ft pool has been planned in two phases. The design of the EAA reservoir included evaluation of the reservoir footprint, pool depths, levee, seepage canal, and seepage cutoff walls. The storage reservoir project planned for the EAA lies between the Miami Canal and North New River Canal. The project is to be phased with the construction of an east and a west reservoir. The present project features include construction of an earthen-embankment reservoir, seepage collector canal, and seepage cutoff wall along with the associated hydraulic structures and pump stations.

To evaluate the offsite seepage and groundwater impacts of the Phase I reservoir (16,000 acres for a depth of 12.5 ft), a three-dimensional modeling analysis based on the USGS MODFLOW groundwater simulation code (McDonald and Harbaugh, 1988) was conducted. A widely used pre- and postprocessor called the Groundwater Modeling System (GMS; Brigham Young University, 2002) was used as a Graphical User Interface (GUI) for the development of the MODFLOW model. By using the model, several seepage control options, including a seepage canal and barrier wall were investigated. The design of the vertical extent of the barrier wall was based on the comparison of model-simulated heads.

Model Domain and Characteristics

The model domain, consisting of an area of 944 square miles, was discretized horizontally using 500 × 500 ft square cells. In the vertical direction, the model extended 100 ft in the subsurface for a total of 12 layers. For this configuration of the model, a total of 1,257,528 cells were used to represent the groundwater system.

The hydrogeology represented in the model consisted of six main units that consisted of widely different materials in terms of horizontal hydraulic conductivities. The boundary conditions were assigned with some assigned as constant heads while others were assigned as zero flow. The reservoir footprint was assigned a specified head boundary since the proposed operation of the reservoir would keep it filled most of the time. The canals were represented by the river boundary package that can simulate both inflow to the river from the aquifer and outflow from the river to the aquifer.

Model Results and Summary

The initial run was the base model under existing conditions. This base run provides a basis of comparison with other project model runs. The various project alternatives simulations were then compared to the base run to calculate groundwater elevation differences that could indicate offsite flooding impacts.

As part of the comparison efforts, the modeling team established allowable groundwater head differences or impact threshold values on each side of the reservoir. These threshold values were established based on the land use surrounding the EAA. The river cells were assigned for seepage canal around the reservoir. Based on the results for this initial scenario, it appeared that the seepage canals alone would not adequately mitigate offsite flooding impacts so additional seepage control measures were investigated. A number of trial runs were performed with subsurface barrier walls along the sides of the reservoir as a supplemental seepage control feature (in addition to seepage canals). Finally, along three sides, a 34 ft deep barrier wall was included in the model. On two other sides, a 10 ft deep barrier wall was included.

Along the boundary of the reservoir, the groundwater hydraulic head differences were high but were within the threshold values defined based on the land use characteristics. It was found that the selected seepage canal and barrier wall configurations were adequate to control the effects of the reservoir on the ambient groundwater level (i.e., keeping the groundwater differences to within the threshold values).

To investigate the seepage and the water level rise in the ambient groundwater system caused by the reservoirs, various depths of cutoff walls were simulated. Thereafter, the rise in groundwater levels was compared to acceptable threshold values. As an equally important factor, the seepage flow rates between with and without project conditions were investigated.

The combination of seepage canal and barrier was found to be effective in controlling seepage from the reservoir. The seepage flow rates and difference maps ensured the effectiveness of the design characteristics of the EAA reservoir. Together, the GMS and MODFLOW were found to be useful modeling tools for the design of cutoff walls and a seepage canal system.

Lower East Coast Subregional (LECsR) Model Add-On Packages

The SFWMD previously had applied six subregional county-specific groundwater models that were combined into one groundwater model, the Lower East Coast Subregional (LECsR) MODFLOW Model. LECsR uses a modified version of the USGS code, MODFLOW-96 (Harbaugh and McDonald, 1996), to simulate the surficial aquifer system from roughly Martin to Miami-Dade Counties, Florida (Figure 2). Boundary conditions are represented by General Head Boundaries and are specified at regional canals or tidal water bodies. LECsR is a transient model (with a daily time step and stress period), contains three layers and is discretized into 704 × 704 ft cells. The model calibration runs from January 1, 1986, to November 10, 1999; model verification includes the time period after November 10, 1999, to December 31, 2000. LECsR is calibrated (i.e., achieves greater than 75% overall calibration) to over two-hundred stage and flow stations with daily data. Additional MODFLOW packages permit the simulation of integrated surface water and groundwater flow in wetlands, water diversions from pumping stations and gravity structures, redirected drain flows, and water shortage cutbacks.

SFWMD MODFLOW models include add-on packages that allow greater functionality to be introduced into the source code. These add-on packages have been beneficial when evaluating projects for CERP. Table 1 lists select add-on packages used in LECsR.

Wetland Package

This package has been applied extensively in LECsR for CERP projects, such as North Palm Beach County–Part 1. Evaluation of hydropatterns was carried out by relating the Wetland Rapid Procedure Assessment (Miller and

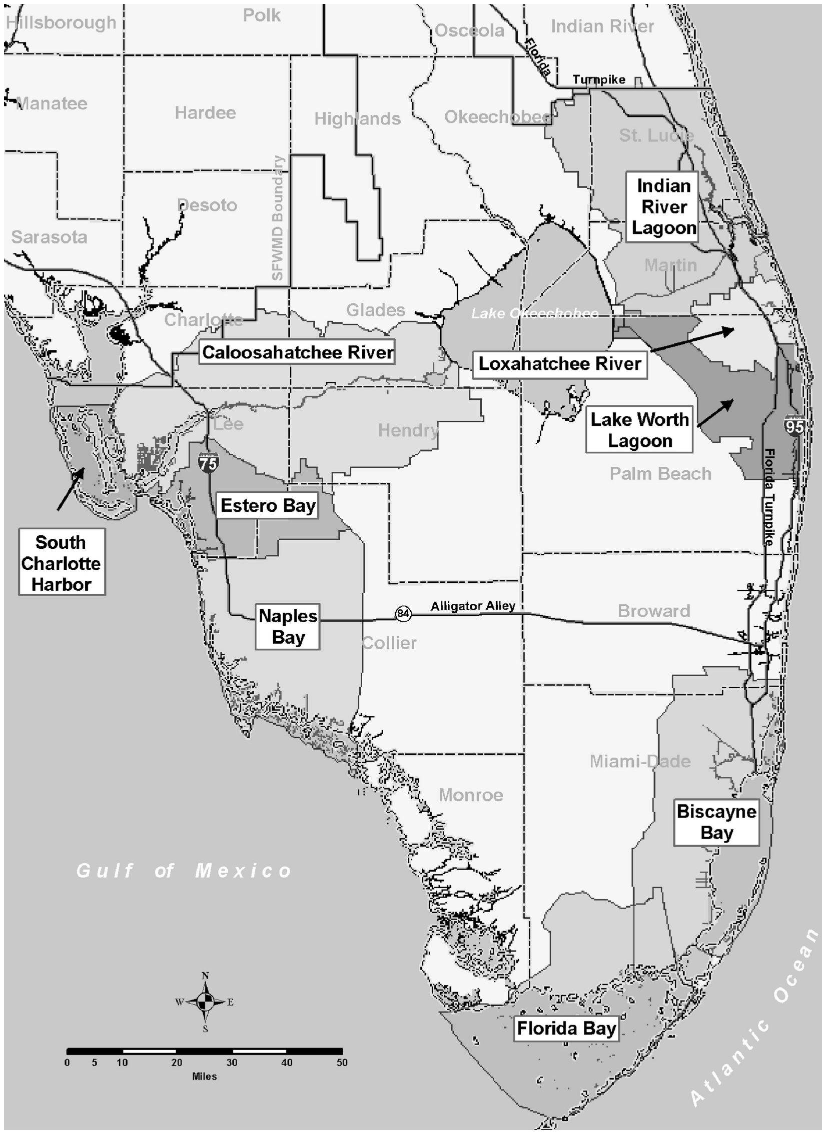

FIGURE 2. South Florida coastal watershed-estuarine systems.

Gunsalus, 1999) to modeled water levels in various wetland systems, such as depressional marsh and mesic flatwoods. When predictions are made the WRAP scores can then be recalculated and applied to the predicted water levels in order to determine a positive or negative impact.

Diversion Package

The Diversion package has been applied to a variety of CERP reservoirs, impoundments and spreader swales. The Diversion package was applied to

TABLE 1. MODFLOW add-on packages used in the LECsR model

Package name	Authors	Description
Wetland (WTL)	Restrepo et al., 1998	Simulates overland flow in wetlands using the uppermost model layer and barriers to flow like levees
Diversion (DIV)	Restrepo et al., 1998	Simulates the effects of water control structures (either pumping stations or gravity flow drains) on water levels
Reinjection Drainflow (RDF)	Jones, 1999	Similar to the Drain package except that it allows water to be redirected to another location in the model instead of being permanently removed from the model
Trigger (TRG)	Randall, 1992	Simulates wellfield withdrawal cutbacks as a function of water level in trigger cells and in Lake Okeechobee; simulates LEC water shortage policy associated with saltwater intrusion
Utility Generation (UGEN)	Restrepo et al., 2003	Creates input files during model execution by linking static (time invariant) data with time series (variant) data

the C-111 Spreader Swale project by using SFWMM regional system inflows to the project's spreader swale. The geometry of the spreader swale was modeled using the Wetland package (e.g., topography, levees). This model showed how the spreader swale impacted water levels in the South Dade Wetlands as well as for adjacent landowners.

Reinjection Drainflow Package

The Reinjection Drainflow (RDF) package can be used, for example, to represent the removal of water from a reservoir and dispersal onto a nearby wetland or injection into an Aquifer Storage and Recovery (ASR) well. This concept was applied in LECsR's predecessors, such as the South Palm Beach Model (Nair et al., 2000) when modeling the Acme Impoundment with ASR. The RDF package allowed the user to specify the ASR source and trigger to redirect that water to another destination while maintaining the mass balance.

Trigger Package

The Trigger (TRG) package (Randall, 1999) was developed to initiate cutbacks in well pumpage in response to head declines in specified trigger cells. Trigger cells are located in areas of concern. If the head (or drawdown) in a trigger cell at the end of a stress period is lower than a standard, which is user-specified, the program looks for each well in the zone and reduces the pumpage for the next stress period by a fraction specified in the input data. TRG package input has been calibrated in both the SFWMM and LECsR to reflect historical water restrictions. This package provides CERP projects the frequency, severity, and duration of water shortages in predictions for base and future with project conditions. LECsR also incorporates cutbacks from the regional system, therefore reflecting both regional and subregional water shortages.

UGEN PACKAGE

The UGEN package can be used to generate these MODFLOW packages: River, Drain, Well, General Head Boundary, Reinjection Drainflow, and Diversion. It can also be used to correct heads due to the presence of the saltwater interface and to calculate the hydraulic conductance for the River, General Head Boundary, and Drain packages.

When activated within MODFLOW, UGEN saves both storage space and execution time. The placement of the static and time series data into separate files also reduces model setup time and aids quality assurance and quality control. CERP model evaluations often require long-term predictions. In the case of LECsR, the model predictions are daily, 36-year runs. By using the UGEN package to separate the time-dependent from the time-independent data much time and storage space is saved.

Experience in Applications

Subregional groundwater models using MODFLOW have the ability to predict and manage groundwater conditions, examine underground barriers, mitigate offsite impacts, and provide boundary conditions to local-scale models. With add-on packages, the capabilities are extended to minimizing water shortage restrictions, maximizing additional storage through ASR systems, reservoirs, and STAs, as well as evaluating wetland hydropattern improvement or impact for ecosystem restoration projects. However, these are not integrated models and have limitations, which include uncoupled unsaturated and saturated zones, limited or no routing capabilities, and no density dependence.

Standardized data help to improve the development and application of subregional groundwater models in the future. A regional, standardized topography is needed for accurate hydropatterns. Evapotranspiration and rainfall data are required at smaller time intervals for better estimation of recharge and runoff. Additionally, more comprehensive water quality (e.g., chlorides, nutrients) data are required to migrate to subregional variable-density models, which could solve the coupled flow and solute-transport equations. It would also be beneficial to couple the unsaturated and saturated zones with a conceptual approach that does not limit model run times.

Overall, the subregional groundwater models continue to contribute to both water supply and restoration efforts when examination of a large area (e.g., from 500 to 10,000 square miles) is required. The models in their simplest form help to understand the system, especially in areas where data are sparse. These models also help identify data gaps that field hydrogeologists investigate and provide data back to the models for recalibration.

These models have been utilized for the preliminary design of projects and to evaluate water supply and restoration components in tandem for longer periods of time (e.g., 36 years). As more capabilities are added to MODFLOW and SEAWAT, these models can be updated to include those capabilities if required.

IV MODELING COASTAL WATERSHEDS

Modeling the coastal watersheds of South Florida poses unique challenges due to the large number of interacting hydrologic processes. In urban areas, freshwater resources are managed using an extensive canal network that provides flood protection during wet periods and prevents saltwater intrusion into shallow coastal aquifers during dry periods. The coastal wetlands are dominated by low hydraulic gradients, winds, tides, and mixing freshwater and seawater. In both the urban and wetland areas, the surface water system is hydraulically connected to the underlying aquifer system. In many instances surface and groundwater interactions comprise a substantial component of the water budget. The aquifers of South Florida also pose many unique modeling challenges. The shallow surficial aquifer system and the deeper Floridan aquifer system consist primarily of very porous carbonate material. Because the surficial aquifer is highly transmissive, and because it is the primary source of potable water in the area, it is easily threatened by saltwater intrusion. Answers to many of the relevant hydrologic questions in South Florida require sophisticated numerical models that can simultaneously handle these complicated and interacting processes.

Numerical Models

The USGS is actively involved in developing hydrologic models of South Florida coastal watersheds. The freshwater and saltwater transition zones in both coastal wetlands and coastal aquifers are two of the areas that have received special attention. Coastal aquifers are under considerable stress. They provide drinking water to the rapidly growing population of South Florida, act as repositories for treated wastewater, and are being considered for regional-scale ASR operations. In each case, models that represent mixing between fresh and saline groundwater are required to identify optimal management strategies. To address these types of groundwater problems, the USGS developed the SEAWAT computer program, which simulates mixing between fresh and saline groundwater and the effects of fluid density on groundwater flow. The program can also be used to assess the fate and transport of contaminants in coastal aquifers and the effects of temperature on groundwater flow. Mixing between fresh and saline surface water is also an important process in coastal wetlands. Many aquatic species are sensitive to salinity fluctuations and can tolerate only specific ranges. To simulate salinity changes in coastal wetlands, the USGS adapted the SWIFT2D computer program, which was originally developed for estuaries, to simulate overland sheet flow through vegetated wetlands. SWIFT2D and SEAWAT were later combined into a single program, called FTLOADDS. As a fully coupled surface and groundwater model, FTLOADDS simulates many of the important hydrologic processes in coastal wetlands such as tides, winds, rainfall, evapotranspiration, exchanges with groundwater, and salinity transport. This section provides a brief description of these computer programs and summarizes some of the findings that resulted from their application to South Florida coastal aquifers and wetlands.

SEAWAT Model

SEAWAT is a coupled version of MODFLOW-2000 and MT3DMS designed to simulate variable density groundwater flow and solute transport (Guo and Langevin, 2002; Langevin and Guo, 2006; Langevin et al., 2003; Langevin et al., 2007). The program is freely available to the public and can be downloaded from the USGS. SEAWAT has become a worldwide industry standard for addressing complex groundwater problems related to saltwater intrusion, ASR, deep injection of wastewater, brine migration, and so forth. In South Florida, the SEAWAT program has been used to address these types of issues for many of the coastal watersheds.

SWIFT2D Model

Surface Water Integrated Flow and Transport in 2 Dimensions (SWIFT2D) is a two-dimensional hydrodynamic flow and transport model previously developed for the simulation of estuaries, tidal embayments, and inland waterways (Schaffranek, 2004). The ability to represent drying and rewetting, flow structures, and the effects of salinity variations on density makes SWIFT2D a useful tool for coastal embayments and wetlands, as well as for representing inundation in urban and agricultural areas. SWIFT2D has been applied in numerous different settings around the world (Bales and Robbins, 1995; Dronkers et al., 1981; Goodwin, 1996; Leendertse et al., 1981; Russell and Goodwin, 1987; Schaffranek and Baltzer, 1990).

The dynamic nature of the surface water regime in South Florida, especially in coastal locations, makes a hydrodynamic model more suitable than models based on more simplified formulations. The low gradients allow transient reversals in flow direction from tidal and wind forcing, and the manmade canal system often resembles a flat pool. Modifications have been made to facilitate application of SWIFT2D in the southern Florida Everglades, including the representation of spatially variable rainfall, evapotranspiration, and vegetative wind sheltering (Swain, 2005). Further enhancements increase the versatility and applicability by defining flow resistance at model cell faces instead of cell centers, simplifying the representation of hydraulic structures, and representing heat transport for temperature computation and latent heat computation for evapotranspiration (Decker and Swain, 2007).

FTLOADDS

The close hydraulic connection between surface water and groundwater makes the interactive simulation of the two systems essential for accurate predictions. The SEAWAT and SWIFT2D models were coupled within the code known as Flow and Transport in a Linked Overland/Aquifer Density-Dependent System (FTLOADDS). The models are executed alternately in FTLOADDS with SWIFT2D simulating the number of surface water time steps corresponding to the time step length in SEAWAT. A sequentially coupled time-lagged approach was implemented to couple the surface water and groundwater systems. The approach is mass conservative in that the exact leakage flux imposed on the surface water system is also imposed on the groundwater system. The leakage between groundwater and surface water is computed based on the head difference in each cell, and temporally distributed according to the time step lengths in each model (Langevin et al., 2005). Salt as a constituent is passed through leakage, and the effects on water density are accounted for in the leakage. Otherwise, SEAWAT and SWIFT2D function as they do when running separately, computing flow and transport in their respective domains. Further modifications have made it possible to define the leakage connection to varying layers of the groundwater model, facilitating the representation of offshore areas with underlying groundwater.

Experience in Applications

For the past decade, the SEAWAT computer program has been used in South Florida to address coastal groundwater issues. Key findings from selected USGS applications of SEAWAT in South Florida include the following:

- For a 10-year period, the average volume of fresh submarine groundwater discharge to Biscayne Bay was estimated to be about 6% of the canal discharge (Langevin, 2001; Langevin, 2003).
- Upconing was identified as the most immediate concern of saltwater intrusion into the Lower Tamiami Aquifer near Bonita Springs (Shoemaker and Edwards, 2003).
- For the permeable Biscayne aquifer of eastern Broward County, moderate rates of sea-level rise will likely cause saltwater intrusion into coastal wellfields during the next century unless canal water levels are elevated (Dausman and Langevin, 2005).

- Excessive well field withdrawals during a period of reduced rainfall are the probable causes of historic saltwater intrusion patterns observed near the Pompano Beach wellfield (Zygnerski and Langevin, 2007, 2008).
- Injection of treated wastewater into the Lower Floridan aquifer in Miami-Dade County is predicted to have regional effects on the depth of the freshwater and saltwater transition zone (Dausman et al., 2008).

Until recently, three-dimensional simulations of flow and transport in coastal aquifers were not possible due to restrictions in computing power. The past decade has demonstrated, however, that it is possible to simulate complex coastal groundwater processes, including both solute and heat transport (Langevin et al., 2007). To quantify uncertainty in model predictions and develop more accurate models, present SEAWAT models are being combined with parameter estimation techniques. Results from these efforts are expected to provide more accurate results that include reliable uncertainty estimates. SWIFT2D was used, uncoupled to SEAWAT, to develop the Everglades in the Southern Inland and Coastal System (SICS) application in a coastal area of the Everglades along northeastern Florida Bay. This application made use of multiple field studies for input data and initially utilized a simple evapotranspiration formulation (Swain et al., 2003). SICS was then combined with a groundwater flow simulation using the FTLOADDS code, which demonstrated that submarine groundwater discharge to Florida Bay was not a large component compared to surface water flows (Langevin et al., 2005). Recently, SICS was used for testing and designing water-supply schemes (Swain and James, 2007), stochastically determining boundary influences (Swain et al., 2008), and providing hydrologic input for ecologic models of fish population (Cline et al., 2004).

The SICS model was expanded to include most of Everglades National Park. This larger model is called the Tides and Inflows in the Mangrove Everglades (TIME) model (Wang et al., 2007). TIME is being used to examine the hydrologic effects of CERP restoration scenarios and provide coastal flow and salinity information for offshore modeling (Wolfert et al., 2006). Model enhancements for the TIME application include evapotranspiration computed by the Penman method, revisions in the representation of wetting and drying, and the zonation of rainfall input. TIME output is also used for ecologic models and to examine coastal surface water/groundwater interactions (Swain and Wolfert, 2007).

To investigate hydrologic effects in the Picayune Strand Restoration Project area, FTLOADDS was applied to the Ten Thousand Island (TTI) area. As in other applications, TTI includes salinity transport, but also includes an enhanced heat-transport algorithm so that water temperature can be simulated (Decker and Swain, 2007). Both salinity and temperature are of interest in the study of local manatee habitats and migration modeling (Stith et al., 2006). The heat transport component computes latent-heat values, which are used to compute evapotranspiration values on a model cell-by-cell basis. The heat-transport capabilities have been implemented in the other FTLOADDS applications as well.

The Biscayne Bay and lower east coast area has a FTLOADDS application to examine hypersalinity effects offshore and the effect of changing coastal discharges (Wolfert-Lohmann et al., 2008). This application is being combined with the TIME to create the Biscayne and Southern Everglades Coastal Transport (BISECT) application. This will allow the exchanges between Everglades National Park in the west and the urban and agricultural areas in the east to be simulated. BISECT will prove useful in many investigations of restoration and climate change effects on hydrology and ecologic effects.

V MODELING OF ESTUARIES/BAYS

Coastal management in South Florida is challenging because of the complexity of several major watershed-estuarine systems and the widespread impacts from freshwater discharges to coastal areas (Figure 2). The constructed Florida Canal system that protects South Florida from flooding and supplies water for agriculture, industry, and municipal purposes has increased the area of land that delivers water to estuaries in an unnatural way. The complexity of these major watershed-estuarine systems and the construction of the canal systems for flood control and water supply cause increasing freshwater inflow, decreasing detention of runoff by natural wetlands, extreme salinity variations in the estuary, increasing the drainage area to estuaries (St. Lucie and Caloosahatchee were not originally directly connected with the Lake Okeechobee watershed), and changes in estuary hydrodynamics (by dredging or permanent inlets to the ocean).

In order to manage freshwater discharge to South Florida's estuaries in a way that preserves, protects and, where possible, restores essential estuarine resources, an integrated modeling framework that includes watershed, estuary hydrodynamic, water quality, and ecological models is proposed and partially implemented in some South Florida coastal areas (e.g., St. Lucie). As part of this integrated modeling framework, watershed hydrological and estuarine hydrodynamic models serve as important links when assessing the impacts from freshwater inflows (water quantity) on estuarine ecosystems. Specifically, the watershed hydrological model estimates the quantity and timing of freshwater inflow to the estuary. The estuarine hydrodynamic model, in turn, simulates the estuarine conditions in terms of flow, salinity, and sediment transport. Finally, the ecological models simulate the responses of estuarine resources (seagrass or oyster) to these estuarine conditions. In other words, they serve as important links in integrating the freshwater inputs and the estuary ecosystem responses.

Present Modeling Systems

Presently, different modeling systems in South Florida coastal areas are applied depending on available data and tools. The modeling systems range from simple mass balance calculations to complicated numerical modeling systems. On the simple end of the spectrum are statistical, empirical relationships, while on the complex end there are deterministic, numerical models. The application of these modeling systems is an iterative or evolutionary process (SFWMD, 2008). For example, a regression flow and salinity model using synoptic survey data provides good information for a regression oyster response model in early 1990s in the St. Lucie estuary. This modeling system was updated or upgraded to a three-dimensional time-variable hydrodynamic model (CH3D) in 2007 when the appropriate data (continuous flow and salinity data) and resources became available.

Present available models and model systems developed for South Florida coastal watershed and estuary areas are shown in Tables 2, 3, and 4. Some systems, such as the St. Lucie system, are model rich, while others lack models, such as Naples Bay. The production of estuary hydrodynamic models in South Florida's coastal areas has been greater than that of watershed, estuarine water quality, or ecological models.

TABLE 2. Tributary watershed modeling systems in South Florida coastal areas

Watershed	Hydrology	Water quality
St. Lucie River and Southern Indian River Lagoon	1. Northern Everglades Regional Simulation Model (NERSM). 2. Calibrated WaSh Model.	WaSh component under development (Florida Department of Environmental Protection).
Loxahatchee River	1. Calibrated WaSh model. 2. Groundwater model under development.	NA
Lake Worth Lagoon	Lower East Coast Regional Modflow model.	NA
Biscayne Bay	1. South Florida Water Management Model. 2. Regional Simulation Model developed.	Preliminary watershed loading estimate using GIS and SFWMM under development.
Florida Bay	1. South Florida Water Management Model. 2. USGS TIME Model calibrated.	
Naples Bay	NA	NA
Estero Bay	NA	NA
Caloosahatchee River and Estuary	1. HSPF under development by DEP. 2. Calibrated MIKE SHE Regional. 3. NERSM.	HSPF development by DEP
Southern Charlotte Harbor	NA	NA

TABLE 3. Estuarine hydrodynamic, water quality, and sediment transport modeling systems in South Florida coastal areas

Estuary	Hydrodynamics/Salinity	Water quality	Sediment
St. Lucie River Estuary and Southern Indian River Lagoon	1. CH3D and RMA calibrated; additional data being collected for verification. 2. Integrated surface and groundwater model under development.	Stand alone Water quality model (based on EFDC/WASP) calibrated and integrated with CH3D; additional data being collected for verification.	CH3D calibrated; additional data being collected for verification.
Loxahatchee River Estuary	1. CH3D and RMA calibrated. 2. Integrated surface/groundwater model under development.		
Lake Worth Lagoon	North Palm Beach EFDC model will be used to establish flow targets to meet desired salinity ranges.	NA	North Palm Beach Plan flow modeling ongoing using LECsR MODFLOW model.
Biscayne Bay	Calibrated TABS-MDS model.	NA	NA
Florida Bay	1. Calibrated EFDC model. 2. FATHOM mass balance model completed.	EFDC water quality developed, but not calibrated.	NA
Naples Bay	CH3D model under development.	NA	NA
Estero Bay	CH3D model calibrated.	NA	NA
Caloosahatchee River Estuary	1. CH3D model calibrated and regression models used to estimate salinity. 2. EFDC model under development (FDEP).	1. EFDC water quality component under development (FDEP). 2. WASP model under development (FDEP).	NA
Southern Charlotte Harbor	NA	NA	NA

TABLE 4. Ecological modeling systems in South Florida coastal areas

Estuary	SAV	Oyster	Fish	Floodplain or wetlands	Other
St. Lucie River Estuary and Southern Indian River Lagoon	NA	Spread-sheet model, daily time step of oyster stress/salinity.	Under development: Spawning and survival success of estuarine dependent fishes	NA	
Loxahatchee River Estuary	NA	NA	NA	Under development: A Digital Elevation Model and plant species composition.	
Lake Worth Lagoon	NA	NA	NA	NA	
Biscayne Bay	Salinity effects on *Thalassia/Halodule* competition.	NA	Salinity habitat suitability models for shoreline fish.	NA	Wading bird abundance based on water levels.
Florida Bay	Dynamic seagrass community model (multispecies; complete for *Thalassia* and *Halodule*).	NA	General additive statistical models (populations and forage base) completed.	NA	Pink shrimp population model: lobster population model; spoonbill statistical model; documentation under way.
Naples Bay	NA	NA	NA	NA	
Estero Bay	NA	NA	NA	NA	
Caloosahatchee River Estuary	(a) HSI model (depends on predicted salinity and inflow; (b) Tape grass numerical model with daily time step of density-salinity, light and temperature.	HSI model (depends on predicted salinity and flow from models).	HSI model (depends on predicted salinity and inflow from other models) –blue crabs, fish and zooplankton.	NA	Target Flow Index –(spreadsheet model) that compares project flows to S-79 target flow distribution.
Southern Charlotte Harbor	NA	NA	NA	NA	NA

Experience in Applications

The models and model systems described previously have been applied by SFWMD to address coastal and estuarine water quantity problems for several years (Table 5). As discussed briefly, the focus of these applications is to quantify the relationships between the freshwater inflow (watershed flow and hydrology), estuary salinity (estuarine hydrodynamic model outputs), and responses from valued ecosystem components (seagrass or oysters; SFWMD, 2008) to maintain ecosystem health. For example, the Caloosahatchee River and Estuary Minimum Flow Level was established to supply enough freshwater discharge to the estuary at S-79 to maintain salinity low enough to avoid hypersalinity-related mortality of *Vallisneria* (SFWMD, 2002). A time-dependent, three-dimensional hydrodynamic model of the Caloosahatchee Estuary (CH3D) had been developed (calibrated and verified) to provide salinity ranges based on different watershed inflow scenarios. This model's salinity output information was used in turn with a simple empirical statistical model relating salinity concentration to mortality of *Vallisneria*. By this application, the appropriate quantity of fresh water inflow from structure S-79 to maintain a tolerable salinity range (envelope) for *Vallisenria* (< 10 ppt) in the upper estuary is determined. The application of this three-dimensional hydrodynamic model also allowed a quantitative

TABLE 5. Model integration and application

Estuary	Description
St. Lucie River Estuary and Southern Indian River Lagoon	Indian River Lagoon—South Feasibility Study Northern Everglade River Watershed Protection Plan
Loxahatchee River Estuary	Restoration Plan for the Northwest Fork of the Loxahatchee River Scenarios for the North Palm Beach Plan–Part 1
Lake Worth Lagoon	Scenarios for the North Palm Beach Plan–Part 1
Biscayne Bay	Scenarios for Biscayne Bay Coastal Wetlands Project
Florida Bay	Scenarios for the Florida Bay and Florida Keys Feasibility Study Scenarios for the Minimum Flow and Level Rule development. Scenarios for the C-111 Spreader Project
Naples Bay	
Estero Bay	
Caloosahatchee River Estuary	C-43 Basin ASR (CERP) and Southwest Florida Feasibility Study Northern Everglade River Watershed Protection Plan
Southern Charlotte Harbor	

partitioning of freshwater inflow between the river basin and tidal estuarine basin, and hence provides better understanding when considering the operation of freshwater discharges from S-79.

Similarly, the Feasibility Study for the Southern Indian River Lagoon focused on hydrologic restoration to the predrained or natural hydrologic characteristics in the watershed to aid the recovery and protection of salinity-sensitive biota in the estuary (Wan et al., 2002). To achieve this goal, a suite of models dealing with watershed hydrology, reservoir optimization, estuary salinity, and oyster stress was applied. The RMA model was used to simulate estuary hydrodynamic and salinity, and the results showed that unfavorable salinity conditions occurs once watershed inflows exceed 2,000–3,000 cfs. The NSM, which simulates the hydrologic response of the predrained watershed to recent climatic conditions, delineated the acceptable exceeding of the flow range. Results of the NSM were used as the basis for establishing the hydrologic restoration target, sizing reservoirs, and justifying flow transfers between basins within the watershed. The Hydrologic Simulation Program—FORTRAN (HSPF)—was used to simulate the hydrology of the present and future conditions. A genetic algorithm-based optimization model (OPTI), was used to size the storage reservoirs and generate operational rules that govern water release to the St. Lucie Estuary. Finally, an oyster stress model was used to develop a numerical performance measure to evaluate the effectiveness of the project on estuarine ecosystem restoration.

Another application using integrated watershed hydrological and estuarine hydrodynamic model was the Restoration Plan for the Northwest Fork of the Loxahatchee River (SFWMD, 2006). The Northwest Fork of the Loxahatchee River has lost freshwater habitat due to saltwater intrusion, caused in part by opening the Jupiter Inlet and construction of the C-18 canal for drainage and flood protection. Formulation and evaluation of alternative restoration flow scenarios were based on the successful application of hydrological and salinity models. These models were a watershed hydrological model (WaSh) that simulated long-term freshwater inflows; a two-dimensional estuarine, hydrodynamic, and salinity model (RMA) that simulated short-term influences in tributary inflows and tide on estuarine salinity; and a long-term salinity management model (LSMM, a regression model) developed from the RMA results capable of predicting daily salinity in the estuary for the period of record used in the watershed model. Valued Ecosystem Components (VECs) were chosen for different portions of the system: floodplain vegetation for the freshwater portion, and oysters, seagrasses, and fish larvae for the saline end of the system. Output from these models was used to evaluate ecosystem responses of these VECs to varying restoration flow scenarios using hydrologic performance measures and salinity tolerance for the freshwater floodplain and salinity-based habitat suitability models for estuarine fauna. The linked models estimated freshwater inflows that would push the salt wedge downstream about 1.5

river miles, allowing for restoration of freshwater floodplain habitat without harming estuarine resources in the saline reaches of the river. The plan not only addressed the water quantity issue, but, using seasonal requirements of the VEC, also went on to suggest a time-varying seasonal distribution of freshwater inflow that could serve as a technical basis for proposed new infrastructure.

These examples and applications illustrate the benefits of the iterative application of the integrated modeling approach. More new data when available can be incorporated into more sophisticated models and hence provide better understanding for adaptive management in the future. To provide the needed technical support for adaptive management, and implementation of management measures, an integrated modeling approach is preferred along with some specific new work to refine or update the existing models described in the previous section. As mentioned before, this integrated modeling and resource assessment framework can be applied at different levels of complexity to provide the information required for sound, science-based management.

VI NEXT GENERATION HYDROLOGIC AND HYDRODYNAMIC MODELS

Unprecedented efforts to restore the Everglades require the analysis of complex water management and restoration alternatives involving competing objectives to balance water needs of multiple stakeholders covering urban, agricultural, and environmental sectors. The modeling of alternatives is complicated further by the federal and state requirements for project evaluation and approval (e.g., Programmatic Regulations). In addition, there are new data, research findings and technology improvements that have prompted the development of a new generation of hydrologic and hydrodynamic simulation models. This section provides a brief description of such models and modeling approaches.

Regional Simulation Model

Recognizing the need for a next generation regional modeling tool, SFWMD embarked on a major development effort to develop the present Regional Simulation Model (RSM) with well-defined design requirements and building blocks (SFWMD, 2005c). While RSM is being developed on a sound conceptual and mathematical framework, its application is primarily targeted for the South Florida environment. The RSM has two principal components, the Hydrologic Simulation Engine (HSE) and the Management Simulation Engine (MSE).

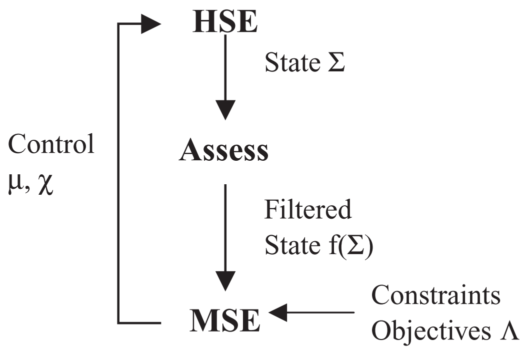

FIGURE 3. RSM state and management information flow.

The HSE component solves the governing equations of water flow through the landscape hydrologic cycle and the water conveyance features using a finite-volume approach implemented on a triangular network of mesh elements. The MSE component provides a variety of system management capabilities by implementing operating rules for both water supply and flood control, regulation schedules (e.g. rules for a reservoir), operation of water control structures, and their coordination within the model domain. The development of RSM has relied mainly on the following building blocks, new computational methods (Lal, 1998, 2000), object-oriented code design and implementation, new and efficient numerical solvers for large matrices (SFWMD, 2005c), and the experience of regional modeling in South Florida gained from operating the SFWMM.

In the RSM, the Hydrologic Simulation Engine (HSE) provides hydrological and hydraulic state information, Σ, while operational policies dictate managerial constraints and objectives, Λ. In the MSE this state and process information can be functionally transformed or filtered by Assessors (A). The MSE then produces water management control signals (χ,μ), which are applied to the hydraulic control structures in order to satisfy the desired constraints and objectives. Figure 3 illustrates this overall cyclic flow of state and management information in the RSM.

Hydrologic Simulation Engine

The governing equations (mass balance and conservation of momentum) for simulating hydrology of the physical system are derived from the Reynolds transport theorem (Chow et al., 1988). In arriving at the solution to the governing equations (mass and momentum) simplifications were made for RSM by assuming inertia terms to be negligible for the intended applications: continuous simulations for planning purposes (SFWMD, 2005c). The resulting diffusive wave formulation has allowed the RSM to combine both the surface water and groundwater flow equations, which can be solved using a single matrix.

The object-oriented design using C++ programming language has evolved into two basic abstractions of the fundamental elements included in the governing equations: (a) waterbodies to represent storage in mesh cells, canal segments, and lakes; and (b) watermovers to represent water movement between waterbodies. The details of the numerical solution of the governing equations and the various forms of waterbodies and watermovers can be found in Lal (1998) and SFWMD (2005c). The sources and sinks of the hydrologic system are computed using the concept of Hydrologic Process Modules (HPM), which can simulate the effects of vertical processes such as rainfall, evapotranspiration, recharge, irrigation, and others using highly detailed information of the landscape (SFWMD, 2005c).

Management Simulation Engine

The Management Simulation Engine (MSE) consists of a multilevel hierarchical control scheme, which naturally encompasses the local control of a particular water control structure, as well as the coordinated subregional and regional control of multiple structures. The RSM architecture emphasizes the decoupling of hydrological state information from the management information processing applied to these states. Given a well-defined interface between the HSE and MSE, this approach enables multiple information processing algorithms to execute in parallel, with higher levels of the hierarchical management able to synthesize the individual results, which are best suited to the managerial objectives.

In the MSE, this data access is achieved by storing hydrological and managerial information relevant to a water control unit (WCU) in a data storage object defined in an MSE network. The MSE network is an abstraction of the stream flow network and control structures suited to the needs of water resource routing and decisions. MSE networks maintain assessed and filtered state information, parameter storage relevant to WCU or hydraulic structure managerial constraints and variables, and serve as an integrated data source for any MSE algorithm seeking present state information. They also provide a mathematical representation of a constrained, interconnected flow network that facilitates the efficient graph theory solution of network connectivity and flow algorithms.

Experience in Applications

Although RSM is being used for analyzing restoration alternatives, there are several key challenges in combining the MSE with HSE for application at a system-wide scale. Incorporation of complex operational rules that have spatially extensive implications in an object-oriented model itself is a major challenge. Probably a larger challenge is to ensure that the full coupling of HSE and MSE is successful with consistent states being used in each component in places such as southeast Florida (e.g., Miami-Dade County) in which strong surface water groundwater interaction may prevent such coupling extremely difficult. In spite of these challenges, RSM is fast becoming a valuable hydrologic simulation tool for analyzing restoration alternatives.

FEMWATER Model

FEMWATER is a modern implementation and combination of two older codes, 3DFEMWATER (flow) and 3DLEWASTE (transport). FEMWATER was written as a collaborative effort between Dr. Gour Tsyh (George) Yeh of the University of Central Florida and Dr. Hsin-Chi (Jerry) Lin of Waterways Experiment Station (WES), Vicksburg, Mississippi. Simulation outputs from the code include spatial and temporal variations of flows, velocities, stages, depths, moisture contents, and concentrations. The model application described herein was conducted to evaluate the design of a subsurface barrier wall intended for construction as a seepage management pilot project adjacent to the Everglades National Park (ENP) area.

The natural hydroperiod of the ENP and WCA-3B depends in part on minimizing seepage flows toward the developed urban and agricultural areas to the east. To this end, management and control of seepage along the L-31N and L-30 canals are needed for the hydroecologic restoration efforts in the ENP and WCA-3B. Under the CERP conditions, the water levels in the eastern parts of the ENP and WCA-3B will be increased. This will create steeper hydraulic gradients from these areas eastward with associated increases in seepage flow (reducing hydroperiod of the wetlands in ENP and WCAs to the west) and the potential for increased groundwater stages and surface water flooding of areas east of L-30/L31N.

To understand the effectiveness and flexibility of seepage management technologies, groundwater modeling has been performed as part of the L-31N (L-30) Seepage Management Pilot Project (SMPP). An appropriate modeling tool based on the finite element method has been selected for a meaningful representation of the physical system as described by the conceptual model for L-31N (L-30) SMPP. Finite elements allow for the representation of small features with irregular geometry situated in regions of rapidly varying flow and rapidly varying subsurface characteristics. While it is a general perception that the computational time for finite element models is relatively high, model simulation times can be reduced by using a well-designed mesh with significantly fewer elements that make the finite element models efficient for simulating groundwater systems, even at system-wide scales.

The groundwater system was investigated to understand the effectiveness and flexibility of seepage management technologies. In the present study, the finite element model FEMWATER, which is the base groundwater model for the integrated WASH123D code (Yeh et al., 1988), was employed to represent a discontinuous system including a highly conductive porous medium and a less conductive flow barrier. The focus was to design an effective seepage control barrier at the L-31N (L-30) site. The analysis first determined the existing steady-state seepage flows for several hydrolologic conditions (average, dry, and wet conditions). This analysis was needed to design a system for managing seepage flows from west to east (in general, retarding wet season flows and allowing for the continuance of dry season flows).

L-31N (L-30) SMPP is located along L-30 on the eastern side of WCA-3B in Miami-Dade County, as shown in Figure 4. The hydraulic structures that regulate flows in the canals are shown in the figure. The site for investigating the seepage control technology is located within the 1.25 mile segment of the L-30 levee and adjoining canal, between hydraulic structures S-335 and S-336. For L-31N (L-30) SMPP, the initial focus was to optimize a seepage control subsurface barrier 1,000 feet in length including a window opening (in the barrier wall for seepage management) to maintain dry condition base flows. After sizing the opening, the simulation then included and evaluated an extraction-injection well configuration to prevent wet condition flows passing through the barrier wall window. In general, the project and modeling objective are to investigate seepage management technologies that might reasonably be employed at L-31N and L-30 in order to control wet season seepage while minimizing impacts to existing legally authorized water users and the natural environment during the dry season.

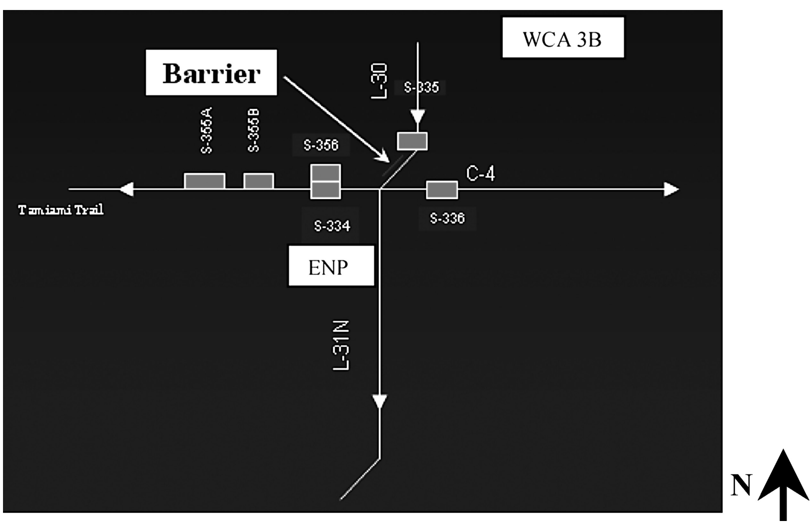

FIGURE 4. Location of L-31N (L-30) SMPP (not to scale).

Model Domain

The model domain was selected to adequately represent the flow processes associated with the desired barrier wall and the pumping wells. While selecting the model domain, an attempt was made to observe the effects of the barrier wall and the pumping wells in both local and subregional perspectives. A subdomain of the subregional-scale model domain based on MODBRANCH model code (Swain and Wexler, 1988) was used for the present pilot project. The model boundaries were set at a reasonable distance (5 miles for the west boundary and 3.3 miles for the north boundary) away from the area of concern to minimize the effects of any uncertainties in the descriptions of the boundary conditions. The finite element mesh for modeling the L-31N (L-30) SMPP subsurface is generated using the GMS (Brigham Young University, 2002) for the entire model domain. The refined finite element mesh represented the barrier wall in a physically meaningful fashion.

Model Results

The dry and wet hydrologic modeling conditions are described by the annual average flows and stages of the dry year (1989) and wet year (1995), respectively. In the existing condition, the seepage barrier is not included because it is a project feature for the pilot study. The results indicate that the groundwater flows from northwest to southeast. Under the existing conditions, simulated groundwater flows have been tabulated across transects defined as coincident to the 1,000 ft barrier wall alignment and across transects extended 1,500 ft to the northeast and 1,500 ft to the southwest from the end of the barrier wall. Simulated average Darcy velocities of 5.1 ft/day and 8.4 ft/day are obtained respectively, for the dry and wet conditions, under the no barrier wall configuration.

The effectiveness of the 1,000 ft barrier wall (including a 100 ft wide window opening) to control seepage is simulated by assigning the material properties along the small model mesh triangles. The barrier wall configuration includes a window opening. For the pilot project, it was important to clearly distinguish the effect of the wall opening for increasing flow velocities in order to facilitate both baseline and future with-project monitoring of groundwater velocities in the area. Therefore, a number of different sizes of window openings in the barrier wall were simulated. It was recognized that a 100 ft wide window provided a significant increase in the velocity through the window (from 5.1 ft/day to 22.3 ft/day for dry condition and from 8.4 ft/day to 32.5 ft/day for wet condition) and required a reasonable amount of injection water to retard the flow during the wet season. For the future full-scale seepage management project, it is recognized that either the frequency of window openings or the size of window openings within the barrier wall will likely need to be increased in order to maintain the present volume of dry-season flows.

The extraction-injection wells are simulated to investigate the control of seepage through the 100 ft window opening during the average wet year condition. The injection wells can be used to either completely retard or variably retard the seepage flows through the window opening in the barrier wall. The extraction wells supply water to the injection wells. There are three injection wells each injecting at 2 cfs and two extraction wells each extracting at 3 cfs (to supply water to the three injection wells). The path lines for the extraction-injection well scenario including barrier wall and window are shown in Figure 5. These lines are the trajectories that individual fluid particles in the groundwater follow. The flow vectors at varying depths were reversed by the injection wells across the window. The magnitudes of the velocities that occurred in different model layers were retarded by the injection wells through the window. Stagnation no-flow zones were created as depicted in Figure 5.

In summary, the FEMWATER model represented and simulated existing and with-project conditions successfully for the L-31N (L-30) SMPP. The model results indicated that the simulated groundwater hydraulic heads generated flow patterns consistent with the conceptualization of flow direction from northwest to southeast. The model was used to determine the effects

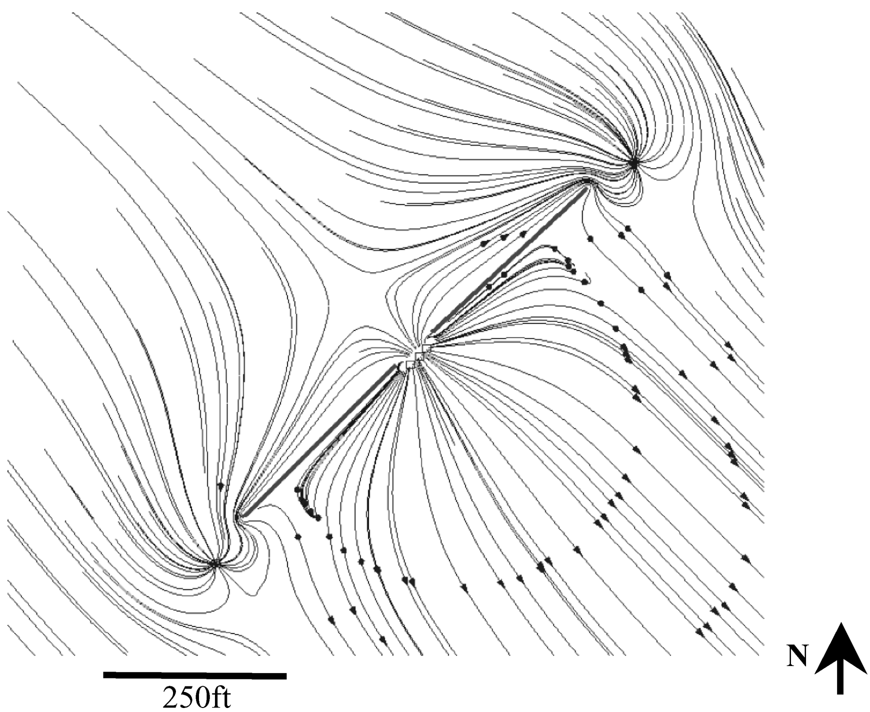

FIGURE 5. Path lines showing the flow field for barrier wall and window including two extraction (at the ends) and three injection wells (in the middle).

of the barrier wall and optimize the size of the window opening in order to allow the continuance of dry season flows. A 100 ft wide window in the 1000 ft barrier was selected based on the investigation of the simulated velocities.

Lattice-Boltzmann Models

High-resolution models of local-scale hydrodynamics are needed to predict the developmental trajectories of Everglades vegetation communities caused by hydrologic restoration or changes in management. For example, tree islands and the ridge and slough habitat are shaped by and influence surface water flow patterns in the marsh (National Research Council, 2003). These interactions, in turn, control other important biogeochemical processes in the marsh, including sediment and nutrient transport and peat accretion. Information about how surface water flows in and around vegetation features, and about how changes in landscape patterns affect flow is needed to predict the responses of these communities to hydrologic changes associated with restoration. A new approach utilizing Lattice-Boltzmann (LB) hydrologic models is being developed by Dr. Michael Sukop (Florida International University) to address this issue. These models calculate advection and dispersion patterns at small (m) scales in the marsh for (a) the type and distribution of existing vegetation communities and (b) the hydraulic gradients expected with restoration. These models can therefore serve as companions to the larger regional-scale models when evaluating the potential local effects of restoration on the natural communities. Future modifications will resolve solute and sediment transport at similar scales.

LB models are a class of computational fluid dynamics (CFD) methods for fluid simulation (Sukop and Thorne, 2007). Instead of solving the Navier-Stokes equations explicitly, the discrete Boltzmann equation is solved to simulate the flow of a Newtonian fluid with collision models such as Bhatnagar-Gross-Krook (Sukop and Thorne, 2007). By simulating the interaction of a limited number of particles, the viscous flow behavior emerges automatically from the intrinsic particle streaming and collision processes.

Unlike the traditional CFD methods, which solve the conservation equations of macroscopic properties (i.e., mass, momentum, and energy) numerically, LB models the fluid as fictive particles, and such particles perform consecutive propagation and collision processes over a discrete lattice mesh. Due to its particulate nature and local dynamics, LB has several advantages over other conventional CFD methods, especially in dealing with complex boundaries, incorporating microscopic interactions and parallelization of the algorithm.

For the ridge and slough habitat, steady flow and a velocity field that is constant with respect to the vertical dimension z are assumed. The Navier-Stokes equations can be formulated where the velocity fields—$u(x, y)$ and $v(x, y)$—are spatially variable and temporally invariant (Sukop and Thorne, 2007). Because no general analytical solution is available, a numerical solution to these equations must be employed for all but the simplest cases. However, numerical solutions capable of resolving the velocity gradients at high resolution are computationally expensive. As an alternative, a simpler model can be obtained by decomposing u, and v, into spatial averages and the local variations about those averages (e.g., u = U + u') where capital letters represent spatial averages.

In this study, numerical solutions to these equations governing marsh flow are obtained using a LB model that is able to handle irregular boundaries, and which incorporates a spatially variable subgrid stress term, ϵ_{SGS}. This LB model uses the BGK method and a two-dimensional grid. The model is distributed as LB2D prime (http://www.fiu.edu/~sukopm/). This model is open source and has low computational cost, a simple user interface, and the ability to import landscape features into the simulation domain as raster graphics. In this framework, aerial images of patterned marshland are imported as grayscale bitmap images directly into the code, with pixel intensity setting the value of ϵ_{SGS}. The local subgrid-scale dissipation is modeled as a Darcy-type resistance term.

The alternating ridges and sloughs that characterize the study domain present a spatially variable resistance to flow. This is characterized by the spatial distribution of the subgrid dissipation via ϵ_{SGS}. Setting this distribution is essential, as it is one of the physical characteristics of the simulation that attempts to exactly replicate the structure of the Everglades marshes. To achieve dynamic similarity, the nondimensional forces acting on the model (m) and real world (p) are matched. Matching non-dimensional numbers between (m) and (p) in this way is an application of what is commonly referred to as Buckingham's pi theorem (Buckingham, 1914). If the LB model parameters are set in this way, then the modeled hydrologic properties can be translated to their real-world values. The governing geometric property is the grid-length scale ($\mathscr{L}$) determined from the dimensions of the imported aerial image and pixel size. The governing dynamic property is the velocity field (U_t). When both geometric and dynamic similarities have been achieved, kinematic similarity is also automatically satisfied, implying an equality of Reynolds numbers.

An image processing routine was developed to convert RGB aerial imagery of the Everglades (USGS Digital Orthophoto Quarter Quadrangle, http://edc.usgs.gov/) into an LB domain. Vegetation types such as sawgrass ridges and periphyton mats in the images were identified by intensity thresholds applied to the R, G, or B channels. An example the resulting binary domain is seen in Figure 6a. This region is the location of one of the EverTREx large-scale tracer releases performed in 2006–2007 (Ho et al., 2009). EverTREx data provide a ground truth for these simulations. The pressure gradient at the model boundaries is derived from stage values recorded near the site and provided by the USGS Everglades Depth Estimation Network

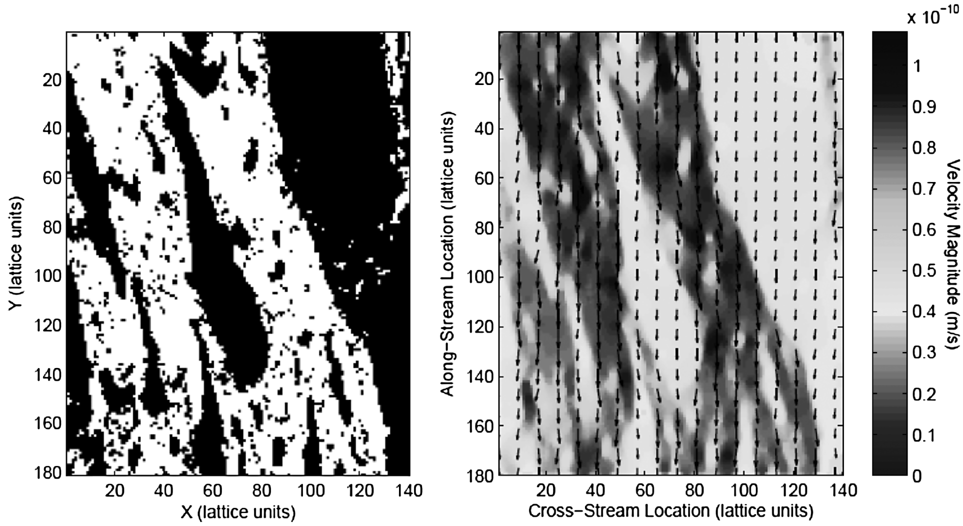

FIGURE 6. (a) Grayscale bitmap image of an area of ridge and slough that forms the domain of a Lattice-Boltzmann (LB) simulation of sheetflow given EDEN stage gradients. White denotes areas of slough or open water. (b) A surface water velocity field determined from the LB simulation. Velocity vectors were determined at each grid point, but are shown at only every eighth grid point for clarity. The landscape features and the relative permeabilities of ridges and sloughs match those values found in the Everglades. The flow direction in the sloughs matches observations derived from surface water tracer studies (Ho et al., 2009). Flow directions in the ridges were not measured, but the LB simulations suggest they are not aligned with the orientation of the ridge and slough.

(EDEN). The velocity field produced by the LB simulation on this domain is shown in Figure 6b.

Using a series of sensitivity analyses altering the pressure gradient, $\partial P/\partial x$, the model described above was used to generate a general relationship between stage gradients and the velocity vectors in this ridge and slough habitat. These results, along with those of the EverTREx tracer experiments, confirm that the limited extent to which landscape structures act to channel the flow holds implications for the persistence of the ridge and slough habitat. Larger velocity gradients between ridges and sloughs indicate a greater difference in their respective ability to filter and trap suspended sediment (Larsen et al., 2007). However, the results also show the control over flow patterns created by the landscape patterns can be overridden when basin-scale water management generates stage gradients that force sheetflow in directions not aligned with the longitudinal axes of ridges and sloughs (Variano et al., 2008).

The translation of aerial imagery into the LB model domain provides a method for rapidly evaluating the potential changes in sheetflow patterns caused by restoration of stage gradients. This technique will utilize stage gradients produced in the SFWMM or other regional models of hydrologic restoration to forecast sheetflow properties in marsh habitats throughout the Greater Everglades. This information, when combined with dynamic vegetation models and knowledge of sediment and nutrient transport processes, will provide highly detailed projections of developmental trajectories of the Everglades marsh communities.

Bayesian Models

To ensure that the Everglades ecosystem improves as a direct result of management and restoration activities, it is first necessary to understand (and model) the linkages between hydropatterns and ecological indicators. Unfortunately, process-level information regarding the causal linkages between hydrologic conditions and ecological parameters often contains relatively high levels of uncertainty. In this context, Bayesian-type and other probabilistic approaches can be particularly useful, since the processes linking hydrologic and ecological parameters can also be described as a set of hierarchical, conditional models that incorporate the uncertainty explicitly into the calculations. In effect, the Bayesian approach can be used to identify the hydrologic conditions that yield the highest probabilities that an ecological target will be met. Climate and weather variations in the region also influence ecological outcomes and these factors can be easily incorporated into this framework. Indeed, an assessment of the relative impact of climate variations and water releases in determining ecological outcomes is a key to the evaluation of the success or failure of any restoration plan. An example of this approach developed by Drs. Upmanu Lall (Columbia University) and Hyun-Han Kwon (Chonbuk National University) in a recent study is provided below.

Wading bird foraging patterns in the freshwater marshes of the Everglades depend on hydrologic factors such as water depths and recession rates (Russell et al., 2002). Seasonal water depths in the Everglades in turn depend on managed water releases from control structures and direct rainfall. In this study, a Bayesian statistical approach was used to link observational counts of foraging wading birds—a fundamental aspect of the Everglades ecology—to hydrologic management and rainfall. The study focused on the Great Egret and White Ibis in ENP and consisted of multiple objectives. First, 1960–2005 water levels at a gage (P33) in Shark Slough were modeled as a function of rainfall and discharges from upstream structures. The water levels at this station were shown to be highly correlated with depths throughout other areas of ENP where wading birds are observed to forage. Second, a hierarchical Bayesian model was developed to relate numbers of foraging wading birds across ENP to water levels at a long-term monitoring station in central Shark Slough (P33). A third objective that will be addressed elsewhere seeks to use the relationships between water levels and foraging birds derived from this Bayesian scheme to evaluate ENP management alternatives. The second objective is described in more detail subsequently as an introduction to this type of analysis.

General Approach

It is necessary to explain the source of the variability in hydrologic variables en route to an explanation and prediction of the variability in ecological variables. For this application, consider the ecological variable of interest to be the numbers of wading birds foraging in ENP averaged over the domain and over a season. In this case, the conditional probability distribution given rainfall, water release and water depth:

$$f(\mathbf{B}\text{ird Count}\,|\mathbf{R}\text{ainfall},\ \mathbf{W}\text{ater }\mathbf{R}\text{elease},\ \mathbf{W}\text{ater }\mathbf{D}\text{epth})$$

represents a predictive model for bird counts, as the mean or median of the conditional distribution can be considered as the forecast and the uncertainty about the forecast is encoded in the fifth and 95th percentiles of this distribution. The simplest model that could be considered takes the form

$$\begin{aligned} f(\mathbf{B}\,|\mathbf{R},\ \mathbf{WR},\ \mathbf{WD}) &= N(m,\ s2) \\ m &= a0 + a1\mathbf{R} + a2\mathbf{WR} + a3\mathbf{WD} \end{aligned}$$

where m and s2 are the mean and variance of a normal distribution, respectively, and a0–a3 are analogous to regression coefficients. If this model has high predictive skill (low uncertainty) then s2 will be smaller. Of course, this model is not restricted to a linear relationship or a normal distribution. Thus, seeing how much the variance is reduced with the addition or deletion of a particular predictor allows the assessment of the relative contributions of the different variables. In many cases, it is possible to estimate the uncertainty associated with each model parameter and then use that estimate to quantify the overall uncertainty associated with the prediction. The parameter uncertainty typically depends on the sample size and the number of parameters.

Selecting Hydrologic Predictor Variables

It is first necessary to consider the seasonal statistics of the daily water levels recorded at P33 that may be useful predictors of the foraging bird counts. The approach followed is generally similar to that used by Russell et al. (2002), except that the predictors are derived from actual daily water level data from a single location instead of using the qualitative aerial observations of water level at a monthly scale.

A linear regression of dry season (January–April) water depths versus time formed the basis of the selection of hydrologic variables. The *y*-intercept is taken as an estimate of the initial water level at the beginning of the dry season, and the slope as an estimate of the recession rate. Disruptions to the

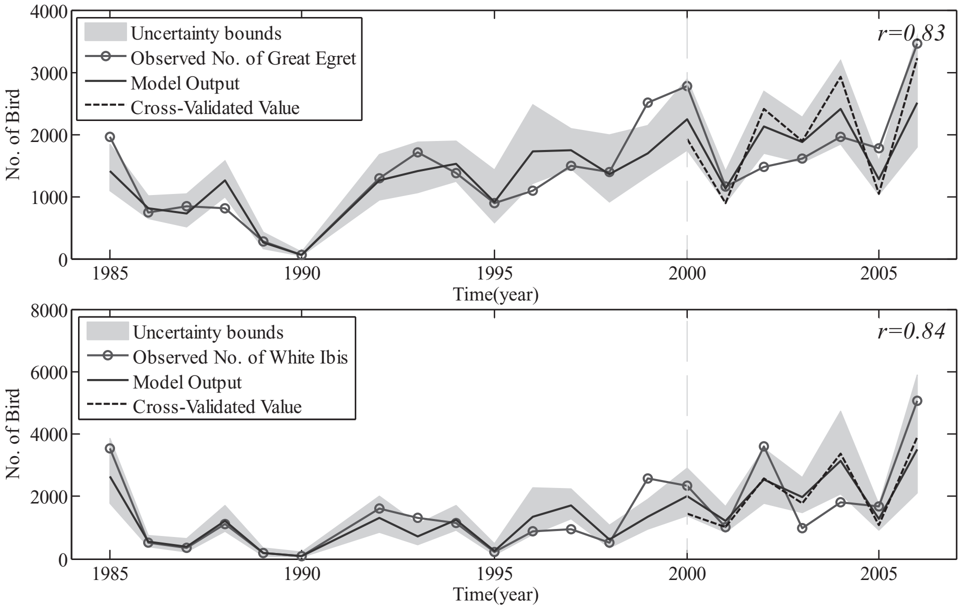

FIGURE 7. Model predictions (solid line) and observed bird counts at Everglades National Park in May (open circle), using Bayesian quadratic regression with values of the three hydrologic predictors derived from water levels at P33 for 1985–2006. *Model output* refers to the posterior mean from the Bayesian model, and *cross-validated value* refers to the posterior mean estimated with the model fit without using that data (from 2000 to 2006). The *r* values shown at the top right refer to the correlation between the posterior mean and the observed values. The uncertainty bounds represent the 5% and the 95% of the posterior conditional distribution.

recession rate are then defined as a positive residual from the linear regression line. For each season, the number of disruptions, a standard deviation of disruption, a maximum consecutive disruption, the average water stage, and the intercept and the recession slope at P33 are computed as potential predictors. A stepwise regression procedure together with exploratory data analysis was used next to screen these potential predictors for each bird count (Figure 7). For example, a cross-validated thin-plate smoothing spline (Wahba, 1990) was used to model the bird counts as a function of initial water stage and disruption. This provides some information regarding the strength and the form of independent relationships between each variable and the bird count data. The initial water level, the averaged water level, and the number of disruptions from January to April were selected as predictors.

A Predictive Bayesian Model for Foraging Wading Birds

A Bayesian generalized nonlinear (quadratic) model is proposed to formulate a predictive model for wading birds counts using time-dependent hydrological predictors. The objective of Bayesian inference is to compute the posterior distribution of the desired variables, in this case the parameters of the wading bird population distribution. The posterior distribution $p(\theta\,|x)$ is given by Bayes' Theorem (Congdon, 2003).

The model is expressed in terms of both a location (mean) parameter $\mu(t)$ and a scale (standard deviation) parameter $\sigma(t)$, which both change with time, t. The parameters are hypothesized to be functions of the hydrologic parameters, which in this case are the initial and seasonal average water levels and the stage recession rate.

The model considers that the numbers of foraging birds $Z(t)$ of each species j follows a log-normal distribution with time varying mean $\mu(t)$ and a constant variance σ. A quadratic model, the mean $\mu_j(t)$ for bird species j in terms of each predictor, is then formulated. Noninformative priors are assumed for each of the parameters and hyperparameters (e.g., β_{ij}, $\mu_{\beta_{ij}}$, $\mu_{\mu_{\beta i}}$, σ_j) and their optimal values are selected through a maximization of the posterior likelihood of observing the data. A Markov Chain Monte Carlo procedure is used.

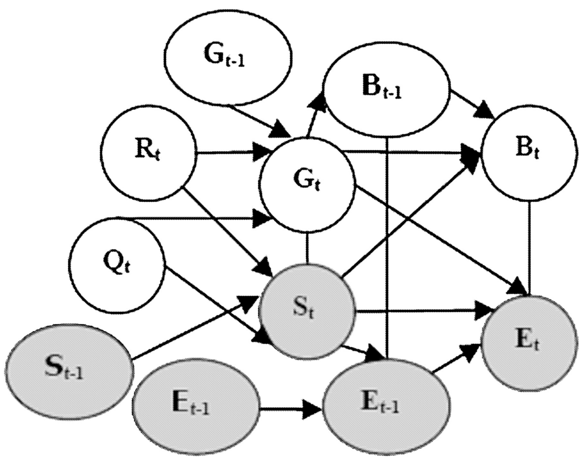

FIGURE 8. Conceptual representation of how different variables may interact to determine ecological indices such as wading bird foraging numbers. The hydrological statistics are considered to depend on climate and release attributes, and the ecological attributes in turn depend on the hydrologic attributes. Each circle refers to a statistic of a biophysical variable computed over the domain and over the time window. Arrows indicate the direction of information flow. Thus, water level gage statistics, $\mathbf{G}_t$, depend on rainfall, $\mathbf{R}_t$, and water release, $\mathbf{Q}_t$, statistics. The bird count statistics, $\mathbf{B}_t$, depend on the $\mathbf{G}_t$, as well as on prior bird count $\mathbf{B}_t$ and in this example, the SFWMM computed water depth statistic $\mathbf{S}_t$. The shaded circles represent model computed variables, and the open circles observations at some locations. A line without an arrow (e.g., the $\mathbf{B}_t$ and the Ecological Index $\mathbf{E}_t$) represents a relationship that could be interpreted in either direction (i.e., sometimes we may be interested in predicting $\mathbf{B}_t$ given a model computed value of $\mathbf{E}_t$, and at other times we may be interested in computing the value of $\mathbf{E}_t$ that is the best analog to an observed value of $\mathbf{B}_t$.

Evaluating Restoration Scenarios

A future goal of this study is to develop a parsimonious model of wading bird foraging counts (or other ecological variable of interest) with the appropriate functional form and target probability distribution, while at the same time estimating the model and parameter uncertainty. The general framework shown in Figure 8 will be used to evaluate the ecological outcomes of simulations of the regional hydrologic models such as the SFWMM.

VII CONCLUSIONS

Decades of hydrologic modeling by various state and federal agencies have allowed the scientists and engineers to:

1. Understand the unique hydrologic processes in South Florida and develop appropriate tools for evaluating restoration alternatives at regional, subregional, and local scales linking various subsystems of lakes, regional wetlands, aquifers, and receiving water bodies such as estuaries and bays.
2. Develop information on performance measures and performance indicators of various Everglades restoration alternatives and their effects on present and future water use in urban and agricultural sectors.
3. Use new technologies in simulation algorithms, software development, and GIS/database techniques for the development of next generation hydrologic and hydrodynamic models useful for implementation of present and future restoration alternatives.
4. Take advantage of increasing computing power and utilize parameter estimation techniques for better model accuracy.
5. Create a comprehensive model inventory to facilitate learning and understanding of the available tools, including their objectives, strengths, and limitations.
6. Provide more coordination with partner agencies on South Florida hydrologic and hydrodynamic modeling to anticipate, address, and solve critical issues as they surface.

REFERENCES

Bales, J. D., and Robbins, J. C. (1995). *Simulation of hydrodynamics and solute transport in the Pamlico River Estuary, North Carolina*. U.S. Geological Survey Open-File Report 94–454.

Brigham Young University. (2002). *GMS version 2.0*. Provo, UT: Brigham Young University.

Buckingham, E. (1914). "On physically similar systems; illustrations of the use of dimensional equations". *Phys. Rev.* 4: 345–376.

Cadavid L. G., Van Zee, R., White, C., Trimble, P., and Obeysekera, J. (1999). Operational hydrology in South Florida using climate forecasts. In H. J. Morel Seytoux (Ed.), *American Geophysical Union, 19th Annual Hydrology Days*. Fort Collins, CO: Hydrology Days Pub.

Chow, V.T., Maidment, D.R. and Mays, L.W. (1988). *Applied Hydrology*, McGraw-Hill, New York.

Cline, J. C., Lorenz, J. J., and Swain, E. D. (2004, June). *Linking hydrologic modeling and ecologic modeling: An application of adaptive ecosystem management in the Everglades mangrove zone of Florida Bay*. Paper presented at the International Environmental Modelling and Software Society iEMSs 2004 International Conference, University of Osnabrück, Germany.

Congdon, P. (2003). *Applied Bayesian Modeling*. England: John Wiley & Sons, Ltd.

Dausman, A. M., and Langevin, C. D. (2005). *Movement of the saltwater interface in the Surficial Aquifer System in response to hydrologic stresses and water-management practices, Broward County, Florida*. U.S. Geological Survey Scientific Investigations Report 2004–5256.

Dausman, A. M., Langevin, C. D., Sukop, M. C., and Walsh, V. (2008, June). *Saltwater/freshwater interface movement in response to deep-well injection in a coastal aquifer*. Paper presented at the 20th Salt Water Intrusion Meeting, Naples, Florida, USA.

Day, G. N. (1985). Extended streamflow forecasting using NWSRFS. *Journal of Water Resources Planning and Management*, 111, 157–170.

Decker, J. D., and Swain, E. D. (2007, October). *Numerical modeling of heat and salinity transport for West Indian manatee habitats in Southwest Florida*. Paper presented at the 2007 GSA Annual Meeting & Exposition, Denver, Colorado, USA.

Dronkers, J., van Os, A. G., and Leendertse, J. J. (1981). Predictive salinity modeling of the Oosterschelde with hydraulic and mathematical models—Transport models for inland and coastal waters. In *Proceedings of the Symposium on Predictive Abilities* (pp. 451–482). New York, Academic Press.

Goodwin, C. R. (1996). *Simulation of tidal-flow, circulation, and flushing of the Charlotte Harbor estuarine system, Florida*. U.S. Geological Survey Water-Resources Investigations Report 93–4153.

Guo, W., and Langevin, C. D. (2002). User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow. In *Techniques of Water-Resources Investigations* (Book 6, Chapter A7). Washington, DC: U.S. Geological Survey.

Harbaugh, A. W., and McDonald, M. G. (1996). *User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model*. U.S. Geological Survey Open-File Report 96–485.

Hirsch, R. M. (1978). Risk analysis for a water-supply system—Occoquan reservoir, Fairfax and Prince William counties, Virginia. *HydroL Sci B*, 23, 476–505.

Ho, D. T., Engel, V. C., Variano, E. A., Schmieder, P. J., and Condon, M. E. (2009). Tracer studies of sheetflow in the Florida Everglades. *Manuscript submitted for publication*.

Jones, M. (1999). *A reinjection drainflow package for MODFLOW*. Albuquerque, NM: U.S. Geological Survey.

Lal, A. M. W. (1998). Performance comparison of overland flow algorithms. *Journal of Hydraulic Engineering*, 124, 342–349.

Lal, A. M. W. (2000). Numerical errors in groundwater and overland flow models. *Water Resources Research*, 36, 1237–1247.

Langevin, C. D. (2001). *Simulation of groundwater discharge to Biscayne Bay, Southeastern Florida*. U.S. Geological Survey Water-Resources Investigations Report 00–4251, 127 p.

Langevin, C. D. (2003). Simulation of submarine ground water discharge to a marine estuary: Biscayne Bay, Florida. *Ground Water*, 41, 758–771.

Langevin, C. D., and Guo, W. (2006). MODFLOW/MT3DMS-based simulation of variable density ground water flow and transport. *Ground Water*, 44, 339–351.

Langevin, C. D., Shoemaker, W. B., and Guo, W. (2003). *MODFLOW-2000, the U.S. Geological Survey modular groundwater model—Documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS Transport Process (IMT)*. U.S. Geological Survey Open-File Report 03–426, 43 p.

Langevin, C. D., Swain, E. D., and Wolfert, M. A. (2005). Simulation of integrated surface water/ groundwater flow and salinity for a coastal wetland and adjacent estuary. *Journal of Hydrology*, 314, 212–234.

Langevin, C. D., Thorne, D., Dausman, A. M., Sukop, M. C., and Guo, W. (2007). SEAWAT Version 4: A computer program for simulation of multispecies solute and heat transport. In *U.S. Geological Survey Techniques and Methods* (Book 6, Chapter A22). Washington, DC: U.S. Geological Survey.

Larsen, L. G., Harvey, J. W., and Crimaldi, J. P. (2007), A delicate balance: Ecohydrological feedbacks governing landscape morphology in a lotic peatland. *Ecological Monographs*, 77, 591–614.

Leendertse, J. J., Langerak, A., and de Ras, M. A. M. (1981). Two-dimensional tidal models for the Delta Works—Transport models for inland and coastal waters. In *Proceedings of the Symposium on Predictive Abilities* (pp. 408–450). New York: Academic Press.

Loucks, D. P. (1992). *Water resources systems models: Their role in planning*. Unpublished manuscript, Department of Civil and Environmental Engineering, Cornell University.

McDonald, M. G., and Harbaugh, A. W. (1988). A modular three-dimensional finite-difference groundwater flow model. In *U.S. Geological Survey Techniques and Methods* (Book 6, Chapter A1). Washington, DC: U.S. Geological Survey.

Miller, R. E. Jr., and Gunsalus, B. E. (1999). *Wetland rapid assessment procedure (WRAP)*. Technical Publication REG-001. Natural Resource Management Division, Regulation Department, South Florida Water Management District.

Nair, S. K., Montoya, A. M., Welter, D. E., Wilsnack, M. M., Switanek, M. P., Herr, J., Adam, D. M., Zamorano, L. M., Restrepo, J. I., and Obeysekera, J. T. B. (2000). *South Palm Beach County ground water flow model*. Hydrologic Systems Modeling Department, South Florida Water Management District, West Palm Beach, Florida.

National Research Council. (2003). *Does water flow influence Everglades landscape patterns?* Washington, DC: National Academy Press.

Randall, D. (1999). *User's documentation for the MODFLOW96 Trigger Package*. Water Resources Management.

Restrepo, J. I., Montoya, A. M., and Garces, D. (2003). *The updated utility generation package (USGEN) for the groundwater flow model, MODFLOW*. Developed by the Hydrological Research Center at Florida Atlantic University, Boca Raton, FL in cooperation with the South Florida Water Management District, West Palm Beach, FL.

Restrepo, J .I., Montoya, A. M., and Obeysekera, J. (1998). A wetland simulation module for the MODFLOW ground water model. *Ground Water*, 36, 764–770.

Russell, G. J., Bass, O. L., and Pimm, S. L. (2002). The effect of hydrological patterns and breeding-season flooding on the numbers and distribution of wading birds in Everglades National Park. *Animal Conservation*, 5, 185–199.

Russell, G. M., and Goodwin, C. R. (1987). *Simulation of tidal flow and circulation patterns in the Loxahatchee River Estuary, southeastern Florida*. U.S. Geological Survey Water-Resources Investigations Report 87–4201.

Schaffranek, R. W. (2004). Simulation of surface water integrated flow and transport in two dimensions: SWIFT2D user's manual. In *U.S. Geological Survey Techniques and Methods* (Book 6, Chapter 1). Washington, DC: U.S. Geological Survey.

Schaffranek, R. W., and Baltzer, R. A. (1990). Horizontal density-gradient effects on simulation of flow and transport in the Potomac estuary: New York. *Proceedings of the 1990 ASCE National Hydraulic Engineering Conference*, 1251–1256.

Shoemaker, W. B., and Edwards, K. M. (2003). *Potential for saltwater intrusion in the lower Tamiami aquifer beneath Bonita Springs in southwestern Florida*. U.S. Geological Survey Water-Resources Investigation Report 03–4246.

Smith, J. A., Day, G.N., and Kane, M. D. (1992). Non-parametric framework for long-range streamflow forecasting. *Journal of Water Resources Planning and Management*, 118, 82–92.

South Florida Water Management District. (2002). *Technical documentation to support development of minimum flows and levels for the Caloosahatchee River*. West Palm Beach, FL: South Florida Water Management District.

South Florida Water Management District. (2005a). *Documentation of the South Florida Water Management Model, Version 5.5*. West Palm Beach, FL: South Florida Water Management District.

South Florida Water Management District. (2005b). *Review of the SFWMM Adequacy as a Tool for Addressing Water Resources Issues*, Final Panel Report. West Palm Beach, FL: South Florida Water Management District.

South Florida Water Management District. (2005c). *Regional simulation model (RSM), hydrologic simulation engine (HSM) user's manual, Version 2.2.9*. West Palm Beach, FL: South Florida Water Management District.

South Florida Water Management District. (2006). *Restoration plan of the northwest fork of the Loxahatchee River*. West Palm Beach, FL: South Florida Water Management District.

South Florida Water Management District. (2008). Management and restoration of coastal ecosystems. In *2008 South Florida Environmental Report* (Volume I, Chapter 12). West Palm Beach, FL: South Florida Water Management District.

Stith, B. M., Swain, E. D., Reid, J. P., and Langtimm, C. A. (2006, June). *Linking a manatee individual-based model to assess restoration effects in the Everglades and Ten Thousand Islands*. Paper presented at the 2006 Greater Everglades Ecosystem Restoration Conference, Lake Buena Vista, Florida, USA.

Sukop, M. C., and Thorne, D. T. Jr. (2007). *Lattice Boltzman modeling: An introduction for geoscientists and engineers*. New York: Springer.

Swain, E. D. (2005). *A model for simulation of surface water integrated flow and transport in two dimensions: SWIFT2D user's guide for application to coastal wetlands*. U.S. Geological Survey Open-File Report 2005–1033, 88 p.

Swain, E. D., and James, D. E. (2007). Inverse modeling of surface-water discharge to achieve restoration salinity performance measures in Florida Bay, Florida. *Journal of Hydrology*, 351, 188–202.

Swain, E. D., Langevin, C. D., and Wang, J. D. (2008). Utilizing spectral analysis of coastal discharge computed by a numerical model to determine boundary influence. *Journal of Coastal Research*, 24, 1418–1429.

Swain, E. D., and Wexler, E. J. (1988). Techniques of water-resources investigations of the United States Geological Survey: A coupled surface water groundwater flow model (MODBRANCH) for simulation of stream-aquifer interaction. In *U.S. Geological Survey Techniques and Methods* (Book 6, Chapter A6). Washington, DC: U.S. Geological Survey.

Swain, E. D., and Wolfert, M. A. (2007, July). *Numerical modeling to determine freshwater/saltwater interface configuration in a low-gradient coastal wetland aquifer: In a new focus on groundwater-seawater interactions*. Paper presented at the IAHS Red Book Series, IUGG General Assembly, Perugia, Italy.

Swain, E. D., Wolfert, M. A., Bales, J. D., and Goodwin, C. R. (2003). *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.

Tarboton, K. C., Neidrauer, C. J., and Santee, E. R. (2001, May). *Application of the South Florida water management model to develop the Everglades Restoration Plan*. Paper presented at Specialty Symposium, World Water and Environonment Congress, Orlando, Florida.

Tasker, G. D., and Dunne, P. (1997). Bootstrap position analysis for forecasting low flow frequency. *Journal of Water Resources Planning and Management*. 123, 359–367.

U.S. Army Corps of Engineers and South Florida Water Management District. (1999). Central and Southern Florida project. Comprehensive review study. Final Integrated Feasibility Report and Programmatic Environmental Impact Statement (Vol I). Jacksonville and West Palm Beach, FL: U.S. Army Corps of Engineers and South Florida Water Management District.

Variano, E. A., Ho, D. T., Engel, V. C., Schmieder, P. J., and Reid, M. C. (2009). Flow and mixing dynamics in a patterned wetland: Part 1, kilometer-scale tracer releases in the everglades. *Water Resources Research*, 45. doi:10.1029/2008WR007216.

Wahba, G. (1990). *Spline models for observational data*. Paper presented at CBMS-NSF Regional Conference Series in Applied Mathematics, Society for Industrial and Applied Mathematics, Philadelphia.

Wan, Y., Konyha, K., and Sculley, S. (2002, July/August). *An integrated modeling approach for coastal ecosystems restoration*. Paper presented at the Second Inter-Agency Hydrologic Modeling Conference, Las Vegas, Nevada.

Wang, J. D., Swain, E. D., Wolfert, M. A., Langevin, C. D., James, D. E., and Telis, P. A. (2007). *Applications 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.

Wolfert, M. A., Swain, E. D., and Wang, J. D. (2006, June). *Utilizing the TIME model to simulate Comprehensive Everglades Restoration Plan (CERP) scenarios for Florida Bay and Florida Keys Feasibility Study (FBFKFS)*. Paper presented at the 2006 Greater Everglades Ecosystem Restoration Conference, Lake Buena Vista, Florida.

Wolfert-Lohmann, M. A., Langevin, C. D., Jones, S. A., Reich, C. D., Wingard, G. L., Kuffner, I. B., and Cunningham, K. J. (2008). *U.S. Geological Survey science support strategy for Biscayne National Park and surrounding areas in Southeastern Florida*. U.S. Geological Survey Open-File Report 2007–1288, 47 p.

Yeh, G.-T., Cheng, H.-P., Cheng, J.-R., and Lin, H.-J. (1998). *A numerical model simulating flow, contaminant, and sediment transport in watershed systems (WASH123D)*. Report CHL-98–15, U.S. Army Corps of Engineers.

Zygnerski, M. R., and Langevin, C. D. (2007, October). Long-term saltwater intrusion in a coastal limestone aquifer: quantifying effects of natural and anthropogenic stress. Paper presented at the 3rd International Symposium on Technology of Seawater Intrusion into Coastal Aquifers, Almeria, Spain.

Zygnerski, M. R., and Langevin, C. D. (2008, June). Quantifying effects of natural and anthropogenic stresses on long-term saltwater intrusion in a coastal aquifer. Paper presented at the 20th Salt Water Intrusion Meeting, Naples, Florida.