SOUTH FLORIDA WATER MANAGEMENT DISTRICT

Coastal Ecosystem Sciences Division
Restoration Sciences Department
South Florida Water Management District

Loxahatchee River Science Plan

December 2010

In Cooperation with
Florida Park Service District Five
Loxahatchee River District
Loxahatchee River Interagency Science Team

Loxahatchee River Science Plan

South Florida Water Management District

Florida Park Service District Five

Loxahatchee River District

Loxahatchee River Interagency Science Team

December 2010

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND UNITS OF MEASUREMENT

BEST3D-ISGO	Bay/Estuary Hydrodynamics and Sediment/Contaminant Transport Model for 3D Integrated Surface, Groundwater, and Overland Regimes
CDOM	chromomorphic dissolved organic matter
CERP	Comprehensive Everglades Restoration Plan
cfs	cubic feet per second
CH3D	Curvilinear-grid Hydrodynamics Model in Three Dimensions
DEM	Digital Elevation Model
EFDC	Environment Fluid Dynamic Code Model
FDEP	Florida Department of Environmental Protection
FIU	Florida International University
FWC	Florida Fish and Wildlife Conservation Commission
FY	Fiscal Year
GIS	geographic information system
GPS	global positioning system
km^2	square kilometers
LAS	Files that conform to the ASPRS LIDAR data exchange format standard and are named with an LAS extension
LIDAR	Light Detection and Ranging
LRD	Loxahatchee River District
LRMCC	Loxahatchee River Management Coordination Council
LRPI	Loxahatchee River Preservation Initiative
LSMM	Long-term Salinity Management Model
MCDEQ	Martin County Division of Environmental Quality
NAVD	North American Vertical Datum
PBCERM	Palm Beach County Environmental Resources Management

ppt	parts per thousand
psu	practical salinity units
RECOVER	Restoration Coordination and Verification Program
RMA models	Refers to a series of hydrodynamic/salinity models developed by Resource Management Associates
SAV	submerged or submersed aquatic vegetation
SFWMD	South Florida Water Management District
TMDL	total maximum daily loads
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VEC	valued ecosystem component
WaSh	Watershed Model

ACKNOWLEDGEMENTS

This document is the result of a cooperative effort between the Coastal Ecosystem Sciences Division and Martin/St. Lucie Service Center of the South Florida Water Management District (SFWMD), the Florida Department of Environmental Protection's (FDEP) Florida Park Service (FPS) District 5, the Loxahatchee River District (LRD), and the rest of the Loxahatchee Interagency Science Team (LIST).

Principle authors:

Wan, Yongshan	SFWMD	Buzzelli, Chris	SFWMD
Chang, Miao-Li	SFWMD	Haunert, Daniel	SFWMD
Gunsalus, Boyd	SFWMD	Roberts, Richard	FDEP FPS (retired)
Zheng, Fawen	SFWMD	Rossmanith, Rob	FDEP FPS
Hedgepeth, Marion	SFWMD	Howard, Bud	LRD

Loxahatchee Interagency Science Team:

Arrington, Albrey	LRD, Director
Chang, Miao-Li	SFWMD, Director, Coastal Ecosystems Division
Rice, Paul	FDEP FPS, Bureau Chief, District 5

Alleman, Richard	SFWMD	Kacvinsky, Beth	SFWMD
Carter, Kevin	SFWMD	Kennedy, Chad	FDEP
Chen, Zhiqiang	SFWMD	Layman, Craig	FIU
Conrad, Cecilia	SFWMD	Miller, Paul	MCDEQ
Cowan, Ernest	FDEP FPS	Moody, Barron	FWC
Davis, Paul	PBCERM	Nelson, Mark	FDEP FPS
Gostel, Pat	SFWMD (retired)	Reinert, Tom	FWC
Gorman, Patti	SFWMD	Robbins, Rebecca	SFWMD
Hu, Gordon	SFWMD	Robbins, Robert	PBCERM
Hughes, Dianne	FDEP	Sun, Detong	SFWMD
Hudak, Christy	FWC	Swift, David	SFWMD
Jud, Zack	FIU	Welch, Barbara	SFWMD

EXECUTIVE SUMMARY

The *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006) recommended the development of a science plan for the Loxahatchee River to (1) monitor effects of restoration efforts to support adaptive management of the system, and (2) fill knowledge gaps critical to ecosystem restoration success. The Loxahatchee Interagency Science Team (LIST) was formed to undertake a cooperative effort to develop the Loxahatchee River Science Plan. The team is composed of representatives from the South Florida Water Management District, Florida Park Service District 5, Loxahatchee River District, Florida Department of Environmental Protection Southeast District, Martin County Division of Environmental Quality, Palm Beach County Environmental Resources Management, Florida Fish and Wildlife Conservation Commission, and Florida International University. The **overall management goal** of the science plan is to restore the Northwest Fork of the Loxahatchee River and enhance the estuary and watershed. **Issue-specific management objectives** to attain the overall management goal are to (1) maximize watershed restoration benefit; (2) enhance riverine and estuarine abiotic conditions; and (3) restore and protect riverine and estuarine biotic resources. These three management objectives seek a balance between the restoration of the Northwest Fork of the Loxahatchee River and protection of the Loxahatchee watershed and estuary.

Each management objective is supported by a suite of **research objectives** to be achieved through monitoring, modeling and evaluation. The research objectives are centered on a series of practical science questions concerning quantitative and qualitative understanding of the linkages between the riverine and estuarine ecological resources, riverine and estuarine abiotic conditions (e.g., salinity, stage and water quality), and watershed inflows in terms of quantity, quality, distribution and timing. Based on a review of existing information, the Loxahatchee River Science Plan identifies ongoing projects to be continued, and data and information gaps that need to be filled to attain the research objectives. In addition to data collection, the science plan proposes applied research to quantify how the characteristics of freshwater inflow (i.e., quantity, quality, distribution and timing) influence conditions in the Loxahatchee River (e.g., salinity and nutrient concentrations), and how these conditions affect different resources (e.g., species and communities) or processes (e.g., productivity and nutrient cycling) in the riverine and estuarine ecosystems. The information obtained will be used to develop predictive tools and performance measures for assessing biological and hydrological effects of our water management practices on the ecosystem. Ultimately, evaluation of restoration success will be achieved with monitoring and research programs proposed in this science plan.

To fulfill the **management objective of maximizing watershed restoration benefit**, hydrologic data from representative sites will be collected and used to assess wetland function and quantify the contribution of these restored wetlands to dry season flows to the Northwest Fork. Water quality data, representing different land use types, will continue to be collected and used to estimate the watershed nutrient loadings into the river and estuary. As restoration plans are implemented in the watershed, ecological and hydrologic performance measures will be incorporated into operational protocols of water management structures and facilities in the watershed to ensure the achievement of the target quantity, quality and timing of freshwater inflows. These operational protocols will be developed through analysis of the hydrologic and ecological database established through the implementation of this science plan.

Under the **management objective to enhance riverine and estuarine abiotic conditions,** the science plan recommends the continuation of ongoing monitoring projects including water flow, salinity, water quality, and water stage monitoring programs in the river and estuary. The proposed research aims to link the quantity, quality, and timing of watershed inflows with salinity, water quality and stage in the lower river and receiving estuary. These quantitative relationships will be used to evaluate water quality trends, floodplain inundation, and salinity under various flows. Developing a three-dimensional estuarine hydrodynamic and water quality model, which can be used as a management tool, is integral to this effort.

Under the **management objective to restore and protect the riverine and estuarine biotic resources**, the science plan recommends the continuation of ongoing monitoring projects to establish a baseline condition of floodplain vegetation, fishes, oysters, and seagrasses, the valued ecosystem components (VECs) identified in the document *Restoration Plan for the Northwest Fork of the Loxahatchee River*. The proposed research focuses on quantifying the condition of these VECs during various flows and water quality conditions with their watershed and abiotic drivers. The information obtained will be used to develop quantitative performance measures and modeling tools to measure the progress toward restoration. Data collection and analyses to quantify the impact of human use of the River on the quality of the ecosystem is proposed to define a recommended carrying capacity for the River.

The Loxahatchee River Science Plan serves as a guide for scientific data collection and analysis to be conducted over the next five years and for the efficient application of resources to prioritize and implement the needed science to protect and restore the Loxahatchee River. The modeling tools developed will improve the understanding of linkages between watershed hydrologic restoration and ecological responses in wetland, riverine and estuarine habitats. As the scientifically-based understanding of the ecosystem evolves and additional watershed restoration projects are completed, adaptive management decisions will be scientifically justified and documented to proceed toward the goal of restoring the Northwest Fork of the Loxahatchee River.

1.0 INTRODUCTION

The Loxahatchee River watershed ecosystem has experienced adverse environmental impacts due to alterations in watershed hydrology and the opening of Jupiter Inlet. The most significant alteration is the reduction of dry season flows to the Northwest Fork and the resulting saltwater intrusion into freshwater wetland vegetation communities in the lower and upper tidal reaches of the River. The *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006) provided the basis for the management of flows to protect and restore the freshwater floodplain, tidal floodplain, and estuarine reaches of the Northwest Fork of the Loxahatchee River. Using the best available information, the restoration plan identified a "preferred restoration flow scenario" that specifies deliveries of water at the Lainhart Dam and other tributaries of the Northwest Fork. Beyond the resource evaluations relative to inflows, this restoration plan recommended the development of a science plan for the Loxahatchee River and Estuary. This science plan is intended to guide and prioritize science activities associated with the River with a focus on (1) monitoring system response to restoration efforts, and (2) to fill knowledge gaps critical to successful restoration.

1.1 Mission, Goal and Scope

While the concept and a brief outline of a science plan are presented in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006), a Loxahatchee Interagency Science Team was formed to provide detail and focus to the Loxahatchee River science planning effort. The team was composed of representatives from the South Florida Water Management District (SFWMD), District 5 and Jonathan Dickinson State Park (JDSP) of the Florida Park Service, Loxahatchee River District (LRD), Florida Department of Environmental Protection Southeast District (FDEP), Martin County Division of Environmental Quality, Palm Beach County Environmental Resources Management (PBCERM), Florida Fish and Wildlife Conservation Commission (FWC), and Florida International University (FIU). The Science Plan is designed to establish and support monitoring programs and applied research studies that will support the overall management goal to "restore the Northwest Fork of the Loxahatchee River and enhance the watershed and estuary". The aim of these studies is to gather data on a structured, focused basis providing information on the quantity, quality, timing and distribution of freshwater inflows and the effect of those flows on the key ecosystem health indicators. The information will be used for ecological evaluations, modeling, and predictive analyses, which will, in turn, form the technical basis for adaptive management decision-making (SFWMD 2006).

In the beginning, it was envisioned that a science plan be developed specifically for the Northwest Fork; however, the Loxahatchee Interagency Science Team broadened the scope of the plan to include the watershed and estuary since all are interconnected through the land-sea continuum. The Loxahatchee River Science Plan presents an integrated description of the overall management goal for the system, management and research objectives, and the information required to achieve these goals and objectives with a focus on Northwest Fork of Loxahatchee River and Estuary. The science plan is envisioned to serve as a handbook of research and monitoring activities for the next five years. The science plan's purpose is to guide future scientific efforts and enable the efficient application of limited resources to prioritize development of infrastructure, water management, monitoring projects and research studies with the goal of adaptively managing the system.

1.2 Overview and Framework

The organization of the science plan mimics the hierarchical decision analysis framework for environmental science and management developed by Reckhow et al. (1997), which is shown in). The decision analysis hierarchy links specific research topics with the overall management goal and issue specific management objectives in a vertical array. Three areas of emphasis in the decision analysis framework are: watershed, abiotic (non-living) conditions, and biotic (living) resources

Three **management objectives** have been developed for the science plan based on these areas of emphasis:

- Management Objective 1: Maximize watershed restoration benefits.
- Management Objective 2: Enhance riverine and estuarine abiotic conditions.
- Management Objective 3: Restore and protect riverine and estuarine biotic resources.

The three management objectives and inter-related avenues of research featured in this science plan and illustrated in are congruous with the three elements of coastal aquatic studies proposed by Alber (2002). **Figure 2** shows the conceptual model for the science plan modified from Alber (2002). The quantity, quality and timing of freshwater inflows influence abiotic conditions in the downstream river and estuary, which in turn, trigger ecological responses by the biota. An overlap and linkage among all three management objectives is acknowledged. This science plan features predictive tools for ecological evaluation that permit analyses of interactions among watershed drivers, abiotic factors and biotic responses.

Each management objective is supported by a suite of research objectives ranging from quantifying watershed loading to predicting ecological responses (). Appropriate research methods are derived from the driving research objectives. For example, present status of key ecological resources (assess status of Value Ecosystem Components) requires compilation, analyses and exploration of available data. The outcome of this logical sequence from the overall management goal through research methods should improve understanding of linkages between watershed hydrologic restoration and biotic responses in wetland, riverine and estuarine habitats.

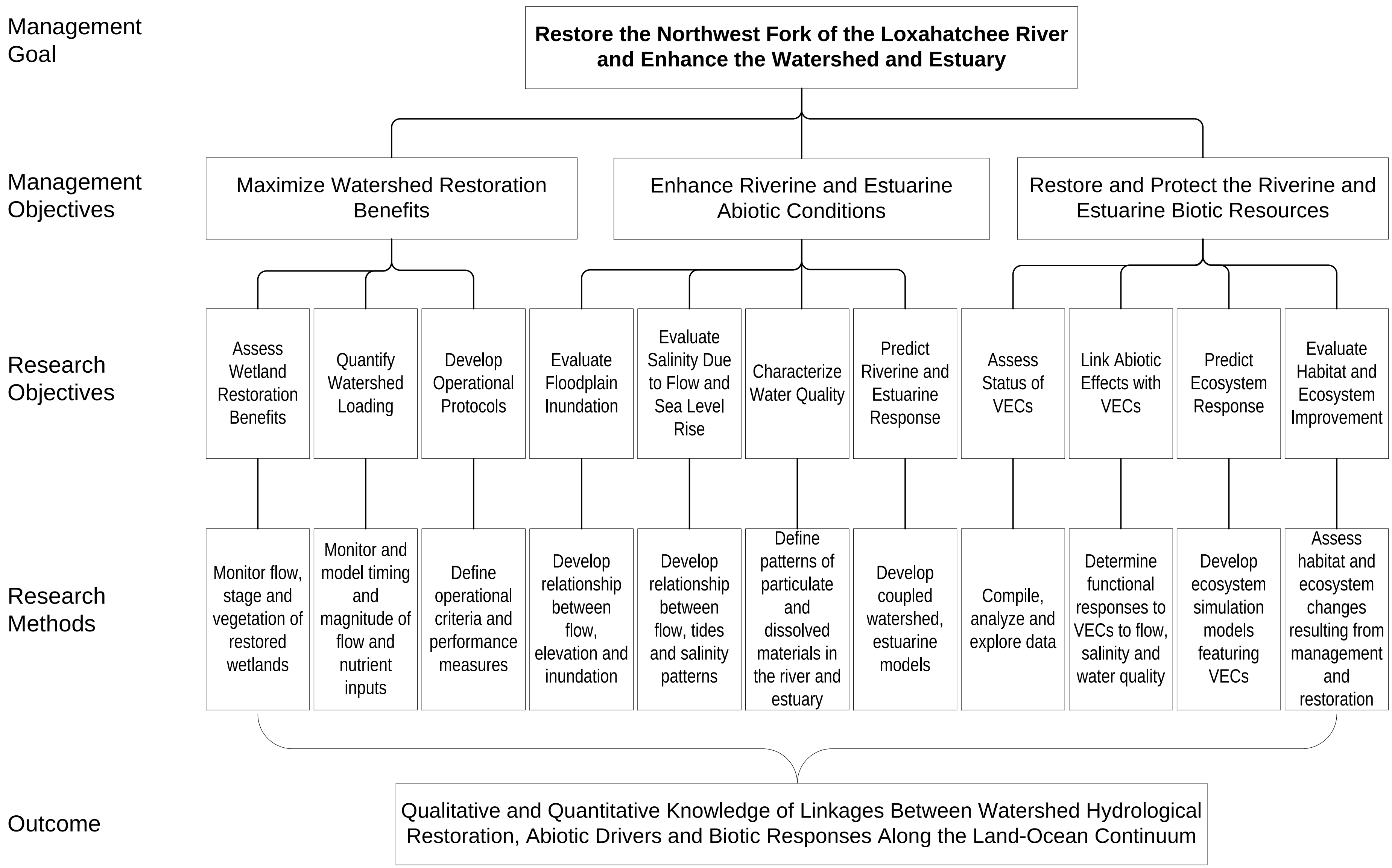

Figure 1. Hierarchical science decision analysis framework.

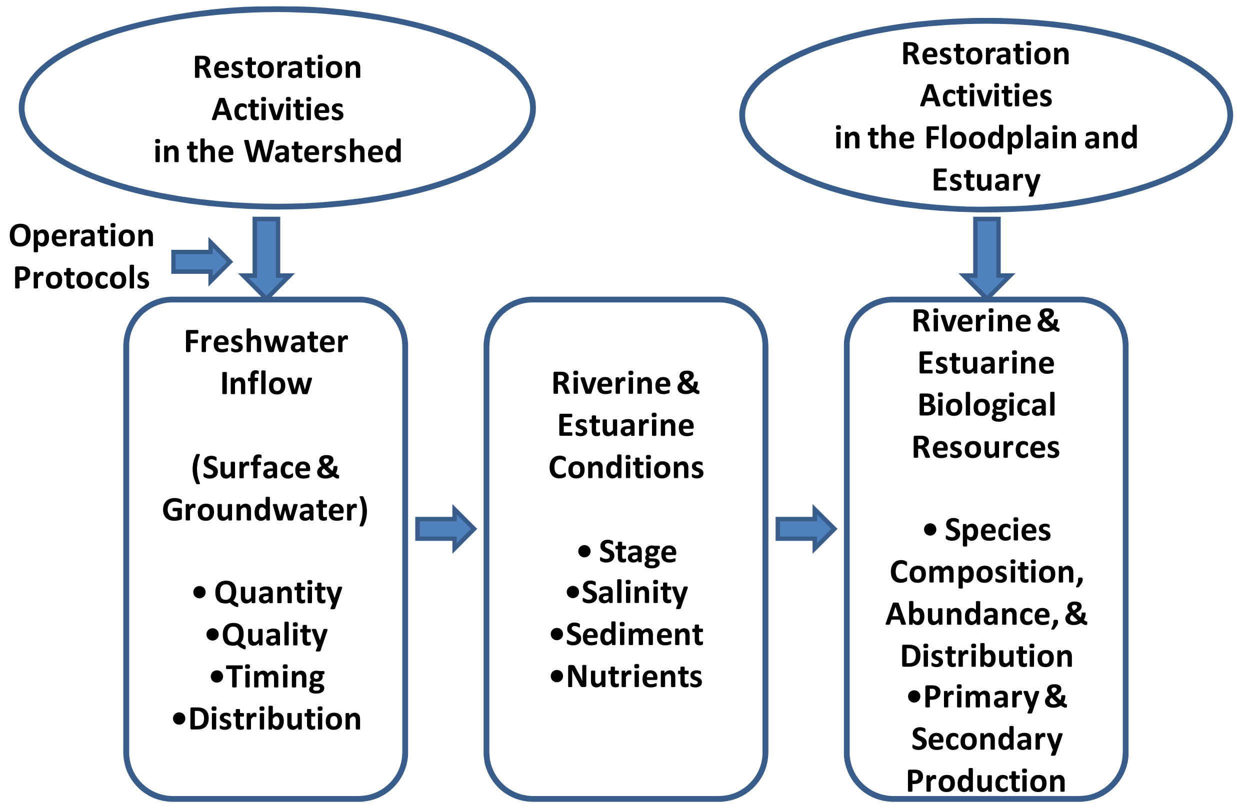

Figure 2. Conceptual model for the Loxahatchee River Science Plan. (Modified from Alber 2002).

1.3 Valued Ecosystem Components (VECs) and Guiding Research Questions

Valued ecosystem components (VECs) are desired biotic elements within habitats that signify favorable abiotic conditions for all associated flora and fauna. VECs are defined as species, communities or habitats present within an ecosystem considered important in assessing the impact of a proposed project or management action. These VECs represent the overall health of a given section of the ecosystem and therefore serve as sentinel species.

A VEC is subject to a set of criteria for incorporation (Doren et al. 2009). VEC criteria include: scales of variability and potential responses, applicability of and capacity to measure VEC responses, specificity to proposed water management actions, status or health versus cost effectiveness of management action, potential for misleading false negative and positive responses, and requirements for VEC process and patterns' details of responses (Doren et al. 2009). In other words, the chosen VEC should possess a measurable response that is negative enough, with regards to the objectives of a plan, to merit a change in water management.

In the *Restoration Plan for the Northwest Fork of the Loxahatchee River (SFWMD 2006),* five primary VECs in the riverine and estuarine portions of the Northwest Fork were selected with interagency participation. These VECs include:

- Cypress swamp and hydric hammock in the riverine floodplain (river miles 16.0 to 9.5);
- Cypress swamp in the tidal floodplain (river miles 9.5 to 5.5);
- Fish larvae in the low salinity zone (river miles 9.5 to 5.5);
- Oysters in the mesohaline zone (river miles 6.0 to 4.0); and
- Seagrasses in the downstream polyhaline zone (river miles 4.0 to 0.0).

The VECs utilized in the restoration plan were selected by conceptual ecological models derived from key ecological drivers and attributes (VanArman et. al 2005), grounded in ecological theory and empirical information from the restoration region, and linked to the ecological targets that are fundamental components of assessing restoration success. **Table 1** provides a preliminary evaluation of these existing VECs used in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* to contrast the effects of proposed water management alternatives. Any additional VECs proposed should satisfy these preliminary criteria.

Table 1. Example of a preliminary evaluation of VECs presently used in the restoration plan.

VEC	**Is the VEC considered important?**	**Is the VEC documented to have important ecological or water resource functions?**	**Is the VEC's health measure efficiently quantifiable and have a high probability of being predictable?**	**Is the VEC's negative response significant enough, with regards to the objectives of a plan, to merit a change in water management?**
Cypress swamp and hydric hammock in the riverine floodplain	Yes	Yes	Yes, but could be improved	Yes
Cypress swamp in the tidal floodplain	Yes	Yes	Yes, but could be improved	Yes
Fish larvae in the low salinity zone	Yes	Yes	To be determined	Yes
Oysters in the mesohaline zone	Yes	Yes	Yes, but could be improved	Yes
Seagrasses in the polyhaline zone	Yes	Yes	Yes, but could be improved	Yes

To link VECs with abiotic conditions in the riverine and estuarine basins and watershed hydrologic restoration, the following **Guiding Research Questions** were developed. These questions are centered on quantitative and qualitative understanding of the connectivity or linkage between the riverine and estuarine ecological resources represented by VECs and riverine and estuarine abiotic conditions and watershed inflows (**Figure 2**). Addressing this sequence of questions will eventually lead to watershed management to obtain the optimal amount of freshwater required for the restoration of the Northwest Fork of the Loxahatchee River and Estuary (question 8):

- Research Question 1: What is the baseline status of the VECs at present?

- Research Question 2: What are the abiotic conditions (e.g., stage, salinity, submarine light, inorganic nutrient concentrations) that favor growth and survival of the VECs from seasons to decades?

- Research Question 3: How do the VECs respond to altered abiotic conditions (e.g., increased flow and salinity) over time?

- Research Question 4: Are there predictable relationships between the loading of fresh water and dissolved materials from the watershed and the abiotic conditions that favor particular VECs in particular locations?

- Research Question 5: If predictable relationships exist, are abiotic conditions in the floodplain, riverine and estuarine habitats manageable through modifications in watershed inputs?

- Research Question 6: If manageable, what are the ranges of inputs of watershed-derived fresh water and dissolved materials that VECs could proliferate?

- Research Question 7: Do direct mathematical relationships exist between the VECs and watershed attributes?

- Research Question 8: What types of watershed modifications could provide the amount of fresh water estimated to be optimal to restore and protect Northwest Fork of the Loxahatchee River while not degrading downstream estuarine habitats and organisms?

2.0 BACKGROUND

The Loxahatchee River Watershed is located within northern Palm Beach and southern Martin counties and currently drains an area of approximately 240 square miles (**Figure 3**). 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 historical Loxahatchee River watershed was much larger, consisting primarily of pine flatwoods, cypress sloughs, wet prairies and fringing wetlands (VanArman et al. 2005).

The Loxahatchee River extended from the watershed just east of Lake Okeechobee to Jupiter Inlet, which was previously a narrow, opening until permanently dredged in 1947 (VanArman et al. 2005). Expansion and maintenance of Jupiter Inlet had large-scale implications for estuarine circulation, hydrodynamic residence time, and potential upstream salinity intrusion. Just west of the inlet is a central embayment resulting from the confluence of three major tributaries, the Northwest, North and Southwest Forks (**Figure 4**). Distance designation for the Loxahatchee River and Estuary starts at Jupiter Inlet (river mile 0) and extends upstream into the Northwest Fork to river mile 16 within Riverbend Park (**Figure 4**). The Loxahatchee River watershed originates in Grassy Waters, extends south through the Loxahatchee Slough, and flows into the Northwest Fork of the Loxahatchee River from the C-18 canal through the G-92 structure in northern Palm Beach County. The Northwest Fork flows north into Martin County and bends east through Jonathan Dickinson State Park, and continues southeast back to Palm Beach County near the central embayment. Historically, the Northwest Fork received considerable fresh water from the Loxahatchee and Hungryland Sloughs. However, the landscape-level combination of flow diversion, channelization, wetland drainage, deforestation and development have greatly decreased watershed area and raised salinity in upstream riverine segments.

Over the past several decades, adverse environmental impacts to this ecosystem have occurred. The most widely recognized alteration is the reduction of dry season flows to the Northwest Fork and associated saltwater intrusion into downstream freshwater wetland vegetation communities and the decrease in groundwater levels. The historical flows through Loxahatchee and Hungryland Sloughs to the Northwest Fork were disrupted for agricultural and urban use. Construction of numerous small drainage canals in the early 1900s, inlet dredging in 1947, and construction of the C-18 Canal in 1958 diverted freshwater flows at the S-46 structure to tide. Today, the C-18 Canal diverts much of the runoff from the headwaters of the watershed to the Southwest Fork of the river (**Figure 4**).

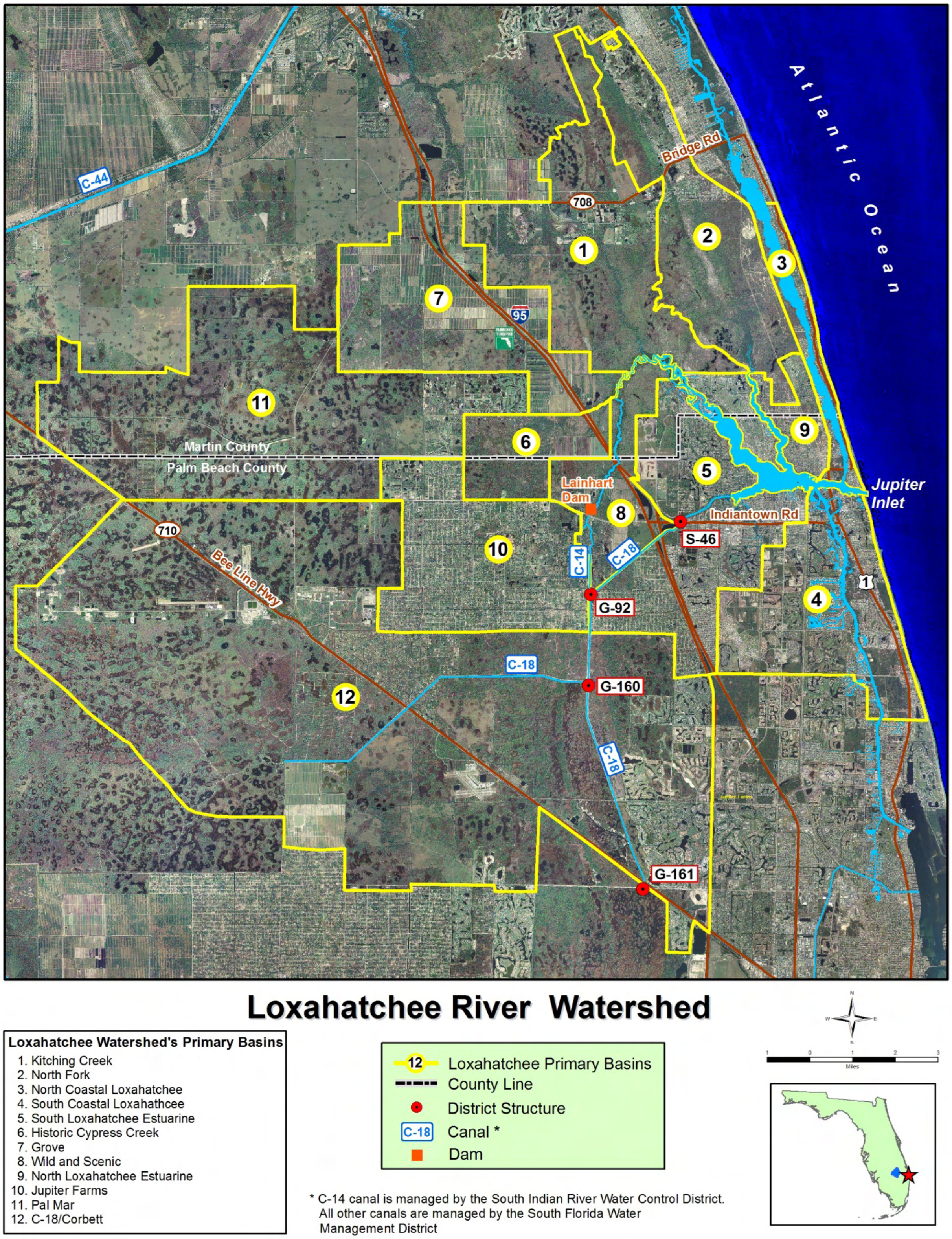

Figure 3. Map of the Loxahatchee River watershed depicting important hydrologic units and boundaries.

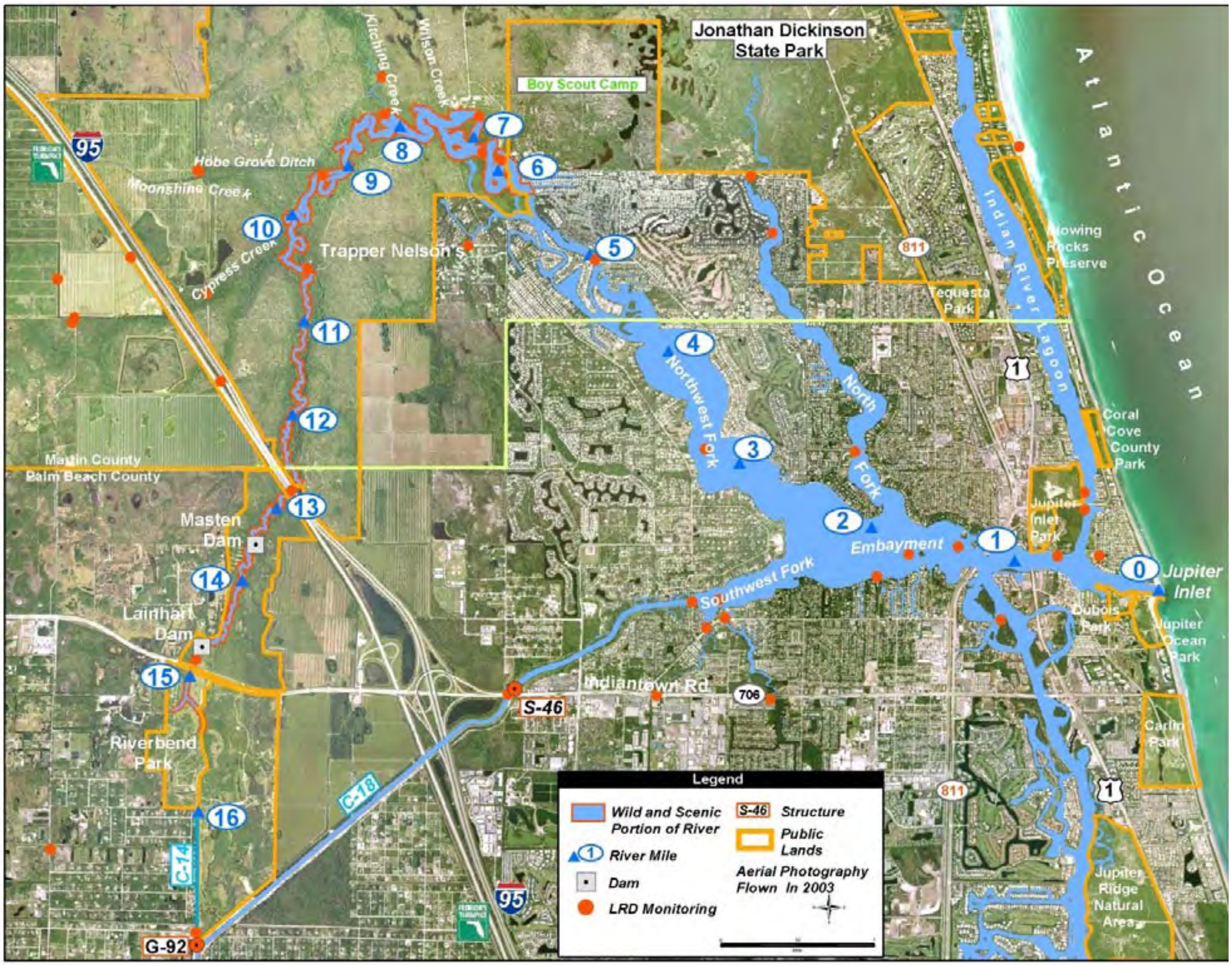

Figure 4. Map of the Loxahatchee River and Estuary showing mile designations, central embayment and lateral forks, Wild and Scenic River boundaries and water quality stations.

During the past 58 years, vegetation along the Northwest Fork from lower and upper tidal reaches of Northwest Fork has changed from freshwater floodplain swamp to mangrove forest from the combination of saltwater intrusion and reduced freshwater flows. Alteration of freshwater inflow has triggered a suite of negative ecological responses in the river and estuary including the replacement of cypress and floodplain swamp wetlands by mangrove forests across many portions of the upstream floodplain, changes in hydrology and water chemistry, shifting and losses of seagrass and oyster habitats, and degradation of fisheries stocks (VanArman et al. 2005).

Corrective actions by local and state agencies have attempted to increase freshwater flow to the Northwest Fork. In 1975, the SFWMD and LRD agreed to construct the G-92 water control structure to improve the flow linkage of the Loxahatchee Slough, through the C-18 Canal, to the Northwest Fork. In 1982, the Florida Wildlife Federation filed a lawsuit against the state concerning the S-46 structure and the restoration of fresh water to the Northwest Fork. The

SFWMD and the FDEP entered a consent decree to provide at least 50 cubic feet per second (cfs) of freshwater flow to the Northwest Fork. In 1989, an agreement between the South Indian River Water Control District and the SFWMD provided operational guidelines for 400 cfs of freshwater to flow through the G-92 structure to the Northwest Fork when feasible and allowing flood waters to backflow to the C-18 canal under certain conditions (SFWMD 2006 appendix A).

On May 14, 1985 with the Secretary of Interior's signature, the Loxahatchee River became Florida's first National Wild and Scenic River. This portion of the river is about 10 miles in length beginning at the Boy Scout Dock at river mile 5.9 and ending at Riverbend Park at river mile 15.5 (**Figure 4**). In April 2003, the SFWMD followed the Minimum Flows and Levels Rule, Chapter 40E-8 of the Florida Administrative Code, to establish a minimum flow and level for the Northwest Fork. The criteria for the determination of an MFL violation are as follows:

A MFL violation occurs within the Northwest Fork of the Loxahatchee River when an exceedance of the minimum flow criteria occurs more than once every six years. A "MFL exceedance" occurs within the Northwest Fork of the Loxahatchee River when within any given calendar year 1) flows over Lainhart Dam decline below 35 cfs for more than 20 consecutive days; or 2) the average daily salinity concentration expressed as a 20-day rolling average exceeds two parts per thousand (ppt). The average daily salinity is representative of mid-depth in the water column (average of salinities measured at 1.6 feet or 0.5 meter below the surface and 0.5 meter above the bottom) at river mile 9.2.

Because the minimum flow could not be achieved, a recovery plan was established, which called for the creation and operation of new structures to achieve the minimum flow over Lainhart Dam.

The SFWMD partnered with FDEP to develop a practical restoration plan for the Northwest Fork (SFWMD 2006). The agencies documented data collection and analysis, proposed analytical tools and models, and identified constraints and assumptions essential to the restoration of freshwater inflows and biota within the restoration plan. The best available scientific and technical information was used to develop a practical restoration goal and plan to provide restorative flows to the Northwest Fork. At present, several ongoing restoration efforts within the Loxahatchee River watershed seek to increase base flows into the Northwest Fork, while not compromising the ecological integrity of downstream reaches (i.e., estuary) nor impairing estuarine VECs (SFWMD 2006).

3.0 SCIENCE PLAN COMPONENTS

The approach adopted by the Loxahatchee Interagency Science Team for the creation of the Loxahatchee River Science Plan combines aspects of inflow-, condition- and resource-based criteria for Northwest Fork and illustrates inter-dependence between these criteria.

The first management objective features alteration of watershed hydrologic patterns to restore the Northwest Fork of the Loxahatchee River. This objective offers the potential for the development of an inflow-based approach to water management where criteria are relative to freshwater supply versus demand in the watershed.

The second management objective assumes restorative flows will lead to changes in abiotic factors such as stage, salinity, and water quality in riverine and estuarine habitats. This objective offers the opportunity to implement condition-based criteria where target freshwater inflow serves to maintain desirable environmental conditions in the Loxahatchee River and Estuary (Alber 2002).

Finally, for the third management objective, freshwater inflow criteria are needed to protect and enhance riverine and estuarine biological resources or VECs (Alber 2002, Estevez 2002, Mattson 2002). The biological variables chosen for these resource-based criteria not only illustrate how alterations in freshwater inflow will change the riverine and estuarine ecosystem, but also provide a road map for management. Targets must be defined for biological variables and the ranges of the variables' associated responses to abiotic changes are critical characteristics of these targets. Connecting variations in the magnitude of watershed inflow to different hydrologic effects and other drivers to VECs is central to the Loxahatchee River Science Plan as the status of VECs is assumed to reflect the status of the ecosystem.

The health and sustainability of the study area are being examined primarily through the identification and assessment of VECs including submerged aquatic vegetation (SAV), oysters, low salinity zone larval fishes, and floodplain vegetation as described in Chapter 10 of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006).

3.1 Maximize Watershed Restoration Benefits (Management Objective 1)

The **management objective** for the watershed portion of the science plan is to *maximize watershed restoration benefits*. The three **research objectives** to support the management objectives are as follows:

- Research Objective 1.1: Assess hydrologic and ecologic benefits of wetland restoration (see Section 3.1.1)
- Research Objective 1.2: Quantify watershed hydrology and nutrient loading (see Section 3.1.2)
- Research Objective 1.3: Develop operational protocols and feasibility study (see Section 3.1.3)

Research Objective 1 will be utilized to assist in establishing additional surface water storage and groundwater recharge potential as well as document changes in biodiversity as a result of hydrologic restoration activities.

Research Objective 2 will identify watershed tributary load contributions and support the development of an overall water budget for the watershed.

Research Objective 3 will apply the hydrologic performance measures for the estuarine ecosystems into day-to-day operations to provide the needed freshwater inflows for coastal ecosystem restoration. These research objectives will address Guiding Research Questions 6, 7 and 8 proposed in Section 1.3.

3.1.1 Assess Hydrologic and Ecologic Benefits of Wetland Restoration (Research Objective 1.1)

Key natural areas within the watershed include Jonathan Dickinson State Park, Cypress Creek, Pal Mar, J.W. Corbett Wildlife Management Area, Loxahatchee Slough and Grassy Waters Preserve/Water Catchment Area (**Figure 5**). These key areas are composed of a mosaic of upland and wetland systems. Nine major habitat types were previously identified within the watershed according to Florida Natural Areas Inventory classification. These include seven wetland (freshwater depression marsh, dome swamp, floodplain swamp, strand swamp, hydric hammock, wet prairie, hydric flatwood) and two upland (mesic flatwood, mesic hammock) communities. These habitats support diverse biological communities including protected species. The wetland systems of the Loxahatchee River watershed provide important benefits to local residents by enhancing water quality, detaining stormwater and providing habitat for fish, wildlife and plants.

In 2000, The United States Environmental Protection Agency (EPA) and the United States Army Corps of Engineers (USACE) completed the final report of the Loxahatchee River Basin Wetland Planning Project (Treasure Coast Regional Planning Council 1999, Martin County Growth Management Department 2000). This project was instrumental in providing information on the relative function of wetlands within the project area relative to the Clean Water Act. The Loxahatchee River Basin Wetland Planning project included portions of Martin and Palm Beach Counties and incorporated 77,000 acres of which 19,959 acres were wetlands. The maps and report developed by an interagency team identified both highly functional and degraded wetlands and provided suggestions to compensate for future wetland losses. The project team utilized a wetland functional assessment method known as the Wetland Rapid Assessment Procedure (WRAP), which takes into consideration wildlife habitat, wetland hydrology and water quality factors (Miller and Gunsalus 1997). Wetlands were categorized as high, medium or low quality based on the relative level of functions. The planning project concluded land development, construction and operation of drainage and flood control facilities, and consumptive use withdrawals, especially during the past 50 years, have disrupted predevelopment surface flow and resulted in localized and region wide changes in major wetland systems in the watershed. Wetlands have been degraded in quality due to excessive flooding or drainage, resulting in increased susceptibility to fires and shifts in vegetation patterns from natural wet prairie and cypress communities to uplands or cattail- and willow-dominated wetland systems (VanArman et al. 2005).

Figure 5. Basins and natural areas in the Loxahatchee River watershed.

Changes in hydrologic regimes have also allowed invasive exotic plants to move into areas that were once high quality wetlands (i.e., Loxahatchee Slough, Moonshine Creek floodplain, historic Cypress Creek).

Ongoing and planned watershed restoration activities will improve surface water storage, groundwater recharge and increase native biodiversity. The entities that are either implementing or have planned restoration activities are Martin and Palm Beach Counties, SFWMD and USACE. The following is a breakdown of priority projects that will fulfill this research objective and should be considered for additional monitoring and assessment.

Moonshine Creek Tributary and Hobe Grove Ditch Restoration

A special study under this research objective is the examination of restorative benefits of reconnecting the natural Moonshine Creek tributary to the surrounding lands within the sub-basins that are now under public ownership. Hobe Grove Ditch was excavated through uplands in the 1960s to drain flood waters from newly planted citrus groves into the Northwest Fork of the Loxahatchee River. With the creation of the ditch, runoff from the surrounding groves was directed to Hobe Grove Ditch. The groves have been purchased by the SFWMD and Martin County. These agencies are planning to restore the area to its natural condition of pine flatwoods and wet prairies. The hydroperiod of the floodplain forest community on Moonshine Creek will be restored and more treatment of the surface waters will be provided prior to its entry into the Loxahatchee River. Before upstream restoration can be completed, an engineering study is required to examine the best structural methods to reconnect Moonshine Creek, maintain or reduce existing drainage levels, and fill in Hobe Grove Ditch. As part of this engineering study, the quantity and quality (nutrient loads) of water within Moonshine Creek and Hobe Grove Ditch will be monitored to obtain baseline information. The measured data will then be analyzed to quantify improvements to water quantity and quality resulting from creek and upstream restoration activities.

Cypress Creek Restoration

The Cypress Creek project area covers approximately 4,000 acres and is equally divided between Martin and Palm Beach Counties as the county line bisects the property. The area provides approximately one-third of the historic flow to the Wild and Scenic Northwest Fork of the Loxahatchee River. This area is important because it has a direct drainage connection to the Northwest Fork of the Loxahatchee River through Cypress Creek. The area is interspersed with numerous marshes, cypress swamps and wet prairies. The protection and restoration of the wetlands in the Cypress Creek area will be extremely beneficial in improving the supply of fresh water to the Northwest Fork. These actions will assist in reducing saltwater intrusion. Other benefits include floodwater attenuation, protection of fish and wildlife habitat, and enhancement of water quality.

The project area has been heavily impacted by agricultural practices and development. Construction of drainage ditches in the early 1950s impacted the sites hydrology, creating favorable conditions for non-native invasive species to flourish. Currently, the floodplain of the creek experiences abnormal dryness and sedimentation problems. The floodplain needs to be analyzed in relation to the bathymetric depth of the channel and floodplain inundation. Restoration activities to eradicate non-native invasive vegetation began in 1999. To date, over

1,600 acres have been treated within the project area. Hydrologic activities began in spring 2007 and have resulted in over six miles of ditch filling and plugging.

The Cypress Creek Restoration project is funded by Martin and Palm Beach Counties and the Loxahatchee River Preservation Initiative (LRPI). It entails construction that will provide for redistribution, storage and timed delivery of basin stormwater. It is anticipated that existing conveyances and the creation of a large stormwater treatment area on land currently owned by Martin County and SFWMD will provide the needed facilities. Flows from the Pal Mar basin will be delivered to the Northwest Fork of the Loxahatchee River to assist in ecosystem restoration. The re-distribution of seasonal flows will also reduce channel erosion and its impact on the floodplain. Its connection with the Flow Way 3 of the North Palm Beach County Part 1 Project will also enhance the benefit of the project.

Kitching Creek Phase IV Restoration

The historic flows that fed Kitching Creek provided key freshwater contributions to the Northwest Fork of the Loxahatchee River. Urban development of the upper watershed has diverted and affected the timely distribution of these flows to Jonathan Dickinson State Park and the Northwest Fork. The Kitching Creek Phase IV Restoration project entails the restoration of the historical discharges of the headwaters of the Kitching Creek watershed.

The project area is located south of Cove Road, east of the South Fork of the St. Lucie River and west of U.S. Highway 1 in southern Martin County. The project is designed to improve water quality and quantity by enhancing surface water deliveries to Kitching Creek and restore up to 1,000 acres of habitat in the upper Kitching Creek watershed. This will create rehydration of the historical portion of Kitching Creek that has been dewatered by the ditch to the east on Kitching Creek Road. Rehydration of this watershed will also increase nesting and roosting by wading birds, improve habitat for fish, invertebrates and other riverine-dependent species, and lead to improved water quality.

Pal Mar East Restoration

Pal Mar East covers 3,100 acres in southern Martin County. Martin County and the SFWMD, in conjunction with the Natural Resources Conservation Service of the United States Department of Agriculture are currently developing a restoration plan for the 1,350 acre portion of Pal Mar East within the Natural Resources Conservation Service conservation easement. This plan is being implemented as part of the Comprehensive Everglades Restoration Plan (CERP, USACE & SFWMD 1999) North Palm Beach County Part 1 project and should only be considered an interim step in the restoration of Pal Mar East. The Natural Resources Conservation Service plan will focus on those areas within the conservation easement but will also include some restoration measures for the entire site.

Flow Way 3 is a component of one the North Palm Beach County Part 1 project’s alternatives. Flow Way 3, if carried forward as part of the selected plan, will help to reestablish sheet flow and hydrologic connectivity across areas in the northern section of the North Palm Beach County Part 1 project boundary and help ensure adequate and timely flows to the Loxahatchee River. The Flow Way 3 portion of the project includes measures to restore several former agricultural and ranch lands back to wetlands, improve hydroperiods in existing wetlands, provide improved water deliveries to the Loxahatchee River via Cypress Creek and improve flood protection for Ranch Colony; all of which rely in part on being able to successfully promote sheet flow through Pal Mar East.

Loxahatchee Slough Natural Area Restoration

The Loxahatchee Slough Natural Area is the Palm Beach County's largest natural area, comprising a total of 12,836 acres. The slough serves as the headwaters for the Wild and Scenic Loxahatchee River. To date, hydrologic restoration activities include backfilling of over 15 miles of agricultural ditches and an extensive eradication program targeting exotic and nuisance plant species. Palm Beach County currently has surface water staff gauges located within specific wetlands and data is recorded on a monthly basis.

Pine Glades Natural Area Restoration

The Pine Glades Natural Area restoration includes 3,124 acres of pine flatwoods, wet prairies and freshwater marshes. The restoration area supplies water to the federally designated Wild and Scenic Northwest Fork of the Loxahatchee River. Large portions of the project area have either been drained for development or channelized through the construction of large canal systems. The restoration of the wetland and upland systems within Pine Glades will improve the ecological conditions within the watershed and ultimately the river.

North Palm Beach County Project (CERP)

As part of the CERP planning process, opportunities to enhance or restore the hydrologic regimes on the impacted wetland areas within the North Palm Beach County project study area are being evaluated. During this plan formulation process, several alternative plans will be developed and analyzed to determine which plan provides the best opportunity for environmental restoration and water supply. Selecting the plan with the best opportunities for restoration requires quantification of ecological benefits that could be used to conduct cost effectiveness and incremental cost analyses.

Recommended Technical Needs

- Use the Wetland Rapid Assessment Procedure to quantify the 'lift' that occurred in restored segments of the Loxahatchee watershed.
- Use the current functional conditions for quantitative evaluation of benefits achievable with the different alternatives, and for evaluation of other potential hydrologic impacts of alternatives on environmental quality.
- Assess additional biodiversity benefits to realize the results of watershed restoration activities.
- Conduct additional monitoring of groundwater and surface water stages and the establishment of long-term ground truth points in a restored wetland parcel.
- Conduct instrumentation and sampling in strategic locations including: project culverts, discharge points, and selected transects within the wetland parcel.
- Coordinate with stakeholders before implementation of the monitoring activities.
- Evaluate the wetland hydrologic function and develop land management plans to provide the needed dry season flow to the Northwest Fork while maintaining a healthy wetland hydroperiod.

3.1.2 Quantify Watershed Hydrology and Nutrient Loading (Research Objective 1.2)

In order to conduct a full-scale evaluation of watershed hydrology and nutrient loading for ecosystem restoration, watershed hydrology and water quality models are needed as evaluation tools to conduct simulations and predict changes. To date, the SFWMD has applied the WaSh hydrological model (Wan et al. 2003) during the development of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006) and the Lower East Coast Sub-Regional Model during project implementation report development for the North Palm Beach County Part I project. Both models simulated hydrology, but not water quality for those efforts.

The WaSh model was developed for four sub-basins including Jonathan Dickinson State Park, Pal Mar-Grove basin, Jupiter Farms basin, and C-18 basin. This model was calibrated using data from 1980 to 1996 and validated using data from 1997 to March 2004. A user friendly version of the WaSh model was developed by the SFWMD allowing users to conduct simulations for individual basins or the entire watershed. The land use data used in the updated model is from the year 2000. A new land use survey conducted in 2004 better reflects the recent land use development. The original WaSh model was calibrated; however, some individual basin models where developed with limited data. Additional flow and water quality data from 2004 to 2009 are now available to better calibrate and validate the model.

Rainfall data with 15-minute time intervals and 2-kilometer squared resolution are available from 2002 to 2009. This new data captures the rainfall spatial variation much better and should be used to calibrate and validate the model. Light Detection and Ranging (LIDAR) topographic data are now available in portions of the watershed and can be used to enhance the model.

The previous watershed hydrology studies have mainly focused on the surface water hydrology. Groundwater is an important source of fresh water to the river. More groundwater field data are necessary to analyze the groundwater trends for a better understanding of the effects of groundwater on the river.

Recommended Technical Needs

- Update the hydrological module and develop a water quality module of the WaSh model with new hydrological and water quality information for water budget and nutrient loading assessment.
- Collect water quality data representing different land use types for model calibration.
- Continue current watershed water quality monitoring program conducted by LRD (see Section 3.2.3) for identification of hot spots (high loads).
- Expand water quality and flow monitoring to other structures or tributaries such as G-160, G-161, Lainhart Dam, S-46, and Cypress Creek.
- Evaluate the impacts from future deliveries of basin water (i.e., L-8 reservoir water) on water quality (nutrient loading) in the Loxahatchee River.
- Conduct groundwater data analysis and quantify groundwater input to the river.

3.1.3 Develop Operational Protocols and Feasibility Study (Research Objective 1.3)

The focus of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006) was to identify the flows necessary for the protection and restoration of the Northwest

Fork. It was assumed that the additional water needed would be delivered through the G-92 structure from an undefined upstream water source supplemented by the tributaries downstream of the Lainhart Dam. The intent of an operational feasibility study is to provide the SFWMD with operational protocols and rules for use in regulating water deliveries from the regional system including the L-8 Reservoir, Grassy Water Preserve, Loxahatchee Slough and the C-18 Canal through the G-92 structure to the Northwest Fork. These rules would incorporate the potential ecological impacts of flows from the S-46 structure into the estuary. In order to implement these rules, they must be translated into an operational range of gate openings that are adjusted periodically, depending on the relative upstream and downstream water levels, and flows across Lainhart Dam. Management of water levels upstream of G-92 (Loxahatchee Slough) must be taken into account to ensure that sufficient water is available for dry season deliveries. This will also require consideration of water deliveries through the South Indian River Water Control District and the G-160 (Loxahatchee Slough) structures, as well as consideration of water elevations in the C-18 Canal. Operational protocols should be developed to link all operations of structures and related natural areas necessary to deliver restoration flows into Northwest Fork. These protocols will include S-46, G-92, G-160, adjacent project culverts in the Loxahatchee Slog, G-161 (Northlake Boulevard Structure), Grassy Waters Preserve/West Palm Beach Water Catchment Area, M-Canal, C-2 (Loxahatchee) Pump Station, L-8 Canal and L-8 Reservoir.

In this operational feasibility study, a preferred scenario analysis will be needed to determine the ability of the overall system of structures, storages and flow ways to meet water needs of the Northwest Fork and to minimize flood control releases from the C-18 canal through S-46 and to the Southwest Fork of the Loxahatchee River. An environmentally sensitive flow regime can be developed by integrating information from the watershed model (WaSh), the Curvilinear-grid Hydrodynamics 3D (CH3D) model, and VEC criteria. An operation model such as OPTI (Wan et al. 2006) is needed to aid the development of operational protocols.

Recommended Technical Needs

- Develop an operational feasibility study to refine operation protocols with three focus levels: (1) operation to achieve the MFLs; (ii) operation for incremental flows between the MFLs and the flow target set in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006); and (iii) operations to achieve the flow target of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006).
- Identify and assess flow conveyance pathways or critical structures limiting flow delivery.

3.2 Enhance Riverine and Estuarine Abiotic Conditions (Management Objective 2)

This **management objective** seeks to *enhance abiotic conditions in the riverine and estuarine* through emphasis upon the effects of seasonal flow variation on salinity, nutrients and sediments, and floodplain inundation. The abiotic condition of the river and estuary is highly influenced by freshwater inflow including its timing, distribution, quantity and quality (nutrient and sediment loads). These abiotic conditions are the linkage between protecting estuarine resources and regulating inflow. This management objective helps address Guiding Research Questions 2, 3, 4, 5, and 8 discussed in Section 1.2. Four research objectives for this management objective are as follows:

- Research Objective 2.1: Evaluate floodplain inundation (see Section 3.2.1)
- Research Objective 2.2: Evaluate salinity due to flow and sea level rise (see Section 3.2.2)
- Research Objective 2.3: Characterize water quality (see Section 3.2.3)
- Research Objective 2.4: Predict riverine and estuarine responses (see Section 3.2.4)

The ongoing and proposed projects to achieve these research objectives are listed in **Table 2**. A large part of these projects are based on monitoring data of inflow, riverine and estuarine conditions, which will provide direct feedback allowing managers to determine if the decisions being made are actually effective in terms of meeting the restoration target (Alber 2002). Developing a numerical model platform, based on solid understanding of the river and estuary system, plays a key role in predicting abiotic responses in the receiving water body to freshwater inflow management scenarios. These project activities under each of the research objectives are discussed in the following sections.

3.2.1 Evaluate Floodplain Inundation (Research Objective 2.1)

Flora utilizing the swamp and hydric hammock elevations in the Northwest Fork have been identified as one of five VECs in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006). The performance measure established in the restoration plan to protect the riverine floodplain for bald cypress swamp and hammock communities were established as annual inundation of four to eight months and one to two months, respectively. The research objective is to *evaluate floodplain inundation* in the riverine and estuarine tidal portions of the system. The primary focus is to quantify if inundation targets are being met and better quantify the relationship between freshwater inflow and floodplain hydroperiod. Specifically, Northwest Fork tributary inflows with inundation stage, duration and area will be utilized to determine hydrologic relationships that may affect biota.

Floodplain inundation stage and area, flow velocities and floodplain storage are essential information necessary to quantify restoration success. Groundwater elevations and conductivity were monitored on Transects 1, 3, 7, 8 and 9 at 12 sites every 30 minutes. These data were used in conjunction with river stage to analyze stage response to rainfall and flow at the Lainhart Dam. Dynamic factor analysis (Zurr et al. 2003, Zurr et al. 2007) was applied to establish a relationship among the groundwater stage, rainfall (measured at S-46 and Jonathan Dickinson State Park), and river stage at the Lainhart Dam upstream, river mile 9.1, Kitching Creek, Boy Scout Dock, and Coast Guard station (Muñoz-Carpena et al. 2008). Soil moisture was determined along Transects 1 and 7 for approximately four years from 2004 to 2007 and was analyzed together with river stage, rainfall and groundwater elevations. An empirical relationship was established that links soil moisture in the floodplain to upstream stage at the Lainhart Dam (Kaplan et al. in press). Results indicated that the flow at the Lainhart Dam significantly affects the upstream riverine floodplain groundwater, but does not affect the downstream floodplain groundwater stages, which are mostly affected by tide. Rainfall influenced both riverine floodplain and downstream floodplain groundwater tables.

Table 2. Inventory of ongoing, completed and proposed projects to enhance riverine and estuarine abiotic conditions (Management Objective 2).

Research Objective	Information Needed	Projects	Project Status	Recommend
Evaluate Floodplain Inundation	● River stage data ● Lainhart Dam flow data ● Groundwater level ● LIDAR Data ● Floodplain Digital Elevation Model (DEM) ● Inundation requirements of swamp and hydric hammock	Stage Monitoring at Vegetation Transects 1 and 3 (SFWMD)	Ongoing	Continue
		District Flow Monitoring Network (SFWMD)	Ongoing	Continue
		Transects 1, 3, 7, 8 and 9 groundwater stage, conductivity, temperature and dissolved oxygen monitoring (SFWMD)	Ongoing	Continue
		LIDAR data acquisition (SFWMD)	Completed	
		Floodplain DEM Development (SFWMD)	Ongoing	Continue
		Refine the flow-stage relationships	Proposed	
		Latest floodplain topographic and bathymetric data	Proposed	
		Develop entire floodplain digital elevation model	Proposed	
Evaluate Salinity Due to Flow & Sea Level Rise	● Flow, velocity and salinity data ● Bathymetry data ● Shoreline survey/mapping ● Groundwater Data ● Channel features ● Tidal stage data ● Salinity impact on floodplain.	LRD Long-term Tide and Salinity DataSonde Monitoring (LRD/SFWMD/LRPI)	Ongoing	Continue
		USGS Long-term Tide and Salinity Monitoring (SFWMD)	Ongoing	Continue
		Groundwater stage, conductivity, temperature and DO monitoring (SFWMD)	Ongoing	Continue
		Groundwater table and conductivity advanced analysis (SFWMD)	Completed	
		Update flow and salinity regression relationship using new measured data	Proposed	
		Impact of sea level rise on the salinity variation	Proposed	
		Evaluate benefits of additional sources of water	Proposed	
Characterize Water Quality	● Water quality data in river and estuary ● Nutrient budget ● Benthic nutrient flux and sediment oxygen demand (SOD) ● Flow data ● Evaluation of water quality of new water (interbasin transfer) ● Background nutrient offshore	LRD Water Quality Monitoring - Riverkeeper Project (LRD/SFWMD/LRPI)	Ongoing	Continue
		LRD Water Quality Monitoring - Datasonde Project (LRD/SFWMD/LRPI)	Ongoing	Continue
		LRD Water Quality Monitoring - Stormwater Event Sampling (LRD/SFWMD/LRPI)	Ongoing	Continue
		Water quality trends analysis	Proposed	
		Nutrient budget computation and analysis	Proposed	
		Total maximum daily load (TMDL) sampling 2012 (FDEP Southeast Office project)	Proposed	
Predict River & Estuary Response	● Soil, land use , Meteorological, Hydrological, Salinity, Tidal stage, and Water quality data ● Watershed (Hydrologic and Water Quality), Estuarine Hydrodynamic/ salinity and Water quality models	Hydrodynamic and salinity model update	Proposed	
		Watershed model update	Proposed	
		Update integrated model of the floodplain habitat hydroperiod in Northwest Fork Loxahatchee River	Proposed	
		Water quality model development	Proposed	

To evaluate floodplain inundation, a flow and stage relationship was established at vegetation Transects 1 and 3 in the Northwest Fork (**Figure 6**) with surveyed elevation data and field measurements of river stages. This relationship was used to evaluate floodplain inundation of various restoration flow scenarios in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006). Critical flows and stages were identified for inundation of swamp and hydric hammock communities at both transects. This relationship needs to be refined with continuous flow and stage data. Spatial elevation data are needed for additional floodplain inundation and utilization analyses.

Newly available LIDAR (topographic) data can be used to create a digital elevation model (DEM) of the entire floodplain. In February 2007, numerous points of ground elevations were documented with LIDAR allowing for the development of a comprehensive elevation dataset for the floodplain. The LIDAR data needs to be analyzed for quality and accuracy using updated survey vertical datum in North American Vertical Datum (NAVD). The land survey data along the four transects has been adjusted to NAVD and this adjusted data needs to be used to check the quality of the LIDAR data. Currently, the LIDAR Digital Elevation Model (DEM) includes the "top of water" elevations and is classified as water in the LIDAR LAS files (LAS files conform to the ASPRS LIDAR data exchange format standard and are named with an LAS extension). The course of the river was delineated from averaging global positioning system (GPS) measurements and an estimated uniform width was applied to the entire river upstream of Trapper Nelson's. The lack of bathymetric data will not affect the floodplain inundation analysis but would have an effect on quantifying the volume of fresh water delivered to the river. River bed elevations could be measured in the field by laser level, employing a survey quality GPS unit or photogrammetry.

Since August 2008, recorders have measured stage near the Lainhart Dam at Transects 1 and 3 every 15 min (**Figure 6**). Newest stage results indicate that tide may affect the flow-stage relationship as far inland as Transect 3. The flow-stage relationship established in the restoration plan needs to be revisited using the new river stage data and groundwater stage data obtained from 12 wells. The results from this analysis can be used to quantify the floodplain inundation and area at different stages using the DEM.

A model (Bay/Estuary Hydrodynamics and Sediment/Contaminant Transport Model for a 3D Integrated Surface, Groundwater, and Overland Regimes [BEST3D-ISGO]) has been developed by the SFWMD to simulate floodplain hydroperiod and salinity in Northwest Fork riverine and estuarine floodplain (SFWMD 2007). The model will be updated with the new DEM derived from latest LIDAR data to conduct better simulation for floodplain hydroperiod and salinity. The model results could be used to create an inundation map for different restoration scenarios. This would provide a comprehensive picture of how the differing flows over the Lainhart Dam affect the hydrologic conditions in the floodplain.

Recommended Technical Needs

- Refine the flow-stage relationships established in the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006) using recently acquired continuous flow, stage and groundwater stage data.

- Obtain the latest topographic data of the floodplain and bathymetric data and incorporate into the model.
- Develop a digital elevation model (DEM) of the entire floodplain.

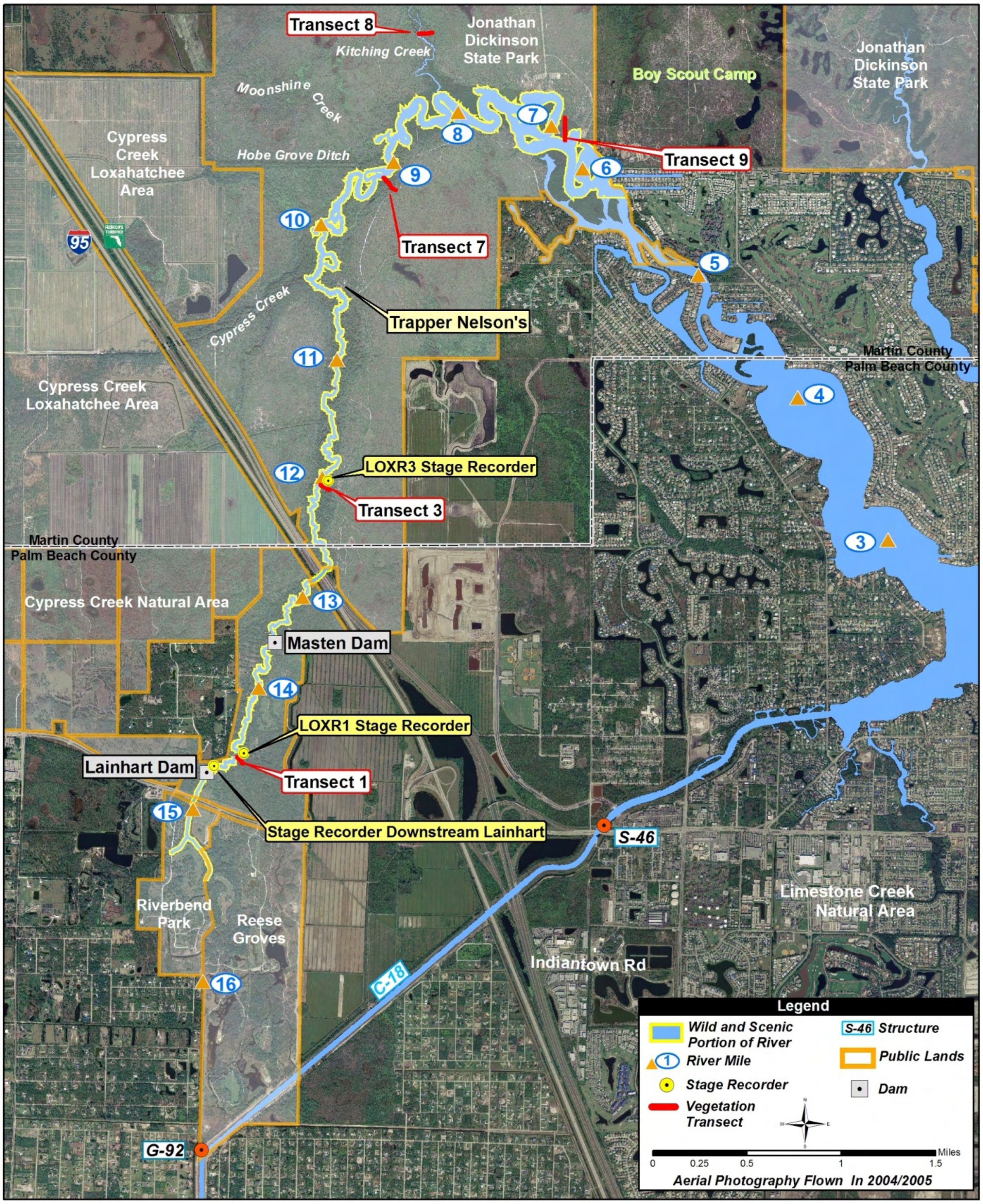

Figure 6. Vegetation transects in the Northwest Fork of the Loxahatchee River.

3.2.2 Evaluate Salinity Due to Flow and Sea Level Rise (Research Objective 2.2)

Salinity regimes are crucial to all VECs along the land-sea continuum. Salinity in the Northwest Fork is controlled by surface freshwater and groundwater inflows, and tidal exchange with the Atlantic Ocean (SFWMD 2006). Both field data and model simulations reveal a strong correlation between freshwater inflow and the salinity gradient in the estuary. During the dry season, the saline water advances into areas that were historically freshwater habitats. A well established relationship between freshwater inflow and salinity provides a scientific base for managing inflows to achieve the desired salinity regime in the system.

Since 2002, tidal stage and salinity have been monitored in the Northwest Fork. This salinity monitoring effort includes (1) the River Keeper project with monthly or bimonthly sampling, (2) a program with high frequently sampling (every 60 minutes) conducted by the LRD in partnership with the SFWMD, and (3) a SFWMD-sponsored United States Geological Survey long-term tide and salinity monitoring program since 2003 at the Coast Guard, Pompano Drive, Boy Scout Dock, Kitching Creek and river mile 9.1 sites. Twelve groundwater wells at Transects 1, 3, 7, 8 and 9 were also established to monitor groundwater stage and salinity since 2003. Soil pore water salinity data (Transects 1 and 7) from 2004 to 2008 and the groundwater salinity data (see above) from 2004 to present were collected. Groundwater salinity along 12 wells at five transects were analyzed together with river surface water salinity data at the Indiantown Road, river mile 9.1, Kitching Creek Outlet, Boy Scout Dock and Coastal Guard sites. The result indicated that the major factors affecting groundwater salinity are rainfall, Lainhart Dam flow, and salinity at the Kitching Creek outlet.

To simulate salinity and stage in the estuary, the SFWMD calibrated and verified a two-dimensional finite element hydrodynamic model (Hu 2002). In the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006), a quantitative relationship has been established between freshwater input and salinity at 20 locations in the estuary by conducting eleven model simulations with various levels of freshwater inflow along with statistical analysis of measured flow and salinity data. The correlation is strongest in the upper Northwest Fork. Both the field data and model results indicate that a change of freshwater input as small as 10 cfs can cause detectable salinity changes in this area (SFWMD 2002). The flow-salinity relationship at the 20 locations will need to be verified using new data collected since the completion of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006). The impact of additional sources of freshwater such as those from the L-8 Canal and L-8 Reservoir and groundwater seepage also needs to be considered concerning salinity in the estuary and hydroperiod in the freshwater floodplain.

In addition to freshwater inflows, changes in long-term sea levels also have an impact on salinity regime in the system. The sea level record from a site in south Florida indicates that the sea level has been rising at a rate of approximately 2.3 millimeters per year (SFWMD 2002). Sea level rise has had a significant impact on the river and estuary during the past century (McPherson et al. 1982). Rising sea level will alter upstream hydrodynamics and salinity conditions in the river as salt water moves further upstream (Hu 2002). Future sea level rise may also affect exchange of sediment through the inlet and deposition of sediment in the river channel (Douglas 1991). If sea level rise continues as predicted, it is foreseeable that saline water will move further upstream along with the sea level rise (SFWMD 2002). Understanding the potential influence of sea level rise on salinity regimes in the river is important to evaluate the opportunities for long-term restoration success within the Loxahatchee River. It is conceivable that adaptive management may be a critical aspect of fending off the anticipated effects of various sea level rise scenarios.

Recommended Technical Needs

- Continue flow, salinity, and stage monitoring programs.
- Update flow and salinity regression relationship using new measured data.
- Evaluate benefits of additional sources of freshwater from the L-8 Reservoir and groundwater seepage along with the operational feasibility study.
- Evaluate the impact of sea level rise on the stage and salinity of the river for the evaluation of the full benefit of restoration and the development of strategies to address or offset sea level rise. More sophisticated models and topographic data that are now available will be used for these evaluations and analyses.

3.2.3 Characterize Water Quality (Research Objective 2.3)

Changes in water quality within the river and estuary has caused substantial ecological consequences (Ridler et al. 2006), and is closely related to upstream water management and human development (McPherson and Sonntag 1984, Millie et al. 2004). Key water quality parameters are total suspended solids, temperature, salinity, nutrients (nitrogen and phosphorus), chlorophyll *a*, dissolved oxygen and turbidity. The thrust of this component is to characterize water quality condition through analyses of short-term and long-term water quality patterns in the river and estuary.

From about the 1970s, water quality monitoring in the river and estuary was performed by the USGS, FDEP, SFWMD and LRD. In the 1990s, the LRD began the River Keeper project, which sampled water quality bi-monthly or monthly throughout the Loxahatchee River watershed at approximately 40 sites. Water quality parameters can vary substantially and quickly under different freshwater flow conditions having serious implications for an array of aquatic habitats and organisms. To address this variability, a high temporal frequency monitoring program was conducted using *in situ* monitoring devices at approximately nine locations throughout the Loxahatchee River. At seven saltwater influenced locations, the units collected salinity, temperature and depth data every 15 minutes, and dissolved oxygen and pH every 60 minutes at two freshwater locations. In 2006, a water quality storm event sampling program was initiated to estimate the event mean concentrations of nutrients and suspended solids in stormwater runoff to quantify loadings to the river and estuary. This event sampling has been conducted on the Northwest Fork, Cypress Creek, and the lateral canals in Jupiter Farms.

Numerous factors influence the water quality of the system. The primary pressures and drivers on water quality are freshwater inflow, nutrient inputs, temperature, irradiation, rainfall and evaporation. These factors can be evaluated in a variety of ways (Møhlengerg et al. 2007, Zurr et al. 2003, 2007, Muñoz-Carpena et al. 2009). The Loxahatchee River and its watershed is a Group 2 Basin in FDEP's total maximum daily load (TMDL) program. Some portions of River and tributaries are impaired due to low levels of DO, nutrients, bacteria, and impaired biology.

Recommended Technical Needs

- Continue the River Keeper, high frequency, and storm event monitoring.
- Analyze long-term trends and short-term variability of water quality to provide a comprehensive view of existing water quality data.
    - Efforts should be made to identify the temporal trends, seasonal variation, spatial variation, typical statistics and statistical distribution of water quality data (Doering 1996, Chamberlain and Hayward 1996, Møhlengerg et al. 2007).
    - Emphasis should be placed on quantitative relationships between water quality and primary drivers such as relationship between nutrients and chlorophyll *a* concentrations so as to provide technical basis for water quality management.
- Develop nutrient budgets for the Northwest Fork over a range of time scales from month to decade to determine the primary sources and pathways of nutrients in the River.

3.2.4 Predict Riverine and Estuarine Responses (Research Objective 2.4)

Predictions of riverine and estuarine abiotic response to altered watershed hydrology and saltwater intrusion rely on a solid understanding of system hydrology, hydraulics, hydrodynamics, salinity dynamics and nutrient cycling. More specifically, formulation of the preferred restoration scenario for the Northwest Fork largely depended on models to accurately predict long-term freshwater flow and salinity. The relationship of inflow and floodplain inundation, flow and salinity, and water quality characteristics resulted from the research efforts identified in previous sections (3.2.1, 3.1.2, and 3.2.3) provide a sound scientific base to develop an integrated modeling tool to predict riverine and estuarine responses.

During the past several years, the SFWMD has initiated several data collection and numerical model development projects. Three numerical models have been developed to simulate riverine and estuarine responses. The following paragraphs provide a description of these models and the need for model refinements.

<u>CH3D</u>

A Curvilinear-grid Hydrodynamics Model in Three-dimension (CH3D) model was developed to examine the effectiveness of saltwater barriers for salinity management of the Northwest Fork. The CH3D model was calibrated with 2003 data, and verified with the first four months of 2004 data. Since the model was developed, more contemporary results (e.g., salinity, tide, freshwater inflow) have been collected, and some of the data reflect the influence of new land use development and submarine groundwater discharge.

Recently, the USGS and the SFWMD conducted a study that demonstrated the utility of ^{222}Rn and four naturally occurring isotopes of radium to estimate rates and occurrence of submarine groundwater discharge to the system during two sampling events that target high and low discharge conditions (Swarzenski et al. 2006). The study shows that estimates of average submarine groundwater inflow ranged from 100,000 to 380,000 cubic meters per day ($m^3\ d^{-1}$) or 20 to 74 liters per square meter per day ($L\ m^{-2}\ d^{-1}$). It is recommended that the CH3D be updated with these new data including the recent submarine groundwater discharge information.

The results of the water quality monitoring efforts and studies conducted by the LRD, USGS, FDEP and SFWMD (see Section 3.2.3) provide the foundation for calibrating a water quality model. A well developed numerical water quality model is an effective and important tool to predict water quality response to watershed water quantity and quality loading to the Northwest Fork. Since a standalone water quality model based on the Environment Fluid Dynamic Code (EFDC) model has been successfully coupled with CH3D for the St. Lucie Estuary, a similar approach is recommended in developing a water quality model for the Loxahatchee River and Estuary.

BEST3D-ISGO

A Bay/Estuary Hydrodynamics and Sediment/Contaminant Transport model for 3D Integrated Surface, Groundwater, and Overland Regimes (BEST3D-ISGO) was developed to simulate floodplain habitat, hydroperiod and salinity in the Northwest Fork. The model domain encompasses the upstream portion of Northwest Fork, from river mile 13.2 to river mile 4.0. It is recommended that the current model be extended to cover all of the Northwest Fork floodplain and estuary starting from Lainhart Dam (river mile 14.8) to Jupiter Inlet (river mile 0.0). In this way, the model will be able to simulate all floodplain hydroperiod and salinity, including all the upstream riverine and estuarine floodplains. Furthermore, groundwater table and salinity data were collected beginning in 2004, and soil moisture and pore water salinity data were collected from 2004 to 2007. The model should be recalibrated using these newly available data.

Estuarine Hydrodynamic/Salinity (RMA) Model

A Hydrodynamic/Salinity (RMA[1]) Model was developed to study the influence of freshwater flows from the tributaries of the Northwest Fork and the S-46 structure on the salinity conditions in the river and estuary. The salinity data collected at five sites from the Jupiter Inlet (river mile 0.70) to river mile 9.1 were used for model calibration. The main focus of salinity modeling has been on the upper reaches of the Northwest Fork. The two-dimensional (2-D RMA-2) model is used to simulate hydrodynamics and the salinity model (RMA-4) is applied to simulate the salinity using RMA-2 results. The developed RMA model was used to simulate 12 scenarios of freshwater inflow determined by the WaSh model output for 20 sites, from which the regression equation was established to quantify the relationship between freshwater flow and salinity. The RMA model was applied in the course of the MFL study. A long-term salinity model was developed using the regression equations from the RMA model output and field data.

Recommended Technical Needs

- Further develop the CH3D model with additional model calibrations using flow and salinity data collected recently considering the need to understand stratifications and water quality of the Loxahatchee River and model computation efficiency.
- Develop a water quality model based on EFDC water quality mechanisms to enhance predictive capacity of estuary water quality.
- Further calibrate the BEST3D-ISGO model with groundwater table and salinity data collected beginning in 2004, and soil moisture and porewater salinity data collected from 2004 to 2007 and extending the model domain to cover all of the Northwest Fork floodplain and estuary to simulate the changes of water level and salinity in the floodplain.

[1] RMA models refer to a series of hydrodynamic/salinity models developed by Resource Management Associates.

3.3 Enhance Riverine and Estuarine Biotic Resources (Management Objective 3)

Enhancement of riverine and estuarine biotic resources is the third **management objective** of this plan emphasizing resource-based freshwater inflow management for receiving waters such as the Northwest Fork of the Loxahatchee River (Alber 2002). Major ecological resources include isolated wetlands and sloughs, sub-tropical cypress swamp and mixed hardwood forest, fish, oysters, and seagrasses in the estuary. These ecological communities have been and still are primarily influenced by variation in freshwater inflow.

Favorable distribution, abundance and composition of riparian wetland communities, fish and invertebrates, oysters, and SAV have the capacity to indicate responses to freshwater input along the land-sea continuum over a range of temporal scales (daily to decadal). These VECs were defined and described along with the Guiding Research Questions in Section 1.3. This management objective addresses Guiding Research Questions 1 (VEC baseline status), 2 (favored abiotic conditions), 3 (VEC responses over time), 6, 7 and 8 (VECs versus watershed attributes). In this section, four research objectives for riverine and estuarine biotic resources were established to serve as a guide to inventory and summarize ongoing projects, identify information gaps, and prescribe potential new projects:

- Research Objective 3.1: Assess baseline status of VECs (see Section 3.3.1)
- Research Objective 3.2: Characterize (define) mechanisms linking abiotic factors and VECs (see Section 3.3.2)
- Research Objective 3.3: Predict ecosystem responses to changes in abiotic and watershed attributes (see Section 3.3.3)
- Research Objective 3.4: Evaluate habitat and ecosystem improvement (see Section 3.3.4)

A variety of ongoing projects conducted in the study area were categorized by the particular research objective, project title and status (i.e., historical, periodic, ongoing). Each research objective has an associated inventory of research projects and an evaluation of necessary and/or missing information (**Table 3**).

Table 3. Inventory of ongoing, completed and proposed projects to restore and protect riverine and estuarine biotic resources (Management Objective 3).

Research Objectives	Information Needed	Projects	Project Status	Recommend
Assess baseline status for VECs	• SAV community composition and abundance • SAV distribution over a range of scales • Oyster biomass, condition index and disease frequency • Oyster distribution through Northwest Fork • Characterization of oyster reef-related fauna • Low salinity zone fauna characterization • Floodplain vegetation community composition • Floodplain vegetation comparisons with previous years • Characterization of fish communities • Responses of particular indicator fish species • Assessment of terrestrial and aquatic wildlife • Characterization of bottom type	LRD Patch-scale Monitoring	Ongoing bi-monthly	Continue
		LRD Landscape Monitoring	Semi-annually	Continue
		Spatial Mapping of SAV	Last mapped in 2010	Continue
		RECOVER Oyster Monitoring	Monthly and semi-annually	Continue
		Spatial Mapping of Oysters	Last mapped in 2008	Continue
		FIU Oyster-Associated Fauna	2009	Continue
		Northwest Fork Low Salinity Zone Study	Last conducted in 2004	Continue* w/optimization
		Freshwater Benthic	1991-2008	Continue w/modification
		Riverine and Tidal Floodplain Vegetation	Ongoing since 1984	Continue
		Baseline Watershed Fish Survey	2007	Continue*
		FIU Snook Movement	2009	Continue
		FIU/LRD Snapper Habitat/Feeding	2008	Continue
		FWC/MRL Snook Tagging	Since 1980s	Continue
		FWC Mercury Testing	As needed	Continue
		Amphibian Study	2008-2009	Continue w/optimization
		Reptile Study	2008-2009	Discontinue
		Alligator Study	2008-2009	Continue
		Small Mammal Study	2008-2009	Continue w/optimization
		General Survey of Birds	2008-2009 monthly	Continue w/optimization
		Osprey Nesting Survey	Annual (Initiated 1989)	Continue
		FWC Manatee Synoptic Surveys	Annual (Initiated 1970s)	Continue
		Manatee Carcass Recovery and Rescue Program	As needed	Continue
		PBC Manatee Aerial Surveys	2009-2011 bi-weekly	Continue
		FIU/LRD Snapper Age and Growth	Proposed*	
		Biomass data for SAV model calibration	Proposed	
Characterize (define) mechanisms linking abiotic factors and VECs	• Salinity-flow relationships • Salinity envelopes for individual VECs • Floodplain elevation, shape and hydroperiod • Suspended solid inputs and concentrations • Dissolved nutrient inputs and concentrations • Submarine light dynamics	Floodplain wetland and salinity indices	Initiated 2009	Continue
		FIU S-46 Release Event Monitoring	Test initiated 2009	Continue
		Freshwater Fish Flow Study	2008	Continue w/optimization
		Larval Frog Flow/Stage Assessment Study	Proposed	
		Pulse Release Event Study	Proposed	

Research Objectives	Information Needed	Projects	Project Status	Recommend
Predict ecosystem responses of changes in abiotic & watershed attributes	• Evaluate and understand empirical data • Incorporate abiotic driving variables • Functional responses for VECs • Systematic series of simulations to test VEC responses to range of altered hydrology • Scenario runs based on realistic changes in watershed and abiotic factors	Develop VEC response models for Northwest Fork	Initiated 2009	Continue
		Data analyses for parameter estimation	Initiated 2009	Continue
		Develop functional responses for VECs	Initiated 2009	Continue
		Calibration, verification and application of VECs models	Proposed	
Evaluate habitat and ecosystem improvement	• Integrated models (hydrologic, abiotic and biotic) • Spatial datasets and geographic information system (GIS) applications • Manipulative experiments (mesocosm and in situ) • Habitat restoration projects • Public outreach and community projects	LRD/FIU/Nature Conservancy Oyster Restoration	Ongoing	Continue
		FDEP River Carrying Capacity Project	Surveyed in 1985,1995,2000	Continue
		FPS Jonathan Dickinson State Park River Demonstration Project	Ongoing	Continue
		Wild Taro Project	Proposed	
		Osprey Artificial Nest Utilization Project	Proposed	
		Evaluate cumulative effects and summarize impacts	Proposed	

*Conduct fish studies in both the riverine reach and the low salinity zone to establish flow and salinity performance measures relating to the abundance and diversity of fishes in the river.

3.3.1 Assess Baseline Status of VECs (Research Objective 3.1)

This research objective is to establish baseline condition of VECs in the Northwest Fork. The baseline conditions will be used to compare restoration benefit in terms of habitat enhancement or ecosystem improvement (**Section 3.3.4**). To achieve this goal, conceptual models were developed for each VEC to identify drivers, stressors, and effects affecting the VEC. This is important since changes in VECs and habitats are deemed to be measureable through implementation of management and restoration activities. An example of a conceptual ecological model for the floodplain forest VEC is shown in **Figure 7**. Sea level rise, climate change and water management are identified as the drivers while nutrients, hydrodynamics, soil type and other factors are identified as stressors. Effects are shown as salinity, saltwater intrusion, flow, altered hydroperiods, hurricane, fire, lumbering, changes in light and canopy cover, and the invasion of exotic vegetation species. The major concern in the riverine reach is the lack of post development inundation. This lack of inundation encourages the intrusion of native transitional, upland and non-native plant species; modifies the subcanopy vegetation into multiple forest types of communities; and reduces the utilization of the floodplain swamp by aquatic organisms. The tidal portions of the river have experienced a loss of freshwater vegetational species (i.e., bald cypress [*Taxodium distichum*]) and a shift to more saltwater tolerant plants (i.e., red [*Rhizophora mangle*] and white [*Laguncuaria racemosa*] mangroves) associated with increases in salinity and tidal amplitude (Roberts et al. 2008). The following paragraphs describe the major on-going monitoring activities listed in **Table 3** to establish the baseline conditions for each of the VECs identified in the Restoration Plan (SFWMD 2006).

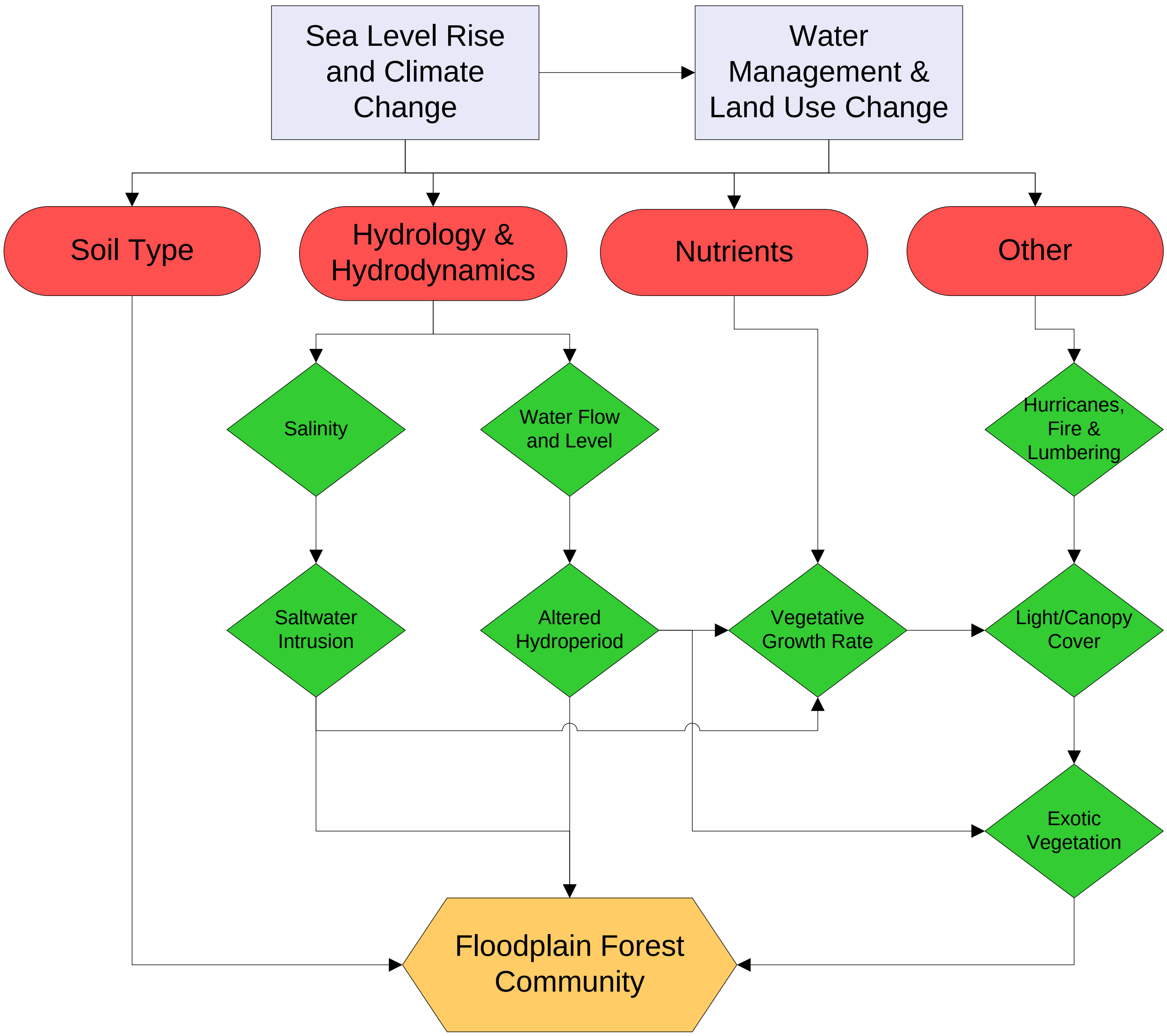

Figure 7. Example of a floodplain forest conceptual ecological model for the Loxahatchee River.

<u>Floodplain Vegetation</u>

Since 1984, the SFWMD and FPS have monitored the major plant communities identified as swamp, bottomland hardwoods, hammocks and uplands (SFWMD 2009). Additional vegetation studies consisted of bald cypress and pond apple (*Annona glabra*) mesocosm and field studies, hurricane impacts, and photo points to compare changes. As a result of these studies and literature review, the recommended restoration flows to the riverine floodplain will be inundated for four to eight months with the hydric hammock flooded for one to two months in a year. This inundation should also improve habitat for tadpoles and juvenile and adult fishes. Within the upper tidal floodplain, the increased freshwater flows will allow for recruitment and re-establishment of freshwater plants and animal species. The preferred restoration scenario will push the saltwater front from near river mile 9.5 to between river miles 8 and 7.5 (SFWMD 2006).

Fisheries

During natural inflow conditions, the low salinity zone, which has salinity from 1 to 10 psu, can be a superior habitat for fish larvae and juveniles due to the exclusion of marine predators; reduced visibility from high levels of suspended solids, color and phytoplankton; and the abundance of nutritious food (Day et al. 1989). The low salinity zone is an area of high biological productivity due to the interactions of physical, geological, biogeochemical and faunal processes (Wolanski et al. 2004). Freshwater inflows play a major role in maintaining high production rates within the low salinity zone (Fisher et al. 1988, Day et al. 1989, Montagna and Kalke 1992).

The SFWMD conducted low salinity zone larval fish studies (**Table 3**) from 1986 through 1988 and again in 2004 for the restoration plan (SFWMD 2006). Greatest densities of larval fish were captured at salinity from 2 to 8 psu. While productivity is often positively correlated with the quantity of freshwater discharge, both reductions and increases in discharge can result in reduced productivity (Wilbur 1992, Livingston et al. 1997, Turner 2006). Reductions in inflows, with associated nutrient and detritus losses, can decrease the primary productivity of phytoplankton and, in turn, secondary productivity (e.g., benthos and predatory fishes). Too great a flow can flush planktonic organisms downstream and, therefore, decrease productivity in the inner estuary. Management of inflows during the dry season will allow the productive low salinity zone to exist in areas that will provide physical habitat for fish larvae and juveniles.

In 2007, the multi-agency Baseline Watershed Fish Survey was conducted to provide a list of fish species present in the watershed, isolated wetlands and sloughs, and the river and its tributaries. The composition of fish fauna determined from this analysis indicated river channel, wet prairie and tributary creeks supported common native freshwater species along with a few exotics species. In 2008, the Freshwater Fish Flow Study was conducted on the riverine reach of the Northwest Fork by the SFWMD and CSA International, Inc. (2009). The objectives of this study included summarization of the status of endangered and threatened species, species of special concern, and exotic fish species. This survey represented the first systematic fish sampling program undertaken in this portion of the river.

The FWC and their Wildlife Research Institute are conducting fish studies on habitat utilization and resource partitioning of largemouth bass (*Micropterus salmoides*) and common snook (*Centropomus undecimalis*) in the Loxahatchee River. FIU used acoustic tags to monitor long-term movements of snook and gray snapper (*Lutjanus griseus*), and to assess shorter-term movements of gray snapper in proximity to docks where oyster reefs were created. Future work will attempt to identify snook dietary patterns based on river location and level of freshwater inflow. The FWC also works with the Florida Department of Health to document mercury levels in fish tissue from the Loxahatchee River watershed and offshore marine environment to issue special consumption advisories if necessary. Results from these studies will be used to create best management practices for fisheries production in relation to inflows from the watershed.

Oysters

RECOVER monitors larval recruitment, adult disease infection frequency, live versus dead and overall health status of the Eastern oyster (*Crassostrea virginica*) in south Florida estuaries including the Loxahatchee Estuary. In addition to the efforts of RECOVER, LRD monitors and maps oyster populations (2003 and 2008) and monitors recruitment of the American oyster every 28 days in upstream and downstream sites of the Northwest and Southwest Forks. Finally, FIU is conducting a study in the Northwest Fork between river miles 4.0 and 6.5 to determine faunal species composition of the oyster reef community and examine whether any of these organisms can be used as sensitive indicators of water quality.

SAV

The final VEC targeted for fundamental assessment are seagrasses. The seagrasses growing within the Loxahatchee Estuary are *Halodule wrightii* (shoal grass), H. johnsonii (Johnson's grass), *Halophila decipiens* (paddle grass), *Syringodium filiforme* (manatee grass), and smaller amounts of *Thalassia testudinum* (turtle grass) and *Halophila engelmanni* (star grass). LRD conducts both landscape- and patch-scale monitoring for seagrass species cover and canopy height at bi-monthly intervals, and performs ground level spatial mapping at four sites in the Central Embayment (Northwest Fork, Pennock Point, Sand Bar and North Bay) as well as at a reference site in the Intracoastal Waterway in Hobe Sound. One species-specific seagrass map with acreage calculations was completed resulting from information obtained from April to October 2007 and a second species-specific seagrass map was just completed with information obtained from April to August, 2010.

Wildlife

A suite of wildlife population studies were conducted by Jonathan Dickinson State Park in 2008 and 2009 to assess the status of amphibian, reptile, alligator, bird and small mammal populations. These studies are listed in **Table 3**.

Amphibians. The monitoring of adult and metamorphic amphibian populations was specifically recommended in Chapter 10 of the *Restoration Plan for the Northwest Fork of the Loxahatchee River* (SFWMD 2006). Amphibian auditory surveys were conducted by the FPS in Jonathan Dickinson State Park.

Alligators. The FPS concentrated on surveying American alligator (*Alligator mississippiensis*) populations between February and December 2008 in the lower river between river miles 6.2 and 10.2 and upstream in fresh water between river miles 10.2 and 14.8. Results from this study are forthcoming.

Birds. Avian population monitoring can provide a baseline against which future changes can be measured (Morrison 2002). Because of the dense vegetation within the floodplain community, most birds are noted by sound rather than sight, requiring the surveyor to have knowledge of species vocalizations. In 2008 and 2009, the FPS conducted baseline bird surveys to assess the variety of birds utilizing the floodplain including songbirds, owls, raptors and wading birds.

Mammals. Since small and medium size mammals utilize the floodplain during different times of year, the FPS employed mammal traps targeted for cotton mice (*Peromyscus gossypinus palmarius*) and cotton rats (*Sigmadon hispidus littoralis*) and established scent stations with a camera between February and May 2008 at six vegetative transects. The scent station was appropriate for marsh rabbit (*Sylvilagus palustris*), squirrels, white-tailed deer (*Odocoileus virginianus*), feral hog (*Sus scrofa*), nine-banded armadillo (*Dasypus novemcinctus*), common opossum (*Didelphis marsupialis*) and raccoon (*Procyon lotor*).

Manatees. The FWC conducts an annual survey of West Indian manatee (*Trichechus manatus*) populations and a Manatee Carcass Recovery and Rescue Program over a period of a few days in the winter when manatees are congregated at warm water habitat sites. Understanding patterns of mortality can discern potential areas of concern related to boat traffic, winter temperatures, and /or the presence of harmful algal blooms. The PBCERM is implementing a Palm Beach County Manatee Protection Plan by conducting aerial surveys every two weeks for two years to determine estuarine and oceanic manatee pathways in Palm Beach County. In the Loxahatchee River, this includes the Northwest, Southwest, and North Forks up to the county line.

Ospreys. In addition to general bird surveys, surveys of osprey (*Pandion haliatus*) populations have been conducted in Jonathan Dickinson State Park from 1989 through 2004. Their breeding success is based on food, weather, timing and experience of the breeding pair, with the key being a reliable food source (Poole 1989, Newton 1979). In the last two years of this survey, the number of occupied nests markedly increased but the reason for the increase is unclear. The reinstatement of the monitoring of these birds is needed both to assess the health of the population as well as to serve as an indicator in the event in prey (fish) availability increases as the river is restored. Improved hydrology in the floodplain should potentially increase the availability of food such as invertebrates, amphibians and fish and improve nesting habitat suitability for wading birds and birds of prey (Bancroft et al. 1988).

<u>Recommended Technical Needs</u>

- Continue all VECs baseline monitoring activities.
- Conduct fish studies in both the riverine reach and the low salinity zone to establish flow and salinity performance measures relating to the abundance and diversity of fishes in the river. The fish data should be collected during the dry season in conjunction with monitoring of flow, stage, salinity and other water quality parameters.
- Collect semi-annually dry weight seagrass biomass and macronutrient (e.g., carbon, nitrogen and phosphorus) contents for seagrass model development to predict the responses of seagrass to changes in abiotic (and biotic) drivers.

3.3.2 Characterize (Define) Mechanisms Linking Abiotic Factors and VECs (Research Objective 3.2)

This biotic research objective connects patterns of flow, hydroperiod, salinity and light to historical, observed and potential responses of the biological processes unique to each VEC. The information needed for this objective includes the flow-salinity relationships, floodplain attributes and hydroperiod, material (particulate and dissolved) loads from the watershed and concentrations in the water column, and submarine light dynamics (**Table 3**). While conservative in nature, salinity is both an indicator of flow and a modulating factor for all of the VEC responses. Flow-salinity relationships will be used to derive salinity envelopes, or optimal spatial ranges under varying discharge, for each VEC from the upstream reaches of the Northwest Fork to the main embayment and the Southwest Fork. The following paragraphs highlight the data needs to quantify the responses of VECs to watershed and abiotic drivers.

Fisheries

Fish utilize the freshwater reach and low salinity zone of River throughout the year. A strong influx of fish larvae occurs during the late dry season from March to June (Flannery et al. 2002). This does not diminish the importance of the low salinity zone as fish nursery habitat during the winter dry season (November to February), when many spring, summer and fall larval migrants have become juveniles that utilize benthic and littoral areas in the low salinity zone. Since planktonic fish larvae are highly sensitive to environmental conditions, the management of freshwater inflow to restore the floodplain vegetation will also be important to fishes during this time of year (November to June). To better understand and manage freshwater flow within this system, data on naturally occurring pulsed events should be collected to determine how the system responds both physically (includes hydrography and salinity) and biologically (includes benthic and planktonic organisms).

Floodplain Vegetation

The next step in research and management of the floodplain community is the development of a floodplain wetland and salinity indices specifically for the Loxahatchee River. Similar floodplain indices were developed for the Apalachicola River. In a 2008 USGS study of the Apalachicola River, forest composition and field observations from 1976 data were used as a baseline comparison (Darst et. al. 2008), with data from plots sampled in 2004. In 2008, the FPS and SFWMD created both wetland and salinity categories for each canopy species on the Loxahatchee River floodplain. Salinity categories were determined for each canopy species from the literature, University of Florida mesocosm studies of bald cypress and pond apple (Liu et al. 2007), and observations on the Loxahatchee River floodplain. Further analysis of the Loxahatchee wetland and salinity indices will better quantify the changes observed over time. Canopy species are re-examined every six years on the Loxahatchee River floodplain. Data from the 2009 canopy study will be compared with 1994 and 2003 datasets.

Oysters

The eastern oyster is very sensitive to extreme salinity preferring mid-range values of 10 to 30 psu with greatest larval recruitment occurring from 17 to 24 psu (Shumway 1996, Turner 2006). Oyster survival data under varying degrees of exposure and duration of extreme low and high salinity conditions are lacking.

SAV

Since the SAV within the Northwest Fork are marine species (e.g., seagrasses) they require salinity greater than or equal to about 15 psu, but grow optimally closer to 25 psu. Freshwater discharges influence SAV presence/absence, community structure, aerial extent and productivity by (1) timing; (2) quantity; and (3) quality. Alterations to freshwater inflows can have dramatic effects on both estuarine salinity as well as water column light attenuation. Environmental boundaries and tolerances for each of the various SAV species need to be assessed through field manipulations, enhanced monitoring information, and modeling exercises. Ridler et al. (2006) showed that excessive salinity variability had a severe negative impact on seagrass in the Loxahatchee River. Additional studies need to compare affects of chronic low salinity to effects of extreme salinity variability in the Loxahatchee River. Seagrasses are also sensitive to both the quantity (greater than 20 percent surface irradiance at the bottom) and quality of down-dwelling light, which in turn, is influenced by a combination of chromomorphic dissolved organic matter (CDOM), inorganic suspended solids and phytoplankton biomass (as indicated by chlorophyll *a* concentration). These factors need to be considered when the seagrass to light relationship is assessed.

Amphibians

A new VEC under consideration for the Loxahatchee River are adult and larval amphibian populations. In the restoration plan (SFWMD 2006), the literature was reviewed for information on the days of inundation required for complete metamorphosis of frogs and toads reported from south Florida. No information was gathered at the time on the effects of saltwater intrusion and reduced freshwater flow on amphibian populations. This information is needed to determine how local amphibian populations in the watershed and on the floodplain might respond to proposed restorative increases in wetland hydroperiod and reductions in salinity. Baseline studies in 2008 and 2009 have been conducted on adult amphibian populations. However, additional adult frog studies and new tadpole (metamorphic stage) studies are recommended to be designed to determine if seasonal restorative flows are adequate and timely for native frog species to reproduce and determine if salinity is a factor in native and exotic frog abundance and distribution.

Recommended Technical Needs

- Continue analyses comparing flow to salinity, nutrients, productivity, larval fish production, freshwater fish assemblages, oysters, seagrasses, and suspended solids to further examine the connections between VECs and abiotic drivers.
- Continue the development of a floodplain salinity index.
- Conduct pulse release event study to determine how the system responds both physically (includes hydrography and salinity) and biologically (includes benthic and planktonic organisms) for better understanding and managing freshwater flow within this system.
- Analyze the relationship between flow and adult and larval amphibians.

3.3.3 Predict Ecosystem Responses to Changes in Abiotic and Watershed Attributes (Research Objective 3.3)

Models rooted in ecological processes, scaled to the environmental questions and drivers, and heavily tested through empirical data and experimental results have great potential as management tools. Users can manipulate inputs, rate constants and other variables in order to test VEC responses to variable abiotic conditions related to watershed hydrologic changes. This biotic research objective links multiple stressors to multiple response variables of VECs with varying mathematical forms in an ecosystem context. Initiated and proposed projects must focus on potential responses and feedbacks between extant and altered abiotic conditions and the enhancement of biotic resources or VECs. This research objective builds upon the changes in hydroperiod, salinity-flow relationships, salinity envelopes, material loading and water column concentrations, and other drivers defined through Research Objectives 3.1 and 3.2. Development of predictive frameworks requires an infusion of analyzed and digested observational data, incorporation of abiotic drivers that vary at specified spatial and temporal resolution and functional responses for individual VECs. The model results may function as valuable hypotheses that can and should be tested with empirical data.

Data for this research objective can be divided into that used for baseline definitions, model calibration and model output validation. Definition of the extent or spatial domain of the model must be initial and explicit so that boundary conditions can be established. Inputs of water and materials from the watershed to the surface water of the Loxahatchee River and Estuary will be derived from the suite of studies associated with Management Objective 2, which concerns abiotic conditions. An important step is the analyses of existing water column data (i.e., physical properties, particulate matter and dissolved substances). Advanced data analyses allow for relationships and linkages between abiotic drivers and biotic responses to be quantified. This backdrop of model boundaries, system biogeochemical attributes, and lateral inputs sets the stage for development of process-based, ecosystem simulation models.

It is very difficult to integrate all information and predict possible feedbacks and responses to changes in flow and salinity without appropriately resolved time series water column data. Contiguous time series for salinity, submarine light, temperature, dissolved oxygen, suspended solids, and dissolved substances including color dissolved organic matter and nutrients are useful to describe the systems, calibrate predicted concentrations, or use to validate or verify model results. Proper development of predictive and prescriptive modeling tools will minimally require daily salinity observations at multiple locations along a gradient in the Northwest Fork.

While some physical, chemical, geological and biogeochemical data are needed to initiate and calibrate simulated variables during model development, other data must be customized and reserved for validation of model output. Predicting the responses of each of the VECs (i.e., floodplain forest species composition, low salinity zone food web, oyster location and status, and seagrass distribution and abundance) requires observational data gathered at the appropriate scale. For example, re-establishment of cypress forest in the upstream floodplain may take a decade, while changes in food web structure and carbon cycling at the low salinity zone interface occurs on a daily or weekly time scale. Changes in oyster and seagrass habitats with changing freshwater inflow occur on seasonal and annual time scales. The spatial and temporal questions associated with a given VEC should be addressed at a scale at which the management action can be linked to an observable and quantifiable response.

Recommended Technical Needs

- Continue data analyses for VEC model parameter estimation.
- Develop and apply ecological models to quantify responses of the biotic resources or VECs to the changes in altered abiotic and watershed attributes including hydroperiod, salinity, flow, material loading, and water column concentrations.

3.3.4 Evaluate Habitat and Ecosystem Improvement (Research Objective 3.4)

This final research objective of the science plan biotic component will serve to identify and quantify habitat and ecosystem responses to landscape-scale changes in hydrology, abiotic drivers, and biotic patterns caused by watershed and estuarine restoration activities. This objective will integrate and implement the cumulative information gained by establishing baseline values for the VECs (Research Objective 3.1), connecting VEC responses to changes in hydrology and abiotic drivers (Research Objective 3.2), and the ecosystem models and map depictions of changes in VECs with altered freshwater input (Research Objective 3.3). The ultimate goal of this research shall provide the needed technical basis of management decisions and resulting actions and direct future restoration activities.

Large-scale change in hydrology, abiotic drivers, and biotic patterns are typically achieved cumulatively through many of the ongoing restoration projects. These projects are sponsored by CERP, the Loxahatchee River Preservation Initiative Program (http://www.lrpi.us/), the Indian River Lagoon License Plate Program, and by various government agencies including SFWMD, FDEP, LRD, and Palm Beach and Martin Counties.

Ongoing restoration projects on the Loxahatchee River are focused primarily on oyster and seagrass. **Figure 8** shows oyster restoration locations in the Northwest Fork. In 2009, volunteers from school groups, scouts, and the community assembled over 1,300 bags of oyster and fossilized shell and deployed them beneath nine residential docks. Monitoring of the restoration sites shows high oyster recruitment with 50 to 900 oyster spat per square meter, and remarkable utilization by more than 22 species fish, shrimp, crabs and other macro fauna. In 2010, the Loxahatchee River District partnered with Martin County to win a grant funded through the American Recovery and Reinvestment Act of 2009. A total of 5.84 acres of oyster habitat was created in the Northwest Fork. In the floodplain, the Florida Park Service has an ongoing demonstration project to restore native species by removing exotic plants. So far, the natural recruitment of bald cypress seedlings has occurred.

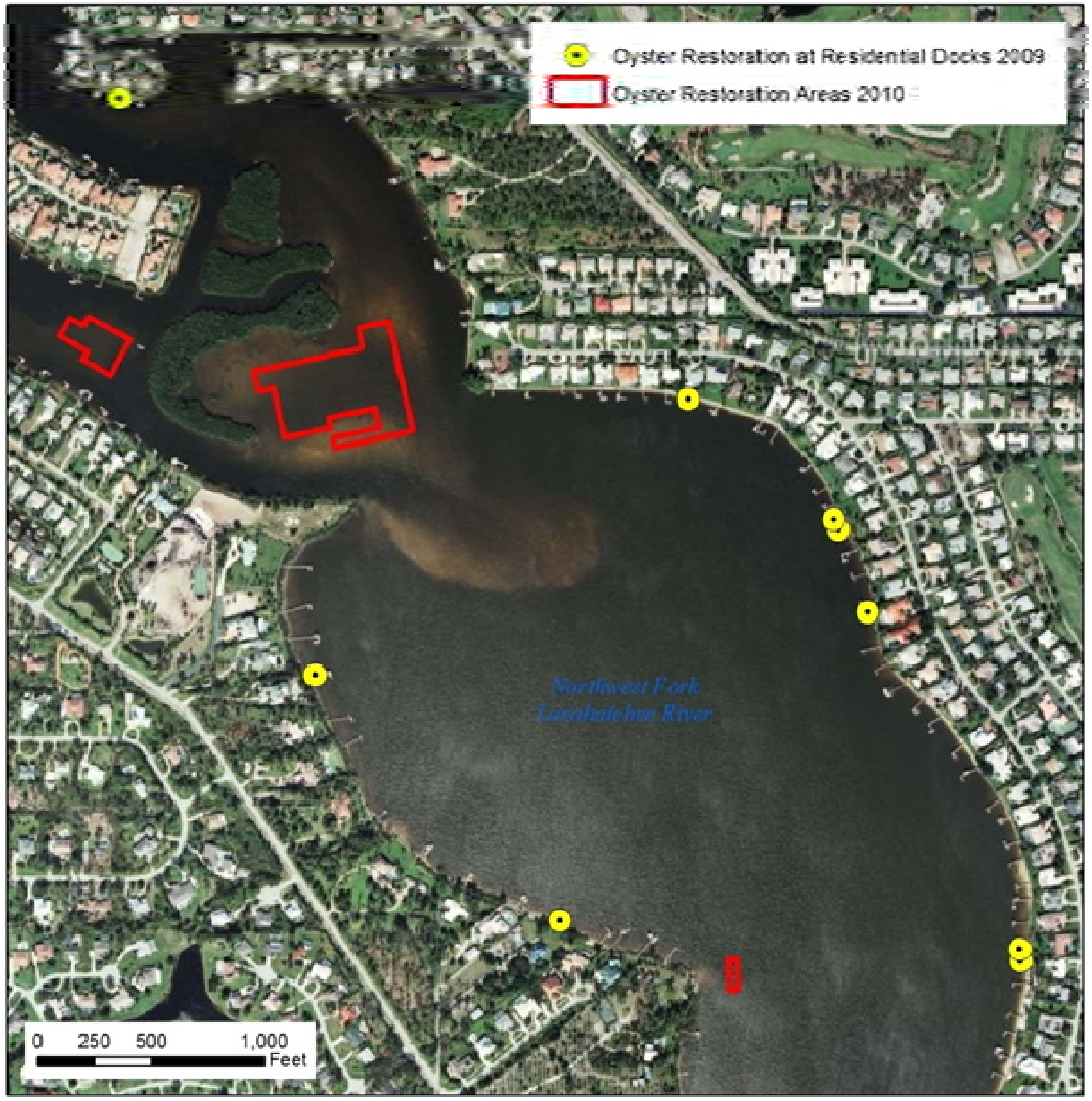

Figure 8. Oyster restoration sites in the Northwest Fork of the Loxahatchee River.

It is recommended that results of previous surveys of the FDEP river carrying capacity study completed in 1985, 1995, and 2000 be evaluated to develop a new work plan to quantify the impact of intense human use of the River on the quality of habitat and ecosystem. The interactions between use and affect on the resource conditions and perceived quality of impacted resources shall be evaluated using data collected in project. Eventually, carrying capacity thresholds will be referenced as key decision making tools throughout the development of preferred numbers and distribution of River users. This will help Loxahatchee River stakeholders make informed decisions regarding visitor use and protection of the sensitive wildlife habitats of the River.

Recommended Technical Needs

- Evaluate the cumulative effects of large scale restoration projects on changes in ecological resources or VECs in the River using integrated information from predictive modeling frameworks with a variety of experimental, demonstration and restoration projects.
- Quantify the impact of intense human use of the River on the quality of habitat and ecosystem using baseline data collection for the river carrying capacity study.

4.0 SUMMARY

The Loxahatchee River Science Plan was developed based on a hierarchical decision analysis framework (Reckhow et al. 1997). This analysis sequentially defines the overall management goal, issue-specific management objectives, research objectives, and research methods that provide qualitative and quantitative knowledge of linkages between watershed hydrologic restoration, abiotic drivers, and biotic responses along the land-ocean continuum. The overall management goal established for the science plan is to restore the Northwest Fork of the Loxahatchee River and enhance the estuary and watershed. Issue-specific management objectives to attain the overall management goal include (1) maximizing watershed restoration benefit; (2) enhancing riverine and estuarine abiotic conditions; and (3) restoring and protecting riverine and estuarine biotic resources.

Following a hierarchical decision analysis, eleven research objectives were identified for data collection and analysis to measure the success of restoration. These research objectives are centered on the theme concerning the science needed to understand the responses of the Loxahatchee River valued ecosystem components (VECs), at both spatial and temporal scales, to variations in estuarine abiotic conditions (e.g., salinity, stage and water quality) and watershed freshwater inflows in terms of quantity, quality, distribution and timing. Since enhancement of the watershed and abiotic conditions is a requisite to enhancing VECs, a list of resource-based research questions to further guide specific research methods was created. By structuring individual projects to address the resource-based questions, the science plan focuses on obtaining information and tools to provide the scientific documentation needed to rationalize potential water management decisions and infrastructure to enhance watershed and river ecology. Inventories of current research and monitoring programs were developed. Information gaps and technical needs were identified to provide qualitative and quantitative knowledge of linkages between watershed hydrological restoration, abiotic drivers and biotic responses along the land-ocean continuum. This outcome will improve understanding of linkages between watershed hydrologic restoration and ecological responses in wetland, riverine and estuarine habitats. As the scientifically-based understanding of the ecosystem evolves and new water management facilities become operational, adaptive management decisions will be scientifically justified and documented to proceed toward the goal of achieving a healthy ecosystem.

The Loxahatchee River Science Plan is envisioned as a guide for scientific efforts to be conducted over the next five years. Implementation of the science plan requires a collaborative effort among the inter-agency team including the South Florida Water Management District, Florida Park Service District 5 and Jonathan Dickinson State Park, Loxahatchee River District, Florida Department of Environmental Protection Southeast District, Martin County Division of Environmental Quality, Palm Beach County Environmental Resources Management, Florida Fish and Wildlife Conservation Commission, and other agencies such as Jupiter Inlet District that are not yet involved. The science plan will serves as the guide for these agencies and stakeholders to efficiently allocate resources to prioritize and implement the needed science, modeling and monitoring projects toward the mutual goal of restoring and protecting the Loxahatchee River's ecological health.

This science plan can also be used by policy makers and stakeholders such as the Loxahatchee River Management Coordination Council (LRMCC) and the LRPI as a communication tool to prioritize, coordinate, and implement applied science activities in the Loxahatchee River watershed to obtain management information and feedback. Scientists conducting the work described in this science plan can provide regular updates to the LRMCC and the LRPI regarding the status of Loxahatchee River valued ecosystem components (VECs). The LRMCC and the LRPI agency representatives, in turn, can use the scientific feedback as guidance to better coordinate individual agency activities.

The Loxahatchee River Science Plan, along with the *2006 Restoration Plan for the Northwest Fork of the Loxahatchee River* and the new *2010 Loxahatchee National Wild and Scenic River Management Plan* directly address state legislative mandates initiated by the Loxahatchee River Wild and Scenic Preservation Act of 1983 and the Federal Wild and Scenic Rivers Act of 1968. The three documents identify the principal governmental authorities responsible for assessing the natural and cultural resources within the river area, and additionally provide recommendations for restoration and preservation strategies and tasks. The role that the science plan plays is to provide the needed technical basis for the implementation of the Restoration Plan and the Management Plan with the concept of adaptive management. It is the strength of these three documents that will guide our future efforts towards true scientific understanding of the issues, best day-to-day operation of water management facilities, and ultimately the restoration and protection of the Loxahatchee River ecosystem.

5.0 REFERENCES

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. Estuaries 25:1246-1261.

Bancroft, G.T., J.C. Ogden and BW. Patty. 1988. Wading bird colony formation and turnover relative to rainfall in the Corkscrew Swamp area of Florida during 1982 through 1985. Wilson Bulletin 1000(1):50-59.

Chamberlin, R. and D. Hayward. 1996. Evaluation of water quality and monitoring in the St. Lucie Estuary, Florida. Journal of the American Water Resources Association 32(4): 681-696.

CSA International Inc. 2009. Loxahatchee River Freshwater Fish Study Phase II: Relationships between Fish Assemblages and Dry Season Flow and Stage Levels on the Riverine Reach of the Northwest Fork of the Loxahatchee River. Report prepared for South Florida Water Management District, West Palm Beach Florida, FL.

Darst M.R. and H. M. Light 2008. Drier Forest Composition Associated with Hydrologic Change in the Apalachicola River Floodplain, Florida. U.S. Geological Survey Scientific Investigations Report 2008-5062, 81p., plus 12 aps.

Day, J.W., Jr., C.A.S. Hall, W.M. Kemp and A. Ynez-Arancibia. 1989. Estuarine Ecology. John Wiley and Sons, New York, NY.

Doering, P. 1996. Temporal variability of water quality in the St. Lucie Estuary, south Florida. Water Resources Bulletin 32(6): 1293-1306.

Doren, R.F., J.C. Trexler, A.D. Gottlieb, and M.C. Harwell. 2009. Ecological indicators for system-wide assessment of the greater Everglades ecosystem restoration program. Ecological Indicators 9(6) Supplement 1:S2-S16.

Douglas, B.C. 1991. Global sea level rise. J. Geophys. Res. 96(C4):6981-6992.

Estevez, E.D. 2002. Review and assessment of biotic variables and analytical methods used in estuarine inflow studies. Estuaries 25:1291-1303.

Fisher, T.R., L.W. Harding, D.W. Stanley and L.G. Ward. 1988. Phytoplankton, nutrients, and turbidity in the Chesapeake, Delaware, and Hudson Estuaries. Estuarine, Coastal and Shelf Science 27:61-93.

Flannery, M.S., E.B. Peebles and R.T. Montgomery. 2002. A percent-of-flow approach for managing reductions of freshwater inflows from un-impounded rivers to southwest Florida estuaries. Estuaries 225(6B):1318-1332.

Harwell, M.A., V. Myers, T. Young, A. Bartuska, N. Gassman, J.H. Gentile, C.C. Harwell, S. Appelbaum, J. Barko, B. Causey, C. Johnson, A. McLean, R. Smola, P. Templet and

S. Tosini, S. 1999. A framework for an ecosystem integrity report card. Bioscience 49:543-556.

Hu, G. 2002. The effects of freshwater inflow, inlet conveyance and sea level rise on the salinity regime in the Loxahatchee Estuary. In Environmental and Water Resources Institute, Proceedings of 2002 Environmental Engineering Conference, July 21–24, 2002, American Society of Civil Engineers-Canadian Society of Civil Engineers, Niagara Falls, Ontario, Canada.

Hu, G. 2006. A salinity management model for restoration of a coastal riverine ecosystem. Pages 1-12 in Estuarine and Coastal Modeling, American Society of Civil Engineers.

Kaplan, D., R. Muñoz-Carpena, Y. Wan, M. Hedgepeth, F. Zheng, R. Robert and R. Rossmanith. In Press. Linking river and floodplain hydrology in a bald cypress (*Taxodium distichum*) swamp impacted by saltwater intrusion. Journal of Environmental Quality.

Liu, G., Y. Li, R. Roberts, M. Hedgepeth, and Y. Wan. 2007. Effects of Solid Oxygen Fertilizer on Alleviating Impacts of Flooding and Salinity on Bald Cypress and Pond Apple. University of Florida Report for Florida Department of Environmental Protection, Florida Park Service 5th District, Tallahasee, FL, and South Florida Water Management District, West Palm Beach, FL.

Livingston, R.J., X. Niu, F.G. Lewis, III and G.C. Woodsum. 1997. Freshwater input to a gulf estuary: long-term control of trophic organization. Ecological Applications 7:277-299

Martin County Growth Management Department. 2000. Loxahatchee River Basin Wetland Planning Project for Martin County. Final report to United States Environmental Protection Agency, Atlanta, GA.

Mattson, R.A. 2002. A resource-based framework for establishing freshwater inflow requirements for the Suwannee River estuary. Estuaries 25:1333–1342.

McPherson B.F. and W.H. Sonntag. 1984. Transport and distribution of nutrients in the Loxahatchee River Estuary, Southeastern Florida, 1979–81. Water Resources Bulletin 20(1):27-34.

Miller, R.E. and B.E. Gunsalus. 1997. Wetland Rapid Assessment Procedure. Technical Publication REG-001, South Florida Water Management District, West Palm Beach, FL.

Millie, D.F., H.J. Carrick, P.H. Doering, and K.A. Steidinger. 2004. Intra-annual variability of water quality and phytoplankton in the North Fork of the St. Lucie River Estuary, Florida (USA): a quantitative assessment. Estuarine, Coastal and Shelf Science 61:137-149.

Møhlenberg, F., S. Petersen, A.H. Petersen and C. Gameiro. 2007. Long-term trends and short-term variability of water quality in Skive Fjord, Demark – nutrient load and mussels are the primary pressures and drivers that influence water quality. Environ Monit. Assess 127:503-521.

Montagna, P.A. and R.D. Kalke. 1992. The effect of freshwater inflow on meiofaunal and macrofaunal populations in the Guadalupe and Nueces Estuaries, Texas. Estuaries 15(3):307-326.

Morrison, M.L. 2002. Wildlife Restoration: Techniques for Habitat Analysis and Animal Monitoring. Island Press, Washington, DC.

Muñoz-Carpena R., D. Kaplan and F. Gonzsalez, 2009. Groundwater data processing and analysis for the Loxahatchee River basin. Contract 4500020860. Final Report submitted to South Florida Water Management District.

Newton, I. 1979. Population of Raptors. Buteo Books, Vermillion, SD.

Poole, A.F. 1989. Ospreys: A Natural and Unnatural History. Cambridge University Press, Cambridge, MA.

Reckhow, K.H., K.S. Korfmacher and N.G. Aumen. 1997. Decision analysis to guide Lake Okeechobee research planning. Journal of Lake and Reservoir Management 13:49-56.

RECOVER. 2009. CERP Monitoring and Assessment Plan. Restoration Coordination and Verification Program, c/o United States Army Corps of Engineers, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL.

Ridler, M.S., R.C. Dent and D.A. Arrington. 2006. Effects of two hurricanes on *Syringodium filiforme*, manatee grass, within the Loxahatchee River Estuary, southeast Florida. Estuaries and Coasts 29(6A):1019-1025.

Roberts, R.E., M.Y. Hedgepeth and T.R. Alexander. 2008. Vegetational Responses to Saltwater Intrusion along the Northwest Fork of the Loxahatchee River within Jonathan Dickson State Park. Florida Scientist 71(4):383-397.

SFWMD. 2002. Technical Documentation to Support Development of Minimum Flows and Levels for the Northwest Fork of the Loxahatchee River. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2006. Restoration Plan for the Northwest Fork of the Loxahatchee River. South Florida Water Management District, West Palm Beach, FL, April 2006.

SFWMD. 2007. Development of BEST3D-ISGO for floodplain habitat hydroperiod in Northwest Fork of Loxahatchee River. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2009. Riverine and Tidal Floodplain Vegetation of the Loxahatchee River and Its Major Tributaries. South Florida Water Management District, West Palm Beach, FL and Florida Department of Protection Florida Park Service, 5th District Office, Tallahassee, FL.

Shumway, S.E. 1996. Natural Environmental Factors. Pages 467-503 in The Eastern Oyster (*Crassostrea virginica*). V.S. Kennedy, R.I.E. Newell and A. Eble (eds), Maryland Sea Grant College, College Park, MD.

Swarzenski, P.W., W.H. Orem, B.F. McPherson, M. Baskaran, and Y. Wan. 2006. Biogeochemical transport in the Loxahatchee River Estuary, Florida: The role of submarine groundwater discharge. Marine Chemistry 101(3-4):248-265

Treasure Coast Regional Planning Council. 1999. Loxahatchee River Basin Wetland Planning Project for Palm Beach County. Final Report to United States Environmental Protection Agency, Atlanta, GA.

Turner, R.E. 2006. Will lowering estuarine salinity increase Gulf of Mexico oyster landings? Estuaries and Coasts 29:345-352

USACE and SFWMD. 1999. Comprehensive Everglades Restoration Plan. Final Feasibility Report and Programmatic Environmental Impact Statement. U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL, and South Florida Water Management District, West Palm Beach, FL.

VanArman, J., G.A. Graves, and D. Fike. 2005. Loxahatchee Watershed Conceptual Ecological Model. Wetlands 25(4):926-942

Wan, Y., C. Reed, and E. Roaza. 2003. Modeling watersheds with high groundwater tables and dense drainage canals. Page 10 in Proceedings of 2003 American Water Resources Association International Congress: Watershed Management for Water Supply, American Water Resources Association, New York, NY.

Wan, Y., J. Labadie, K. Konya, T. Conboy. 2006. Optimization of frequency distribution of freshwater inflows for coastal ecosystem restoration. J. Water Resour. Plann. Manage. 132, 320-329.

Wilbur, D.H. 1992. Associations between freshwater inflows and oyster productivity in Apalachicola Bay, Florida. Est. Coast. Shelf Science 35:179-190.

Wolanski, E., L.A. Boorman, L. Chicharo, E. Langlois-Saliou, R. Lara, A.J. Plater, R.J. Uncles, and M. Zalewski. 2004. Ecohydrology as a New Tool for Sustainable Management of Estuaries and Coastal Waters. Wetland Ecology & Management 12:235-276.

Zurr, A.F., R.J. Fryer, I.T. Lolliffe, R. Dekker, and J.J. Bekema. 2003. Estimating common trends in multivariate time series using dynamic factor analysis. Environmetrics 14:665-685

Zurr, A.F., E.N. Leno, and G.M. Smith. 2007. Analyzing Ecological Data. Springer, New York, NY.