Appendix 12-1: Modeling Freshwater Inflows and Salinity in the Loxahatchee River and Estuary

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SUMMARY

This appendix describes the hydrologic and salinity models applied in the Northwest Fork of the Loxahatchee River Restoration Plan. The Loxahatchee Watershed (WaSh) model was developed to simulate freshwater flow from each of the tributaries into the Northwest Fork. The WaSh model is based on restructuring HSPF (Hydrologic Simulation Program – Fortran) into a cell-based system with the addition of a groundwater model and a full dynamic channel routing model (Wan et al., 2003). The model is capable of simulating surface water and groundwater hydrology in watersheds with high groundwater tables and dense drainage canal networks. Using long-term flow data collected at S-46, Lainhart Dam, Cypress Creek, Hobe Grove Ditch, and Kitching Creek, the WaSh model was calibrated and validated. The daily flow outputs from the 39-year simulation (1965–2003) provide the basis for the base condition and flow restoration scenarios of the Northwest Fork ecosystem restoration.

The Loxahatchee River Hydrodynamics/Salinity (RMA) model was developed to simulate the influence of freshwater flows on salinity conditions in the Loxahatchee River and Estuary. The RMA model is based on the RMA-2 and RMA-4 and was calibrated against field data from five locations and provided salinity predictions for many other sites where field data are not available. Tide/salinity data collected since 2002 have provided a field database for the investigation of the impact of freshwater inflow on the salinity regime in the Northwest Fork.

To perform long-term predictions of daily salinity, a Long-Term Salinity Management Model (LSMM) was developed to predict salinity and calculate several other performance parameters under various ecosystem restoration scenarios. Field data, regression analyses, and results from multidimensional hydrodynamic computer models were integrated into the LSMM as a system simulation and management tool. This salinity management model is applied to predict daily salinity from for the simulation period from 1965 to 2003 under the base condition and various restoration scenarios.

INTRODUCTION

The Loxahatchee River and Estuary, containing a federally designated Wild and Scenic River system located on the east coast in South Florida, provides habitats supporting a wide spectrum of ecological resources including seagrasses, oysters, saltwater vegetation, and freshwater vegetation. During the past 100 years, the natural hydrologic regime of the Loxahatchee River watershed has been altered by drainage activities associated with urban and agricultural development. Historically, most of the watershed was drained by the Northwest Fork of the Loxahatchee River. Today, much of the watershed has been impacted by the construction of canals and levees for drainage and opening of the Jupiter Inlet. These anthropogenic alterations have resulted in significant encroachment of saltwater-tolerant, mangrove-dominated community into the freshwater, bald cypress-dominated floodplain. Restoration and protection of the Northwest Fork floodplain ecosystem depends largely on providing healthy flow patterns to the river. Development of models capable of predicting long-term freshwater inflow and salinity in the Loxahatchee River and Estuary is critical for the formulation and evaluation of the restoration plan for the Northwest Fork of the Loxahatchee River and Estuary.

The map in **Figure 1** shows the locations of major tributaries and assessment sites that are referred to in this appendix.

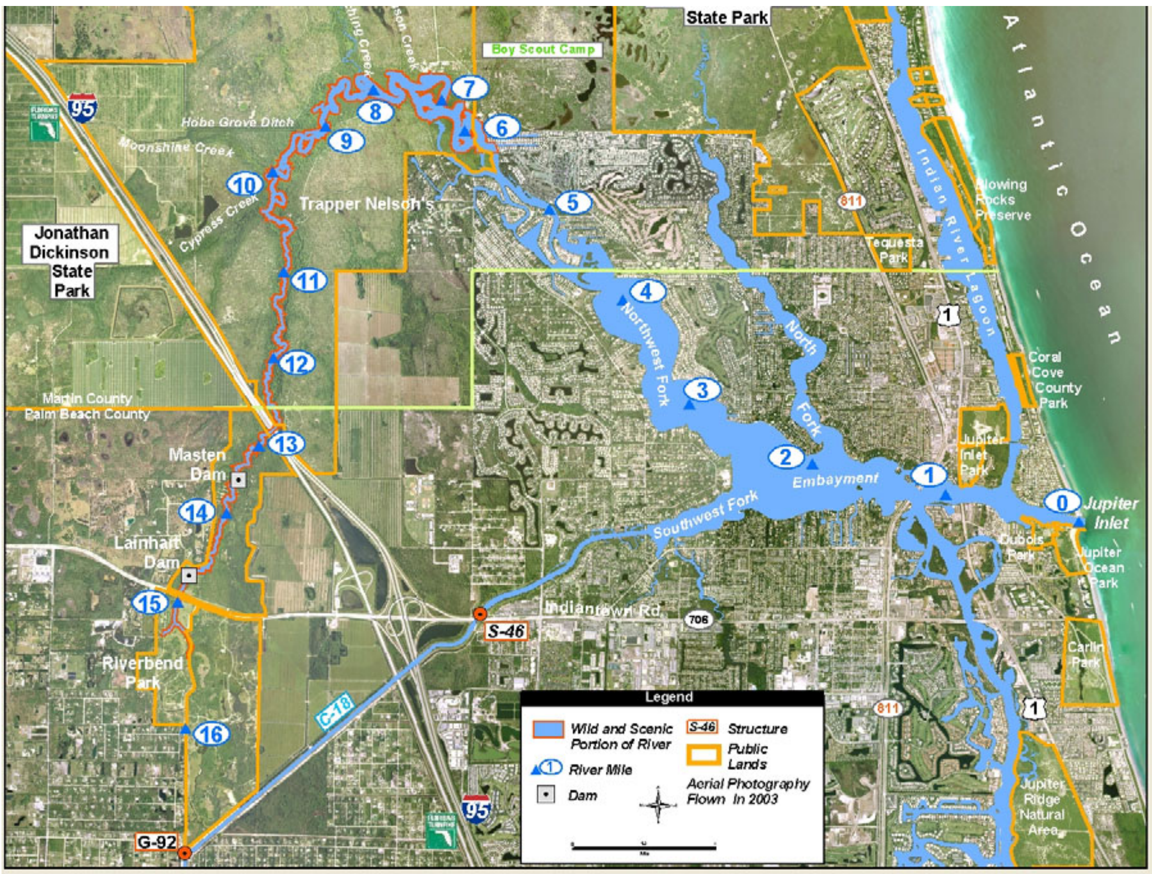


Figure 1. Locations of major tributaries and river miles.

Over the past several years, the South Florida Water Management District (SFWMD or District) has initiated several projects for data collection and model development. To date, three models have been developed to simulate freshwater inflows and salinity conditions in the Loxahatchee River and Estuary (**Figure 2**). These models include a watershed hydrologic model (WaSh) simulating long-term freshwater inflows from all tributaries into the Northwest Fork, a two-dimensional (2-D) estuarine hydrodynamic and salinity model (RMA) that simulates the influence of the freshwater inflows and tide on salinity conditions within the Loxahatchee River and Estuary, and a Long-Term Salinity Management Model (LSMM) that predicts daily salinity conditions according to freshwater inflows from the Loxahatchee River watershed. The LSMM was developed based on the modeling result of the RMA model. During the planning process, a 39-year period of daily freshwater inflow into the river was simulated with the watershed model to ensure that a wide range of climatic conditions was included. Various flow scenarios were proposed and the resulting daily salinity along key assessment locations was simulated with the LSMM. An integrated ecological assessment was carried out to evaluate the ecological benefits with respect to the health of freshwater floodplain vegetation, oysters, and seagrasses in response to these flow scenarios. Such an assessment is critical in selecting restoration alternatives to achieve the comprehensive ecologic benefit of all the ecologic components in the entire system. The purpose of this appendix is to document the calibration and validation results of these models and to provide a description of how these models are used in the evaluation of the Northwest Fork restoration alternatives.

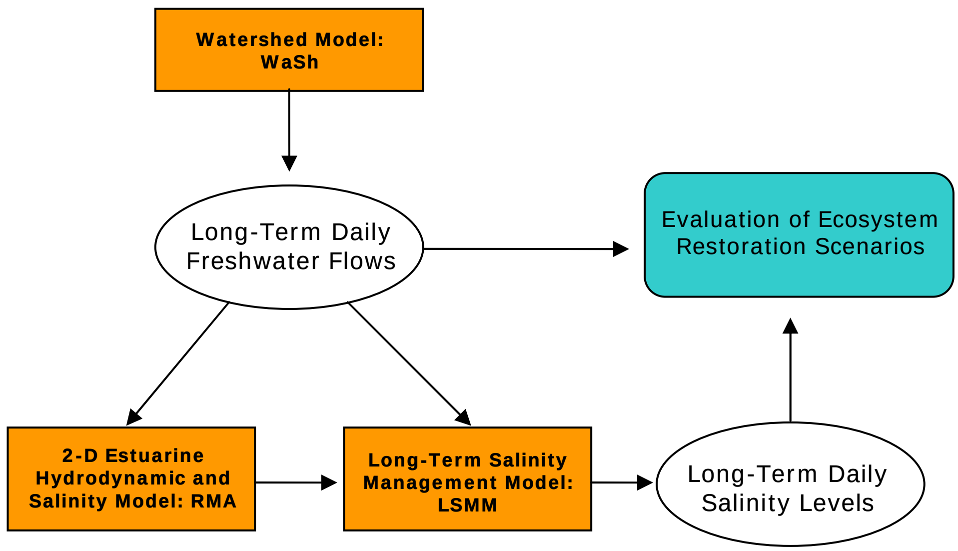


Figure 2. The relationship among the three models used to evaluate restoration plan scenarios for the ecosystems in the Loxahatchee River watershed.

Table 1 lists the time steps and the length of simulations that the models were designed for. Apparently the ecological assessments require long periods of simulations that are beyond the capability of a multiple dimensional hydrodynamic model. The Long-Term Salinity Management Model (LSMM) provided a bridge between the hydrodynamic model and the VEC models so that they could connect on the same time scale.

Table 1. The time scale of computer models.

Study Components/models	Spatial Resolution	Time Step	Maximum Length of Simulation
Watershed model	Site-specific output	Daily or monthly	Several years to several decades
Estuary model	Thousands of output points that may not coincide with specific sites	One to 30 minutes	Several months to several years
Ecosystem Evaluation Tools	Require site-specific information	Daily, monthly, or annual	Require long-term (several decades) information

MODELING FRESHWATER INFLOWS

THE WATERSHED MODEL DESCRIPTION

Freshwater inflows from major tributaries of the Northwest Fork of Loxahatchee River and Estuary are simulated with a watershed model. This model was developed based on restructuring HSPF (Hydrologic Simulation Program – Fortran, Donigian et al., 1984) into a cell-based system with the addition of a groundwater model and a full dynamic channel routing model (Wan et al., 2003). The WaSh model is capable of simulating hydrology in watersheds with high groundwater tables and dense drainage canal networks, which is typical in South Florida. The model consists of four basic components: (1) a cell-based representation of the watershed basin land surface, (2) a groundwater component that is consistent with the basin cell structure, (3) a surface water drainage system, and (4) water management practices. Key features of the model are surface water and groundwater interactions, irrigation demands, and transfers between elements of the surface water drainage network. For each cell, the model uses an infiltration routine to determine the amount of rainfall that infiltrates into the groundwater, evaporates into the atmosphere, or drains to the surface water system. Currently, the HSPF (Version 12) modules PWATER and IWATER are used for this portion. The infiltrated water is routed to a groundwater model that represents the unconfined aquifer in the watershed. The groundwater model receives the infiltrated water, exchanges groundwater between cells, and also exchanges water between surface water flow and groundwater flow. The surface water drainage system consists of a cell-based system and a reach-based system. The reach-based system is typically configured to follow the major canals, streams, and rivers and supports branches and common flow structures. The water quality component of WaSh is built on the surface water, groundwater, and channel flow components of the model. The application of the model in the Loxahatchee River watershed focuses on hydrologic simulation. The WaSh model is supported by a Graphic User Interface (GUI) that is developed as an ArcView extension. The GUI handles file management (both on the local platform and on the server), model configuration, execution, and post processing. The WaSh model also supports numerous water management practices such as irrigation, reservoirs, Stormwater Treatment Areas (STAs), and land use changes. Key components of the WaSh model are summarized in **Table 2**.

Table 2. The watershed (WaSh) model components and functions.

Model Component	Modeling Approach	Functions
Surface Water Flow	PWATER and IWATER of HSPF with PQUAL, SEDMNT, IQUAL, and SOLIDS for water quality	High water table algorithms of HSPF
Groundwater Flow	A new 2-D unconfined groundwater flow model with a prescribed leaching function for water quality constituents	Canal drainage and recharge
Channel Flow	A new 1-D fully dynamic shallow wave model with a scalar mass transport function for water quality	Structures, branching, point sources
Water Management	Reservoirs, Stormwater Treatment Areas, irrigation supply and demands, land use changes	Executed by an ArcView GUI

Model Cell Structure and Cell-Based Routing

The WaSh model uses a uniform structured grid network. Each cell represents a discrete part of the model domain and has associated physical characteristics such as land use, soil type, ground elevation, impervious area, and a representative ground slope. Hydrological parameters relating runoff, infiltration, and evaporation are specific to these attributes, particularly land use types. If tertiary canals are present in the cell, then the length and width of canals in the cell are computed and added as a cell attribute. Generally, the cell attributes are obtained by combining the cell network with Geographic Information System (GIS) coverage for each of the physical characteristics. For the purpose of routing the simulated daily runoff from each cell, a special cell attribute is assigned to indicate where runoff from that cell is directed. Each cell is labeled as one of three primary types: (1) free cell, (2) canal cell, or (3) reach cell. A free cell represents an area of the basin that does not contain canals. Canal cells are any cells with tertiary canals that are not coincident with the reaches. Reach cells are cells that contain a reach (major canals) in the primary canal system. Some secondary canals can be included in the reach system. These labels are needed to designate the types of surface water and groundwater interactions that may occur for a given cell. **Table 3** lists the methods in which water is routed for each type of cell.

Table 3. WaSh water routing operations for each cell type.

Cell Type	Flow Routing Operations
Free	Infiltration is directed to cell groundwater Surface water is directed to a nearby cell's canals
Canal	Infiltration is directed to cell groundwater Surface water is directed to cell canals Groundwater can be exchanged with canal surface water Surface water can be exchanged between the canal and the reach
Reach	Infiltration is directed to cell groundwater Surface water is directed to the cell's reach or nearby cell's canals Groundwater can be exchanged with canal or reach surface water Reach water can be exchanged with canal water

Surface Water and Groundwater Interaction

The surface water and groundwater is modeled in the same grid network. For each cell, WaSh uses the PWATER and IWATER modules of HSPF (Version 12) to simulate surface water hydrology (**Table 2**). A detailed description of these modules is available in the HSPF user's manual (Donigian et al., 1984). Version 12 includes recent model enhancements that simulate irrigation demand, high water tables, and wetland conditions that are common in South Florida (Aqua Terra, 1996; 1998). The HSPF routine is implemented in one-hour time step for 24-hour blocks. Thus, the HSPF-based routine is applied daily for each cell and water balance, consisting of rainfall, evaporation, soil storage, surface runoff, and infiltration to groundwater. At the end of each one-day simulation period, the accumulated surface runoff and infiltration are routed to the drainage and groundwater systems, respectively. All HSPF model parameters are calibrated and assigned to each cell based on the land use and soil type characteristics as additional cell attributes.

The groundwater module in WaSh is based on the numerical solution of the standard groundwater flow equation for an unconfined aquifer. The model operates on a daily time step, during which it receives infiltrated water, loses water to evaporation, and exchanges water with adjacent cells and with canals. The basic governing equation for the groundwater module is:

$$\rho \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} K_x (h - h_c) \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} K_y (h - h_c) \frac{\partial h}{\partial y} + S_i - S_e + S_c + S_r \qquad [1]$$

where h is the groundwater elevation, ρ is the porosity, K_x and K_y are the hydraulic conductivity in the x-, and y- directions, h_c is the aquifer base elevation, and S_i, S_e, S_c, and S_r are source/sink terms representing infiltration, evaporation, exchanges with the canal cells, and exchanges with reaches. The governing equation is solved numerically using the basin cell structure. A second-order finite difference approximation is used for the second derivatives, and an explicit backward difference approximation is used for the time derivative. During each time step the right-hand side of the equation is evaluated based on current time level conditions, and the new water elevation is found. By designating the equation parameters and water elevation h for each cell by the indexes $_{i,j}$, and the time level by the index ^{m}, the resulting finite difference equation for each cell is:

$$\frac{1}{\rho_{i,j}}\frac{h_{i,j}^{m+1}-h_{i,j}^{m}}{\Delta t}=K_x\left[\frac{(\frac{h_{i,j}^{m}+h_{i+1,j}^{m}}{2}-h_c)}{\Delta x}\left(\frac{h_{i+1,j}^{m}-h_{i,j}^{m}}{\Delta x}\right)-\frac{(\frac{h_{i,j}^{m}+h_{i-1,j}^{m}}{2}-h_c)}{\Delta x}\left(\frac{h_{i,j}^{m}-h_{i-1,j}^{m}}{\Delta x}\right)\right]+$$

$$Ky\left[\frac{(\frac{h_{i,j}^{m}+h_{i,j+1}^{m}}{2}-h_c)}{\Delta y}\left(\frac{h_{i,j+1}^{m}-h_{i,j}^{m}}{\Delta y}\right)-\frac{(\frac{h_{i,j}^{m}+h_{i,j-1}^{m}}{2}-h_c)}{\Delta y}\left(\frac{h_{i,j}^{m}-h_{i,j-1}^{m}}{\Delta y}\right)\right]+S_{i_{i,j}}^{m}-S_{e_{i,j}}^{m}+S_{c_{i,j}}^{m}+S_{r_{i,j}}^{m} \qquad [2]$$

where Δt is the time step (one day), and Δx and Δy are the grid cell dimensions in each direction. During each time step the right-hand side of the equation is evaluated based on current time level conditions, and the new water elevation is found by solving for $h_{i,j}^{m+1}$. When an active cell is adjacent to the grid boundary or to an inactive cell, a no-flow condition is imposed.

Implementation of the groundwater model has required some modification to the PWATER module, primarily to account for evaporation from groundwater and also to link to the irrigation and high water table modules. The original HSPF groundwater algorithm is based on groundwater storage, AGWS. Changes to the storage for each time step are due to infiltration (GWI), evaporation (BASET), and discharge to surface water (AGWO). Infiltration is predicted using subroutines representing the Stanford Watershed Model approach. Evaporation is modeled as a loss term, which is based on a model parameter BASETP. The discharge is based on a rating curve, specified by the model parameters AGWRC and KVARY. This groundwater discharge algorithm in HSPF has been disabled and replaced by the equivalent parameters in WaSh. For each of the cells, two of the source terms on the right-hand side of the equation, $S_{i_{i,j}}^{m}$ and $S_{e_{i,j}}^{m}$ are set equal to output variables from HSPF PWATER groundwater subroutine related to infiltration (GWI) and evaporation (BASET). The groundwater elevation $h_{i,j}$ replaces the storage variable, AGWS, and when combined with the two source terms, represent essentially the same processes as AGWO in HSPF. However, this modification provides a process-based approach to represent surface water and groundwater interactions when compared with the rating curve-based groundwater discharge approach in HSPF. For example, the source/sink terms for a canal/reach cell are now defined as:

$$S_{c_{i,j}}^{m}=\frac{\Delta H\ C_c}{A} \qquad [3]$$

$$S_{r_{i,j}}^{m}=\frac{\Delta H\ C_r}{A} \qquad [4]$$

where ΔH is the difference in groundwater elevation and canal or reach surface water elevation, which are dynamically tracked in WaSh, A is the cell area, and C_c and C_r are the conductance of canal or reach, respectively. The conductance is physically related to the hydraulic conductivity of the stream bed material and the length and width of the canal. In the Loxahatchee River watershed, the hydraulic conductivity of the deep canals (reaches) and shallow canals is different. The hydraulic conductivity and canal dimension are provided as input data for each cell according to the basin hydrography and land use.

Irrigation Demand and High Water Table Conditions

The WaSh groundwater module has also been developed to interact with the irrigation module and the high water table module of the HSPF. WaSh simulates the irrigation demand by monitoring the moisture in the upper and lower soil zones and generating a demand for water based on the existing moisture relative to the desired moisture level that is specified by the user. After the irrigation demand is calculated, the algorithm tries to meet the demand by supplying water from a number of sources. Groundwater can serve as both an irrigation source and an irrigation sink (receptor) in the HSPF irrigation algorithm. In each case, the amount of water demanded from, or applied to, the groundwater is extracted or added to the cell's groundwater volume. At the beginning of each day, the irrigation demand is calculated and if groundwater is affected, then the groundwater elevation $h_{i,j}$ is adjusted according to the following equation:

$$h_{i,j} = h_{i,j} + \Delta V / \rho \qquad [5]$$

where ΔV is the volume (expressed as depth) of groundwater irrigation demand or application for the cell calculated by the HSPF irrigation module, and ρ is the aquifer porosity as defined previously in Equation [1].

The high water table module in the HSPF requires certain vertically referenced parameters and variables to allow for exchange of water between storage components when the groundwater level interferes with the upper and lower zone storage (UZS and LZS). For applications in WaSh, the vertical referencing is already completed, as the surface elevation (a cell attribute) and the groundwater elevation h are all referenced to the same datum. Thus, the only required modification is to provide these two variables to the high water table algorithms. The HSPF high water table algorithm then calculates the exchange between the storage zones and the groundwater. The groundwater elevation is updated with Equation [5], where ΔV now represents the exchange between the upper and lower storage zones.

Drainage Canal Network and Canal Routing

The surface water drainage canal network is modeled implicitly in the cell-based system and explicitly in the reach-based system. The major channels are simulated in the reach-based system which consists of a series of reaches and nodes. This drainage system is separated from the cell system, but its elements (reaches and nodes) overlay the cell network and coincide with a subset of the cells. This system is typically configured to follow the major canals, streams, and rivers in the basin. The small or tertiary canals are represented in the cell-based system. These canals receive surface and subsurface runoff from the adjacent cells and exchange water with neighboring canal cells.

Flow through the reach-based systems is modeled using the continuity equation, Equation [6], and the depth- and width-averaged shallow water wave equation, Equation [7]. The governing equations are:

$$\frac{\partial wh}{\partial t} = \frac{\partial q}{\partial s} + Q_e \qquad [6]$$

where q is the flow, u is the width- and depth-average flow velocity, g is the acceleration due to gravity, w is the canal width, h is the water depth (referenced to the canal bed), η is the bed elevation, t is time, and s is distance along the canal. The bottom stress τ_b is based on a Manning's n formulation. Boundary conditions can be one of two types: a specified flow or a

$$\frac{\partial q}{\partial t} + \frac{\partial uq}{\partial s} + \frac{gw}{2}\frac{\partial h^2}{\partial s} = -w\tau_b - gwh\frac{\partial \eta}{\partial s} \qquad [7]$$

specified water elevation. Specified flow conditions are typically used when a flow structure controls the flow out of the system. The water elevation (or head) condition is used when the system drains unobstructed into a receiving water body. The governing equations are solved using a finite volume procedure, with the reach and node system for a single branch equivalent to a finite volume staggered grid approach.

The source term Q_e in the continuity equation, Equation [6], consists of point sources or sinks, exchange with groundwater, and exchange with canals from the cell-based system. The units for the source term are flow per unit length of channel. The general form for the source term can be expressed as:

$$Q_e = Q_{kp} + Q_{ki} + Q_{r,gw} \qquad [8]$$

where Q_{kp} are external sources or sinks (user-specified time series), $Q_{r,gw}$ is the exchange with the groundwater and is equal to S_r, the exchange calculated in the groundwater model, Equation [1], and Q_{ki} is the exchange with the canal cells where the tertiary canals are connected with the reach.

When the reach-based system contains branches, the flow in each branch is determined independently. The method for estimating the flow between branches depends on whether the flow is natural at the connection or whether a structure exists. When a structure is present at the branch connections, the flow is determined using a rating curve specific to the structure. Since the flow can be bi-directional, the flow direction for the time step is first determined from the water elevations in the reaches at the branch juncture. The water elevations for headwater and tailwater are then assigned appropriately and the rating curve is used to calculate the flow. It is noted that structures can also occur at any node along the reach node system. When a structure is present, the flow at that node is determined at the beginning of the time step using the structure flow formulas and its value replaces the momentum equation for that node. When no structures are present at the branch connections, the flow is solved using the shallow water wave equation, Equation [7], and the continuity equation, Equation [6]. The two equations are solved explicitly for the flow between branches using the two reaches that connect the branches. The calculated flow in the 'local' explicit solution is then used as a boundary condition for the implicit solution for the upstream branch and as a source to the downstream reach.

Flow in the cell-based canal system (i.e., the tertiary canals) is represented in the WaSh model using the same governing equations and numerical scheme as used for the reach-based system. To implement this approach, the cell-based canal parameters are first mapped into a 'local' branch and reach network. When this mapping is completed, the solution algorithm for the reach system can be applied to the local system with only minor modifications to the downstream boundary condition and the source terms. The source term in the cell canal would then include surface runoff simulated with HSPF routines.

The tertiary canals are characterized by the total length LC of these canals within the cell, the average canal width w_c, the average canal bottom elevation, and a critical or 'design' water depth.

These parameters are attributes of the cell. They can be obtained by mapping GIS hydrologic data onto the basin grid and then specifying widths, bottom elevations, and critical depths based on the cell land use. The surface water elevation is the dependent variable in the system. In order to map these parameters into a branched network, each cell's canals are designated as a single reach. The reach parameters for the cell are determined as follows:

If the total canal length L is less than the cell length LC, then:

$$\Delta s = L, \quad and \;\; w = w_c \qquad [9]$$

If the total canal length L is greater than the cell length LC, then:

$$\Delta s = LC, \quad and \;\; w = w_c * \frac{L}{LC} \qquad [10]$$

After the cell-based canal parameters are transformed into reach parameters, the connectivity of the branch network is determined. The connectivity of the cells is used directly to establish branches and the assignments of reaches within each branch. The canal-to-canal flow is generally towards the reaches, but the instantaneous flow is determined by the difference in relative surface water elevations between hydraulically connected canal cells. When canal cells exist in cells with reaches, the canals are assumed to be hydraulically connected to the reach via a structure. It is in these cells that water can flow between the canals and reaches. Between the reaches and tertiary canals, the flow is assumed to be controlled by pumps. The pumping capacity is derived from land use types, representing the design (or estimated) drainage capacities for the canal systems associated with each land use. The drainage capacities of the major land use types are the key parameters for calibrating the magnitude of peak flow during a high magnitude and low frequency event.

IMPLEMENTING THE WaSh MODEL

Watershed Delineation

The Loxahatchee River watershed is located within northern Palm Beach and southern Martin counties and currently drains an area of approximately 240 square miles. Much of the watershed remains as undeveloped sloughs and wetlands. In the upper portion of the watershed, nearly half of the drainage basin is comprised of wetlands. Agriculture and forested uplands in the northern area of the basin comprise one quarter of the watershed. The remaining quarter of the watershed consists of developed urban areas.

The Loxahatchee River watershed was delineated into 12 drainage basins based on local hydrology, land use, topography, detailed aerial photography, and field observations. These basins represent the same areas as the seven sub-basins described in the Loxahatchee River Watershed Action Plan (FDEP, 1998); four of the FDEP sub-basins have been subdivided into separate basins to reflect the specific needs of modeling. The basins vary in size from 5 to 100 square miles, and they provide flow to the three forks of the Loxahatchee River (**Figure 3**).

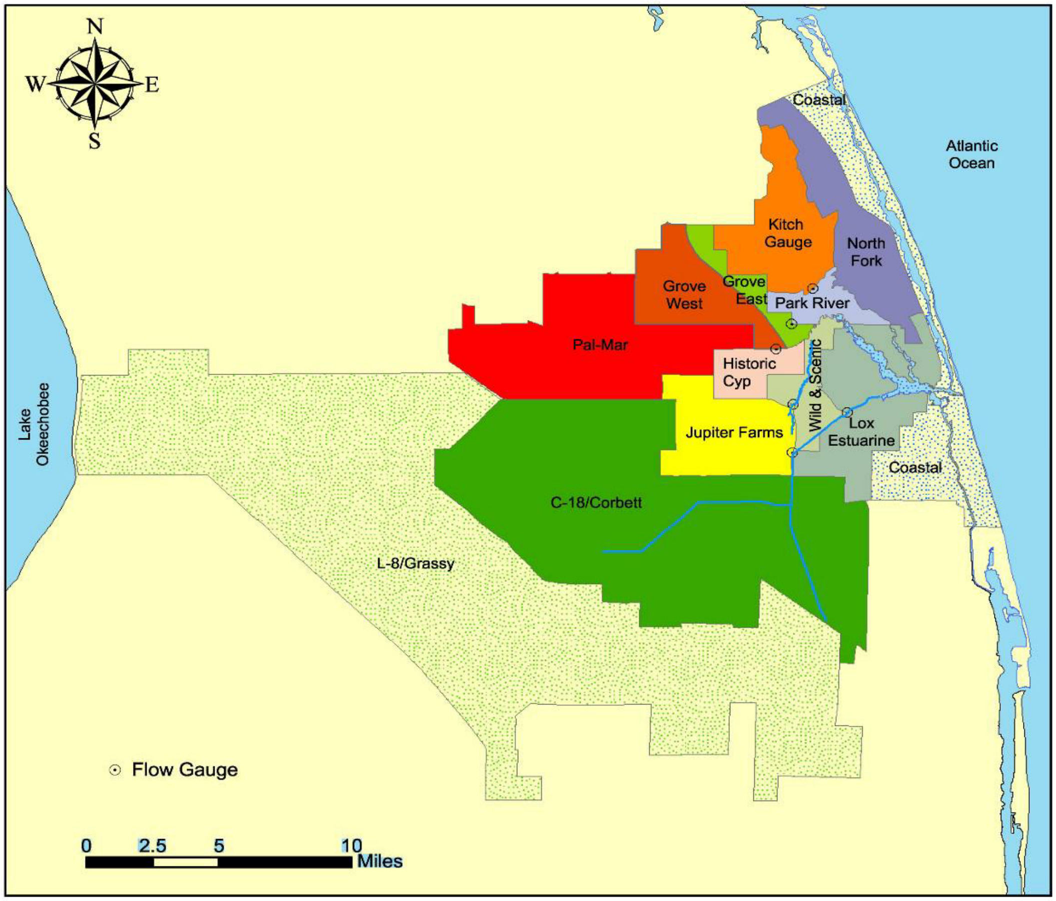


Figure 3. Major drainage basins in the Loxahatchee River watershed.

The 1995 land use for these basins has been modified to include changes in the developed areas for the year 2000. For purposes of this plan, the 133 land use codes were reduced to six land use categories: citrus and vegetables, forest, marsh wetland, other wetland, urban, and other land. **Table 4** shows the breakdown of land use by basin for the Loxahatchee River watershed.

Table 4. Loxahatchee River watershed 1995 land use by basin; developed areas updated for the year 2000.

Basin		Land Use (acres)						Total Area by Basin	
		Citrus & Vegetables	Forest	Marsh Wetland	Other Wetland	Urban	Other Land	Acres	Square Miles
1. Kitch Gauge		16	876	4,954	1,010	309	3,177	**10,342**	**16.2**
2. North Fork		0	95	8,238	735	1,774	156	**10,999**	**17.2**
3. Park River		14	60	2,483	47	31	408	**3,044**	**4.8**
4. Lox Estuarine		591	305	1,155	617	10,536	34	**13,237**	**20.7**
5. C-18/Corbett		1,821	822	43,591	4,749	9,199	3,312	**63,494**	**99.5**
6. Historic Cypress Creek		340	12	2,993	132	85	20	**3,581**	**5.6**
7. Pal-Mar		266	88	19,477	555	1,672	605	**22,663**	**35.4**
8. Grove West		4,107	168	2,878	86	54	906	**8,199**	**12.8**
9. Grove East		1,709	143	397	105	309	345	**3,010**	**4.7**
10. Jupiter Farms		8	89	494	168	9,359	128	**10,246**	**16.0**
11. Wild & Scenic		752	142	2,562	220	278	392	**4,345**	**6.8**
12. Coastal		0	2,190	2,212	2,180	8,899	391	**15,872**	**24.9**
Total Area by Land Use	Acres	**9,624**	**4,990**	**91,434**	**10,603**	**42,505**	**9,874**	**169,031**	
	Square Miles	**15.1**	**7.8**	**143.3**	**16.6**	**66.6**	**15.5**	**264.9**	

Note: Blue shaded rows are watershed basins that discharge into the Northwest Fork of the Loxahatchee River.

Basin 1: Kitch Gauge. This basin contains the 16.2-square-mile area that contributes water to the USGS Kitching Creek flow gauge in Jonathan Dickinson State Park. Almost 50 percent (4,654 acres) of this basin is characterized as marsh wetland. Downstream of this basin, Kitching Creek discharges into the Northwest Fork.

Basin 2: North Fork. This basin contains the 17.2-square-mile area that contributes water to the North Fork of the Loxahatchee River. Approximately 75 percent (8,238 acres) of this basin is marsh wetland. The flow from this basin is not gauged.

Basin 3: Park River. This basin contains the 4.8-square-mile area that drains to the Northwest Fork of the Loxahatchee River. It includes the portion of land draining to Kitching Creek downstream of the gauge and some smaller tributaries such as Wilson Creek and the creek flowing through the Boy Scout Camp. Approximately 82 percent (2,483 acres) of this basin is marsh wetland. The flow from this basin is not gauged.

Basin 4: Lox Estuarine. This central drainage basin is a 20.7-square-mile area and is highly developed with urban land uses that contribute significant runoff to the embayment of the Loxahatchee River. Consisting of 20.7 square miles of the watershed, this basin provides aquatic recreational opportunities that sometimes exceed the river's carrying capacity on weekends and holidays. Runoff and groundwater from this basin discharge to brackish waters of the estuary. Approximately 80 percent (10,536 acres) of this basin is urban. The flow from this basin is not gauged.

Basin 5: C-18/Corbett. With 100 square miles, this is the largest basin in the Loxahatchee River watershed. Much of the land in this basin encompasses the southwestern portion of the watershed, and it is publicly owned and protected. This basin includes the remnants of the Hungryland and Loxahatchee sloughs, which historically fed the Northwest Fork of the Loxahatchee River. Historically, the Loxahatchee Slough extended south into the area currently known as the Grassy Waters Preserve (West Palm Beach Water Catchment Area), which is the present source of drinking water for the City of West Palm Beach. Water from this basin discharges to the C-18 canal and is either discharged into the Southwest Fork of the Loxahatchee River through the S-46 structure or directed through the G-92 structure to the upper end of Northwest Fork of the Loxahatchee River. Approximately 69 percent (43,591 acres) of this basin is marsh wetland. Flow gauges are located at the G-92 and the S-46 structures.

Basin 6: Historic Cypress Creek. Cypress Creek is a 5.6-square-mile basin that drains to Cypress Creek just downstream of the Cypress Creek flow gauge. The majority of this basin has recently been purchased by state and local governments for restoration and preservation. Water from this basin flows into Cypress Creek and discharges at the upper end of the Northwest Fork near River Mile (RM) 10.3. Approximately 84 percent (2,993 acres) of this basin is marsh wetland. The flow from this basin is not gauged.

Basin 7: Pal-Mar. Pal-Mar is a 35.4-square-mile basin that drains a sizable wetland located along the western edge of the watershed and is one of the major tributaries to the Northwest Fork of the Loxahatchee River. Most of these wetlands remain intact; however, the eastern flow-ways leading to Cypress Creek have been disturbed by rural development. Approximately 86 percent (19,477 acres) of this basin is marsh wetland. Water from this basin flows into Cypress Creek upstream of the Cypress Creek flow gauge and discharges at the upper end of the Northwest Fork near RM 10.3.

Basin 8: Grove West. The predominant land use in this 12.8-square-mile basin is citrus. Although the hydrology in this basin was altered to support agriculture, wildlife utilization is relatively good, and the land provides a valuable greenway link between large natural areas within the watershed. Approximately 50 percent (4,107 acres) of this basin is used for vegetables and citrus. Water from this basin flows into Cypress Creek upstream of the Cypress Creek flow gauge and discharges at the upper end of the Northwest Fork.

Basin 9: Grove East. The predominant land use in this 4.7-square-mile basin is citrus. Although the hydrology in this basin was altered to support agriculture, wildlife utilization is relatively good, and the land provides a valuable greenway link between large natural areas within the watershed. Approximately 57 percent (1,709 acres) of this basin is used for vegetables and citrus. Water from this basin flows into Hobe Grove Ditch (RM 9.07) and Moonshine Creek (RM 10.0), both of which discharge into the Northwest Fork near RM 9.0.

Basin 10: Jupiter Farms. This 16-square-mile basin supports substantial rural residential development known as Jupiter Farms. The South Indian River Water Control District (SIRWCD) manages a stormwater management system of canals to serve this area. Water quality and saltwater intrusion in the Northwest Fork are concerns in this basin (FDEP, 1998). Water from this basin discharges into the SIRWCD C-14 canal, which flows over Lainhart Dam feeding the upper end of the Northwest Fork. The C-18 canal is connected to this basin by the G-92 structure, which also provides periodic flows of water over the Lainhart Dam from the C-18 canal. Approximately 91 percent (9,359 acres) of this basin is urban land. There is a flow gauge at both G-92 and Lainhart Dam.

Basin 11: Wild and Scenic. This 6.8-square-mile area basin contains the "Wild and Scenic" Northwest Fork of the Loxahatchee River and the northern portion of Riverbend Park. Approximately 59 percent (2,562 acres) of this basin is marsh wetland. The flow from this basin is not gauged.

Basin 12: Coastal. The coastal basin contains the 34-square-mile area that drains to the Atlantic Ocean or the Intracoastal Waterway and out the Jupiter Inlet. This basin has been developed for maximum urban residential, commercial, and recreational use. Very few small and isolated natural areas remain. Most of the surface water and groundwater from this basin discharge to marine waters rather than toward the freshwater portion of the Northwest Fork. The flow from this basin is not gauged.

Adjacent Basin: L-8/Grassy. This 192.5-square-mile basin is not considered part of the Loxahatchee River watershed. However, this basin has several outflow locations, one of which is to the C-18/Corbett Basin. Thus, the inter-basin transfers of waters from Grassy Waters to the C-18 canal are considered in this plan. There are no flow gauges at this inter-basin location.

Model Setup

The WaSh model was implemented into four regions of the Loxahatchee River watershed (**Figure 3**). These regions include all of the major drainage basins except the Coastal Basin. The JDSP region (A) includes the North Fork, Kitch Gauge, Park River, and the Loxahatchee Estuary basins. The Pal-Mar and Grove region (B) includes the Pal-Mar, Historic Cypress Creek, Grove West, and Grove East basins. The Jupiter Farms region (C) includes the Jupiter Farms and the Wild and Scenic basins. The C-18 region (D) represents the C-18/Corbett Basin and flow diversion from the L-8/Grassy Basin. The cells for each of the regions are shown in **Figure 2.** The cell size was 750 ft by 750 ft for the Jupiter Farms region, 1000 ft by 1000 ft for the JDSP region and Pal-Mal/Grove region, and 1500 ft by 1500 ft for the C-18 region.

Input data required to generate the model grid include primary and secondary basin coverages, polygon features with basin name attributes, hydrography including streams and canals as line or polyline features, the 2000 base land use coverage, soil coverage, and land surface elevation. The land surface contour was resampled (100-foot intervals) based on 5 ft by 5 ft Light Detection and Ranging (LIDAR) data to get a smooth land surface profile and to remove data artifacts. For limited areas where LIDAR data are not available, the 1-foot contour was used. Using the ArcView GUI, these coverages are overlaid to get an aerial extent of the model domain along with cell attributes of land use type, soil, canal length and width, and elevation.

When creating the primary reaches for the basins, the hydrography theme is overlaid on the grid and those grid cells intersecting with polylines of the hydrography theme are classified as canal cells. The canal length in a grid cell is calculated with all the intersecting canal segments inside a grid cell. Reach cells are created by digitizing major river segments and canals starting from the basin outlet. After digitizing, the length of a reach, which is typically the grid cell size, is specified to allow for redistribution of the nodes along the reach network. Each of the reach segments has a reach ID along with the width and bottom elevation assigned according to the cross-section of the major canal and river segment. In **Figure 4**, the cells are color coded to represent canal cells (turquoise), reach cells (pink), and free cells (light green). The surface elevation of cells is used to create flow paths. In general, flow in free cells is routed to the nearest canal or reach cell (**Figure 4**, Region B). A no flow boundary condition is imposed along the boundary cells.

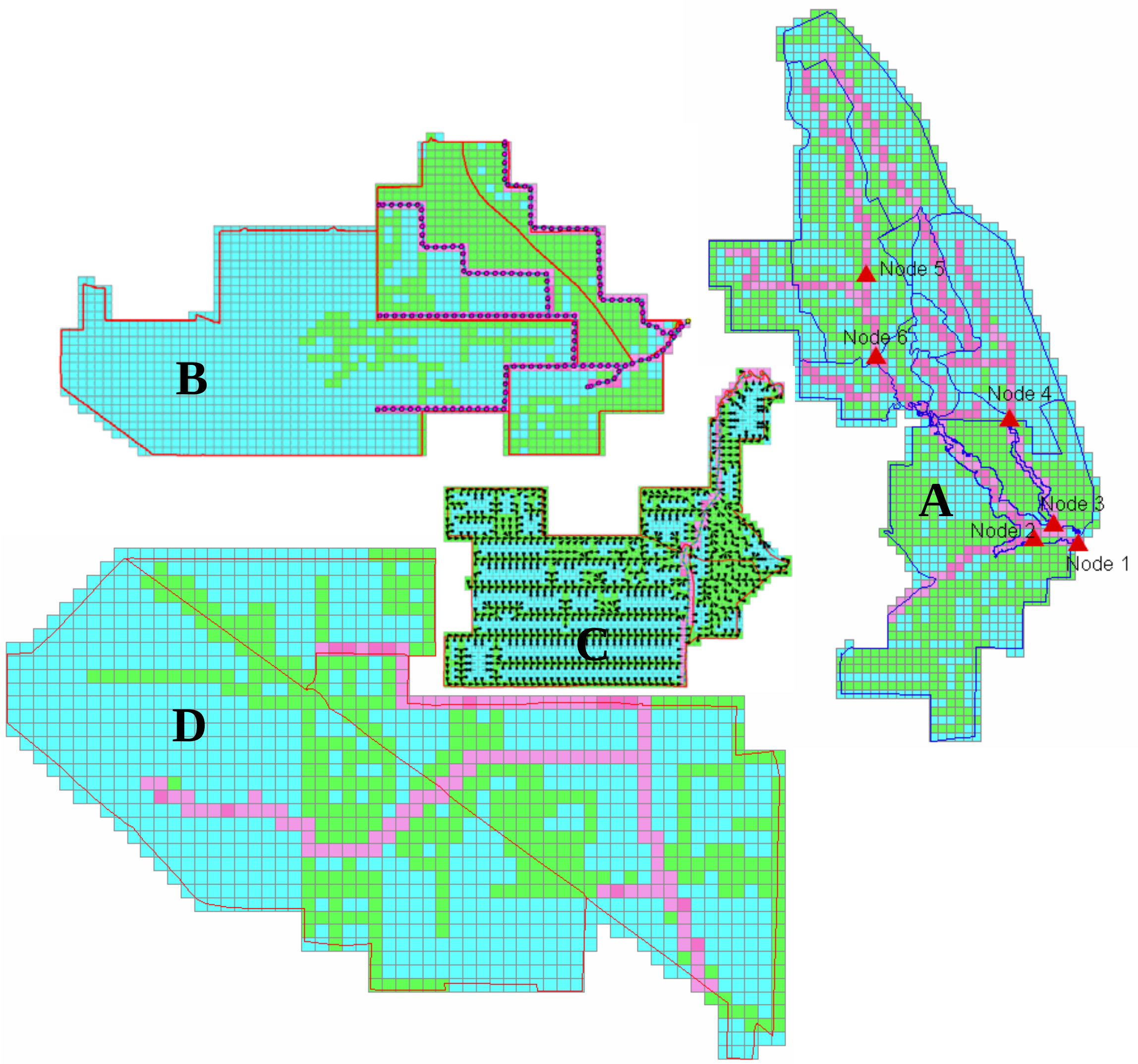


Figure 4. The Loxahatchee WaSh model grids: (A) JDSP model, (B) Pal-Mar-Grove model, (C) Jupiter Farm model, and (D) C-18 model. Free cells, canal cells, and reach cells are color coded turquoise, light green, and pink, respectively. In Region A, the blue line represents the model boundary, and the nodes represent examples of possible model output locations. In Region B, the nodes are shown in the reach system. In Region C, flow routing directions are shown with arrows.

Each of the cells is linked with a Master Lookup Database consisting of HSPF parameters, evapotranspiration (ET) coefficients, canal parameters, and aquifer properties. Based on the grid cell attribute, this master database is queried to populate the respective parameters for each cell in the grid. Some of the model parameters can be changed during the model calibration process.

The other important input data required by the model are rainfall and ET. These data were obtained from the District's South Florida Water Management Model (SFWMM) for the period from 1965–2000. The dataset was extended to March 2004 with available rainfall and ET data stored in the District's DBHYDRO database in the model area. Daily rainfall is disaggregated into hourly rainfall based on an analysis of available hourly rainfall distribution in South Florida.

Model Calibration and Validation

The Loxahatchee WaSh model has been calibrated with five flow monitoring stations (**Figure 5)**. Flow data collected at the G-92 structure are not used since it was found that the data are likely not accurate. The Kitching Creek station started to collect data in the early 1980s. The data are not continuous until 1990, and thus only the data collected after 1990 are used for calibration and validation of the JDSP model. The Hobe Grove and the Cypress Creek stations have been collecting data since 1980; however, there are significant periods of time when data were not collected or are missing. Data collected from the flow stations at S-46 and Lainhart Dam have the longest record. Only the data collected after 1987 were used for WaSh model calibration and validation due to structure changes of G-92. All the collected flow data were evaluated for their validity before being used for model calibration and validation. In addition, water level data collected in two groundwater wells (PB-689 and M-1234) were used. PB-689 is located in the C-18/Corbett basin where the land use is dominated by wetland while M-1234 resides in a forest land of the Cypress Creek basin.

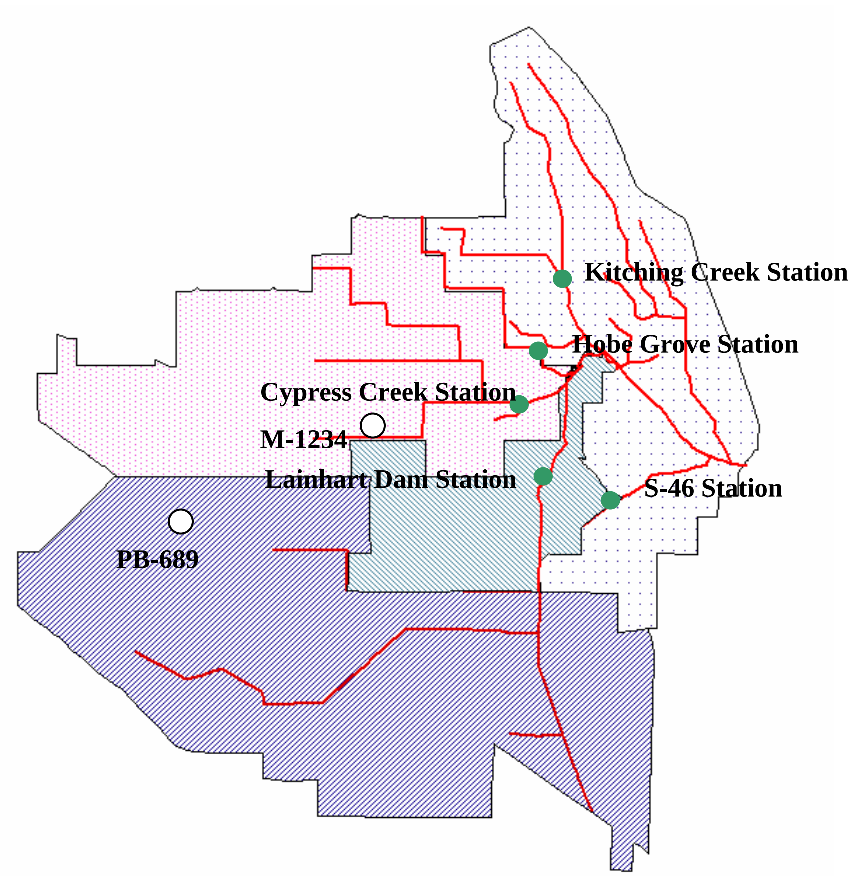


Figure 5. Flow (green dots) and groundwater (white dot) monitoring stations in the Loxahatchee River watershed for WaSh model calibration arrows.

Model calibration involves conducting a model simulation of each region for the period of record (POR) and comparing the simulated flow with the observed flow. The model parameters are then adjusted in subsequent simulations to improve the shape of simulated flow time-series until the model output meets the performance criteria. In general, the hydrological calibration is conducted in two main steps:

1. Macro Scale: Adjust hydrological parameters to obtain the long-term basin water budget.
2. Micro Scale: Fine tune model parameters to get the best match between observed and simulated flow. At this stage, the shape of the hydrograph with respect to peak and base flow is adjusted. Groundwater levels were also checked with data from observation wells.

In the first step, the long-term water budget is used to ensure that the model calibrations are not biased for one type of climatic condition. Another component of the water budget calibration is verifying that the fractions of groundwater and surface water contribution to runoff properly reflect the partitioning between surface runoff and subsurface runoff. For this component of the simulation, the average annual water budget for each of the land uses as well as for the entire watershed were used to make decisions to adjust parameters. An initial run of the model was made using model parameters that were calibrated in the St. Lucie Estuary watershed (Wan et al., 2003). The most sensitive model parameters in completing the water budget calibrations are evaporation coefficients for individual months and infiltration parameters of the HSPF. An example of the water budget is provided in **Table 5** for the Pal-Mar and Grove regions. The water budget is partitioned into the Pal-Mar and historic Cypress Creek basins, which consist mostly of wetland and forest, and the Grove West and Grove East basins, which consist mostly of irrigated citrus groves. Citrus irrigation significantly increases the runoff from a water budget perspective.

Table 5. Average annual water budget (inches) for the Pal-Mar and Grove regions.

Basins	Rainfall	Irrigation	ET	Runoff		Storage
				Surface	Subsurface	
Pal-Mar & Historic Cypress Creek	61.2	--	44.9	13.6	2.6	1.7
Grove West & Grove East	61.2	8.2	40.2	16.9	11.9	0.2

Once the long-term calibration is completed, the next step is to validate the model by matching the simulated daily flow hydrograph to the measured daily flow values recorded for each of the flow stations. The more significant parameters to be calibrated during this step includes the groundwater cell conductance parameters that control the rate at which groundwater flows to the canals, the irrigation parameters, and the canal pumping parameters that control the rate at which tertiary canals flow to primary reaches. To a lesser degree, the length-scale parameter associated with surface drainage (LSUR) has an effect on the shape of the hydrographs. Reducing the LSUR increases runoff and decreases infiltration. The model validation process is similar to the calibration process, except that a different POR is used for the relevant input data. The model parameters are kept constant. Model validation is considered complete if the simulation meets the performance criteria. Otherwise, the model is recalibrated and validated.

Model calibration and validation performance are evaluated with two of three criteria recommended by the ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models (1993): the deviation of volume, the Nash-Sutcliffe coefficient, and the coefficient of daily gain. The coefficient of gain from the daily mean is not used because of its similarities with the Nash-Sutcliffe coefficient in this particular case. Instead, the coefficient of determination (R^2) is calculated as part of the hydrologic analysis.

The deviation of volume, *DV*, quantifies the difference in observed and predicted water volumes and is calculated:

$$DV = \frac{\sum_{i=1}^{n}(Vm - Vs)}{\sum_{i=1}^{n} Vm} \times 100\% \qquad [11]$$

where *DV* is the deviation of volume (%), *Vm* is the measured water yield for the period of comparison, and *Vs* is the modeled water yield for the period of comparison. The calibration and validation is considered satisfactory if the absolute value of CV is less than 10 percent. Donigian et al. (1984) indicated that HSPF calibration is considered to be very good if the absolute value of DV is less than 10 percent, and good when DV is between 10 and 15 percent.

The Nash-Sutcliffe coefficient, *NS*, measures how well the daily simulated flow corresponds with the measured flow. This coefficient is calculated:

$$NS = 1 - \frac{\sum_{i=1}^{n}(Qm - Qs)^2}{\sum_{i=1}^{n}(Qm - Q)^2} \qquad [12]$$

where *Qm* is the measured daily discharge, *Qs* is the simulated daily discharge, and *Q* is the average measured daily discharge. A Nash-Sutcliffe value of 1.0 indicates a perfect fit, while a value of 0 indicates that the model is predicting no better than the average of the observed data. Daily flow calibration and validation is considered to be satisfactory if NS value is larger than 0.4.

The model calibration and validation performance results are summarized in **Table 6**. Note that during the period of model calibration or validation, those days with missing or problematic data were excluded, so the count of days indicates the number of days with valid flow data. In general, the model simulates daily flow reasonably well with R^2 and *NS* values of most of the stations above 0.5 for both calibration and validation analyses except for the Hobe Grove station.

Table 6. WaSh model calibration and validation performance results.

Monitoring Station	S-46	Lainhart Dam	Cypress Creek Station	Hobe Grove Station	Kitching Creek Station
Calibration Results					
Period	1987–1996	1987–1996	1980–1986	1981–1985	1990–1996
Number of days	3193	3193	1680	1058	2192
DV (%)	–1.78	–0.83	–7.50	–14.67	0.21
NS	0.69	0.47	0.43	0.08	0.51
R^2	0.71	0.53	0.53	0.54	0.51
Validation Results					
Period	1997–2004	1997–2004	1987–1990	1987–1989	1997–2000
Number of days	2587	2587	990	687	1461
DV (%)	12.52	9.43	–2.87	10.66	9.09
NS	0.71	0.56	0.61	0.27	0.54
R^2	0.73	0.32	0.72	0.63	0.57

To aid in the evaluation of model calibration and validation performance, three types of plots are prepared:

1. Daily flow distribution: Plot of the distribution of the measured and modeled daily flow to visually examine the overall model performance. Particular attentions are paid to the low flow regime.
2. Double mass curve: To compare the measured and modeled daily flow in a cumulative manner along with increasing rainfall. This is a visual check of the *DV* calculated in **Table 6**.
3. Daily flow time series of modeled flow and observed flow for selected periods.

Figure 6 includes the three plots for the Lainhart Dam and S-46 stations, which provide the longest period of flow data for model calibration and validation. Panels A and B in **Figure 5** compare the frequency distribution of the modeled versus the observed daily flows. A slight high frequency of flow in the range of about 10 cubic feet per second (cfs) is predicted by the model at Lainhart Dam, possibly due to low flow leakage at the structure becoming significant but is not measured. The double mass curves for both stations (**Figure 6,** Panels C and D) show consistent model performance when comparing the patterns of the increase of modeled and measured flow with increasing rainfall. At Lainhart Dam, the model over-predicted flow for a 3-month period during the wet season of 1999. This has been attributed partly to the 9 percent of *DV* in **Table 5**. Panels E and F in **Figure 6** are the time-series plots of measured flow and modeled flow from 2000 through 2003. Overall, the figure shows that the model simulates daily flows over Lainhart Dam and S-46 stations reasonably well.

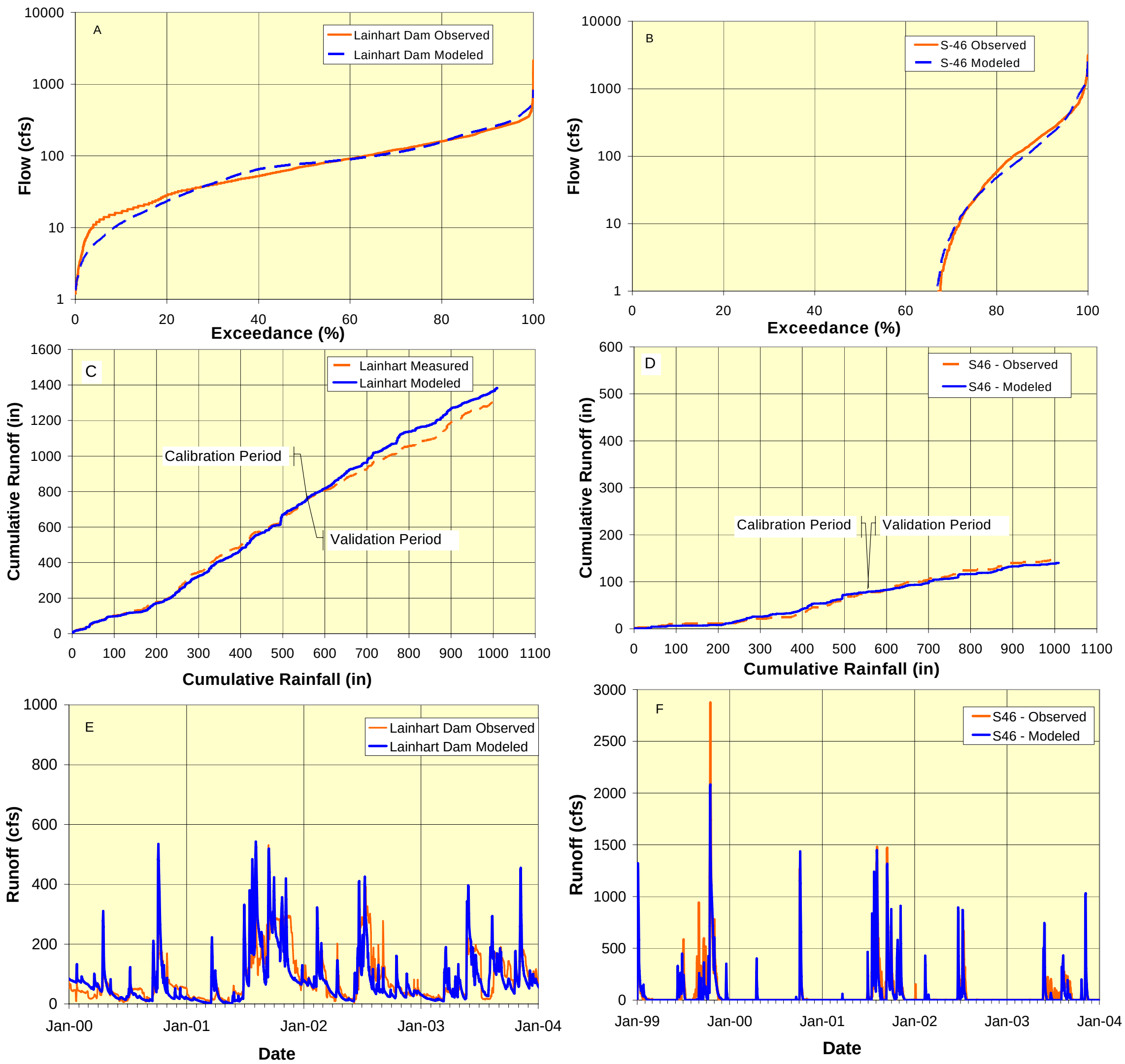


Figure 6. WaSh model calibration and validation plots at Lainhart and S-46 stations (1/1/87–1/31/04): (A) daily flow distribution at Lainhart Dam station, (B) daily flow distribution at S-46 station, (C) double mass curve at Lainhart Dam station, (D) double mass curve at S-46 station, (E) time-series plot at Lainhart Dam station (2000–2004), and (F) time-series plot at S-46 station (1999–2004).

Calibration of the C-18 and Jupiter Farms portion of the model is difficult because the Jupiter Farms Basin, the C-18/Corbett Basin, and the Grassy Water Preserve Basin are hydrologically connected. The model represented the G-92 structure by using the 'special structure' option. In its simplest form, the special structure consisted of a weir with a 12-foot elevation located in a reach consistent with its location along the C-18 canal. When the water elevation in the C-18 canal is above 12 feet, the weir structure will allow water from the C-18 canal to flow out of the basin. This discharge was subsequently used as input into the Jupiter Farms Basin as the model boundary condition. The flow rate is determined internally by the model, and is dependent on the prescribed weir configuration and the water elevation in the C-18 canal. The width of the special weir was adjusted in a series of simulations until approximately 50 cfs of water flows during normal operations and a maximum of approximately 400 cfs flows under the flood control mode.

Similarly, for the inter-basin transfer of water from the Grassy Waters Preserve (West Palm Beach Water Catchment Area) into the C-18 canal, a special structure was imposed in a separate model set up for the L-8 Basin to allow for a time series of flow as the boundary condition for the C-18 basin model. Water flow was based on stage in the Water Catchment Area. According to a water budget model developed for the West Palm Beach Water Catchment Area (Sculley, 1995), an annual contribution of 20,000 ac-ft of water from the Water Catchment Area to the C-18 Basin during April 1992 to March 1995 was used as a target to calibrate the special structure. The time-series plots for Lainhart Dam and S-46 station (**Figure 5,** Panels E and F) indicate that the special structures provide a reasonable estimation of inter-basin transfers over the G-92 structure and through the existing culverts in Grassy Waters Preserve into the C-18 basin.

The Kitching Creek station collects flow from a large area dominated by forest and wetland. **Figure 7** presents the performance of the model calibrated and validated at Kitching Creek. Overall, the figure shows that the model is capable of simulating flow fairly well in this area. The daily flow distribution of the modeled flow matches very well with the measured flow. The double mass curves are consistent with 0.21 percent of *DV* for calibration and 9.09 percent for validation shown in **Table 5**. However, the time-series plot (**Figure 7**, Panel C) did show that in 1998 there were a few significant events that are not predicted by the model. Such deviations are likely related to the quality of rainfall data.

The plots for the Cypress Creek and Hobe Grove Ditch stations are shown in **Figure 8**. The plots for the Cypress Creek station are consistent with the model calibration and validation performance measures shown in **Table 5**. Model calibration and validation at the Hobe Grove Ditch station is considered to be fair for the total volume. Daily flow calibration, however, did not meet the performance criteria. This is likely due to the quality of the data collected at the site. The Hobe Grove Ditch dataset is obtained from a stage–flow relationship downstream from several culverts that discharge from Gulf Stream Grove (owned by the District) and the structure owned by the Hobe St. Lucie Water Control District. Measuring flows under these conditions is challenging due to the complexity of the hydrologic connections and grove operations along with slight tidal influence in the downstream area. The stage-flow relationship is not as accurate as other flow gauges in the District. For example, in 1987 the Hobe Grove Ditch station failed to collect accurate data during several significant storm events; these significant events were accurately recorded by the nearby Cypress Creek station (**Figure 8**, Panels E and F). In this case, model simulation is considered to be acceptable in light of the poor data quality.

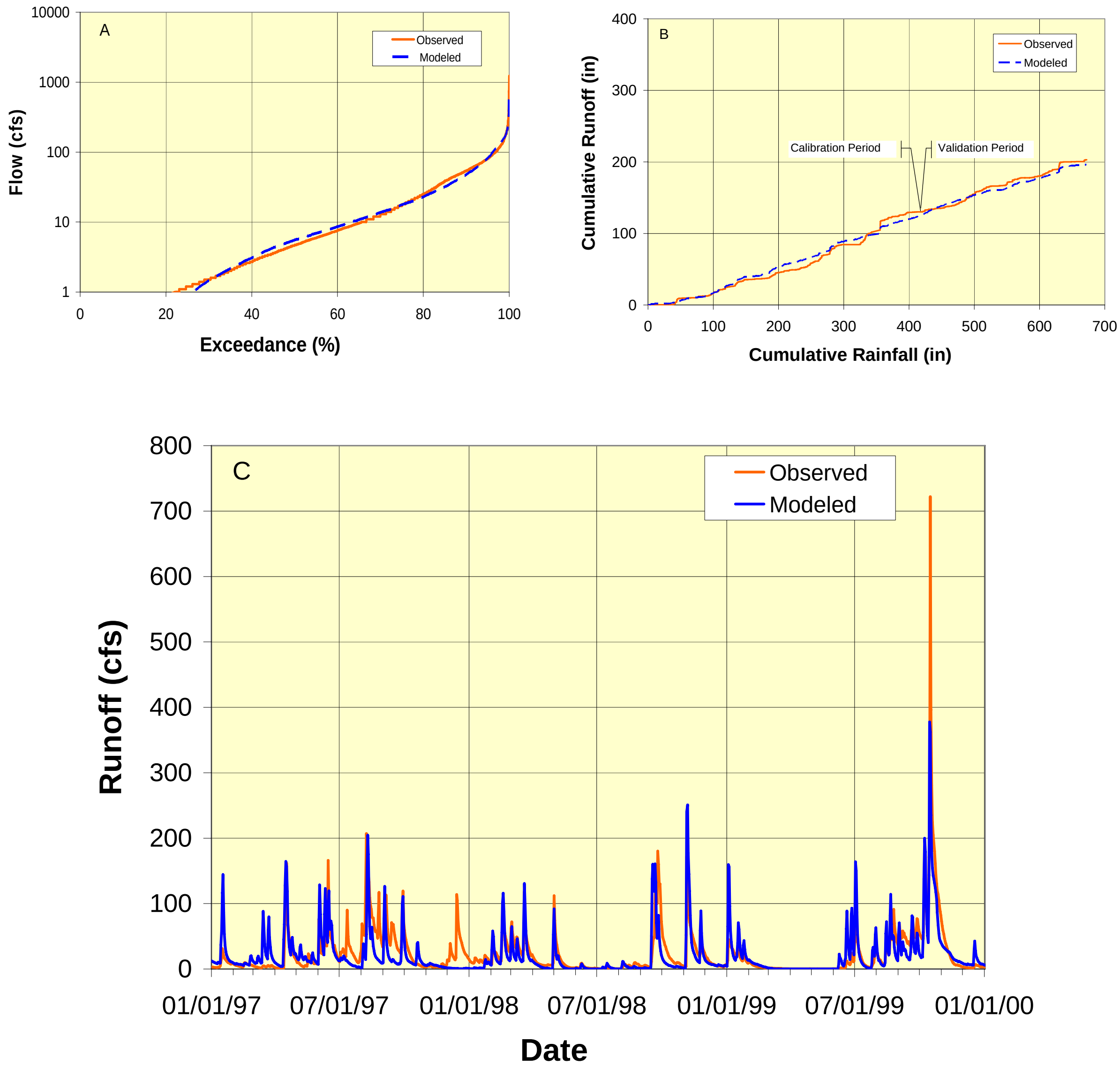


Figure 7. WaSh model calibration and validation plots at Kitching Creek station (1990–2000): (A) daily flow distribution, (B) double mass curve, and (C) time-series plot (1997–2000).

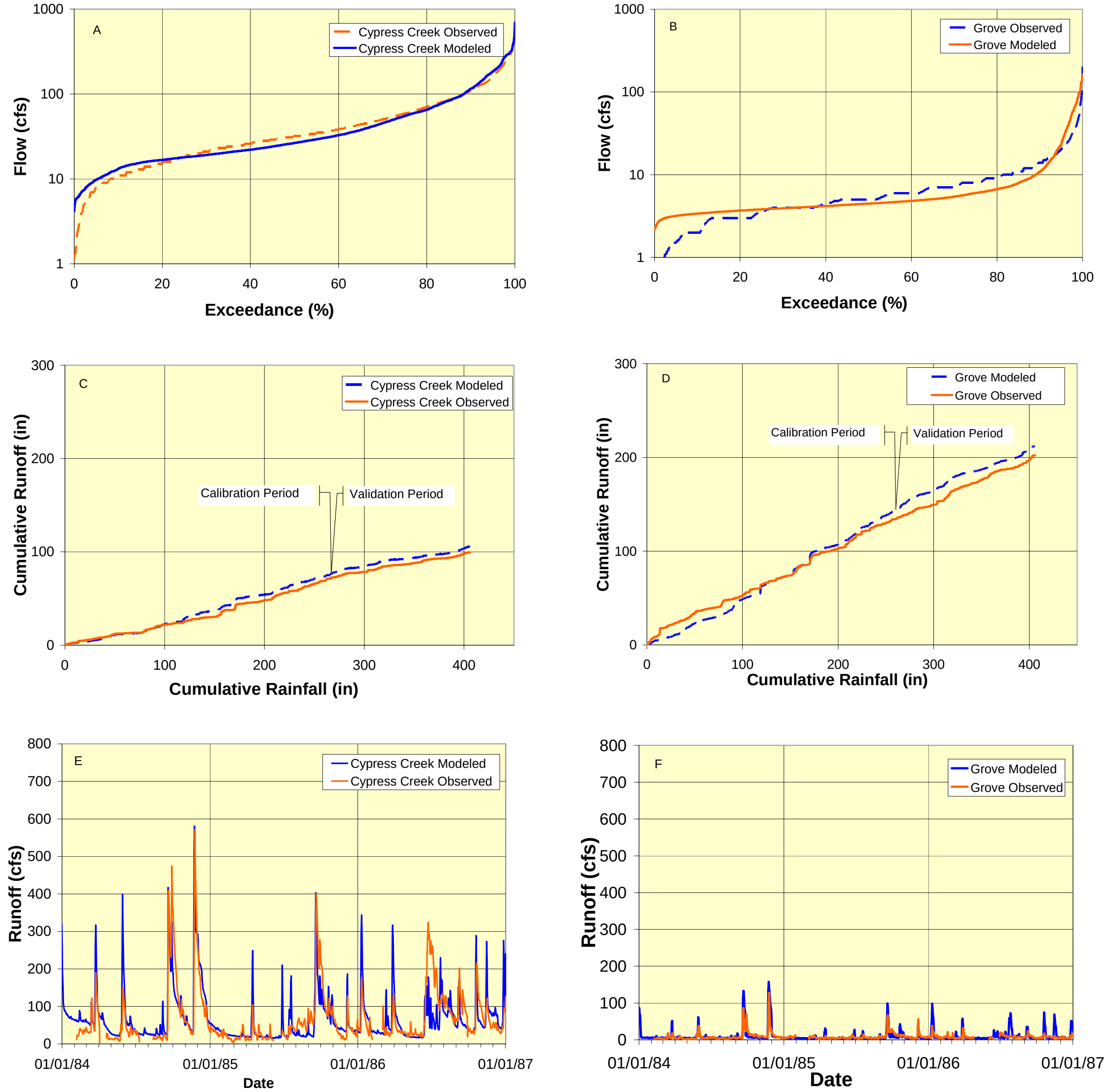


Figure 8. Model calibration and validation plots at Cypress Creek and Hobe Grove Ditch stations (1981–1990): (A) daily flow distribution at Cypress Creek station, (B) daily flow distribution at Hobe Grove Ditch station, (C) double mass curve at Cypress Creek station, (D) double mass curve at Hobe Grove Ditch station, (E) time-series plot at Cypress Creek station (1984–1987), and (F) time-series plot at Hobe Grove Ditch station (1984–1987).

The calibration of the groundwater level was conducted in the last step of WaSh model validation. **Figure 9** shows the time series of the observed and modeled water levels at the two groundwater monitoring wells used for validation. The cell hydrology simulated by the model is reasonable. Water level predictions could be further refined if the model is to be used for water level evaluations.

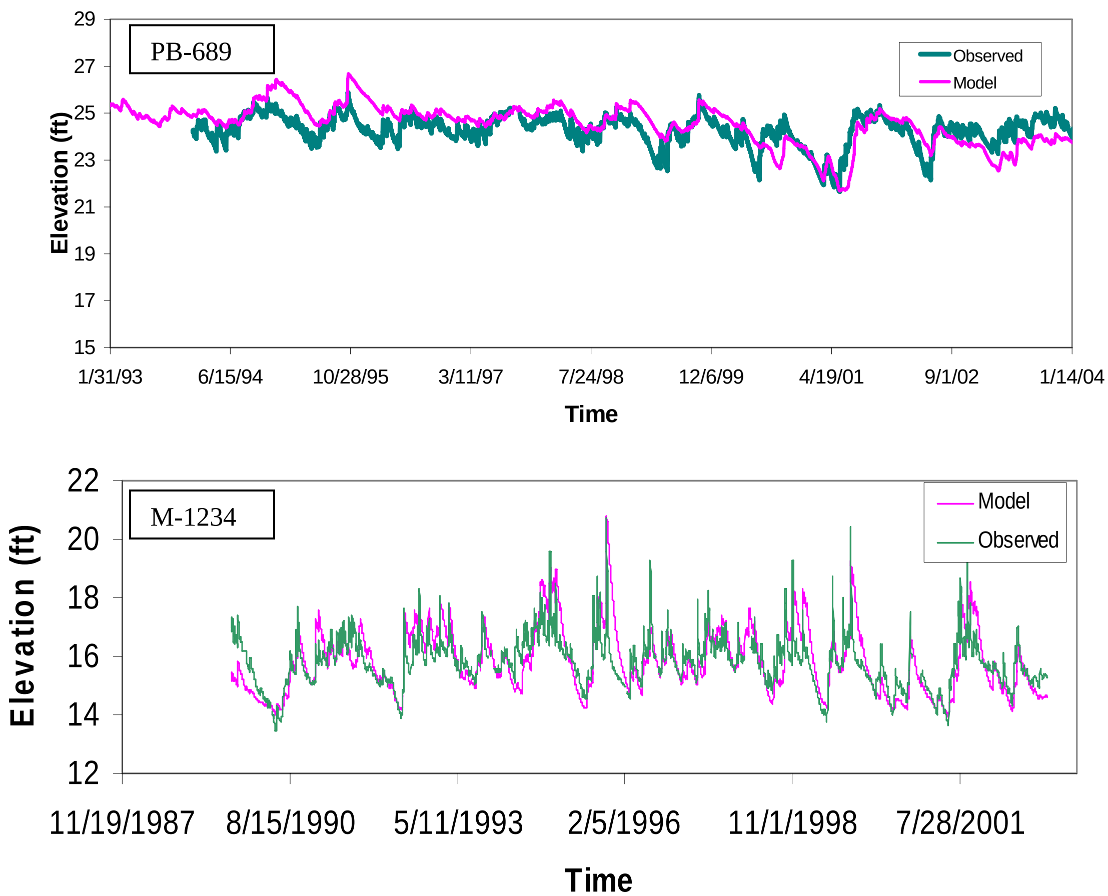


Figure 9. Observed and modeled water levels in Groundwater Monitoring Well PB-689 and M-1234. Land surface elevation is 24.43 feet at PB689 and 21.15 feet at M-1234.

WaSh MODEL SIMULATION RESULTS

A final long-term simulation for the period from 1965–2003 was conducted after the calibration and validation of the Loxahatchee WaSh model was completed. Daily flows from each of the tributaries and each of the basins were averaged based on the model output of the 39-year simulation. **Table 7** is a summary of the data expressed as daily average flows and percentage of contributions from each of the basins (tributaries) into the Loxahatchee River and Estuary and the Northwest Fork. On average, the Northwest Fork receives about 65 percent of total freshwater inflow into the entire Loxahatchee River and Estuary. For total freshwater inflows into Northwest Fork, flow over Lainhart Dam (C-18/Corbett G-92 plus Jupiter Farms) accounts for about

45 percent. The next largest contributor is Cypress Creek (32 percent with Pal-Mar and Grove West combined). Kitching Creek at the monitoring station contributes about 8 percent, and Hobe Grove Ditch contributes about 5 percent. The remaining 8 percent is contributed from the areas that are not currently covered by flow monitoring stations. However, the actual freshwater flow contribution varies on a daily basis, depending on the specific hydrologic condition and water management practices. For example, there is little freshwater flow from S-46 during the dry season, whereas a disproportionately large quantity of fresh water is released from S-46 during a flood event.

Table 7. Flow contributions from each of the basins and major tributaries into the Northwest Fork and Loxahatchee River and Estuary.

Basin	Average Daily Flow (cfs)	Flow Contribution	Northwest Fork Average Daily Flow (cfs)	Northwest Fork Flow Contribution
1. Kitching Gauge	17.4	5%	17.4	8%
2. North Fork	20.2	6%	--[a]	--[a]
3. Park River	5.1	2%	5.1	2%
4. Lox Estuarine	14.4	13%	--[a]	--[a]
5. C-18/Corbett G-92	69.7	22%	69.7	34%
5. C-18/Corbett S46	51.3	16%	--[a]	--[a]
6. Historic Cypress Creek	7.0	2%	7.0	3%
7. Pal-Mar	57.7	18%	57.7	28%
8. Grove West	11.1	3%	11.1	5%
9. Grove East	10.6	3%	10.6	5%
10. Jupiter Farms	21.9	7%	21.9	11%
11. Wild and Scenic	6.9	2%	6.9	3%
Totals	320.3	100%	207.4	100%

[a] This basin does not contribute flows to the Northwest Fork of the Loxahatchee River.

Tables 8 and **9** summarize the monthly mean flow for each of the years from 1965–2003 for flows over the Lainhart Dam and total flow into Northwest Fork covered by the four flow monitoring stations (Lainhart Dam station, Cypress Creek station, Hobe Grove station, and Kitching Creek station). For flows over Lainhart Dam (**Table 7**), mean monthly flows less than 35 cfs are shaded in red, and flow from 35–65 cfs are shaded in light green. These two flow ranges were selected because 35 cfs is the Minimum Flow and Level (MFL) for the Northwest Fork (SFWMD, 2002a), and 65 cfs is defined as a flow target in the model for the development of the Northern Palm Beach County Comprehensive Water Management Plan (SFWMD, 2002b). The Lainhart Dam data (**Table 7**) shows that a low flow period occurred from 1970–1978. For some years, monthly mean flows were less than 35 cfs even during the wet season (June through November). Another low flow period occurred from 1987–1990. Extended high flow years occurred from 1991–1999. This pattern is consistent with the total Northwest Fork flow presented in **Table 8**; mean monthly flows less than 70 cfs are shaded in red, and flows from 70–130 cfs are shaded in light green. The extended low-flow dry season periods in the 1960s, 1970s, and 1980s probably coincide with the period during which the floodplain experienced the most significant saltwater encroachment. The high flow regime instituted in the 1990s has likely helped the floodplain hydrologic condition to recover from the preceding dry years.

Table 8. Monthly mean flows (cfs) over Lainhart Dam from 1965–2003.

	Month												
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
1965	39	35	14	2	1	14	29	45	10	136	71	10	34
1966	90	76	34	22	53	211	220	127	88	203	63	37	102
1967	22	40	37	18	5	52	89	114	67	193	79	26	62
1968	14	13	7	2	19	302	173	136	197	274	147	62	112
1969	71	45	116	35	154	120	79	131	135	269	173	86	119
1970	113	104	208	237	97	155	112	64	56	71	29	18	105
1971	16	18	12	3	47	19	38	46	136	79	194	73	57
1972	44	39	21	41	191	204	85	50	33	33	68	28	70
1973	28	36	14	9	13	80	66	124	134	168	41	39	63
1974	150	39	45	14	8	131	151	156	54	134	57	63	84
1975	27	30	20	7	33	104	141	31	85	108	39	15	54
1976	9	20	27	5	106	114	30	67	182	72	72	28	61
1977	60	19	10	2	25	33	11	24	271	42	24	139	55
1978	72	30	32	6	14	145	140	145	88	168	263	190	108
1979	193	79	56	47	61	51	31	19	161	146	113	66	85
1980	47	58	39	20	33	29	86	34	32	80	26	17	42
1981	7	9	3	1	2	6	6	152	176	46	53	9	39
1982	12	26	150	200	166	241	124	93	110	145	302	182	146
1983	143	200	172	108	76	141	77	135	268	342	198	157	168
1984	123	86	127	84	102	124	65	48	179	120	196	150	117
1985	72	43	28	61	21	25	65	40	144	110	53	71	61
1986	125	42	102	82	14	93	112	72	76	80	92	99	83
1987	112	36	69	25	15	24	43	30	39	137	234	34	67
1988	57	47	42	14	29	91	116	184	75	18	14	7	58
1989	4	2	17	8	7	8	30	85	25	79	14	15	25
1990	11	6	7	10	7	15	17	77	93	151	22	16	36
1991	142	118	53	141	119	160	128	86	134	192	92	83	121
1992	49	117	66	56	20	122	125	188	217	164	198	95	118
1993	231	204	200	122	92	104	87	85	164	281	149	89	150
1994	96	142	84	82	70	143	114	223	273	209	278	285	166
1995	140	96	98	85	69	101	131	288	186	352	271	153	165
1996	82	73	156	116	137	140	176	96	128	163	123	78	123
1997	81	104	84	121	93	214	109	200	222	105	83	149	130
1998	148	204	161	88	106	53	84	66	208	133	289	102	136
1999	227	89	70	39	30	172	122	109	198	335	206	109	142
2000	81	74	62	91	34	19	40	18	52	174	29	23	58
2001	16	9	46	24	8	43	197	260	254	236	145	78	110
2002	69	125	60	44	15	116	185	57	40	51	43	36	70
2003	22	14	62	46	119	137	48	149	90	73	146	75	82
Monthly Mean	78	65	67	54	57	104	94	104	130	151	120	77	92

Table 9. Monthly mean flows (cfs) into the Northwest Fork of the Loxahatchee River passing the Lainhart Dam, Cypress Creek, Hobe Grove Ditch, and Kitching Creek Flow stations from 1965–2003.

	Month												
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
1965	89	106	56	16	10	44	95	129	34	457	259	53	112
1966	281	258	115	82	184	678	682	418	271	628	206	125	328
1967	83	132	122	68	35	158	270	336	210	607	238	94	197
1968	60	54	39	23	74	952	530	420	652	848	436	181	356
1969	204	136	346	108	438	372	256	395	426	876	523	253	363
1970	337	300	671	728	268	452	328	178	167	200	93	64	315
1971	58	64	48	28	148	68	121	135	403	246	633	239	182
1972	138	133	78	137	593	639	252	155	107	110	222	95	221
1973	99	121	59	44	56	242	205	405	408	517	134	126	202
1974	483	133	145	53	39	367	428	479	175	398	181	181	257
1975	89	95	65	36	107	299	436	107	260	323	124	59	167
1976	40	77	80	29	332	354	100	208	560	227	220	99	193
1977	193	67	44	22	95	97	41	78	853	142	84	406	177
1978	234	102	106	32	50	504	449	438	244	522	840	573	343
1979	544	226	152	139	164	147	91	62	517	483	342	192	255
1980	152	173	122	66	110	95	260	107	120	285	106	70	139
1981	39	53	25	18	16	26	28	476	542	154	188	43	134
1982	55	103	504	685	566	749	417	284	356	458	983	476	470
1983	455	656	552	330	203	418	202	388	853	1,074	606	487	517
1984	367	247	382	237	300	345	166	130	563	360	615	466	348
1985	192	116	83	183	65	89	185	115	448	350	160	210	183
1986	400	122	336	232	51	272	341	259	237	255	305	334	263
1987	335	113	218	84	62	88	134	89	143	441	741	119	214
1988	176	154	138	52	92	250	348	583	254	73	58	36	185
1989	30	24	62	38	30	32	88	233	88	246	58	58	83
1990	49	41	34	42	31	46	63	243	333	435	85	68	123
1991	495	374	161	417	345	481	361	267	400	594	282	240	368
1992	147	326	179	160	64	372	415	584	645	496	632	293	359
1993	740	619	598	340	244	274	233	237	447	867	416	238	437
1994	269	438	225	216	185	465	344	670	842	675	887	874	507
1995	417	275	284	227	172	256	343	858	568	1,146	812	401	482
1996	228	186	430	304	380	389	545	270	383	543	409	225	359
1997	247	300	241	372	262	689	343	594	671	314	224	446	392
1998	431	639	485	233	279	133	228	174	661	414	908	301	404
1999	749	261	181	103	84	495	343	299	599	1,079	606	314	427
2000	216	187	161	255	100	60	114	56	150	516	85	73	165
2001	53	37	126	66	39	149	477	794	792	668	387	203	318
2002	175	343	156	151	51	288	532	164	114	138	115	102	193
2003	65	47	202	136	372	392	126	354	235	184	381	181	224
Monthly Mean	241	201	205	166	172	314	280	312	403	470	374	231	281

Because of the hydrologic variability during the past 39 years, the 39-year daily flow data at Lainhart Dam were analyzed to determine the daily flow distribution for each of the 12 months of all the 39 years. This analysis indicates that the daily flow distribution in a month during the 39 years is not normally distributed. The results are summarized in **Figure 10** which plots the median flow and the 75th percentile flow in the month. The 75th percentile flow represents the flow that is exceeded by only 25 percent of days in that month during the 39 years. Daily flow from Lainhart Dam is less than 50 cfs for 50 percent of time during the months of February, March, April, and May. Flows in April and May are the lowest among all the months. This also shows the importance of flow augmentation during these low flow months.

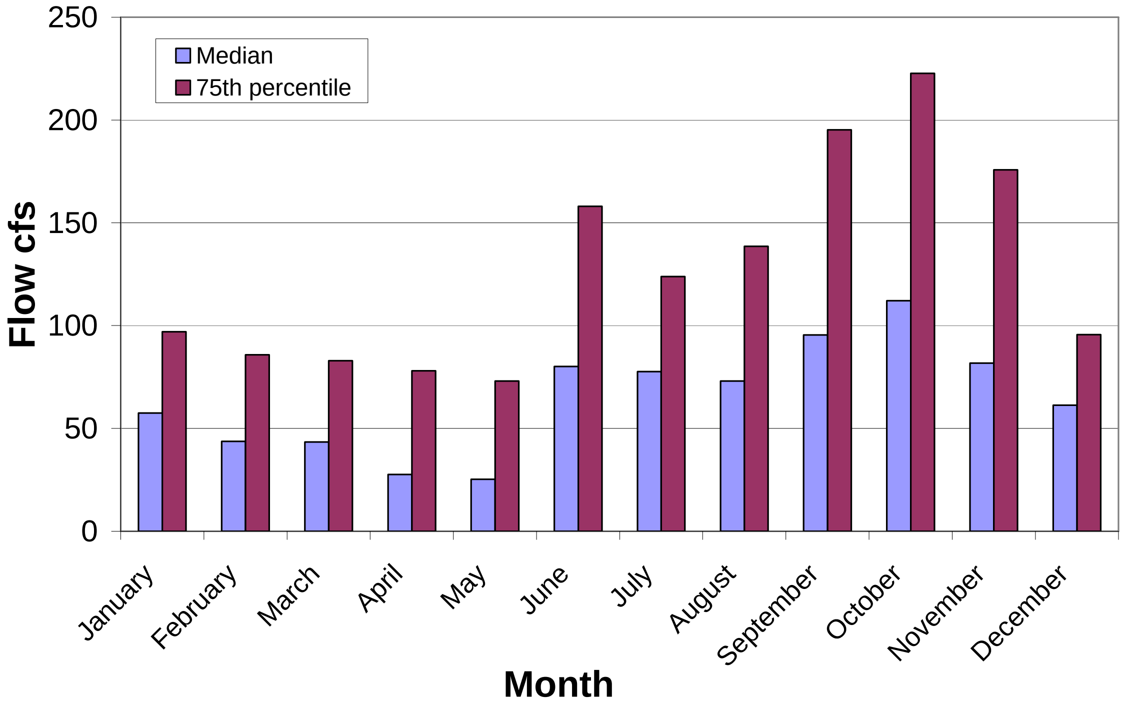


Figure 10. Monthly median flow and the 75th percentile flow over Lainhart Dam from 1965–2003.

MODELING SALINITY

THE HYDRODYNAMIC/SALINITY (RMA) MODEL DESCRIPTION

Salinity in the Northwest Fork of the Loxahatchee River and Estuary is controlled by both freshwater inflows and tidal circulation, which represent the competition between river and ocean influences. A hydrodynamic/salinity (RMA) model was developed to study the influence of freshwater flows from the tributaries of the Northwest Fork and S-46 on the salinity conditions in the Loxahatchee River and Estuary. In parallel with model development, a data collection network was established to measure tide and salinity at five sites from the embayment area near the Jupiter Inlet (RM 0.70) to RM 9.12. The objective of salinity data collection and model development was to establish the relationship between salinity and the amount of freshwater inflow. The requirement to the model is to predict daily average salinity over a long period of time such as 30 years under various project scenarios. The main focus of the data collection and salinity modeling has been on the upper Northwest Fork of the Loxahatchee River.

The software programs used in developing the Loxahatchee River hydrodynamics/salinity model were RMA-2 and RMA-4 (USACE, 1996). RMA-2 is a 2-D depth-averaged finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. RMA-2 computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning's n or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady state (dynamic) problems can be analyzed. The program has been used to calculate water levels and flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; circulation and transport in water bodies with wetlands; and general water levels and flow patterns in rivers, reservoirs, and estuaries.

The water quality model, RMA-4, is designed to simulate the depth-average advection-diffusion process in an aquatic environment. The model is used for investigating the physical processes of migration and mixing of a soluble substance in reservoirs, rivers, bays, estuaries, and coastal zones. This model was used to evaluate salinity and the effectiveness of various restoration scenarios. For complex geometries, the model utilizes the depth-averaged hydrodynamics from RMA-2.

Figure 11 is a bathymetric map of the estuary. The estuary is shallow and well-mixed with depth for the most part of the estuary ranging from 3 to 10 feet.

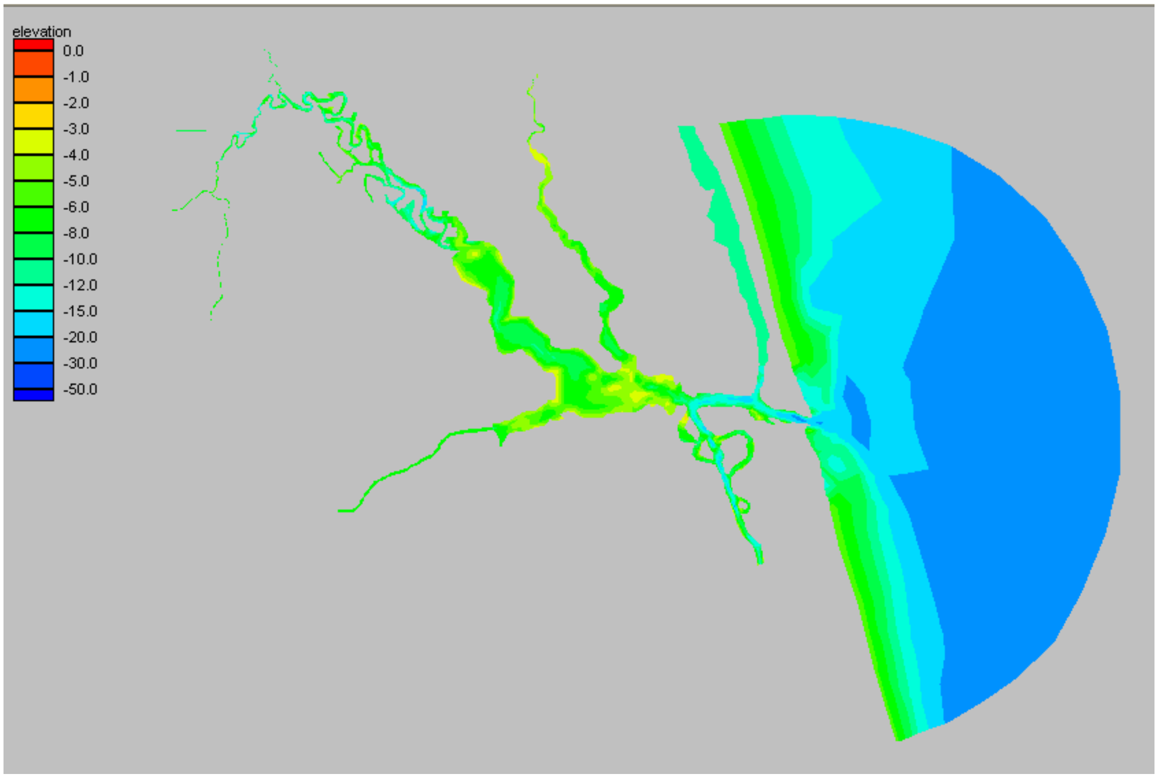


Figure 11. Loxahatchee Estuary bathymetry.

IMPLEMENTING THE RMA MODEL

Model Setup

Based on the most recent bathymetry, freshwater inflow, and tide data, the RMA model was updated in early 2004. The current model mesh includes a total of 4,956 nodes with elevations derived from the survey data provided by the U.S. Geological Survey (USGS). **Figure 12** shows the RMA model mesh construction with 1,075 quadrilateral elements and 231 triangular elements. Arrows in the figure indicate the locations where freshwater inflows are applied. The four tributaries that contribute freshwater to the Northwest Fork are Lainhart Dam, Cypress Creek, Hobe Grove Ditch, and Kitching Creek. The RMA model domain also includes the Southwest Fork and flows from the S-46 structure. The RMA itself does not predict the amount of fresh water entering the system from the watershed or discharge structures. The freshwater discharge amounts from these tributaries and structures are provided by the WaSh model or from recorded data from the flow gauges.

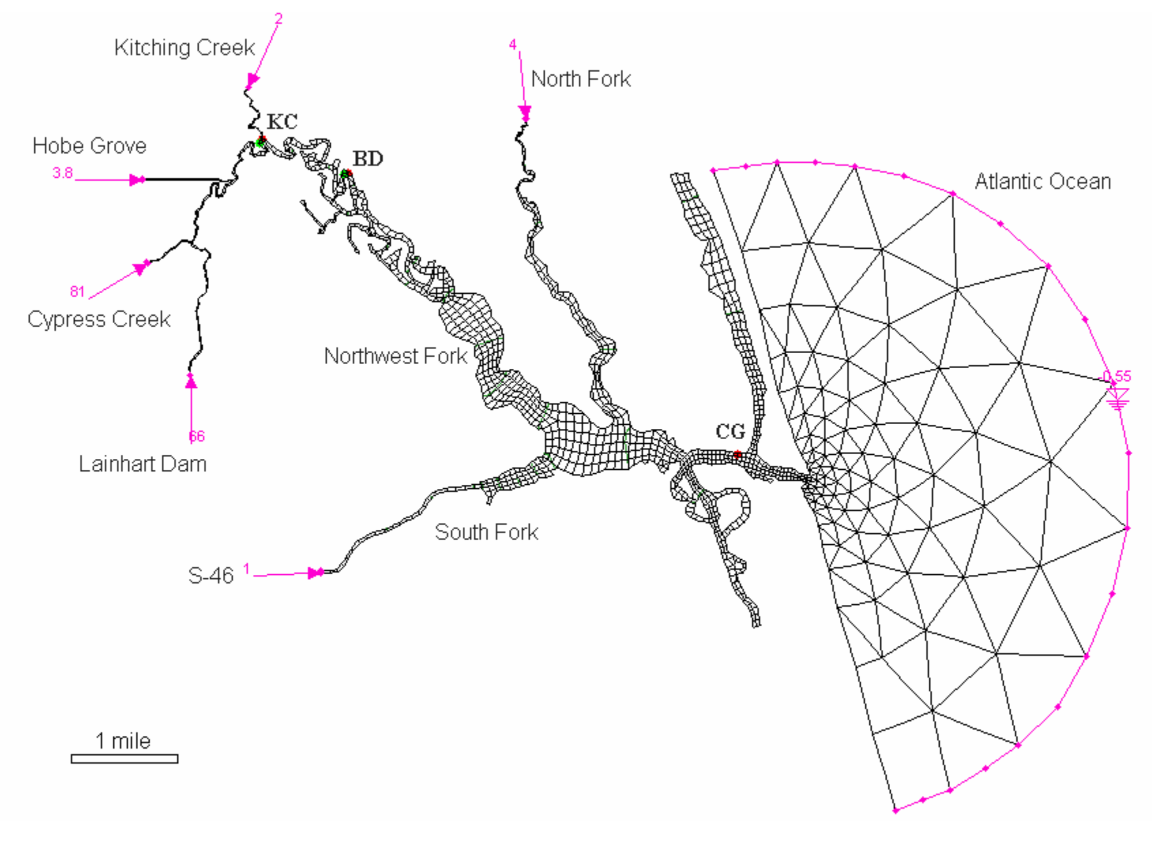


Figure 12. The RMA model domain map. KC = Kitching Creek USGS station; BD = Boy Scout Dock station, CG – U.S. Coast Guard Station.

The meandering river channel pattern is one of the fundamental characteristics of the natural system of the Northwest Fork of the Loxahatchee River. The previous studies have demonstrated that restoring the natural oxbows to the Northwest Fork can effectively reduce saltwater intrusion into the historically freshwater reaches. The meandering river channel and oxbows of the Northwest Fork are preserved in the construction of the RMA model mesh.

Several natural river channel restoration projects have been implemented in the past decade to restore oxbows to the Northwest Fork. Salinity measurements taken before and after the implementation of the projects indicate that the oxbows can reduce the extent of saltwater intrusion to the Northwest Fork. The RMA model mesh contains the geographic features of the river channel. Depending on the time period, the model simulation can be conducted with the oxbow restoration projects completed for the post-project period or without the restored oxbows for the pre-project period. The current model mesh is also detailed enough to simulate the effectiveness of potential channel restoration projects in river reaches up to the Trapper Nelson Interpretive Site. The channel above the Trapper Nelson Interpretive Site will be further refined in the mesh after an ongoing GIS project is completed that will provide more detailed geometry for the river channel above the Trapper Nelson Interpretive Site. On the ocean side, the model mesh was extended three miles offshore into the Atlantic Ocean to obtain a relatively stable salinity boundary condition (Hu, 2004).

The RMA model was applied to establish the relationship between the amount of freshwater inflow and the salinity regime in the Northwest Fork. The freshwater/salinity relationship provided means to assess restoration plan scenarios.

Model Verification

In parallel with the preliminary RMA model setup, a data collection program was implemented. A bathymetric survey was conducted by the USGS in early 2003. Water depth was recorded along survey lines in the Northwest Fork and the North Fork of the Loxahatchee River. The Northwest Fork survey covered river reaches from RM 4.0 to the Trapper Nelson's Interpretive Site (RM 10.50). Approximately three miles of the North Fork were also surveyed. In addition to the flow gauges located at Lainhart Dam and Kitching Creek, two additional gauges were established on Cypress Creek and Hobe Grove Ditch in November 2002. These four flow gauges monitor the majority of freshwater input to the Northwest Fork. Four tide and salinity stations have also been deployed in the estuary since November 2002 by the USGS. An additional tide/salinity gauge was installed at RM 9.12 in October 2003 by the District's Water Supply Department. These five tide/salinity stations monitor the tide and salinity in the estuary continuously and record the data at 15-minute intervals. The data is retrieved at scheduled maintenance times and reported quarterly after quality assurance and quality control (QA/QC) has been conducted. To detect temperature and salinity stratification, three of the tide/salinity stations record salinity and temperature measurements at two water depths. The three sites with double temperature/salinity sensors are located at RM 9.12, Boy Scout Camp dock (RM 5.92) and the U.S. Coastal Guard Station near the Jupiter Inlet (RM 0.70). All sensors were installed at water levels below lower low tides to avoid exposure to air.

In addition to tide and salinity measurements obtained from the USGS sites, the Loxahatchee River District (LRD) also has an estuarine data collection program at several additional locations that are not covered by the USGS monitoring network. The LRD uses multi-parameter datasondes to record time, dissolved oxygen, water depth, conductivity/salinity, pH, and temperature. The meters are located near the bottom of the channel in order to track maximum salinity changes in the water column. The LRD data were collected at North Bay seagrass survey site (RM 1.48), Pennock Point seagrass survey site (RM 2.44), Northwest Fork near the mouth of Kitching Creek (RM 8.13), Station 66 in the Wild and Scenic Loxahatchee River, and Station 69 near the

Indiantown Road (RM 14.93). To measure current velocity, the LRD contracted Scientific Environmental Applications to install two bottom mount Acoustic Doppler Current Profiler (ADCP) units at various locations in the estuary in 2003.

The Loxahatchee hydrodynamic/salinity (RMA) model was verified against field data for the period from May 1 to August 12, 2003. **Figure 13** shows the combined freshwater inflow from four major tributaries to the Northwest Fork for this period. Daily averaged flow rates (cfs) from flow gauges on upper Northwest Fork at Lainhart Dam, Cypress Creek, Hobe Grove, and Kitching Creek were used for the calculation. Discharge from S-46 into the South Fork was based on measurements at the discharge structure for the model simulation period.

Figure 14 is a comparison of tidal data from the Coast Guard station (RM 0.70) with the RMA-2 model output for the same location. Because the two curves overlap each other when printed in the same chart, the model output and field data are plotted in separate charts using the same scale and grid lines for ease of comparison. For RMA-4 applications, a constant salinity of 35.5 parts per thousand (ppt) was applied on the ocean boundary.

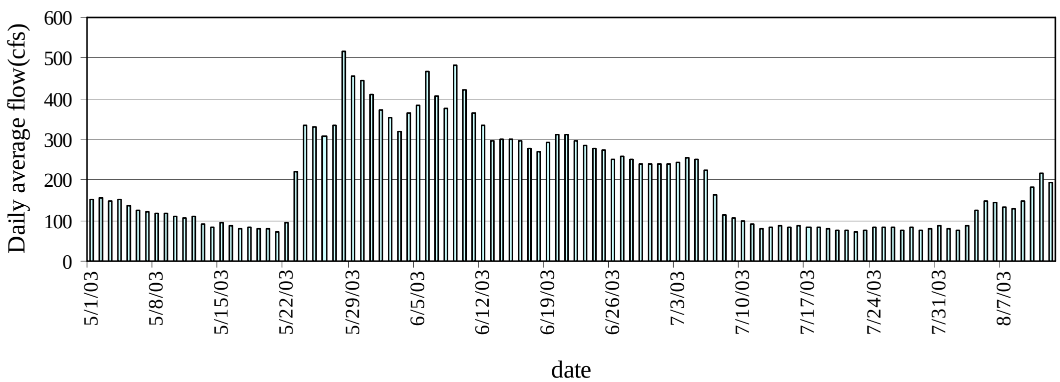


Figure 13. Freshwater inflow from major tributaries to the Northwest Fork of the Loxahatchee River.

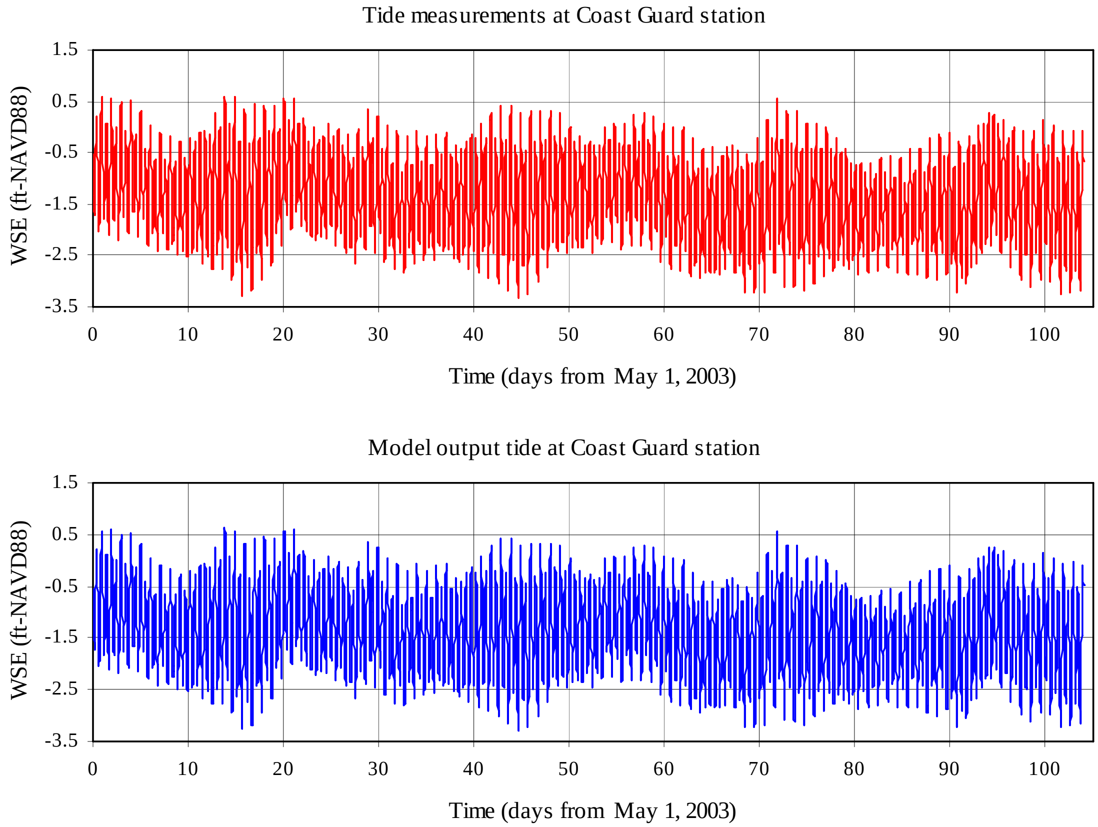


Figure 14. Tide measurements at the Coast Guard station (RM 0.70): field data and RMA model output.

Field data and model output of tides at Boy Scout Dock (RM 5.92) and Kitching Creek (RM 8.13) are plotted in **Figure 15** for comparison. The two stations are approximately 2 river miles apart and there is no major tributary between these locations. Both field data and model output indicate that the tidal regimens at these two sites are similar in terms of range.

In order to evaluate the model accuracy more precisely, statistical analysis was also conducted. The root mean square error (RMS) and the relative RMS error (RRE) were used to evaluate model performance. The RMS is the average of the squared differences between observed and predicted values:

$$RMS \text{ Error} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(O^n - P^n\right)^2} \qquad (13)$$

where N = number of observed-predicted pairs

O^n = the value of the nth observed data

P^n = the value of the nth predicted data

The smaller the RMS is, the better the model output tracks the field observation. A RMS error of zero is ideal.

The relative RMS error (RRE) is defined as the ratio of RMS error to the observed change:

$$RRE = \frac{RMS\ Error}{Observed\ \text{Change}} \times 100 = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(O^n - P^n\right)^2}}{O_{\max} - O_{\min}} \times 100 \qquad (14)$$

where O_{max} = maximum value of observations

O_{min} = minimum value of observations

$(O_{max} - O_{min})$ is the range of the observation data and N is the total number of the observation records. The relative error provides another measurement of the model performance. A zero percentage RRE indicates a perfect match.

Table 10 lists the RMS and RRE of the model tide output at two sites in the Northwest Fork and one site near the model boundary. CG is the station ID for the tide gauge at the Coast Guard station. BD and KC are station IDs for tide gauges at the Boy Scout Camp Dock and at the mouth of the Kitching Creek, respectively. The mean square errors were less than two inches at all the three sites. The relative error was less than 3 percent near the model boundary and less than 5 percent in the Northwest Fork.

Table 10. Statistics of model tide output.

Station ID	No. of Obs.	RMS(feet)	RRE(%)	Obs. Range(feet)
CG	4983	0.1058	2.71%	3.90
BD	4423	0.1700	4.78%	3.56
KC	4423	0.1612	4.40%	3.66

Table 11 compares the model output and field observations in terms of maximum, minimum, and mean values. The difference in mean tide over the entire simulation of a three-month period was less than one-tenth of an inch near the model boundary. The difference in mean tide in the Northwest Fork was about an inch.

Table 11. Comparison of model tide output with field observations (unit: feet).

Station ID	Obs. Max	Model Max	Obs. Min	Model Min	Obs. Mean	Model Mean
CG	0.5900	0.6150	-3.3100	-3.2900	-1.3710	-1.3833
BD	0.6300	0.7230	-2.9300	-2.9590	-1.2104	-1.3316
KC	0.6500	0.7740	-3.0100	-2.9370	-1.1982	-1.2900

Figure 16 compares model output of depth-averaged salinity with actual field salinity measurements from instruments at fixed elevations However, although these two quantities are similar, they do not represent the same physical parameters and are not directly comparable. The difference between the model output (representing depth-averaged salinity) and the actual field measurement (representing salinity at a fixed depth) could be significant when the system is stratified.

The salinity record at Boy Scout Dock increased to 10 ppt between Day 50 and Day 60. This sudden salinity increase does not seem to be related to or supported by data from other field records. A salinity of 10 ppt usually occurs at this site when freshwater inflow is below 100 cfs. The flow gauges actually recorded over 200 cfs for this period. The salinity record from the adjacent Kitching Creek station is also inconsistent with the salinity increase at the Boy Scout Dock station. Previous studies indicated that 10 ppt at Boy Scout Dock station would have raised salinity at Kitching Creek station to 2 ppt or above (Russell and McPherson, 1984); however, there was no salinity increase for Kitching Creek during this time period (see the Kitching Creek chart in **Figure 16**). Therefore, the accuracy of the salinity field measurements at Boy Scout Dock between Day 50 and Day 60 is questionable.

Both RMA-2 and RMA-4 are two-dimensional depth-averaged models. When the system is minimally stratified, such as the condition near the Jupiter Inlet at the Coast Guard station, the modeled salinity output tracks the field salinity data rather closely. However, when the system is highly stratified, as occurs in certain areas, the modeled salinity output for that area could give a smaller salinity variation between high tide and low tide when compared to the field salinity measurements from fixed depths (see the Boy Scout Dock chart in **Figure 16**).

The RMA-4 output is depth-averaged salinity, which differs from salinity measured by a transducer at a fixed elevation. The conductivity transducers were installed at elevations that would remain below the water surface at low tide. Because the range between higher high and lower low water is close to 4 feet and the overall water depth is only about 6 feet to 10 feet, the conductivity transducers would be situated in the lower water column during high tide. Under these conditions, the instrument would take measurements from the surface layer at low tide and from the bottom layer at high tide. If the system is well mixed (i.e., no stratification), then there should be no difference between the modeled depth-averaged salinity and field salinity measurements. However, when the system is stratified, the daily salinity variation recorded by the instruments would be wider than the daily salinity variation output from depth-averaged salinity model.

Table 12 lists the statistics of model salinity output accuracy analysis at Stations Kitching Creek, Boy Scout Camp Dock, and the U.S. Coast Guard Station**. Table 13** lists the statistical characteristics of both model salinity output and the observed values.

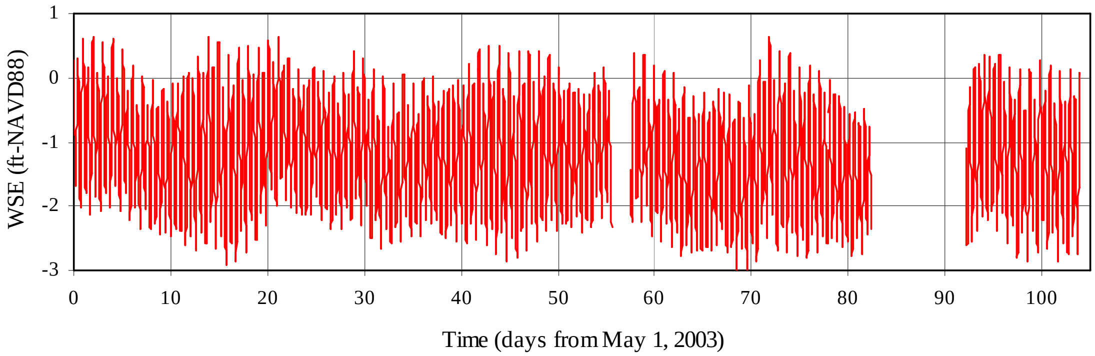
Table 12. Statistics of model salinity output.

Station ID	No. of Obs.	RMS(ppt)	RRE(%)	Obs. Range(ppt)
KC	4509	0.6047	6.65%	9.1
BD	3951	2.5454	10.76%	23.65
CG	4507	1.8713	9.70%	19.3

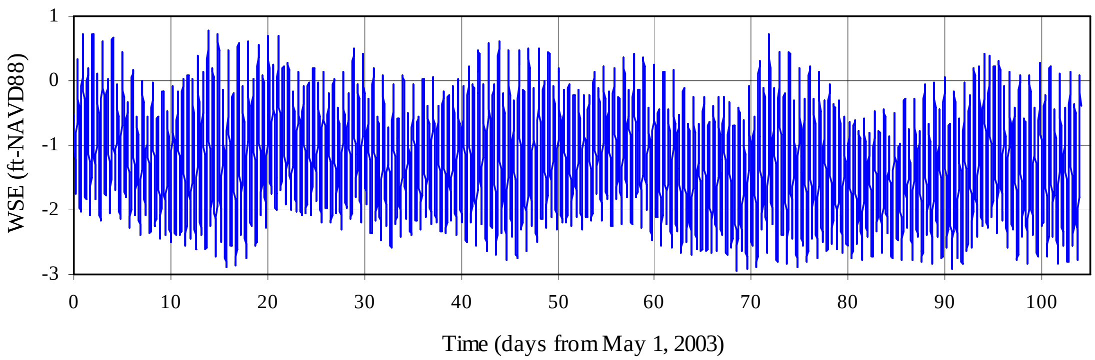
Table 13. Comparison of model salinity output with field observations (unit: ppt).

Station ID	Model Mean	Obs. Mean	Model Max	Obs. Max	Model Min	Obs. Min
KC	0.7507	0.5732	4.3670	9.2000	0.1500	0.1000
BD	6.3726	4.6928	19.0380	23.8000	0.2220	0.1500
CG	32.3625	31.9756	35.4250	36.0000	19.5460	16.7000

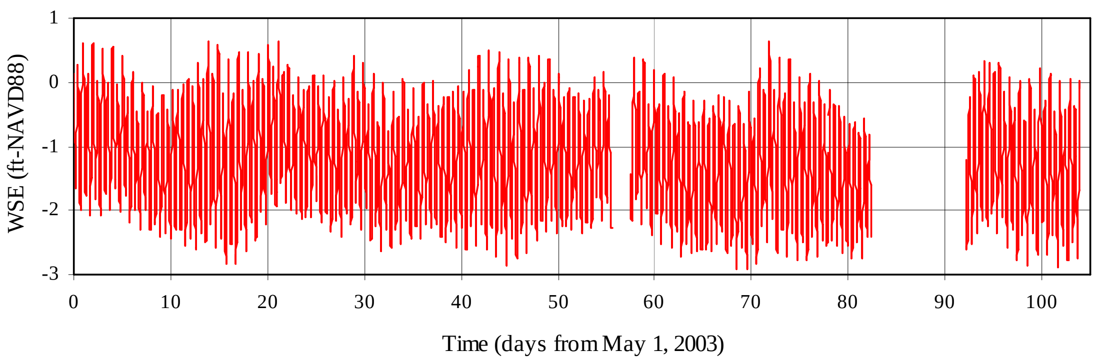
Tide measurements near Kitching Creek



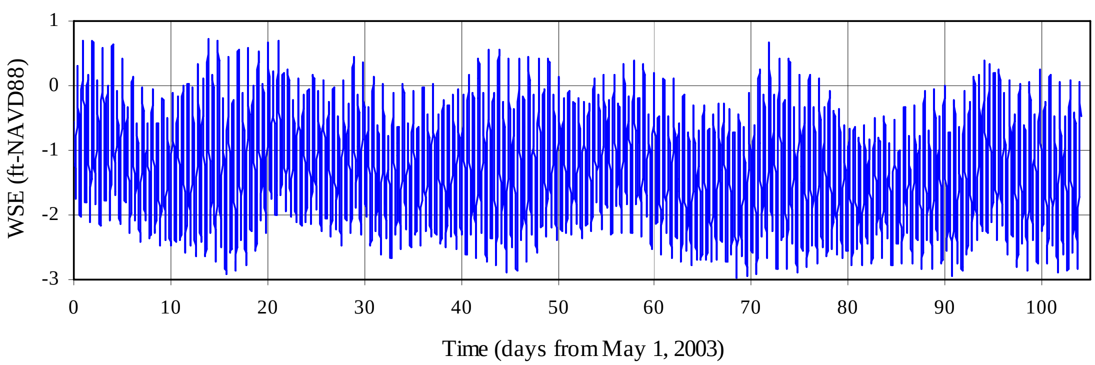
Model output tide near Kitching Creek



Tide measurements at Boy Scout Dock



Model output tide at Boy Scout Dock



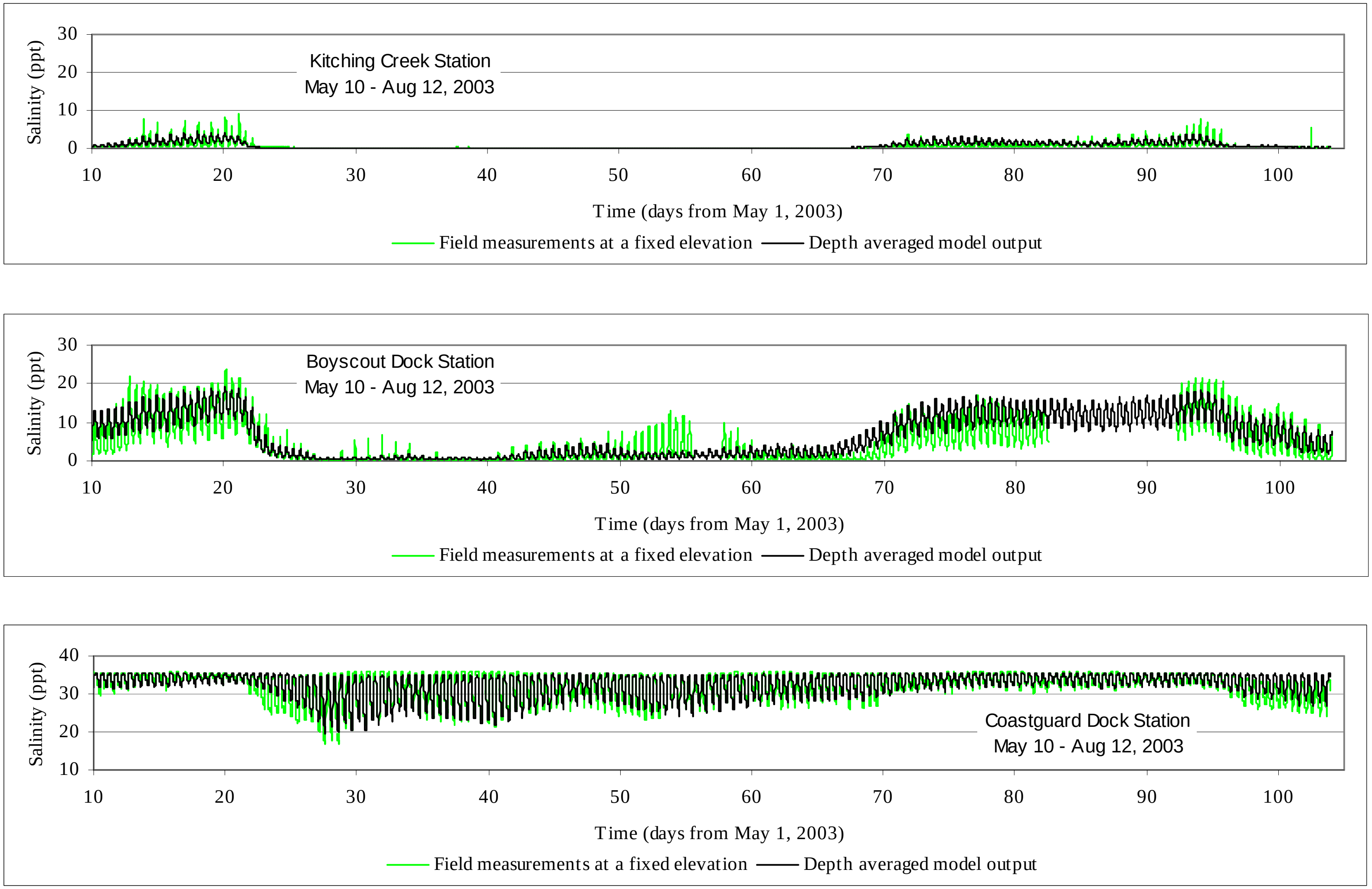


Figure 16. Model output of depth-averaged salinity and field measurements at fixed elevations in the water column.

The most likely reason for the difference between model prediction and field measurements is that there is additional freshwater inflow to the system that bypasses the four stations on the river and the major tributaries. Such additional sources of fresh water may include overland flow and groundwater seepage into the system. A groundwater monitoring network that was established in 2003 indicates active exchanges between the river and the groundwater table. The model predicted higher salinity at the beginning of dry periods when the groundwater tables are still relatively high and therefore provide additional fresh water to the system. Including groundwater input in the model will likely increase the accuracy in salinity prediction. The current model, without the input of groundwater input and overland flow, tends to be conservative (predicting higher salinity).

The current model does not include driving forces such as wind, precipitation/evaporation, and the exchange between the river and the groundwater which can be significant in the upper river reaches. The model verification simulation, which was only driven by major tributary freshwater input and ocean tide, was able to predict the tide regimen rather accurately and predict the trend of salinity changes over the three-month simulation period that included both low and high freshwater input to the estuary. This seems to indicate that the amount of freshwater inflow to the estuary and tide are the two most dominant factors that affect the salinity regimen in the upper Northwest Fork.

RMA MODEL SIMULATION RESULTS – FRESHWATER INFLOW AND SALINITY RELATIONSHIP

The tidal circulation and salinity structure of estuaries involves competition between freshwater river flows and ocean influences. River flow persistently adds fresh water to the estuary, however saltwater may still penetrate far inland due to gravitational and diffusive fluxes (MacCready, 2004). Although there are other factors in addition to tide and freshwater inflows that affect the salinity regime, the analysis of the field data from the Loxahatchee River suggested that tide and freshwater inflow are the two most important factors that determine the salinity conditions in the Northwest Fork (Hu, 2004). To establish the relationship between freshwater inflow and salinity in the Northwest Fork of the Loxahatchee River, the RMA model was used in 12 modeling scenarios where the amount of total freshwater flow from all three forks of the Loxahatchee River into the estuary was held constant for rates varying from 40 cfs at the low flow end to 7,000 cfs at the high flow end. These flow rates were determined based on an analysis of freshwater inflows simulated by the watershed model. During RMA model output processing, 15 study sites were identified for ecological assessment where salinity predictions are needed. Information about study and assessment sites is provided in **Table 14**. Sites noted as USGS stations are locations where tide and salinity measurement data are collected by the U.S. Geological Survey as discussed in the previous sections. **Figure 17** shows the locations of the 15 assessment sites.

Table 14. Salinity and ecological assessment sites.

Coordinates[a]		Site		Description
X (feet)	Y (feet)	Station ID	River Mile	
955325	951200	CG	0.70	USGS Coast Guard
951456	952232	SGNB	1.48	Seagrass site - North Bay
949616	951344	SGSB	1.74	Seagrass site - Sand Bar
949538	950648	PD	1.77	USGS Pompano Drive
945680	951761	SGPP	2.44	Seagrass site - Pennock Point
945105	953335	O1	2.70	Oyster site 1
942902	954999	O2	3.26	Oyster site 2
942332	957383	O3	3.74	Oyster site 3
940923	958927	O4	4.13	Oyster site 4
938854	961625	O5	4.93	Oyster site 5
936681	963169	O6	5.45	Oyster site 6
935708	965258	BD	5.92	USGS Boy Scout Dock
934679	966363	VT9	7.06	Vegetation Transect 9
931399	966948	KC	8.13	USGS Kitching Creek
929733	964696	RM9	9.12	USGS RM 9.1; Vegetation Transect 7

[a] State Plane Florida East NAD83.

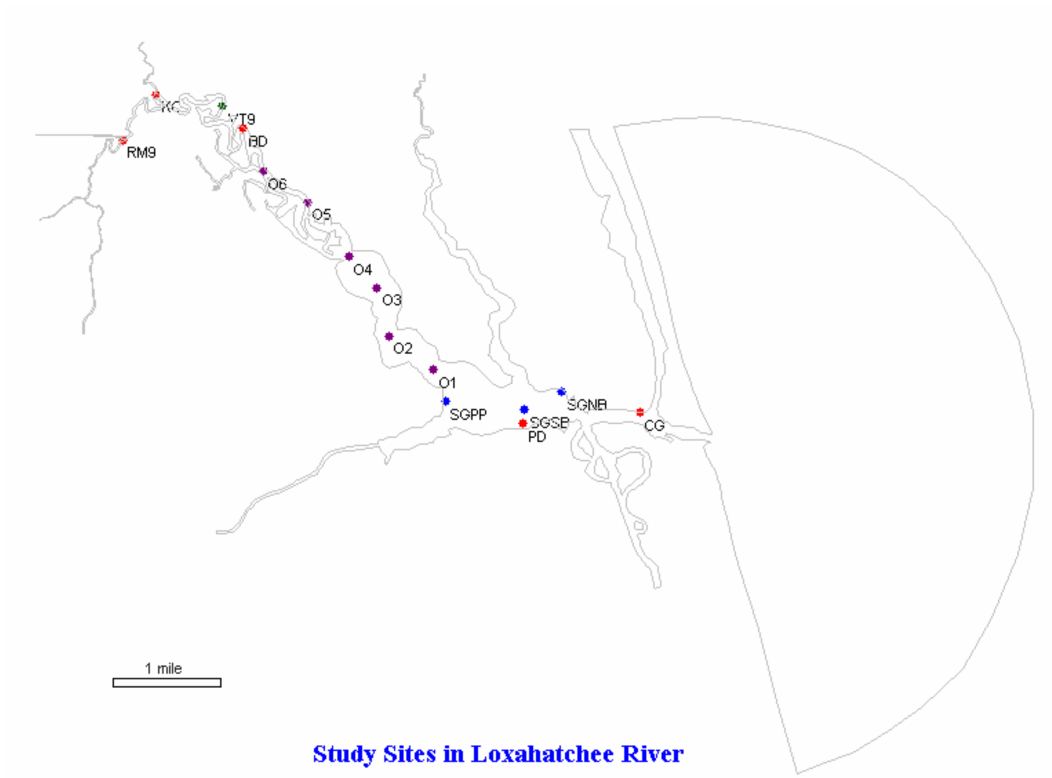


Figure 17. Location of salinity and ecological assessment sites. Red dots represent USGS sites; blue dots represent seagrass sites; purple dots represent oyster sites; and green dots represent vegetation sites.

The objective of the RMA model application is to establish a relationship between the amount of freshwater inflow and tidally averaged salinity. The RMA model output was averaged over a lunar month that includes a full lunar tidal cycle with both spring and neap tides. Thus, these results reflect the daily averaged salinity under an average tidal condition.

Table 15 is a summary of the RMA model output of average salinity for 12 flow scenarios at each of the 15 sites. Regression analysis of the results yielded regression equations with excellent curve fitting. The best fit (R^2 = 0.999 for all the 15 sites) was achieved with exponential functions in the form of

$$Y = Y_0 + a\ e^{-bX} \qquad [15]$$

where X is freshwater inflow in cubic feet per second and Y is salinity in parts per thousand. Y_0, a, and b are regression parameters that are listed in **Table 10** for each of the 15 sites.

Table 15. Tidally averaged salinity (ppt) versus freshwater inflow (cfs) for the 15 study sites in the Loxahatchee River.

Flow(cfs)	CG	SGNB	SGSB	PD	SGPP	O1	O2	O3	O4	O5	O6	BD	VT9	KC	RM9
40	34.6	34.1	33.9	33.8	33.2	32.7	32.0	31.1	30.5	27.8	25.8	23.6	16.8	9.7	4.2
70	34.4	33.6	33.3	33.2	32.3	31.7	30.5	29.2	28.3	24.4	21.6	18.8	11.0	4.9	1.4
100	34.1	33.1	32.7	32.7	31.5	30.6	29.0	27.4	26.2	21.5	18.1	15.0	7.2	2.5	0.5
150	33.7	32.4	31.8	31.7	30.1	29.0	26.8	24.7	23.1	17.3	13.5	10.3	3.6	0.9	0.2
200	33.3	31.6	30.9	30.8	28.8	27.4	24.8	22.2	20.4	13.9	10.0	7.1	1.9	0.4	0.2
300	32.5	30.1	29.1	29.0	26.4	24.5	21.1	18.0	15.9	9.1	5.6	3.4	0.6	0.2	0.2
500	31.0	27.4	26.0	25.8	22.2	19.6	15.4	11.8	9.6	3.9	1.8	0.9	0.2	0.2	0.2
800	28.8	23.8	21.8	21.6	17.1	14.0	9.6	6.3	4.6	1.2	0.5	0.3	0.2	0.2	0.2
1200	26.1	19.6	17.3	17.0	12.1	9.0	5.2	2.8	1.8	0.4	0.2	0.2	0.2	0.2	0.2
2400	19.3	10.9	8.5	8.3	4.3	2.5	0.9	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2
4800	10.1	3.1	1.9	1.8	0.6	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
7000	5.0	0.6	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
y0	-3.074	-0.753	-0.334	-0.291	0.118	0.223	0.225	0.215	0.219	0.224	0.2	0.19	0.16	0.153	0.151
a	38.04	35.51	34.99	34.94	34.25	34.02	33.83	33.68	33.52	32.92	32.47	31.83	29.3	24.76	19.4
b	3E-04	6E-04	7E-04	7E-04	0.001	0.001	0.002	0.003	0.003	0.006	0.008	0.01	0.018	0.03	0.049

The freshwater flow versus salinity relationships tabulated in **Table 15** are plotted in **Figures 18** and **19**. Each curve in **Figure 18** represents the flow/salinity relationship for each of the 15 sites. For each site, salinity increases as freshwater inflow decreases.

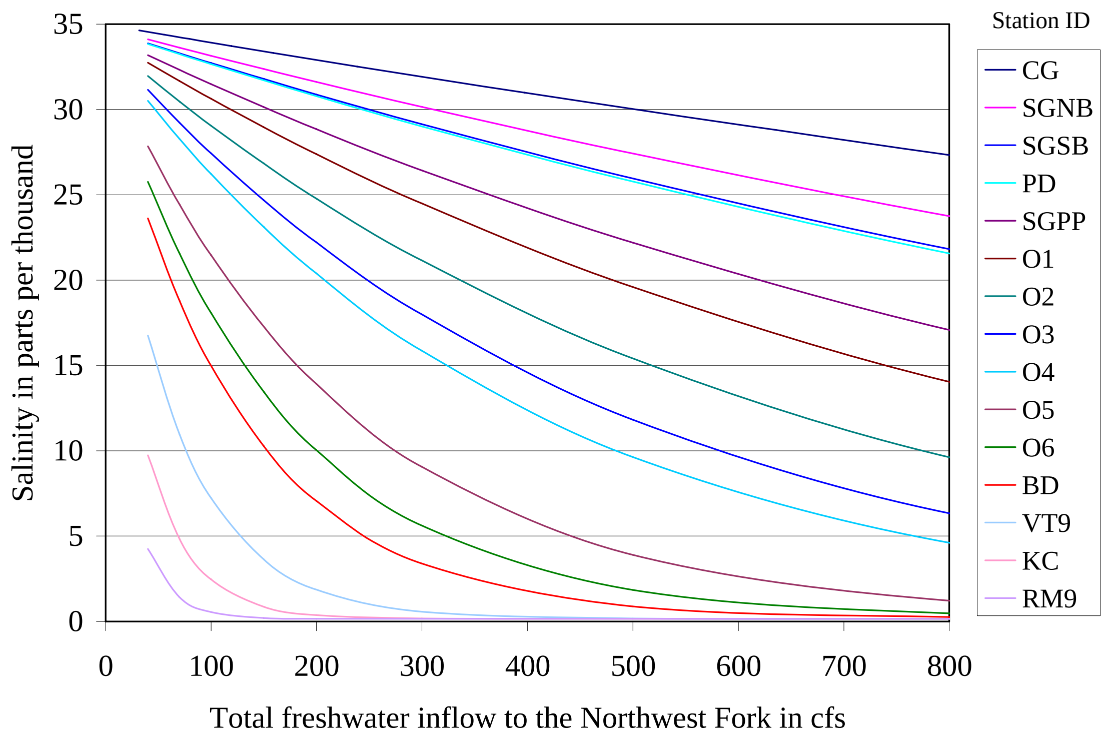


Figure 18. The relationship between freshwater inflow and salinity at the 15 study sites.

In order to show the details of salinity variation at low flow end, the charts were plotted only for inflows up to 800 cfs. For salinity regimens with freshwater inflows greater than 1,200 cfs, either **Table 15** or Equation [15] can be used to determine the salinity value. The curves in **Figure 19** represent the salinity gradients at various levels of freshwater inflow. Each line represents the spatial salinity distribution for a particular inflow scenario.

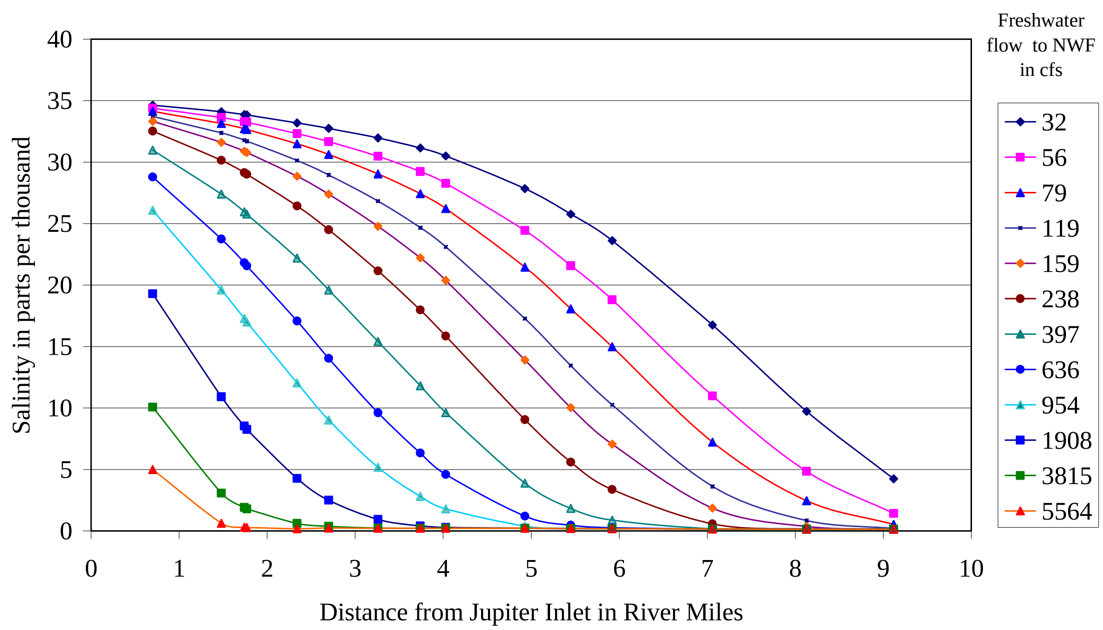


Figure 19. Salinity gradients for various freshwater inflow conditions.

Although Equation [15] expresses salinity as a single dependent variable function, there are other driving forces that affect salinity including tide, wind, flux between river and groundwater, precipitation, and evaporation. However, the analysis of field data indicated that freshwater inflow is the most important factor affecting salinity. When salinity is plotted against freshwater flow, the data points form a clear trend line. Comparing results from Equation [15] with actual field data provides a reality check. **Figures 20** through **23** compare the model results from Equation [15] with actual field measurements. As expected, deviations from the modeled flow/salinity curve indicate the existence of other driving forces that affect salinity. Nonetheless, the correlation between salinity and freshwater inflow is significant. Another factor that could cause deviations is that the system is under constant transition in response to the changes in the driving forces. Therefore, it is rare for the system to reach equilibrium as the case in the constant flow simulations. The overall trend of the field measurements shows a strong correlation between the amount of freshwater inflow and salinity throughout the estuary.

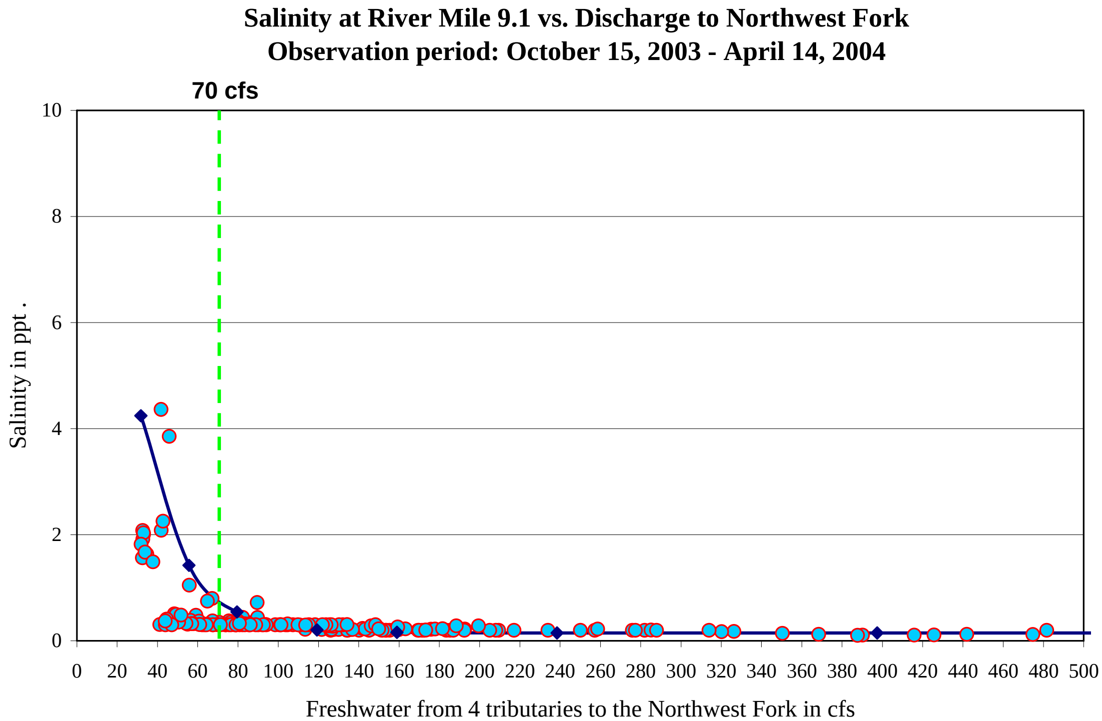


Figure 20. The effects of freshwater inflow on salinity at RM 9.1 from October 15, 2003–April 14, 2004.

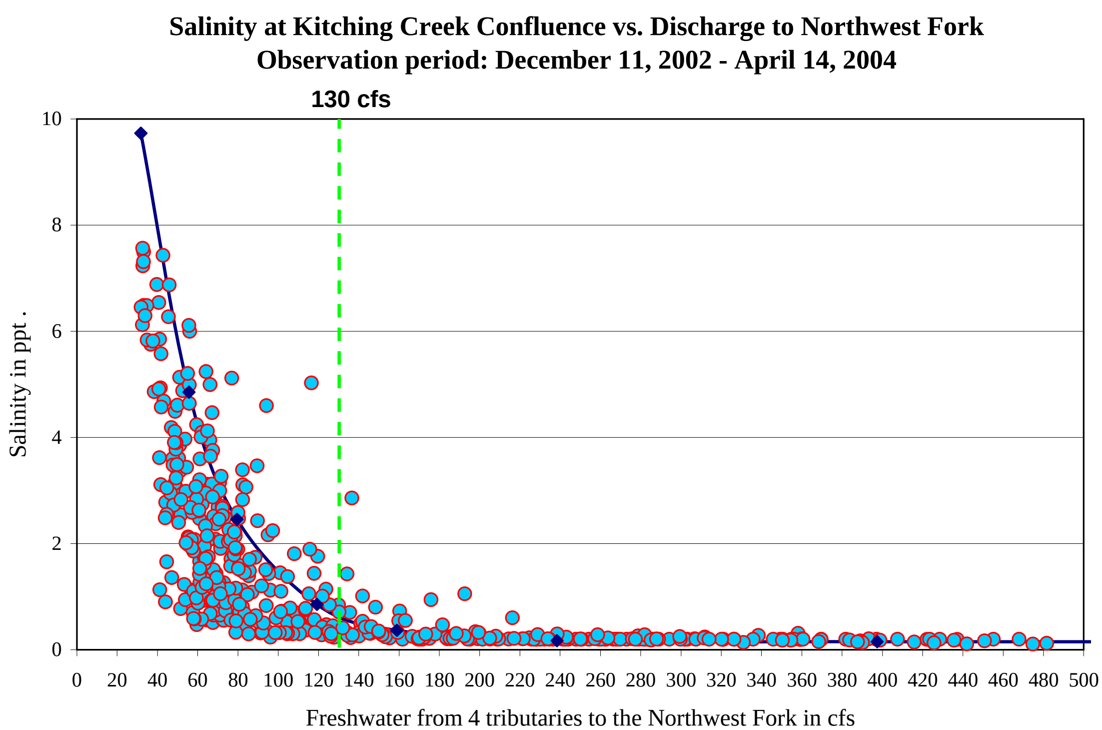


Figure 21. The effects of freshwater inflow on salinity at RM 9.1 from October 15, 2003–April 14, 2004.

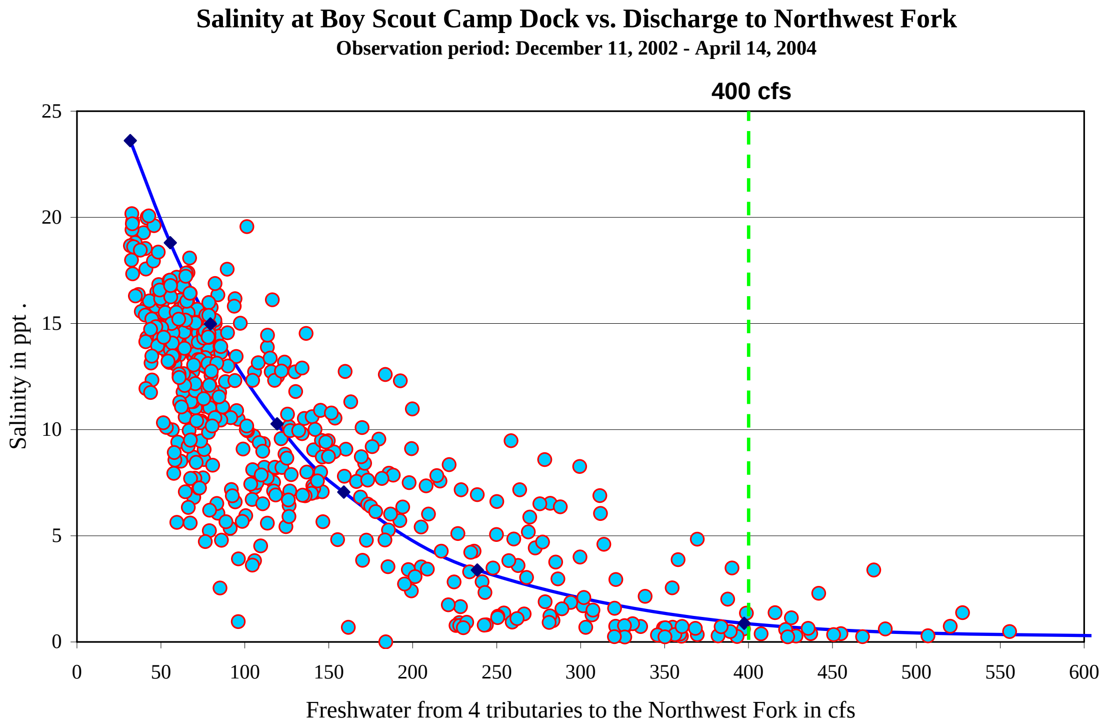


Figure 22. The effects of freshwater inflow on salinity at Boy Scout Dock from December 11, 2002–April 14, 2004.

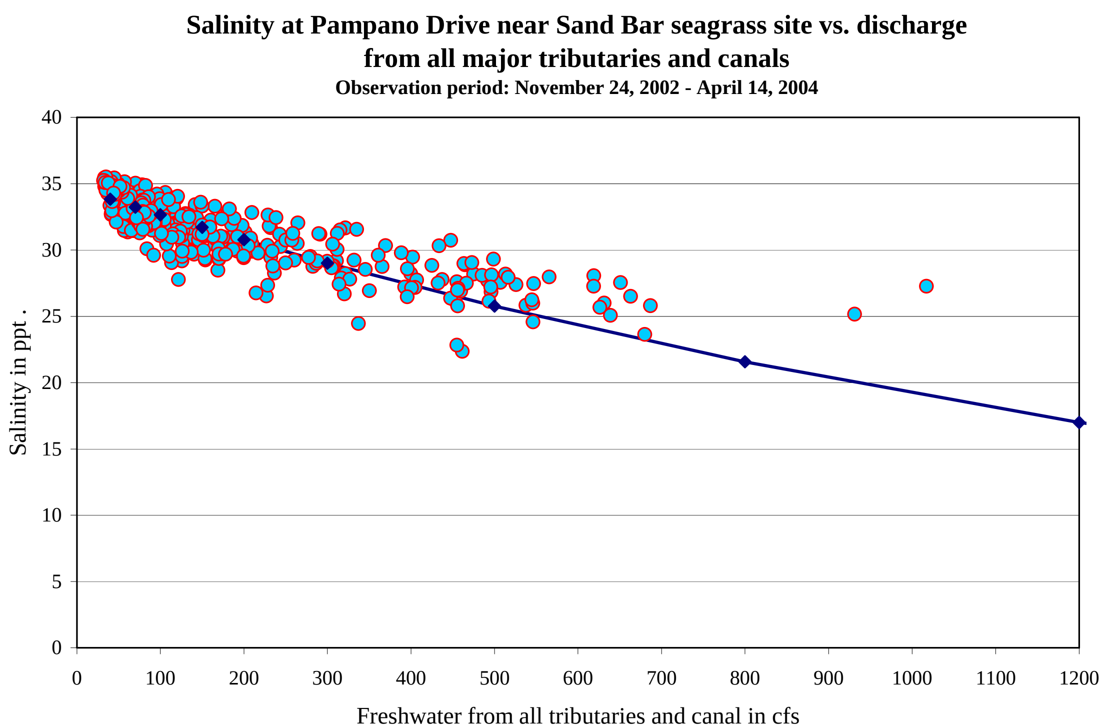


Figure 23. The effects of freshwater inflow on salinity at Embayment from November 24, 2002–April 14, 2004.

Freshwater inflows to the Northwest Fork from the four major tributaries, several small tributaries, and overland flow were modeled. If the inflows from all the tributaries were considered individually, they would form a large array of scenarios. The analysis of the field data indicates that there is a good correlation between salinity at various sites with the total freshwater flow volume to the Northwest Fork. The physical explanation for this correlation is the strong tidal mixing in the Northwest Fork. For example, when the tide rises, freshwater inflows from Kitching Creek will be pushed upstream into the river reaches above the mouth of Kitching Creek and thus influence the salinity there. It is the total volume of fresh water entering the Northwest Fork that matters the most for the reaches between RM 6 and RM 9. The origin of fresh water (whether the fresh water was from Kitching Creek or some other tributary) does not seem to be an important factor in the current analysis. Such a finding has two implications:

1. Freshwater from all the tributaries affects the salinity in the Northwest Fork. Therefore, any increase of freshwater discharge from any combination of tributaries will help achieve the salinity management goal of the Northwest Fork between RM 6 and RM 9. In addition to increasing freshwater flows from the G-92, flows from other tributaries and basins such as Cypress Creek/Pal Mar, and Kitching Creek should also be fully utilized.
2. Salinity predictions in the Northwest Fork between RM 6 and RM 9 can be based on total freshwater inflow to the Northwest Fork instead of freshwater inflow from each individual tributary. Such an approach will allow the testing of more restoration scenarios with limited resources. This capability is especially critical in the initial alternative assessment phase of the restoration plan since numerous scenarios need to be analyzed. When the total amount of freshwater demand is determined, the analysis can then evolve into the next phase, that is, to consider the freshwater contribution from each tributary individually to meet the Northwest Fork freshwater demand. At that phase, a model with more refined spatial resolution, such as the RMA model that was described in the previous sections, can be used for scenarios where tributaries are simulated separately from each other.

The salinity value predicted by Equation [11] is tidally averaged salinity over a lunar tidal cycle. The actual salinity in the river constantly varies in response to tides. If the hourly salinity variation over each tidal cycle needs to be considered, then the information is available from the original model output.

Figure 24 is the model output of salinity at the Pennock Point seagrass transect in a lunar month. The graphs are the output under three freshwater inflow conditions. Total freshwater inflows of the three simulations are 500 cfs, 800 cfs, and 1,200 cfs. The amount of freshwater inflow affects both the overall salinity level and the range of salinity variation (the difference of salinity between high tide and low tide).

Figure 24 represents the salinity predictions for only one site under three flow conditions. The model simulation output included salinity for 15 sites under 12 different inflow conditions; thus 180 sets of time-series data were produced.

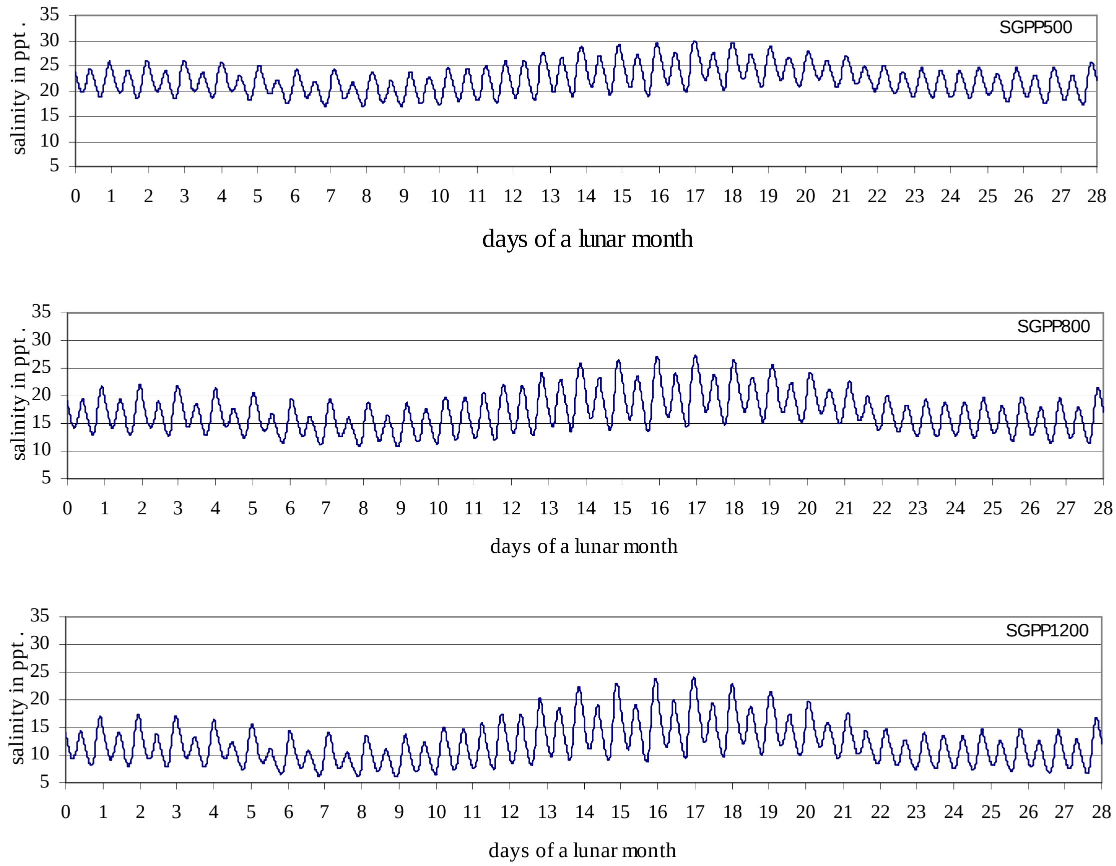


Figure 24. Salinity at Pennock Point seagrass transect in a lunar month; total freshwater inflow to the Loxahatchee River: 500, 800, and 1,200 cfs.

Figure 24 represents one example from a large array of charts in the model output that cover a wide range of freshwater flow. The salinity conditions represented by 500, 800, and 1,200 cfs are relatively high flows that begin to affect salinity conditions at the Pennock Point seagrass site (RM 2.44).

The RMA was applied to scenarios with varying amounts of freshwater inflow. Both the field data and model simulation indicated that there is a strong correlation between freshwater inflow and the salinity regimen in the estuary. Based on model output and field data analysis, a relationship was established to predict salinity at various points in the estuary with respect to freshwater inflow rates and tidal fluctuations. The salinity/freshwater relationship was applied in the Loxahatchee River MFL study (SFWMD, 2002a). The RMA model was also used to provide a preliminary assessment of the impacts that inlet deepening and sea level rise have had on the salinity regime in the estuary (Hu, 2002).

LONG-TERM SALINITY MANAGEMENT MODEL

The freshwater/salinity relationship described in the previous section was coded into the Loxahatchee Estuary Long-Term Salinity Management Model (LSMM) to predict tidally averaged salinity in response to various restoration scenarios. This model can also simulate system operation rules and calculate the amount of freshwater demand for salinity management.

The salinity values in **Table 15** are based on an equilibrium state with constant freshwater inflows. In the applications of the freshwater input versus salinity relationships, the dynamic nature of the system needs to be considered. Under natural conditions, freshwater inflow is rarely constant. The salinity conditions observed in the estuary are the result of a series of transitions from one state to the next. The changes in salinity lag behind the changes in freshwater inflow. Following an increase of freshwater inflow, salinity in the estuary will decrease accordingly and gradually approach a new equilibrium state. As the amount of freshwater decreases, the salinity in the estuary will increase gradually. Depending on the direction of salinity changes, the process can be described as an exponential increase or decay. **Figure 25** is a graphic description of salinity transition when an increase of freshwater inflow occurs. The dotted line indicates the equilibrium salinity at the higher level of freshwater inflow.

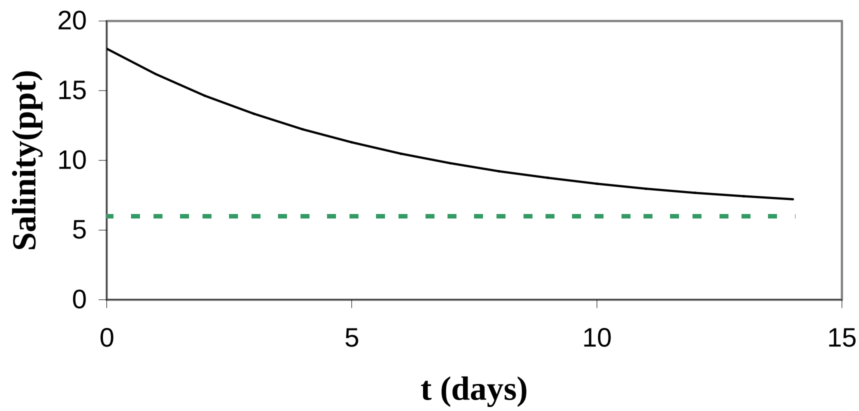


Figure 25. Salinity regimen transition process.

The salinity condition within the estuary consists of a series of transitions from one quasi-equilibrium condition to another. This concept was reflected in the LSMM program. The program calculates the potential target (equilibrium) salinity based on the amount of freshwater inflow. It then calculates the salinity change on daily time steps using the following equation:

$$SAL2 = SALEQ + (SAL1-SALEQ)*Exp(-cT) \quad [16]$$

where SAL1 is the salinity at the beginning of the time step, SAL2 is the salinity at the end of the time step, SALEQ is the equilibrium salinity for certain amount of freshwater inflow after the transition has completed. T is time and c is a constant that determines the speed of transition. Apparently at the beginning of the time step (T=0), SAL2 = SAL1 and if the freshwater inflow remains the same, SAL2 will eventually reach SALEQ.

Because the freshwater inflow is provided by the watershed model in daily time steps, the calculation of the Long-Term Salinity Management Model is carried at fixed time steps of 24 hours. The predicted salinity depends on both target (equilibrium) salinity and the initial salinity condition at the beginning of the time step. If the amount of freshwater inflow changes before the transition is completed, then a new transition begins and the program repeats the same computational procedure under the new flow condition.

The LSMM is designed to assess daily average salinity over a long period of time. Because the program operates on daily time steps (versus minutes or seconds of a full hydrodynamic model), it allows the assessment of long-term data (39 years in this model simulation) at minimum cost and computing time. In addition to using hydrologic data provided by the WaSh model, the LSMM can also modify the hydrograph based on certain operational rules such as MFL criteria. The model also calculates the amount of freshwater demand for salinity management and nutrient loadings assuming a target concentration for inflows.

Figures 26 through **29** depict the salinity calculations of the LSMM. The output was compared with real data from four salinity stations in the Northwest Fork and the embayment area near the Jupiter Inlet. **Table 16** lists the statistical characteristics of both model prediction and field data. Statistics of the entire period of 517 days shows that the mean salinity of model output is slightly higher than field data at the four stations by 0.1 to 0.6 ppt. This is probably because the flow gauges on the Northwest Fork and major tributaries did not control 100 percent of the fresh water entering the system. **Tables 17** and **18** list the statistics of model prediction and field data for two relatively dry periods (March through May) and the rest of the year, respectively. In general, the simulated daily salinity matches well with the observed salinities statistically.

Table 16. Comparison of statistical characteristics of model and field data.

Station Name	PD		BD		KC		RM9	
Date Type	Model	Field	Model	Field	Model	Field	Model	Field
Maximum	34.7	35.5	21.8	20.2	7.6	7.6	2.9	4.4
Minimum	25.0	22.4	1.1	0.2	0.1	0.1	0.0	0.1
Mean Value	32.1	31.8	11.1	9.7	2.1	1.5	0.6	0.5
Median Value	33.1	32.4	12.5	10.1	1.8	0.7	0.4	0.3
Standard Deviation	2.40	2.50	6.22	5.49	1.94	1.71	0.62	0.58
Data Count	517	477	517	502	517	506	517	199
Number of Missing Records	0	40	0	15	0	11	0	318

Table 17. Comparison of statistical characteristics of model and field data – March through May.

Station Name	PD		BD		KC		RM9	
Date Type	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**
Maximum	34.7	35.5	21.8	20.2	7.6	7.6	2.9	4.4
Minimum	26.2	30.1	3.4	0.3	0.5	0.2	0.2	0.3
Mean Value	33.5	33.7	15.9	12.3	3.6	2.5	1.0	1.0
Median Value	33.8	33.9	15.9	13.1	3.1	1.7	0.7	0.5
Standard Deviation	1.40	1.19	3.98	4.97	2.04	2.08	0.78	0.87
Data Count	153	117	153	150	153	153	153	61
Number of Missing Records	0	36	0	3	0	0	0	92

Table 18. Comparison of statistical characteristics of model and field data – June through February.

Station Name	PD		BD		KC		RM9	
Date Type	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**	**Model**	**Field**
Maximum	34.5	35.1	20.3	19.6	6.0	6.9	2.0	0.8
Minimum	25.0	22.4	1.1	0.2	0.1	0.1	0.0	0.1
Mean Value	31.5	31.1	9.1	8.6	1.5	1.1	0.4	0.3
Median Value	32.2	31.7	7.9	8.6	0.7	0.3	0.2	0.3
Standard Deviation	2.48	2.48	5.90	5.34	1.52	1.32	0.41	0.10
Data Count	364	360	364	352	364	353	364	138
Number of Missing Records	0	4	0	12	0	11	0	226

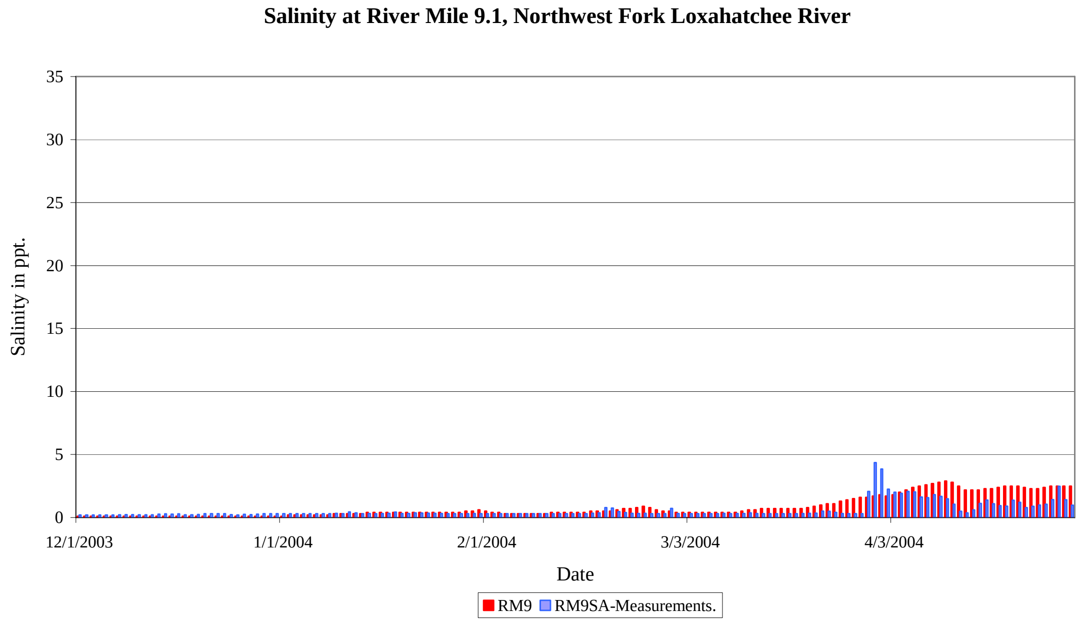


Figure 26. Field measurements versus salinity computation results for RM 9.12.

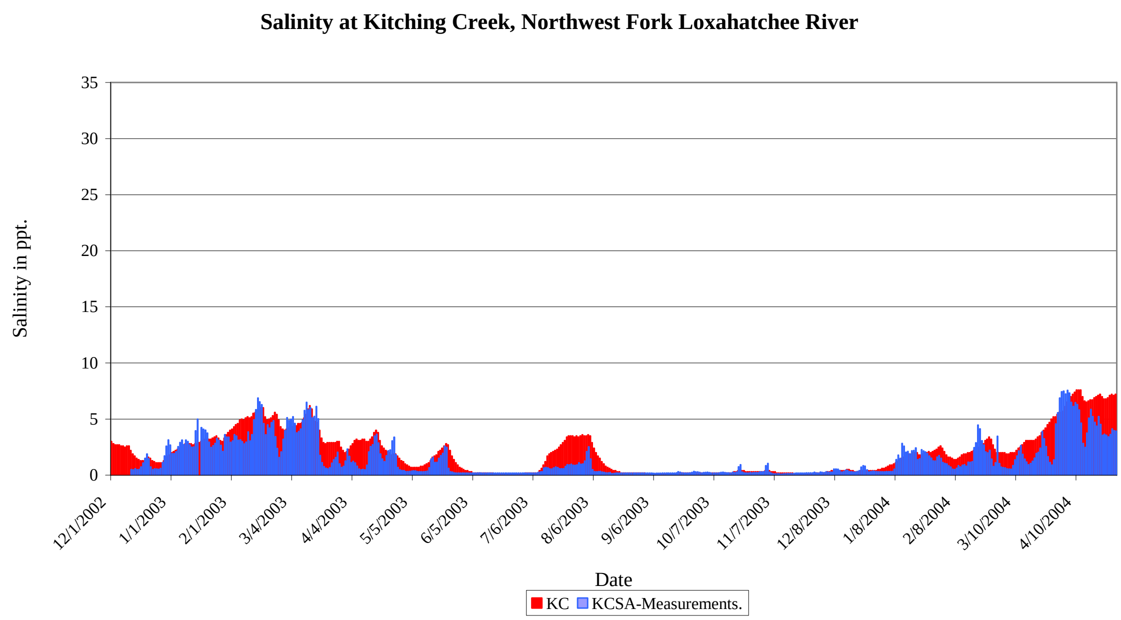


Figure 27. Field measurements versus salinity computation results for Kitching Creek (RM 8.13).

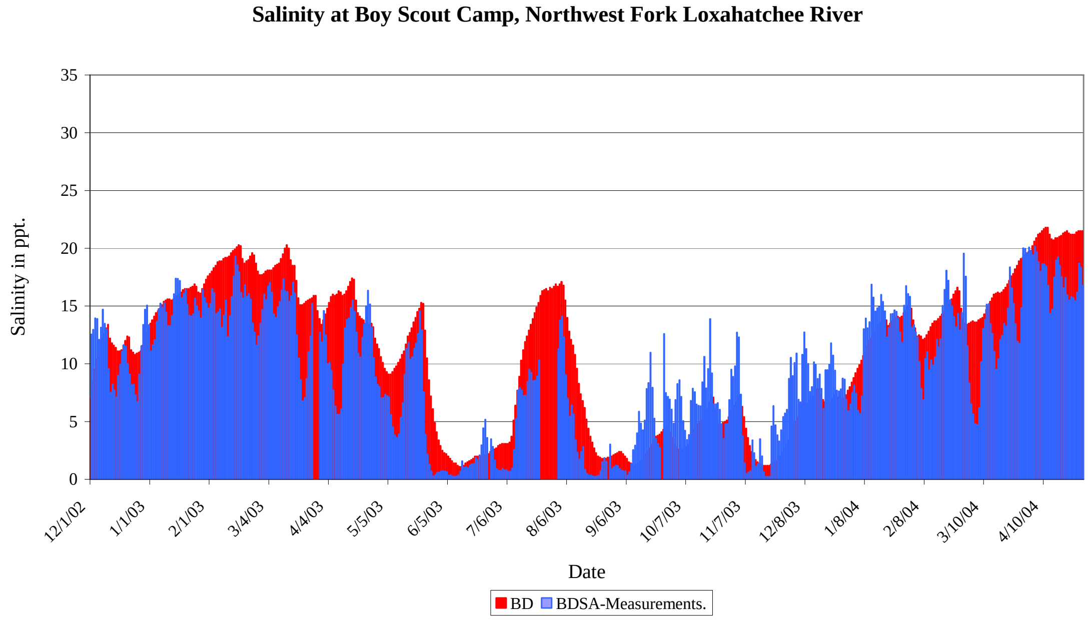


Figure 28. Field measurements versus salinity computation results for Boy Scout Dock (RM 5.92).

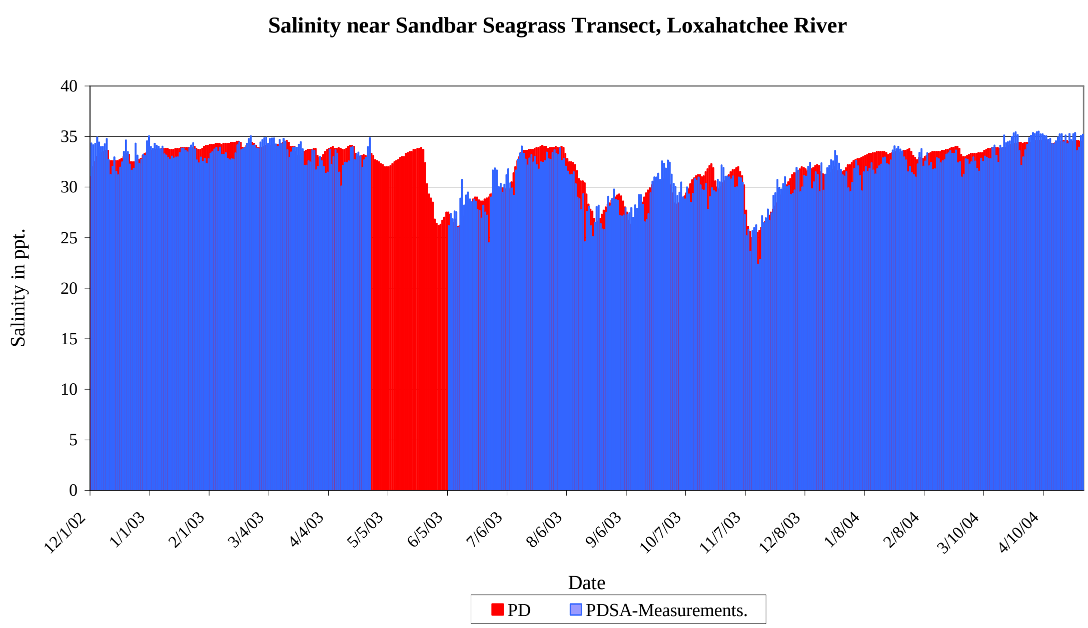


Figure 29. Field measurements versus salinity computation results for Pompano Drive Embayment Area (RM 1.77).

MODELING THE NORTHWEST FORK ECOSYSTEM RESTORATION SCENARIOS

The modeling results of the Loxahatchee WaSh model for the POR from 1965–2003 were used to establish the base project condition for scenario evaluation of Northwest Fork ecosystem restoration. The BASE simulation represents the existing or current conditions with no modifications. Five additional simulations were conducted with certain modifications to the BASE simulation hydrographs. The modifications represent scenarios that provide additional freshwater flows to upper Northwest Fork at Lainhart Dam and tributaries (Cypress Creek, Hobe Grove, and Kitching Creek) to reduce salinity in the freshwater segments of the Northwest Fork. The five restoration flow scenarios were designed to represent different levels of flows from a tributary or a combination of tributaries to the Northwest Fork. The scenarios were selected based on information provided by members of the public and agency representatives at meetings held to discuss the restoration of the Northwest Fork. For example, a flow of 65 cfs had been used as a flow target in the model for the development of the Northern Palm Beach County Comprehensive Water Management Plan (SFWMD, 2002b). **Table 20** summarizes the flow component(s) of each scenario. The LSMM was then used to predict daily salinity under the five scenario conditions at 15 locations (**Figure 18**). The simulated flow and salinity results were used to evaluate the ecological benefit with respect to each of the ecological components in the Northwest Fork.

Table 21 presents the salinity gradient of each scenario for the 15 study sites. Salinity ranges from near ocean conditions at the U.S. Coast Guard Station (RM 0.70; CG) near Jupiter Inlet to freshwater conditions at RM 9.12 in the Northwest Fork of the Loxahatchee River. The five scenarios that increase freshwater flows also lower the salinity throughout the river and the estuary. It is important to point out that the salinity condition in the Northwest Fork is extremely sensitive to the amount of freshwater inflow. A small change in freshwater flow of less than 10 cfs can cause changes in salinity as high as several ppt in the upper Northwest Fork. **Table 21** only provides the average salinity for each site. Ecological evaluation of these scenarios is based on an analysis of daily salinity for the POR. **Figure 30** is the graphic presentation of the model results in **Table 16**. The plots shows the average salinity gradients under base condition and each scenario that was modeled.

Table 20. Long-Term Salinity Management Model simulation of restoration scenarios.

Scenario	Base Condition Hydrograph	Added Flows From Lainhart Dam	Added Flows From Tributaries	Total Added Flows	Approximate 2 ppt Saltwater Front Position
Base	1965-2003 base condition generated by watershed model	No additional flows	No additional flows	No additional flows from Lainhart Dam or tributaries	RM 9.5
LD65	1965-2003 base condition generated by watershed model	Water added as needed so flow is a minimum of 65 cfs at all times	No additional flows	Additional flows only from Lainhart Dam for a minimum of 65 cfs; No additional flows from tributaries	RM 8.5
LD65TB65	1965-2003 base condition generated by watershed model	Water added as needed so flow is a minimum of 65 cfs at all times	Water added as needed so flow is a minimum of 65 cfs at all times	Additional flows from Lainhart Dam and tributaries. Total flow is a minimum of 130 cfs at all times.	RM 8.0
LD90TB110	1965-2003 base condition generated by watershed model	Water added as needed so flow is a minimum of 90 cfs at all times	Water added as needed so flow is a minimum of 110 cfs at all times	Additional flows from Lainhart Dam and tributaries. Total flow is a minimum of 200 cfs at all times	RM 7.5
LD200	1965-2003 base condition generated by watershed model	Water added as needed so flow is a minimum of 200 cfs at all times	No additional flows	Additional flows only from Lainhart Dam for a minimum of 200 cfs; No additional flows from tributaries	RM 7.0
LD200TB200	1965-2003 base condition generated by watershed model	Water added as needed so flow is a minimum of 200 cfs at all times	Water added as needed so flow is a minimum of 200 cfs at all times	Additional flows from Lainhart Dam and tributaries. Total flow is a minimum of 400 cfs at all times	RM 6.0

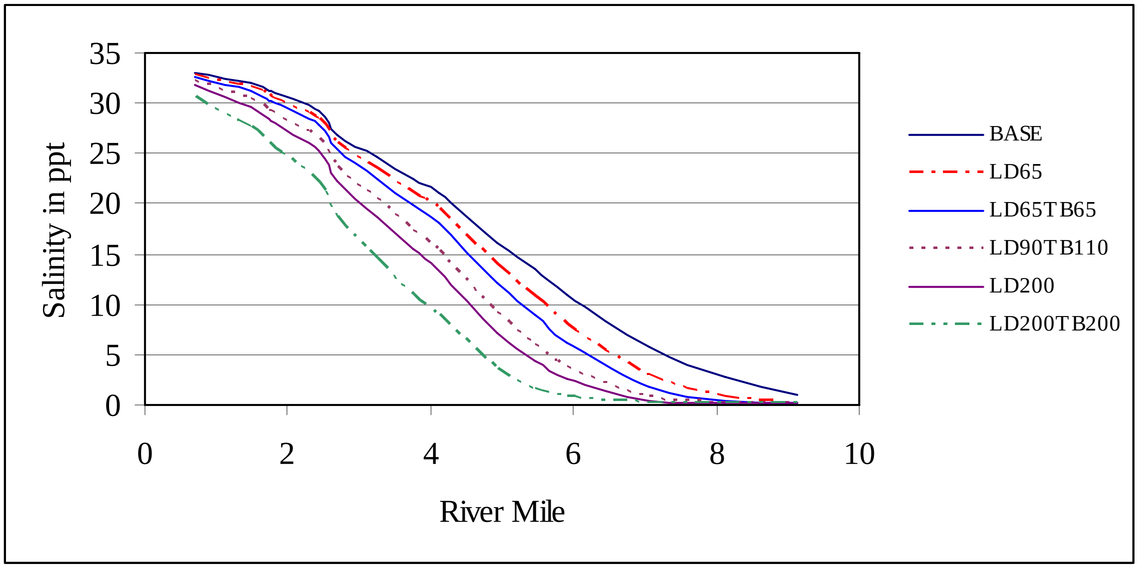


Figure 30. Salinity gradient under base condition and five flow scenarios.

Table 21. Average salinity (ppt) at 15 study sites over the 39-year simulation period.

Salinity Study Site		Restoration Scenarios					
Site ID	**River Mile**	**BASE**	**LD65**	**LD65TB65**	**LD90TB110**	**LD200**	**LD200TB200**
CG	0.70	33.0	32.8	32.6	32.2	31.8	30.7
SGNB	1.48	32.0	31.6	31.3	30.4	29.6	27.6
SGSB	1.74	31.3	30.8	30.3	29.3	28.4	26.0
PD	1.77	31.2	30.6	30.2	29.2	28.3	25.8
SGPP	2.44	29.2	28.5	27.9	26.5	25.2	22.0
O1	2.70	26.9	26.1	25.4	23.7	22.3	18.7
O2	3.26	24.6	23.5	22.5	20.4	18.7	14.5
O3	3.74	22.5	21.0	19.9	17.4	15.5	11.0
O4	4.13	21.0	19.4	18.1	15.4	13.4	8.9
O5	4.93	16.2	13.9	12.2	9.1	7.2	3.5
O6	5.45	13.5	10.7	8.9	5.9	4.3	1.6
BD	5.92	10.9	7.9	6.2	3.7	2.5	0.7
VT9	7.06	5.8	3.0	1.8	0.7	0.4	0.2
KC	8.13	2.7	0.8	0.4	0.2	0.1	0.1
RM9	9.12	1.0	0.2	0.1	0.1	0.1	0.1

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